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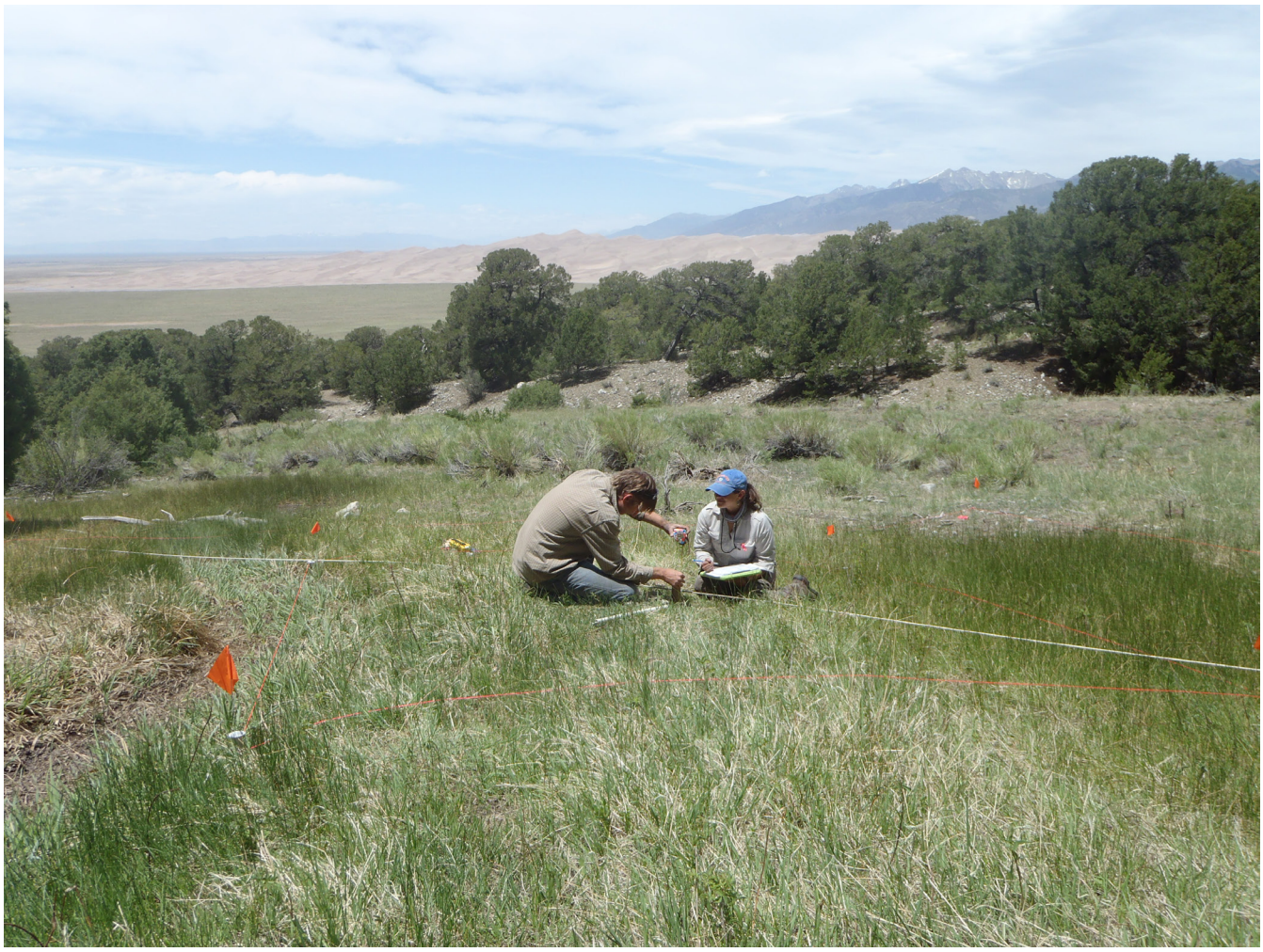
Natural Resource Stewardship and Science

Great Sand Dunes National Park and Preserve Wetland Ecological Integrity

2010–2014 Status and Trend Report

Natural Resource Report NPS/ROMN/NRR—2017/1569





ON THIS PAGE
Establishing a wetland monitoring site at the Great Sand Dunes National Park and Preserve, 2010
(J. JONES)

ON THE COVER
Bison graze a sandsheet wetland at Great Sand Dunes National Park and Preserve
(NPS/SCOTT HANSEN)

Great Sand Dunes National Park and Preserve Wetland Ecological Integrity

2010–2014 Status and Trend Report

Natural Resource Report NPS/ROMN/NRR—2017/1569

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The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

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Executive Summary

Wetlands at Great Sand Dunes National Park and Preserve (GRSA) are important because they are biodiversity hotspots and support iconic wildlife. They also provide valuable "ecosystem services" such as flood attenuation and storage, aquifer discharge and recharge, sediment stabilization and sequestration, carbon storage, water quality enhancement, and nutrient cycling. Wetlands also provide important aesthetic values and are highly valued by visitors.

This report summarizes five years (2010–2014) of wetland monitoring at GRSA. Monitoring included a survey of wet meadow and salt flat wetlands conducted across the sandsheet (essentially across the national park) in 2010 and annual monitoring (2010–2014) at a small set of wetlands, which we call "sentinel sites," on the sandsheet and also at higher elevations in the preserve.

We used this monitoring data to develop two new multimetric models that will enable the National Park Service (NPS) to predict the "ecological integrity" of GRSA wetlands. Ecological integrity is the capacity to support and maintain a balanced, integrated, and adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of natural habitats of the region.

Overall, if we assume that ecologically healthy wetlands in a national park should have minimal human disturbance, the ecological integrity of sandsheet wetlands in GRSA during 2010 warrants moderate to significant concern. Only one (out of more than 90) of our wetland monitoring sites was in a reference (or ecologically healthy) condition as measured by our multimetric indices of ecological integrity. Human disturbances to GRSA wetlands include impacts from ditches, roads, wells installed for livestock, and historical and ongoing human landuse. There are also likely excessive ungulate (especially elk and bison) disturbances and impacts to GRSA wetlands due to overconcentration of these species in wetlands in the national park.

The following sections of the Executive Summary offer a synopsis of the most important methods and results. This is followed by a "summary condition table" that graphically highlights key results and provides a synthetic interpretation of overall status and trend for key indicators, or vital signs, of the park's wetlands.

Methods

Our methods are documented in the peer-reviewed and published *Rocky Mountain Network Wetland Ecological Integrity Monitoring Protocol*. They are largely derived from well-established and existing protocols developed by Rocky Mountain Inventory and Monitoring Network (hereafter, Network) partners, including the U.S. Environmental Protection Agency, Colorado and Montana Natural Heritage Programs, and the U.S. Geological Survey. The application of a standardized monitoring protocol facilitates future comparison of the park's wetlands to those within the ecoregions the park is embedded in.

Network Wetland Ecological Integrity (WEI) monitoring at GRSA includes three sample types/designs: 1) a broad scale random "survey" of all salt flats and wet meadows on the sandsheet (in the national park) conducted every 5–10 years, 2) annual "sentinel" site monitoring at select wetland complexes in the park and at high elevations in the preserve, and 3) sampling at subjectively selected "gradient" sites every 5–10 years (especially sites that have heavy human or natural disturbance and at pristine sites).

At each site, we collect data on vascular and nonvascular plant species composition, woody species (if present), stand structure (primarily cottonwood and willows), and damage and mortality of woody stems. We also collect field and laboratory soil chemistry samples, document *in-situ* groundwater electrical conductivity and pH, and measure depth to water at a shallow groundwater well in the center of the plot. Finally, we document human disturbance and ungulate overuse of habitat in and around each plot and in the wetland complex.

A key step in analyzing and reporting WEI data is interpreting the meaning behind a given result or set of results. In broad stroke, we compare our monitoring results to "assessment points" using qualitative and/or statistical methods. We interpret these comparisons in a collaborative way with park staff and management in the context of ecological theory, NPS Inventory and Monitoring (I&M) Division guidance, NPS resource management policies, and park management objectives. We use various terms to label classes of ecological condition (i.e., integrity), including reference, intermediate, and non-reference, and to label classes of disturbance, including negligible, minor, moderate, and major. A vital sign/indicator in a reference state is within a range of values considered functional, intact, or loosely speaking, "good condition," from an ecological integrity perspective. A non-reference status is degraded, dysfunctional or in a "bad" condition.

Results and discussion

Climate

Long-term climate is one of the key determinants of wetland occurrence, area, biological diversity and ecological functioning. Since 1950, both temperature and precipitation have increased in GRSA, with a notable precipitation increase in the preserve. More recently, a drought that began in 2007 peaked in 2010. Therefore, the wetland data and information from our 2010 survey of park wetlands reflect wetland responses during a time of higher water stress.

Water balance

"Water balance" refers to the flux or changes over time in water in soils or a stream. Soil water balance is, of course, influenced by precipitation and climate but also by other factors inherent in the soil (e.g., particle size or the amount of organic matter). Preliminary work with David Thoma, Ecologist with the NPS Greater Yellowstone Network, and others to model water balance in GRSA soils shows: 1) soil water lags climate and precipitation variables (e.g., drought) by about one year, and 2) there is clear soil water variation among sites (they still follow the same temporal pattern, however). Soil water balance modeling therefore should help us better understand wetland condition and separate out other factors (e.g., ground and surface water hydrology) that impact GRSA wetlands.

Climate change

Recent temperature patterns in GRSA and the San Luis Valley already exceed the historical range of variability and projections are for temperatures to continue to increase. Projections for precipitation are not as clear, but the variability in rain and snowfall will likely increase. Changes in temperature and precipitation patterns will interact with other factors, such as soil water balance and groundwater hydrology, complicating understanding. Regardless, projections suggest that climate change will likely reduce the number and extent of wetlands, cause declines in wetland vegetation and biodiversity, and reduce ecological functioning of park wetlands.

Wetland area

Monitoring wetland extent or area is a primary objective of the Network WEI protocol because larger wetlands tend to have greater biodiversity and proper ecological functioning (both at the individual wetland scale and at the landscape scale). We estimated wetland area on the GRSA sandsheet using 2010 Network survey data and the GRSA vegetation map and report (based on 2007 remotely sensed data). The Network WEI survey estimate is that ~30% of the sandsheet is wetland while the vegetation map based estimate is that 7% of the sandsheet is wetland. We believe the substantial difference is the result of different methods and not a true difference in wetland area between 2007 and 2010. Regardless, both estimates provide a baseline for future comparison and understanding of changes in wetland area (as long as similar methods are used to make these comparisons).

Disturbance

We estimated disturbance at WEI sites during the 2010 park-wide wetland survey and from 2010 to 2014 in select sentinel wetland complexes on the sandsheet. We assembled six disturbance indices (from Network field data and auxiliary data from other sources) in order to better understand the most important and complementary components of disturbance to GRSA wetlands, including: Human Disturbance Index (HDI), Ungulate Use Index (UUI), Landscape Disturbance Index (LDI), Bison Index, Elk Index, and Trail Index.

All sandsheet salty wet meadow habitat had at least some human disturbance in 2010, with no wetland on the sandsheet in a negligible (HDI = 0) disturbance class. Around 50% of the salty meadow on the sandsheet had minor disturbance (HDI < 48), where HDI was low enough that we would expect fewer or less dramatic impacts on the condition of wetlands. In contrast, around 25% had major disturbance (HDI > 60), where we would expect degraded ecological integrity. Similarly, around 13% of the salty meadow wetland on the sandsheet had an ungulate usage level we assumed was sustainable (UUI = 0). An additional 27% had levels below the minor disturbance threshold (UUI < 57). However, 26% of the sandsheet wetland had major ungulate overuse, likely associated with degraded condition. Finally, at sandsheet sentinel wetlands from 2010 to 2014, there was a trend for less human disturbance associated with decreasing impacts from hydrologic alterations. However, there was an increasing trend of more ungulate use and likely stress.

Soil chemistry

Wetland soils store chemicals (e.g., nutrients) and are the medium for chemical reactions that influence wetland plant communities. Wetland soil chemistry at GRSA was typical for the wetland types we monitor in the park and preserve. Soil chemistry data play an important role in models of disturbance and ecological integrity; however, we currently lack ways to assess relationships between soil chemistry, disturbance and ecological integrity. Over the long term, as we accrue data and develop assessment points with the park, we will be able to evaluate potential changes in GRSA wetland soil chemistry, with possible shifts in wetland condition.

In Situ water chemistry

In situ groundwater chemistry at GRSA plays an important role in models of wetland disturbance and ecological integrity. Currently, however, we lack ways to assess relationships between *in situ* groundwater chemistry, disturbance and ecological integrity. Our results do reveal some interesting patterns with disturbance metrics that may assist in the development of assessment points with the park as we accrue more data over the long term. This will also enable us to evaluate potential changes in GRSA wetland *in situ* groundwater chemistry with possible shifts in wetland condition.

Hydrology

Hydrologic regime is fundamental to wetlands and is the primary site-level ecological driver of wetlands, strongly influencing wetland type, vegetation, biogeochemistry, and ecosystem processes such as primary production and decomposition. Understanding hydrology is critical to understanding influences (and interactions) of other drivers and stressors on wetlands, such as ungulate use. Because of this, the Network measures depth to water at all wetland sites.

In 2010 many salt flats and wet meadows had relatively dry (or low) water tables, although some wet meadows were highly variable and often near saturation during later summer. Riparian wetland was generally saturated, with more stable hydrology over time if connected to a spring fed creek. Trend in depth to water varied with the site's context and hydrologic regime drivers. At the Elk Springs sentinel sites, groundwater depth significantly decreased each year from 2010 to 2014, likely reflecting residual impacts from a drought. However, at Big Spring Creek, groundwater depth either significantly increased from 2010 to 2014 or was variable.

Bioassessment

In this report, we provide measures for many individual indicators, including vegetation composition and structure, hydrology, and qualitative or categorical indicators of condition and stress (including anthropogenic, ungulate, and natural stressors). However, wetlands are complex systems and NPS is responsible for protecting and managing ecosystems. Therefore, we focus in this report on two park-specific integrative bioassessment tools (multimetric models) using vegetation community structure as the response and a suite of stressor/drivers and other covariates collected at wetland monitoring sites. Wetland vegetation is our primary indicator of ecological integrity because it is a major component of biodiversity in wetlands and provides habitat for a broad range of other species. Its composition reflects, as well as influences, the hydrology, water chemistry, soil properties and other ecological processes of wetlands. Because plants respond to physical, chemical, and biological drivers and disturbances at multiple temporal and spatial scales, they provide an integrated assessment of wetland health over time and space. Both multimetric models focus on vegetation response to disturbance, but they differ in how they include the two primary stressors of wetlands at GRSA: human disturbance and ungulate habitat use. In one model, given the causal relationship between humans and ungulates (i.e., humans influence how and where ungulates disturb wetlands) we include both as "total disturbance" but focus on human disturbance. In the second, we exclusively use ungulate habitat use as the potential disturbance gradient.

Multimetric Index 1: total disturbance

Our first multimetric index (MMI 1) integrates vegetation metrics, environmental covariates (factors other than human disturbance that also influence wetland health, e.g., precipitation), and human disturbance into an overall measure of ecological integrity. Evaluating wetland ecological integrity on the sandsheet relative to human disturbance, roughly 39% of the salty meadow in 2010 was in a non-reference (degraded) condition, with MMI 1 scores under 4.7. Around 50% was in reference (good) condition, and around 1% was in a near pristine reference state. The remainder (around 10%) was in an intermediate condition.

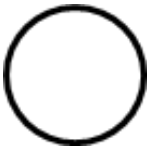
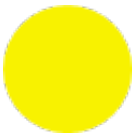
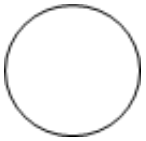
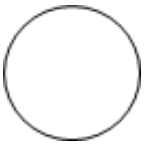
Multimetric Index 2: ungulate use

Our second multimetric index (MMI 2) integrates vegetation metrics, environmental covariates, and ungulate disturbance into an overall measure of ecological integrity. Because GRSA wetlands co-evolved with bison and elk use over thousands of years, some level of native ungulate use is likely "good" for GRSA wetland communities. Because of this, a complete lack of ungulate use of wetlands is not the "best" level for ecologically healthy wetlands. We estimate the appropriate range of ungulate use in wetlands that is "natural" versus the level of ungulate use that "stresses" wetlands (in other words, where ungulate *disturbance* is zero, there is no "stress," but if ungulate disturbance is >0, it is a stressor). Evaluating wetland ecological integrity on the sandsheet relative to ungulate disturbance, roughly 31% of the salty meadow in 2010 was in a non-reference (degraded) condition, with MMI 2 scores under 3.57. Around 38% percent was in reference (good) condition and around 8% was in a near pristine reference state. The remainder (around 23%) was in an intermediate condition.

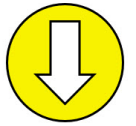
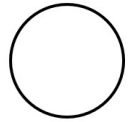
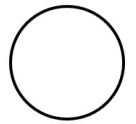
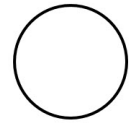
Summary condition table

Summary condition statements for GRSA are given in the table below. We include key indicators, a brief description of results, and symbolize the status, trend, and our confidence in those summaries (as applicable). This table is a considerable simplification of the detail in the full report—it should be used with caution. For example, some indicators within a category have divergent patterns (i.e., one may be in a reference state and another is not). We qualitatively weigh this variance using our best professional judgment to derive an overall assessment within each category.

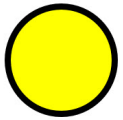
Key for summary condition table.

Condition status		Trend in condition		Confidence in assessment	
Symbol	Description	Symbol	Description	Symbol	Description
	Non-reference condition Major disturbance		Condition is improving		High
	Intermediate condition Moderate disturbance		Condition is unchanging		Medium
	Reference condition Minor disturbance		Condition is deteriorating		Low
	Pristine reference condition Negligible disturbance	No symbol	Unknown trend		
	Unknown or indeterminate condition				

Summary condition table for Great Sand Dunes National Park and Preserve, 2010–2014. Each major results section in the report narrative contains a more detailed summary condition table.

Indicator	Condition description	Condition and confidence
Human Disturbance Index (HDI) (2010)	In 2010 there was a broad gradient in human disturbance, with many sites experiencing relatively high levels of human stress. About 25% of the wetlands on the sandsheet were in a major disturbance class, with another 24% with a moderate disturbance level. No site had zero disturbance—all had at least some measurable disturbance or a "human footprint." Models suggest that HDI did not vary much by wetland type, that it was largely structured by human hydrologic modification and human landuse in and around wetlands, and that it had a strong positive relationship with ungulate use. We interpret this last element as HDI driving or structuring ungulate use.	
Human Disturbance Index (HDI) (2010–2014 trend)	Trend models indicate decreasing human disturbance (8% decrease) at Big Spring Creek, Big Spring Creek Terminus, and Elks Springs sentinel sites through 2014. The reason(s) behind the improvement are unclear as there was no change in wetland management by the park over this time frame at these sites. Models suggest it may be due to decreasing impacts from hydrologic alterations, but more work is needed on this.	
Ungulate Use Index (UUI) (2010)	There was a broad gradient in ungulate disturbance across all sites in 2010. Around 21% and 33% of the park and preserve's wetlands were in a major or moderate ungulate use class (respectively). Around 13% of sites were in a negligible use class, with no indication of overuse by ungulates. Models suggest that UUI varied by wetland type (with more use in riparian wetland), that it was largely structured by human landuse (i.e., fences and roads used in ranching operations), and that higher productivity increased ungulate use.	
Ungulate Use Index (UUI) (2010–2014 trend)	Trend models indicate increasing ungulate use (24% increase) at Big Spring Creek, Big Spring Creek Terminus, and Elks Springs sentinel sites through 2014. The reason(s) behind the increased levels use are likely due to elk as there was a decrease in the bison herd size over this time frame (more research is needed on this) at these sites.	
Soil chemistry	Wetland soils store chemicals (e.g., nutrients, salts) and are the medium for reactions that influence wetland vegetation and plant communities. We are not yet able to analyze soil data relative to human or other disturbances or threats; for the time being, therefore, we do not assign a condition or a trend. We will use this information as a baseline for future comparisons as monitoring continues.	
In situ groundwater chemistry	Groundwater is an important matrix for chemical reactions that influence wetland vegetation and reflects large scale and local disturbances. We are not yet able to analyze water chemistry data relative to human or other disturbances or threats; for the time being, therefore, we do not assign a condition or a trend. We will use this information as a baseline for future comparisons as monitoring continues.	
Peak season depth to water (2010)	*For the time being, we do not assign a condition to peak season depth to water (DTW).* We will use this information as a baseline for future comparisons as monitoring continues. We measure DTW at the peak of the summer when water stress is likely highest at all WEI sites. DTW in sandsheet sites ranged from a low of just over 2 m below ground to 8 cm above ground, with a mean of -75.3 cm (SD = 45.1). Salt flats were the driest type, with riparian wetland the wettest, on average, on the sandsheet. Models suggest higher DTW occurs where there is higher monsoon precipitation in 2008 to 2010, suggesting some GRSA wetlands are likely influenced by precipitation. The degree of human hydrologic alteration was also highly significant in predicting peak season DTW, with greater degrees of alteration lowering (drying) water tables. This pattern plays an important role in bioassessment models, where DTW covaries with important vegetation metrics that influence overall estimates of integrity. Wetland type was also significant, with riparian and marsh sites wetter than salt flats and wet meadows.	

Summary condition table (*continued*) for Great Sand Dunes National Park and Preserve, 2010–2014. Each major results section in the report narrative contains a more detailed summary condition table.

Indicator	Condition description	Condition and confidence
Big Spring Creek depth to water (2010–2014 trend)	Groundwater depth significantly increased over 2010 to 2014 at one site where the hydrologic regime is driven almost entirely by Big Spring Creek. Impacts from a drought began to lessen in 2010, and, while more data is needed given that the site's hydrology is largely buffered by the creek, the improving trend (increasing water table) may reflect this. Our other Big Spring Creek site had a more variable hydrologic regime with no clear pattern. This well was farther from the creek and thus more influenced by variable precipitation and groundwater flows.	
Elk Springs depth to water (2010–2014 trend)	Groundwater depth at both Elk Springs sites significantly decreased each year from 2010 to 2014. Elk Springs hydrologic regimes are nearly entirely driven by groundwater flows likely originating from several diffuse sources, especially a large groundwater mound between Sand Creek and the site. Unlike on Big Spring Creek, there is no perennial spring fed channel that stabilizes the hydrology of the site. The sandsheet area at GRSA has been under drought conditions since at least 2010. While the drought began to wane in 2014, groundwater depths likely were reduced or even still dropping over 2010–2014, with a one to several year lag, perhaps explaining the decreasing trend (dropping water tables) in depth to water at the site.	
Ecological integrity Multimetric Index 1 —total disturbance (2010)	We used custom multimetric (MMI) indices of wetland vegetation condition scaled to the sandsheet portion of the park for bioassessment of ecological integrity. Our first model (MMI 1) estimates the overall ecological condition of wetlands on the sandsheet in 2010 based on the response of multiple vegetation metrics to combined human disturbance and ungulate wetland habitat use. It indicated that aspects of wetlands, like non-conservative species cover, bare ground, and grass cover (mostly weedy annuals) increased with human disturbance and ungulate overuse. Conversely, woody cover, aster cover, and endemic richness decreased. Importantly, the overall model performed better at estimating the response to disturbance than any of its component metrics. Given the integrated nature of the MMI modeling process, we consider these results our primary estimate of ecological integrity of the parks sandsheet wetland. Overall, the MMI 1 model revealed a strong response in wetland ecological integrity to human disturbance and ungulate use at GRSA. Only 1% of the salty meadow wetlands on the sandsheet had pristine reference ecological integrity in 2010. In general, lower MMI 1 estimates of integrity occur along the Big Spring Creek corridor and near ranching infrastructure inside the bison fence. This is an important area of concern for the park.	
Ecological integrity Multimetric Index 1 —total disturbance (2010 – 2014 trend)	We have annual estimates of our first multimetric index (MMI 1) at sentinel wetlands beginning in 2010. Trend models indicate increasing ecological integrity (roughly 4%) at the Big Spring Creek, Big Spring Creek Terminus, and Elks Springs sites through 2014. This matches a decreasing trend in human disturbance (although the reason(s) behind the improvement are unclear as there was no change in wetland management by the park over this time frame at these sites). Several monitoring plots within these complexes moved from an intermediate to a reference condition class, with several transitioning into pristine reference class.	
Ecological integrity Multimetric Index 2 —ungulate use (2010)	Our second multimetric index of wetland vegetation (MMI 2) estimates the overall ecological condition of wetlands on the sandsheet in 2010 based on the response of multiple vegetation metrics to ungulate habitat use alone. It indicated that aspects of wetland vegetation, like native forb and halophyte cover, increased with ungulate use. Conversely, woody and sedge cover decreased. Interestingly, and in contrast to the MMI 1 model that combines human disturbance and ungulate use of wetlands, the MMI 2 model suggested that non-conservative (i.e., weedy) taxa decreased with ungulate overuse. This, perhaps along with increased native forbs, may suggest that the impact of ungulate overuse on wetlands had complex effects, with select aspects of wetland vegetation improving with more ungulate use. Nevertheless, overall the MMI 2 model revealed a strong response in wetland ecological integrity to ungulate (over)use at GRSA. Around 8% of the salty meadow wetlands on the sandsheet had pristine reference ecological integrity in 2010. This is therefore an important area of concern for the park, but perhaps slightly less so than the situation when both human disturbance and ungulate use is modeled (MMI 1, see above).	
Ecological integrity Multimetric Index 2 —ungulate use (2010 – 2014 trend)	We have annual multimetric index 2 (MMI 2) estimates at sentinel wetlands beginning in 2010. Trend models indicate increasing ecological integrity (roughly 1.8%) at the Big Spring Creek, Big Spring Creek Terminus, and Elks Springs sites through 2014. However, this does not match the marginally increasing trend in ungulate use at these sites and requires more research to better understand.	

Management application and future Wetland Ecological Integrity monitoring

A fundamental goal of Network long-term inventory and monitoring is to provide park managers with data and information useful for protecting and managing park resources. Our estimates of wetland ecological integrity can serve as baselines for understanding the current status and future changes/trends in wetlands in GRSA. This information can help GRSA management report on and meet basic regulatory requirements and assist with management in new areas of the park. Our models can be used to document the condition of individual wetlands, and that information could be used by park managers to prioritize wetlands for restoration (e.g., a highly degraded wetland) or protection (e.g., fencing a wetland that has very high ecological integrity and/or significance). Our data can be used to quantify the importance of various "stressors" and "drivers" of wetland health (e.g., ungulate use, groundwater hydrology, etc.). Specific metrics, when interpreted in the context of the larger WEI dataset, can also enhance general understanding of wetland ecology.

Finally, WEI results should also help park staff understand and communicate to the public about the condition of wetland resources in GRSA. They allow interpretation of specific wetlands in the context of the broader resource as well as provide a unique perspective across the park as a whole.

This effort has been, and will continue to be, a cooperative undertaking between Network staff and our partners—most importantly, park management and staff. GRSA is currently preparing an Ungulate Management Plan/EIS to address ungulate over concentration and resulting impacts to park resources. We believe the wetland ecological integrity data, analyses, and interpretations from wetland ecological integrity monitoring can inform the planning effort and adaptive management of ungulates and wetlands in GRSA to meet NPS mandates and goals over the long term. To better inform park management, the Network will continue to work with park managers to adapt and improve Network WEI monitoring to best meet GRSA natural resource planning and management needs.

Acknowledgments

This report was prepared by staff from the Rocky Mountain Inventory and Monitoring Network and Jennifer Jones. Errors are the responsibility of Network staff.

We would like to thank everyone who assisted with, or facilitated, field work on GRSA wetlands monitoring. Colorado State University employees Carrie Cimo and Alex Simon assisted with the main field component during the 2010 field survey. Network staff, including Alexa Armstrong, Katie Driver, Thomas Faust, Evan Gohring, Kyle Motley, Scott Sveiven, Donna Shorrock, and Molly Wiebush, also contributed in the data collection effort in 2010 and/or at sentinel sites from 2010 to 2014.

We would like to especially thank Lisa Carrico, Fred Bunch, Phyllis Pineda-Bovin, Andrew Valdez, Sharyl Cyphers, John White and all the staff at GRSA for being accommodating and supportive with logistics, housing, and use of office resources and with adapting Network wetland (and all) monitoring to the management needs for the park.

The Network Technical Committee laid the groundwork for long-term wetland ecological integrity monitoring in GRSA and all Network parks and continues to provide vision and guidance for our long-term inventory and monitoring program. Thanks to the current and past members of the committee: Isabel Ashton, Mark Biel, Ben Bobowski, Fred Bunch, Tara Carolin, Jeff Connor, Ken Czarnowski, Chris Ford, Sallie Hejl, Therese Johnson, John Mack, Paul McLaughlin, Brendan Moynahan, Phyllis Pineda-Bovin, Jack Potter, Jason Smith, Melana Stichman, Michael Stops, Terry Terrell, Kathy Tonnessen, Judy Visty, Leigh Welling, Phil Wilson, and Rick Wilson.

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Finally, we gratefully acknowledge Joel Wagner and Kate Miller, both from the NPS, for careful and detailed peer reviews. Their insight and guidance greatly improved this report.

List of Abbreviations

CNHP	Colorado Natural History Program
CWA	Clean Water Act
DTW	depth to water
EPA	U.S. Environmental Protection Agency
FLFO	Florissant Fossil Beds National Monument
GPRA	Government Performance and Results Act
GRSA	Great Sand Dunes National Park and Preserve
GRTS	Generalized Random Tessellation Stratified sampling design
HDI	Human Disturbance Index
I&M	National Park Service Inventory and Monitoring Program
LDI	Landscape Disturbance Index
NAIP	National Agricultural Imagery Program
Network	National Park Service Rocky Mountain Inventory and Monitoring Network
NLCD	National Land Cover Database
NMDS	nonmetric multidimensional scaling
NPS	National Park Service
NRCS	Natural Resources Conservation Service
NWCA	National Wetland Condition Assessment
PCoA	Principal Coordinates Analysis
ROMO	Rocky Mountain National Park
SSURGO	Soil Survey Geographic Database
USGS	U.S. Geological Survey
UUI	Ungulate Use Index
WEI	Wetland Ecological Integrity

1 Introduction

1.1 The National Park Service Inventory and Monitoring Program

The purpose of the National Park Service (NPS) Inventory and Monitoring (I&M) Program (Fancy et al. 2009) is to develop and provide scientifically sound information on the current status and long-term trends in the composition, structure, and function of park ecosystems (i.e., ecological integrity). As part of the NPS's effort to improve park management through greater reliance on scientific knowledge, a primary role of the I&M Program is to collect, organize, and make available natural resource data and to contribute to the Service's institutional knowledge by facilitating the transformation of data into information through analysis, synthesis, and modeling of specific key vital signs.

The Rocky Mountain Inventory and Monitoring Network (hereafter, Network) and its partner parks and scientific collaborators identified 12 high-priority vital signs for focused, long-term monitoring. The vital signs include: wet and dry deposition; weather and climate; water chemistry; surface water dynamics; freshwater communities; invasive/exotic aquatic biota; groundwater dynamics; wetland communities; invasive/exotic plants; vegetation composition, structure, and soils; focal species (beaver, elk, grizzly bear, and GRSA endemic insects); and landscape dynamics (Britten et al. 2007).

Wetland Ecological Integrity (WEI) monitoring in Great Sand Dunes National Park and Preserve (GRSA) addresses four of Network's 12 high priority Vital Signs (VS): wetland communities, groundwater dynamics, invasive/exotic plants, and focal species - elk. Two other high priority vital signs are indirectly linked with the WEI protocol, including landscape dynamics, and weather and climate.

1.2 Great Sand Dunes National Park and Preserve

GRSA is among the most ecologically diverse national parks in the world (NPS 2007b), owing to a wide range of habitats and microclimates. The park (Figure 1) comprises 60,400 ha and ranges in elevation from 2292 to 4147 m. GRSA is composed of two major management units: 1) the park proper, which includes the main dune field and a large extensive sandsheet area to the west of the dunes, and 2) the preserve, which includes the higher elevations of the Sangre de Cristo Mountains east of the dunes. For clarity we refer to wetlands in these two areas as "sandsheet" and "high elevation" wetlands, respectively.

GRSA was originally preserved for the water- and wind-driven sand dunes, the tallest in North America, reaching 230 m in height. GRSA also supports rare biological communities that are mostly intact and functional, and contains some of the oldest (9000+ ybp) known archaeological sites in the United States (NPS 2007b). Wetlands within the park are also diverse, ranging from alpine fens occurring above 3600 m, to montane riparian wetlands and seasonal wet meadows, to marsh and salt flat wetlands embedded in the sandsheet west of the main dunes (2290 m). Wetlands on the sandsheet are supported by different sources. One source is surface runoff flowing out of the adjacent Sangre de Cristo Mountains. Another source is unique groundwater systems, many of which emerge from under the main dune field (Wurster et al. 2003). And finally, some are "introduced wetlands" (NPS 2007b) created by human actions, including building ditches and other agricultural features, such as stock tanks, which have created wetland.

1.3 Purpose of report

This report presents summaries and general interpretation of WEI monitoring conducted from 2010 to 2014. We focus mostly on data from an extensive 2010 survey of 48 randomly selected wetland sites on the sandsheet (the western, lower elevation portion of the park) and 14 hand-picked sites (Figure 2). Additional models are constructed from data spanning 2010 to 2014 at five sentinel wetland complexes spread across the park with a total of 21 sites.

The WEI protocol (Schweiger et al. 2015) provides the rationale for the WEI design and field elements, summaries of analytical methods, an overview of data management, and an administrative plan for long-term implementation. The WEI protocol also includes a series of standard operating procedures (SOPs) that provide detailed instructions for executing field, data management, analytical, and administrative components of the protocol.

1.4 Rationale and justification for wetland monitoring in Great Sand Dunes National Park and Preserve

There were several reasons behind the choice to conduct long-term wetland monitoring in GRSA. Though wetlands compose a small percentage of the landscape in the park and preserve, they are an important component of the ecosystem (NPS 2007b; Schweiger et al. 2015). Wetland resources are considered especially vulnerable to climate change due to

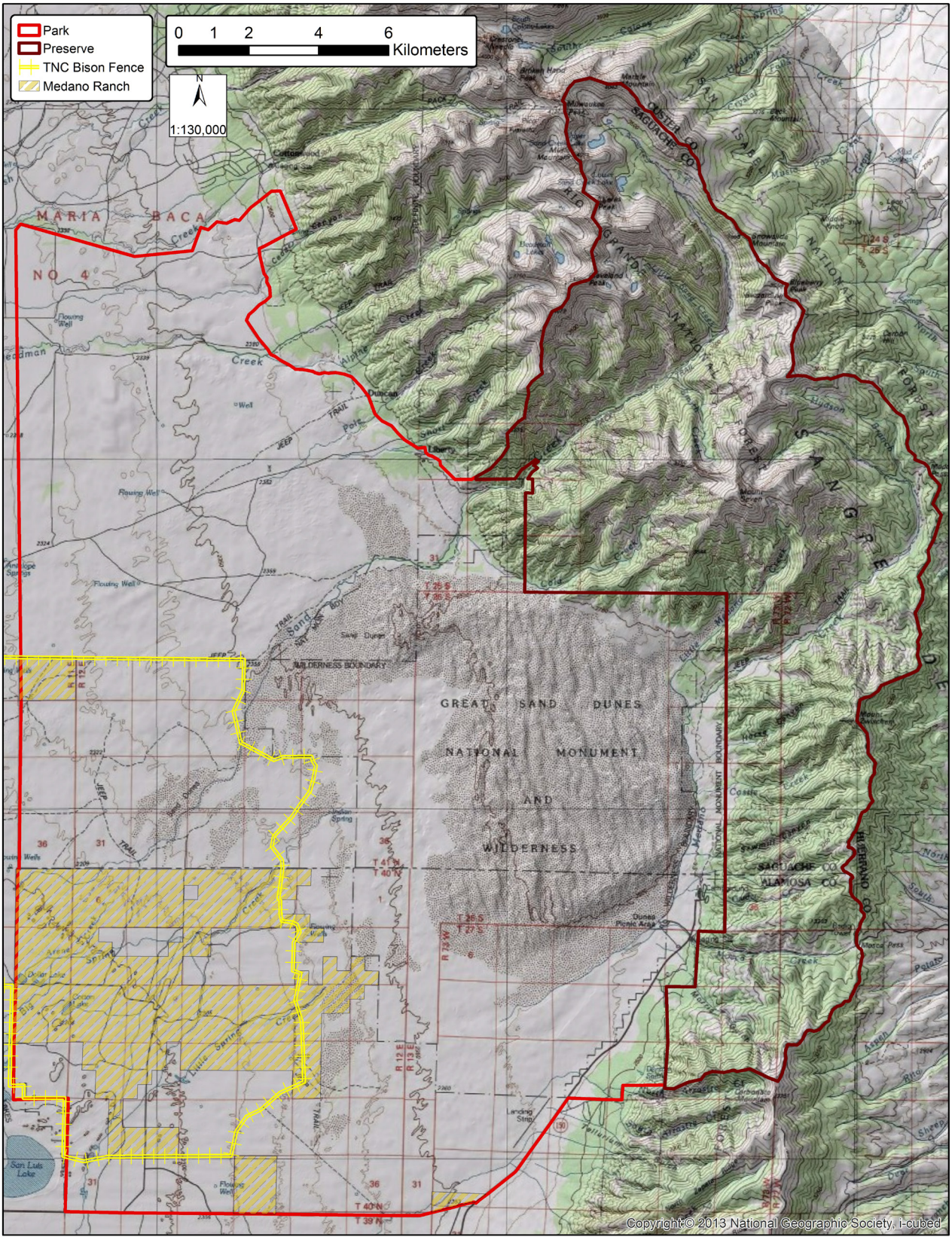


Figure 1. Administrative boundaries within and around Great Sand Dunes National Park and Preserve, Colorado. Map shows the park boundary in red, the preserve in dark red, the Medano ranch in shaded crosshatch, and the bison fence in bright yellow.



Figure 2. Rocky Mountain Inventory and Monitoring Network wetland crews sampling a wetland site at Indian Springs, Great Sand Dunes National Park and Preserve, in 2010. NPS/JENNIFER JONES.

their relationship to ground and surface water dynamics (Larson 1995; Baron et al. 2000; Burkett and Kusler 2000; Voldseth et al. 2009). GRSA supports a variety of wetland types, from fens to important riparian corridors on the more xeric sandsheet. In the San Luis Valley, water is an especially limiting resource and wetlands provide critical habitat and ecological functions (Grimm et al. 1997; Wurster et al. 2003; Harvey et al. 2007). Some of the important ecological functions that wetlands in the park provide include wildlife support, flood attenuation and storage, aquifer discharge and recharge, sediment stabilization and sequestration, carbon storage, water quality enhancement, and nutrient cycling (Mitsch and Gosselink 2000; Sutula et al. 2006). Wetlands also provide important aesthetic values and are highly valued for visitor experiences.

1.4.1 Ecological integrity

WEI monitoring focuses on the estimation and the interpretation of the ecological integrity of wetlands in the park (Schweiger et al. 2015). Ecological integrity is the capacity to support and maintain a balanced, integrated, and adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of natural habitats of the region (Karr 1991). It is a complex, multidimensional concept and usually a single indicator is insufficient to characterize it. Therefore, we use an integrated set of response measures, including community-level floristic composition and vegetation structure, hydrology, and soils. Our primary focus is on multimetric and multivariate indices of wetland ecological integrity from wetland vegetation data (Schweiger et al. 2015). We use indicators of stress, including anthropogenic, "natural", and ungulate overuse of habitat, to help understand patterns in these responses and develop bioassessment models of wetland condition.

1.4.2 Regulatory considerations

Regulatory considerations under the NPS Organic Act, the Clean Water Act, and other laws, regulations and policies relative to Network wetland monitoring are summarized in the Network WEI protocol (Schweiger et al. 2015). While regulatory considerations provide an important context for Network WEI monitoring, our emphasis on long-term ecological integrity monitoring is a key distinction from wetland monitoring conducted by other federal agencies like the EPA and states.

1.4.3 Ungulate Management Plan

Network monitoring in GRSA is designed to inform park management (Britten et al. 2007). Partly because wetlands are such important habitat for bison and elk (Figure 3; Schoenecker 2012, Schoenecker et al. 2015), the GRSA General Management Plan (GMP; NPS 2007b) required NPS to develop an Ungulate Management Plan and Environmental Impact Statement (UMP/EIS or simply UMP). The UMP will develop ungulate management alternatives, especially for elk and bison and attempt to link the alternatives and subse-



Figure 3. Bison graze a Rocky Mountain Network Wetlands Ecological Integrity monitoring site on the Great Sand Dunes National Park and Preserve sandsheet, 2010. Wallows and hoof punches are visible in the foreground of the image. NPS/JENNIFER JONES.

quent management actions with the condition (i.e., ecological integrity) of wetlands. Therefore, we have conducted analyses and interpretations of WEI data in ways we hope will inform the developing UMP. In addition, GRSA management is collaborating and supporting "enhanced" Network WEI monitoring towards this goal. As Network WEI monitoring continues in GRSA, we will strive to integrate Network monitoring into adaptive ungulate management by the park and its partners.

1.5 The wetlands of Great Sand Dunes National Park and Preserve

Great Sand Dunes National Park and Preserve supports several types of wetlands including fens, marshes, riparian wetlands, salt flats, and wet meadows (Table 1). Several wetlands on the sandsheet are "introduced wetlands" (NPS 2007b) that exist due to some combination of natural hydrologic regimes and/or ground or surface water created by human manipulation (i.e., ditches, overflowing stock tanks). We made a decision early on, in direct consultation with the park, to include these wetlands in our WEI monitoring at GRSA. As Network WEI monitoring progresses and GRSA shifts wetland management priories or strategies there will be an important opportunity to better understand how the different types of supporting hydrologic mechanisms affect wetland integrity.

1.5.1 Jurisdictional wetland definition

The National Research Council (1995) and the Corps of Engineers (2010) establish a technical standard for wetland hydrology as 14 or more consecutive days of ponding or a water table within 30 cm of the soil surface during the growing season at a minimum frequency of 5 in 10 years. Following Cooper (1998) and Gage and Cooper (2013) the Network does not adhere to this strict jurisdictional standard to classify a site as a wetland included in our monitoring. Rather we use a standard of "two out of three" and allow a site as a wetland if it instead has 1) wetland vegetation, 2) predominantly hydric soils, and/or 3) is saturated or covered by water at some point during the growing season (Schweiger et al. 2015).

1.5.2 Fen

Fens are groundwater-supported wetlands characterized by organic soils, high water tables, saturation to the ground surface throughout the growing season of most years and peat accumulation. Peat accumulation is generated by minimal plant matter decomposition due to anaerobic conditions. Fens are ecologically diverse due to variability in groundwater sources, landscape setting, and vegetation composition. In GRSA, fens are only found high in the Sangre de Cristo Mountains where cool temperatures and landscape features can support their development.

Table 1. Wetland types at Great Sand Dunes National Park and Preserve (GRSA) following Cooper (1998) and Gage and Cooper (2013).

Type	Water source	Hydrologic regime	Soils	Status in GRSA	Notes
Salt flats	Groundwater resurfacing from open aquifer, precipitation	Highly variable	Mineral, seasonally saturated, high salt content	On the sandsheet W of the main dune field	In GRSA, salt flats and wet meadows occur on a gradient and we treat them as "salty meadows"
Wet meadows	Groundwater	Seasonally variable	Mineral, seasonally saturated	Sandsheet and in the mountains	Minimally or not connected to rivers
Marshes	Groundwater (depressional wetlands)	Frequent flooding and standing water	Mineral, seasonally saturated	Sandsheet; common around the termini of Big and Little Spring Creeks and Sand Creek in SW corner of park	–
Riparian	Snowmelt and springs	The larger mountain streams are snowmelt driven primarily, with high spring flows declining over summer, fall and winter; spring fed streams are more stable	Mineral, seasonally saturated	Occur along high-gradient mountain streams AND along spring-fed and ephemeral streams on the sandsheet (e.g., Medano, Sand, and Deadman Creeks.	Many riparian wetlands in GRSA are dominated by woody species including cottonwood and willow communities
Fens	Groundwater	Elevated and relatively stable water table	Organic saturated peat-accumulating soils	Fens are uncommon to rare in GRSA in the high mountains only	Peat accumulation due to low plant decomposition rates in anaerobic conditions

1.5.3 Marsh

Marshes are depressional wetlands characterized by frequent flooding and standing water during much of the growing season of most years. In GRSA, marshes are relatively common around the terminus areas of Big and Little Spring and Sand Creek in the far southwest corner of the park.

1.5.4 Riparian

Riparian corridors in GRSA include typical, high gradient mountain streams as well as ephemeral and perennial spring-fed corridors on the sandsheet. Medano and Sand Creeks are both losing systems of braided, sand channels that depend heavily on winter snows and spring melts to determine the extent of their surface reach. In many years, there is no surface flow on lower Medano and Sand Creeks. Big and Little Spring Creeks are supported in part by water from the unconfined aquifer that resurfaces at points on the landscape, producing perennial corridors that end in the San Luis Lakes marsh area. Riparian wetlands at GRSA are often dominated by woody vegetation, especially willows and, in some lower elevation sites, cottonwood.

1.5.5 Salt flat

Salt flats are common in closed basins of the Intermountain West, occurring west of the main dune field in GRSA, where water resurfaces from the open aquifer. These habitats are similar to playas, being intermittently wet, often dry for long periods, and support few obligate wetland species. Salt flats occur where high water tables, dry climate, and evapotranspiration cause surface salt accumulations.

1.5.6 Wet meadow

Wet meadows have mineral, seasonally saturated soils that are not connected or minimally connected to rivers. They function similarly to fens, being supported mainly by groundwater inputs, but lack thick organic accumulations in the upper soil horizons and their water tables are seasonally variable. Along with variable hydrology, wet meadows have a wide range of soil types and water chemistry, especially in GRSA where they are common on the sandsheet and the high country.

Note that in this report we often use a gradient of wetland type from salt flat to wet meadow and may use the term “salty meadow” to describe this class. Salty meadows include the continuum of wetlands from salt flats through wet meadows; there is likely no distinct boundary between these two wetland types in GRSA, although patterns in soil and groundwater chemistry, vegetation, and hydrology do differ in meaningful ways.

1.6 Monitoring objectives

The general goals for long-term ecological monitoring of GRSA wetlands focus on documenting the status and trend in extent and condition, helping to understand the causes of changes—especially where change is relatable to human disturbance—and assisting in the application of WEI results and relevant auxiliary information to park management. While not an objective per se, WEI monitoring in GRSA does serve to add to the general ecological knowledge regarding wetlands in the park. We summarize our objectives here—see Schweiger et al. (2015) for more detail.

1.6.1 Population scale status

This report describes the first survey of park-sandsheet wetlands. We lack repeated data at the population scale, therefore we can only estimate population scale status. Trend at the population scale will be estimated in future reports. Population scale status estimates in GRSA are for two wetland types: wet meadows and salt flats within the sandsheet zone of the park. We combine data across these two wetland types to estimate most responses.

Population scale status objectives:

1. Determine the status in wet meadow and salt flat wetland area using two different data sources:
    a. Remotely sensed data
    b. For salt flats and wet meadows using 2010 survey data
2. Determine status in a suite of drivers and response measures:
    a. Anthropogenic and natural disturbances, including ungulate overuse of wetland habitat
    b. Soil chemistry
    c. *In situ* water chemistry
    d. Peak season depth to groundwater
    e. Vegetation community composition as indicators of ecological integrity
3. Assess status of select responses detailed in objective 2a-e based on available types of assessment points:
    a. GRSA management derived assessment points (which may include any of the following)
    b. Relevant state/federal/tribal nation regulatory criteria (rare for wetlands)
    c. Ecological thresholds
    d. Ecoregion assessment points derived from reference site data within GRSA using WEI survey data or partner/auxiliary data

1.6.2 Site specific status and trend

We estimate site specific status for all sampled sites (or a subset based on wetland type or location) and specific sentinel site complexes. Analyses of these data do not use design-based methods and thus are specific to the sites included in a model (i.e., sites on the sandsheet or specific sites in a sentinel complex). Statistically rigorous estimates of trend at sentinel sites are possible after five to ten years of monitoring. This report uses 5 years of data at sentinel sites and includes our first estimates of trend in responses in GRSA's sentinel wetland complexes. Importantly, these trend models must be interpreted with caution, recognizing this is a minimum timeframe for reliable trend estimates.

Site specific status and trend objectives:

4. Determine status for select sites in a suite of drivers and response measures (as in objective 2a-e),
5. Determine the long-term trend in the condition of select wetland drivers and responses at specific sentinel sites or complexes:
    a. Wetland area
    b. Anthropogenic and natural disturbances, including ungulate overuse of wetland habitat
    c. *In situ* water chemistry
    d. Groundwater hydrologic regime (a more detailed treatment is possible given continuous groundwater depth data at sentinel sites)
    e. Vegetation community composition
6. Assess the status and trend of select responses at specific sites using methods in objective 3.
7. Relate spatial and temporal patterns in select wetland drivers and responses detailed in objectives 5a-e to important ecological and anthropogenic drivers, including the effects of ungulate overuse of habitat. These models depend on scale appropriate covariate WEI and auxiliary data (e.g., groundwater levels and precipitation) with clear connections to WEI responses.

2 Methods

Figure 4 illustrates our general approach to assessing wetland ecological integrity in GRSA. The subsequent sections of the Methods present brief summaries of how and why sites were selected, how data were collected in the field or harvested from auxiliary sources, and how data were analyzed and interpreted. For a more complete treatment, see the Network WEI monitoring protocol (Schweiger et al. 2015) and the appendices to this report.

2.1 Sample designs

WEI monitoring at GRSA includes three sample design types: 1) a broad scale random "survey" of all salt flats and wet meadows on the sandsheet (in the national park) conducted every 5–10 years, 2) annual "sentinel" site monitoring at four wetland complexes in the park and at high elevation in the preserve, and 3) sampling at subjectively selected "gradient" sites every 5–10 years (especially sites that have heavy human or natural disturbance or sites that are pristine with little to no disturbance) (Table 2). The surveys allow us to describe the sandsheet-wide status of GRSA wetlands and understand spatial patterns in wetland condition, whereas annual sentinel site monitoring allows us to understand trends (at those sites only). Repeat surveys will allow us to document parkwide wetland condition changes over the long term. Gradient site monitoring provides a way to better evaluate how wetlands respond to human and natural disturbances to wetlands.

2.1.1 Survey

We worked with park management in 2009 to plan for implementing the Network WEI protocol in GRSA. At that point, we determined that sandsheet wetlands in the authorized park boundary were of primary interest to park management due to a history of cattle and bison management and associ-

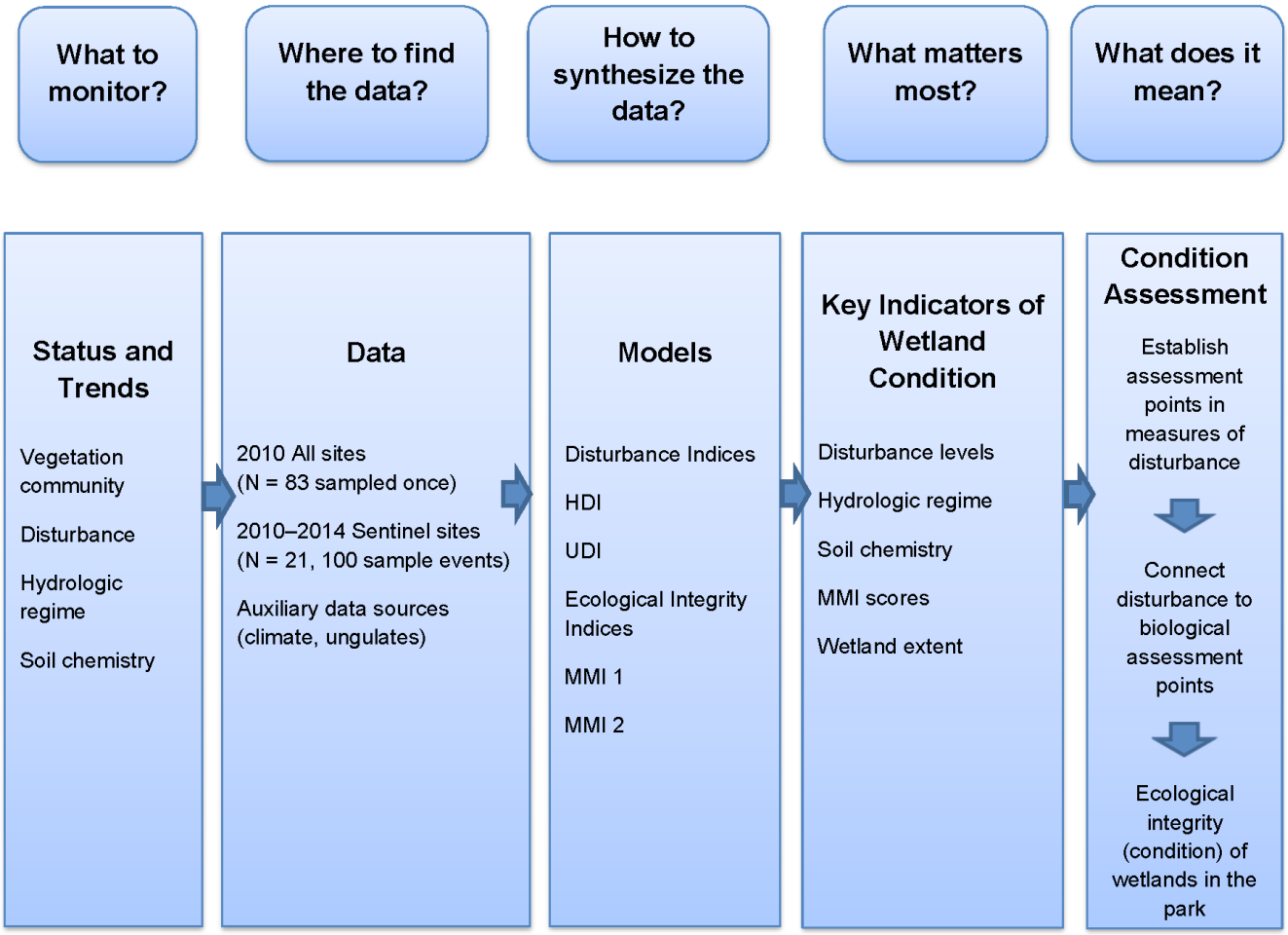


Figure 4. High-level approach to assessing the ecological integrity of wetlands at Great Sand Dunes National Park and Preserve.

Table 2. Summary of sample designs used in Great Sand Dunes National Park and Preserve Wetlands Ecological Integrity monitoring. GRTS = generalized random-tessellation stratified spatially balanced design. Event counts are for complete sample events (additional partial visits not included here) and are through 2013, except where noted.

Survey	Sentinel	Gradient
Two wetland types across the sandsheet zone of the park, with a total sample size of 48, mostly sampled once every 5–10 years (a subset of the sites is revisited within each survey implementation). Design is a two-stage GRTS with unequal probability discrete sampling across accessibility weighted wetland types (1st stage) and an areal sample (2nd stage) of locations within selected wetland complexes treated as strata. In the 2010 survey, there were 56 events at the 49 sites.	Five sentinel complexes, with a mix of five wetland types and 3-5 sites per complex, sampled biannually once or twice per season. As of 2014, there were 21 sites, sampled 100 times (from 2010 to 2014).	Fourteen sites within two wetland types sampled once or twice each, every 5–10 years. As of 2014, these had been sampled 16 times (from 2010 to 2014).

ated hydrologic modifications and plans by park managers to restore sandsheet wetlands if/when resources and capacity allowed. Therefore we decided to implement a parkwide (sandsheet) wetland survey in 2010. Figure 5 and Table A-1 in Appendix A present survey sites and Figure 6 presents wetland type boundaries on the GRSA sandsheet sampled in the 2010 survey. Note that 20 sites selected by the survey but not included in design-based inference are treated as sentinel or gradient sites.

2.1.2 Sentinel

The GRSA sentinel design subjectively includes wetlands judged by experts and/or park management as important to the understanding of wetland dynamics in GRSA. As such, there is no intention to make inference beyond the sentinel wetland. We have sampled these annually or biannually as resources allow since 2010.

Sentinel complexes were located subjectively based on a suite of criteria developed by Network staff, collaborators (especially David Cooper, Colorado State University, who has been working in GRSA wetlands for decades) and GRSA staff. Key criteria included: 1) ecologically important sites (expert opinion), 2) sites with a long history of wetland research data, and 3) easy access. All sentinel complexes were represented in the survey sample frame, so while they cannot be used as is in design-based inference, future work could add sample sites following design requirements.

Sentinel complexes in GRSA (Figure 7 and Table A-2 in Appendix A) include Upper Sand Creek Lake, Upper Sand Creek Lake Trail, Elk Springs, Big Spring Creek, and the terminus of Big Spring Creek. Elk Springs and Big Spring Creek have a long history of wetland research. The Upper Sand Creek Lake sites are new locations for wetland work but incorporate high elevation wetlands into the array of GRSA sentinel sites. The Big Spring Creek terminus site is co-located with a deep well monitoring the closed aquifer that is sampled by park staff on a weekly basis.

2.1.3 Gradient

The GRSA gradient design is similar to WEI sentinel designs, including (1) an expert opinion or judgment based selection of wetland complexes, and (2) no intention to make inference beyond the sites or the sentinel wetland complex. However, gradient sites were selected primarily to characterize wetland condition at the extremes of anthropogenic and natural drivers that influence wetland ecology. Therefore sites were targeted to wetlands we expect to be either under stress or in pristine condition. Gradient sites were selected by Network staff, collaborators (especially David Cooper, who has been working in GRSA wetlands for decades), and GRSA staff. Key criteria used to select gradient sites included the following: allocation of complexes across important wetland types, geographic contexts, and existing wetland monitoring locations (especially established groundwater wells). Sites were also targeted to wetlands that were expected to be either highly disturbed or in a more pristine state. This was based largely on expert opinion and in some cases was done while visiting survey or sentinel sites. The disturbances targeted included general human disturbance, invasive plant cover (as an indication of disturbance), bison and/or elk disturbance, and specific hydrologic alterations. Less impacted sites were targeted largely based on the absence of these disturbances.

Figure 8 shows the 14 gradient sites across the park, and Table A-3 in Appendix A identifies important attributes of each site. Most gradient sites were in wetland polygons represented in the survey design sample frame, so while they cannot be used in design-based inference as is, future work could be structured following design requirements and incorporate these sites into design-based analyses.

2.2 Field methods

All field methods are described in Schweiger et al. (2015) and only briefly summarized here. The WEI protocol includes a broad spectrum of indicators to help evaluate the ecological integrity of wetlands in GRSA. We collect vascular

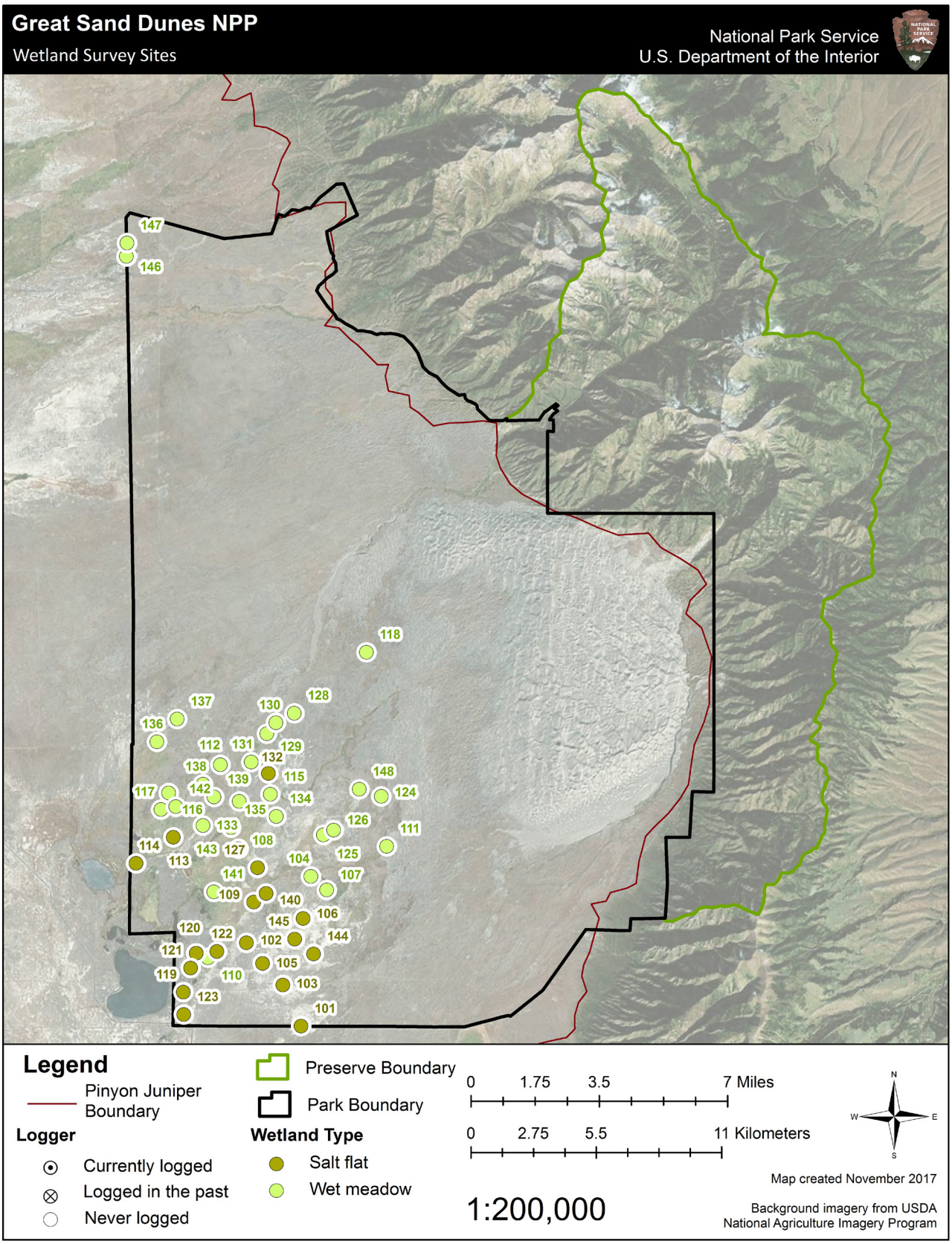


Figure 5. Great Sand Dunes National Park and Preserve Wetland Ecological Integrity survey sites sampled in 2010. See also Figure 6 and Table A-1.

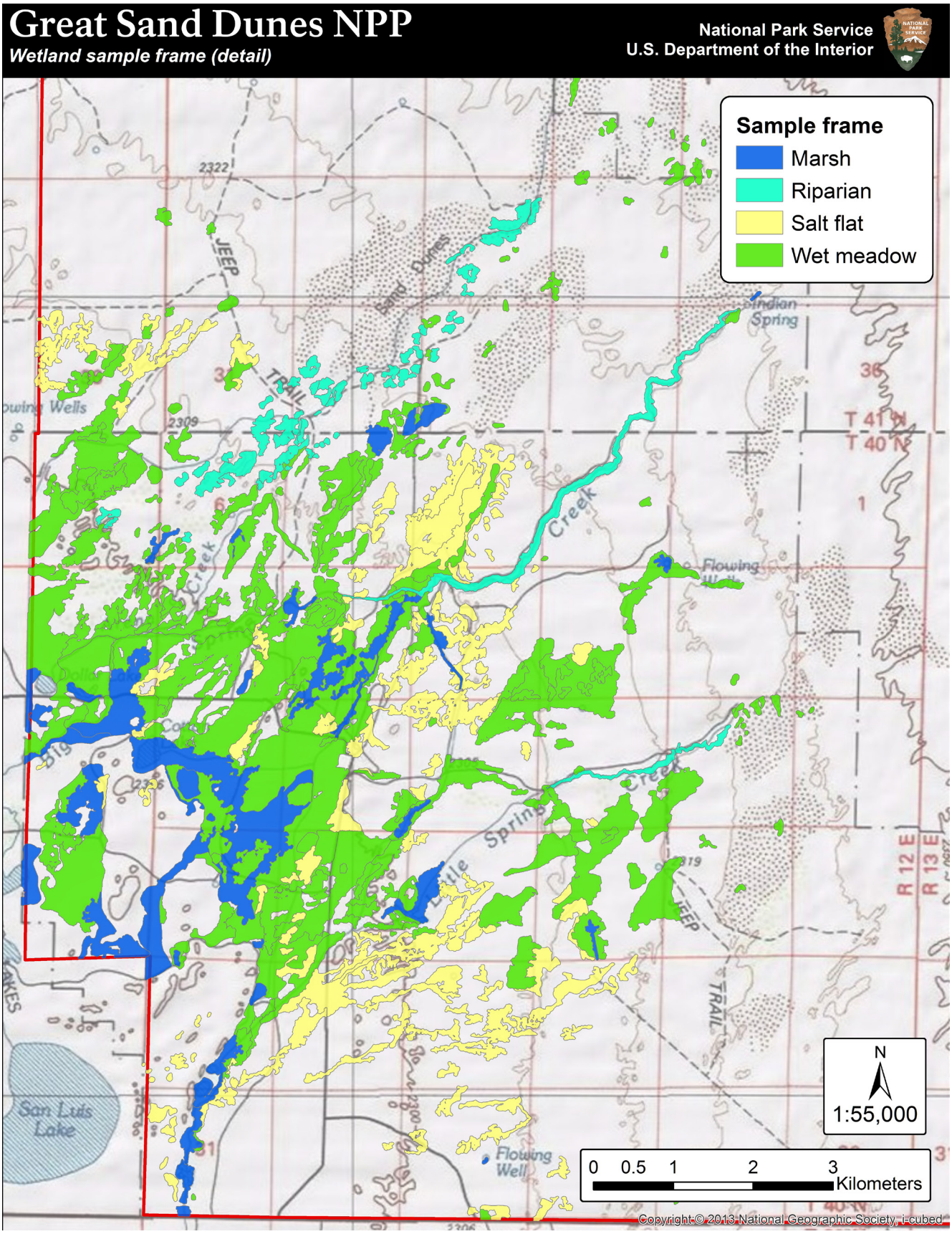


Figure 6. Close-up of first-stage wetland complex boundaries between San Luis Lake and the headwaters of Big and Little Spring Creeks in Great Sand Dunes National Park and Preserve.

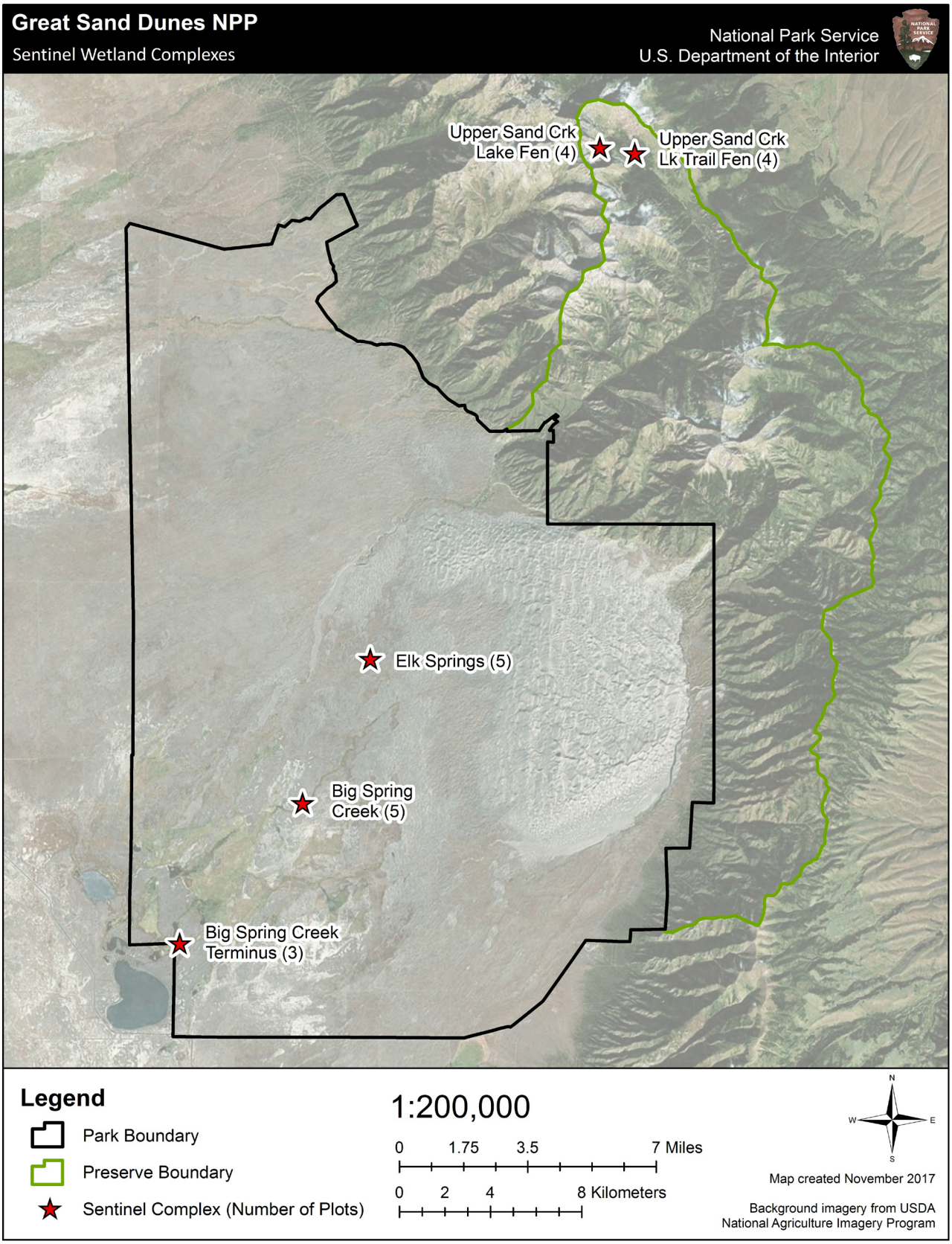


Figure 7. Great Sand Dunes National Park and Preserve sentinel wetland monitoring complexes. As of 2015, each complex had from three to five individual plots (not shown). See also Table A-2 in Appendix A.

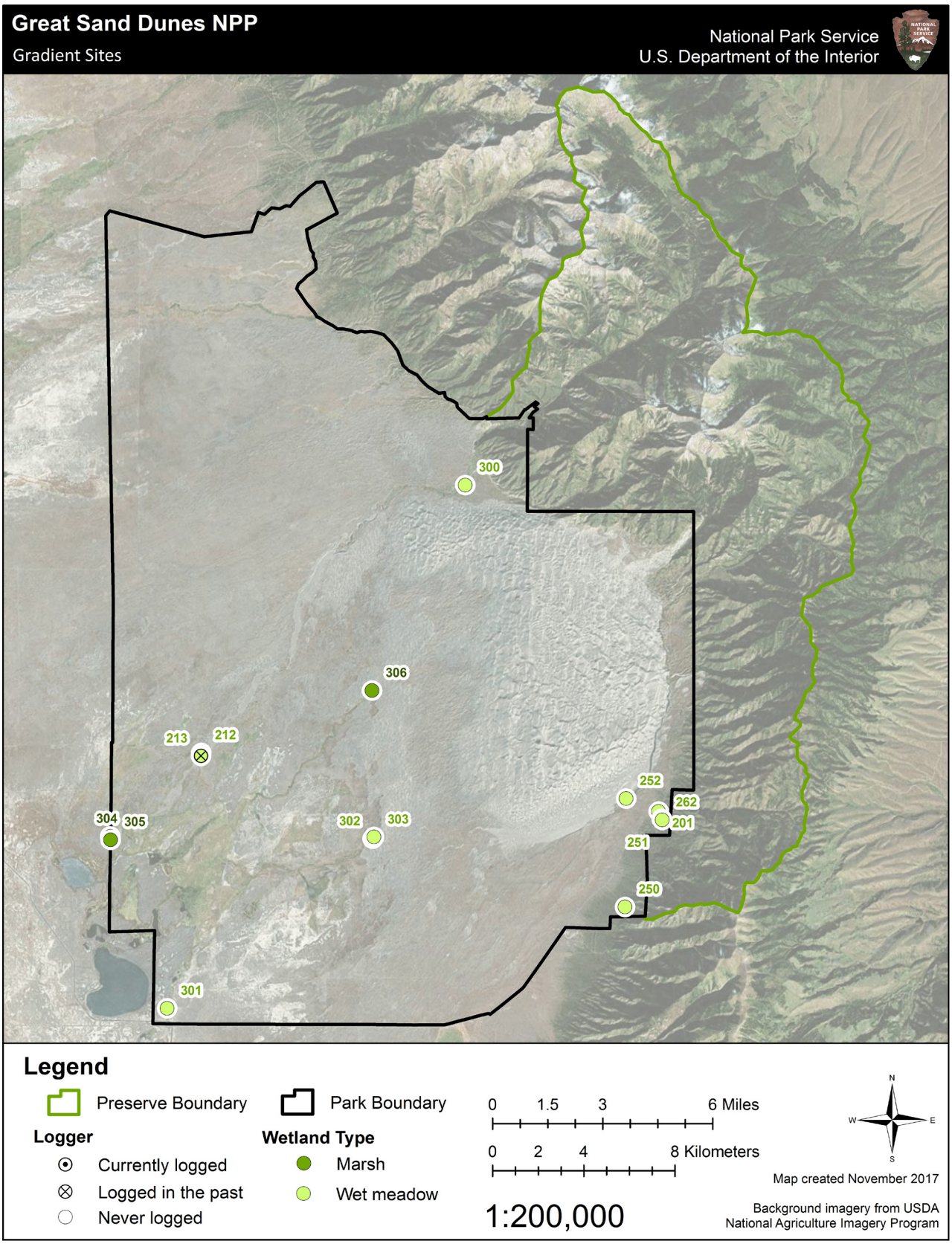


Figure 8. Great Sand Dunes National Park and Preserve Wetland Ecological Integrity gradient sites. See also Table A-3 in Appendix A.

and nonvascular plant species composition, woody species stand structure (primarily cottonwood and willows), and document damage and mortality of woody stems. We also collect field and laboratory soil chemistry samples, document in-situ groundwater electrical conductivity and pH, and measure depth to water at a shallow groundwater well in the center of the plot. Finally, we document human disturbance and ungulate overuse of habitat in and around each plot and in the wetland complex. Most data were collected from 10 m2 plots with two scales (1 m2 and 4 m2) of nested subplots arranged systematically around a groundwater monitoring well (Figure 9). This plot design adequately samples multiple wetland drivers and responses in GRSA (Schweiger et al. 2015).

2.2.1 Vegetation

Plant species composition was quantified within six nested subplots in each site. All vascular and nonvascular taxa in each plot were identified to species and the canopy cover visually estimated for each taxon (Mueller-Dombois and Ellenberg 1974). Areal cover was averaged across all subplots before inclusion in models. Plant species nomenclature followed Weber and Wittman (2001). Woody stand structure was estimated by enumerating stems by taxa and age/size class within each subplot. Damage to and mortality of woody stems was evaluated following Potter (2015) by estimating the percent of stems that were dead, the percentage of live stems with browse (limited to evidence typical of ungulate foraging), and the percent of live stems with dieback (from sources other than browse).

2.2.2 Hydrology

Groundwater monitoring wells at each site were hand-augured and cased with slotted PVC pipe to a depth adequate for measuring depth to the water table (usually 1 to 2 meters). Continuous depth to water (DTW) was recorded ever hour year-round at 12 wells in sentinel sites with submersed pressure transducers. We also manually measured DTW at each visit using an electronic tape with an accuracy of +/- 2.0 mm. Most of these instantaneous DTW readings occurred at peak growing season when water stress on vegetation was likely highest.

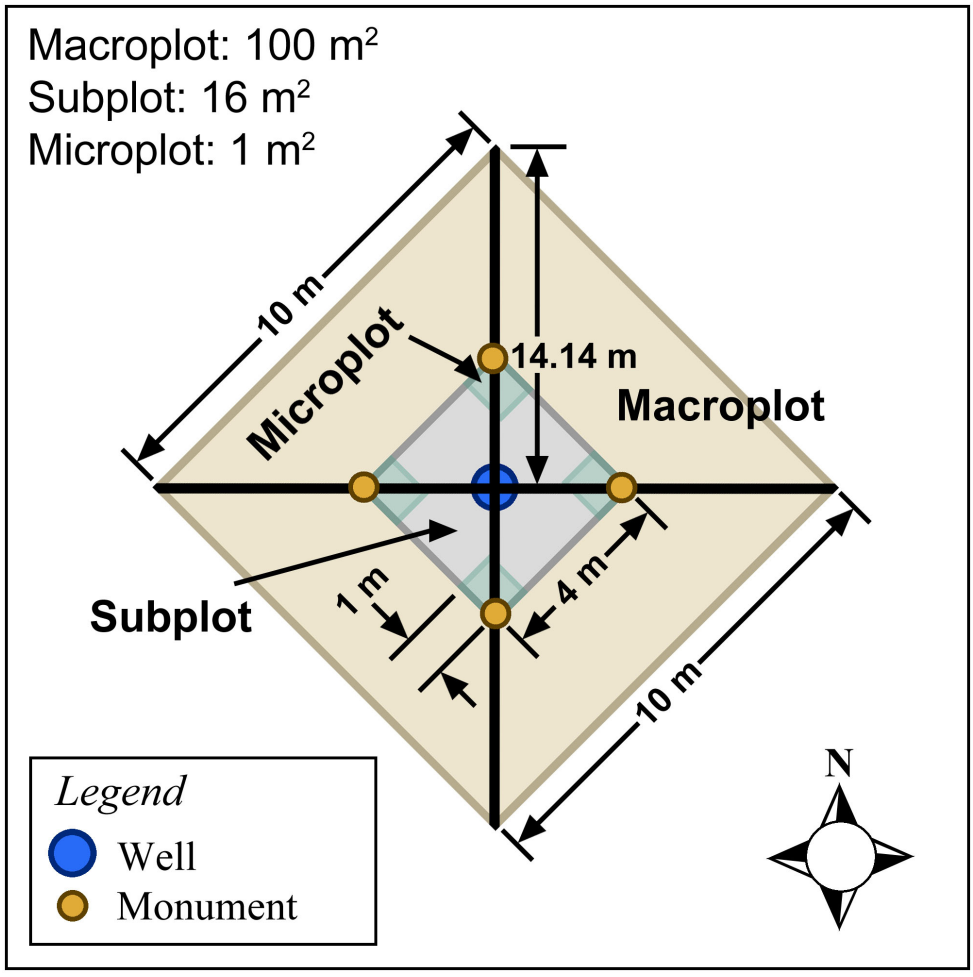


Figure 9. Default Wetland Ecological Integrity sample plot used by the Rocky Mountain Inventory and Monitoring Network. Plots are always oriented with North at the top of the plot. Rebar is capped with a standard Rocky Mountain Network monument cap. The center of the plot is a groundwater well (except in most gradient sites). Pins are placed temporarily to aid in plot layout and then removed following sampling.

2.2.3 Soil and water chemistry

A composite soil sample was taken from the well bore or a soil pit at 0 to 20 cm and analyzed in a lab for 23 parameters, including pH, conductance, cation exchange capacity, nutrient concentrations, and several ions or salts (e.g., P, Mg, Mn, Al, Ca). A second sample was taken at around 40 cm and analyzed for percent organic matter. Field measures of soil at each site included a general characterization of soil layers and total peat thickness in the top 80 cm of the soil profile. Soil samples are taken every 5–10 years. Groundwater electrical conductivity and pH were measured *in situ* at the time of each sample event.

2.2.4 Disturbance and ungulate use

An important part of the WEI protocol is a characterization of human disturbance and ungulate use levels in and around each wetland site and complex (Table 3). These field methods are rapidly employed measures modified from Faber-Langendoen et al. (2006), Rocchio (2007a, b), and Mack (2007). They are mostly categorical measures. Importantly crews do not make judgment calls on wetland condition in the field. Several measures are also evaluated in the office using a GIS (in some cases GIS data will be more precise and accurate). As summarized below, these data are synthesized into a semi-quantitative Human Disturbance Index (HDI, common to multiple Network parks) and an Ungulate Use Index (UUI; unique to GRSA). These indices provide independent measures of wetland condition against which vegetation attributes and other WEI responses are assessed to determine relationships with changes in disturbance regimes and ungulate use across the park and over time.

2.3 Auxiliary data: climate, landscape, ungulates

Many analyses of WEI data at GRSA use predictors or covariates beyond those developed within the protocol itself as ways to help understand patterns and lend insight into the factors controlling or impacting wetland response. Auxiliary data were developed within six major categories: climate (including metrics of water balance), atmospheric deposition, landscape composition, ungulate trails, bison and elk range counts, and vegetation productivity. Table 4 gives the auxiliary data sources and the metrics or variables created from them. We present important detail on these data in Appendix B. Note that dozens of other variables were created, but after evaluation were not used in our current models.

2.4 Analyses

By design, WEI monitoring is information rich. Distilling this large amount of information into meaningful reports is a challenge; however, the diversity and extent of WEI results provide many opportunities for enhanced interpretation of status and trend of wetland condition at GRSA. The Network analytical strategy also incorporates feedback from park management and protocol review for purposes of improving efficiency (e.g., modifying sample sizes or response measure selection to lower costs or enhance precision). Schweiger et al. (2015) provides a summary of the general WEI analytical approach and Appendix C provides specific details for all analyses presented in this report. Summaries of our most important analyses follow.

2.4.1 Synthetic metrics

We address several objectives by estimating derived indices from WEI monitoring data. These include synthetic metrics for human disturbance, ungulate use, and vegetation community structure as an indicator of ecological integrity (bioassessment). The creation of these indices involves complex analyses that are in and of themselves informative. Many of these indices are also used in estimates of status and trend and/or included as important covariates in models.

2.4.1.1 Human disturbance and ungulate use

The Human Disturbance Index (HDI) is calculated as fol-

Table 3. Human Disturbance Index and Ungulate Use Index component metrics. "R" indicates used only in riparian sites. "GIS" indicates measure includes data from both field and GIS-based data sources.

Alterations within buffers and landscape context	Hydrological alterations	Physical/chemical disturbances
Average Buffer Width (GIS)	Hydrological Alterations	Substrate/Soil Disturbance
Land Use in 100 m Buffer	Upstream Surface Water Retention (GIS)	Onsite Land Use
Percentage of Unfragmented Landscape within 1 km (GIS)	Upstream/Onsite Water Diversions/Additions (GIS)	Bank Stability
Riparian Corridor Continuity (R)	Floodplain Interaction (R)	Algal Blooms
–	–	Invasive Dominance
–	–	Sediment/Turbidity
–	–	Toxics/Heavy Metals

Table 4. Summary of auxiliary data sources and metrics derived from these data as used in models of Great Sand Dunes National Park and Preserve Wetlands Ecological Integrity data.

Category	Metric	Scale, units	Data source(s)
Climate	Total precipitation, 2010	Site, cm	PRISM Climate Group (2015)
	Total precipitation, 2008 to 2010	Site, cm	PRISM Climate Group (2015)
	Total monsoon precipitation, 2008 to 2010	Site, cm	PRISM Climate Group (2015)
	Mean annual precipitation, 1980 to 2010	Catchment, cm	PRISM Climate Group (2015)
	Mean water year soil water deficit (water balance)	30m, (mm)	PRISM Climate Group (2015)
	Total water year potential evapotranspiration (water balance)	30m, (mm)	PRISM Climate Group (2015)
	Total water year actual evapotranspiration (water balance)	30m, (mm)	PRISM Climate Group (2015)
Deposition	Total nitrogen wet deposition	Catchment, kg/N/ha/year	PRISM Climate Group (2015), NADP (2015), Baron et al. (2011)
Landscape composition	Road-stream crossing	Number per unit area in catchment	GRSA GIS data; Attila (Riitters et al. 2000)
	Percent of catchment with anthropogenic landuse	Catchment, %	Vegetation map (Salas et al. 2011); NLCD (Fry et al. 2001); Attila (Riitters et al. 2000))
	Interior wetland	Catchment, score	Vegetation map (Salas et al. 2011); NLCD (Fry et al 2001); Attila (Riitters et al. 2000)
	Distance to closest anthropogenic feature	Meters	GRSA GIS data
	Road density	Number per unit area in catchment	GRSA GIS data
	Distance to closest sand dune	Meters	GRSA GIS data
	Elevation	Meters	GPS based field data
	Landscape Disturbance Index	Total score in 1km buffer	NLCD (Fry et al. 2001); Lemly et al. 2011
Ungulates	Vegetation productivity	Pounds/acre	Vegetation map (Salas et al. 2011); NRCS SSURGO (2015); Wockner et al. 2015
	Trail Index	Density of trail in 100m buffer	NPS (2013)
	Elk Index	Number of overlapping ranges per 30m cell, total in 1km buffer	Wockner et al. (2015)
	Bison Index	Number of overlapping ranges per 30m cell total in 100m buffer	Wockner et al. (2015)

lows. First, field data are scored into four classes 0, 3, 7 and 10 (or 0, 4, 12 and 20 for hydrologic alteration). For all metrics, higher scores indicate higher and/or closer levels of disturbance. Metrics are grouped into three categories (Alterations within buffers and landscape context, Hydrological alterations, and Physical/chemical disturbances) with the two highest scores across all categories for each site summed and normalized. Finally, the score from each category is weighted and averaged into final HDI index. The index ranges from 0 to 100 with higher scores indicating higher levels of human disturbance.

We estimate the use of wetland habitat by ungulates with the Ungulate Use Index (UUI) developed from a subset of the landuse metrics measured for the HDI. Ungulate habitat use can become a disturbance when it surpasses a level where any beneficial effects from grazing or browse (i.e., stimulating production) are exceeded by negative impacts from how and when ungulates use habitat. These disturbances might include, for example, removal of select plant species, erosion and soil compaction caused from hoof punching, wallows or trails, and introduction of invasive species. Given the extensive ranching of bison and (historically) cattle on the sandsheet, this is an important potential stressor at GRSA. The focus of our modeling and assessment is on the range of ungulate use that is more likely a stress; however, at least conceptually, the index includes a level of use that is sustainable and that may even have beneficial effects on wetlands at GRSA. Ongoing research by the Network, the U.S. Geological Survey (USGS), and the park will seek to identify assess-

ment points in UUI where ungulate habitat use becomes disturbance.

To create the UUI, we use estimates of the percent browse in low, medium, and high intensity categories in each wetland and its 100 m buffer. Crews did not discriminate among bison, elk, and other ungulates for these estimates. A fourth category of "other land use" was available and consistently attributed to grazing (i.e., of herbaceous vegetation) using the same intensity categories. The final UUI is a normalized weighted sum of these four metrics, with heavy herbivory weighted by a coefficient of 0.5, medium by 0.3, light by 0.1 and other by 0.1.

2.4.1.2 Vegetation metrics

We generated 187 vegetation metrics (Appendix D) within 11 groups: floristic quality (conservatism), duration, ground cover, life form composition, degree of invasion, endemism (perhaps better thought of as "conservation value"), noxiousness, taxonomic diversity, taxonomic composition, wetland status and salt tolerance. These metrics are direct and purposefully one-dimensional assays of vegetation composition and structure. They have significant explanatory power in and of themselves and we present and interpret several throughout this report. Details of metric calculation are in Schweiger et al. (2015). Given their importance (Ervin et al. 2006; Johnston et al. 2008), we briefly summarize two types of metrics here, conservatism and degree of invasion.

The conservatism of a species is defined as its degree of fidelity to a specific habitat or range of environmental conditions (Wilhelm and Ladd 1988; Herman et al. 1997; Matthews et al. 2015). Anthropogenic impacts may cause dramatic shifts in ecological processes and habitat conditions and push disturbance regimes outside a natural range of intensity, frequency, and duration. Species that are more conservative are not able to quickly adapt to such rapid alterations compared to broad-niche generalists and are often the first to disappear from habitats heavily impacted by human activities. We use an expert-derived metric of the degree of conservatism in a wetland community calculated as the mean of conservatism scores (also known as "C-scores") for all species in a sample. Rocchio (2007a, b) assigned C-scores to all species in the Colorado flora following the methods described by Swink and Wilhelm (1994). C values range from 0 to 10 and represent an estimated probability that a plant is likely to occur in a landscape relatively unaltered from pre-European settlement conditions. Nonnative species are given a default C value of 0. A low C value is assigned to plants that have demonstrated little fidelity to any remnant natural community or area or species with a wide ecological tolerance that may be found almost anywhere. A C value of 10 is assigned to species that are obligate to high quality natural areas and that cannot tolerate habitat degradation.

Invasive, often exotic or nonnative, species can have undesirable effects on ecosystem function (Byers et al. 2002; Levine et al. 2003; Fridley et al. 2007). Invasive species have been linked to reduced overall species diversity (Meiners et al. 2001), altered resource dynamics (Ehrenfeld 2003), and shifted interactions between species (Christian and Wilson 1999). We calculate a community scale degree of invasion following Iacona et al. (2014) by averaging the relative cover-weighted scores of the invasiveness of all species in a sample (also known as "I-ranks", Morse et al. 2004). I-ranks are scored based on the ability of a species to: change ecosystem processes; invade relatively undisturbed ecological communities; disperse to new areas readily; and cause substantial impacts on rare or vulnerable species or ecological communities, or high-quality examples of more common communities. Invasive species also tend to have wide distribution and general abundance where present and are difficult to control.

2.4.1.3 Multimetric index of ecological integrity (bioassessment)

The primary way in which we analyze and interpret biological data is through bioassessment (Barbour et al. 2000). Bioassessment is, generally speaking, the use of biologically based response measures to assess and monitor natural systems. Bioassessment assumes that the composition of biological communities reflects the overall ecological integrity of a system. Evidence suggests it may detect stressors that other approaches fail to reveal and that it is an efficient, integrative way of conducting long-term monitoring (Karr and Dudley 1981; Karr and Chu 1997). Bioassessment has become a central element of most federal, state, and other monitoring programs. We use the approach to help meet multiple WEI objectives.

Schoolmaster et al. (2012) and Schoolmaster et al. (2013a, b) refine the theory behind a well-established tool in bioassessment, multimetric indices (MMI). We apply this approach to GRSA WEI data. Overall, this approach requires fewer assumptions and is more efficient than classic methods; thus, it represents an important advance for creating synthetic bioassessments of system response. Appendix C provides details on the methods, with a brief summary in the following.

We construct MMIs from candidate vegetation metrics (see above and Appendix D), HDI, UUI and a suite of environ-

mental covariates following Schoolmaster et al. (2012) and Schoolmaster et al. (2013a, b). Our models are based on the assumption that human disturbance and/or ungulate use at GRSA has a complex, multivariate effect on park wetlands and that therefore it is the multivariate relationship with disturbance that needs to be evaluated and incorporated into index construction. In practice, this means selecting sets of metrics based on how they respond to disturbance as a group, as opposed to how each metric responds individually, as is done in more classic bioassessments. Schoolmaster et al. (2013a, b) showed that the characteristics of metrics that will combine to produce the most sensitive MMI cannot be deduced from the bivariate relationships between the metrics and disturbance. Instead, whether a candidate metric improves the sensitivity of an MMI (or not) depends on the strength of the disturbance signal in the candidate metric and its unique explanatory power within the set of candidate metrics. We therefore incorporate the way that metrics combine to convey information about disturbance into the construction of MMIs for GRSA's wetlands.

We construct two unique but related MMI models. Our first is based on HDI as the primary disturbance gradient. However, given the causal relationship between HDI and UUI (i.e., humans influence how and where ungulates disturb wetlands—the whole point of a fence!), we cannot statistically treat UUI as a valid covariate (Schoolmaster et al. 2013a, b). Therefore, MMI 1 is more of a "total disturbance" model because any patterning in UUI that is due to HDI is included in the model. The second uses UUI as the disturbance gradient, but because our conceptual modeling, exploratory analyses, and collective experience at GRSA suggests there is little causal connection from ungulate to human disturbance (i.e., ungulates do not drive how and where humans disturb the landscape), we can statistically control for HDI in MMI 2, resulting in an "ungulate disturbance only" model. We create two MMIs to better understand the differences between these disturbance gradients.

An important feature of our models is that they include all sandsheet wetland sites—they are not limited to one wetland type. We did generate initial models based on only salty meadows (available upon request). These were predictive and contained interpretable metrics. However, analysis suggested that sandsheet riparian and marsh vegetation communities were almost entirely nested in the vegetation community multivariate space of salt flats and wet meadows. These models had interpretable component metrics, fit the data well, had high correlations with HDI or UUI, and had lower Akaike Information Criterion (AIC) values than salty meadow models. Therefore, we elected to use these models such that all sandsheet sites and wetland types were included in our results. Given small sample sizes for marsh and riparian wetland, our MMIs may not fully represent the unique ecology of these types on the sandsheet. When we have larger samples of these types (i.e., as part of the Ungulate Management Plan project), we will look at the model composition again.

We consider environmental covariates to be relevant factors for a model if they have demonstrated relationships in the literature or clearly expected relationships with vegetation metric(s) and disturbance and are exogenous with respect to the disturbance gradient and candidate metrics (i.e., the covariates have no arrows pointing to them from other variables in the model). We used the ordinations, predictive models, and our collective experience with the wetlands at GRSA as the sources for deciding what variables to include as covariates.

2.4.2 Status

We define status as a "snap shot" evaluation of a WEI response over a well-defined and relatively concise range in time (Olsen et al. 1999). It is estimated using a variety of tools for all WEI variables at both population and site scales.

For objectives one and two (determine population scale status in wetland area and a suite of response measures), we use data from survey sites and design-based analyses that provide inference to an extensive target population of the park's wetlands. Design-based analyses are well specified (Horvitz and Thompson 1952; Overton and Stehman 1996; Stevens 1997) and are the foundation of long-established analyses used in socioeconomics, politics, medicine and other fields. While beyond our scope here, in summary, design-based analyses use the inclusion probabilities (or sampling weights) from the design to extrapolate results or provide inference to unsampled elements of the target population. Results from design-based analyses apply (with the precision given in a confidence interval or standard error about an estimate) to all sandsheet salt flat–wet meadows in GRSA in 2010. We report design-based results for WEI responses in tables and for select examples in plots (using a cumulative distribution function; CDF). CDFs include a confidence interval around the distribution of probabilities as estimates of the uncertainty in population scale inference (Stevens 1997).

For the assessment of population scale results (objective three), where assessment points are known we estimate and graphically show the proportion and/or real unit-based

extent of a wetland response that is above or below the assessment point and interpret these patterns using ecological theory and NPS management guidance. This process is well suited to Figures created from CDFs as we can locate the proportion and/or real unit-based percentage of the response that is above or below the assessment point on these plots. We also use simple pie charts to illustrate the proportion of a population in an assessment class, although these limit the inclusion of estimates of the variance around a value and should be used with caution.

For objective four (determine status at a site scale), we use a variety of traditional model-based analyses. Importantly, model-based results, including both simple descriptive statistics as well as more complex predictive models, apply only to the sites included in an analysis. In general we summarize data as means (or medians) and always include various measures of the variance around these statistics. Results are presented in simple tables and with a variety of graphics. For the assessment of site scale results (objective six), we follow the methods given below.

Objective seven (relate spatial and temporal patterns in select wetland responses to important ecological and anthropogenic drivers) requires more complex analyses that facilitate understanding ecological and statistical connections among WEI responses, drivers of wetland condition, and important covariates that influence these patterns. To address this we develop exploratory linear models for select responses, focusing on independent variables (also referred to as drivers or predictors) that might best help understand patterns in a response and that therefore might aid in wetland management. Importantly, these models apply only to the sampled sites and we make no inference to unsampled wetlands in GRSA. However, given our representative sample design, we expect the results to be broadly generalizable.

We keep these models as simple as possible by assuming all independent variables are fixed effects and we omit interaction terms. Given limitations in sample size and period of record, we do not consider these models to be predictive or tests of any hypothesis. Rather they are (examples of) explorations into potentially important connections among drivers and wetland response. While these models are descriptive and limited in predicting novel data, they are useful in that they reveal patterns and connections that might assist the park in improving or protecting wetland condition. Future work may support complementary predictive models, with more rigorous confirmation via techniques such as cross validation.

We tested each candidate variable for the assumptions of linear models and transformed as needed. We selected candidate independent variables for each model using a series of steps. First, we developed an initial list based on inclusion of interpretable variables from across the classes of variables measured in WEI monitoring. Second, we selected variables that were not confounded with one another based on checks for multicollinearity, and choosing the most interpretable variable from pairs or sets of highly correlated variables. We then conducted forwards and backwards stepwise selection based on Akaike Information Criterion (AIC) values (Venables and Ripley 2002). Final models were constructed by hand based on the stepwise output, followed by additional rounds of expert opinion for culling or re-including independent variables based on a variables interpretation and change in AIC value of the candidate model. While stepwise procedures have been criticized (i.e., Zuur et al. 2010), our approach is not entirely automated and we feel that the use of AIC (v. p values) coupled with expert selection based interpretations of the ecological relationships among a response and a candidate predictor(s) largely deals with these criticisms. Note that we do report p values for the final included independent variables and for the model overall. While this is a subject of debate, we felt it appropriate for our exploratory purposes (*sensu* Murtaugh 2014).

To assist in the interpretation of variables in the final model, we estimated the relative contributions of each of the predictors to a model's total explanatory value. We used a classic (but recently much improved; Grömping 2006) approach that averages sequential sums of squares over orderings of regressors (Lindeman et al. 1980; Kruskall 1987). This produces estimates of each predictor's importance relative to the total amount of explained variance expressed as a simple percentage. These estimates consider both direct effects (i.e., correlations with the response) and its effect when combined with the other variables in the regression equation. The method averages over all possible orderings of predictors in a model, thereby dealing with multicollinearity (Grömping 2006).

Finally, we use conditional plots of partial residual to visualize these models (Larsen and McCleary 1972; Breheny and Burchett 2013). A partial residual plot is a graphical tool that shows the relationship between a given independent variable and the response variable given that other independent variables are also in the model. The plot shows the value of the variable on the x-axis and the change in response on the y-axis, holding all other variables constant (by default, median for numeric variables and most common category for factors).

2.4.3 Trend

We define trend as a non-cyclic, directional change in a response measure that can be with or without pattern (Urquhart et al. 1998). It is estimated using a variety of tools for a subset of WEI variables. Trend can be estimated at single sentinel sites through time (Larsen et al. 1995) or, in future reports when we resample survey sites, across an extensive population. Note that, as of publication, methods for including complex GRTS (generalized random-tessellation stratified) design attributes in trend estimates do not exist (Asparouhov 2006; Piepho and Ogutu 2002; Pfeffermann et al. 1998). Under the assumption that our surveys are simple random samples, future trend model results will be conservative given the properties of GRTS designs (Urquhart et al. 1998). Starcevich et al. (in press) develops interesting applications for developing population scale trend estimates that analytically include GRTS design properties and we will investigate the use of these methods in future reports.

Objective five (determine the long-term trend in the condition of select wetland responses at specific sentinel sites or complexes) requires analyses that estimate trend in WEI responses collected annually at sentinel sites. Our approach follows work by the Sierra Nevada I&M network (Heard et al. 2012), especially the statistical tools applied by L. Starcevich. We construct linear mixed-effects models using a restricted maximum likelihood approach (REML; VanLeeuwen et al. 1996) that specifically address trend estimation for correlated data (i.e., the correlations across time that naturally occur in repeated measures ecological data). We first test and correct for the assumptions of parametric models including independent and normally distributed errors with equal variance. Mixed models allow effects to be considered either "fixed" or "random." Fixed effects contribute to the mean of the outcome and random effects contribute to its variance. Following Piepho and Ogutu (2002), we model sites as fixed and years as random effects. The designation of terms as either fixed or random is an important and complex process; however, Piepho and Ogutu (2002) develop methods that for REML allow site as we use it to be fixed or random based on the type of design used. GRSA sentinel sites were selected by a targeted (vs. random) design and so the proper form for the site effect is fixed. We treat years as a random variable given that we only have a small sample of all possible years and thus we assume the years included in our models are realized values of a truly random variable. Moreover, Piepho and Ogutu (2002) recommend modeling the site intercept as fixed so that convergence problems are avoided and because this optimizes test power when residual variance is large. For select responses we use the single year (2010) exploratory models (see above) to select a limited set of covariates and include these in each model as additional fixed effects. Because we have an interest in measuring net trend over time as a percent change (i.e., what is the total percent change from 2010 to 2014), we use both a logged and untransformed version of each response. We use Satterthwaite degrees of freedom (Piepho and Ogutu 2002) for the tests of trend and confidence interval construction. Finally, because mixed models do not generate a model R2, yet this is a very useful metric of the model's quality, we approximate this using the correlation between fitted and observed values (Xu 2003). We implement the mixed models in the R libraries lmerTest (Kuznetsova et al. 2013) and lme (Bates et al. 2014).

To estimate trend in hydrologic parameters (depth to water collected daily at select sentinel sites) requires models that are more specific. Groundwater hydrology time series data typically exhibit strong periodicity and often nonlinear patterns of change. Methods such as linear regression have no provision to deal with such serial autocorrelation and may therefore provide a poor fit to groundwater time series data. We therefore used a generalized additive model (GAM; Wood 2011) in which smooth functions were used for select predictor(s) and an autocorrelation-moving average model applied to account for temporal structure in the DTW data (Box et al. 1994). We structured the DTW data as the daily average for spring to fall periods within each year where nearby climate stations and field visits suggested the well was not covered in snow (snow confuses the pressure transducers in the loggers and makes DTW data unreliable). We fit various GAM models to estimate these daily data to estimate the pattern of within-year variation, and then tested for across-year variation (trend). Models that used one smooth form for all sites versus individual smooths by site were compared via AIC. We used the mgcv library in R for the gam with the corARMA function from the nlme library to test for autocorrelation. All models were constructed following guidance from T. Philippi (NPS). Given limited data and incomplete understanding of the drivers of site level hydrologic regimes, they should be considered draft.

2.4.4 Assessment and interpretation

A key element of WEI monitoring and central to objectives three and six (assessing status and trend) is the interpretation of results in a way that is both scientifically defensible and relevant to the management of GRSA wetlands. We follow assessment approaches and use terminology modified from Stoddard et al. (2006), Bennetts et al. (2007) and Mitchell et al. (2014) as these methods have become established in other federal monitoring programs such as the National Wetland

Condition Assessment (NWCA; EPA in review). They are also used in part by the Colorado Department of Public Health and Environment (CDPHE 2012) and are beginning to coalesce within the NPS. Most importantly, GRSA has accepted our approach as a general and flexible framework for interpreting WEI data.

In broad stroke, we compare our monitoring results to "assessment points" (defined below). We stress numeric over narrative assessment points to remove as much subjectivity from the process as possible. We interpret these comparisons in a collaborative way with park staff and management in the context of park management objectives, NPS resource management policies, and general ecological theory. We do not perform statistical tests of WEI data relative to an assessment point. Comparisons are instead whether a WEI response at a site or for the population of streams in the park, during a defined time period or over time, is above or below an assessment point, with no estimate of the statistical probability of this occurrence. Given continued development of our assessment approach since the publication of the WEI protocol in 2015, an overview of the process is provided here. The next version of the WEI protocol will include these additions.

2.4.4.1 Assessment points: disturbance and ecological condition

To define classes in distributions of WEI data we use assessment points (Bennetts et al. 2007). Assessment points are values in a response where scientists and managers have together agreed that they want to assess the status or trend of a resource relative to program goals, natural variation, or potential concerns. They establish boundaries between alternate states or classes in measures of disturbance or ecological response. Network monitoring and assessment includes a variety of types of assessment points, including management specified values, regulatory criteria, and well-defined ecological thresholds (see Schweiger et al. 2015). Assessment points may or may not correspond to patterns in ecological processes—although it is preferred that assessment points have ecological meaning. Nevertheless, even essentially arbitrary assessment points still have value as a basis for comparisons across streams or over time if they are well defined and explicit.

For measures of disturbance or stress (for example, general human use in and around a wetland), we propose a set of four class labels developed in the Great Sand Dunes National Park and Preserve (GRSA) General Management Plan (GMP; NPS 2007). "Negligible" defines a level of stress where human disturbance is barely detectable and/or would result in no measurable or perceptible changes to wetlands. Importantly, we restrict "negligible" to cases where there is no measurable disturbance—true "zero" values. "Minor" describes a range of human disturbance where an impact is slight but detectable and/or would result in small but measurable changes in wetlands, but with all effects localized. This may not be possible depending on the response (i.e., most soil chemistry parameters cannot have a known true zero) and in these cases the lowermost class for the measure would use the label "minor." "Moderate" defines the range where impacts are readily apparent and/or would result in easily detectable changes to wetlands with most but not all effects localized. Finally, "major" applies to a range of stress where impacts can be severely adverse and result in appreciable changes to wetlands, with the effects often regionally important.

For measures of ecological or biological condition, we use terms derived from the ecological assessment literature (Steedman 1994; Karr and Chu 1999; Hughes 1995; Jackson and Davis 1995; Davies and Jackson 2006; Stoddard et al. 2006, 2008). First we use "reference" for classes or ranges that correspond to "good," intact, high ecological integrity, and "non-reference" for "bad," degraded, low ecological integrity states. Where applicable we use "intermediate" for condition range(s) in between reference and non-reference. We reserve a special case (see below) for the distribution of near "pristine" ecological condition values that correspond to negligible human disturbance. A pristine reference state is the desired condition in GRSA wilderness.

The sets of terms for disturbance/stressor and biological response condition classes are applied across all types of assessment points. Assessment points may be set by GRSA resource management, be defined by criteria, be derived from ecoregional reference sites, etc.; we label classes on either side of these values using these terms with the following clarifications. Following Stoddard et al. (2006, 2008), we restrict the use of the suite of terms that contain "reference" to the assessment of ecological or biological condition or, in rare cases where there is a clear connection to ecological condition, to other types of responses. Thus, we will not label classes of a stressor, like general human disturbance or groundwater depth out of its natural range, with "reference" or "non-reference," rather they are labeled as in a major, moderate, minor, or negligible disturbance class. In cases where there is only one assessment point (meaning that there will only be two classes), we choose labels based on the type of assessment point, its intended use, and where it falls

in the distribution of values for a response. For ecological response, this is usually "reference" and "non-reference" (omitting intermediate and pristine reference). For disturbance/stressors, this is usually "major" and "minor."

Finally, the NPS Organic Act establishes the purpose of national parks, monuments and recreation areas to include conserving natural resources "unimpaired" for the enjoyment of future generations. This term is also used in the Clean Water Act (CWA) where regulatory criteria are defined that set "impairment" (i.e., that a wetland is not meeting its designated uses as set by the CDPHE or the EPA). To avoid confusion and because NPS is not responsible under the CWA for regulating uses, we do not use the term impairment in Network assessments. In the rare cases where regulatory criteria exist under the CWA for wetlands, we label a wetland response that exceeds the criterion as in a "major" stress class.

2.4.4.2 Assessment strategy for GRSA wetlands

A summary of our assessment methods as applied to GRSA WEI data follows. See also Schweiger et al. (2015).

Identify and prioritize assessment points

At this early stage of WEI monitoring at GRSA, we lack many assessment points for either measures of disturbance (stress) or ecological response to this stress. Assessment points will be added in collaboration with park management as we progress in our work and come to better understand patterns and relationships between wetland condition and drivers at GRSA. Priorities for application of existing or development of new assessment points can vary with a given response. In many cases one or more of these options do not exist, but in general the hierarchy is as follows: 1) GRSA management derived assessment points (which may include any of the following), 2) state/federal/tribal nation regulatory criteria, 3) ecological thresholds, and 4) "ecoregion" assessment points derived from reference site data within GRSA. Note that while ecoregion assessment points are the last in the hierarchy, in many cases, these are the only assessment point(s) available and they are thus often widely used.

Ecoregional assessment points

Given continued development of our assessment approach since the publication of the WEI protocol in 2015, an overview of the process behind ecoregional assessment points is provided here. We use a methodology known as the "reference site approach." This is well-accepted and common in state and other federal monitoring programs (Stoddard et al. 2006, 2008; Huber et al. 2007; Suplee et al. 2005; Kusnierz et al. 2013). Key assumptions include that reference sites are ecologically similar to WEI sites and that wetland monitoring methodologies used across sites are comparable—this is why the WEI protocol is based on methods common to our state and federal partners. Use of properly defined reference sites helps assure that reference state assessment points are based on a "natural" condition shaped by a broad spectrum of drivers such as climate, geography, or successional dynamics. In contrast, non-reference sites are structured by both direct and indirect anthropogenic stress and natural variation and thus confound these two types of drivers. Intermediate states tending towards the reference end of the spectrum are influenced increasingly only by natural drivers and vice versa.

The process includes five steps: 1) define relevant reference sites from the ecoregion(s) a park is embedded in (or in this report, from only the park itself), 2) collect data from these sites for the indicators being assessed, 3) classify the appropriate context for the park, 4) set percentile based thresholds in the distributions of the reference site indicator data following EPA guidelines, and 5) compare WEI data to the disturbance or condition classes defined by ecoregional assessment points.

There are currently no data from ecoregional wetland reference sites around GRSA. This may change in the near future as the EPA National Wetland Condition Assessment (NWCA) results become available. Therefore, we use a subset of data from the large and representative sample of GRSA wetlands in 2010 as ecoregional reference sites. We select *a priori* candidate reference sites from all WEI monitoring locations using methods from EPA (in review) and Stoddard et al. (2006, 2008). Sites are filtered based on their physiochemical and landscape context (i.e., landuse patterns across large areas). This methodology has been applied by the National Wetland Condition Assessment conducted by EPA (EPA, in review) and in several other national monitoring efforts. The Network uses similar approaches for stream and wetland monitoring in other parks. Stressor gradients at candidate wetland sites are examined in a GIS using various criteria, including:

Presence of anthropogenic impact

- hydrological modifications
- forestry activities
- agricultural development
- residential/urban development, and/or
- industrial and recreational development

- presence/absence of roads or trails within 1 km of the wetland

Distance to the nearest

- ditch
- human landuse
- road or trail

Sites are scored based on the proximity/intensity of the disturbance within each of these classes. The maximum score for a most disturbed site is 33. EPA (in review) defines a reference site as having a score of 11 or less.

These criteria were developed by the EPA and its partners for a national assessment scale. They are general by design. When we applied these to GRSA WEI sandsheet sites, all sites were classified as having minor stress and thus in a reference condition (Appendix E). However, as we present in this report, when examined in more detail it is clear that all GRSA wetlands (at least on the sandsheet) are not in a true reference state in the context of criteria relevant to NPS (NPS 2007b). We develop more specific and, we think, appropriate to the park (NPS 2007b) and NPS (Fancy et al. 2009; Colwell et al. 2012) classifications of sites based on our monitoring data for GRSAs wetlands as presented in this report. Nevertheless, as a starting point with a basis in other published and accepted approaches, using the EPA derived *a priori* classification allowed us to efficiently move on to the next step in the assessment process.

Next we define assessment points within these *a priori* reference sites following guidance (confirmed by GRSA resource management) from the EPA. The details of the assignment are based on the degree of historical and extant disturbance in and around a park and may be either defined as a "least disturbed condition" (LDC) or a "minimally disturbed condition" (MDC). LDC applies when there has been historical human disturbance in and around a park or where a park is nested within a largely human modified matrix. MDC applies where there has been no measureable stress beyond diffuse large scale impacts (i.e., low level nutrient deposition) and includes parks surrounded by wilderness area or other low use protected landscapes (Stoddard et al. 2006, 2008). The use of an MDC or LDC alters the percentile values at which assessment point values are set in the distribution of an indicator at reference sites (see below). The choice of whether a park is in an MDC or LDC context is an important step in the assessment process and should ultimately be made by a park in consultation with the Network. We propose in this report that the appropriate context for GRSA is an LDC. An LDC reference context allows a degree of physical, chemical, and biological alteration (Stoddard et al. 2006; Bailey et al. 2004; Hughes 1995; Hughes et al. 1986). Most of the sandsheet at GRSA has been used for agriculture or ranching (often intensively) for many decades and thus we believe an LDC is appropriate. Assessment points in an LDC context are based on percentile values from Stoddard et al. (2006, 2008). The percentile values used in an LDC are less conservative than those applied in an MDC context—in other words, it is "easier" for a response at a GRSA WEI site to be assessed as in a reference state than it would be if we assumed an MDC was the correct context for the park.

For responses that increase with decreasing condition (or increasing stress; i.e., HDI) we use the >75th or <50th percentile values to define or bound the major disturbance and minor disturbance classes (respectively). For responses that increase with increasing condition (or decreasing stress; for example, as we assume for depth to water) we use the <25th and >50th percentile for major disturbance and minor disturbance bounds (respectively). Values in between these percentiles fall in the moderate disturbance class. Note that we reserve negligible disturbance as a special case at a true zero value (or the 0th percentile). This zero value must be reliably estimable and conceptually sensible.

Percentile based ecoregional assessment points are arbitrary. However, they are well defined, explicit, allow for quantitative comparisons over time and are in use by several other long-term monitoring programs (EPA in review; Stoddard et al. 2006, 2008). We consider them baseline values to use as we develop more meaningful ecological assessment points and/or as we work with park management to define relevant management assessment points for wetland protection in the park. They have the important strength of being derived from empirical distributions that account for natural variability across a wide variety of wetland types in reference conditions relevant for GRSA. Table 5 provides a summary of the various assessment points we use to interpret GRSA WEI data.

Special case: predicting pristine ecological response
For our park-scaled bioassessment metrics (i.e., the MMI), we develop more specific and meaningful assessment points by modeling the relationship between disturbance and ecological response (Figure 10). We predict MMI scores at assessment point values in HDI, including a value of zero or negligible disturbance. We define the predicted response at HDI = 0 as a "pristine reference condition" and feel that this has real ecological meaning as it is based on an absence of

Table 5. Wetland disturbance classes and scores related to wetland ecological integrity reference condition classes. Disturbance classes and scores come from the Great Sand Dunes National Park and Preserve General Management Plan (NPS 2003).

Disturbance class	Assessment point[1]	Scale, units	Data source(s)
Major	Value in the top 75th percentile	Non-reference	Ecological state is "bad," degraded, and/or with "low" ecological integrity.
Moderate	Value between the 75th percentile and 50th percentile	Intermediate	Ecological state between reference and non-reference.
Minor	Value <50th percentile	Reference	Ecological state is "good" but allows for a degree of physical, chemical, and biological alteration.
Negligible[2]	Value <= 0	Pristine reference	Ecological state is "pristine" with no measurable human impact.

[1]Response illustrated here increases with decreasing condition (i.e., HDI, or most water physiochemistry parameters) and assumes an MDC context landscape. For a response that decreases with decreasing condition (i.e., depth to water), the percentile values are the inverse of those shown here (25th and 50th percentiles).

[2]Negligible disturbance requires a response that can logically be zero and/or is measurable and reportable at a zero value. It is discussed further below.

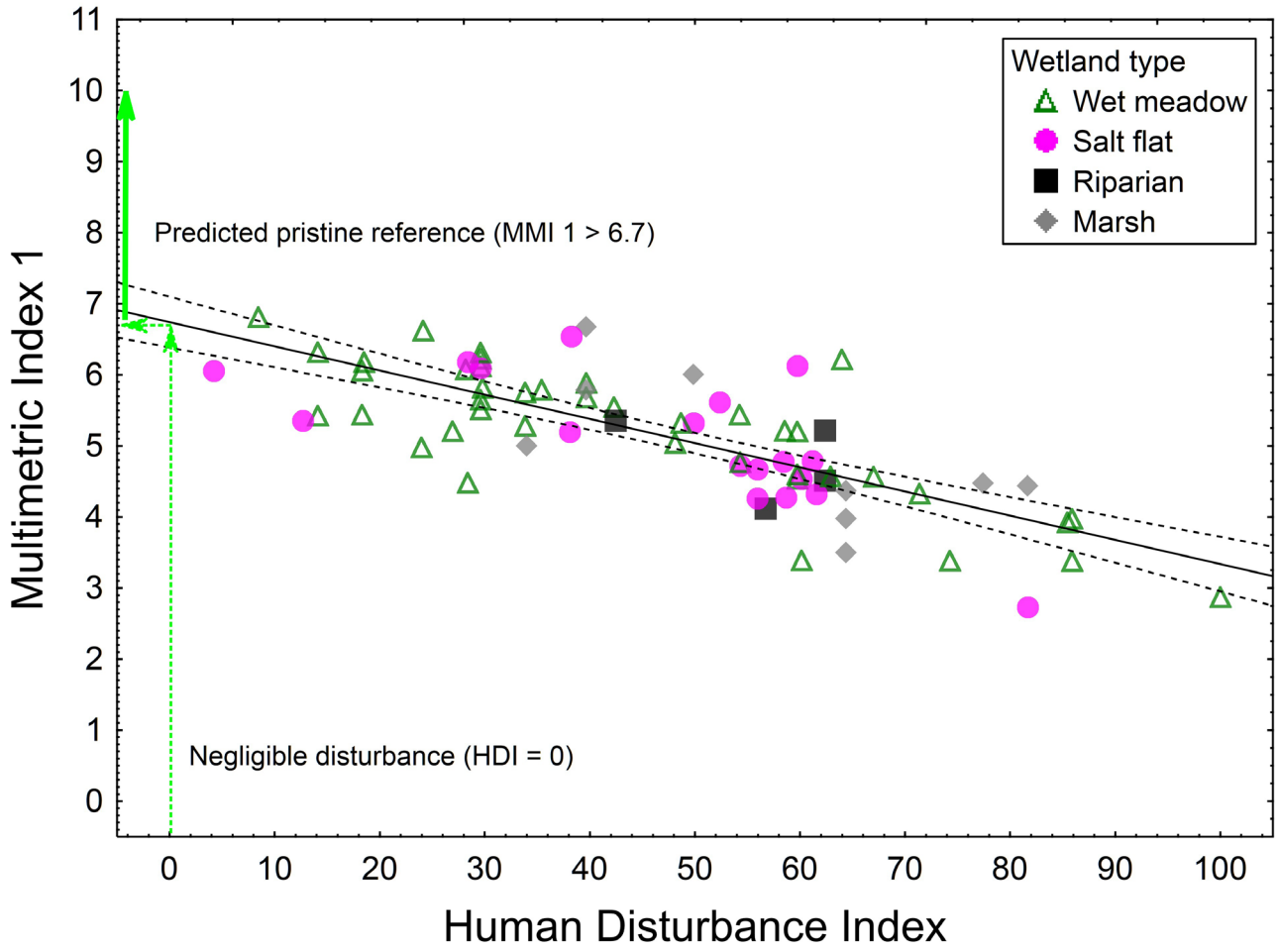


Figure 10. Illustration of relationships between human disturbance (HDI) and associated assessment points and predicted ecological response assessment points and classes in a Great Sand Dunes National Park and Preserve multimetric index. As an example, dotted vertical and horizontal light green lines indicate a HDI = 0 negligible assessment point value used to predict the pristine reference assessment point (MMI =6.7) and the pristine reference condition class above this value. A similar pattern follows for other HDI assessment points and their predicted MMI response (not shown). Note these data are actual MMI results for GRSA—details are provided in the bioassessment results section below.

significant human disturbance, not an essentially arbitrary (but useful) percentile. We can estimate the natural variation around each predicted condition assessment point using the 95% prediction interval around each predicted value. A prediction interval takes into account the variability in the conditional distributions of a predicted MMI assessment point as well as the uncertainty in our estimate of the conditional mean value (both of which play a role in the ability to predict a MMI score at HDI = 0). However, for simplicity we use the centroid of the prediction interval.

A site in pristine reference would have the following characteristics (using the components of HDI):

1. no hydrologic alterations in the complex,
2. no retention of upstream surface water,
3. a sufficient buffer (~100 m) around the wetland such that any adjacent anthropogenic disturbance has zero measurable impact on the wetland,
4. no anthropogenically caused landscape fragmentation within 1 km,
5. riparian corridors not broken up by anthropogenic features,
6. appropriate hydrologic interaction with riparian floodplains,
7. no anthropogenic soil disturbance,
8. no anthropogenic landuse in complex or its 100 m buffer,
9. riparian banks stable and not influenced from anthropogenic disturbance,
10. no anthropogenically caused algal blooms,
11. invasive taxa not dominant (>70% cover),
12. no anthropogenically caused sedimentation,
13. no anthropogenic toxicity from heavy metals.

Because GRSA wetlands have "co-evolved" with native ungulate use over thousands of years (Geary 2016), removing all ungulates from the area would not likely equate to a more ecologically healthy ecosystem. Therefore, the interpretation of the predicted reference condition at a zero UUI value is more nuanced. UUI is not a measure of the abundance (counts) of elk or bison. Rather, UUI = 0 is a sustainable level of ungulate use of wetland habitat that in most years or over time likely maximizes condition of the habitat. It includes select positive effects of elk or bison use on wetlands. There are many mechanisms whereby this happens, including stimulation of productivity, creation of substrates suited for recruitment, removal of competitive dominants, and more. (Gough and Grace 1998; Augustine et al. 1998; Xiong et al. 2003; Wolf et al. 2007; Kaczynski and Cooper 2015). As UUI increases, however, at some point ungulate habitat (over) use begins to have a negative effect and the expected condition or ecological integrity decreases. This is a complex pattern and our current data do not adequately or sufficiently describe it.

2.4.4.3 Summary condition tables

Select GRSA WEI results are summarized in "summary condition" tables that include a brief description of our indicators of wetland ecological integrity, summaries of the status and/or trend in the condition of the vital sign(s), and our confidence in the result. They are accompanied by simple graphic symbols that visualize important features of summary condition statements. Figure 11 provides a legend for the summary condition tables.

Summary condition statements are important for rapid integration into park resource management and interpretation. However, they are a simplification of details presented in our full results and discussion sections and should be used with caution. They are most reliable when we have assessment points for a given measure or metric, especially when these have either a direct connection to ecological processes, management of streams, or have relevancy from other studies or research.

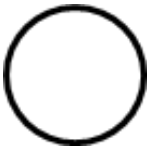
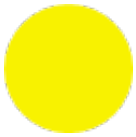
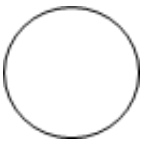
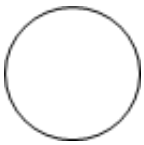
Condition status		Trend in condition		Confidence in assessment	
Symbol	Description	Symbol	Description	Symbol	Description
	Non-reference condition Major disturbance		Condition is improving		High
	Intermediate condition Moderate disturbance		Condition is unchanging		Medium
	Reference condition Minor disturbance		Condition is deteriorating		Low
	Pristine reference condition Negligible disturbance	No symbol	Unknown trend		
	Unknown or indeterminate condition				

Figure 11. Symbology and terminology for summary condition tables used in this report.

3 Results and Discussion

3.1 Results and discussion section organization

We order the results and discussion section logically, beginning with results from our estimates of the stressors and drivers of ecological condition in GRSAs wetlands. We conclude with the multimetric index (MMI) models built from these supporting data. However the order of importance to the park may be the "other way around," given our emphasis on bioassessment in interpreting wetland condition at GRSA. Therefore, readers may wish skip ahead to section 3.8, *Bioassessment of wetland ecological integrity*, and/or focus on the summary condition table in the Executive Summary above.

Each of the following sections presents key results and select interpretation for GRSA WEI data collected in 2010–2014. We focus on results summarized across all sites in the sandsheet portion of the park sampled in 2010, organized by response measure (i.e., soil, vegetation, bioassessment). For select measures, we also include models of trend at sandsheet sentinel sites from 2010 to 2014. Within all of the results sections, we include general interpretation and discussion of patterns in the data.

Several sections begin with a summary condition table. These provide concise overviews of select responses and a generalized synthetic assessment. These overviews are also presented in a condensed summary condition table in the Executive Summary of this report.

3.2 Climate context

Climate plays an important role in wetland ecological integrity at GRSA (i.e., Colwell et al. 2012). We include measures of climate as covariates in many of our models. The scale of climate effects is likely larger and longer than our data, and future, more detailed analysis will be needed to expand upon this.

Average annual temperatures increased in the park and the preserve over the period 1950–2010 at about a rate of 1.3 degrees (F) per century (the rate was not statistically significant; Figure 12). Over this same time period, total annual precipitation increased at statistically significant rates (at around 54% per century) in the park and especially the preserve (Figure 13; Gonzalez 2016; Monahan and Fisichelli 2014). Changes of this magnitude may have important implications in GRSA. For example, analysis of 22 bison herds, including on the sandsheet in GRSA, indicate that hotter and drier conditions may reduce forage quality and animal weight (Craine 2013).

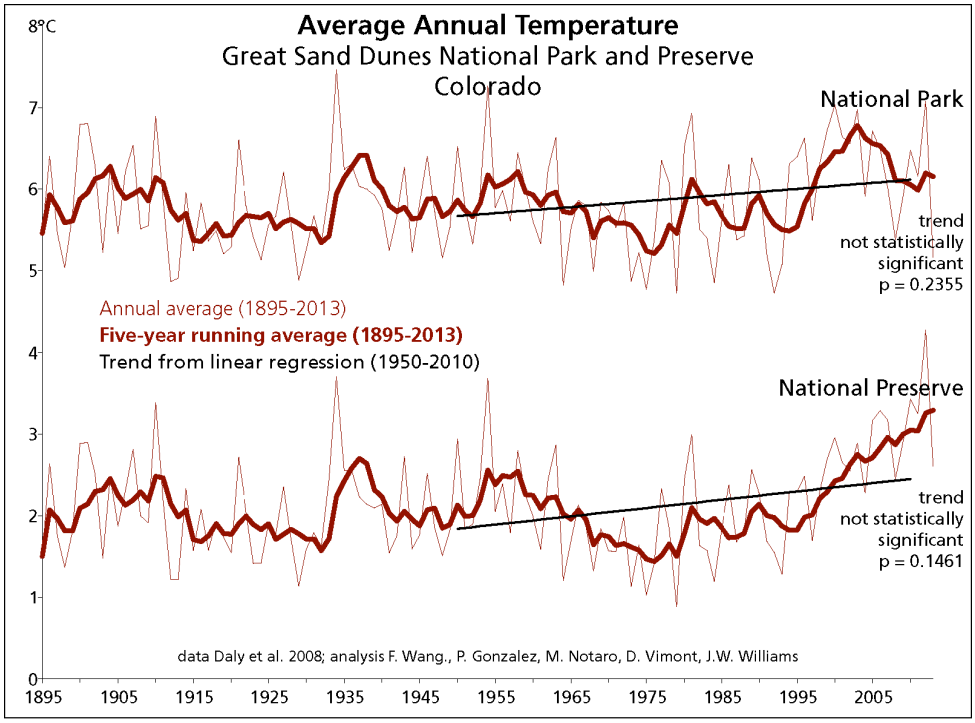


Figure 12. Mean annual temperature from 1895 to 2014. Data from 1950 to 2014 show a positive but non-significant increase. Data are from PRISM (Parameter Elevation Regression on Independent Slopes Model; PRISM Climate Group 2015; Daly et al. 2008) clipped to the Great Sand Dunes National Park and Preserve boundaries. Figure from Gonzalez (2016).

Perhaps more relevant to our analyses in this report are patterns closer in time to our sample years. Using data from the National Weather Service station at park headquaters, by 2010 a drought that began in 2007 was at its peak. Figure 14 shows a normalized Reconnaissance Drought Index (RDI) by water year from 2004 to 2014 (Tsakiris et al. 2007, Figure and results courtesy Walking Shadow Ecology, 2016). RDI is the ratio of precipitation to evapotranspiration divided by the average of this ratio for the time period analyzed. Evapotranspiration was generated using the Penman-Montieth equation (Allen et al. 1998). Negative numbers correspond to periods when evapotranspiration exceeds precipitation. Figure 15 shows annual mean precipitation by water year over this same time period. The five year running average is still above the long-term average in water year 2010 but the annual value is well below the mean. Precipitation and drought do not recover at the park until 2014. Thus, most of the WEI data we include in this report were collected when water stress was likely high.

3.2.1 Water balance

Measures of water balance are biologically meaningful, well correlated with the distribution of vegetation, and perform well over several orders of magnitude of spatial scale (Stephenson 1998). They have more predictive capacity than simpler climate parameters given the intrinsic difference of the effects of evaporative demand and water availability. For example, the "dry" experienced by plants on south facing slopes (high evaporative demand) is not comparable to the "dry" experienced by plants on soils with low water-holding capacities (low water availability), and these differences are reflected in vegetation patterns. Thoma et al. (2016) show that water balance parameters can predict the influence of climate on vegetation at a fine temporal scale, which presents an opportunity to forecast vegetation response with short lead times.

Figure 16 shows climatic deficit (D; actual evapotranspiration minus potential evapotranspiration) at all sandsheet sites over water years 2004 to 2014. Sites at the bottom of the array of curves with low D (lower absolute drought) are near the mountain toe slope (with higher elevation) or two sites at the far northern extent of the park. These sites are all wet meadows that have hydrologic regimes driven by a mixture of surface and groundwater sources. Soil water generally tracks precipitation, with peaks in 2007 and lower values in 2011 (see Figure 14 and Figure 15), suggesting there is not much water storage in soils. Moreover, while all sites follow a similar trajectory through time, there is clear variation by site.

3.2.2 Climate change

It is unclear if future precipitation in and around the park will increase or decrease, especially during summer (even though we see fairly strong trends in historical data). Much of this depends on the future global climate regime. There

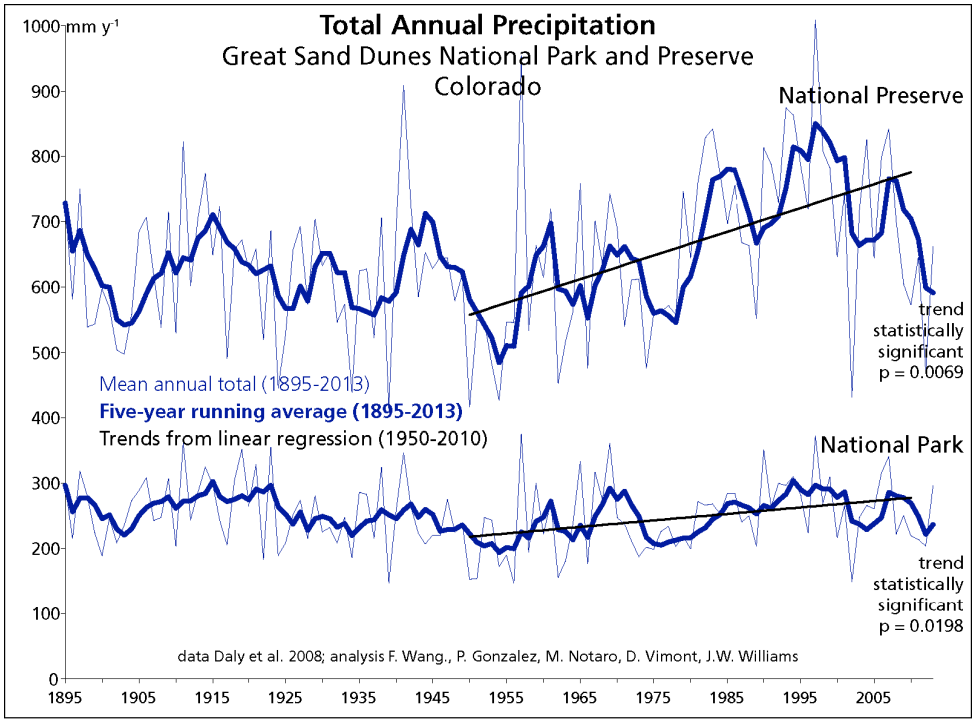


Figure 13. Mean annual precipitation from 1895 to 2014. Data from 1950 to 2014 show a positive and significant increase. Data are from PRISM (Parameter Elevation Regression on Independent Slopes Model; PRISM Climate Group 2015; Daly et al. 2008) clipped to the Great Sand Dunes National Park and Preserve boundaries. Figure from Gonzalez (2016).

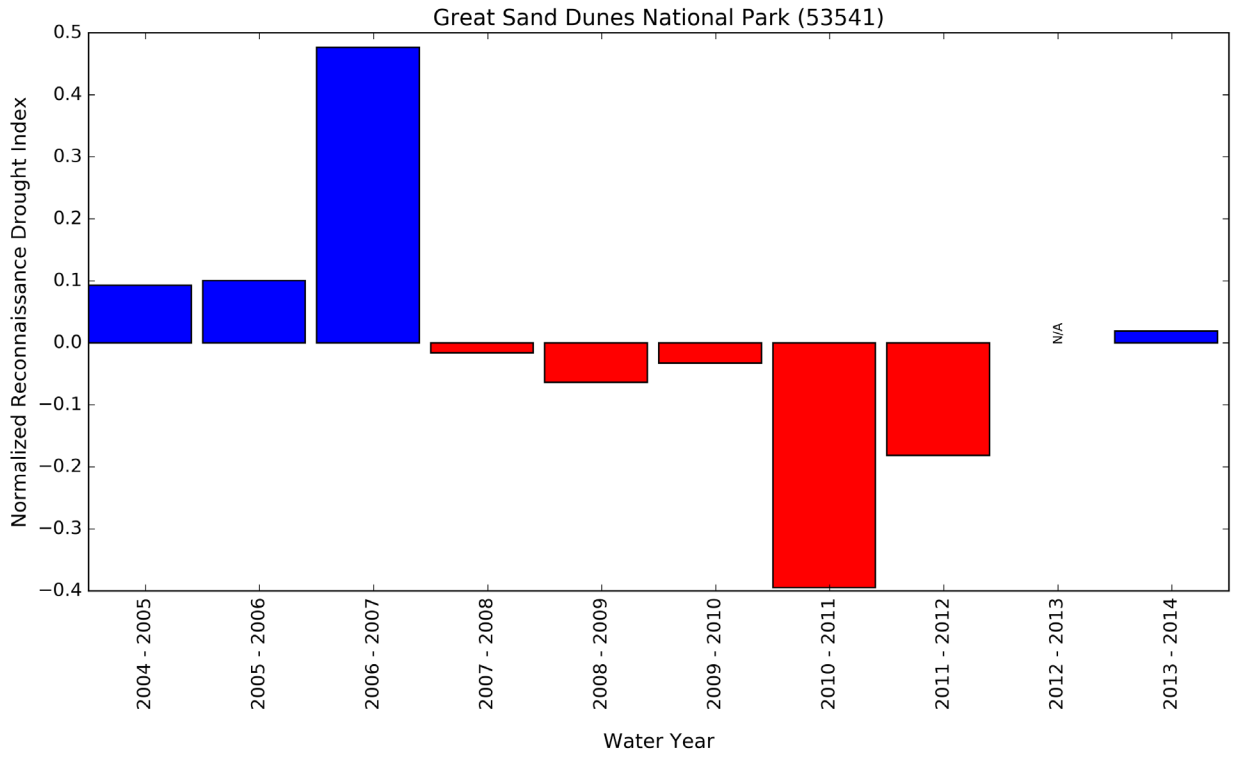


Figure 14. Reconnaissance Drought Index by water year for Great Sand Dunes National Park and Preserve, 2004 to 2014 (Tsakiris et al. 2007, Figure and results courtesy Walking Shadow Ecology 2016). This index is the ratio of precipitation to evapotranspiration divided by the average of this ratio for the time period analyzed. Negative values (red) indicate periods when evapotranspiration exceeds precipitation.

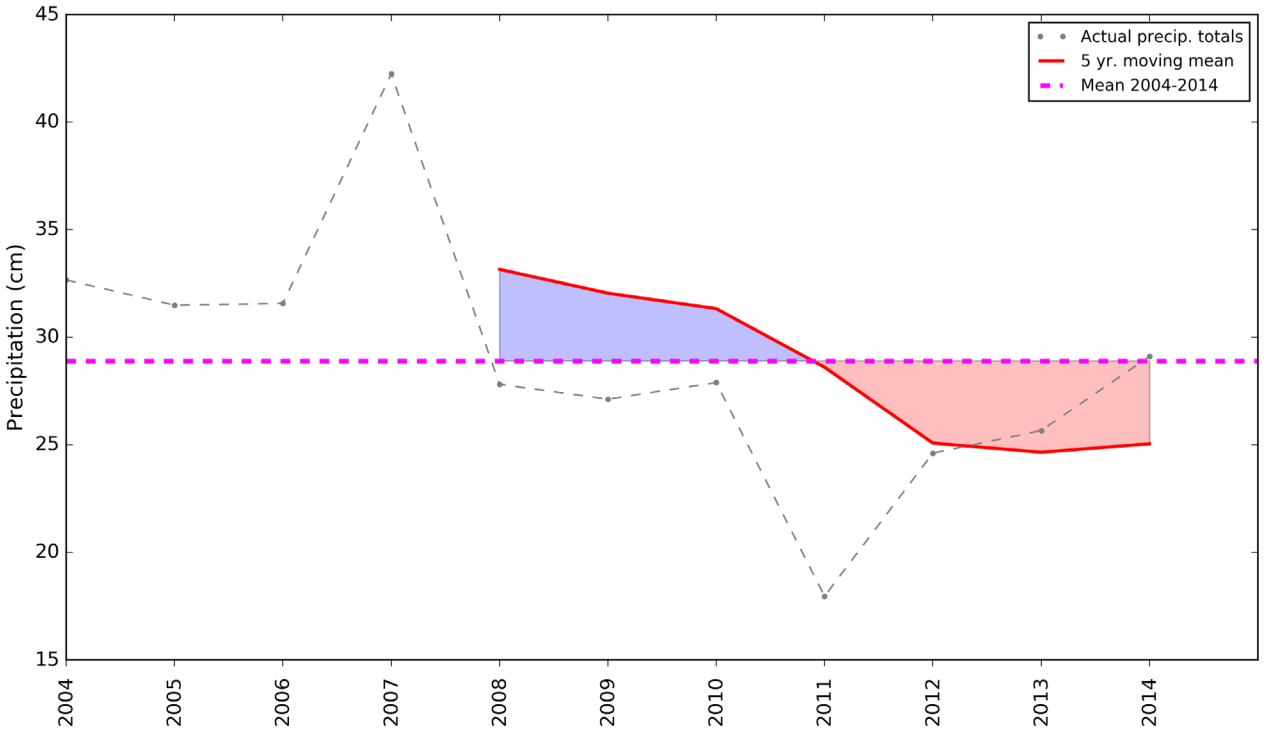


Figure 15. Mean annual precipitation by water year for Great Sand Dunes National Park and Preserve, 2004 to 2014 (Figure and results courtesy Walking Shadow Ecology, 2016). Blue shaded area shows that the 5-year running average is still above the long-term average in water year 2010, but actual precipitation is below the long-term average.

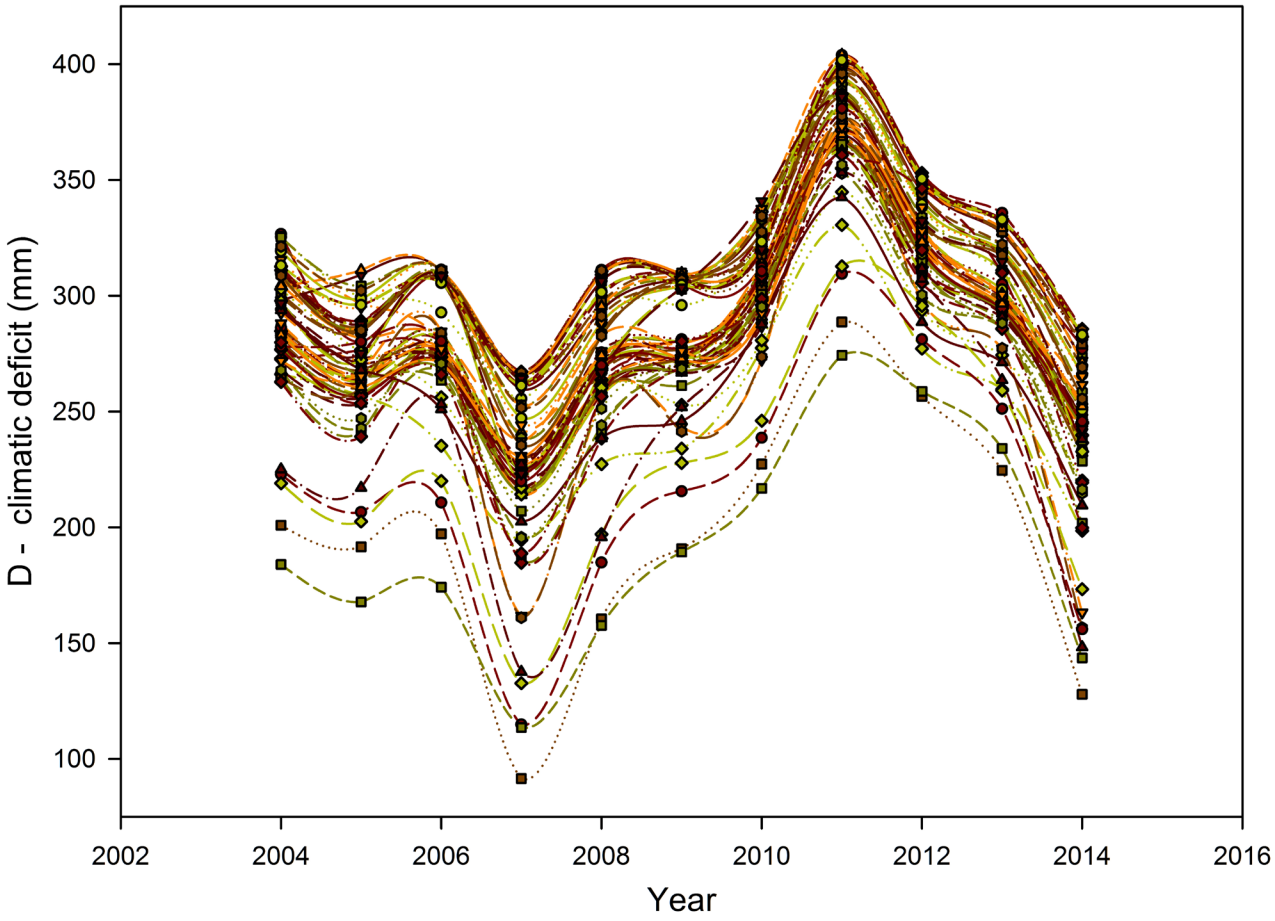


Figure 16. Climatic deficit (actual minus potential evapotranspiration) from 2004 to 2014 at all sandsheet sites, Great Sand Dunes National Park and Preserve. Sites in the bottom array of curves have lower absolute drought, and in this sample, represent wet meadows at higher elevation or in the far northern extent of the park.

is more certainty that variation in precipitation will increase across the region (Schlesinger and Mitchell 1987; Mitchell et al. 1990). Moreover, it is fairly clear that GRSA is projected to be hotter under nearly all possible climate change scenarios (Seager et al. 2007; Garfin et al. 2014; Ault et al. 2014). Many patterns in temperature already regularly exceed their historical range of variability (Monahan and Fisichelli 2014). The interaction between temperature and precipitation creates the suite of other, potentially more important "water balance" variables as discussed above. How these change in the future will likely have the most important effects on GRSA's wetlands.

Current projections suggest that climate change will likely reduce the number and extent of wetlands and cause declines in the condition of associated flora and fauna and critical functions, such as carbon and water storage (OTA 1993; Field et al. 2007). Protected landscapes such as GRSA do not insulate wetlands from the direct and indirect impacts of a changing climate regime. Expected shifts in climate that will impact the hydrologic regimes supporting GRSA wetlands include less snow (the increase in precipitation shown above is largely as rain), earlier peak flows, overall less stream flow, warmer water temperatures, more frequent droughts, and more intense storms (Barnett et al. 2008). The partial loss of winter snowpack in the Sangre de Cristo Mountains will reduce a major source of groundwater recharge and summer runoff, resulting in a potentially significant lowering of water levels in streams and wetlands on the sandsheet.

3.3 Wetland area

Wetland area is often used as an indicator of the condition of wetland across a landscape. Many functions are more secure when wetlands are large or well buffered from disturbance. Moreover, vegetation remains more intact or diverse, and hydrologic services, like water storage and purification, are more enabled when wetlands are protected from alteration. Tables 6, 7, and 8 present results for wetland extent and composition. Additional details on methods and more specific results for this indicator are given in Appendix C.

Table 6. Great Sand Dunes National Park and Preserve (GRSA) wetland extent by data source and wetland type. Values are from Salas et al. (2011), using 1:12k imagery, hand and auto digitized with park-specific map unit names, and cross walked to Ecological Systems and Wetland Ecological Integrity types. See Appendix C for break out by Vegetation Map and Ecological Systems wetland types.

Site location	Wetland Ecological Integrity type	Count	Total (ha)	Mean patch size (ha)	SD patch size (ha)	% of total wetland area	*% of total GRSA area
High elevation	fen	9	5.21	0.58	0.74	0.15	0.03
	riparian	59	315.31	5.34	10.14	9.17	1.87
	wet meadow	49	167.17	3.41	5.76	4.86	0.99
	Total	**117**	**487.69**	**4.17**	**8.23**	**14.18**	**2.89**
Sandsheet	marsh	34	421.78	12.41	28.72	0.76	0.97
	riparian	92	331.00	3.60	8.04	1.29	0.76
	salt flat	119	562.56	4.73	7.37	3.75	1.29
	wet meadow	224	1637.23	7.31	23.45	6.76	3.75
	Total	**469**	**2952.57**	**6.30**	**18.82**	**85.82**	**6.76**
All sites	**Grand Total**	**586**	**3440.27**	**5.87**	**17.26**	**100.00**	**5.69**

*For comparison to design based estimates, we use separate totals for high elevation (16854.2 ha) and sandsheet (43651.6 ha) areas in calculations.

Table 7. Mean and standard deviation of the proportion of wetland type, water, and upland in 100 m² around each evaluated site at Great Sand Dunes National Park and Preserve in 2010. Table rows show sample design expected type and table columns show actual types as assessed in the field. The type with the highest proportion for each type is in bold.

Sample design expected type	Metric	Wetland type as measured in the field					
		Salt flat	Wet meadow	Riparian	Marsh	Water	Upland
All points (N = 302)	Mean	25.63	34.60	0.66	2.17	0.00	37.27
	SD	40.33	43.83	8.11	14.20	0.00	40.33
Salt flat (N = 113)	Mean	**57.30**	6.24	0.00	0.00	0.00	36.46
	SD	**43.94**	21.42	0.00	0.00	0.00	43.94
Wet meadow (N = 189)	Mean	6.69	**51.56**	1.06	3.47	0.00	37.75
	SD	22.06	**45.01**	10.23	17.83	0.00	22.06

Table 8. Design-based estimates of sandsheet salt flat and wet meadow wetland extent and patch size at Great Sand Dunes National Park and Preserve (GRSA), 2010.

Wetland type	% of GRSA area	Metric	Area estimate (ha)	SE	Lower confidence bound	Upper confidence bound
Salt flat (N = 15)	7.9	Mean patch size	6.14	2.28	1.68	10.6
		Total area	3485.6	1332.3	874.3	6096.9
Wet meadow (N = 26)	22.5	Mean patch size	22.53	7.26	8.29	36.76
		Total area	9811.5	3854.7	2256.3	17366.7

Remotely sensed data showed that at the time the Vegetation Map imagery was collected (2007), the sandsheet was almost 7% wetland. However, site-level extent data and design-based methods suggested around 30% of the sandsheet was salt flat and wet meadow in 2010. We do not think this difference is due to a large increase in wetland from 2007 to 2010 but rather is due to the two different methods. The design based approach should result in a better estimate. Additional research is needed to resolve this.

We lack estimates of the historical extent of wetland in GRSA prior to the 1991 National Wetland Inventory (USFWS 1991) or the 2007 Vegetation Map (Salas et al. 2011), thus we do not know the historical natural range of variability in wetland area. Our interpretation of these results is limited and we use extent estimates as baseline assessment points for future monitoring.

3.4 Human disturbance and ungulate wetland use

3.4.1 Summary condition

In general, human disturbance and ungulate use at GRSA is extensive and thus an area of concern for the park. In 2010 no wetlands on the sandsheet were undisturbed by human use. A few sites did lack measurable evidence of ungulate use. Importantly, at least at select sentinel sites on the sandsheet, human disturbance decreased from 2010 to 2014, although the cause of this is unclear. However, over this same time period, there was an increase in our estimates of ungulate habitat use at these sites. This may be due to higher numbers of elk or more intense elk habitat use as the bison herd was reduced over this time period. We link these patterns in disturbance and ungulate use to ecological response in our MMI models that explore the relationships among human disturbance, ungulate use, and wetland ecological condition. Table 9 presents a summary condition table for our human disturbance results only. See the Executive Summary for a summary condition table that includes all indicators of wetland condition.

3.4.2 Overview

We begin the presentation of our results and their discussion with estimates of disturbance across the GRSA landscape in 2010 and, at sentinel sites with select indices, annual trend from 2010 to 2014. We lead with this subject in large part because many of the successive sections use disturbance as a key gradient or covariate by which a wetland response is interpreted.

Estimating disturbance is an important part of wetland monitoring. Documenting and interpreting the response of wetland to disturbance across time and space is in many ways the core purpose of WEI monitoring. Wetlands are highly sensitive to anthropogenic and other disturbances. Road-zone effects have been especially well documented (Boarman and Sazaki 2006; Palomino and Carrascal 2007; Wilbert et al. 2008; Eigenbrod et al. 2009; Parris and Schneider 2008). There is also evidence for impacts from both urban and exurban development (Odell and Knight 2001; Hansen et al. 2005; McDonald et al. 2009), energy development (BLM 1999; Wilbert et al. 2008; Nasen 2009; Lovich and Ennen 2011; Naugle 2011), and agriculture (Davis et al. 1993; de Jong et al. 2008). Finally, large ungulates may also influence wetland condition (i.e., Zeigenfuss et al. 2002; Coughenour 2002) although this is more complex given the many interactions among ungulates and other species (i.e., beavers) relevant in wetland condition and the important role of the carrying capacity of a site.

We use six metrics of disturbance that incorporate the various types of disturbance summarized above, including HDI and UUI developed from WEI field data, the Colorado Natural History Program (CNHP) Landscape Disturbance Index (LDI), the Elk and Bison Indices derived from USGS data, and the Trail Index. While using multiple metrics is more complex, we believe each of these has merit as estimates of meaningfully different aspects of how wetland is potentially impacted by disturbance across the park's landscape. Importantly our measures of disturbance are relative—they are unitless and in most cases should be interpreted only in comparison to GRSA wetland specific assessment points and/or in comparison to data from GRSA WEI sites.

3.4.3 Human disturbance and ungulate wetland use: results and interpretation

We first present overviews of disturbance via traditional descriptive statistics and maps of spatial patterns in each index. We include interpretations of correlations among the six metrics in an attempt to illustrate how they are usefully different (or the same). Appendix F presents select site level examples of disturbance.

Table 10 gives means and measures of dispersion for each index. Note that each index is normalized and ranges from 0 to 100, with increasing levels of disturbance. High elevation fens and wet meadows are the least disturbed wetlands in the park, with peak disturbance in low elevation riparian and marsh sites. Some wetland types have a small sample size and a non-representative sample design. In salt flats and wet meadows, which are sampled more robustly, disturbance tends to be more in the middle of the index ranges. Most disturbance indices have a fairly normal distribution.

3.4.3.1 Comparison with other Network parks

We use the same HDI methods in other Network parks and we therefore can make qualified comparisons between GRSA and Rocky Mountain National Park (ROMO) (and in the future with Florissant Fossil Beds National Monument (FLFO)). Likewise, the Colorado Natural History Program

Table 9. Summary condition table for disturbance at Great Sand Dunes National Park and Preserve in 2010, and, for select measures, at sentinel sites from 2010 to 2014. Key to the condition and confidence symbol: red, textured color = non-reference condition/major disturbance, yellow color = intermediate condition/moderate disturbance, dark green color = reference condition/minor disturbance, light green color = pristine reference condition/negligible disturbance, no color = unknown or indeterminate; upward arrow = condition is improving, sideways arrows = condition is unchanging, downward arrow = condition is deteriorating, no arrow = unknown trend; heavy border = high confidence, regular border = medium confidence, dashed border = low confidence. Figure 11 offers a visual key.

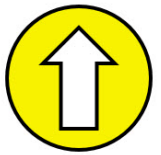
Disturbance and ungulate use indicators	Condition description	Condition and confidence
Human Disturbance Index (HDI) (2010)	One of the foundations of WEI monitoring is the estimation of disturbance regimes potentially impacting GRSA's wetlands. We evaluated human disturbance at all of our wetland sites and constructed a Human Disturbance Index (HDI) based on that information. HDI quantifies a diverse suite of historical and extant human stressors across multiple scales. We link these patterns in disturbance and ungulate use to ecological response in our MMI models—this is where the 'rubber meets the road' in exploring how human disturbances affect the long-term ecological condition of the wetlands of GRSA. In 2010 there was a broad gradient in human disturbance, with many sites experiencing relatively high levels of human stress. Based on assessment point methodology established and used by other agencies and scientists, about 25% of the wetlands on the sandsheet were in a major disturbance class, with another 24% having a moderate disturbance level. We create an additional information rich assessment point by assuming that an HDI value of zero has real ecological meaning. This conservatively assumes that human disturbance of wetlands (or any ecosystem) in a national park like GRSA should be negligible (no disturbance or so little disturbance such that it is not detectable). In 2010, there were no sites on the GRSA sandsheet with a zero total disturbance level—all sites had at least some measurable disturbance or a "human footprint." We suggest that this is an important area of concern for the park. We further model HDI to better understand how it might relate to environmental covariates and other measures of disturbance. These models suggest that HDI did not vary much by wetland type, that it was largely structured by human hydrologic modification and human landuse in and around wetlands, and that it had a strong positive relationship with ungulate use. We interpret this last element as HDI driving or structuring ungulate use (an important detail for our bioassessment modeling). We have high confidence in our overall assessment given an unbiased sample design, rigorous data collection and quality assurance, and the exploratory modeling we employ. While the standardized percentiles are arbitrary and thus should be used with some caution (they are best viewed as baselines for future assessment), the negligible disturbance assessment point is more interpretable and immediately useful for understanding status in 2010 and subsequent changes over time.	
Human Disturbance Index (HDI), (2010–2014 trend)	We have annual HDI data at sentinel wetland complexes beginning in 2010. Trend models indicate decreasing human disturbance (8% decrease) at the Big Spring Creek, Big Spring Creek Terminus, and Elks Springs sites through 2014. Several sites moved from a major or moderate to a minimal disturbance class, with most sites in a minor disturbance class by 2014. However, all sites retained at least some human footprint (i.e., none had a desired negligible disturbance level). The reason(s) behind the improvement are unclear as there was no change in wetland management by the park over this time frame at these sites. Models suggest it may be due to decreasing impacts from hydrologic alterations, but more work is needed on this. Given the improvement in HDI scores (i.e., there was less disturbance), this indicator warrants a moderate concern summary condition assessment. We have medium confidence in these results given important assumptions about scale and the short time frame used in the trend modeling. The data themselves are high quality given an unbiased sample design, rigorous data collection, and quality assurance.	

Table 9 (*continued*). Summary condition table for disturbance at Great Sand Dunes National Park and Preserve in 2010, and, for select measures, at sentinel sites from 2010 to 2014. Key to the condition and confidence symbol: red, textured color = non-reference condition/major disturbance, yellow color = intermediate condition/moderate disturbance, dark green color = reference condition/minor disturbance, light green color = pristine reference condition/negligible disturbance, no color = unknown or indeterminate; upward arrow = condition is improving, sideways arrows = condition is unchanging, downward arrow = condition is deteriorating, no arrow = unknown trend; heavy border = high confidence, regular border = medium confidence, dashed border = low confidence. Figure 11 offers a visual key.

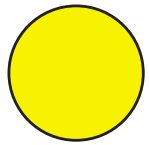
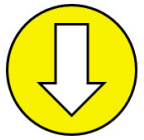
Disturbance and ungulate use indicators	Condition description	Condition and confidence
Ungulate Use Index (UUI) (2010)	The role of ungulate use of wetlands at GRSA as a possible disturbance is very important. The park is currently developing an Ungulate Management Plan in which Rocky Mountain Network Wetlands Ecological Integrity monitoring will play a key role. Our Ungulate Use Index (UUI) quantifies the level of use based on several site level indicators. (Note this index currently does not differentiate between bison and elk disturbance—we are addressing this in ongoing research.) Because the bulk of our UUI data was collected in 2010—both a dry year and the year after the highest bison numbers on the ranch to date—this is a useful index year for when ungulate use stress should have been highest. There was a broad gradient in ungulate disturbance across all sites in 2010. We link these patterns in disturbance and ungulate use to ecological response in our MMI models. These models are key in exploring how ungulate use affects long-term ecological condition of the wetlands of GRSA. We use percentiles set and used by other agencies and scientists to estimate assessment points in UUI, classifying sites as having major, moderate, or minor disturbance regimes. Around 21% and 33% of GRSA wetlands were in a major or moderate ungulate use class (respectively). These assessment points function as baselines for future analyses—for now we do not have a way to statistically or ecologically interpret how they might be related to wetland integrity. However, in contrast to human disturbance, which was ubiquitous across the sandsheet, around 13% of sites were in a more meaningful negligible use class (UUI = 0), with no indication of (over) use by ungulates. Importantly, UUI = 0 does not mean elk or bison abundance is zero or that there is no habitat use. Rather we assume that this level of use (or lower) of a site is sustainable and will likely have negligible (or possibly positive) impacts on a site's ecological integrity. As we continue monitoring GRSA wetlands, we will evaluate how ungulate use changes over time given park resource management actions and important dynamics with human disturbance. We will also be able to refine (with park management) UUI assessment points. We suggest that ungulate use warrants moderate concern. We model UUI to better understand how it might relate to environmental covariates and other measures of disturbance. These exploratory models suggest that (1) UUI did vary by wetland type, with more use in riparian wetland, (2) it was largely structured by human landuse (i.e., fences and roads used in ranching operations), and (3) higher productivity increased ungulate use. In addition, research by U.S. Geological Survey biologists in the park beginning in 2005 demonstrates sometimes dramatic differences in vegetation and other ecological responses in and out of exclosures. We have medium confidence in these results given our untested assumption that a UUI = 0 is a sustainable ungulate use level. However we are confident in our high quality sample design, quality assured data and exploratory modeling.	
Ungulate Use Index (UUI) (2010–2014 trend)	We have annual UUI data at sentinel wetland complexes beginning in 2010. Trend models indicate increasing ungulate use (24% increase) at the Big Spring Creek, Big Spring Creek Terminus, and Elks Springs sites through 2014. Several sites moved up in use class, with many sites in a major or moderate class by 2014. These trends did vary by sentinel site, with less increase in ungulate use at Elk Springs and a few sites in Big Spring Creel retaining the desired negligible use level. The reason(s) behind the increased levels of use are likely due to elk as there was a decrease in the bison herd size over this time frame (more research is needed on this) at these sites. Given the complex pattern in UUI scores, this indicator warrants a moderate concern summary condition assessment. We have medium confidence in these results given important assumptions about scale and the short time frame used in the trend modeling. The data themselves are high quality given an unbiased sample design, rigorous data collection, and quality assurance.	

Table 10. Summary of six measures of disturbance at Great Sand Dunes National Park and Preserve in 2010. All indices range from 0 to 100 with increasing levels of disturbance. Values in bold are the highest and lowest means for each metric across all subcategories. LCL/UCL are lower and upper 95% confidence intervals. Standard error is for the mean. Source data are the best sample events in 2010. HDI = Human Disturbance Index. UUI = Ungulate Use Index. LDI = Landscape Disturbance Index.

Site type	Disturbance measure	Valid N	Mean index score	LCL	UCL	Min	Max	Standard deviation	Standard error
All sites	HDI	82	43.3	38.3	48.4	4.2	100.0	23.1	2.6
	UUI	82	40.7	33.1	48.3	0.0	100.0	34.6	3.8
	LDI	82	36.4	30.8	42.1	0.0	100.0	25.7	2.8
	Elk Index	82	44.0	38.5	49.5	0.0	100.0	25.1	2.8
	Bison Index	51	31.3	24.2	38.5	0.1	100.0	25.3	3.5
	Trail Index	82	16.8	11.5	22.0	0.0	100.0	23.7	2.6
Sandsheet sites	HDI	74	47.1	42.2	52.0	4.2	100.0	21.1	2.5
	UUI	74	45.1	37.4	52.9	0.0	100.0	33.5	3.9
	LDI	74	40.4	34.8	45.9	3.4	100.0	23.9	2.8
	Elk Index	74	48.5	43.4	53.6	6.3	100.0	22.0	2.6
	Bison Index	51	31.3	24.2	38.5	0.1	100.0	25.3	3.5
	Trail Index	74	18.6	12.9	24.2	0.0	100.0	24.3	2.8
High Elevation Sites (7 fens, 1 wet meadow)	HDI	8	**8.5**	–	–	8.5	8.5	0.0	0.0
	UUI	8	**0.0**	–	–	0.0	0.0	0.0	0.0
	LDI	8	**0.0**	–	–	0.0	0.0	0.0	0.0
	Elk Index	8	**2.4**	0.2	4.5	0.0	5.4	2.6	0.9
	Bison Index	–	–	–	–	–	–	–	–
	Trail Index	–	–	–	–	–	–	–	–
Sandsheet Salt Flats	HDI	19	46.0	36.2	55.8	4.2	81.7	20.3	4.7
	UUI	19	45.8	29.0	62.5	0.0	100.0	34.8	8.0
	LDI	19	**51.8**	38.4	65.3	10.8	100.0	27.9	6.4
	Elk Index	19	44.2	34.3	54.1	8.9	71.5	20.6	4.7
	Bison Index	11	27.5	13.3	41.7	5.2	74.8	21.2	6.4

Table 10 (*continued*). Summary of six measures of disturbance at Great Sand Dunes National Park and Preserve in 2010. All indices range from 0 to 100 with increasing levels of disturbance. Values in bold are the highest and lowest means for each metric across all subcategories. LCL/UCL are lower and upper 95% confidence intervals. Standard error is for the mean. Source data are the best sample events in 2010. HDI = Human Disturbance Index. UUI = Ungulate Use Index. LDI = Landscape Disturbance Index.

Site type	Disturbance measure	Valid N	Mean index score	LCL	UCL	Min	Max	Standard deviation	Standard error
Sandsheet Salt Flats (continued)	Trail Index	19	**8.4**	0.0	17.8	0.0	79.9	19.4	4.4
Sandsheet wet meadows	HDI	42	44.6	37.6	51.6	8.5	100.0	22.6	3.5
	UUI	42	45.3	34.2	56.3	0.0	96.0	35.5	5.5
	LDI	42	34.9	29.2	40.5	3.6	94.1	18.1	2.8
	Elk Index	42	49.3	42.6	55.9	6.3	90.8	21.3	3.3
	Bison Index	29	36.0	25.6	46.4	4.4	100.0	27.3	5.1
	Trail Index	42	17.4	9.8	25.0	0.0	100.0	24.4	3.8
Sandsheet riparian	HDI	4	56.0	41.0	70.9	42.4	62.4	9.4	4.7
	UUI	4	**70.8**	30.5	111.0	33.0	85.0	25.3	12.6
	LDI	4	44.8	38.3	51.3	39.6	48.8	4.1	2.0
	Elk Index	4	36.6	28.0	45.2	31.3	42.0	5.4	2.7
	Bison Index	4	**49.0**	29.9	68.1	33.7	58.9	12.0	6.0
	Trail Index	4	**32.7**	10.7	54.6	17.5	45.5	13.8	6.9
Sandsheet marsh	HDI	9	**57.3**	44.0	70.5	34.0	81.7	17.2	5.7
	UUI	9	31.7	18.5	44.9	0.0	57.0	17.2	5.7
	LDI	9	40.0	12.3	67.7	3.4	84.6	36.1	12.0
	Elk Index	9	**59.1**	36.0	82.2	28.9	100.0	30.1	10.0
	Bison Index	7	8.1	1.1	15.0	0.1	19.0	7.5	2.8
	Trail Index	9	39.0	20.0	58.0	3.9	79.2	24.7	8.2

LDI has been estimated across the state and we can thus make select comparisons between GRSA, ROMO, and FLFO. These contrasts must always consider the ecological context of the wetland in question—ROMO, GRSA and FLFO are very different systems. In particular, neither ROMO nor FLFO have salt flats. The HDI is also normalized relative to data from each park.

Qualitative analysis of LDI across the Rocky Mountain Front Range and central mountain corridor suggests that ROMO, GRSA, and FLFO are much less disturbed than the developed and heavily agricultural areas outside of parks and at lower elevations. Landscape disturbance level is visually represented in Figure 17. The analysis suggests that landscape disturbance on the GRSA sandsheet is more similar to

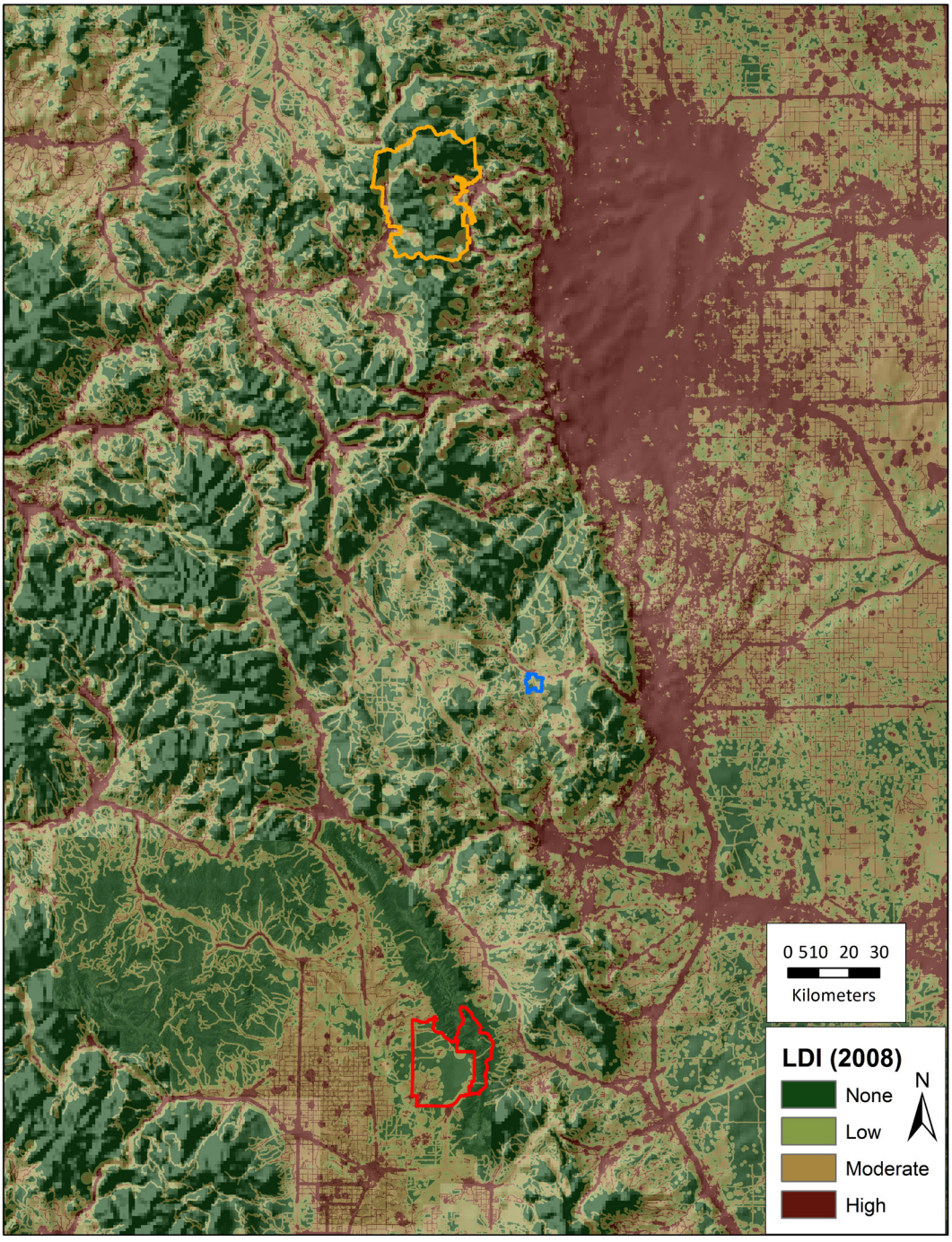


Figure 17. Landscape Disturbance Index (LDI) created by the Colorado Natural History Program (Lemly et al. 2011) across the Colorado Front Range, including Rocky Mountain National Park (orange outline), Florissant Fossil Beds National Monument (small, blue outline), and Great Sand Dunes National Park and Preserve (red outline). Higher disturbance values are shown with orange and red colors.

FLFO and heavily used areas of ROMO. The least disturbed areas are in the high elevation ROMO wilderness and GRSA Preserve (also a wilderness area).

Mean LDI was lowest in GRSA high elevation wilderness and highest in ROMO non-wilderness (Table 11). Fens tend to be high elevation and isolated from most direct human disturbances due to their landscape position and topography (in addition to elevation). There can be diffuse impacts from climate change driven disturbances or atmospheric deposition of excess nutrients on fens. Low elevation wet meadows in GRSA tended to have LDI values about twice that in ROMO. The few riparian sites sampled in GRSA also had higher disturbance. Both of these patterns are consistent with the lower elevation of these sites and the more anthropogenic landscape in and around the sandsheet portion of GRSA. There are no comparable salt flat wetlands in ROMO.

Salt flats are a unique wetland type that tends toward "natural" extremes of soil and water chemistry and often high proportion of bare ground. The vegetation community in salt flats may have a low cover of obligate wetland species and often surprisingly low species diversity, even in wetlands with little or no human disturbance. As noted above, we treat salt flats and wet meadows together in our analysis, so it is important to bear this in mind when interpreting our analysis of wetland integrity in sandsheet wetlands in GRSA.

3.4.3.2 Spatial patterns among indices of disturbance

We use six indicators of disturbance. Each has its own merits and differs in its intention along with its spatial and temporal scale. Most modeling (especially MMIs) in this report focuses on HDI and UUI, given their specialization to the wetlands at GRSA and resampling with every visit (most other disturbance data do not have the same update frequency). The following present brief graphical and qualitative comparisons of the six indices.

Table 11. Landscape disturbance values (not normalized) for Great Sand Dunes National Park and Preserve (GRSA), Rocky Mountain National Park (ROMO), and Florissant Fossil Beds National Monument (FLFO). LDI = Landscape Disturbance Index. Values in bold are the highest and lowest values across all subcategories.

Park and wetland type	LDI mean	LDI max
GRSA high elevation (wilderness)	**11.9**	**485.3**
ROMO (wilderness)	39.3	**1376.4**
GRSA sandsheet	108.3	1096.3
FLFO (non-wilderness)	110.9	951.5
ROMO (non-wilderness)	**214.0**	1378.3

Most disturbance indices have a positive correlation with each other (Table 12). HDI and UUI measure disturbance at a similar scale (in and near each site), likely enhancing their strong positive correlation. We interpret this relationship as causal from HDI to UUI—human usage controls ungulate disturbance. Importantly, our UUI index does not distinguish between elk and bison. However, based on the Elk and Bison Indices, Schoenecker et al. (2015), and our personal experience, it is clear that human landuse does drive bison habitat use (i.e., via fences, some supplemental feeding, and closely managed population numbers). The relationship between elk disturbance and human disturbance is more complex. Elk are managed directly by hunting (in the preserve and outside the park boundary) and via various indirect effects of habitat modification, predator removal, and other activities (Colorado Parks and Wildlife 2010). However, elk are also attracted to the park due to manmade water features such as ditches and wells, less human disturbance than surrounding private lands, and no public hunting. Overall there is a much smaller correlation between HDI and the Elk Index, reflecting this more complex pattern.

The LDI characterizes disturbance at a broader scale than HDI, both in the nature of its construction by CNHP and

Table 12. Correlations among disturbance indices at Great Sand Dunes National Park and Preserve. Data are drawn from the best events from all sandsheet sites in 2010. * indicates significant correlations at $p < 0.05$.

Disturbance Index	HDI	UUI	LDI	Elk Index	Bison Index	Trail Index
HDI	1.00	0.58*	0.26*	0.03	0.42*	0.04
UUI	0.58*	1.00	0.18	0.24	0.65*	0.16
LDI	0.26*	0.18	1.00	0.28	0.22*	-0.27*
Elk Index	0.03	0.24	0.28*	1.00	-0.08	-0.09
Bison Index	0.42*	0.65*	0.22	-0.08	1.00	-0.04
Trail Index	0.04	0.16	-0.27*	-0.09	-0.04	1.00

in the reporting unit at which we summarize it for each site (a 1 km buffer around each site). This likely contributes to the lower correlation with HDI (but the pattern is still positive suggesting they respond to similar drivers in and around each site). Figure 18 shows a bivariate plot and the spatial distribution of HDI and LDI. LDI is driven strongly by roads, which are concentrated in the southwest corner of the sandsheet. The set of sites above the regression line (with a high LDI relative to HDI) are wetlands, where larger scale disturbance plays a more important role.

The Elk and Bison Indices have a positive relationship with UUI (Table 12, Figure 19, Figure 20), although it is stronger for Bison, suggesting the UUI may be biased towards the impacts of bison. We have more sites inside the bison fence, so this may also be a sample size effect. The Bison and Elk Indices are in essence indices to the total count of animals in 2005–2007 based on estimated ranges. UUI is more a measure of habitat usage and impact. The Bison and Elk Indices are weakly negatively correlated, supporting the partitioning of habitat described in Schoenecker et al. (2015). Figure 19 and Figure 20 give bivariate plots and the spatial distributions of the Bison and Elk Indices and UUI. The strong patterns among these three indices are evident, although we lack samples in the northwest portion of the sandsheet where elk numbers are highest.

The Trail Index is interesting but more difficult to interpret. High trail density does not necessarily indicate the direction of travel and thus may be associated with sites that are visited or left more often. Its weak negative correlation with the Elk and Bison Indices suggest that trails lead away from areas with higher animal counts, yet its weak positive relationship with UUI suggests more trails occur in areas with higher animal use (Figure 21a). There are clear patterns with "watering holes" (Figure 21b, see also Figure F-3 and Figure F-4 in Appendix F), which are either stock tanks or springs and their associated wetlands.

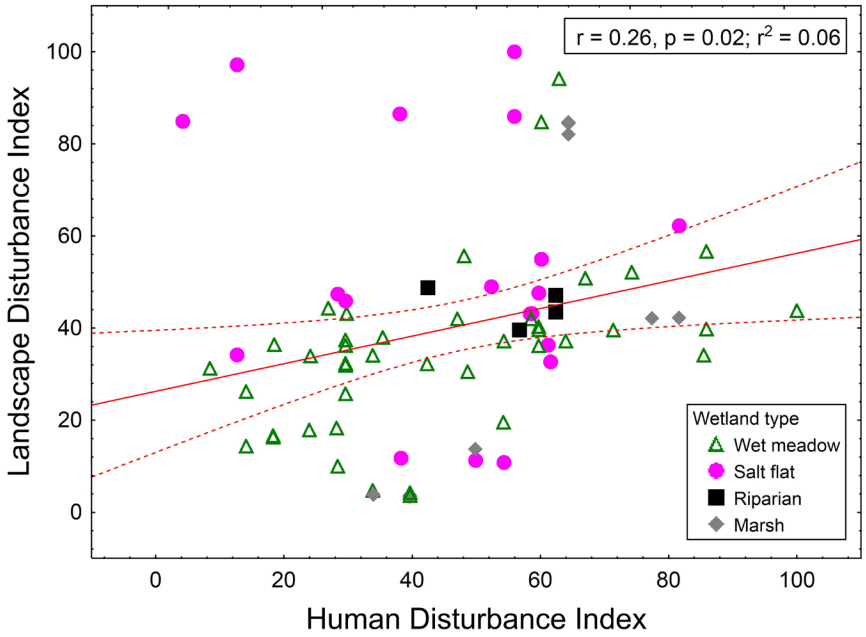
3.4.3.3 Population scale disturbance: sandsheet salty meadows

Next, we present population scale disturbance and ungulate use results for all salty meadows (sites on a continuum between salt flat and wet meadow) on the GRSA sandsheet in 2010. Design-based inference uses a suite of algorithms to estimate population means and various estimates of the error in these means. Figure 22 gives the cumulative distribution of disturbance and ungulate use metrics. The cumulative value is given both as a proportion of the total resource and as estimates of total area of wetland. An estimate of the error in the population scale inference is given by a 95% confidence interval around the cumulative value. Table 13 presents these estimates in the context of ecoregional and negligible assessment points (see above) and the proportion of wetland area in each of the four classes defined by these. We also illustrate the proportion of wetland area in each disturbance class with pie charts embedded in Figure 22. While visually useful, a pie chart does not show the confidence interval around the proportion of wetland in each class as in the cumulative distribution and should be used with caution.

With the exception of the Bison and Trail Indices, most mean disturbance index scores were around 50, suggesting the expected or "usual" disturbances in GRSA wetlands were near the middle of their possible values. This is reflected in the shape of the CDFs, with a fairly even accumulation of values from 0 to 100. However, UUI did have a large increase in the accumulation of values at around a score of 60, suggesting this distribution was more bimodal. This generally matches the difference in UUI scores inside (higher) and outside (generally lower) the bison fence. The Bison and the Trail Indices had lower means with steeper curves, suggesting more sites had lower disturbance scores for these types of responses.

While we consider HDI and LDI as measuring disturbance at different spatial and temporal scales, results for these two indices were similar. All sandsheet salty wet meadow had at least some human disturbance in 2010, with no wetland on the sandsheet in a negligible (HDI = 0) disturbance class. Using ecoregional assessment points, around 51% (with 95% confidence intervals of around 39–60%) of the salty meadow on the sandsheet had minor disturbance (HDI < 48), where HDI was low enough that we would expect little or less dramatic impacts on the condition of wetlands. In contrast, around 25% (14–35%) had major disturbance (HDI > 60), where we would expect degraded ecological integrity.

Around 13% (6–20%) of sandsheet salty wet meadow had negligible (UUI = 0) ungulate disturbance in 2010 as measured by UUI. Importantly, UUI is a measure of disturbance, not animal counts. Therefore our results do not mean that there were zero bison or elk at these wetlands or that they did not use habitat in these areas. Rather we assume that a zero UUI value was the level of use that had negligible negative impacts on wetland integrity or that this level of use was sustainable over some period of time. Application of ecoregional assessment points suggests 33%, (with a CI of 22–44%) of the salty wet meadow wetlands had minor disturbance (UUI < 57), with likely low impact on condition. Schoe-



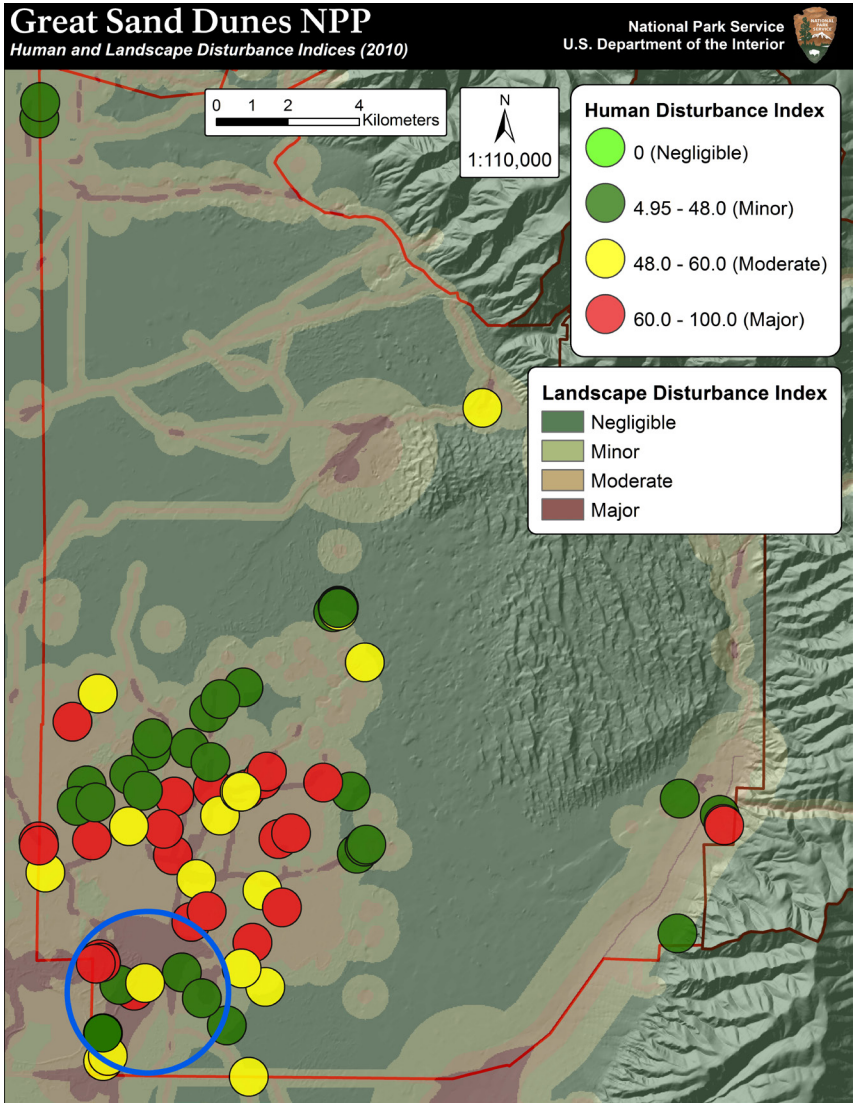
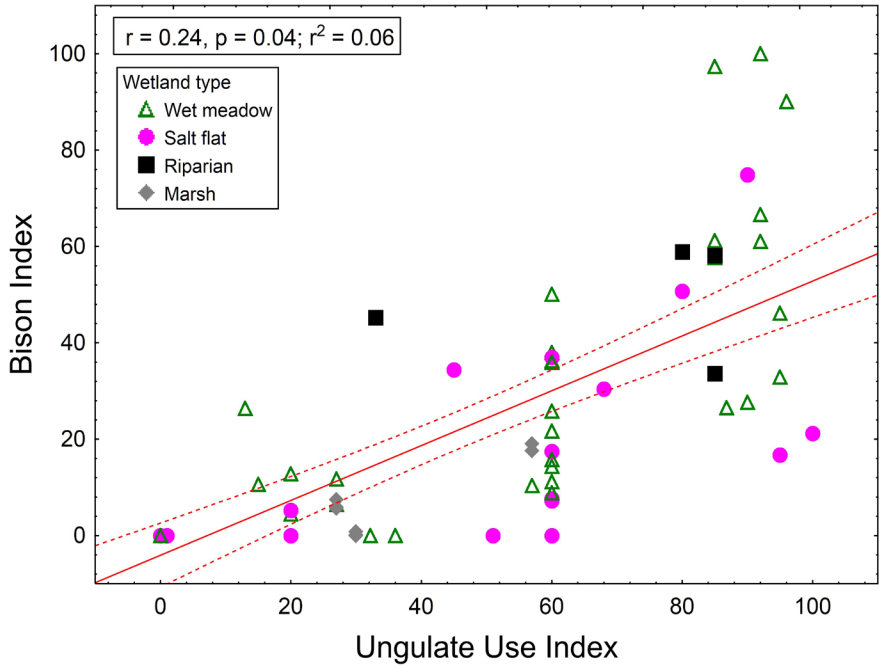


Figure 18. Landscape Disturbance Index (LDI) and Human Disturbance Index (HDI) bivariate relationship (left) and spatial patterns (right) at Great Sand Dunes National Park and Preserve. The map shows "bubbles" for HDI scores overlaid on a contiguous LDI surface. For HDI and LDI in the map, higher values are shown in red. Breaks in HDI symbology follow ecoregional-based and negligibile assessment point cutoff values. Breaks in LDI are from Jenks (1967) natural breaks algorithm. Area of sandsheet with higher road density and LDI is circled in blue. `



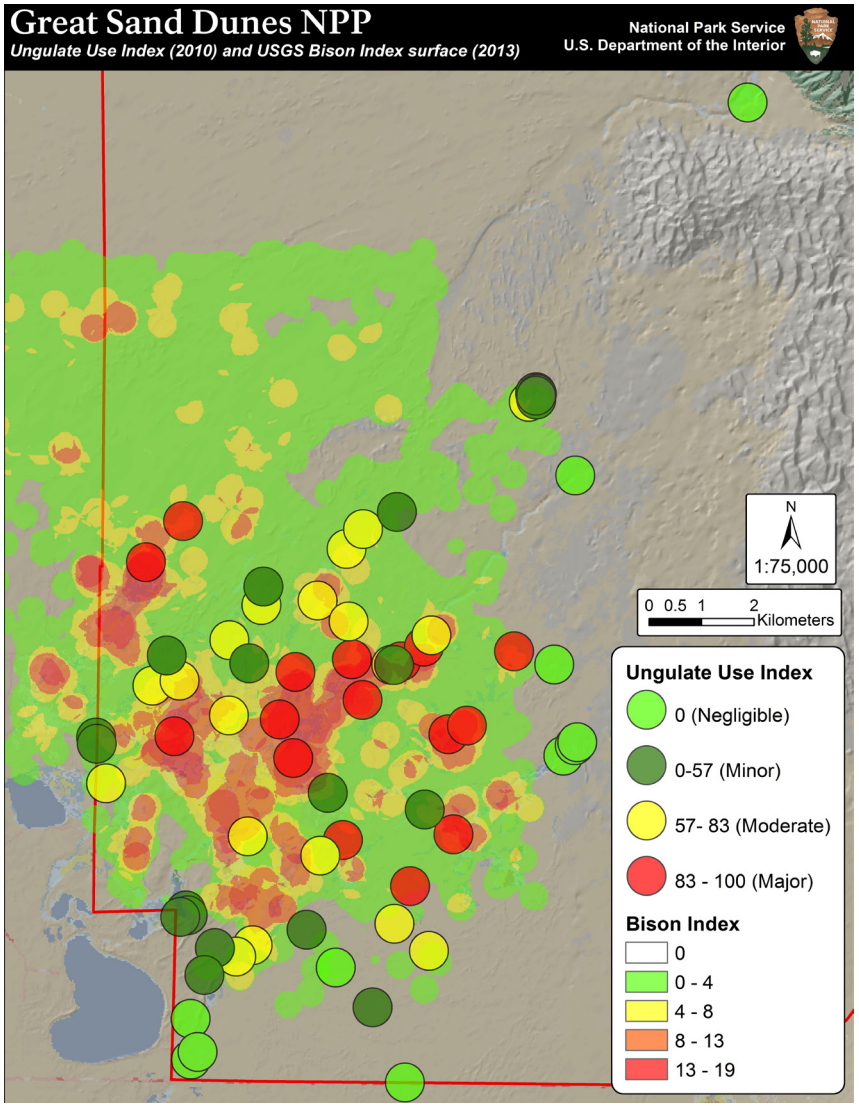
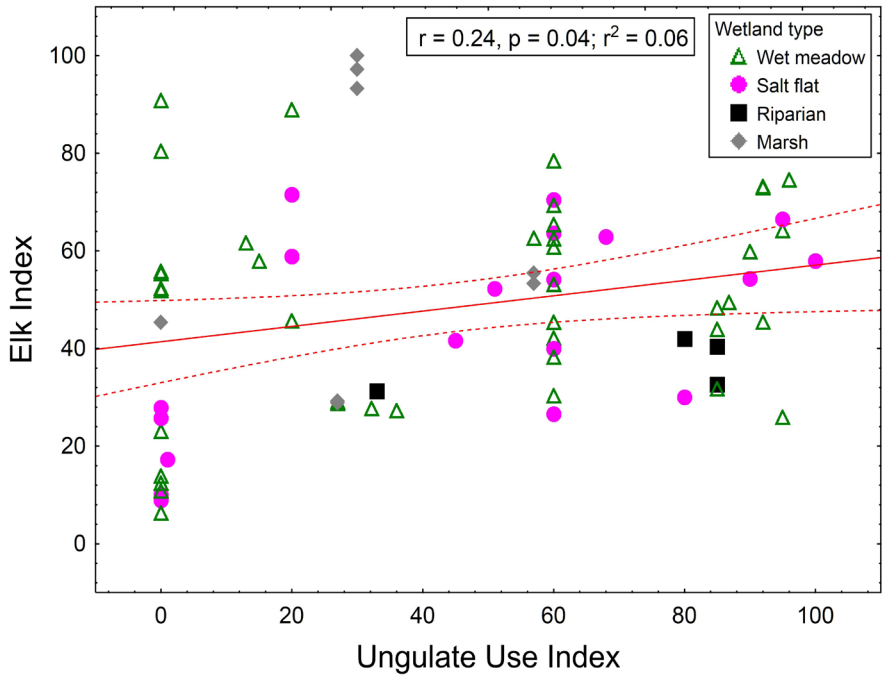


Figure 19. Bison Index and Ungulate Use Index (UUI) bivariate relationship (left) and spatial patterns at Great Sand Dunes National Park and Preserve (right). The map shows "bubbles" for UUI scores overlaid on a contiguous Bison Index surface from 2013 USGS data. For the mapped UUI and USGS Bison Index surface, higher values are shown in red. Breaks in symbology follow ecoregional-based and negligibile assessment point cutoff values.



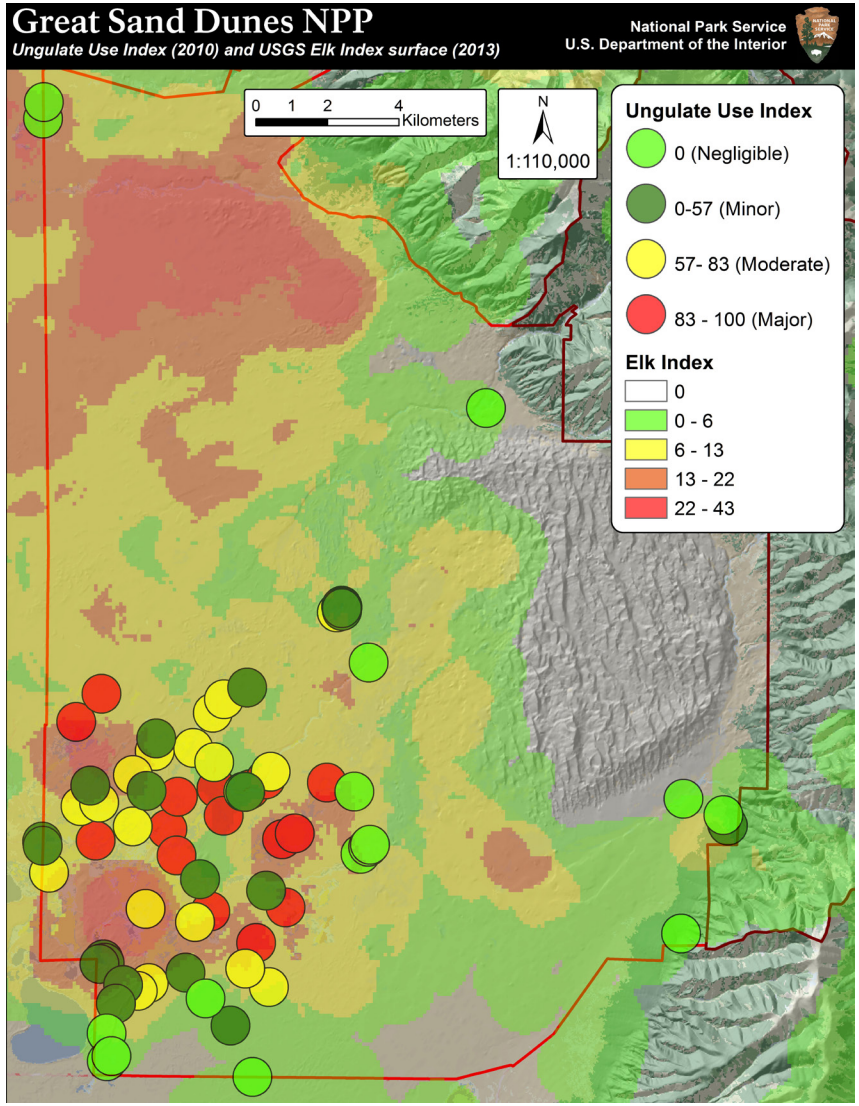
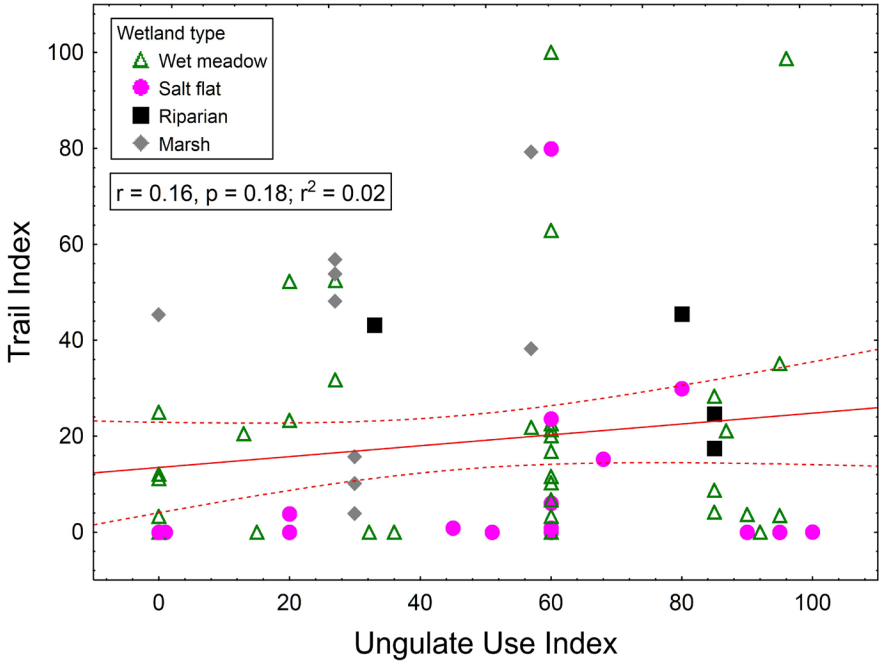


Figure 20. Elk Index and Ungulate Use Index (UUI) bivariate relationship (left) and spatial patterns (right) at Great Sand Dunes National Park and Preserve. The map shows "bubbles" for UUI scores overlaid on a contiguous Elk Index surface from 2013 USGS data. For the mapped UUI and USGS Elk Index surface, higher values are shown in red. Breaks in symbology follow ecoregional-based and negligibile assessment point cutoff values.



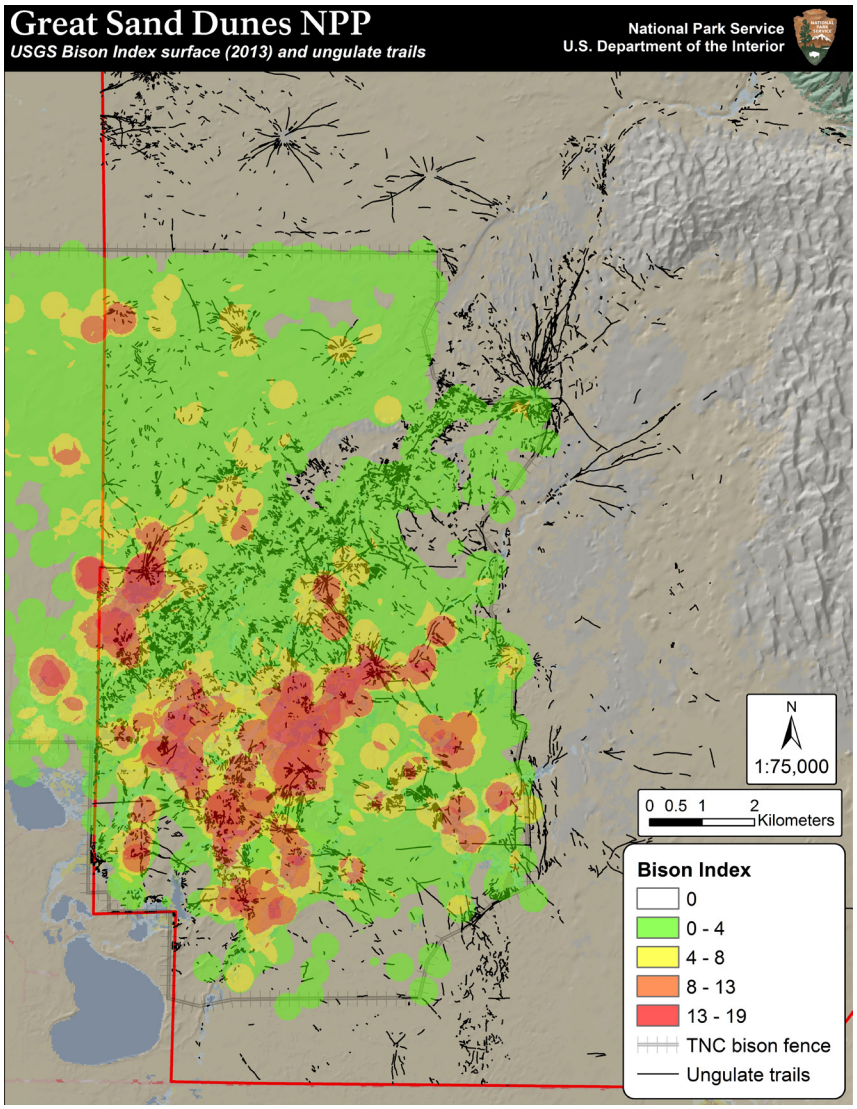
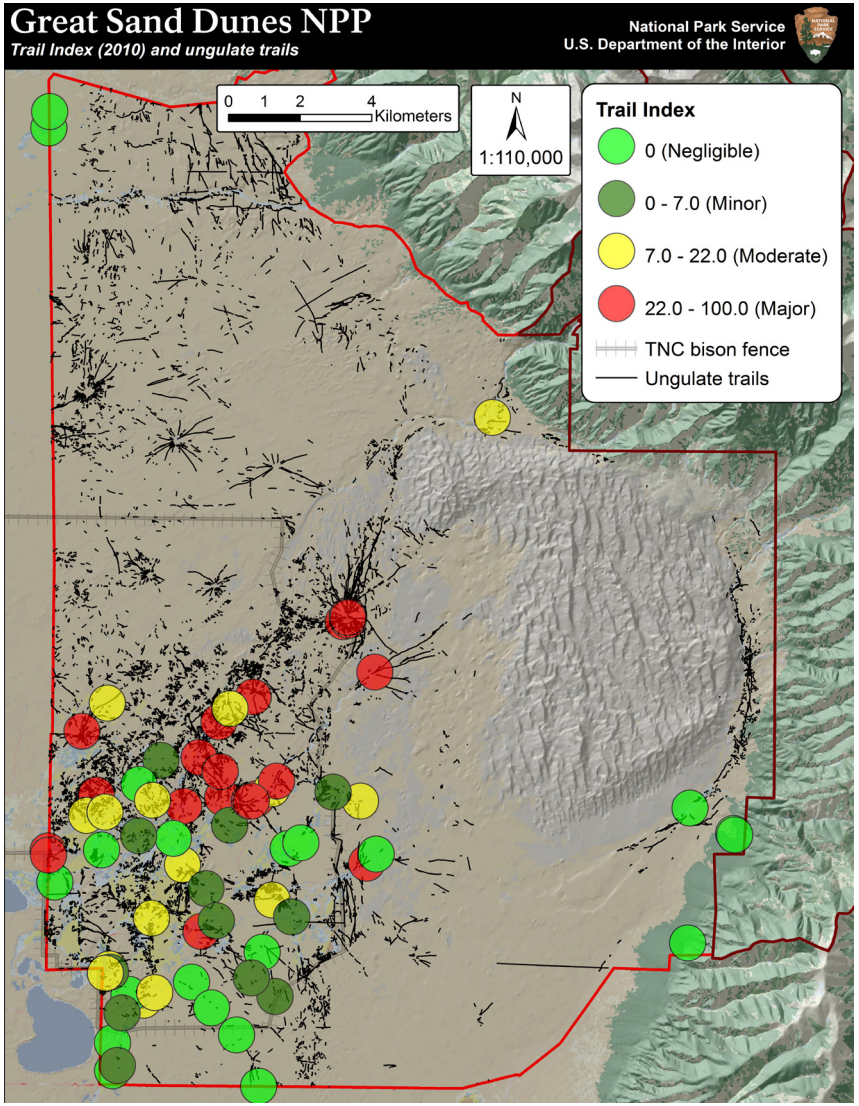


Figure 21a. Relationship between trails and ungulates at Great Sand Dunes National Park and Preserve. Bivariate fit between Trail Index and Ungulate Use Index (UUI) (left); spatial pattern with the trails used in the Trail Index and the contiguous Bison Index surface from 2013 USGS data (zoomed to the bison fence) (right). In all Figure 21 panels, higher disturbance values are shown in red and breaks in symbology follow ecoregional-based and negligibile assessment point cutoff values.



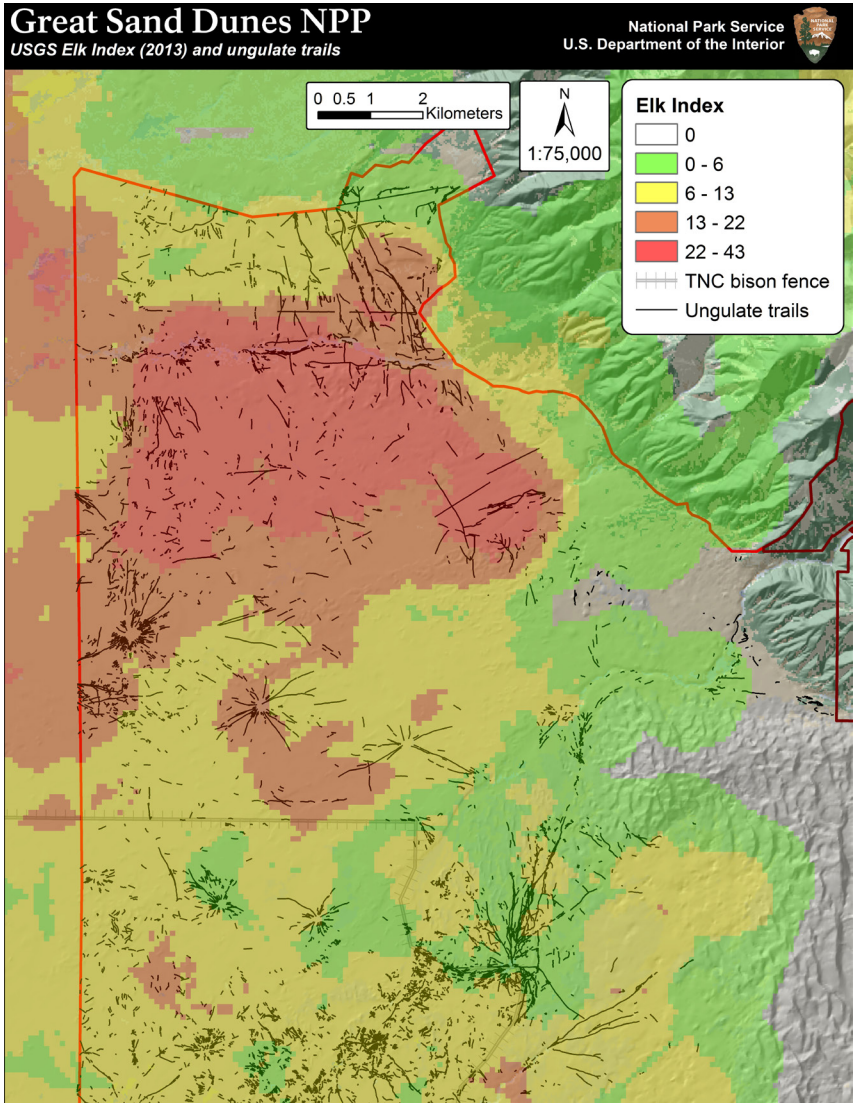


Figure 21b. Relationship between trails and ungulates at Great Sand Dunes National Park and Preserve. Trail Index "bubbles" varying by color with trail density overlaid on trails (left); trails used in the Trail Index and the contiguous Elk Index surface from 2013 USGS data (zoomed to the northern extent of the preserve) (right). In all Figure 21 panels, higher disturbance values are shown in red and breaks in symbology follow ecoregional-based and negligibile assessment point cutoff values.

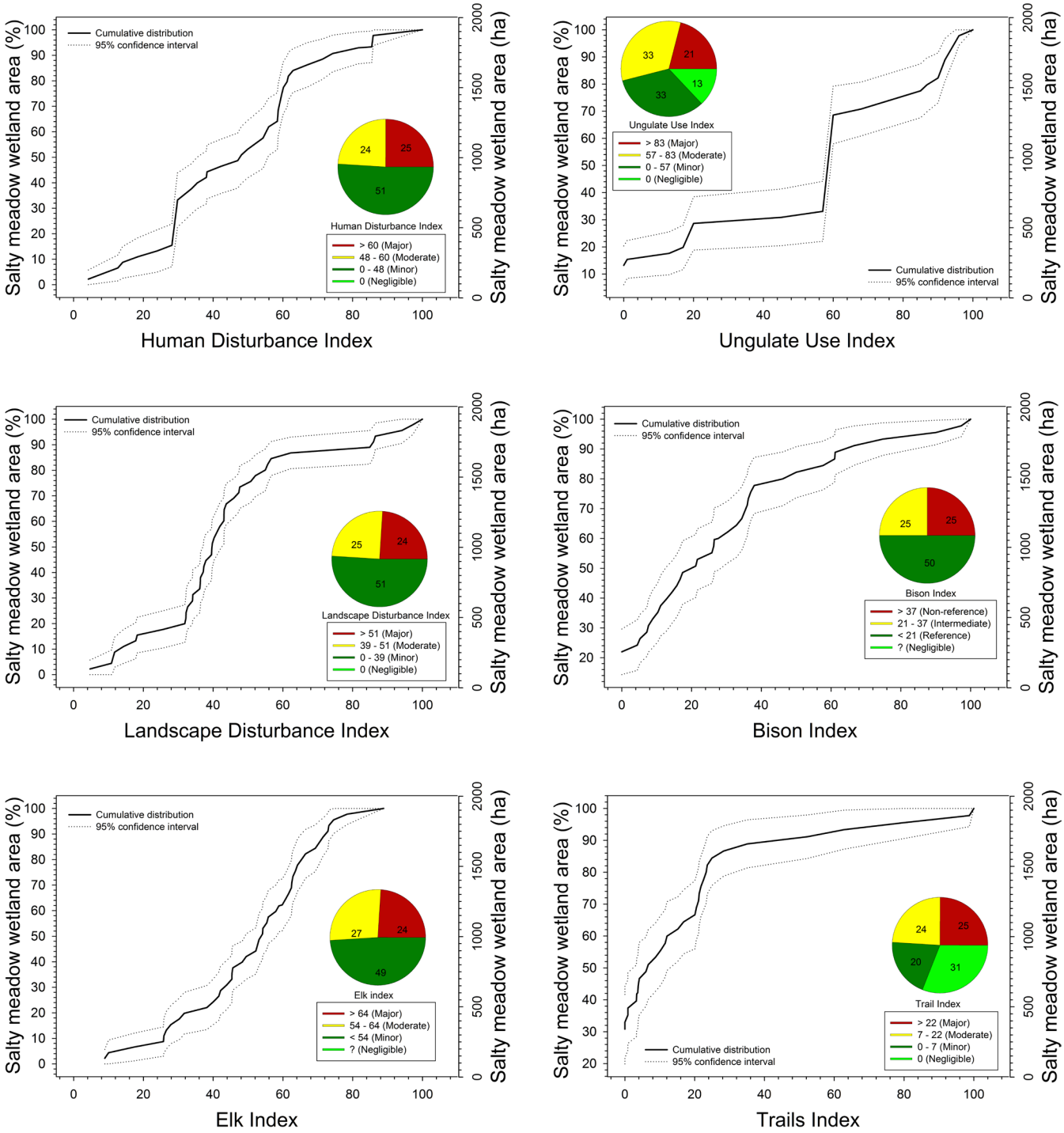


Figure 22. Cumulative distribution functions (CDF) of disturbance indices at Great Sand Dunes National Park and Preserve. CDFs from left to right, top to bottom: Human Disturbance Index (HDI), Ungulate Use Index (UUI), Landscape Disturbance Index (LDI), Bison Index, Elk Index, and Trail Index for the population of salt flat and meadow sandsheet wetlands, 2010. The left y-axis gives the percent of salty meadow wetlands on the sandsheet and the right y-axis shows the actual estimated area of wetland. The 95% confidence interval (dotted lines) around the percent values (heavy line) is shown. Assessment points are set at a zero value for negligible (where applicable, "?" indicates a negligible use level is not estimated) and at the 75th and 50th percentile (for major and minor disturbance or use, respectively). Pie chart shows the percentage of the total area in each disturbance or use class as light green (negligible disturbance/use), dark green (minor disturbance/use), yellow (moderate disturbance/use), and red (major disturbance/use). Pie charts do not include a confidence for each estimate in these classes so they should be used with caution.

Table 13. Summary statistics and application of assessment points to population scale disturbance at all salt flat–wet meadow sandsheet wetlands at Great Sand Dunes National Park and Preserve in 2010. SE = standard error for the mean. LCB/UCB are lower and upper 95% confidence interval boundaries around the population mean, respectively.

					Disturbance or use class assessment points			Percentage in disturbance or use class			
Site type	Mean index score	SE	LCB	UCB	Negligible (0)	Minor (<50th)	Major (>75th)	Negligible	Minor	Moderate	Major
Human Disturbance Index	46.9	*2.4*	42.2	51.7	0*	<48	>60	0	51	24	25
Ungulate Use Index	54.2	*3.5*	47.4	61.0	0*	<57	>83	13	33	33	21
Landscape Disturbance Index	43.8	*2.0*	39.9	47.6	0*	<39	>51	0	51	25	24
Elk Index	51.4	*1.8*	47.9	54.8	na	<54	>64	na	49	27	24
Bison Index	27.6	*2.7*	22.3	32.9	na	<21	>37	na	50	25	25
Trail Index	16.9	*2.7*	11.7	22.1	0*	<7	>22	31	20	24	25

Notes: For responses that increase with decreasing condition (or increasing stress; i.e., HDI), following Stoddard et al. (2008), we use the >75th or <50th percentile values to define or bound the major disturbance and minor disturbance classes (respectively). *We set a negligible disturbance or sustainable ungulate use value at zero for non-count based indices. na = a negligible disturbance condition value for count based ungulate indices is not known.

necker (2012) suggests that where water was not limiting, wet meadows on the sandsheet were resilient to and able to support ungulate grazing pressure as measured in 2005–2009. However, a major disturbance assessment point suggests that around 22% (12–32%) of the salty wet meadow had high disturbance levels (UUI > 83), where we might expect degraded or non-reference ecological integrity in response to ungulate stress. The influence of herbivory on ecosystem processes varies with the types of plants consumed, the intensity of use, the evolutionary history of the vegetation and grazing in the system, and a suite of environmental conditions, such as the availability of water and nutrients (Milchunas and Lauenroth 1993). Bioassessment modeling (see section 3.8 below) and more focused research, (for example, in support of the Ungulate Management Plan plan) are needed to further examine the ungulate disturbance–wetland response dynamic in GRSA.

The Elk and Bison Indices approximate animal counts (at least in a relative sense). We lack sufficient information to set a negligible disturbance assessment point for the number of animals that might be sustainable (unlike UUI, where we assume that disturbance is not strongly density dependent and thus are more or less comfortable with a 0 value). We therefore omit a zero valued assessment point for these indices. Given similar patterns in the Elk and Bison Indices, we summarize results together. Using ecoregional assessment points, 50% (40–60%) of the salty meadow on the sandsheet had minor disturbance, where elk or bison were low enough that we would expect little or less dramatic impacts on the condition of wetlands. In contrast, around 25% (14–35%) had major disturbance, where we would expect more reduced ecological integrity.

If we assume that no trails indicate negligible disturbance or a sustainable level of disturbance, around 33% (20–42%) of sandsheet salty wet meadows in 2010 were in this pristine state. Here, "no trails" does not suggest animals do not use wetlands; rather, it suggests that it is at a level that does not create permanent, easily visible trails in remotely sensed imagery. An additional 20% (or 51% total when combined with the negligible class, with a CI of 40–62%) falls in a minor disturbance class. Around 25% (15–34%) was in a major disturbance class. It is not clear if trail density suggests habitat is used more—are the trails used to funnel animals into the area or away from it? The most dramatic patterns of trails on the sandsheet are those surrounding point water sources (stock tanks or artesian wells, see Figure F-4 in Appendix F). In these cases it is likely that the trails are correlated with higher use (animals use them to travel to and from the water feature). Some wetland sites have a similar pattern, yet others may have a high density of trails in their buffer but less actual usage. The weak positive relationship between UUI and the Trail Index does suggest more trails occur in areas with higher animal use.

3.4.3.4 Exploratory models of human disturbance and ungulate use indices

Next, we present exploratory models that quantify relationships in HDI or UUI with select attributes of wetlands.

Models were initiated with 31 potential environmental and disturbance covariates. We chose the initial independent variables based on statistical attributes (i.e., measures that had strong univariate correlation with HDI), those that might have the most utility for wetland resource management in GRSA, and those that our collective experience suggested might assist in our interpretation of human disturbance to wetlands.

3.4.3.4.1 Human disturbance

The final model of HDI included 13 independent variables (Table 14). It was highly significant ($p < 2.2e\text{-}16$) and had an adjusted R2 of 0.96, indicating nearly all of the variation in HDI was accounted for. The complete model is presented in Appendix G. We focus our interpretation on variables in the model that either had the highest relative importance, lowest p values, and/or interesting relationships as drivers or covariates of HDI. We use conditional plots of partial residuals (Figure 23) to visualize the model (Larsen and McCleary 1972; Breheny and Burchett 2013).

Interestingly, wetland type was not significant, suggesting that HDI may not be strongly controlled by wetland type. Nearly 50% of the variation in HDI was due to a single variable, the degree of human hydrologic alteration in the wetland complex and its catchment. This variable is a component metrc of HDI (see Table 3). It is not real valued—it is an index itself—but it is based on tangible things like the number of diversions in a site's catchment. It could be further decomposed into attributes that GRSA resource management could affect change in. Its dominant role in predicting HDI suggests the overriding importance of hydrological alteration in wetland disturbance. The second most important variable predicting HDI was the percentage of human landuse in the wetland complex. This variable is a component metrc of HDI (see Table 3). It is a weighted summation of 16 potential landuse types, with high values indicating more natural landuse regimes (so again it can easily be decomposed into real attributes like infrastructure, roads, etc.). Next, UUI was positively related with HDI, explaining around 11% of its variance. However, as we discuss further below, we feel this relationship is not causal with UUI structuring HDI, rather UUI should be considered as a covariate with HDI. Many human disturbances (i.e., fences or ranch roads) exist on the sandsheet to control how ungulates use wetlands and other habitats, not the other way around. Finally, while less important, at only around 1%, groundwater pH did have an interesting pattern with HDI. There was marginally higher disturbance in sites with more acidic

Table 14. Exploratory model of Great Sand Dunes National Park and Preserve Human Disturbance Index (HDI) in 2010. Final model selected using Akaike Information Criterion (AIC) and expert opinion from 31 candidate variables. Relative importance is the total amount of explained variance for each variable expressed as a proportion. SE = standard error of coefficient, t = t test value, p = probability of the t.

Model component	Estimate	SE	t	p	Relative importance
Intercept	354.311	102.932	3.442	0.001	–
Ungulate Use Index	0.125	0.039	3.234	0.002	0.107
Elk Index	-0.132	0.026	-5.016	0.000	0.010
Bison Index	-0.098	0.032	-3.048	0.003	0.049
Total monsoon precipitation (2008–10, cm)	0.373	0.116	3.203	0.002	0.014
Elevation (m)	-0.148	0.050	-2.927	0.005	0.013
Human hydrologic alteration	0.305	0.013	24.201	0.000	0.498
Human landuse	-0.265	0.050	-5.267	0.000	0.160
Distance to human feature (m)	-0.004	0.001	-2.681	0.010	0.025
Landscape Disturbance Index	-0.058	0.025	-2.304	0.025	0.026
Soil ph	2.810	0.929	3.026	0.004	0.020
Soil zinc (mg/l, log)	17.348	5.001	3.469	0.001	0.012
Soil carbonate (mg/l, log)	-1.712	0.852	-2.010	0.049	0.054
In situ groundwater pH	-4.481	0.818	-5.475	0.000	0.012

Notes: Residual standard error: 4.133 on 57 degrees of freedom, Multiple R^2: 0.9685, Adjusted R^2: 0.9613, F-statistic: 134.8 on 13 and 57 DF, p value: < 2.2e-16.

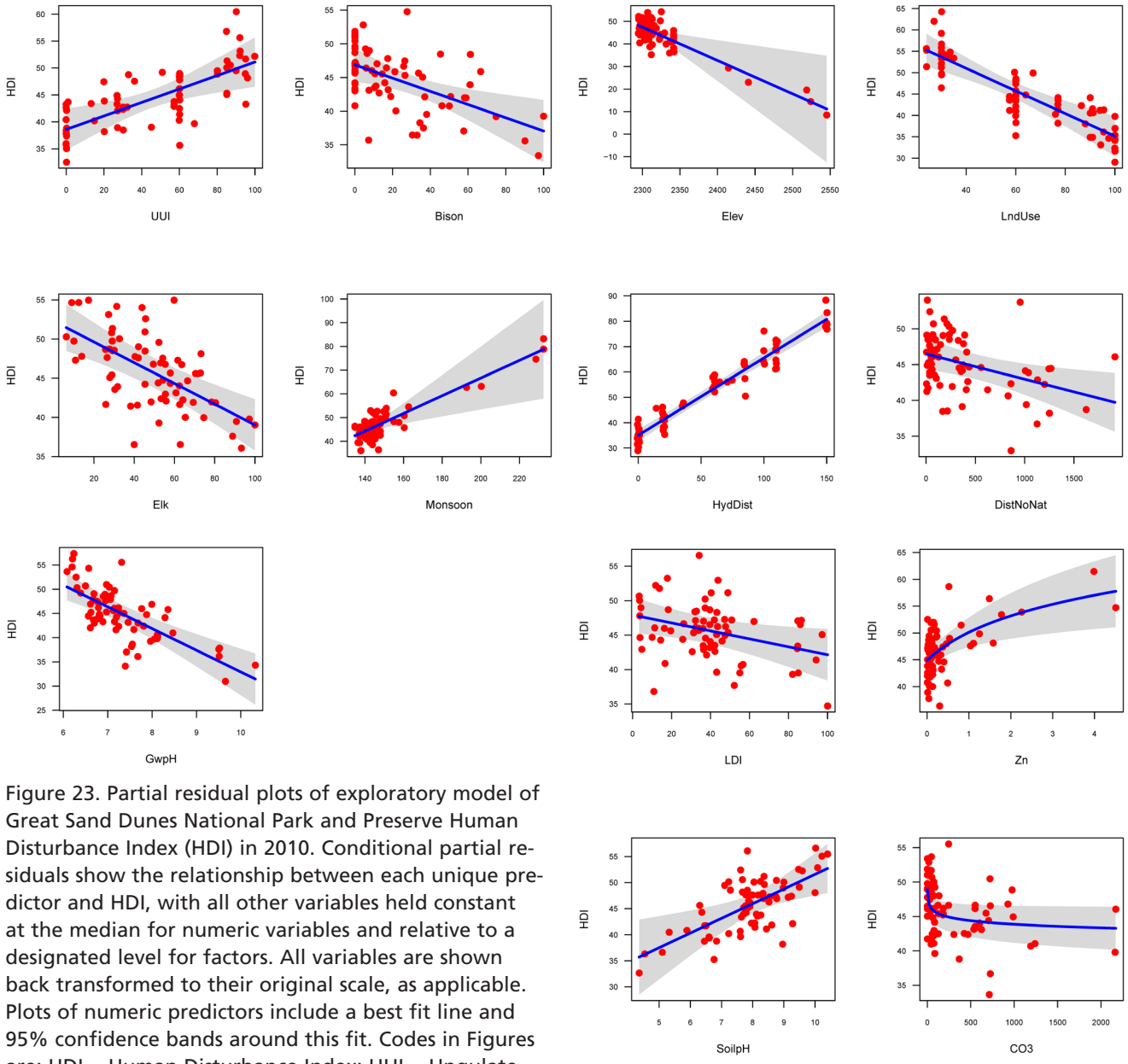


Figure 23. Partial residual plots of exploratory model of Great Sand Dunes National Park and Preserve Human Disturbance Index (HDI) in 2010. Conditional partial residuals show the relationship between each unique predictor and HDI, with all other variables held constant at the median for numeric variables and relative to a designated level for factors. All variables are shown back transformed to their original scale, as applicable. Plots of numeric predictors include a best fit line and 95% confidence bands around this fit. Codes in Figures are: HDI = Human Disturbance Index; UUI = Ungulate Use Index; Bison = Bison Index; Elev =Elevation (m); LndUse = Human Landuse Index; Elk = Elk Index; Monsoon = Total monsoon precip. (2008–10, cm); HydDist = Human hydrologic alteration; DistNoNat = Distance to human feature (m); GwpH= in situ groundwater pH; LDI = Landscape Disturbance Index; Zn = Soil zinc (mg/l, log); SoilpH = Soil ph; CO3 = Soil carbonate (mg/l, log). See the full model results in Appendix G.

groundwater. Anthropogenic landuse can increase the acidity of surface and groundwater (Vitousek et al. 1997; Baron et al. 2000; Fenn et al. 2003). This can be via the effects of "acid rain," from drainage from mines ("acid mine drainage"), or from complex chemical interactions driven by elevated atmospheric nutrient deposition. More work is needed to confirm the details behind this pattern at GRSA.

3.4.3.4.2 Ungulate use

The final model of UUI included eight predictors or covariates (Table 15). It was highly significant ($p < 2.2e\text{-}16$) and had an adjusted R^2 of 0.88, indicating nearly all of the variation in UUI was accounted for. The complete model is presented in Appendix G. We focus our interpretation on

variables in the model that either had the highest relative importance, lowest p values and/or interesting relationships as drivers or covariates of UUI. We use conditional plots of partial residuals (Figure 24) to visualize the model (Larsen and McCleary 1972, Breheny and Burchett 2013).

Table 15. Exploratory model of Great Sand Dunes National Park and Preserve Ungulate Use Index in 2010. Final model selected using Akaike Information Criterion (AIC) and expert opinion from 31 candidate variables. Relative importance is the total amount of explained variance for each variable expressed as a proportion. Wetland type is treated as a factor and all estimates are relative to marsh. *Wetland type's relative importance value is for all three wetland type groups combined. SE = standard error of coefficient, t = t test value, p = probability of the t.

Model component	Estimate	SE	t	p	Relative importance
Intercept	-560.400	235.300	-2.382	0.020	–
Wetland type	–	–	–	–	0.068*
Wet meadow	22.290	5.257	4.241	0.000	–
Riparian	24.750	7.781	3.181	0.002	–
Salt flat	35.090	6.181	5.677	0.000	–
Human Disturbance Index	0.237	0.106	2.234	0.029	0.170
Elk Index	0.228	0.086	2.640	0.011	0.034
Productivity	0.016	0.006	2.813	0.007	0.114
Total 2010 precipitation	-0.598	0.215	-2.781	0.007	0.052
Distance to sand	-0.003	0.001	-2.570	0.013	0.017
Elevation	0.306	0.112	2.741	0.008	0.038
Human landuse	-0.951	0.091	-10.451	0.000	0.508

Notes: Residual standard error: 4.133 on 57 degrees of freedom, Multiple R^2: 0.9685, Adjusted R^2: 0.9613, F-statistic: 134.8 on 13 and 57 DF, p value: < 2.2e-16.

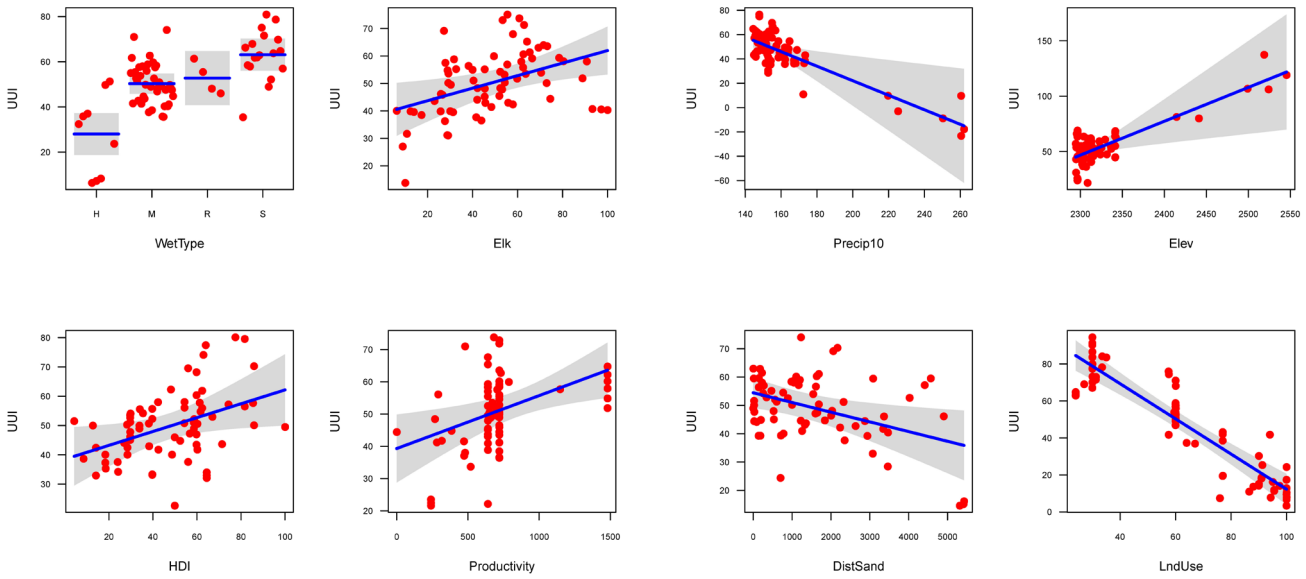


Figure 24. Partial residual plots of exploratory model of Great Sand Dunes National Park and Preserve Ungulate Use Index (UUI) in 2010. Conditional partial residuals show the relationship between each unique predictor and UUI, with all other variables held constant at the median for numeric variables and relative to a designated level for factors. All variables are shown back transformed to their original scale as applicable. Plots of numeric predictors include a best fit line and 95% confidence bands around this fit. Box plots of factorial variables include the reference category first or on the leftmost side of the Figure and the 95% confidence interval as the bounding box around the variable's median. Codes in Figures are: UUI = Ungulate Use Index; WetType = wetland type; Elk = Elk Index; Precip10 = Total precip. (2010, cm); Elev = Elevation (m); HDI = Human Disturbance Index; Productivity = vegetation production; DistSand = Distance to sand (m); LndUse = Human landuse index. See the full model results in Appendix G.

First, wetland type affected UUI (overall or as a group, accounting for about 7% of the variation in the index). Because wetland type is treated as a categorical variable, all estimates were relative to a designated type (arbitrarily chosen as marsh). Ungulate use was higher in salt flats, wet meadows, and riparian wetland than in marshes. The most important variable, at around 50% of the variation in UUI, was the percentage of human landuse in the wetland complex. Sites with more human landuse were also more intensely used by ungulates. A similar pattern happens with higher UUI, where there is higher HDI (HDI accounts for almost 17% of the variance in UUI). In contrast with the HDI model above, we feel this is the proper structural direction—ranching of bison and (the more limited) management of elk on the sandsheet direct where and likely how (to a degree) bison and elk use park wetlands. The next most important driver of UUI was productivity (Wockner et al. 2015), with more productive sites experiencing more ungulate use. While the interaction between herbivores and their resources can be very complex (Gough and Grace 1998; Augustine et al. 1998, Xiong et al. 2003; Wolf et al. 2007; Kaczynski and Cooper 2015), and it is not clear if production drives UUI or vice versa in our data, the pattern may suggest that ungulates prefer wetlands with more production. Using an array of paired sites in and out of large exclosures (Figure 25), Schoenecker (2012) found that production was lower in wet meadows where both elk



Figure 25. An exclosure on Sand Creek at Great Sand Dunes National Park and Preserve in 2010. The interior of the exclosure is on the left of the image. The structure had been in place for 5 years at the time this image was taken. NPS/BILLY SCHWEIGER.

and bison co-occurred but that wet meadows were resilient to and able to support grazing pressure. This pattern did not occur in mesic meadows ("less wet" meadows)—there was no difference across elk–bison vs. elk only sites in production.

Finally, there were seasonal patterns in production but no year effect. Schoenecker (2012) suggested that sites that were not water limited were able to support heavy grazing, with high levels of production. The methods employed in Schoenecker (2012), while rigorous at isolating effects across categorical treatments of site context, do not control for many important covariates nor do they examine an effect of bison and/or historical cattle use across an extensive gradient of potential use. While our models are based on only one year (but see below for sentinel sites from 2010–2014), production and offtake may not vary strongly with time and 2010 was both a dry year and the year after the highest bison numbers on the ranch to date. Thus, 2010 is a useful index year for when stress should have been highest. Our models are simple and lack the quasi-experimental nature of an exclosure study (i.e., Schoenecker 2012). The most important conclusion from them may be that UUI is responsive to several key drivers, most notably human disturbance, and that to fully understand wetland response to disturbance, a broad suite of potential drivers and their impact must be considered.

3.4.3.5 Trend in disturbance at sandsheet sentinel sites: 2010–2014

Finally, we estimate trend in HDI and UUI at sentinel sites on the sandsheet from 2010 to 2014. Table 16 gives summary statistics by year. Importantly, while these models are well constructed, five years is likely too short a period to detect significant ecological changes given the complexity of this system and the time frames over which system components (past cattle grazing, elk populations and use, climate, long-lived perennial plants, etc.) respond to the environment. Future iterations of these models will likely be more revealing and valuable. The area has a long history of changes in disturbance and it will take more years of data to understand whether any trend is relevant over the long term.

We first looked at the homogeneity of the variance in each index across years using Brown-Forsythe and Levene tests (Brown and Forsythe1974; Levene1960). Variance in HDI was homogeneous across years but variance in UUI was not. The UUI model is likely robust to this but the results should be viewed with some caution. We use linear mixed-effects models that specifically address trend estimation for correlated data. We treat year as a random effect to estimate the variation of any linear trend over time. We use the single year (2010) linear models (see above) to select a limited set of the most important potential covariates and include these in each model as fixed effects. These covariates were kept to a minimum and to those that we felt would help isolate any change in HDI or UUI over time. Following Heard et al. (2012), we model HDI and UUI, both logged and untransformed. The logged response allows a test of the net change over the five year interval, while the untransformed response looks at an annual change or effect.

Table 16. Summary statistics for Human Disturbance Index (HDI) and Ungulate Use Index (UUI) at sandsheet sentinel sites in Great Sand Dunes National Park and Preserve from 2010 to 2014. LCB/UCB are lower and upper 95% confidence interval boundaries around the mean, respectively.

Index	Year	N	Mean index score	LCB	UCB	Standard deviation	Variance	Standard error
HDI	2010	15	52.45	45.94	58.96	11.75	138.10	3.03
	2011	13	55.27	48.65	61.88	10.95	119.85	3.04
	2012	13	48.87	40.47	57.26	13.90	193.09	3.85
	2013	10	49.79	39.23	60.36	14.77	218.25	4.67
	2014	12	42.93	33.66	52.21	14.59	212.94	4.21
	All Years	63	50.06	46.69	53.42	13.36	178.42	1.68
UUI	2010	15	50.53	35.13	65.94	27.81	773.55	7.18
	2011	13	55.46	46.12	64.81	15.46	239.10	4.29
	2012	13	39.75	20.32	59.19	32.16	1034.44	8.92
	2013	10	92.00	88.98	95.02	4.22	17.78	1.33
	2014	12	61.08	36.14	86.03	39.26	1541.17	11.33
	All Years	63	57.92	50.07	65.76	31.15	970.11	3.92

3.4.3.5.1 Human disturbance

HDI had a significant decreasing trend at sandsheet sentinel sites, both on an annual basis and net over a five year period (around 18%) from 2010 to 2014 (Figure 26, see Appendix G for the full model). The models had high approximate R2 (correlation between the fitted and the observed values) of around 0.94, suggesting that most of the variance in HDI was explained. The net change calculated from the coefficient of the logged response was -8.3% in HDI. Both models had a marginal site term, suggesting that the trend in HDI may have varied by sentinel site, with the smallest decrease occurring at the Big Spring Creek sites. Of the limited covariates included, the degree of human hydrologic alteration and UUI were significant (both in the logged and untransformed HDI models). Their positive but small coefficients suggested a positive effect of hydrologic alteration on HDI and positive covariance between UUI and HDI. The percentage of human landuse in the wetland complex did not have a significant effect on HDI in either model. While more work is needed here, these results suggest the decrease in HDI may be driven by decreasing impacts from hydrologic alteration (note there were no actual removals of dams or ditches as of 2016, so it would be a decreased effect from existing structures). As noted, we suspect UUI covaries with HDI and does not drive actual change in the index.

While these results are only at the three sentinel complexes and over a short time period, they do suggest that an important impact on wetland condition, human disturbance, decreased. Most values were within a moderate disturbance range, although values were trending towards minor stress. We will continue to investigate this as we add sample events over time.

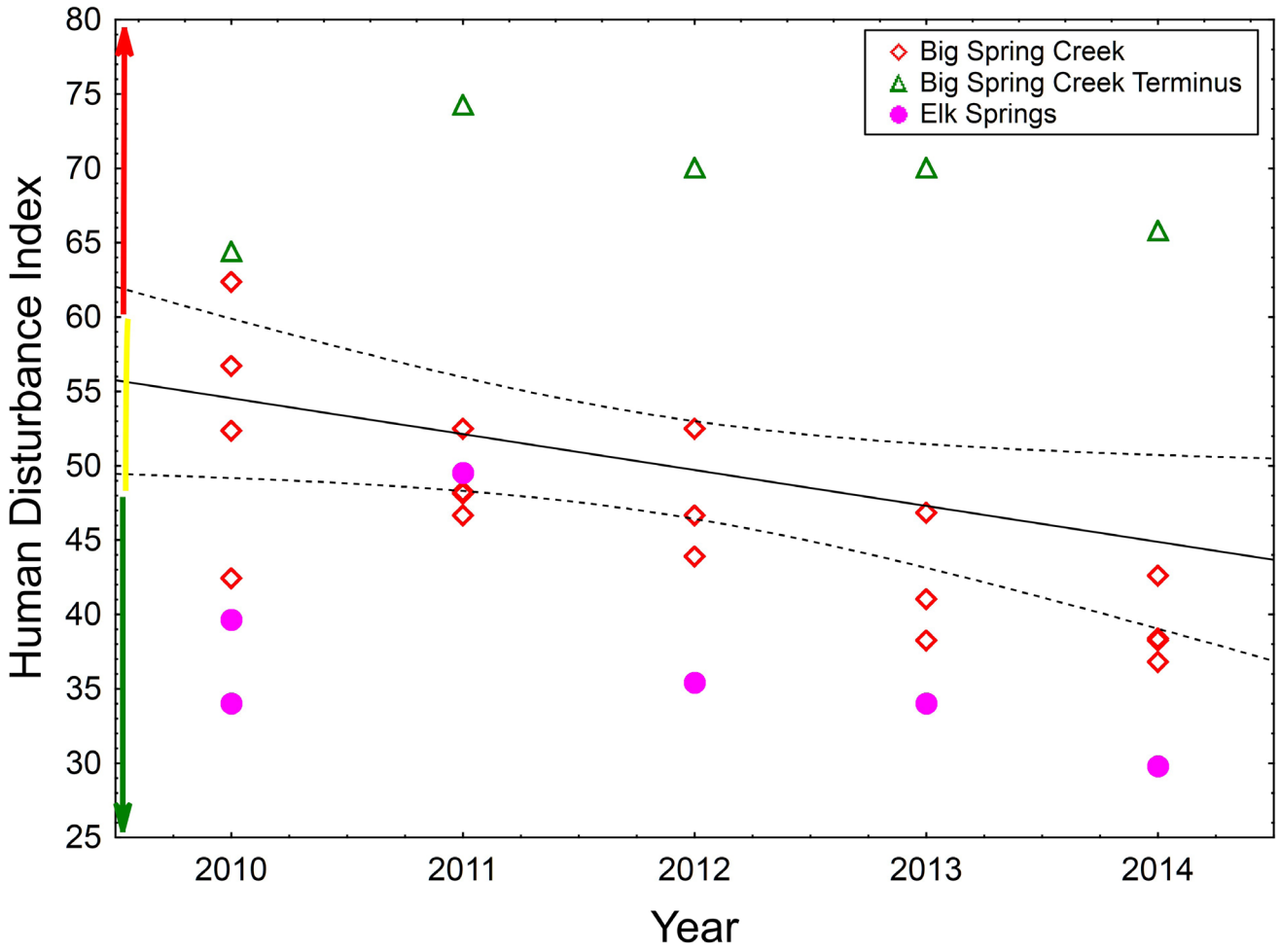


Figure 26. Human Disturbance Index (HDI) at sandsheet sentinel sites by year, 2010 to 2014, Great Sand Dunes National Park and Preserve. Points (representing unique sites) within a year may overlap. Minor, moderate, and major disturbance classes based on ecoregional assessment points are shown along the Y axis, with dark green, yellow, and red vertical arrows, respectively (a negligible class would be at HDI = 0, but no GRSA wetlands were in this state in 2010–2014).

3.4.3.5.2 Ungulate use

UUI had a marginally significant increasing trend at sandsheet sentinel sites, both on an annual basis and net over a five year period from 2010 to 2014 (Figure 27, see Appendix G for the full models). The models had a relatively high approximate R2 of around 0.70 to 0.75, suggesting that a sizable amount of the variance in UUI was explained. The net change calculated from the coefficient of the logged response was a sizable 23.7% in UUI. Both models had a significant site term, suggesting that the trend in UUI varied by sentinel site, with the largest increase occurring at the Big Spring Creek Terminus sites and little increase at Elk Springs. Of the limited covariates included, HDI and landuse had a positive effect on UUI (both in the logged and untransformed models), suggesting a positive effect on mean UUI. This suggests that landscape scale human disturbance may drive the increase in UUI at these sites.

While these results are only at the three sentinel complexes and over a short time period, they do suggest that an important impact on wetland condition, ungulate use, may have increased at GRSA (see also the following discussion of bison and elk counts. In 2010, sites were more or less evenly split into minor, moderate, and major use classes. By 2012, scores tended to be more above the major use assessment point, although some sites also began to show negligible use. We will continue to investigate this as we add sample events over time.

Ungulate disturbance is not necessarily a density dependent phenomenon. Nevertheless, data on animal density over time at our sites would be ideal. Schoenecker (2012) provides the best estimates of bison counts. Bison numbers (Figure 28) fluctuated through time, with peak herd size of around 2400 animals in 2009. Bison numbers declined after this to a herd

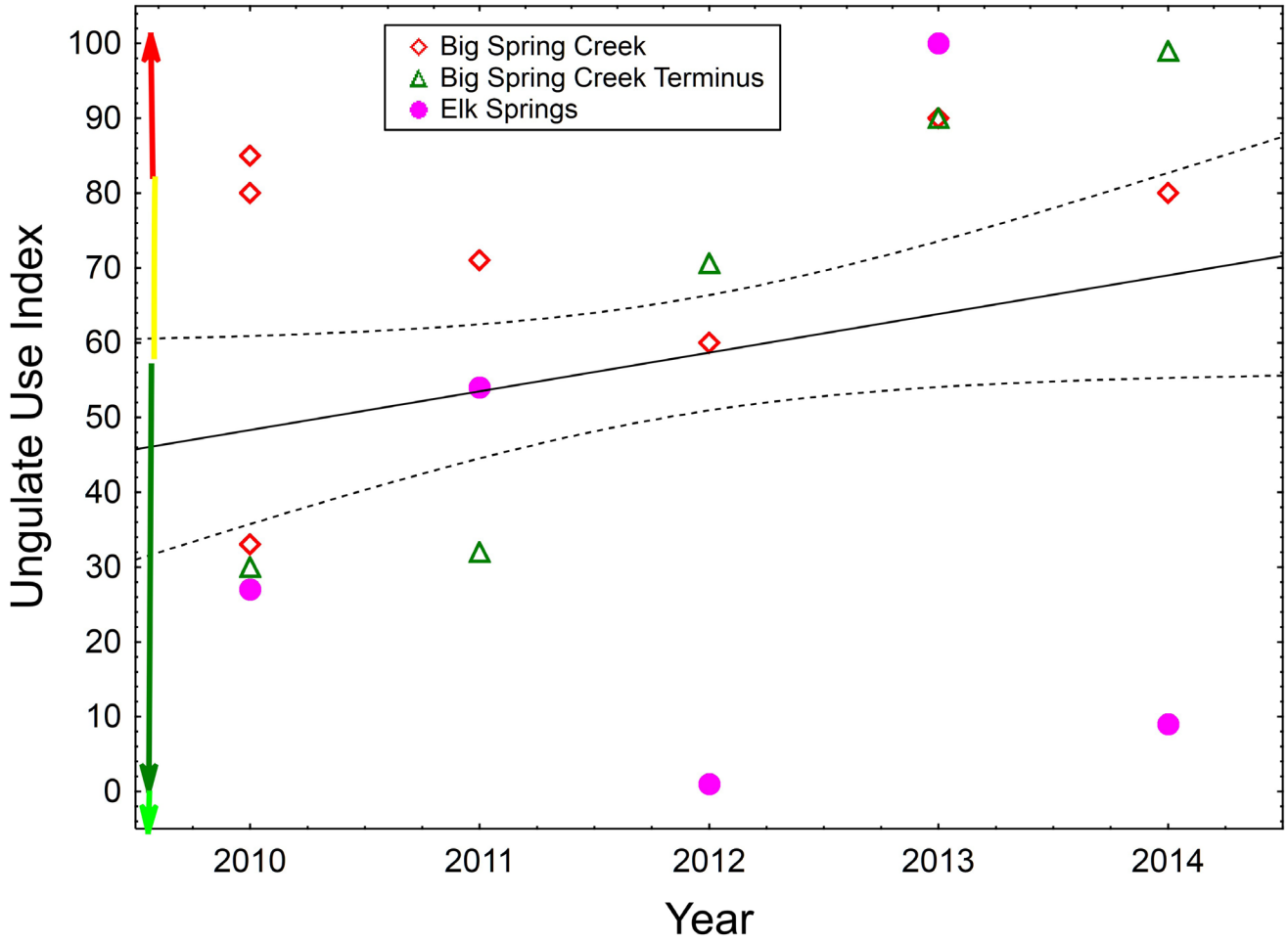


Figure 27. Ungulate Use Index (UUI) at sandsheet sentinel sites by year, 2010 to 2014, Great Sand Dunes National Park and Preserve. Points (representing unique sites) within a year may overlap. Negligible, minor, moderate, and major disturbance classes based on ecoregional assessment points are shown along the Y axis, with light green, dark green, yellow, and red vertical arrows, respectively.

size of around 1400 in 2014. While we do not have counts at our sites, Schoenecker et al. (2015) shows that bison prefer wetland in all seasons and years. The selection of wetland is 11 to 18 times that of upland vegetation. Willow-dominated and cottonwood plant communities were strongly avoided by bison—these habitats have an understory with low biomass of herbaceous species that grazing bison prefer. Thus if the increase in UUI at our wetland sentinel sites is correct, it is either not density dependent in a positive way (more animals equals more disturbance) or the increase is due to elk.

Elk numbers are tracked by Colorado Parks and Wildlife across a large game management unit encompassing approximately the eastern half of the San Luis Valley up to the ridge line of the Sangre de Cristo Mountains (Colorado Parks and Wildlife 2010). Raw data are point counts from aerial surveys. Figure 29 shows elk counts from 2006 to 2014 summarized within and near GRSA. In general, elk numbers in the park decreased from around 2600 in 2006 to 1900 in 2011, and then increased to around 2400 in 2013 and 2014. These data have not been modeled at finer scales to identify habitat selection as in Schoenecker et al. (2015) for bison, so

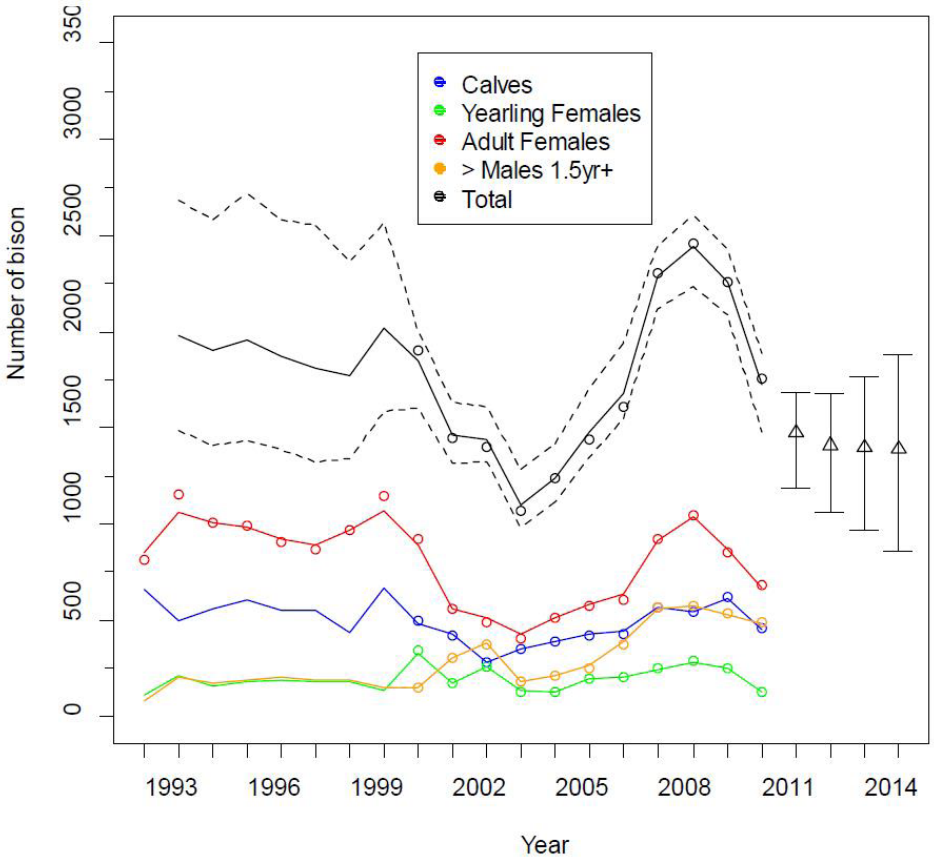


Figure 28. Model estimates for the population size of the San Luis Valley bison population, 1993 to 2011 (with permission from Schoenecker (2012)). Open circles are count data, solid lines are the mean for each age/sex class and total population size, and dotted lines are the 95% credible interval for total population size. Triangles are predictions to 2015, with annual credible interval bars. Predictions were based on a management scenario using the same culling regime in 2012 that was used in 2011, and thereafter removing 75 adult females plus 150 males annually to maintain the population at ~1400 bison. Note that "> Males 1.5 yr+" refers to males older than 1.5 years.

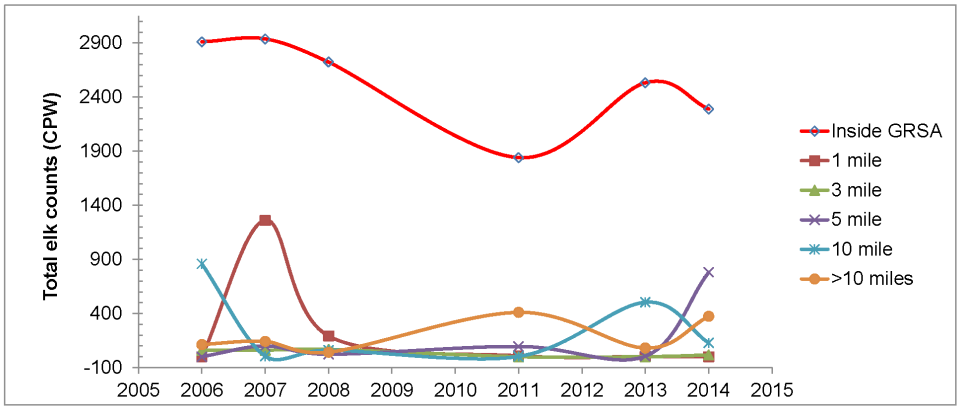


Figure 29. Elk counts by Colorado Parks and Wildlife (CPW) inside Great Sand Dunes National Park and Preserve (GRSA) and at varying distances from the park's boundary, 2006 to 2014.

we do not really know where these elk are on the sandsheet in the park. While speculative, the increase we see in UUI from 2010 and 2014 may be due to higher elk numbers over this time period (when bison were decreasing). Wockner et al. (2015) show a strong partitioning of habitat between bison and elk. Although elk and bison appear to use the same habitat, elk are browsers and prefer woody vegetation. It also appears that there is strong selection of habitat on a diel cycle, with differential use at night (K. Schoenecker and L. Zeigenfuss, USGS, pers. comm.)—this was not included in the Wockner et al. (2015) data and may account for the increased ungulate use at our sites in the years when elk numbers were increasing.

3.5 Soil Chemistry

3.5.1 Summary condition

Because we lack evidence to assess any single soil parameter in and of itself as a direct indicator of disturbance or ecological integrity, we treat our chemistry results largely as a baseline for future assessment. Soil does appear in several exploratory models of patterns in other responses. As illustrative examples, we do model two representative parameters (a salt and a nutrient) as examples of how soils relate to key covariates at GRSA (Table 17). Table 17 presents a summary of our soil chemistry results only. See the Executive Summary for a summary condition table that includes all indicators of wetland condition.

3.5.2 Overview

Wetland soil is both the medium in which chemical reactions take place that influence wetland vegetation and the primary storage area of available chemicals for most wetland plants (Mitsch and Gosselink 2007). Global and local disturbances can alter soil chemistry, which may result in altered vegetation composition. Soil characteristics provide useful indicators of wetland condition. Fens, for example, are distinguished chiefly by the occurrence of organic soils. Certain soil indicators also provide information about hydrologic regime. For example, redoximorphic features, like mottles (blotches of differently colored soil), are most likely to occur in soils that cycle between anaerobic (reduced) and aerobic (oxidized) conditions. By contrast, strongly gleyed soils (sticky, waterlogged soil, typically colored gray to blue) suggest prolonged anaerobic conditions. Soil organic matter, carbon, pH, and plant nutrient concentrations can provide a powerful index of productivity and ecosystem processes and are often determinants of vegetation structure (Sollins et al. 1999). Various salts can have significant effects on soil properties and plant growth and these have been well understood for at least half a century by soil scientists (Wong et al. 2010).

In the following section we present estimates of the status of soil chemistry across the GRSA sandsheet in 2010. We include models of important relationships among all variables. For two example soil parameters we develop exploratory models to help understand factors that might influence wetland soil chemistry on the GRSA sandsheet. Note that soil samples were only taken once during full sample events in 2010 and we therefore cannot estimate trend.

3.5.3 Soil chemistry: results and interpretation

In general, soil chemistry patterns reflect the strong gradients in salts and nutrients typical of sandsheet wetlands at GRSA (Cooper and Gage 2009). Table 18 presents traditional descriptive statistics as estimates of status at the site scale across all sandsheet wetland types in 2010. Appendix H presents additional site scale results. Table 19 presents soil chemistry results at the population scale for all salty meadow sites on the sandsheet. A notable but unsurprising difference between the two sets of status estimates is higher salinity in the population of salty meadows in comparison to site scale estimates across all wetland types.

3.5.3.1 Multivariate patterns across soil chemistry parameters

Lab analyses of 2010 GRSA soil samples focused on 25 parameters. While there are interesting and useful patterns in many of these individual soil characteristics (that are included in various other models in this report), we identify a subset here as examples for more detailed interpretation. We modeled soil chemistry using a principal coordinates analysis (PCoA) to group similar samples across all 25 soil measures at all sandsheet sites. We included several environmental gradients and disturbance measures that potentially influence or covary with soil chemistry to allow the model to better group important soil chemistry measures (by controlling for other gradients important for wetland soils).

For all wetlands on the sandsheet, we found a two dimensional solution with PCoA, representing approximately 69% of the variability in soil chemistry across sites (Figure 30, Table 20). The model suggests that with the exception of salt flats, wetland type does not stron`gly structure soil variation. Salt flats were somewhat unique, with many parameters related to ionic concentration loading in the “salt flat region” of the model. However, the “salt flat region” (red dots in Figure 30) overlaps with wet meadows (green dots in Figure 30), suggesting that, taking soil chemistry as a whole, the two types are better thought of as a true gradient.

Table 17. Summary condition table for soil chemistry at Great Sand Dunes National Park and Preserve (GRSA) in 2010. No assessment points are available for soil chemistry indicators yet. Because we cannot yet assess condition, the symbols for these two soil chemistry indicators lack color and trend arrows.

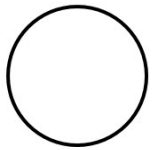
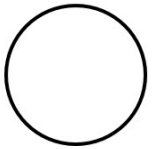
Soil chemistry indicators	Condition description	Condition and confidence
Sodium adsorption ratio (salinity) (2010)	Wetland soils store chemicals (e.g., nutrients, salts) and are the medium for reactions that influence wetland vegetation and plant communities. Global and local disturbances can alter soil chemistry, which may result in altered vegetation composition. We measured 25 soil chemistry parameters at GRSA. We focus on sodium adsorption ratio as an example soil chemistry parameter (SAR; index for the concentration of salts). SAR represents well how soil salinity varies across wetlands in the park. SAR ranged from a low of 0.27 to 1515.13 meq/L, with a mean of 54.49 (SD = 223.76). It was highest in salt flat sites. An exploratory model suggests higher SAR occurs where there is lower nitrogen availability, often in wetter areas. SAR and nutrients have important feedbacks with hydrologic regime and vegetation productivity and composition. These interactions help structure the vegetation community (especially at saltier sites) at GRSA and affect how ungulates use these wetlands. They are thus key, if complex, pieces behind much of our characterization of the integrity of these wetlands. *We have not analyzed these data relative to human or other disturbances or threats, so, for the time being, we do not assign a condition or a trend. We will use this information as a baseline for future comparisons as monitoring continues.* Neverthess we do develop high quality soil chemistry data and models and we are confident that our baselines will be useful for understanding changes over time. We therefore have medium confidence in our use of the selected soil chemistry indicators.	
Total carbon (2010)	We measured 12 nutrient soil chemistry parameters at GRSA. We focus on total carbon (C) as an example because it represents well how these attributes vary across wetlands in the park. The percentage of total C ranged from a low of 0.13 to 11.8, with a mean of 2.7 (SD = 2.8). It strongly covaried with total nitrogen. A predictive model suggests it was higher in sites with more precipitation over the preceding 3 decades—wetter sites are generally more productive and may accumulate more nutrients in the soil profile. It was also positively associated with percent of each site's catchment that had anthropogenic land cover or uses. This may suggests that anthropogenic disturbance reduces nutrients, but the structure behind this pattern will need more research to better interpret. *We have not analyzed these data relative to human or other disturbances or threats, so, for the time being, we do not assign a condition or a trend. We will use this information as a baseline for future comparisons as monitoring continues.* Neverthess we do develop high quality soil chemistry data and models and we are confident that our baselines will be useful for understanding changes over time. We therefore have medium confidence in our use of the selected soil chemistry indicators.	

Table 18. Site level summary of soil chemistry for all sandsheet sites at Great Sand Dunes National Park and Preserve in 2010. LCB/UCB are lower and upper 95% confidence interval boundaries, respectively. Standard error is for the mean. Sample size for all parameters was 74.

Metric	Mean	LCB	UCB	Min	Max	Std. dev.	Std. error
Ammonium (mg/kg)	8.46	6.58	10.34	0.01	44.4	8.1	0.94
Bicarbonate (mg/kg)	153.68	127.13	180.24	0.1	528	114.62	13.32
Calcium (mg/kg)	2011.64	1796.05	2227.22	538	4686	930.54	108.17
Carbon to nitrogen ratio	19.81	16.67	22.95	5	73.4	13.54	1.57
Carbonate (mg/kg)	337.11	223.28	450.95	0.1	2170	491.35	57.12
Cation exchange capacity (meq/100g)	16.85	15.43	18.27	4.95	33.89	6.14	0.71
Copper (mg/kg)	1.72	1.31	2.12	0.39	8.96	1.74	0.2
Iron (mg/kg)	70.2	34.66	105.74	0.62	1019	153.39	17.83
Magnesium (mg/kg)	255.3	220.13	290.47	3.88	667.8	151.82	17.65
Manganese(mg/kg)	4.83	3.75	5.9	0.68	25.99	4.64	0.54
Nitrate (mg/kg)	4.28	1.07	7.48	0.45	118.3	13.82	1.61
Organic matter, ~40 cm (%)	4.36	3.21	5.51	0.67	31.34	4.88	0.58
Organic matter, 0–20 cm (%)	5.3	4.19	6.41	0.51	21.46	4.76	0.56
Peat thickness (cm)	1.8	0.15	3.45	0	40	7.12	0.83
pH	7.9	7.6	8.2	4.36	10.4	1.3	0.15
Phosphorous (mg/kg)	6.47	4.79	8.15	0.6	49.9	7.25	0.84
Potassium (mg/kg)	1152.61	896.75	1408.48	88.73	4449	1104.37	128.38
Sodium (%)	53.7	-0.56	107.95	0.22	1566.5	230.87	27.21
Sodium (mg/kg)	392.78	270.47	515.09	15.31	2376	527.93	61.37
Sodium adsorption ratio (meq/L)	54.49	2.65	106.34	0.27	1515.13	223.76	26.01
Specific conductance (µS/cm)	1862.3	1112.7	2611.8	192	18720	3235.2	376.1
Sulfate (mg/kg)	147.76	51.04	244.48	0.24	2703	417.47	48.53
Total carbon (%)	2.7	2.06	3.34	0.13	11.78	2.76	0.32
Total nitrogen (%)	0.18	0.13	0.22	0	0.96	0.2	0.02
Zinc (mg/kg)	0.42	0.23	0.62	0.01	4.51	0.82	0.1

Thirteen soil and three environmental variables were significantly correlated with the first and second axes of the model. The first axis ("Dim1" in Figure 30) is positively associated with higher concentrations of iron, ammonium, and copper (all logged), as well as high water tables, HDI, and the Bison Index. Axis 1 is negatively associated with sodium adsorption ratio (SAR), soil pH and carbonate (again, all logged). Salt flats tended to fall on the negative end of Axis 1. The second axis ("Dim2" in Figure 30) is positively associated with sulfate, total percent carbon, and zinc. No variables had meaningful negative associations with Axis 1. Sites on the positive end of Axis 2 were a mix of wet meadows and salt flats.

We based our selection of which parameters to further interpret in part on the ordination results, picking a dominant parameter for each end of each Axis (with the exception of the negative side of Axis 2, given the few variables that loaded in this region). We also wanted to include at least one nutrient and one measure of salinity. Given the similarities between soil and groundwater pH and specific conductance, we interpret pH and specific conductance as part of the *in situ* groundwater section (see section 3.6 below). In the end we chose to further interpret SAR and total percent carbon.

SAR is a measure of the sodicity of soil (sodic soils have a high concentration of salts), as determined from analysis of water extracted from the soil and the concentration of Na, Mg, and Ca. In general, salinization occurs in the presence of soluble salts, a shallow water table that promotes capillary wicking, and evapotranspiration demands that exceed fresh water inputs (Metternicht and Zinck 2009). Excessive accumulations can reduce osmotic potential and make plant water uptake more difficult, thus restricting the growth of vegetation and ultimately lowering biomass production (Mass and Hoffman 1977). When SAR is greater than 13, the

Table 19. Population scale summary of soil chemistry for salty meadows in the sandsheet at Great Sand Dunes National Park and Preserve in 2010. LCB/UCB are lower and upper 95% confidence interval boundaries, respectively. Standard error is for the mean. Sample size for all parameters was 46. Note that these statistics were generated using design based methods.

Metric	Mean	LCB	UCB	Min
Ammonium (mg/kg)	6.62	0.576	5.492	7.751
Bicarbonate (mg/kg)	162.63	12.150	138.819	186.447
Calcium (mg/kg)	2074.55	115.802	1847.585	2301.519
Carbon to nitrogen ratio	24.31	1.590	21.198	27.431
Carbonate (mg/kg)	400.57	62.130	278.801	522.344
Cation exchange capacity (meq/100g)	18.02	0.759	16.535	19.511
Copper (mg/kg)	1.15	0.112	0.931	1.369
Iron (mg/kg)	16.55	3.906	8.894	24.205
Magnesium (mg/kg)	233.93	19.879	194.970	272.893
Manganese(mg/kg)	3.74	0.435	2.891	4.595
Nitrate (mg/kg)	2.65	0.464	1.741	3.559
Organic matter, ~40 cm (%)	3.63	0.336	2.973	4.289
Organic matter, 0–20 cm (%)	4.25	0.490	3.287	5.207
Peat thickness (cm)	0.33	0.279	-0.212	0.880
pH	8.35	0.113	8.130	8.572
Phosphorous (mg/kg)	6.34	0.747	4.880	7.806
Potassium (mg/kg)	1378.81	117.342	1148.825	1608.796
Sodium (%)	86.25	36.411	14.888	157.616
Sodium (mg/kg)	498.11	70.370	360.191	636.037
Sodium adsorption ratio (meq/L)	86.21	33.783	19.994	152.421
Specific conductance (µS/cm)	2485.39	420.404	1661.410	3309.363
Sulfate (mg/kg)	140.57	46.173	50.077	231.072
Total carbon (%)	2.21	0.275	1.676	2.754
Total nitrogen (%)	0.12	0.017	0.090	0.157
Zinc (mg/kg)	0.16	0.037	0.083	0.229

soil is called a sodic soil. Excess sodium in sodic soils causes soil particles to repel each other, preventing the formation of soil aggregates. This results in a very tight soil structure with poor water infiltration, poor aeration and surface crusting, which makes tillage difficult and restricts seedling emergence and root growth (Munshower 1994; Seelig 2000; Horneck et al. 2007).

In general, the role of wetlands in carbon sequestration and storage is important (Kayranli et al. 2012). Wetlands cover approximately 6–9% of the Earth's surface and contain about 35% of global terrestrial carbon. While GRSA's wetlands are a small part of this, understanding patterns in carbon (and nitrogen) across these sites may lead to insight useful outside the park. Wetlands sequester and store carbon through accumulation of organic matter in soils, sediments, and plant biomass. In general wetland plants grow at a faster rate than they decompose, contributing to a net annual carbon sink. Saturated wetland soils limit oxygen diffusion into sediment profiles, creating anaerobic conditions. These conditions also slow decomposition rates, leading to the buildup and storage of large amounts of organic carbon in wetland sediments.

3.5.3.2 Assessment: future

Soil chemistry is a key aspect of the wetlands at GRSA. However, relationships with ecological integrity as driven by human and ungulate disturbance are complex. Therefore we cannot apply our assessment strategy that requires important assumptions about the directionality of how condition might relate to a given soil chemistry attribute. This is complicated

Table 20. Final variables in Principal Coordinates Analysis (PCoA) ordination of soil chemistry at sandsheet wetlands at Great Sand Dunes National Park and Preserve. The correlation of each vector with axis 1 or 2 is shown in r 1 or 2. The goodness of fit for each environmental gradient or soil parameter is shown using R^2, with its significance of the fit in p. Variables in bold are the parameters chosen for further interpretation.

Metric	Mean	LCB	UCB	Min
Iron (mg/kg, log)	0.665	0.060	0.732	0.0001
Ammonium (mg/kg, log)	0.486	-0.048	0.360	0.0001
Copper (mg/kg, log)	0.468	0.267	0.550	0.0001
Zinc (mg/kg, log)	0.416	0.443	0.720	0.0001
Manganese (mg/kg, log)	0.339	0.239	0.348	0.0001
Total C (%, log)	0.307	0.493	0.705	0.0001
DTW (depth to water)	0.276	0.105	0.265	0.0001
HDI (Human Disturbance Index)	0.246	0.068	0.140	0.0039
Bison Index	0.147	-0.126	0.086	0.0451
Organic matter (%, log)	-0.012	0.352	0.236	0.0002
Sulfate (mg/kg, log)	-0.097	0.645	0.651	0.0001
Bicarbonate (mg/kg)	-0.140	-0.186	0.130	0.0085
Specific conductance (µS/cm, log)	-0.467	0.431	0.735	0.0001
Carbonate (mg/kg, log)	-0.645	0.131	0.675	0.0001
Sodium adsorption ratio (mg/kg, log)	-0.701	0.250	0.844	0.0001
pH	-0.748	0.064	0.798	0.0001

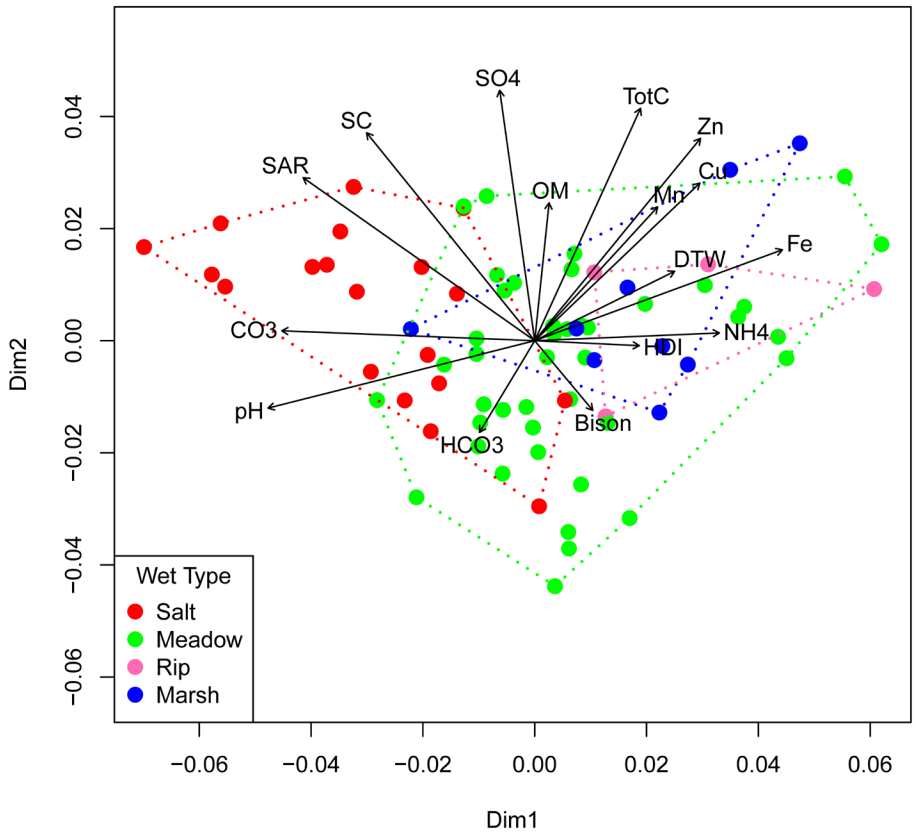


Figure 30. Principal Coordinates Analysis (PCoA) ordination of soil chemistry at Great Sand Dunes National Park and Preserve in 2010. Vectors show soil attributes and environmental covariates with a Bonferroni corrected p value less than 0.05. Polygons group sites by a priori wetland type. Dim1/2 are the first two PCoA axes. Codes are as follows: DTW = depth to water, HDI = Human Disturbance Index, Bison = Bison Index , HCO3 = soil bicarbonate (mg/kg), OM = soil organic matter at 40 cm depth (%, log), pH = pH , SC = specific conductance (µS/cm, log), NH4 = ammonium (mg/kg), Zn = zinc (mg/kg, log), Fe = iron (mg/kg, log), Mn = manganese (mg/kg, log), Cu = copper (mg/kg, log), SAR = sodium adsorption ratio (log), TotC = total carbon (%, log), SO4 = sulfate (mg/kg, log), CO3 = carbonate (mg/kg, log). Legend code: Rip = riparian.

even more so by the unique aspects of the gradient between salt flat and wet meadow wetlands at GRSA. For example, salt flats with high ecological integrity may have extreme sodicity. Likewise, the role of ungulates in influencing nutrient levels requires careful consideration when or if a condition assessment is made. Therefore, in this report, we largely restrict our use of soil chemistry data to its important role as a covariate in bioassessment models and in interpreting patterns within disturbance metrics.

Future assessment will include comparisons of the distributions of soil chemistry parameters to see if there are statistical shifts across time that can be associated with any similar change in condition. Because we only sample soils every 10 years, it will take time to model these patterns. However, assessment of how soil chemistry relates to changes in condition may also be largely case specific. Focused sentinel site data will be useful in this context.

3.5.3.3 Exploratory models of example soil chemistry variables

Next we present exploratory models that describe relationships between example soil chemistry variables and select attributes of wetlands that may covary and help explain patterns in these responses. Details for these models are the same as those given above in the Methods section and with the results for the disturbance metrics. Most soil chemistry predictors and both SAR and total percent carbon were best modeled as logarithmic transformations. However, models on a log-log scale can violate assumptions of linear models—fits may be strong and linear, yet interpretation should be made with caution.

3.5.3.3.1 Sodium adsorption ratio

The final model of SAR included 14 independent variables (Table 21). It was highly significant ($p < < 2.2e\text{-}16$) and had an adjusted R2 of 0.92, indicating nearly all of the variation in SAR was accounted for. The complete model is given in Appendix G. We restrict our presentation here to the variables in the model that either had the highest relative importance, lowest p values, and/or interesting relationships as drivers or covariates of groundwater conductance. We use conditional plots of partial residuals (Figure 31) to visualize the model (Larsen and McCleary 1972; Breheny and Burchett 2013).

Over 26% of the variation in SAR was explained by the specific conductance of groundwater at the site (Table 21). Both

Table 21. Exploratory model of peak season sodium adsorption ratio (SAR; with a log transformation) at Great Sand Dunes National Park and Preserve in 2010. Final model selected using Akaike Information Criterion (AIC) and expert opinion from 31 environmental and climate variables and 24 soil and water chemistry measures. Relative importance is the total amount of explained variance for each variable expressed as a proportion. SE = standard error of coefficient, t = t test value, p = probability of the t.

Model component	Estimate	SE	t	p	Relative importance
(Intercept)	10.070	5.340	1.886	0.064	–
Soil pH	0.216	0.033	6.645	0.000	0.163
Potassium (mg/kg, log)	-0.363	0.133	-2.724	0.009	0.106
Ca (mg/kg)	0.000	0.000	-6.414	0.000	0.055
Specific conductance (µS/cm, log)	1.534	0.166	9.219	0.000	0.262
Sodium (mg/kg, log)	0.227	0.082	2.757	0.008	0.144
Total N (%, log)	1.969	0.602	3.274	0.002	0.031
Carbon:nitrogen	0.006	0.003	2.047	0.045	0.163
Ungulate Use Index	0.001	0.001	1.784	0.080	0.007
Trail Index	0.003	0.001	2.617	0.011	0.009
Elk Index	-0.003	0.001	-1.944	0.057	0.007
Total monsoon 2008–10 precipitation (cm)	0.014	0.006	2.402	0.020	0.014
Elevation (m)	-0.006	0.003	-2.161	0.035	0.015
Distance to human feature (m)	0.000	0.000	1.973	0.053	0.013
Landscape Disturbance Index	0.004	0.001	3.498	0.001	0.010

Notes: Multiple R^2: 0.93, Adjusted R^2: 0.92, F-statistic: 56.77 on 14 and 57 DF, p value: < 2.2e-16.

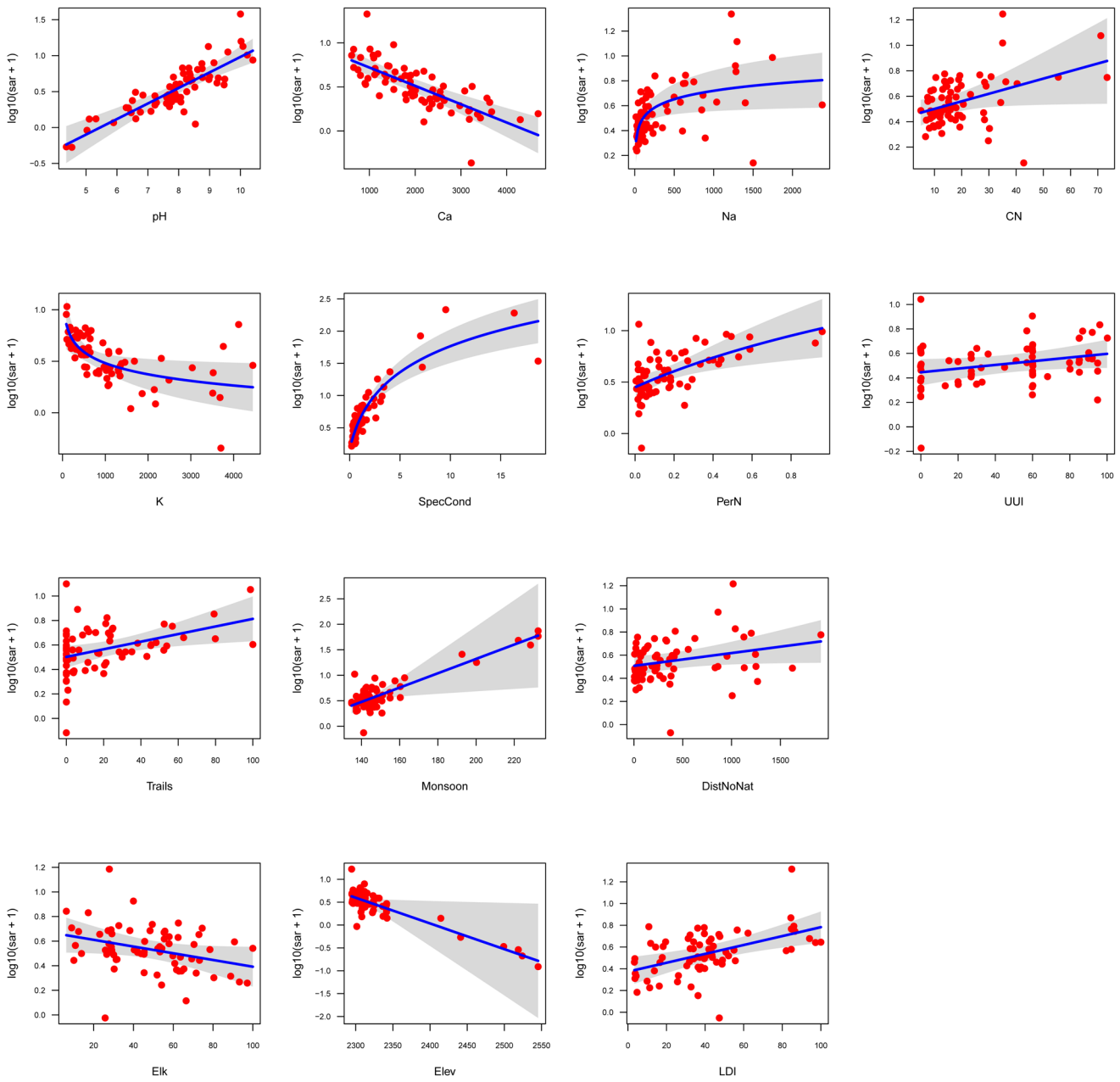


Figure 31. Partial residual plots of exploratory model of peak season sodium adsorption ratio (SAR) at Great Sand Dunes National Park and Preserve in 2010. Conditional partial residuals show the relationship between each unique predictor and SAR with all other variables held constant at the median for numeric variables and relative to a designated level for factors. All variables are shown back transformed to their original scale as applicable. Plots of numeric predictors include a best fit line and 95% confidence bands around this fit. Codes in Figures are: log10(sar + 1) = sodium adsorption ratio (log); pH =soil pH; Ca = calcium (mg/kg, log); Na = sodium (mg/kg, log); CN = carbon : nitrogen; K = potassium (mg/kg, log); SpecCond = soil specific conductance (µS/cm, log); PerN = total nitrogen (%, log); UUI = Ungulate Use Index; Trails = Trials Index; Monsoon = Total monsoon 2008 to 2010 precipitation (cm); DistNoNat = Distance to human feature (m); Elk = Elk Index; Elev = Elevation (m); LDI = Landscape Disturbance Index. See the full model in Appendix G.

SAR and specific conductance measure ionic concentration in a matrix and so this strong positive relationship is somewhat unsurprising. We include it as a control in the model on their covariance. Around 16% of the variance in SAR was accounted for by the (logged) ratio of carbon to nitrogen in a site's soil (Table 21). SAR was higher in sites where the ratio of carbon to nitrogen was in favor of carbon. This is an interesting pattern. It follows from the bivariate relationships between SAR and total percent carbon or nitrogen that show an expected strongly negative pattern—sodic sites with high SAR have lower nutrient levels, as seen in several other landscapes (Wong et al. 2010). However, the derived metric of a C:N ratio had a much stronger fit and thus appeared in our model. High C:N ratios in these sodic sites indicate that organic matter is accumulating faster than it is decomposing (Fazhu et al. 2015). High C:N ratios also occur where there is higher nitrogen availability (manifested as a lower soil C:N ratio). In many landscapes these conditions occur in wetter areas with shallower depths to water (Kuglerova et al. 2014). We do see a fairly strong pattern between shallow water tables and elevated nutrient concentrations, although our limited hydrologic regime data likely keep this from showing up in our DTW and total carbon models (see next section below). Wong et al. (2010) provides an overview of the various feedbacks between salts, nutrients, hydrologic regime and vegetation productivity and composition. These interactions drive the vegetation community at saltier sites at GRSA, drive how ungulates use these wetlands, and lie behind much of our characterization of the integrity of these wetlands. Finally, SAR was positively associated with distance to anthropogenic features (Figure 31). This was a significant relationship but was not one of the predictors with a higher relative importance. We interpret it here as the other important predictors (i.e., sodium or potassium concentration) are less ecologically interesting. It suggests that more sodic sites are more removed from anthropogenic features. We suspect the structure in this pattern is due to human uses being closer to areas that are more productive and have less salt accumulation.

3.5.3.3.2 Total carbon

Our model of total percent carbon in soil included 12 independent variables (Table 22). It was highly significant ($p << 2.2e-16$) and had an adjusted R2 of 0.91, indicating nearly all of the variation in total percent carbon was explained. The complete model is presented in Appendix G. We restrict our presentation here to the variables in the model that either had the highest relative importance, lowest p values, and/or interesting relationships as drivers or covariates of total percent carbon. We use conditional plots of partial residuals (Figure 32) to visualize the model (Larsen and McCleary 1972; Breheny and Burchett 2013).

Table 22. Exploratory model of soil total percent carbon (with a log transformation) at Great Sand Dunes National Park and Preserve in 2010. Final model selected using Akaike Information Criterion (AIC) and expert opinion from 31 environmental and climate variables and 24 soil and water chemistry measures. Relative importance is the total amount of explained variance for each variable expressed as a proportion. SE = standard error of coefficient, t = t test value, p = probability of the t.

Model component	Estimate	SE	t	p	Relative importance
(Intercept)	0.556	0.320	1.737	0.088	–
Organic matter @ 40 cm (%, log)	0.154	0.041	3.754	0.000	0.113
Soil pH	-0.068	0.017	-4.004	0.000	0.091
Zinc (mg/kg, log)	-0.358	0.124	-2.880	0.006	0.141
Specific conductance (µS/cm, log)	0.184	0.068	2.698	0.009	0.009
Sodium (mg/kg, log	0.128	0.032	4.074	0.000	0.032
Total N (%, log)	3.924	0.261	15.022	0.000	0.517
Total potential evapotranspiration	-0.002	0.001	-2.663	0.010	0.012
Elk Index	0.001	0.001	2.025	0.047	0.007
Total precipitation 1980–2010	0.001	0.001	3.379	0.001	0.046
Distance to sand	0.001	0.001	-2.733	0.008	0.008
Landscape Disturbance Index	0.003	0.001	3.592	0.001	0.009
Human landcover in catchment (%)	0.092	0.035	2.643	0.011	0.015

Notes: Multiple R^2: 0.93, Adjusted R^2: 0.91, F-statistic: 60.74 on 12 and 59 DF, p value: <2.2e-16.

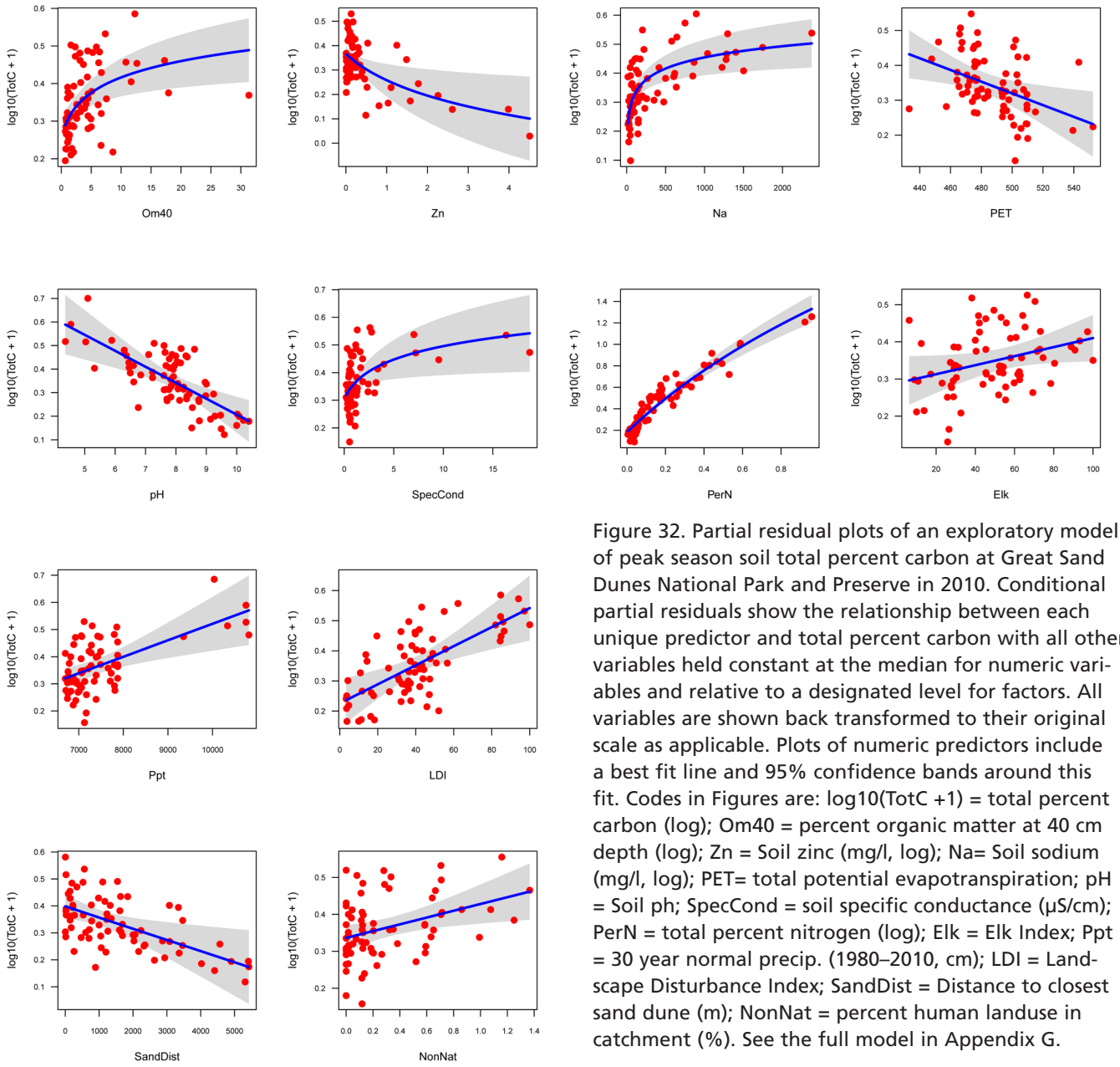


Figure 32. Partial residual plots of an exploratory model of peak season soil total percent carbon at Great Sand Dunes National Park and Preserve in 2010. Conditional partial residuals show the relationship between each unique predictor and total percent carbon with all other variables held constant at the median for numeric variables and relative to a designated level for factors. All variables are shown back transformed to their original scale as applicable. Plots of numeric predictors include a best fit line and 95% confidence bands around this fit. Codes in Figures are: log10(TotC +1) = total percent carbon (log); Om40 = percent organic matter at 40 cm depth (log); Zn = Soil zinc (mg/l, log); Na= Soil sodium (mg/l, log); PET= total potential evapotranspiration; pH = Soil ph; SpecCond = soil specific conductance (µS/cm); PerN = total percent nitrogen (log); Elk = Elk Index; Ppt = 30 year normal precip. (1980–2010, cm); LDI = Landscape Disturbance Index; SandDist = Distance to closest sand dune (m); NonNat = percent human landuse in catchment (%). See the full model in Appendix G.

Almost 52% of the variation in total percent carbon in the exploratory model was explained by total percent nitrogen (Figure 32). Nutrient concentrations in soils are driven by similar processes (Wong et al. 2010), so this is an unsurprising result. We include it as a control on their covariance. Around 5% of the variation in total percent carbon was explained by total precipitation over 30 years (Figure 32). Several potential outlier wet meadow sites on the toe slope of the Sangre de Cristo Mountains appear to drive the pattern. However, with these removed from the model, the relationship is still strong and positive, suggesting that even with the more subdued variation in precipitation at sites further west on the sandsheet, this metric was important in driving total percent carbon. Wetter sites are generally more productive. Finally, total percent carbon was negatively associated with percent of each site's catchment that had anthropogenic land cover or uses (Figure 32)—soil carbon was lower in sites with more natural catchments. This was a significant relationship but was not one of the predictors with a higher relative importance. It suggests that anthropogenic disturbance reduces nutrients, but the structure behind this pattern will need more research to better interpret.

3.6 *In situ* groundwater chemistry

3.6.1 Summary condition

In general, *in situ* groundwater chemistry (hereafter "water chemistry") was typical for the wetland types we monitor at GRSA (Cooper and Gage 2009). Because we lack evidence to assess any parameter in and of itself as a direct indicator of disturbance or ecological integrity, we treat water chemistry results largely as a baseline for future assessment (Table 23). However, we do model pH and specific conductance to explore patterns in these key covariates. Table 23 presents a summary of *in situ* groundwater results only. See the Executive Summary for a summary condition table that includes all indicators of wetland condition.

3.6.2 Overview

Much like wetland soils, groundwater is an important matrix for chemical reactions that influence wetland vegetation (Mitsch and Gosselink 2007). Groundwater chemistry also reflects large scale and local disturbances and thus provides useful indicators of wetland condition. Four core *in situ* parameters are required by the NPS Water Resource Division as part of all NPS aquatic monitoring protocols. These parameters contribute some consistency, and more importantly, they can be key indicators of stress in aquatic systems (NPS 2002). Of the four core parameters, only two are relevant or appropriately measurable in wetland groundwater. First, pH (the measure of water hydrogen ion concentration) has many physical and biological effects in wetland systems. Most plant species occur within specific habitat envelopes of pH conditions, and changes in pH will likely result in changes in vegetation communities. In addition, pH determines the solubility of heavy metals and many salts—important in GRSA, given conditions on the sandsheet. Second, specific conductance (the ability of a water body to conduct an electric current used as an index of dissolved ion concentrations in water bodies) also affects important chemical reactions. Changes in conductance also can indicate shifts in major ions or nutrients, such as potassium, calcium, and other anions and cations.

The following presents estimates of the status of groundwater *in situ* chemistry across the GRSA sandsheet in 2010 and, at sentinel sites, trend from 2010 to 2014. At most sites we only have 2010 peak season single point in time measures. Even at sentinel sites, where we have annual revisit data, we have no way to account for likely important diel and seasonal patterns in our trend models—future work will determine if these are important.

3.6.3 In situ *water chemistry: results and interpretation*

We first present overviews of groundwater specific conductance and pH via traditional descriptive statistics grouped by wetland type within 1) sandsheet and 2) sandsheet plus high elevation (all sites) categories sites. Table 24 gives means and measures of dispersion for each response. Salt flats had the least dilute groundwater (highest conductivity) and most basic pH. In contrast, fens (and our single high elevation meadow) were dilute and more acidic. These patterns fit our expectations based on the general hydrologic regimes and soil chemistry typical for each type (Cooper and Severn 1992; Cooper 1998). Conductivity also varied the most within salt flats (Table 24a). Wetland types other than salt flats on the sandsheet were generally similar in pH but conductance varied across type (Table 24b). Table 25 presents population scale water chemistry results for all salty meadow sites on the sandsheet. A notable but unsurprising difference between the two sets of status estimates includes higher conductance in the population of salty meadows, reflecting the higher levels of salts and other ions in the soil matrix of salt flats.

3.6.3.1 Assessment: future

As with soils, the chemistry of groundwater is an important attribute of the wetlands at GRSA. However, relationships with ecological integrity as driven by human and ungulate disturbance are complex and we cannot apply our assessment strategy, which requires important assumptions about the directionality of how condition might relate to a given water chemistry attribute. Therefore, in this report, we largely restrict our use of soil chemistry data to its important role as a covariate in bioassessment models and in interpreting patterns within disturbance metrics.

Future assessment will include comparisons of the distributions of soil chemistry to see if there are statistical shifts across time that can be associated with any similar change in condition. We can more readily assess how water chemistry relates to changes in condition using focused sentinel site data, but we still lack sufficient data for this task.

3.6.3.2 Exploratory models of groundwater *in situ* chemistry

Next, we present linear models that quantify relationships between peak season groundwater specific conductance and pH and select attributes of wetlands that may predict or covary with patterns in these responses and thus help in interpretation. Details for these models are the same as those given above in the Methods section and with the results for the disturbance metrics.

Table 23. Summary condition table for *in situ* groundwater chemistry at Great Sand Dunes National Park and Preserve (GRSA) in 2010. No assessment points are available for *in situ* groundwater chemistry indicators yet. Because we cannot yet assess condition, the symbols for these two soil chemistry indicators lack color and trend arrows.

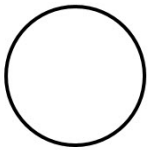
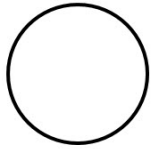
Groundwater chemistry indicators	Condition description	Condition and confidence
In situ groundwater pH (2010)	Groundwater is an important matrix for chemical reactions that influence wetland vegetation and reflects large scale and local disturbances. It is a useful indicator of wetland condition. We measured pH and specific conductance with each visit to GRSA wetland sites. Most plant species occur within specific habitat envelopes of pH conditions, and changes in pH will likely result in changes in vegetation communities. In addition, pH determines the solubility of heavy metals and many salts—important in GRSA. Values for pH ranged from a low of 5.2 to 10.3 across all sites, with a population mean for salty meadows (sites on a continuum between salt flats and wet meadows) of 7.61. A predictive model suggests groundwater pH covaried with the pH of the soil matrix from which the groundwater was extracted. In situ pH was also influenced by human disturbance, as measured by HDI, with lower or more acidic pH values at sites with less HDI. The pattern with ungulate use, as measured by UUI, was marginal, with a very weak suggestion that pH was elevated with UUI. The mechanism here is likely complex, with the covariance likely reflecting indirect connections between disturbance and pH. There was no significant trend at sandsheet sentinel sites in groundwater pH on an annual basis or net trend over a five year period from 2010 to 2014. *We have not analyzed these data relative to human or other disturbances or threats, so, for the time being, we do not assign a condition or a trend. We will use this information as a baseline for future comparisons as monitoring continues.* Neverthess we do develop high quality ground water chemistry data and models and we are confident that our baselines will be useful for understanding changes over time. We therefore have medium confidence in our use of the selected ground water indicators.	
In situ groundwater specific conductance (2010)	Changes in specific conductance can indicate shifts in major ions or nutrients, such as potassium, calcium, and other anions and cations, with important effects on wetland vegetation Specific conductance ranged from 56.8 to 11999.5 µS/cm across all sites with a population mean for salty meadows of 1197.2. An exploratory model suggests specific conductance largely covaried with the specific conductance of the soil matrix from which the groundwater was extracted. It was also strongly negatively associated with higher Bison Index values—bison may actively avoid areas with high ion concentrations (or salinity) in groundwater. These sites have poorer forage and are much drier. Specific conductance was also positively associated with higher values of our Landscape Disturbance Index, perhaps suggesting that elevated conductance is associated with larger scale human disturbance. Finally, elevated conductance occurred in salt flat and, to a lesser degree, marsh type wetlands. There was no significant trend at sandsheet sentinel sites in groundwater specific conductance on an annual basis or net trend over a five year period from 2010 to 2014. *We have not analyzed these data relative to human or other disturbances or threats, so, for the time being, we do not assign a condition or a trend. We will use this information as a baseline for future comparisons as monitoring continues.* Neverthess we do develop high quality ground water chemistry data and models and we are confident that our baselines will be useful for understanding changes over time. We therefore have medium confidence in our use of the selected ground water indicators.	

Table 24a. Summary of peak season groundwater specific conductance in 2010 at Great Sand Dunes National Park and Preserve. The "All sites" category includes sandsheet and high elevation fen and wet meadow sites. LCB/UCB are lower and upper 95% confidence interval boundaries, respectively. Standard error is for the mean. Source data are limited to the best sample events in 2010. Sample size varied as indicated.

Site type	Wetland type	N	Mean specific conductance (µs/cm)	LCB	UCB	Min	Max	Std. dev.	Std. error
All sites	Salt flat	19	2093.33	773.60	3413.07	266.86	11999.50	2738.12	628.17
	Wet meadow	42	439.31	334.48	544.14	56.86	2027.14	336.40	51.91
	Riparian	4	291.93	173.96	409.89	201.86	380.57	74.14	37.07
	Marsh	9	951.37	642.05	1260.68	274.29	1443.86	402.41	134.14
	Fen	7	108.57	55.39	161.75	59.00	229.71	57.50	21.73
	All types	81	848.33	514.29	1182.36	56.86	11999.50	1510.65	167.85
Sandsheet sites	Salt flat	19	2093.33	773.60	3413.07	266.86	11999.50	2738.12	628.17
	Wet meadow	41	448.64	342.89	554.39	126.43	2027.14	335.03	52.32
	Riparian	4	291.93	173.96	409.89	201.86	380.57	74.14	37.07
	Marsh	9	951.37	642.05	1260.68	274.29	1443.86	402.41	134.14
	All types	73	930.10	563.67	1296.54	126.43	11999.50	1570.56	183.82

Table 24b. Summary of peak season groundwater pH in 2010 at Great Sand Dunes National Park and Preserve. The "All sites" category includes sandsheet and high elevation fen and wet meadow sites. LCB/UCB are lower and upper 95% confidence interval boundaries, respectively. Standard error is for the mean. Source data are limited to the best sample events in 2010. Sample size varied as indicated.

Site type	Wetland type	N	Mean pH	LCB	UCB	Min	Max	Std. dev.	Std. error
All sites	Salt flat	19	8.23	7.70	8.75	7.03	10.33	1.10	0.25
	Wet meadow	42	7.09	6.91	7.28	5.73	8.36	0.59	0.09
	Riparian	4	6.65	6.00	7.30	6.31	7.24	0.41	0.20
	Marsh	9	6.79	6.37	7.21	6.20	8.05	0.55	0.18
	Fen	7	5.63	5.31	5.95	5.26	6.22	0.35	0.13
	All types	81	7.18	6.96	7.40	5.26	10.33	1.00	0.11
Sandsheet sites	Salt flat	19	8.23	7.70	8.75	7.03	10.33	1.10	0.25
	Wet meadow	41	7.13	6.95	7.30	6.08	8.36	0.56	0.09
	Riparian	4	6.65	6.00	7.30	6.31	7.24	0.41	0.20
	Marsh	9	6.79	6.37	7.21	6.20	8.05	0.55	0.18
	All types	73	7.35	7.14	7.56	6.08	10.33	0.90	0.11

Table 25. Population scale summary of groundwater chemistry for salty meadows in the sandsheet at Great Sand Dunes National Park and Preserve in 2010. LCB/UCB are lower and upper 95% confidence interval boundaries, respectively. Standard error is for the mean. Note that these statistics were generated using design based methods.

Parameter	N	Mean	Std. error	LCB	UCB
Groundwater pH	46	7.61	0.117	7.381	7.837
Groundwater specific conductance (µS/cm)	46	1197.17	215.10	775.58	1618.76

3.6.3.2.1 pH

Our model of groundwater pH included 11 predictors or covariates (Table 26). It was highly significant ($p < 7.933e-14$) and had an adjusted R2 of 0.70, indicating most of the variation in groundwater pH was accounted for. The complete model is presented in Appendix G. We restrict our presentation here to the variables in the model that either had the highest relative importance, lowest p values, and/or interesting relationships as drivers or covariates of groundwater pH. We use conditional plots of partial residuals (Figure 33) to visualize the model (Larsen and McCleary 1972; Breheny and Burchett 2013).

A large proportion of the variation in *in situ* groundwater pH was explained by attributes of the soil matrix from which the groundwater was extracted (Figure 33). These measures are somewhat redundant but including it in the model improved the fit markedly and confirms that, as with conductance, groundwater chemistry is largely driven by a site's soil type or context. *In situ* pH was influenced by HDI, with lower or more acidic pH values at sites with less HDI (Figure 33). The pattern with UUI was marginal, with a very weak suggestion that pH was elevated with UUI.

3.6.3.2.2 Specific conductance

The final model of peak season groundwater specific conductance in 2010 included 11 independent variables (Table 27). It was highly significant ($p < 2.402e-15$) and had an adjusted R2 of 0.75, indicating that most of the variation in groundwater conductance was accounted for. The complete model is presented in Appendix G. We restrict our presentation here to the variables in the model that either had the highest relative importance, lowest p values, and/or interesting relationships as drivers or covariates of groundwater conductance. We use conditional plots of partial residuals (Figure 34) to visualize the model (Larsen and McCleary 1972; Breheny and Burchett 2013).

Almost 16% of the variation in *in situ* specific conductance was explained by the specific conductance of the soil matrix from which the groundwater was extracted (Table 27). These measures are somewhat redundant, but including the soil measures in the model improved the fit markedly and confirms that groundwater chemistry is largely driven by a site's soil type or context. *In situ* specific conductance was strongly negatively associated with higher values of the Bison Index, with around 16% of the variation explained by this index to bison number (Table 27). We interpret this as bison likely actively avoiding areas with high salinity. These sites have poorer forage and are likely much drier. Most sites above the curve with low a Bison Index and high specific conductance are salt flats. *In situ* specific conductance was positively associated with higher values of LDI, explaining around 7% of the total variation. This suggests that elevated conductance is associated with larger scale human disturbance (Figure 34). Finally, wetland type (Figure 34) was significant, with elevated conductance in salt flat and marsh sites (but as noted we have small samples of riparian and marsh). That salt flats have high conductance is not surprising, but it is interesting that marshes do—this will require more data to interpret.

Table 26. Exploratory model of peak season groundwater pH in 2010 at Great Sand Dunes National Park and Preserve. Final model selected using Akaike Information Criterion (AIC) and expert opinion from 31 environmental and climate variables and 24 soil and water chemistry measures. Relative importance is the total amount of explained variance for each variable expressed as a proportion. SE = standard error of coefficient, t = t test value, p = probability of the t.

Model component	Estimate	SE	t	p	Relative importance
(Intercept)	2.600	1.048	2.480	0.016	–
Groundwater specific conductance (µS/cm)	0.000	0.000	3.855	0.000	0.183
soil pH	0.303	0.094	3.235	0.002	0.208
Nitrate (mg/kg, log)	0.510	0.239	2.133	0.037	0.035
Potassium (mg/kg, log)	0.669	0.208	3.213	0.002	0.192
Carbonate (mg/kg, log)	-0.280	0.117	-2.396	0.020	0.081
Human Disturbance Index	-0.045	0.010	-4.650	0.000	0.056
Ungulate Use Index	0.017	0.003	5.819	0.000	0.089
Trail Index	-0.007	0.003	-2.650	0.010	0.059
Total 2008 to 2010 precipitation	0.003	0.001	2.564	0.013	0.029
Hydrologic alteration	0.014	0.003	4.145	0.000	0.043
Landscape Disturbance Index	-0.008	0.003	-2.505	0.015	0.025

Notes: Multiple R^2: 0.75, Adjusted R^2: 0.7, F-statistic: 15.86 on 11 and 59 DF, p value: 7.933e-14.

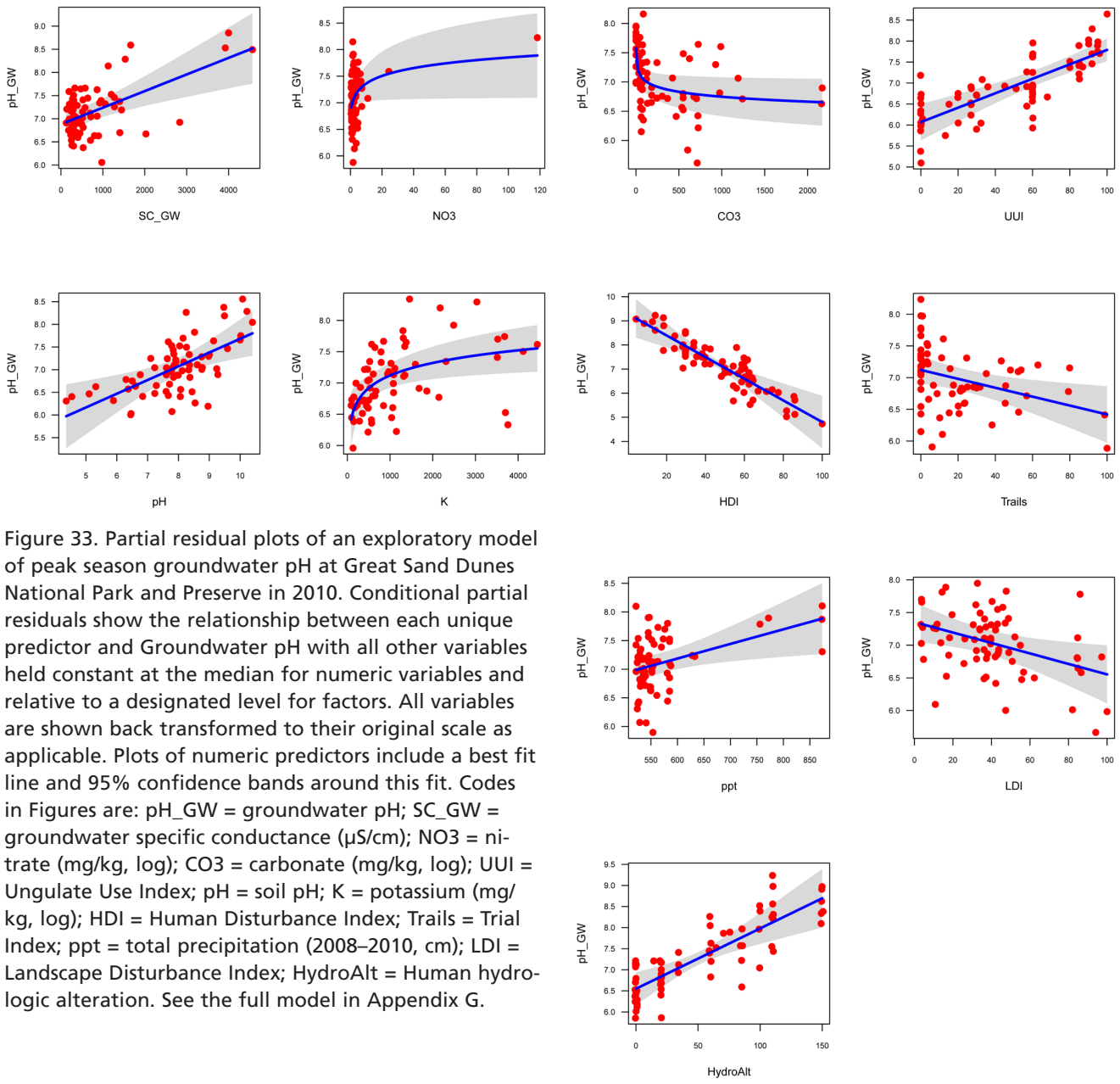


Figure 33. Partial residual plots of an exploratory model of peak season groundwater pH at Great Sand Dunes National Park and Preserve in 2010. Conditional partial residuals show the relationship between each unique predictor and Groundwater pH with all other variables held constant at the median for numeric variables and relative to a designated level for factors. All variables are shown back transformed to their original scale as applicable. Plots of numeric predictors include a best fit line and 95% confidence bands around this fit. Codes in Figures are: pH_GW = groundwater pH; SC_GW = groundwater specific conductance (µS/cm); NO3 = nitrate (mg/kg, log); CO3 = carbonate (mg/kg, log); UUI = Ungulate Use Index; pH = soil pH; K = potassium (mg/kg, log); HDI = Human Disturbance Index; Trails = Trial Index; ppt = total precipitation (2008–2010, cm); LDI = Landscape Disturbance Index; HydroAlt = Human hydrologic alteration. See the full model in Appendix G.

3.6.3.3 Trend in *in situ* groundwater specific conductance and pH at sandsheet sentinel sites: 2010–2014

Finally, we estimate trend in specific conductance and pH at sentinel sites on the sandsheet from 2010 to 2014. Table 28 gives summary statistics by year. Importantly, while these models are well constructed, five years is likely too short a period to detect significant ecological changes given the complexity of this system and the time frames over which system components (past cattle grazing, elk populations and use, climate, long-lived perennial plants, etc.) respond to the environment. Future iterations of these models will likely be more revealing and valuable. The area has a long history of changes in disturbance and it will take more years of data to understand whether any trend is relevant over the long term.

We first looked at the homogeneity of the variance in each index across years using Brown-Forsythe and Levene tests (Brown and Forsythe 1974; Levene 1960). Variance in specific conductance and pH were both statistically homogeneous across years, although this should be viewed with some caution given a large increase in at least pH, especially

Table 27. Exploratory model of peak season groundwater specific conductance (with a log transformation) at Great Sand Dunes National Park and Preserve in 2010. Final model selected using Akaike Information Criterion (AIC) and expert opinion from 31 environmental and climate variables and 24 soil and water chemistry measures. Relative importance (Rel. Imp.) is the total amount of explained variance for each variable expressed as a proportion. Wetland type is treated as a factor and all estimates are relative to marshes. *Wetland type relative importance value is for all three groups combined. SE = standard error of coefficient, t = t test value, p = probability of the t.

Model component	Estimate	SE	t	p	Relative importance
(Intercept)	1.888	0.449	4.206	0.000	–
Wetland type	–	–	–	–	*0.216
Wet meadow	-0.260	0.085	-3.075	0.003	–
Riparian	-0.129	0.118	-1.093	0.279	–
Salt flat	0.005	0.106	0.051	0.959	–
soil pH	0.068	0.028	2.427	0.018	0.114
Copper (mg/kg, log)	0.325	0.176	1.842	0.071	0.021
Magnesium (mg/kg, log)	0.000	0.000	2.107	0.039	0.031
Specific conductance (µS/cm, log)	0.415	0.132	3.142	0.003	0.158
Total N (%, log)	1.757	0.945	1.859	0.068	0.080
Total C (%, log)	-0.783	0.199	-3.931	0.000	0.069
Bison Index	-0.005	0.001	-4.359	0.000	0.162
Total precipitation, 2008 to 2010 (cm)	-0.003	0.002	-1.868	0.067	0.036
Mean precipitation, 1980 to 2010 (cm)	0.000	0.000	1.731	0.089	0.049
Landscape Disturbance Index	0.005	0.001	4.360	0.000	0.064

Notes: Multiple R^2: 0.79, Adjusted R^2: 0.76; F-statistic: 17.51 on 13 and 57 DF, p value: 2.402e-15.

Table 28. Summary statistics for peak season groundwater *in situ* specific conductance and pH at sandsheet sentinel sites at Great Sand Dunes National Park and Preserve from 2010 to 2014. LCB/UCB are lower and upper 95% confidence interval boundaries, respectively. Standard error is for the mean.

Metric	Year	N	Mean	LCB	UCB	Standard Deviation	Variance	Standard Error
Specific conductance (µS/cm)	2010	7	309.67	220.50	398.85	96.42	9297.00	36.44
	2011	5	225.91	114.04	337.79	90.10	8118.00	40.29
	2012	5	421.12	66.08	776.16	285.94	81763.00	127.88
	2013	5	365.55	30.87	700.22	269.54	72650.00	120.54
	2014	5	4028.27	-4842.04	12898.57	7143.89	51035110.00	3194.84
	All Years	27	1013.78	-238.89	2266.45	3166.61	10027433.00	609.42
pH	2010	7	6.80	6.43	7.17	0.40	0.16	0.15
	2011	5	7.68	7.29	8.07	0.31	0.10	0.14
	2012	5	7.58	6.55	8.61	0.83	0.69	0.37
	2013	5	7.59	6.19	8.99	1.12	1.27	0.50
	2014	5	8.13	5.86	10.40	1.83	3.35	0.82
	All Years	27	7.50	7.09	7.91	1.04	1.08	0.20

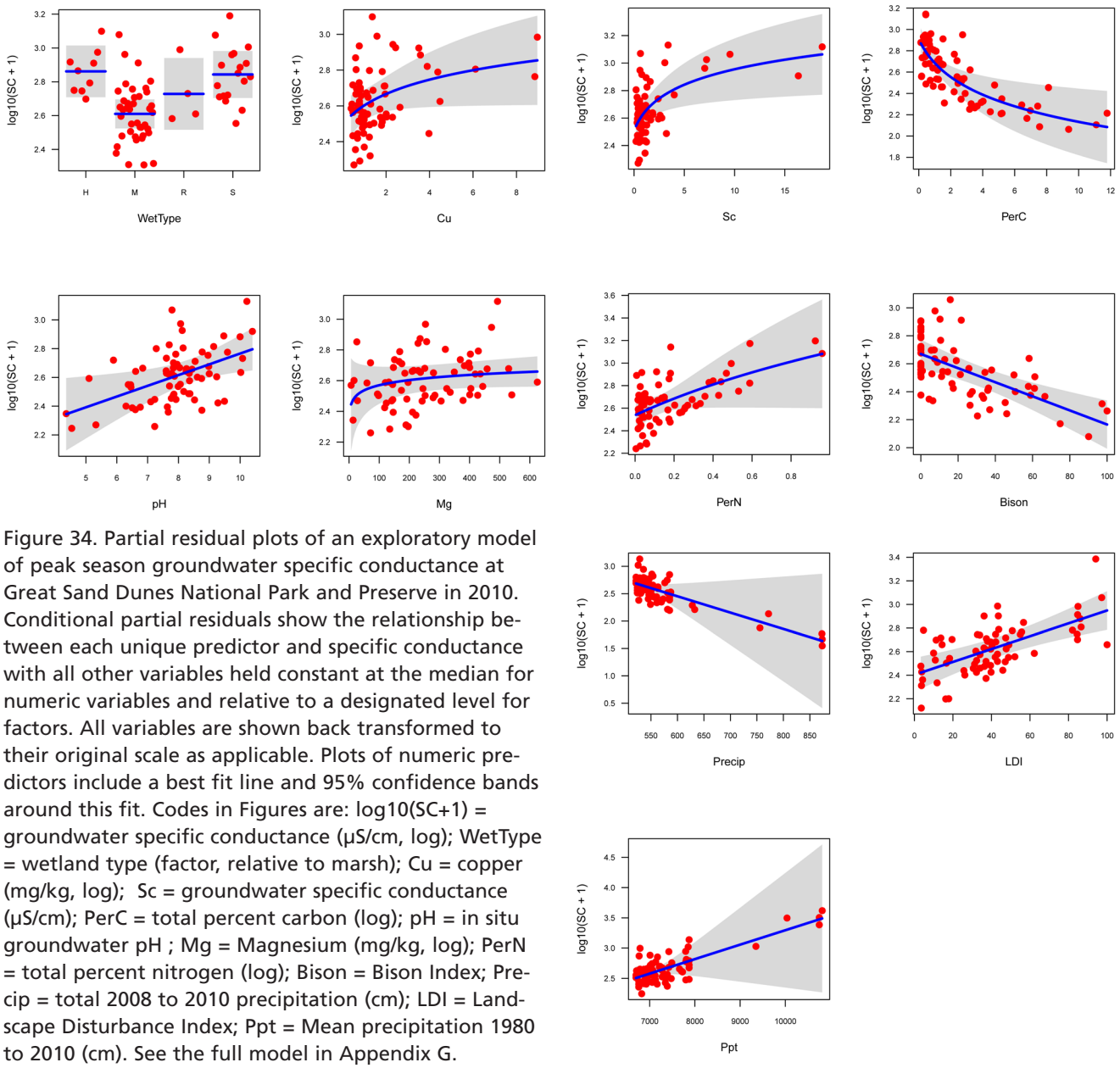


Figure 34. Partial residual plots of an exploratory model of peak season groundwater specific conductance at Great Sand Dunes National Park and Preserve in 2010. Conditional partial residuals show the relationship between each unique predictor and specific conductance with all other variables held constant at the median for numeric variables and relative to a designated level for factors. All variables are shown back transformed to their original scale as applicable. Plots of numeric predictors include a best fit line and 95% confidence bands around this fit. Codes in Figures are: log10(SC+1) = groundwater specific conductance (µS/cm, log); WetType = wetland type (factor, relative to marsh); Cu = copper (mg/kg, log); Sc = groundwater specific conductance (µS/cm); PerC = total percent carbon (log); pH = in situ groundwater pH ; Mg = Magnesium (mg/kg, log); PerN = total percent nitrogen (log); Bison = Bison Index; Precip = total 2008 to 2010 precipitation (cm); LDI = Landscape Disturbance Index; Ppt = Mean precipitation 1980 to 2010 (cm). See the full model in Appendix G.

in 2014. We use linear mixed-effects models that specifically address trend estimation for correlated data. We treat year as a random effect to estimate the variation of any linear trend over time. We use the single year (2010) linear models (see above) to select a limited set of the most important potential covariates and include these in each model as fixed effects. These covariates were kept to a minimum and to those that we felt would help isolate any change in specific conductance or pH over time. Following Heard et al. (2012), we model the responses both logged and untransformed. The logged response allows a test of the net trend over the five year interval, whereas the untransformed response looks at the annual trend.

3.6.3.3.1 Specific conductance

There was no significant trend at sandsheet sentinel sites in groundwater specific conductance on an annual basis or net over a five year period from 2010 to 2014 (Figure 35, see Appendix G for the full models). The model had an approximate R2 (correlation between the fitted and the observed values) of around 0.40, suggesting that some but not most of the variance in specific conductance was explained. Our data only include three sentinel complexes and a short time period, with no real control for diel or seasonal patterns. We will continue to investigate this as we add sample events.

3.6.3.3.2 pH

There was no significant trend at sandsheet sentinel sites in groundwater pH on an annual basis or net over a five year period from 2010 to 2014 (Figure 36, see Appendix G for the full models). The model had an approximate R2 (correlation between the fitted and the observed values) of around 0.60 suggesting that most of the variance in pH was explained. Our data only include three sentinel complexes and a short time period, with no real control for diel or seasonal patterns. We will continue to investigate this as we add sample events.

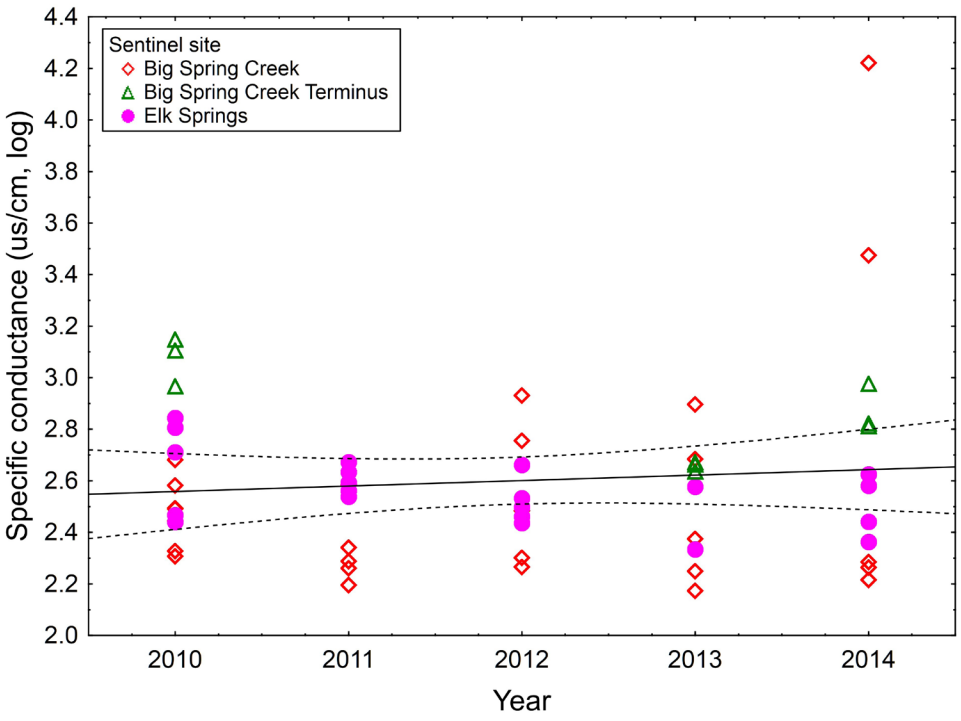


Figure 35. Peak season groundwater in situ specific conductance (µS/cm, logged) at sandsheet sentinel sites by year at Great Sand Dunes National Park and Preserve, 2010 to 2014. Points (representing unique sites) within a year may overlap. See the full model in Appendix G.

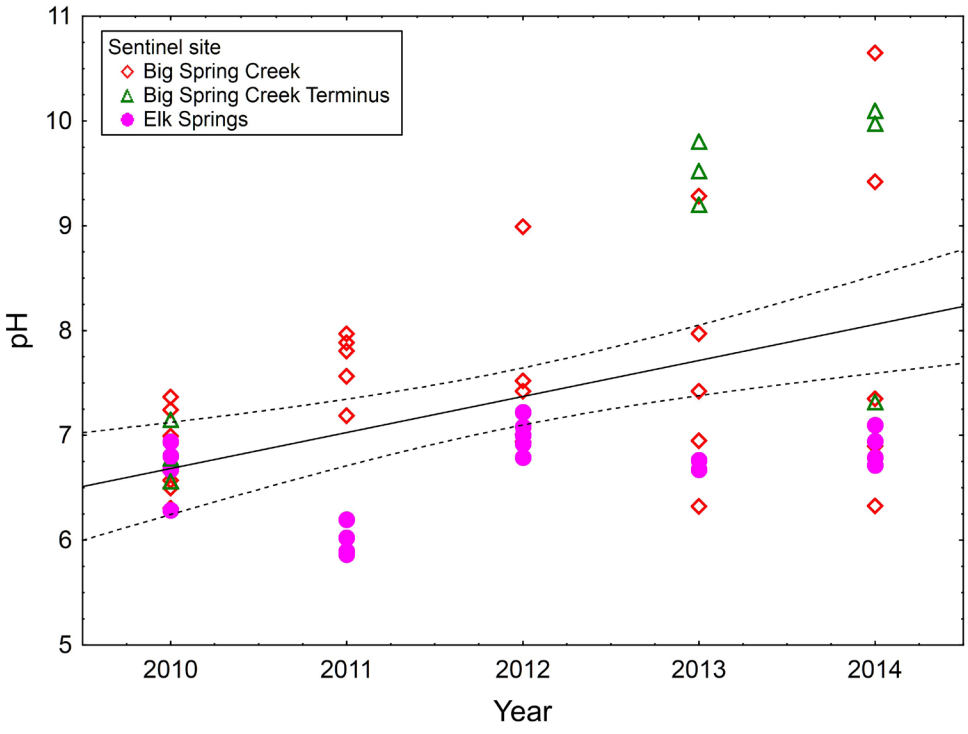


Figure 36. Peak season groundwater in situ pH at sandsheet sentinel sites by year at Great Sand Dunes National Park and Preserve, 2010 to 2014. Points (representing unique sites) within a year may overlap. See the full model in Appendix G.

3.7 Hydrology

3.7.1 Summary condition

Given complex patterns with human and ungulate disturbance, it is difficult to assess our hydrologic data in the context of ecological integrity at this time. On a case specific basis, some sites did have increasing water table depths (i.e., more negative DTW values or a lower water table), yet we assume, depending on wetland type, a wetter wetland is beneficial, up to a point. Table 29 presents a summary of our hydrology results, with more details below. See the Executive Summary for a summary condition table that includes all indicators of wetland condition.

3.7.2 Overview

Next we present estimates of groundwater depth (or depth to water, DTW) across the GRSA sandsheet. At most sites we only have peak season single point in time measures of DTW from 2010. These are useful data and appear in several of our models of wetland condition throughout this report. However, at a subset of sentinel sites we also have DTW data collected via loggers on an hourly time step year round. These data are more valuable as they allow characterization of DTW fluctuation across season and year. Moreover, they allow detailed trend models at these sites from 2010 to 2014.

Hydrologic regime is fundamental to wetlands as one of the three controls on what make habitat a wetland (soils and vegetation being the other two). It is the primary site-level ecological driver of wetlands, strongly influencing vegetation, biogeochemistry, and ecosystem processes, such as primary production and decomposition (Keddy 2000). Hydrologic regime acts as a filter on the pool of potential species capable of occupying a wetland, allowing only those species with the required physiological, morphological, or life history adaptations to establish and be recruited (Mitsch and Gosselink 2007). The source of water supporting a wetland—whether it is principally precipitation, surface, or groundwater—and the flow paths taken before and after entering the system, can also affect a variety of important ecological functions.

Note that many WEI monitoring sites do not necessarily meet requirements for groundwater depths as set by the National Research Council (1995) and the Corps of Engineers (2010). Following the WEI protocol, we do not exclude them from WEI monitoring because of this.

3.7.3 Depth to groundwater: results and interpretation

Summaries of peak season DTW in 2010 grouped by wetland type within 1) sandsheet and 2) sandsheet plus high elevation (All sites) categories are presented in Table 30. In general, fens and high elevation meadows had high water tables at or near the soil surface in late summer. This is expected given higher levels of precipitation at elevation and generally little to no drawdown via human activities in each site's groundwater catchment, with stable groundwater flows that can sustain higher water tables. However, perhaps given the effects of the ongoing drought in 2010 (see Figure 14), there was high variability across sites. Many riparian sites on the sandsheet also had high water tables in late summer. This is not always the case for riparian wetland in the West (Gage and Cooper 2013), but riparian sites at GRSA were all close to the perennial spring-driven channel of Big Spring Creek that maintains near saturated conditions in most years in its valley bottom. Salt flats were the driest of our sites, often with water tables over a meter below the surface—this is an expected pattern as well. Wet meadows on the sandsheet had variable DTW, with some sites nearly as dry as many salt flats yet several others with saturated or even inundated soils.

3.7.3.1 Population scale groundwater hydrology: sandsheet salty meadows

Next, we present design-based results that infer peak season DTW to all salt flat–wet meadow wetlands on the sandsheet. Design-based inference uses a suite of algorithms to estimate population means and various estimates of the error in these means. Figure 37 gives the cumulative distribution of DTW in salty meadows in 2010. Table 31 provides a summary of salty meadow DTW in 2010. The cumulative value is given both as a proportion of the total resource and as an estimate of total area of wetland. An estimate of the error in the population scale inference is given by a 95% confidence interval around the cumulative value. We use ecoregion assessment points to set DTW disturbance class boundaries. In 2010, around 50% (with 95% confidence intervals of around 38–63%) of the salty meadow on the sandsheet had peak season groundwater tables above -99.4 cm. In contrast, around 25% (13–34%) had deeper water tables below -119.6 cm (the 25th percentile).

However, given complex relationships between hydrologic regime and human and/or ungulate disturbance, these should be treated with extreme caution and we do not apply the usual disturbance labels (i.e., major, minor, etc.) nor use the same symbology as for other indicators. To label classes, we would have to assume that for salty meadows on the sandsheet, higher water tables at the peak of the summer growing season correspond to less disturbance. Yet at some point, higher water tables in these wetland types would likely lead to a degraded condition, or if they persisted for long

Table 29. Summary condition table for groundwater depth at all sites in 2010 and select site hydrologic regimes from 2010 to 2014 at Great Sand Dunes National Park and Preserve. No assessment points are available for hydrologic regime indicators yet. Key to the condition and confidence symbol: red, textured color = non-reference condition/major disturbance, yellow color = intermediate condition/moderate disturbance, dark green color = reference condition/minor disturbance, light green color = pristine reference condition/negligible disturbance, no color = unknown or indeterminate; upward arrow = condition is improving, sideways arrows = condition is unchanging, downward arrow = condition is deteriorating, no arrow = unknown trend; heavy border = high confidence, regular border = medium confidence, dashed border = low confidence. Figure 11 provides a visual key.

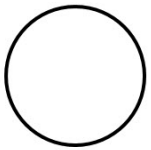
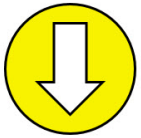
Hydrologic regime indicators	Condition description	Condition and confidence
Peak season depth to water (2010)	We measure depth to water (DTW) at the peak of the summer when water stress is likely highest at all Wetland Ecological Integrity sample sites. DTW in sandsheet sites ranged from a low of just over 2 m below ground to 8 cm above ground, with a mean of -75.3 cm (SD = 45.1) (below soil surface). Salt flats were the driest type, with riparian wetland the wettest on average on the sandsheet. The relationship between human/ungulate disturbances and DTW is complex. For the time being, we do not assign a condition to peak season DTW. However if we assume that for salt flats and wet meadows on the sandsheet, wetter is better, then we can set baseline assessment points of -99.4 cm (below ground) as the deepest water might be at the peak of summer for a site to be in a reference state. We will use this information as a baseline for future comparisons as monitoring continues. An exploratory model suggests higher DTW (smaller negative values; higher water table) occurs where there had been higher monsoon precipitation from 2008 to 2010, suggesting some GRSA wetlands are likely influenced by precipitation. Higher water tables can cause anoxic soils that increase concentrations of anions, like manganese, which can impact wetland. The degree of human hydrologic alteration in the wetland complex and its catchment was also highly significant in predicting peak season DTW, with greater degrees of alteration lowering water tables. This pattern plays an important role in bioassessment models, where DTW covaries with important vegetation metrics that influence overall estimates of integrity. Wetland type was also significant, with riparian and marsh sites wetter (higher water tables) than salt flats and wet meadows. We have medium confidence in this assessment given unmeasured temporal variance in DTW and only a single sample per site. However we are confident that our baselines will be useful for understanding changes over time given high quality design, data, and modeling.	
Continuous depth to water, Big Spring Creek (2010–2014 trend)	We have logged DTW hourly at two sentinel sites (wells 202 and 203) on Big Spring Creek since 2010. Groundwater depth at one of these sites significantly increased each year from 2010 to 2014, with the model accounting for daily and yearly patterns. This site's hydrologic regime is driven almost entirely by Big Spring Creek. Impacts from a drought began to lessen in 2010, and while more data are needed given that the site's hydrology is largely buffered by the creek, the improving trend (increasing water table) may reflect this. The other Big Spring Creek site had a more variable hydrologic regime with no clear pattern. This well was further from the creek and thus more influenced by variable precipitation and groundwater flows. We have medium confidence in this assessment given a relatively short period of record. However we are confident that our baselines will be useful for understanding changes over time given high quality design, data, and modeling.	
Continuous depth to water, Elk Springs (2010–2014 trend)	We also logged DTW hourly at two sentinel sites (wells 204 and 207) at Elk Springs since 2010. Groundwater depth at both sites significantly decreased each year from 2010 to 2014. Elk Springs' hydrologic regimes are nearly entirely driven by groundwater flows likely originating from several diffuse sources, especially a large groundwater mound between Sand Creek and the site. Unlike on Big Spring Creek, there is no perennial spring-fed channel that stabilizes the hydrology of the site. The sandsheet area at the park has been under drought conditions since at least 2010. While the drought began to wane in 2014, groundwater depths likely were reduced or even still dropping over 2010–2014 with a one to several year lag, perhaps explaining the decreasing trend (dropping water tables) in DTW at the site. We have medium confidence in this assessment given a relatively short period of record. However we are confident that our baselines will be useful for understanding changes over time given high quality design, data, and modeling.	

Table 30. Summary of peak season depth to water (DTW) (cm from ground surface) at Great Sand Dunes National Park and Preserve in 2010. The "All sites" category includes all sandsheet and high elevation fen and wet meadow sites. Values in bold are the highest and lowest mean, minimum, and maximum values for each metric across all subcategories. LCB/UCB are lower and upper 95% confidence interval boundaries, respectively. Standard error is for the mean. Source data are limited to the best sample events in 2010.

Site type	Wetland type	N	Mean DTW (cm)	LCB	UCB	Min	Max	Std. dev.	Std. error
All sites	Salt flat	19	**-102.3**	-124.1	-80.6	**-203.1**	-28.4	45.0	10.3
	Wet meadow	43	-84.8	-96.8	-72.8	-163.8	**8.0**	39.1	6.0
	Riparian	4	**-10.4**	-30.9	10.1	-27.5	3.4	12.9	6.4
	Marsh	9	-49.0	-77.0	-21.0	-100.2	-6.1	36.4	12.1
	Fen	7	-14.8	-39.3	9.6	-74.0	2.1	26.5	10.0
	All types	82	-75.3	-85.8	-64.9	-203.1	8.0	47.5	5.2
Sandsheet sites	Salt flat	19	**-102.3**	-124.1	-80.6	**-203.1**	-28.4	45.0	10.3
	Wet meadow	42	-85.9	-98.0	-73.8	-163.8	**8.0**	38.8	6.0
	Riparian	4	**-10.4**	-30.9	10.1	-27.5	3.4	12.9	6.4
	Marsh	9	-49.0	-77.0	-21.0	-100.2	-6.1	36.4	12.1
	All types	74	-81.6	-92.0	-71.1	-203.1	8.0	45.1	5.2

Note: Positive DTW values indicate a water table above the soil surface.

Table 31. Summary statistics and application of assessment points to population scale peak season depth to water (DTW) at all salt flat–wet meadow sandsheet wetlands at Great Sand Dunes National Park and Preserve in 2010. Assessment points are set following EPA (in review) and Stoddard et al. (2008). LCB/UCB are lower and upper 95% confidence interval boundaries around the population mean, respectively.

						Assessment points		Percentage in class		
Parameter	N	Mean	SE	LCB	UCB	>50th	<25th)	>50th	25–50th	<25th
DTW, peak season	46	-99.4	4.1	-107.5	-91.3	<-99.4	>-119.6	49	26	25

Notes: For responses that decrease with decreasing condition, as we assume for DTW following Stoddard et al. (2008), we use the >50th and <25th percentile values to define or bound the minor and major disturbance classes (respectively). SE = standard error for the mean.

time periods, would likely lead to a switch in the site's wetland type (i.e., many wet meadow sites might become marshes). We do not have sufficient data to estimate this threshold and there is little research on this. Nevertheless we do not think that any salty meadow sites on the GRSA sandsheet are currently at risk for this sort of state transition due to very high water tables. These data help us estimate baseline DTW values, develop more meaningful, true ecological assessment points, and/or work with the park to define relevant assessment points for these parameters and wetland management. We illustrate the proportion of wetland area in each class with a pie chart embedded in Figure 37. While visually useful, a pie chart does not show the confidence interval around the proportion of wetland in each class, as in the cumulative distribution, and should be used with caution.

3.7.3.2 Exploratory models of peak season groundwater depth

Next, we present exploratory models that quantify relationships between peak season DTW and select attributes of wetlands. Models were initiated with 46 potential environmental and disturbance covariates. We chose the initial independent variables based on statistical attributes (i.e., measures that had strong univariate correlation with DTW), those that might have the most utility for wetland resource management in GRSA, and those that our collective experience suggested might assist in our interpretation of DTW.

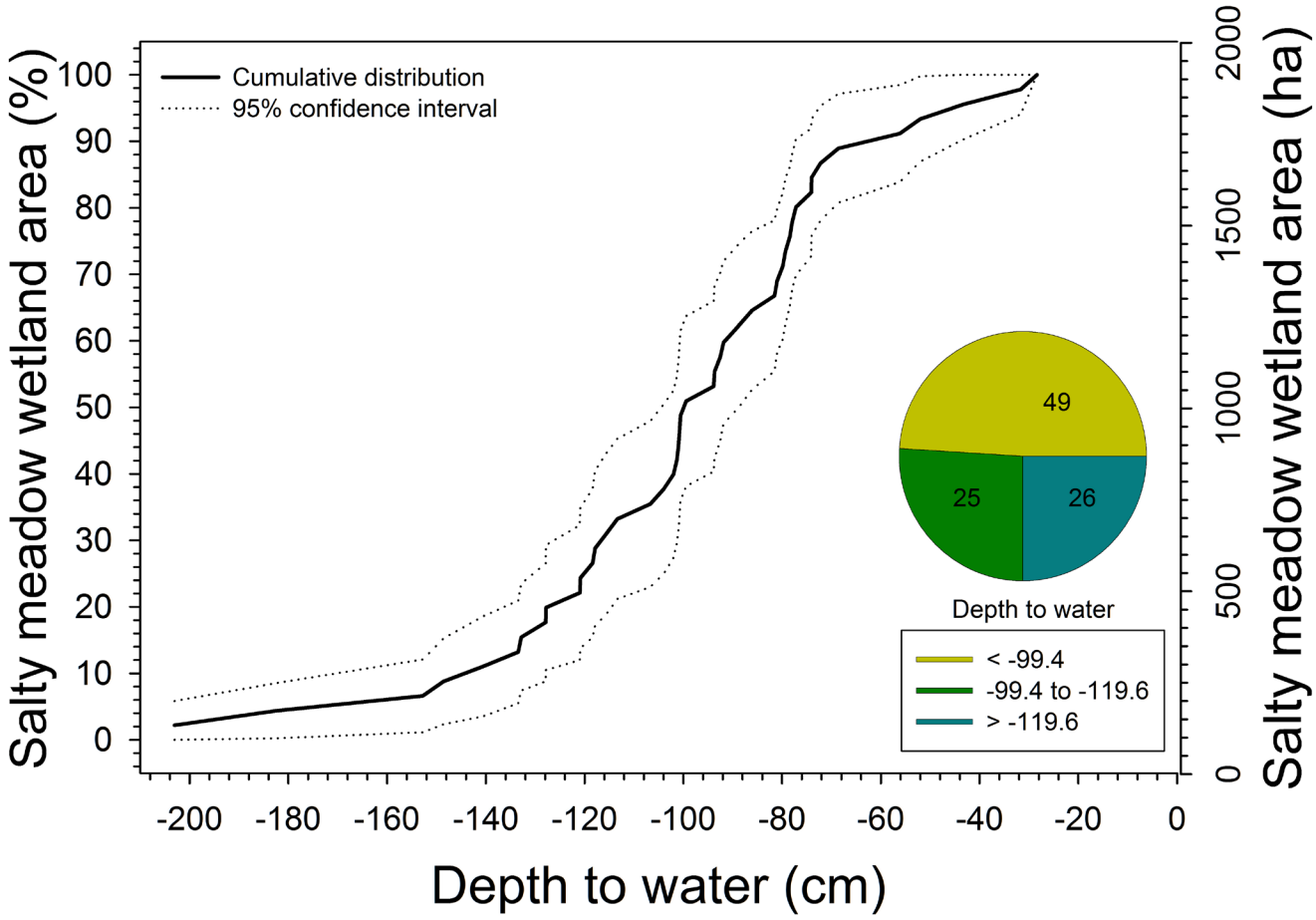


Figure 37. Cumulative distribution function of depth to water for the population of salt flat and meadow sandsheet wetlands at Great Sand Dunes National Park and Preserve in 2010.The left y-axis gives the percent of salty meadow wetlands on the sandsheet and the right y-axis shows the actual estimated area of wetland. The 95% confidence interval (dotted lines) around the percent values (heavy line) is also shown. Pie chart shows the percentage of the total area in classes derived from ecoregional reference sites as blue (>50th percentile or deeper water tables), teal green (50th to 25th percentile), and ochre (<25th percentile or shallower water tables). Pie charts do not include the confidence for each estimate so they should be used with caution.

The final model of peak season DTW in 2010 included 10 predictors or covariates (Table 32). It was highly significant ($p < 5.394e-16$) and had an adjusted R2 of 0.75, indicating most of the variation in DTW was accounted for. The complete model is presented in Appendix G. We focus our interpretation on variables in the model that either had the highest relative importance, lowest p values, and/or interesting relationships as drivers or covariates of DTW. We use conditional plots of partial residuals (Figure 38) to visualize the model (Larsen and McCleary 1972; Breheny and Burchett 2013).

Just over 20% of the variation in DTW was explained by total monsoon precipitation in the three years prior to our sample events (July 1–October 1, 2008–2010; Table 32). We included precipitation in order to capture some of the lag effect in the movement of precipitation via surface water to the shallow aquifers that support salty meadows on the sandsheet. Several potential outlier wet meadow sites on the toe slope of the Sangre de Cristo Mountains appear to drive the pattern. However, with these removed from the model, the relationship is still strong and positive, suggesting that even with the more subdued variation in monsoon precipitation at sites further west on the sandsheet, this metric was important in driving peak season DTW.

The concentration of Manganese (Mn) was strongly positively associated with wetter sites (higher water tables), explaining about 18% of the total variation (Table 32). Elevated Mn does not cause higher water tables; rather, wetter sites have

Table 32. Exploratory model of peak season depth to water (DTW) at Great Sand Dunes National Park and Preserve in 2010. Final model selected using Akaike Information Criterion (AIC) and expert opinion from 46 candidate variables. Relative importance (Rel. Imp.) is the total amount of explained variance for each variable expressed as a proportion. Wetland is treated as a factor and all estimates are relative to marsh. *Wetland type's relative importance value is for all groups combined. SE = standard error of coefficient, t = t test value, p = probability of the t.

Model component	Estimate	SE	t	p	Relative importance
(Intercept)	-296.600	33.290	-8.911	0.000	–
Wetland type	–	–	–	–	*0.293
Wet meadow	-62.870	10.020	-6.275	0.000	–
Riparian	14.250	14.710	0.969	0.337	–
Salt flat	-28.340	11.850	-2.392	0.020	–
Elk Index	0.555	0.150	3.702	0.000	0.022
Productivity (lbs/acre)	0.032	0.012	2.723	0.009	0.021
Total monsoon 2008 to 2010 precipitation (cm)	1.195	0.179	6.659	0.000	0.217
Human hydrologic alteration	-0.377	0.078	-4.837	0.000	0.060
Distance to human feature (m)	0.022	0.007	3.314	0.002	0.024
N deposition (kg/m/year)	24.930	7.976	3.126	0.003	0.068
Manganese (mg/kg, log)	67.440	12.650	5.329	0.000	0.182
Magnesium (mg/kg)	-0.071	0.024	-2.949	0.005	0.021
Soil specific conductance (µS/cm, log)	-57.320	14.250	-4.021	0.000	0.091

Notes: Residual standard error: 22.33 on 59 degrees of freedom, Multiple R^2: 0.79, Adjusted R^2: 0.75, F-statistic: 19 on 12 and 59 DF, p value: 5.394e-16.

more anoxic soils, which alter redox conditions and increase the concentration of Mn in soil. This can matter as excessive Mn has adverse effects on plant growth and may be toxic to some species (Zaidi 2006). High Mn concentrations can also suppress microbial processes that regulate organic matter decomposition. Additional work is needed to confirm if the concentration of Mn in wetter GRSA sites is problematic but, in general, mean concentrations of Mn seen at most sites (5.16 mg/kg) are well below values seen in more developed areas (Zaidi 2006).

The degree of human hydrologic alteration in the wetland complex and its catchment was also highly significant in predicting peak season DTW, with greater degrees of alteration lowering water tables (Figure 38). This pattern plays an important role in the bioassessment models presented in section 3.8 below, where DTW covaries with important vegetation metrics that influence overall estimates of integrity.

Finally, wetland type was significant, with riparian and marsh sites wetter than salt flats and wet meadows (but as noted we have small samples of riparian and marsh; Figure 38). Hydrologic regime is central to how wetlands are classified—it is unsurprising, therefore, that almost 30% of the variation in DTW was due to wetland type.

3.7.3.3 Trend in groundwater hydrology at select sites: 2010–2014

Next we present trend models for DTW (averaged to daily values) at four sentinel sites from 2010 to 2014. These models are complex in their structure—see Appendix C for methodological details. Given only five years of data and incomplete beginning and ending seasons due to the timing of logger downloads, we could only statistically account for random variation in day of year. Therefore, our models test for a linear trend across years, controlling for within year pattern at the daily scale. We examined models for authocorrelation in DTW and adjusted model details as our relatively limited data would allow—controlling for linear dependence (serial correlation) for a given data point from only the preceding day. Neverthess this captured most of the temporal structure in our DTW data. We also compared autocorrelation when models included all data at a site as a whole (all five years) to models restricted to within each year. Results suggested that separate corrections for serial correlation within year were better. Detailed results for these preliminary modeling steps are available upon request.

3.7.3.3.1 Site 202 Big Spring Lower

Site 202 lies approximately 7.2 km upstream of, or north of, the main Medano Ranch house. The well is located in an

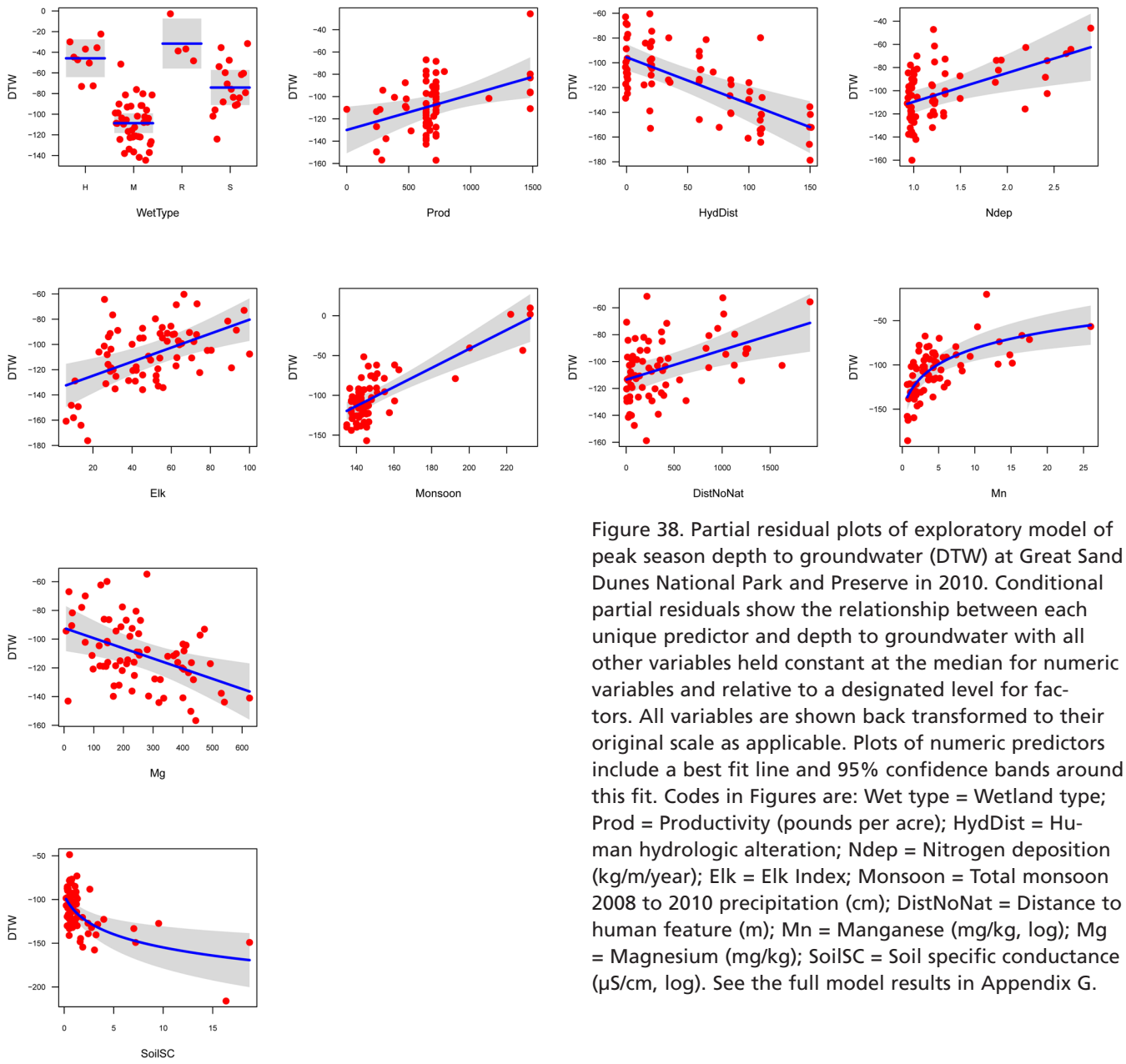


Figure 38. Partial residual plots of exploratory model of peak season depth to groundwater (DTW) at Great Sand Dunes National Park and Preserve in 2010. Conditional partial residuals show the relationship between each unique predictor and depth to groundwater with all other variables held constant at the median for numeric variables and relative to a designated level for factors. All variables are shown back transformed to their original scale as applicable. Plots of numeric predictors include a best fit line and 95% confidence bands around this fit. Codes in Figures are: Wet type = Wetland type; Prod = Productivity (pounds per acre); HydDist = Human hydrologic alteration; Ndep = Nitrogen deposition (kg/m/year); Elk = Elk Index; Monsoon = Total monsoon 2008 to 2010 precipitation (cm); DistNoNat = Distance to human feature (m); Mn = Manganese (mg/kg, log); Mg = Magnesium (mg/kg); SoilSC = Soil specific conductance (µS/cm, log). See the full model results in Appendix G.

oxbow 5 m from the Big Spring Creek channel (Figure 39), just upstream from a Colorado Division of Water Resources flume. The area around the site receives heavy bison and elk use, although the site itself is inside an exclosure.

Groundwater depth at site 202 significantly increased (the water table grew higher) each year from 2010 to 2014. The slope of this increase was 3.4, with a p value less than 0.0001 and an R2 = 0.94. Day or year was also highly significant. Patterns within each year were consistent with a later summer increase in DTW. In most years the site is saturated during the entire snow free period, often with a water table well above ground (Figure 40, and see an example hydrograph in Figure 41). Of our four logged sites, site 202 is consistently the wettest.

The site's hydrologic regime is driven almost entirely by Big Spring Creek, although there is some suggestion of a short term response to precipitation events (Figure 41). In general, with the exception of a 2011 flood, Big Spring Creek has a stable summer discharge across years given its spring (Big Spring) source and this is reflected in relatively



Figure 39. Oblique aerial view of site 202 on Big Spring Creek in Great Sand Dunes National Park and Preserve. Well is immediately adjacent to the channel. Background imagery is from the National Agricultural Imagery Program.

stable groundwater table elevations. Impacts from drought have largely been buffered by the creek. The reason for the increasing trend over the last 5 years at this site is not clear and will need more data to resolve (pers. comm. A. Valdez, GRSA).

3.7.3.3.2 Site 203 Big Spring Creek Upper

Site 203 lies approximately 0.8 km upstream of site 202. The well is located 25 m from the Big Spring Creek channel (Figure 42). The area around the site receives heavy bison and elk use, although like our well at site 202, the well itself is inside an exclosure.

There was no trend in groundwater depth at site 203 from 2010 to 2014 (Figure 40). The model explained only 26% of the variation in DTW. In most years there was significant variation in DTW over the summer period, with near saturated conditions at the beginning and end of the snow free period (Figure 40, and see an example hydrograph in Figure 43). Patterns across years were not consistent, with 2012 the driest, 2010 the next driest, followed by 2011 or 2013 (depending on time of season), and early 2014 the wettest. The timing of the relatively strong monsoon effect at the site also varied and was preceded by very large differences in the magnitude of a mid-summer drawdown, with an especially large drawdown in 2012. There was some consistency in day 120–150 values each year, suggesting that patterns across year developed as DTW trajectories shifted as the summer

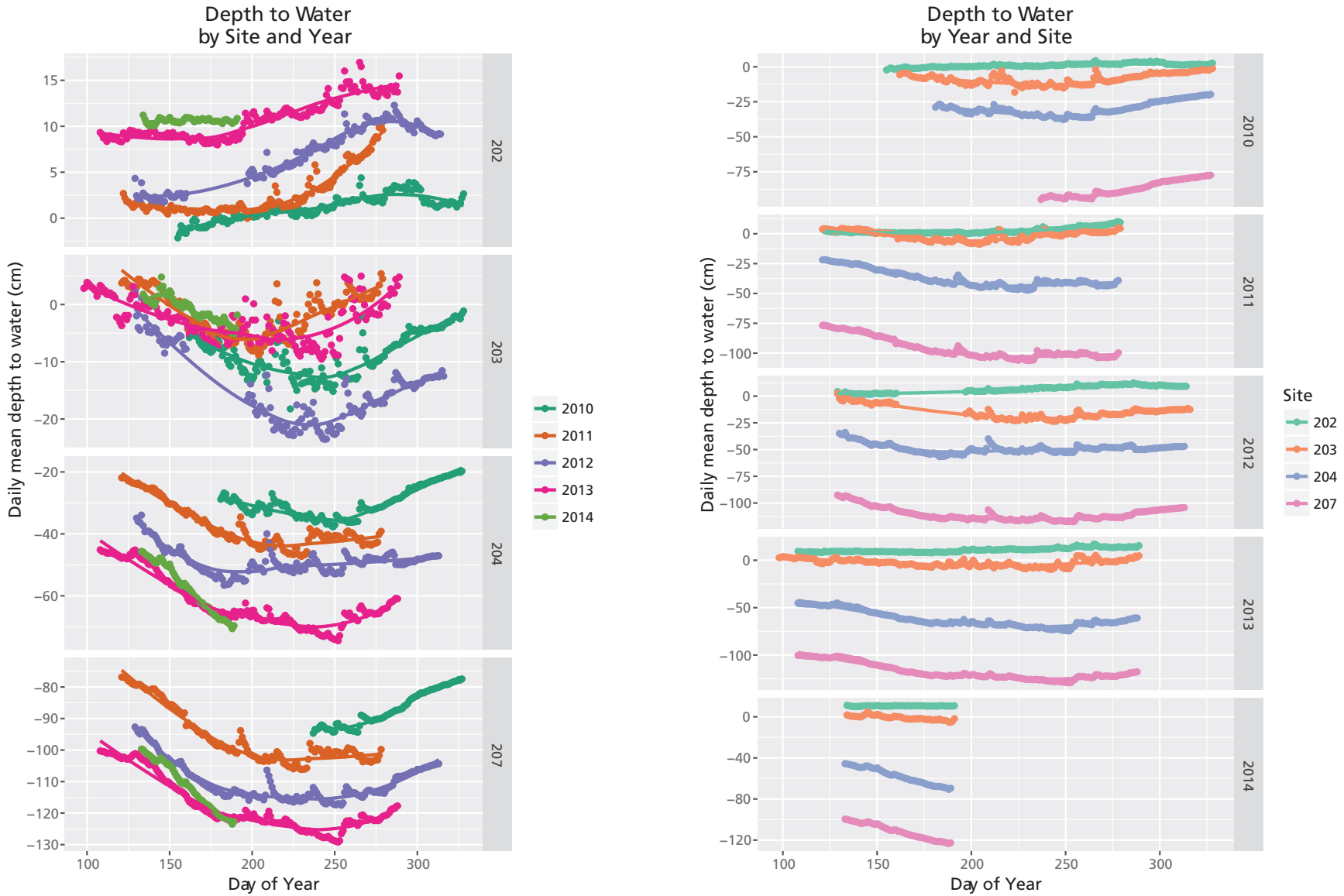


Figure 40. Daily mean depth to water at four Great Sand Dunes National Park and Preserve sentinel sites (202, 203, 204 and 207) from 2010 to 2014. Left panel by year, right panel by site. Data are restricted to snow free periods. Day of year is by year, with the first day on January 1. Note that due to the timing of logger installations and downloads, 2010 and 2014 are truncated.

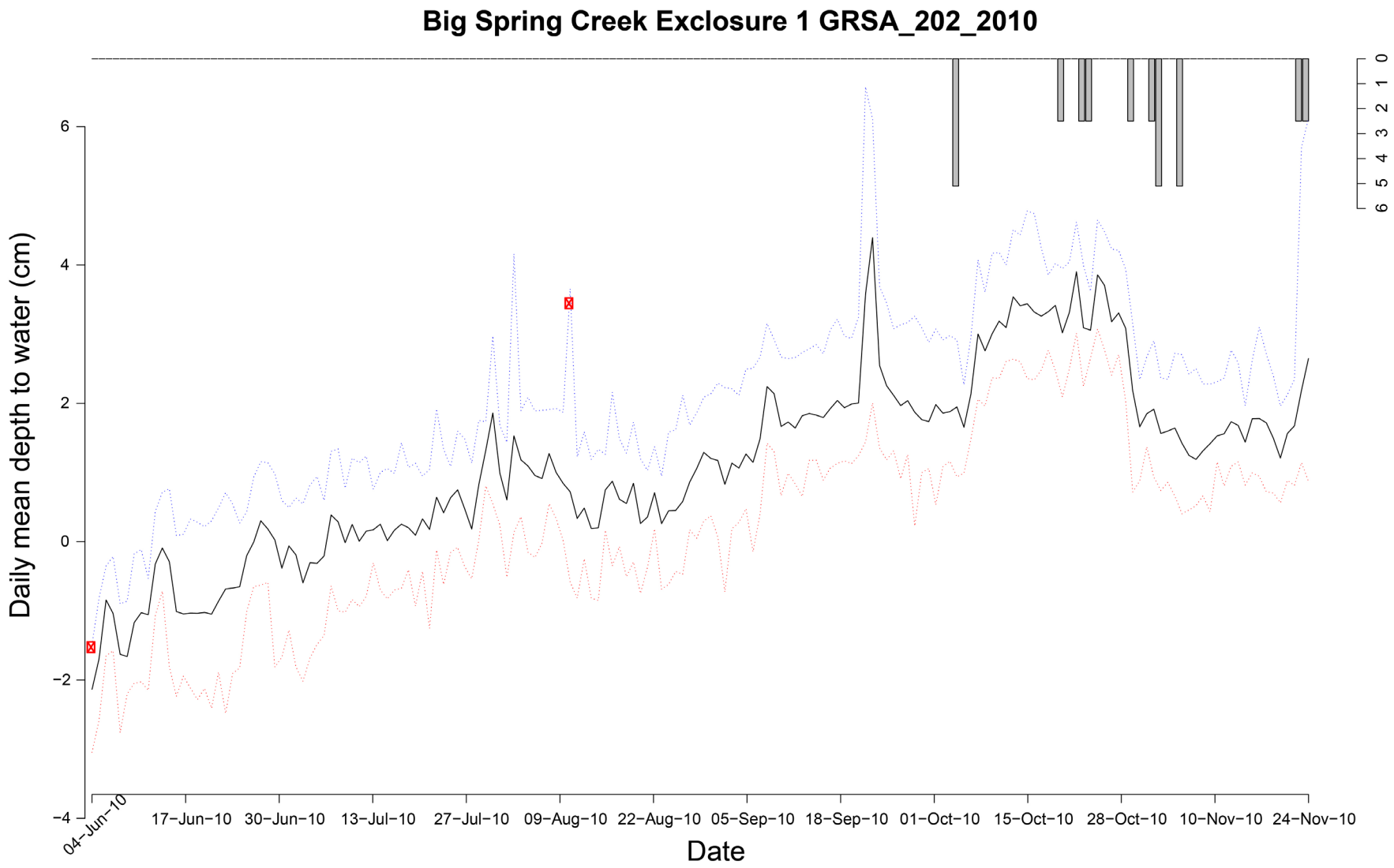


Figure 41. Example hydrograph with precipitation climogram for snow free period at site 202, Big Spring Creek, 2010, Great Sand Dunes National Park and Preserve. Ground elevation is at 0 on the y axis. Black line is the daily mean depth to water (cm relative to ground level, with negative values indicating a water table below ground), with blue and red lines the maxima and minima. Red dots are episodic hand readings. Climogram shows daily precipitation (cm), with higher values shown by longer bars. Note that due to the timing of logger installations, 2010 data started after snow melt-off. Hydrographs from other years are in Appendix I.



Figure 42. Oblique aerial view of site 203 on Big Spring Creek in Great Sand Dunes National Park and Preserve. Background imagery is from the National Agricultural Imagery Program.

progressed. Of our four logged sites, site 203 was consistently the second wettest (Figure 40).

In 2004, a series of synchronous discharge readings showed Big Spring Creek was a gaining system, with discharge increasing by a factor of 26 over about 4.8 river miles from its spring source through our site (Harte et al. 2007). These data are now old; however, there is little evidence that the gaining nature of the stream has changed over the years (pers. comm. A. Valdez, GRSA). The difference between site 202 and 203 may be explained by the difference in the degree the adjacent channel is influenced by the gain in discharge from the head to its terminus. Site 203 is higher in the drainage and experiences a drier and flashier influence from the creek. The site is also further from the channel and thus more influenced by episodic groundwater flows from the adjacent uplands and the creek's hyporheic zone (the zone beneath and adjacent to a streambed where shallow groundwater and surface water mixes). All of these factors may cause any given year to have a different trajectory in DTW and therefore no consistent trend across years.

3.7.3.3.3 Site 204 and 207 Elk Springs

Sites 204 and 207 are on the north and south sides of Elk Springs (Figure 44), an isolated marsh/wet meadow approximately 1.6 km north of the headwaters of Big Spring Creek and 3.2 km south of Sand Creek. Elk Springs is an important watering hole and foraging area for elk and bison.

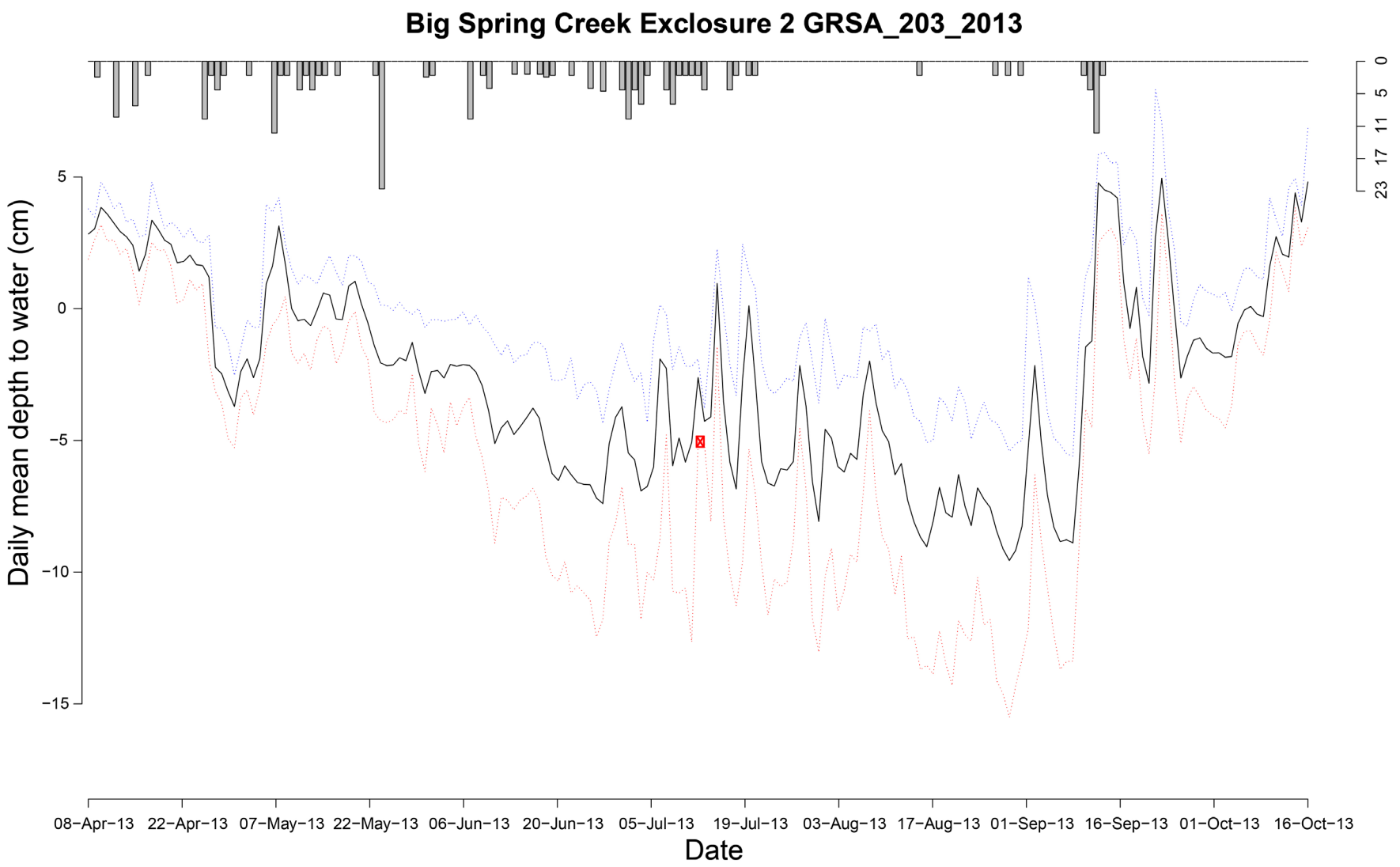


Figure 43. Example hydrograph with precipitation climogram for snow free period at site 203 Big Spring Creek, 2013, Great Sand Dunes National Park and Preserve. Ground elevation is at 0 on the y axis. Black line is the daily mean depth to water (cm relative to ground level, with negative values indicating a water table below ground), with blue and red lines the maxima and minima. Red dots are episodic hand readings. Climogram shows daily precipitation (cm), with higher values shown by longer bars. Hydrographs from other years are in Appendix I.

Groundwater depth at sites 204 and 207 significantly decreased (water tables lowered) each year from 2010 to 2014 (Figure 40, Figure 45, Figure 46). The slope of this decrease was –10.2 at 204 and –8.9 at 207. Both models had p values less than 0.0001 and R2 = 0.91. The DoY smooth terms were also highly significant. Hydrologic regimes at the two sites were very similar from 2010 to 2014. These two sites were the driest of the four we logged over this time period, with 204 the wetter of the pair.

Elk Springs hydrologic regimes are nearly entirely driven by groundwater flows likely originating from several diffuse sources, especially a large groundwater mound between Sand Creek and the site (pers. comm. A. Valdez, GRSA). Unlike on Big Spring Creek, there is no perennial spring-fed channel that stabilizes the hydrology of the site. The sandsheet area at GRSA has been under drought conditions since at least 2010 (see Climate context section 3.2 above, Figure 14, and Tsakiris et al. 2007) and has been in a longer term dry period over at least two decades (Wurster et al. 2003). The drought began to wane in 2014 (pers. comm. A. Valdez, GRSA) but groundwater depths likely were reduced or even still dropping over 2010–2014, with a one to several year lag. This perhaps explains the decreasing trend in DTW at the site. When we analyze data from 2015 and on, it will be interesting to see if the sites' hydrology has recovered.



Figure 44. Oblique aerial view of Site 204 and 207 in Elk Springs at Great Sand Dunes National Park and Preserve. Background imagery is from the National Agricultural Imagery Program.

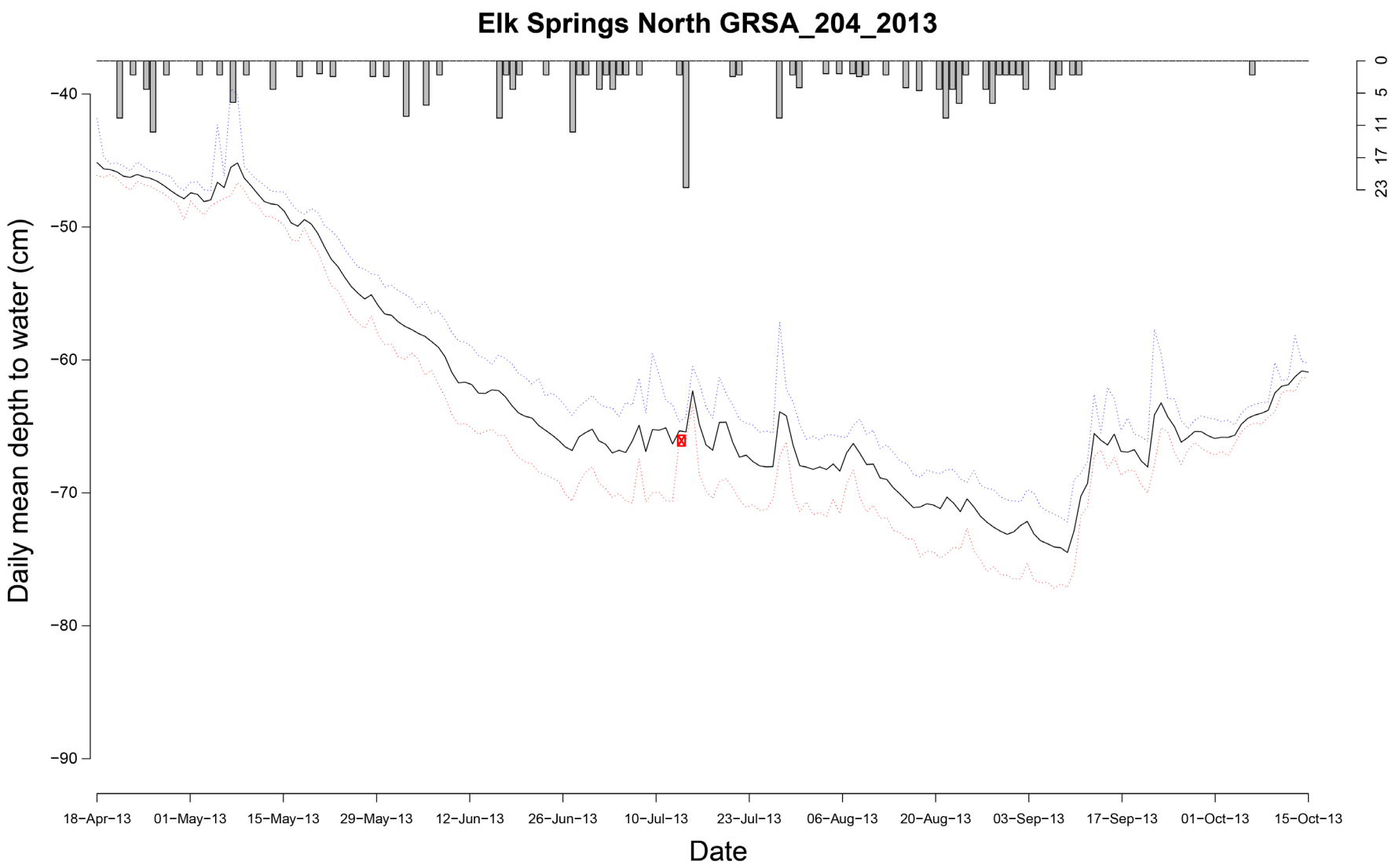


Figure 45. Example hydrograph with precipitation climogram for snow free period at site 204 Elk Springs, 2013, Great Sand Dunes National Park and Preserve. Ground elevation is at 0 on the y axis. Black line is the daily mean depth to water (cm relative to ground level, with negative values indicating a water table below ground), with blue and red lines the maxima and minima. Red dots are episodic hand readings. Climogram shows daily precipitation (cm), with higher values shown by longer bars. Hydrographs from other years are in Appendix I.

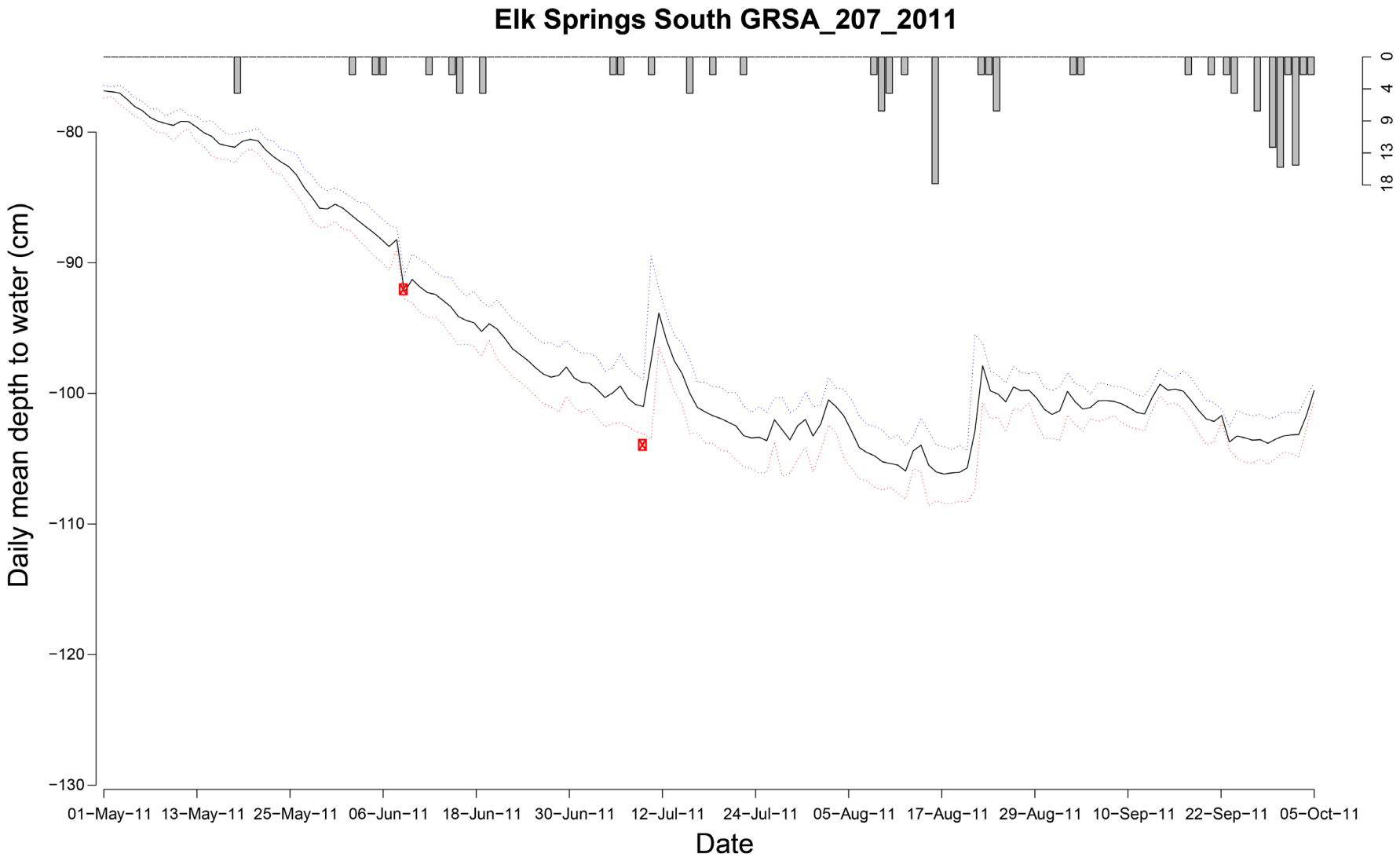


Figure 46. Example hydrograph with precipitation climogram site for snow free period at site 207 Elk Springs, 2011, Great Sand Dunes National Park and Preserve. Ground elevation is at 0 on the y axis. Black line is the daily mean depth to water (cm relative to ground level, with negative values indicating a water table below ground), with blue and red lines the maxima and minima. Red dots are episodic hand readings. Climogram shows daily precipitation (cm), with higher values shown by longer bars. Hydrographs from other years are in Appendix I.

3.8 Bioassessment of wetland ecological integrity

3.8.1 Summary condition

Our bioassessment approach is to develop two multimetric models of ecological integrity that integrate how the GRSA vegetation community responds to different kinds of disturbance. In general, the ecological integrity of GRSA's sandsheet wetlands is an area of concern. In 2010, very few of the wetlands were in a pristine reference state when assessed relative to total disturbance. When only an ungulate disturbance gradient was modeled, slightly more of the salty meadows on the sandsheet were in pristine reference. Importantly, at least at select sentinel sites on the sandsheet, ecological integrity did improve from 2010 to 2014, matching a decrease in our estimates of human disturbance at these sites. The reason(s) behind the improvement are unclear as we know of no change in wetland management by the park over this time frame at these sites—more work is needed on this. Table 33 presents a summary condition of our bioassessment results. See the Executive Summary for a summary condition table that includes all indicators of wetland condition.

3.8.2 Overview

The majority of the results presented to this point in this report are in support of our estimation of the ecological integrity of the park's wetlands. Here we present direct estimates of this using wetland vegetation community composition as our primary indicator. Vegetation is a major component of the biodiversity found in wetlands. It provides habitat for a broad range of other species. Community composition reflects, as well as influences, hydrology, water chemistry, and soil properties of wetlands. We develop bioassessment models that relate wetland vegetation community structure to wetland ecological integrity. These models take advantage of vegetation's ability to integrate different wetland processes and the response of plants to human disturbances at multiple temporal and spatial scales (Rocchio 2007 a, b; Mack 2007; Matthews et al. 2015). Patterns in wetland vegetation community structure are important as they help determine what variables might best inform bioassessment models, for example, as how key variables like wetland type relate to ecological integrity.

3.8.2.1 Vegetation community overview

Across all events from 2010 to 2014, we recorded 228 plant species. Of these, 212 were vascular and 20 nonvascular (Appendix J). An additional 40 taxa were identified to the family or genus level and 47 taxa remain unknown. Identifications not to species level were included in analyses only if we had confidence that the taxon was unique at the identified level across all samples in an analysis.

Over 604 vascular plant species have been identified in the park and preserve (Spackman-Panjabi 2004). Wetlands occupy approximately 4.7% of the area of the park based on the WEI sample frame. Therefore, WEI samples account for approximately 38% of the vascular plant taxa in the park in less than 5% of its area. As in many other landscapes, including Network parks (Schweiger et al. 2015), wetlands are important biodiversity hotspots.

Total taxa richness was 70 in fens and subalpine wet meadows, 53 in marshes, 55 in riparian wetlands, 26 in salt flats, and 130 in wet meadows on the sandsheet. Mean alpha diversity (or average taxa per plot) was 27.88 in fens and subalpine wet meadows, 13.56 in marshes, 19.33 in riparian meadows, 6.35 in salt flats, and 17.45 in wet meadows on the sandsheet. Finally, beta diversity (a measure of the proportion of the total contained in each site or the similarity of a site or set of sites to the total) was 2.5 in fens and subalpine wet meadows, 3.9 in marshes, 2.8 in riparian wetlands, 4.09 in salt flats, and 7.45 in wet meadows on the sandsheet.

Species richness by wetland type suggests that salt flats are the most species poor and wet meadows on the sandsheet are the most species rich. However, sample sizes in riparian wetlands, fens, subalpine wet meadows, and marshes are small and these results should be treated with caution. Salt flats and wet meadows on the sandsheet were sampled more intensively and most were part of the unbiased survey design. Thus, they likely provide a better representation of species richness. Low species richness and turnover in salt flats is not surprising as these wetlands can have harsh soil conditions and variable hydrology. They are therefore inhabited by specialist species such as halophytes. High species richness in wet meadows was also expected due to the broad range of physical conditions found in these wetlands.

3.8.2.2 Community structure in relation to key drivers

Ordination models were used to better understand patterns among key environmental variables and wetland vegetation structure. They provide conceptual support for the structure of the bioassessment models. Importantly, our sample of marshes, riparian wetland, and high elevation wetlands is small and may not be representative. Therefore extending patterns suggested by the ordinations to these wetland types should be done with caution. We have elected to limit the amount of statistical content presented here and we treat

Table 33. Summary condition table for ecological integrity at Great Sand Dunes National Park and Preserve in 2010 and at sentinel sites from 2010 to 2014. Key to the condition and confidence symbol: red, textured color = non-reference condition/major disturbance, yellow color = intermediate condition/moderate disturbance, dark green color = reference condition/minor disturbance, light green color = pristine reference condition/negligible disturbance, no color = unknown or indeterminate; upward arrow = condition is improving, sideways arrows = condition is unchanging, downward arrow = condition is deteriorating, no arrow = unknown trend; heavy border = high confidence, regular border = medium confidence, dashed border = low confidence. Figure 11 offers a visual key.

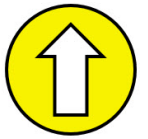
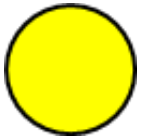
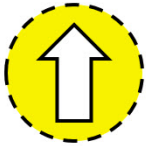
Bioassessment indicator	Condition description	Condition and confidence
Ecological Integrity Multimetric Index 1 —total disturbance (2010)	We used custom multimetric (MMI) models of wetland vegetation condition scaled to the sandsheet portion of the park for bioassessment of ecological integrity. Our first model (MMI 1) estimates the overall ecological condition of wetlands on the sandsheet in 2010 based on the response of multiple vegetation metrics to combined human disturbance and ungulate wetland habitat use. It indicated that aspects of wetlands, like non-conservative species cover, bare ground, and grass cover (mostly weedy annuals) increased with human disturbance and ungulate overuse. Conversely, woody cover, aster cover, and endemic richness decreased. Importantly, the overall model performed better at estimating the response to disturbance than any of its component metrics. The model accounted for natural drivers like precipitation and groundwater depth; thus, the pattern we see in ecological integrity is likely due to human disturbance and ungulate use and not the many variables that might also covary with wetland vegetation response. Given the integrated nature of the MMI modeling process, we consider these results our primary estimate of ecological integrity of the park's sandsheet wetland. Overall, the MMI 1 model revealed a strong response in wetland ecological integrity to human disturbance and ungulate use at GRSA. We used two approaches to setting assessment points for MMI 1. First, we apply a standardized method used by other agencies and scientists that defines reference and non-reference assessment points. These provide useful baselines for future assessments, but we currently lack the ability to assess them without more information. Second, we generated a likely more meaningful assessment point by predicting ecological integrity where there was no or zero measurable human disturbance and a sustainable level of ungulate habitat use. We label this a pristine reference condition. This corresponds to a "negligible impact" disturbance and use level. Applying this to the population of salty meadows on the sandsheet, only 1% of these wetlands likely had this level of ecological integrity in 2010. In general, lower MMI 1 estimates of integrity occur along the Big Spring Creek corridor and near ranching infrastructure inside the bison fence. This is thus an important area of concern for the park. We have high confidence in our assessment given an unbiased sample design, rigorous data collection and quality assurance and exploratory modeling we employ. While the standardized percentiles are arbitrary and thus should be used with some caution (they are best viewed as baselines for future assessment), the negligible disturbance assessment point is more interpretable and immediately useful for understanding status in 2010 and subsequent changes over time.	
Ecological Integrity Multimetric Index 1 —total disturbance (2010–2014 trend)	We have annual MMI 1 estimates at sentinel wetlands beginning in 2010. Trend models indicate increasing ecological integrity (roughly 4%) at the Big Spring Creek, Big Spring Creek Terminus, and Elks Springs sites through 2014. This matches a decreasing trend in human disturbance (although the reason(s) behind the improvement are unclear as there was no change in wetland management by the park over this time frame at these sites). Several sites moved from an intermediate to the reference condition class, with some even transitioning into pristine reference class. We have medium confidence in these results given important assumptions about scale and the short time frame used in the trend modeling. The data themselves are high quality given an unbiased sample design, rigorous data collection, and quality assurance.	

Table 33 (*continued*). Summary condition table for ecological integrity at Great Sand Dunes National Park and Preserve in 2010 and at sentinel sites from 2010 to 2014. Key to the condition and confidence symbol: red, textured color = non-reference condition/major disturbance, yellow color = intermediate condition/moderate disturbance, dark green color = reference condition/minor disturbance, light green color = pristine reference condition/negligible disturbance, no color = unknown or indeterminate; upward arrow = condition is improving, sideways arrows = condition is unchanging, downward arrow = condition is deteriorating, no arrow = unknown trend; heavy border = high confidence, regular border = medium confidence, dashed border = low confidence. Figure 11 offers a visual key.

Bioassessment indicator	Condition description	Condition and confidence
Ecological Integrity Multimetric Index 1 —ungulate use (2010)	Our second custom multimetric (MMI 2) model of wetland vegetation estimates the overall ecological condition of wetlands on the sandsheet in 2010 based on the response of multiple vegetation metrics to ungulate wetland habitat use alone. It indicated that aspects of wetland vegetation, like native forb and halophyte cover, increased with ungulate use. Conversely, woody and sedge cover decreased. Interestingly, and in contrast to the MMI 1 model, where combined human disturbance and ungulate use of wetlands is modeled, the MMI 2 model suggested that non-conservative (i.e., weedy) taxa decreased with ungulate overuse. This, perhaps along with increased native forbs, may suggest that the impact of ungulate overuse on wetlands had complex effects, with select aspects of wetland vegetation improving with more ungulate use. Nevertheless, the MMI 2 model revealed an overall strong response in wetland ecological integrity to ungulate (over)use at GRSA. Importantly, the overall model performed better at estimating the response to disturbance than any of its component metrics. The model also accounted for natural drivers, like precipitation and groundwater depth; thus, the pattern we see in ecological integrity is likely due to ungulate use and not the many variables that might also covary with wetland vegetation response. Given the integrated nature of the MMI modeling process, we consider these results our primary estimate of ecological integrity of the park's sandsheet wetlands response to ungulate use of wetlands. In general, spatial patterns in MMI 2 were similar to those in MMI 1. We used two approaches to setting assessment points for MMI 2. First, we apply a standardized method used by other agencies and scientists that defines reference and non-reference assessment points. These provide useful baselines for future assessments, but we currently lack the ability to assess them without more information. Second, we generated a likely more meaningful assessment point by predicting ecological integrity where there was a sustainable level of ungulate habitat use. We label this a pristine reference condition. This corresponds to a "negligible impact" use level. Applying this to the population of salty meadows on the sandsheet, 8% of these wetlands likely had this level of ecological integrity in 2010. This is thus an important area of concern for the park but perhaps slightly less so than the situation when human disturbance and ungulate use is modeled (MMI 1, see above). We have high confidence in our assessment given an unbiased sample design, rigorous data collection and quality assurance and exploratory modeling we employ. While the standardized percentiles are arbitrary and thus should be used with some caution (they are best viewed as baselines for future assessment), the negligible disturbance assessment point is more interpretable and immediately useful for understanding status in 2010 and subsequent changes over time.	
Ecological Integrity Multimetric Index 1 —ungulate use (2010–2014 trend)	We have annual MMI 2 estimates at sentinel wetlands beginning in 2010. Trend models indicate indicate increasing ecological integrity (roughly 2%) at the Big Spring Creek, Big Spring Creek Terminus, and Elks Springs sites. Severtal sites moved from intermediate to reference or reference to pristine reference conditionwithin each sentinel wetland. However, these increases in ecological integrity do not match the marginally increasing trend in ungulate use at these sites and requires more research to better understand. We have lower confidence in these results given the unresolved mismatch between MMI 2 and the Ungulate Use Index, assumptions about scale, and the short time frame used in the trend modeling.	

these models largely as a descriptive tool. Full details of each model are available upon request.

All sites

For all wetland sites (high elevation and sandsheet), we found a two dimensional solution with Principal Coordinates Analysis (PCoA), representing approximately 70% of the variability in vegetation composition (Figure 47). The model highlights the strong separation between sandsheet and subalpine sites, which is expected given the natural differences in these types of wetlands.

Sixteen environmental variables were significantly correlated with the first and second axes of the model. The first axis ("Dim1" in Figure 47) is positively associated with "high elevation mountain attributes" such as higher precipitation,

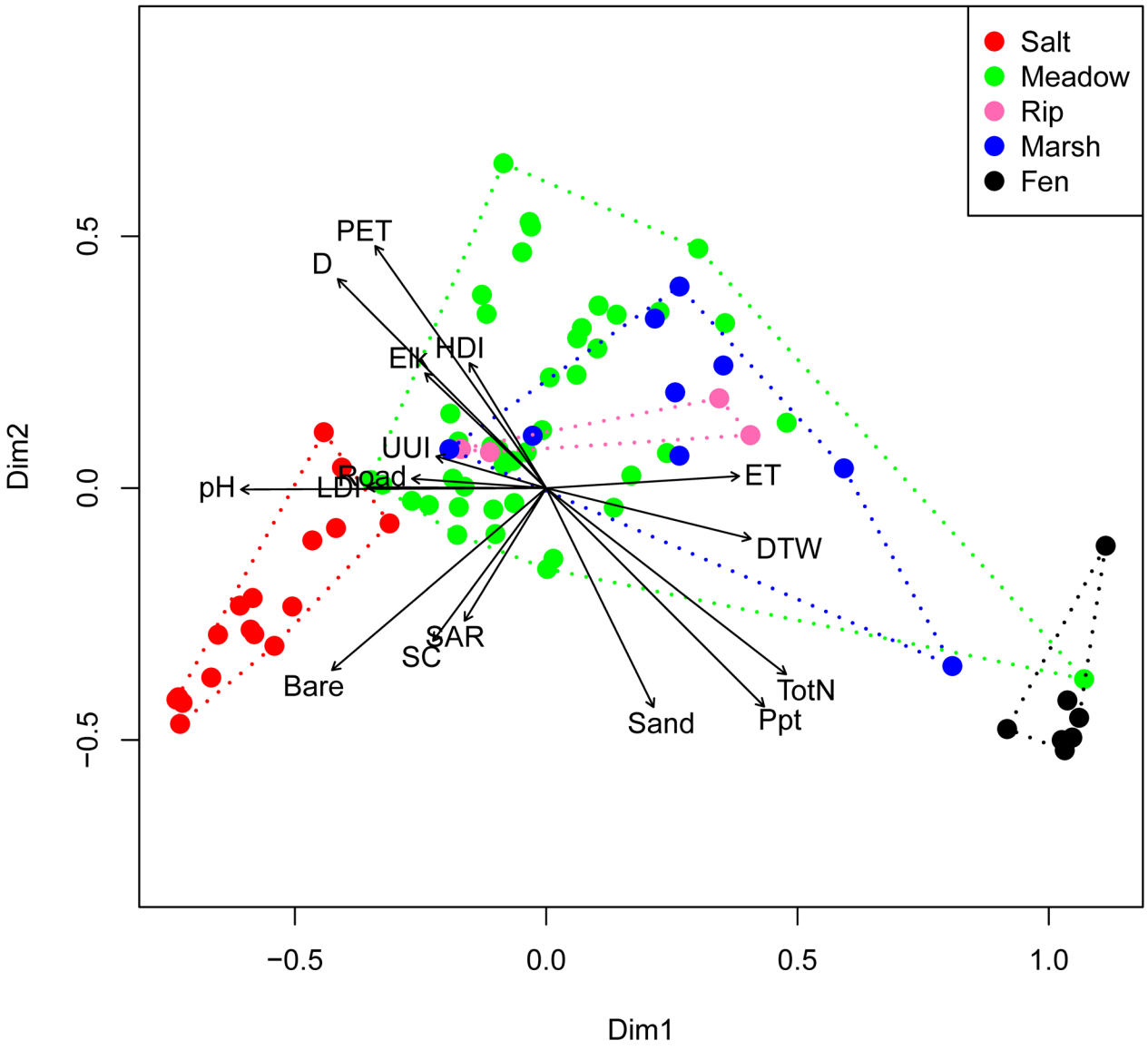


Figure 47. Principal Coordinates Analysis (PCoA) ordination of all wetlands (sandsheet and high elevation sites) in Great Sand Dunes National Park and Preserve. Vectors show important environmental covariates, with Bonferroni corrected p values less than 0.05. Polygons group sites by a priori wetland type. Dim1/2 are the first two PCoA axes. Codes are as follows: DTW = depth to water, HDI = Human Disturbance Index, Elk = Elk Index, UUI = Ungulate Use Index, Road = Road density (m/m2), Bare = bare ground (%),DTW = depth to water (cm), Sand = distance to sand (m), Ppt = 30 year mean precipitation (cm), SAR = sodium adsorption ratio, pH = pH , SC = specific conductance (µS/cm, log), TotN = total nitrogen (%, log), PET = potential evapotranspiration, D = soil water deficit, ET = evapotranspiration. Legend: Rip = riparian, Salt = salt flat.

organic soil chemistry (e.g., percent nitrogen), and high water tables, as well as total evapotranspiration. Axis 1 is negatively associated with road density, basic soil pH, bare ground, LDI and UUI. Almost all sites on the positive end of this gradient were high elevation fens and wet meadows (although some low elevation wet marshes did have a stronger association with this axis). Nearly all salt flats were grouped on the negative side of axis 1. The second axis ("Dim2" in Figure 47) is positively associated with potential evapotranspiration, soil water deficit, HDI, UUI and the Elk Index. It was negatively associated with soil conductivity, soil SAR, and distance from the nearest sand dune. Sites on the positive end of axis 2 were mostly low elevation wet meadows in areas with extensive human and ungulate disturbance. Sites on the negative end of his axis were largely salt flats with saline soils and less human ad ungulate disturbances.

This model (unsurprisingly) suggests that there are distinct differences between the high elevation and sandsheet wetlands in GRSA. Montane wetland habitats support intact, seasonally saturated, minerotrophic fens and wet meadows with dense vegetation cover and deep peat soils. These sites received low HDI and UUI scores due to limited human impacts, no bison, and more distributed elk usage. Soil variables, including the macronutrients, nitrogen and carbon, and the micronutrients, iron, zinc, and copper are higher in montane wetlands and lower in sandsheet wetlands. High carbon and nitrogen reflect higher organic matter, and micronutrients are likely being precipitated out in the high pH conditions of sandsheet wetlands and may be much lower in these sites. Sandsheet sites supported a broad range of disturbance regimes, with many highly disturbed sites (HDI at its maximum value of 100). Disturbed sites in general had much deeper and more seasonally variable water tables, as well as a broad range of soil conditions and vegetation metrics.

Sandsheet sites

In order to assess plant species composition in wetlands located below the Pinyon Pine/Juniper zone, we performed an additional ordination including only sandsheet wetlands. The ordination of high and low elevation sites (above) is largely influenced by the extreme variability in vegetation composition between fens/subalpine wet meadows and sandsheet wetlands. It provides a general description of the differences between mountain and valley wetlands in the park, but not the gradients driving mountain wetlands and sandsheet wetlands themselves.

The sandsheet ordination resulted in a two dimensional solution that represented approximately 62% of the variance in the distance matrix, with 14 significant environmental gradients (Figure 48). Overall, similar patterns appear in the all sites (above) and sandsheet site models for the dominant ordination axis ("Dim1" in Figure 48), suggesting that several environmental gradients occur at GRSA that were somewhat independent of the dominant topographic feature of the park—elevation. Strong positive correlations of environmental variables with the first axis ("Dim1" in Figure 48) included high potential evapotranspiration, organic soils (high percent nitrogen), and elevated groundwater tables—similar to the all sites ordination. Likewise, road density, soil conductivity, pH, and bare ground cover were associated with the negative end of axis 1. However, because this model did not include high elevation fens, the sites on the positive end of axis 1 were not fens, rather they were wet meadows and marshes closer to the toe slope of the mountain front. Sites on the negative end of this axis were salt flats with deep water tables and saline soils. Environmental variables positively associated with axis 2 included high soil water deficit, distance to the nearest sand, and marginally, peat thickness, although many variables also have some degree of correlation with axis 1. Variables negatively associated with axis 2 included precipitation and the Bison Index. In some ways, axis 2 in the sandsheet model is the inverse of axis 2 in the all sites model. Sites on the positive side of axis 2 included salt flats close to sand dunes with less bison usage. Sites on the negative end of axis 2 included wet meadows with higher precipitation and levels of bison use.

3.8.3 Bioassessment: results and interpretation of ecological integrity

In the following sections we present results from and interpretation of multimetric models of ecological integrity for sandsheet wetlands. We first present a brief summary of the potential component metrics evaluated for use in MMI models, followed by the MMIs themselves. We apply the GRSA assessment strategy to these results. Finally, we present trends in ecological integrity via the MMI results at sandsheet sentinel sites. Recall that the detailed summaries for the methods behind our bioassessment modeling are in Appendix C.

The response in ecological integrity to human and other disturbances at high elevation wetlands sites in GRSA is likely quite different from how wetlands respond on the sandsheet. Our classification and ordination results suggest different drivers influence vegetation communities in these areas. We lack sufficient samples to estimate custom models for high elevation wetlands at GRSA. We will explore application of

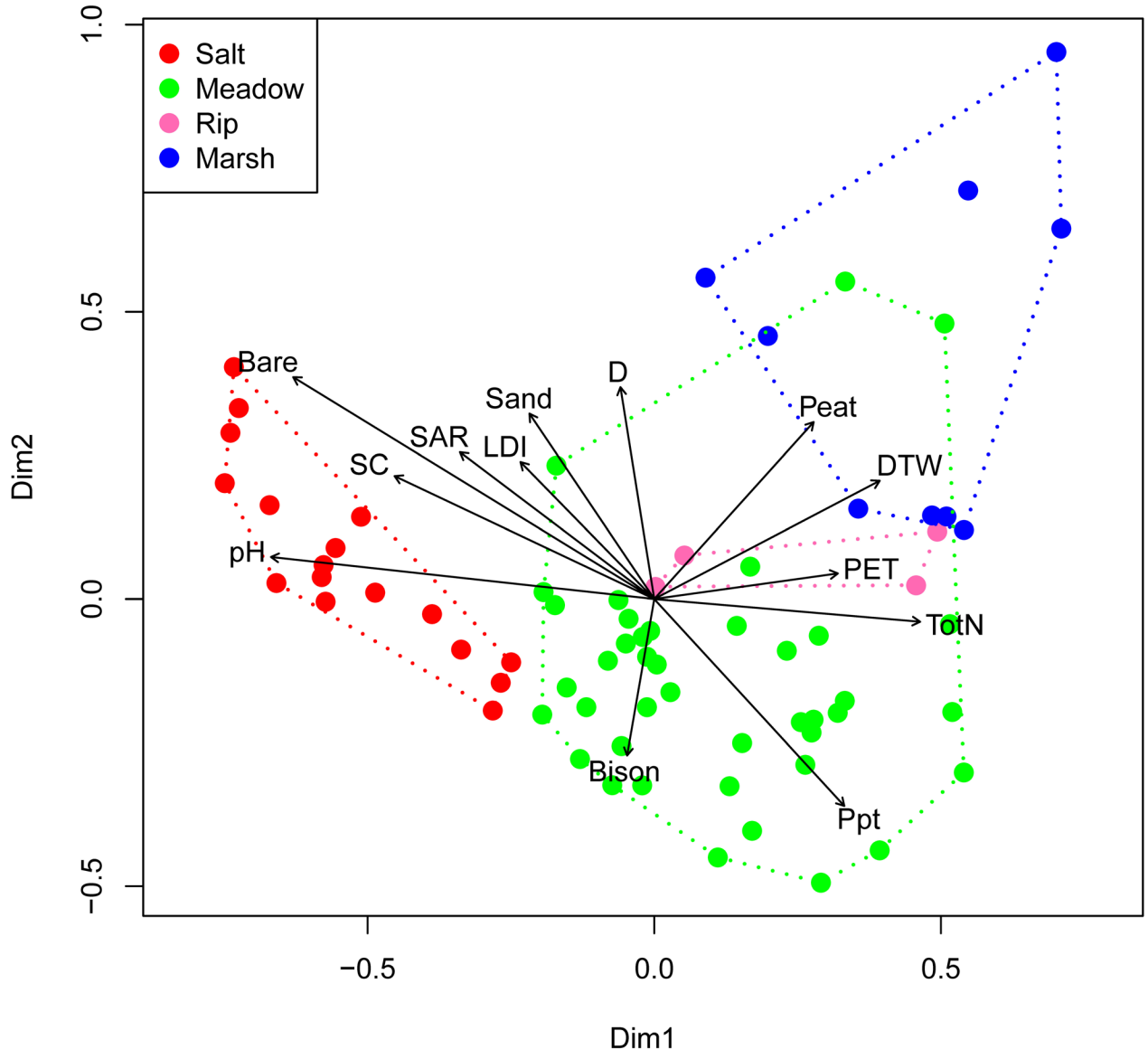


Figure 48. Principal Coordinates Analysis (PCoA) ordination of all sandsheet wetlands at Great Sand Dunes National Park and Preserve. Vectors show important environmental covariates with Bonferroni corrected p values less than 0.05. Polygons group sites by a priori wetland type. Dim1/2 are the first two PCoA axes. Codes are as follows: Bison = Bison Index, LDI = Landscape Disturbance Index, Bare = bare ground (%), DTW = depth to water (cm), Sand = distance to sand (m), Ppt = 30 year mean precipitation (cm), SAR = sodium adsorption ratio, pH = pH , Peat = depth of peat (cm), SC = specific conductance (µS/cm, log), TotN = total nitrogen (%, log), PET = potential evapotranspiration, D = soil water deficit. Legend: Rip = riparian, Salt = salt flat. Legend: Rip = riparian, Salt = salt flat.

models created for similar systems in ROMO (Schweiger et al. 2016), at the state scale (Rocchio 2007a, b), and regional scale models (EPA, in review) in future reports.

3.8.3.1 Multimetric Index 1: total disturbance

The conceptual model behind MMI 1 is shown in Figure 49. The model includes five covariates, each of which likely influences wetland vegetation but with little meaningful covariance with human disturbance. HDI may influence soil chemistry, including the soil conductivity metric we use. However, at GRSA our predictive models (see above) showed that almost 90% of the variation in soil conductivity was due to other chemical attributes of wetland soils. The small positive effect (with a relative importance of 6%) of human landuse on soil conductivity may lead to some loss of predictive power in the MMI, but given the strong

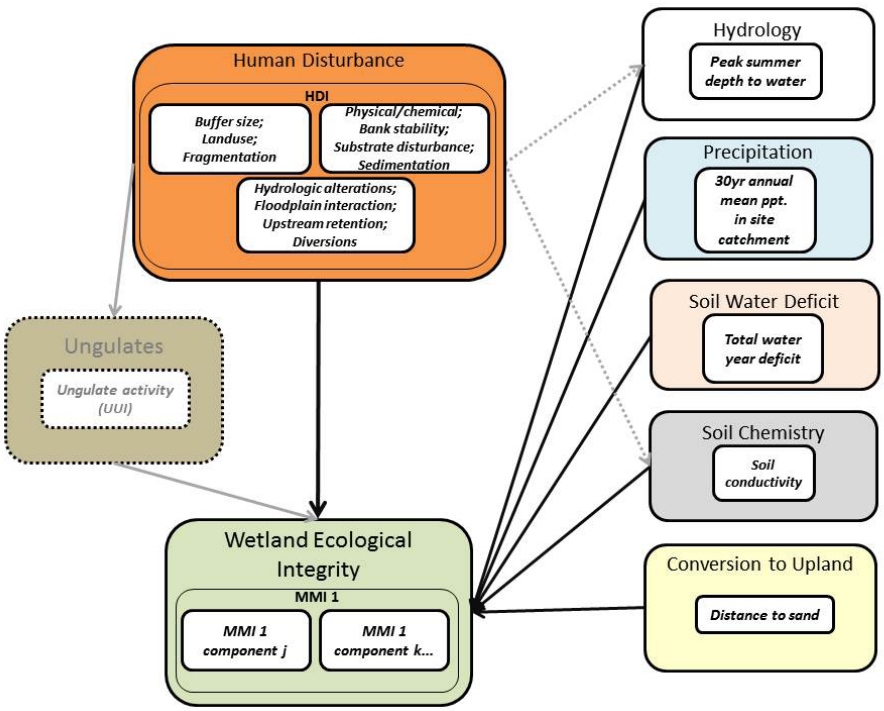


Figure 49. Conceptual model for Multimetric Index 1 (MMI 1). Covariates included in model are shown with solid boxes/arrows, with the assumed or demonstrated causal direction of a relationship indicated by the head of an arrow. Dotted arrows indicate possible causal connections that we assume play a minor role. The effect of ungulate use of wetland is shown within a dotted box to illustrate that this is nested within human disturbance. HDI = Human Disturbance Index, UUI = Ungulate Use Index.

influence of soil chemistry on vegetation, we felt this was an acceptable tradeoff. A similar logic applied to the possible effect of HDI on groundwater hydrology. Our predictive model of depth to water includes three indicators of human disturbance (hydrologic modification, atmospheric deposition of nitrogen, and distance to the closest anthropogenic feature) but not HDI itself. These three predictors had a total relative importance of around 15%. The effect of atmospheric deposition of nitrogen on depth to water is likely not causal and appeared in the predictive model purely as a covariate. Hydrologic modification (an important component of HDI) and distance to anthropogenic features may have causal connections to groundwater depth, and thus we may lose some signal by adjusting for them in the MMI. We felt this tradeoff was necessary given the strong role groundwater hydrology plays in wetland vegetation composition. The combined effect of HDI and UUI as used in MMI 1 is a "total disturbance," with some unknown degree of convolution between HDI and UUI. However, we plot and interpret MMI scores and component metric values against HDI alone.

The final MMI 1 was selected from two statistically equivalent models (similar correlation with total disturbance and similarly low AIC scores) based on a comparison of the interpretability of the component metrics. The selected model includes nine metrics (Table 34). This is a higher count of metrics than is expected or usually seen with the optimization of the metric count in our MMI approach. We suspect this is due to the diversity of wetland types and the complex disturbance gradient included in the model. The final MMI scores have a correlation with disturbance of -0.76, with an R^2 of 0.58 (Figure 50). The correlation between MMI and total disturbance is markedly stronger than any of the individual component metrics, confirming the statistical (and ecological) advantage and parsimony of an MMI. All metrics had at least one meaningful pattern with a covariate and adjustment improved the signal in nearly all cases (note that the sign of the bare ground–total disturbance correlation changed with adjustment). This strongly suggests that adjustment for these environmental gradients improved the model.

3.8.3.1.1 Application of assessment points

Predicted condition classes in the distribution of MMI 1 using negligible, minor, moderate, and major disturbance assessment points are given in Table 35 and shown graphically in Figure 50. We include 95% prediction intervals around these estimates in the table. A prediction interval accounts for both the uncertainty in knowing the value of the population mean, plus data scatter. They provide conservative estimates of each predicted assessment point in MMI 1, and GRSA resource management may choose to use these in place of the actual percentile based value.

One site (wet meadow 146 North of Deadman Creek, see Figure 50 and Appendix F, Figure F-2) was in a pristine reference condition even with a non-zero HDI score (it did have a

Table 34. Final component metrics of Multimetric Index 1 (MMI 1) for sandsheet wetland sites, Great Sand Dunes National Park and Preserve, 2010. Correlation with disturbance is given before and after scaling and adjustment by the five covariates listed. Intercept and coefficients are given for each adjustment equation. * p < 0.05, ** p < 0.01, *** p < 0.001.

Category	Metric Name	r (raw)	r (adjusted, scaled)	Intercept	Depth to groundwater	Precipitation (30 year mean)	Soil conductance	Distance to sand	Total soil water deficit
Conservatism	Tolerant cover	0.36**	0.51***	17.39	0.11	-0.58	0	0	0
Ground cover	Bare ground	-0.03	0.10	23.87	0	0	5.14	0	0
Life form	Woody cover (absolute)	-0.13	-0.33**	-0.21	0	0.10	0	0	0
Life form	Forb cover (relative)	0.26*	0.39***	0.25	0	-0.01	0	4.60E-05	0
Life form	Rhizomatous : Non-rhizomatous	-0.13	-0.46***	-929.27	0	8.94	0	0	3.02
Endemism	S1-S3 EOS score	0.05	0.03	1.29	0	0	0	0	0
Endemism	G1-G3 EOS richness	-0.11	-0.11	0.50	0	0	0	0	0
Taxonomic diversity	Richness Poaceae	0.13	0.28**	4.67	0	-0.06	0	-5.46E-04	0
Taxonomic composition	Asteraceae cover (absolute)	-0.06	-0.05	7.88	0	0	0	0	0

Notes: "EOS" = Element Occurrence Score; S1-S3 and G1-G3 refer to the highest ranking or most endemic taxa on a scale of 1 to 5 at the State or Global scale (NatureServe 2016).

Table 35. Multimetric Index 1 (MMI 1) of ecological integrity assessment points and condition classes based on human disturbance (HDI) for salty meadows on the Great Sand Dunes National Park and Preserve sandsheet. Moderate disturbance and intermediate ecological integrity are between the minor/reference and major/non-reference assessment points. LPI = lower prediction interval, UPI = upper prediction interval, and SE = standard error.

HDI disturbance class	MMI 1 ecological integrity class	SE	LPI	UPI
Negligible ~0	Pristine reference >6.74	0.17	5.48	8.01
Minor <48	Reference >5.11	0.07	3.89	6.33
Major >60	Non-reference <4.70	0.08	3.47	5.92

low disturbance score of 8.46). This may suggest that the site was "over performing" and/or it could be indicative of error in the model. Thirty-nine sites were in a reference condition based on a MMI 1 between 6.754 and 5.11. Of these, nine were potentially misclassified with a higher than expected disturbance level (seven in a moderate disturbance and two with major disturbance). Seven sites were in an intermediate ecological integrity class with a mix of correct and incorrect disturbance levels. Twenty-five sites were classified as non-reference with a MMI 1 below 4.7. Most of these had major disturbance levels. MMI 1 clearly reflected a separation between most condition classes (Figure 51). Note that the paired comparisons described in Figure 51 are unreliable with the low sample in the pristine reference class.

3.8.3.1.2 Spatial patterns

The spatial patterning in MMI 1 is shown in Figure 52. It resembles the general pattern seen with HDI and UUI. This is important as it supports a structural relationship between these drivers and ecological response. In general, lower MMI 1 estimates of integrity occur along the Big Spring Creek corridor and near ranching infrastructure inside the bison fence. Select sites adjacent to park infrastructure also are lower in integrity. Remote sites outside the bison fence near the westernmost extent of the main dune field, along the lower Sand Creek corridor, and in the extreme north portion of the park had higher integrity.

3.8.3.1.3 Population scale

Design-based summaries infer MMI 1 results to all salt flat–

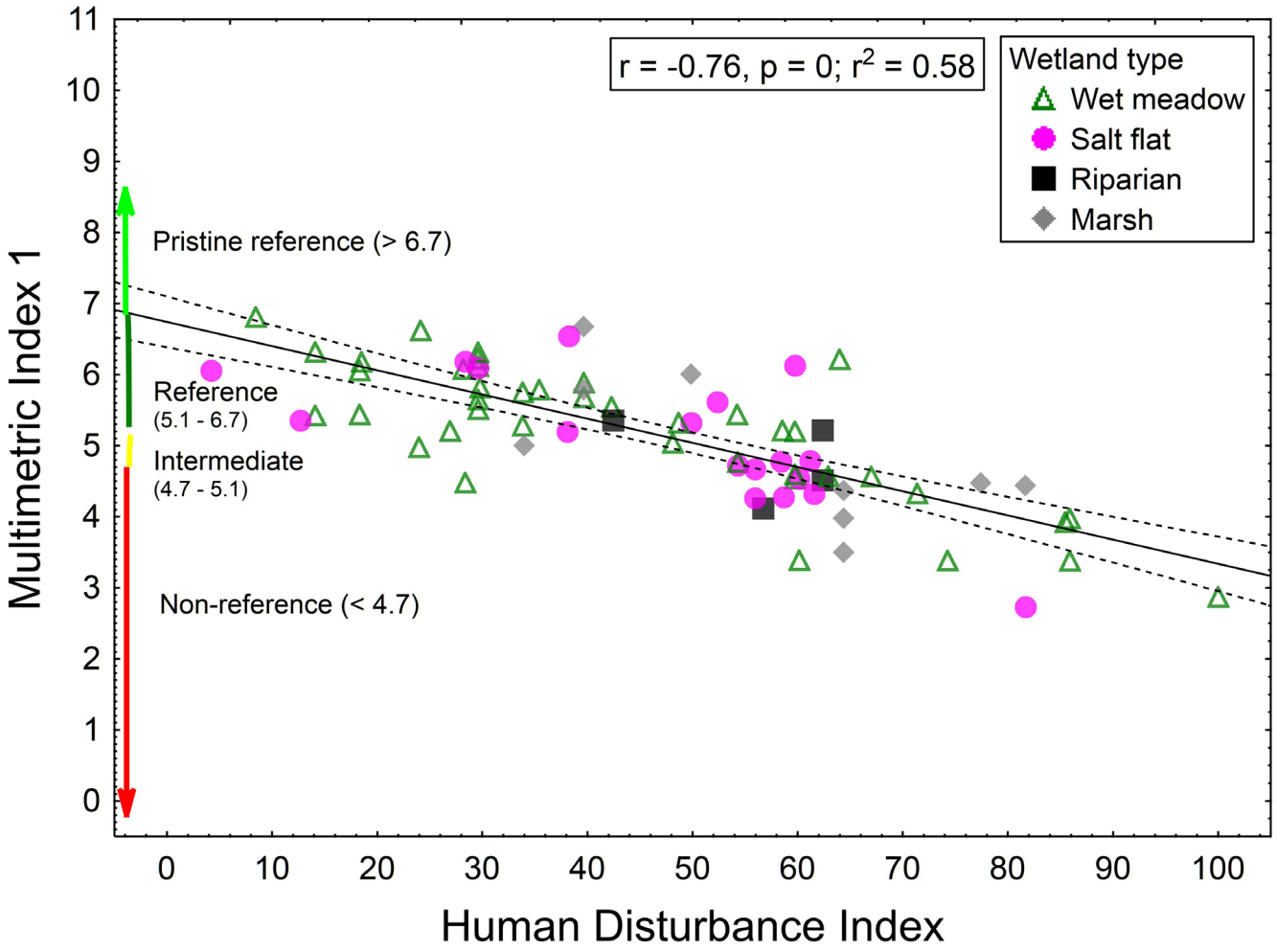


Figure 50. Bivariate relationship between Multimetric Index 1 (MMI 1) and Human Disturbance Index (HDI) at Great Sand Dunes National Park and Preserve, 2010. Linear fit and its 95% confidence intervals area indicated by black solid and dashed lines, respectively. Point symbology derived from wetland type. Vertical lines along the X axis partition MMI 1 scores for each site into pristine reference (MMI 1 > 6.7), reference (MMI 1: 5.1–6.7), intermediate (MMI 1: 4.7–5.1) and non-reference (MMI 1 < 4.7) classes based on predicted response at negligible disturbance (HDI = 0), minor disturbance (HDI < 48), intermediate (HDI: 48–60) and major disturbance (HDI > 60) levels. See also Table 34 and Table 35.

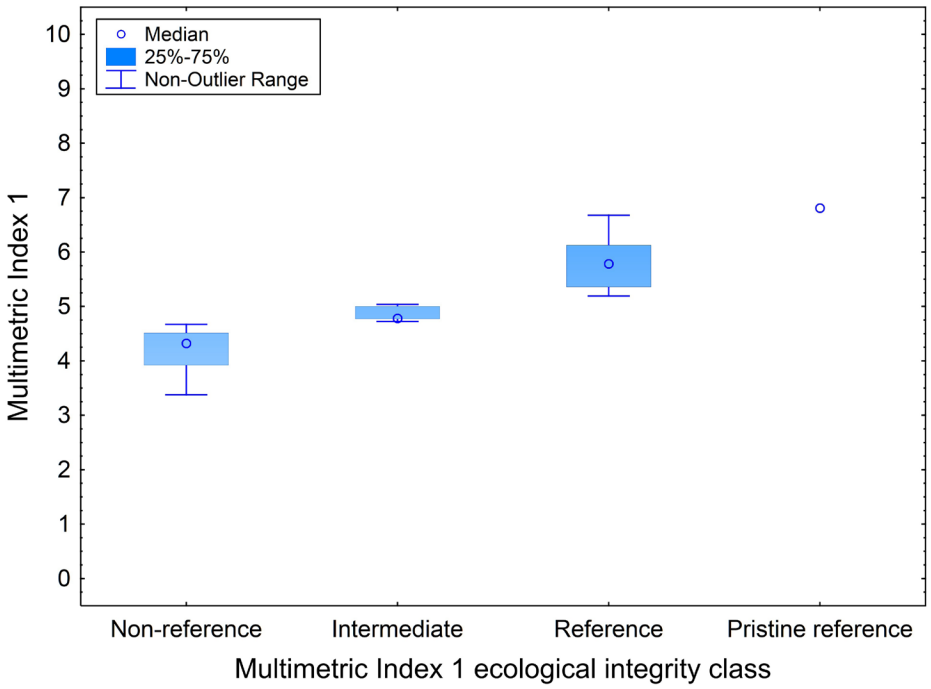


Figure 51. Box plot of Multimetric Index 1 (MMI 1) by ecological integrity class for Great Sand Dunes National Park and Preserve. Overall Kruskal-Wallis test was strongly significant (H (3, N = 72) = 56.68, p = 0). Post hoc paired comparisons (Siegel and Castellan 1988) showed differences between non-reference and all other classes except intermediate, intermediate and reference, and between pristine reference and non-reference (although any test with the pristine class is unreliable due to the small sample in this class). Data for tests include all sites.

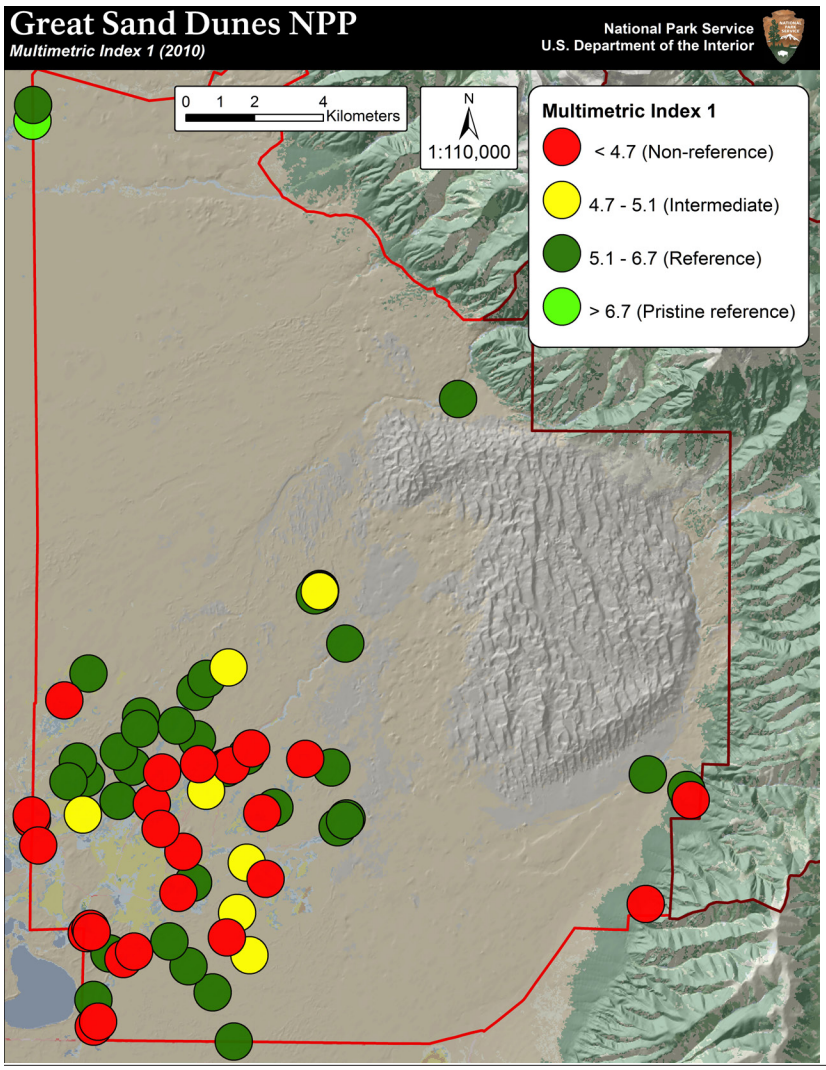


Figure 52. Map of Multimetric Index 1 in Great Sand Dunes National Park and Preserve, 2010. Condition classes are based on assessment points predicted from a model of MMI 1 and HDI at the >75th percentile for major disturbance (red dots) and the <50th percentile for minor disturbance (dark green dots). A moderate disturbance class falls in between these values (yellow dots). For the negligible disturbance class, we use the predicted MMI 1 value at HDI = 0 (light green dots).

wet meadow wetlands on the sandsheet. We must assume that MMI 1, constructed for salty meadows, riparian, and marsh sites can be applied to salty meadows selected with the survey design alone. This is likely a safe assumption as neither riparian or marsh sites appear to force the model (i.e., they are not outliers) and, with the exception of bare ground in salt flats, our examination of the component metrics (see below) suggests that few had patterns driven by a single wetland type.

Roughly 39% (with a 95% confidence interval of 26–51%) of the salty meadow on the sandsheet in 2010 was in a non-reference condition, with MMI 1 scores under 4.7 (Figure 53). Around 50% (38–62%) was in a reference state, and around 1% was in a pristine reference condition (confidence intervals are not estimated in the tails of the Cumulative Distribution Function). The remainder (around 10%) was in an intermediate condition.

This is a somewhat surprising amount of non-reference condition wetland for a national park. However, the sandsheet portion of GRSA was not established until 2003. Prior to NPS management, there had been a relatively long period of human agricultural use and modification of the area.

MMI 1 includes the confounded effects of ungulate disturbance. While the relationship between ungulate habitat use and wetland condition is not as linear as we assume the

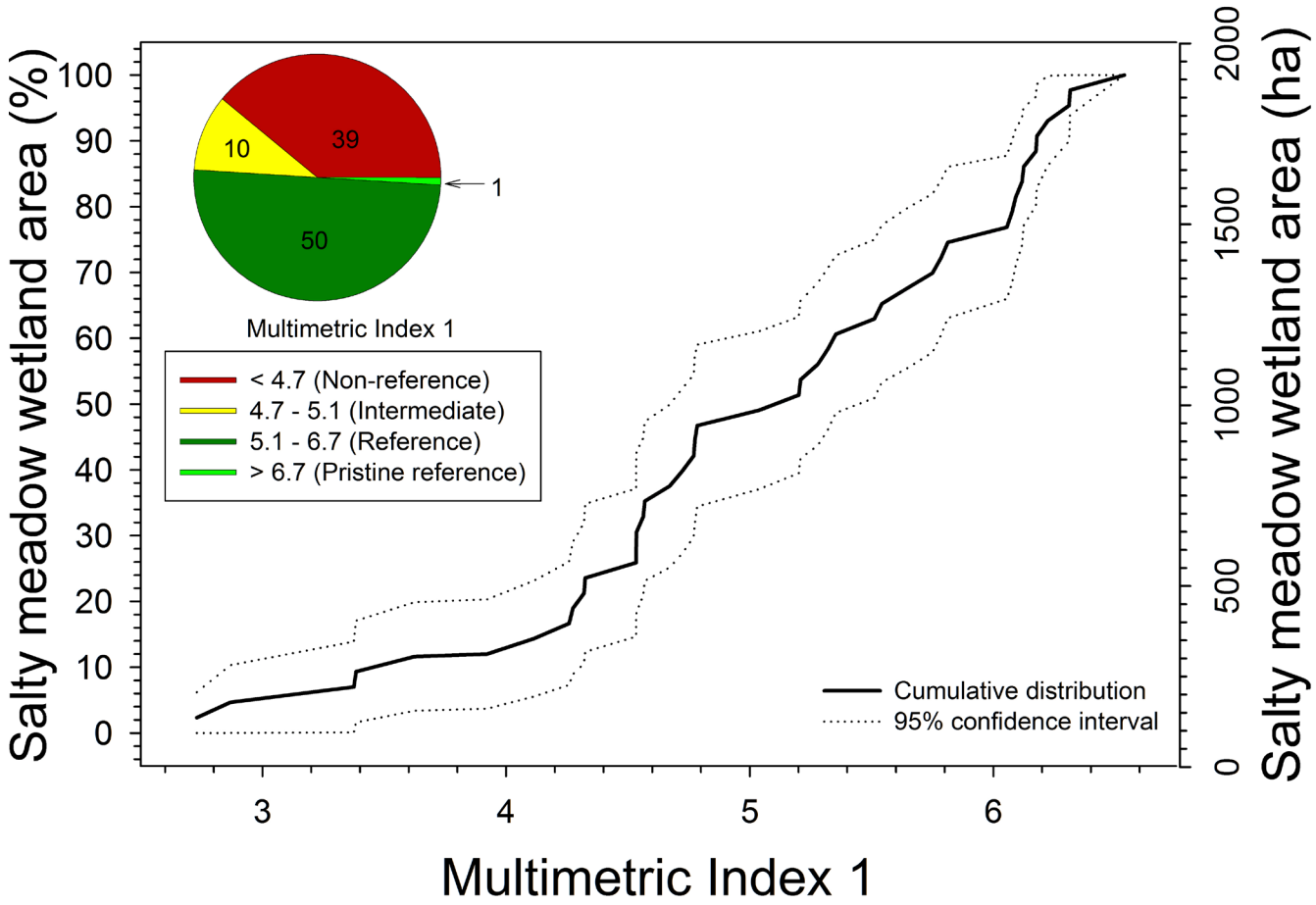


Figure 53. Cumulative distribution function (CDF) of Multimetric Index 1 (MMI 1) for the population of salt flat and meadow sandsheet wetlands at Great Sand Dunes National Park and Preserve, 2010. The left y-axis gives the percent of salty meadow wetlands on the sandsheet and the right y-axis shows the actual estimated area of wetland. A 95% confidence interval (dotted lines) around the percent values (heavy line) is also shown. Pie chart shows the percentage of the total area in each condition class as light green (pristine reference), dark green (reference), yellow (intermediate), and red (non-reference). Pie charts do not include a confidence interval for each estimate in these classes so they should be used with caution.(Siegel and Castellan 1988) showed differences between non-reference and all other classes except intermediate, intermediate and reference, and between pristine reference and non-reference (although any test with the pristine class is unreliable due to the small sample in this class). Data for tests include all sites.

effects of human use are, it is clear that beyond some lower and sustainable level of use, ungulates are also impacting wetland condition (see MMI 2 below).

There are wetlands that are intact with high or relatively high ecological integrity at GRSA. Some of these were sampled by our design and some were not. Our sample is likely representative of all or at least most condition states on the sandsheet and thus these are included in our population estimates. Other sites have complex responses that may suggest issues with the MMI 1 model. Additional research and more data will be needed to resolve structural relationships, causality (i.e., Schweiger et al., in review), and to elucidate species level patterns in our results.

3.8.3.1.4 Interpreting MMI 1: component metrics

The component metrics in MMI 1 integrate the suite of underlying ecological processes and/or response to disturbances in the sandsheet wetlands of GRSA. Interpreting each allows additional insight into the MMI. However, the MMI is ultimately intended as a stand-alone predictive tool—it has statistical and ecological properties as a whole that exceed its parts.

Tolerant taxa cover

The absolute cover of tolerant taxa, or those species with a C score of 3 or less (Rocchio 2007a, b), was one of the more prominent component metrics of MMI 1. This is an intuitive relationship—we would expect the cover of taxa tolerant of disturbance to increase with disturbance (Figure 54). Taxa, like *Argentina anserina* or *Eleocharis macrostachya*, which are able to persist in wetlands with heavy disturbance, often dominate the communities at sites with human disturbance and ungulate use. These taxa may serve as species level indicators of low integrity wetland.

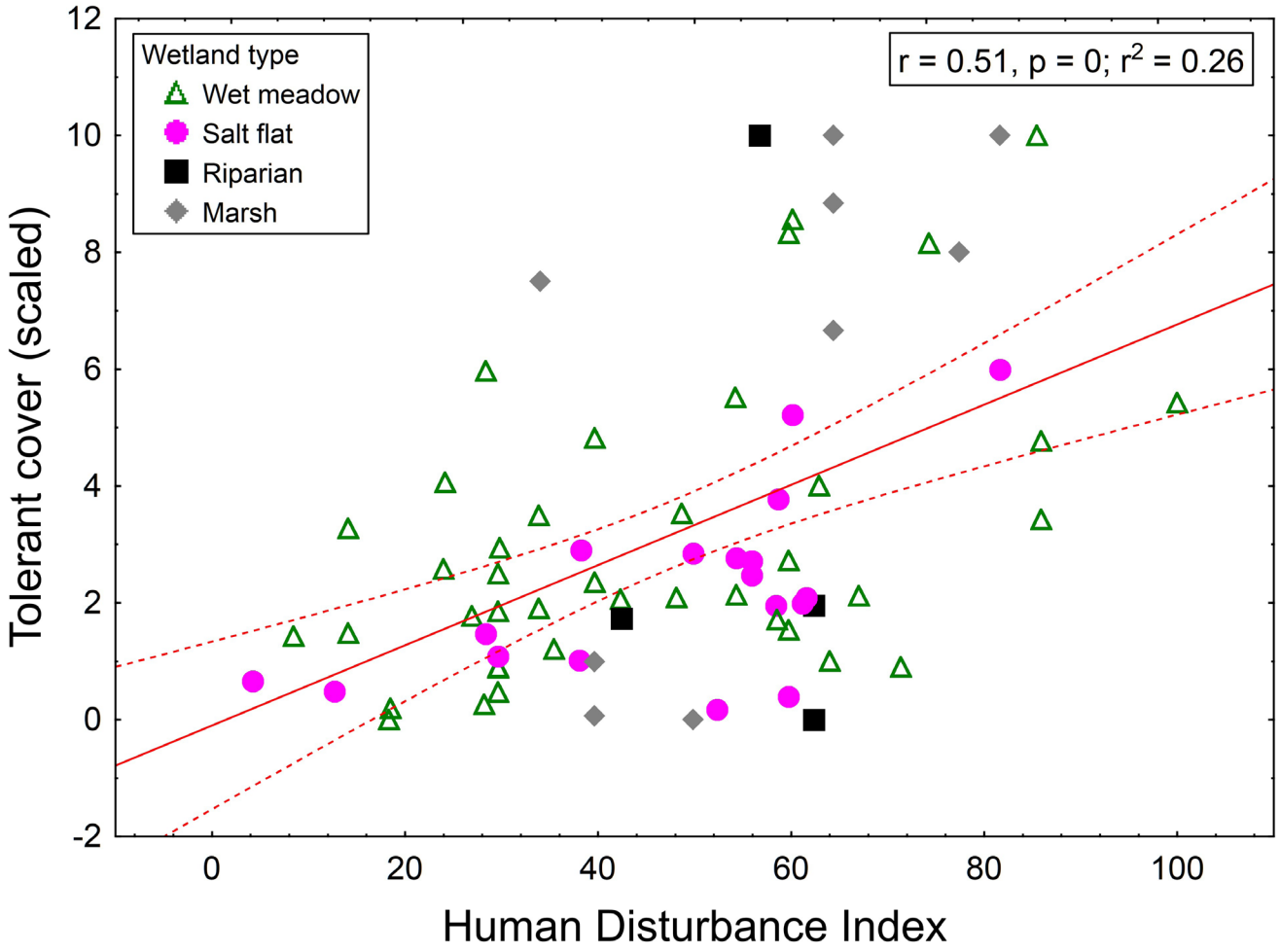


Figure 54. Bivariate relationship between tolerant taxa cover and Human Disturbance Index (HDI) at sandsheet wetland sites, Great Sand Dunes National Park and Preserve, 2010. Response values are quadrisection transformed and scaled by relevant environmental gradients (see Table 34).

Bare ground

Bare ground had a complex response to disturbance. It marginally increased with total disturbance (Figure 55), but only when it was adjusted for its strong positive association with soil conductivity. If this covariance was not removed, the pattern was opposite in sign and even weaker, confirming the importance of controlling for environmental features in our MMI models. Total disturbances that create bare ground can promote establishment and spread of invasive taxa (e.g., Miller et al. 2006), especially at sites with heavy use by ungulates (Manier and Hobbs 2007). However, we were a bit surprised to see this in a GRSA model that included salt flat wetland, where relatively intact high integrity examples still often have significant bare ground (Figure 55). It suggests increasing bare ground with disturbance is a more important response in wet meadows, marshes and riparian areas.

Woody cover

The absolute cover of woody taxa was another important metric in MMI 1, especially when we controlled for its positive covariance with precipitation. Sites with low total disturbance and high integrity had higher woody cover (Figure 56). This metric should be treated with some caution, however. Woody species are naturally rare in salt flat wetland and in most marshes with high water tables, regardless of the disturbance regime—thus the lack of woody cover here should be of little concern. Moreover, this metric likely appears in MMI 1 because the model is based on total disturbance (both HDI and UUI). While human disturbance can directly affect woody cover in wetlands, it is generally via indirect effects on ungulates or beaver. Elk can have strong direct impacts on woody wetland vegetation (Zeigenfuss et al. 2002; Coughenour 2002). Bison are grazers and actively

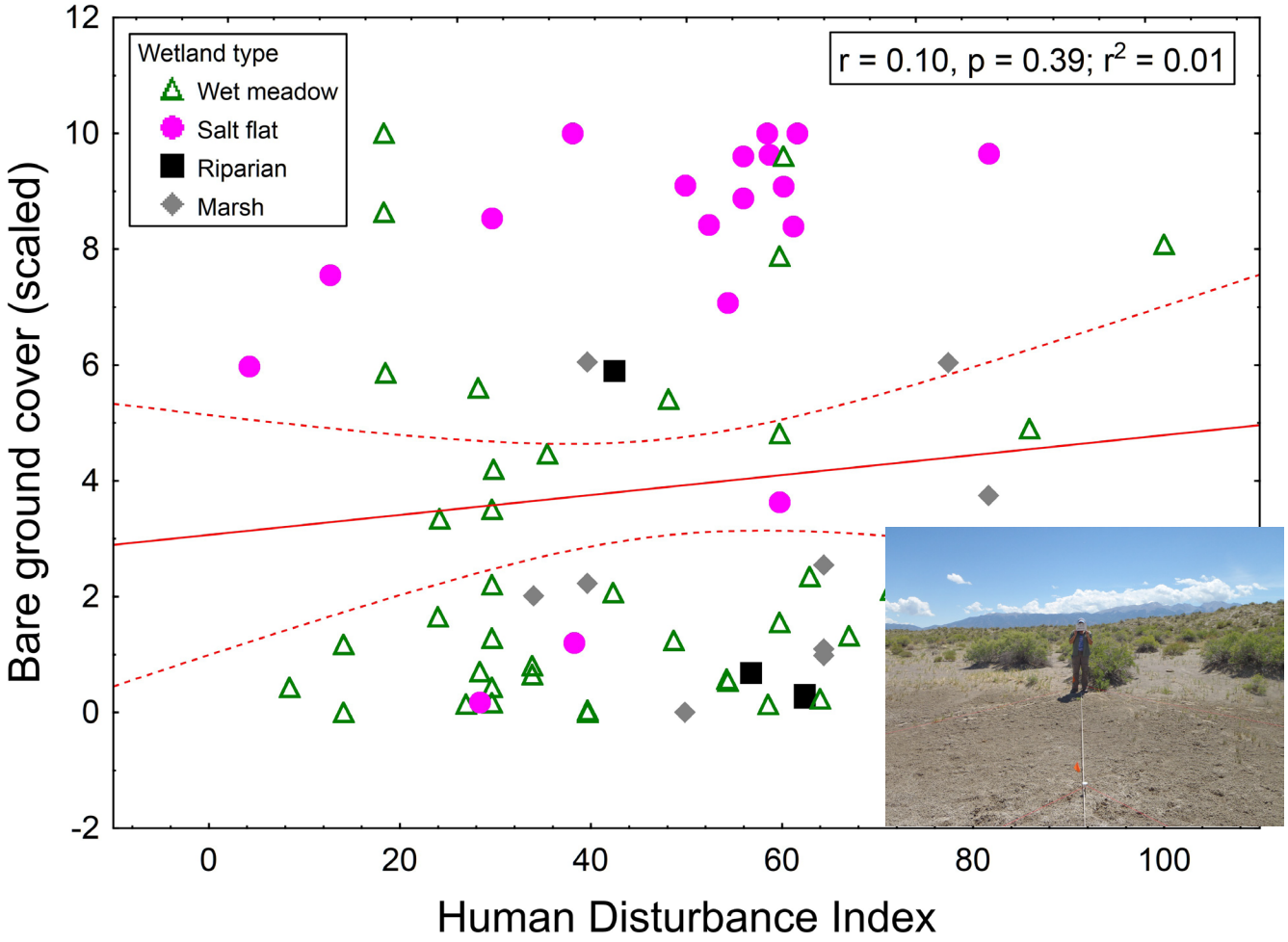


Figure 55. Bivariate relationship between bare ground cover and Human Disturbance Index (HDI) at sandsheet wetland sites, Great Sand Dunes National Park and Preserve, 2010. Response values are quadrisection transformed and scaled by relevant environmental gradients (see Table 34). Inset shows salt flat wetland (site 120) with a low HDI and Ungulate Use Index (UUI), a relatively high Multimetric Index 1 (MMI 1) score, and yet extensive bare ground. This is contrary to the prediction of the MMI 1 model and may suggest a wetland type effect not well captured in the model.

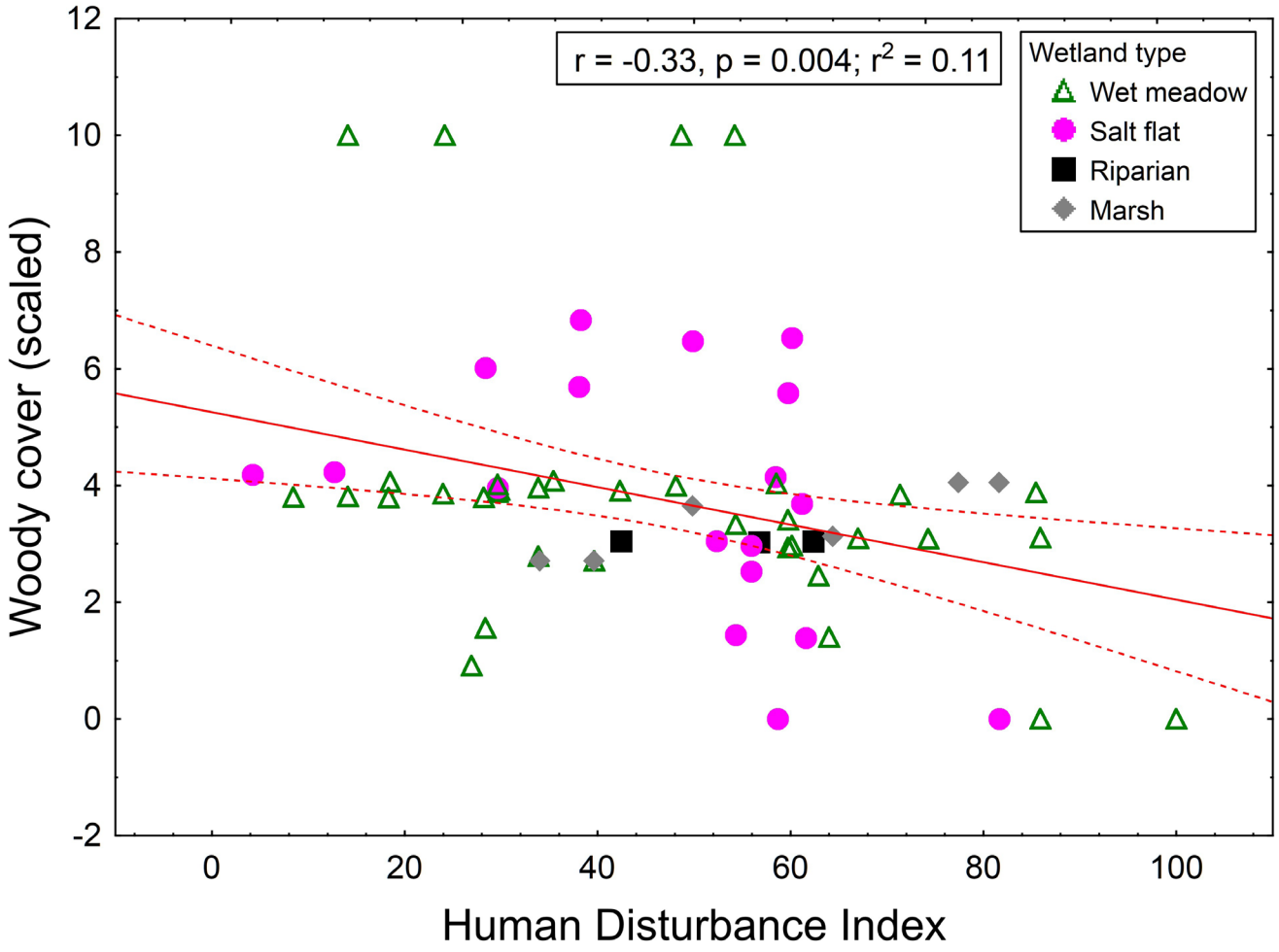


Figure 56. Bivariate relationship between woody cover and Human Disturbance Index (HDI) at sandsheet wetland sites, Great Sand Dunes National Park and Preserve, 2010. Response values are quadrisection transformed and scaled by relevant environmental gradients (see Table 34).

select non-woody habitat at GRSA (Schoenecker et al. 2015). Sites with high woody cover in our 2010 data were all wet meadows because, to date, we have included few riparian sites with cottonwood or willow canopies. Thus, this metric is likely due to few elk using these sites; in some cases, perhaps it is due to exclusion by high bison numbers, but usually because the sites were outside the bison fence. Note the metric also appears in MMI 2, where the disturbance gradient is only UUI.

Forb cover

The relative cover of forbs was a somewhat surprising metric in MMI 1, with higher relative cover in sites with greater total disturbance and lower integrity (Figure 57). Example forb taxa that fit this pattern include *Cleome multicaulis*, a threatened species that has its center of distribution in the San Luis Valley (NatureServe 2016) and has been recognized as a species of concern by GRSA. *Cleome multicaulis* is associated with several metrics in both of our MMIs. Note that this response may not include taxa in the family Asteraceae; disturbance had a negative relationship with the Asteraceae cover metric also included in the MMI. In similar work in ROMO, we see the opposite response to HDI, especially with native forbs (Schweiger et al. 2016). In ROMO this appears to be a complex response driven by the effects of human disturbance on hydrology and reduced wetland canopy cover, with increases in forb taxa that prefer shady sites with fewer canopy gaps. Our GRSA wetland sites naturally have little to no woody canopy and more forb taxa adapted to more intense light regimes. We expect this pattern is a complex response to ungulate use and the inclusion of UUI in the disturbance gradient modeled in MMI 1. (There is also a similar pattern in MMI 2, see section 3.8.3.2 below.) Browsers have been shown to increase the diversity and cover of forbs, often by

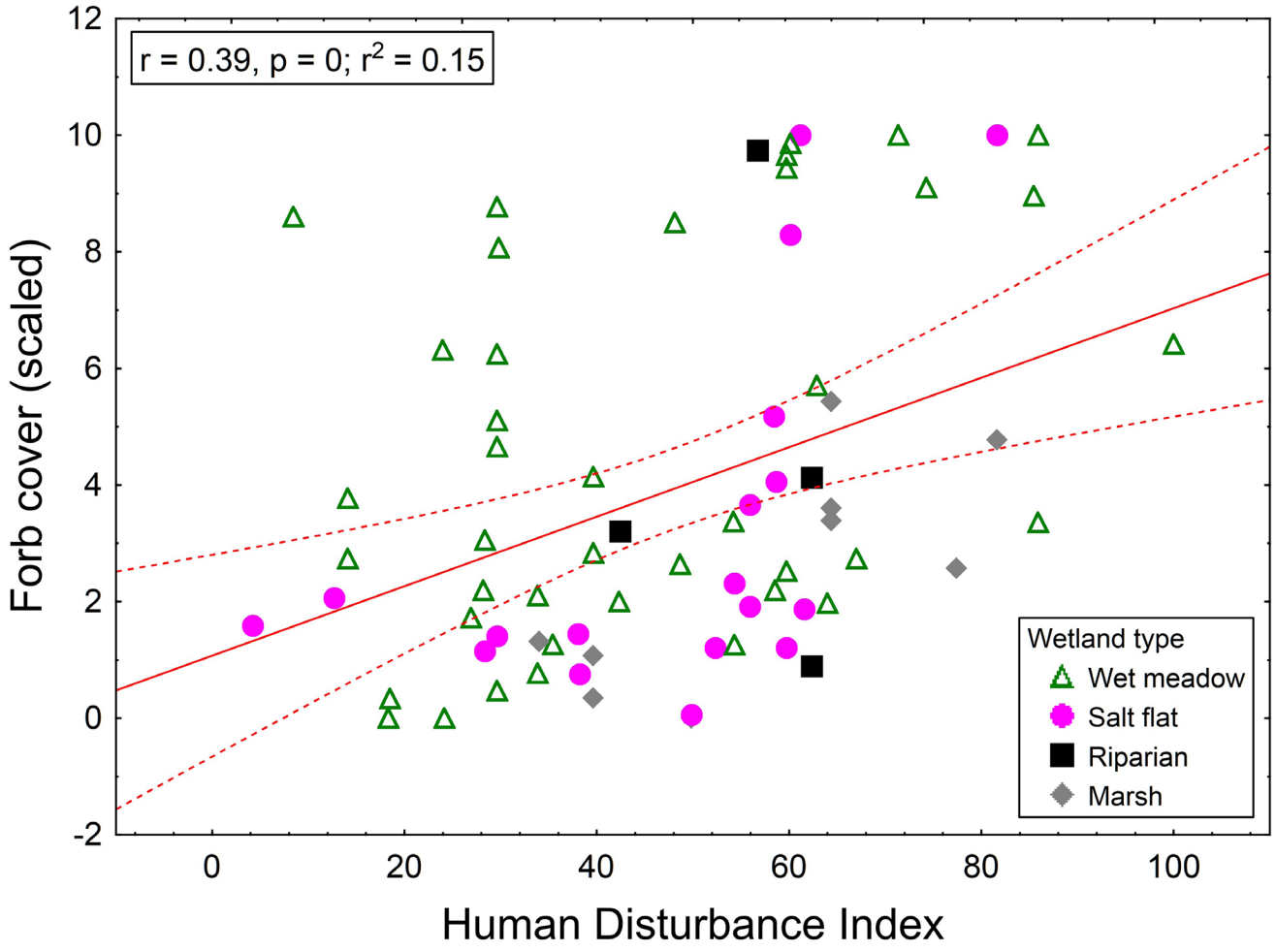


Figure 57. Bivariate relationship between forb cover and Human Disturbance Index (HDI) at sandsheet wetland sites, Great Sand Dunes National Park and Preserve, 2010. Response values are quadrisection transformed and scaled by relevant environmental gradients (see Table 34).

removing palatable woody species that in turn control light regimes or other limiting factors. Often this occurs when ungulate impacts interact with other disturbances like fire or altered hydrology (Royo et al. 2010). We see a similar pattern with another metric in MMI 1, Poaceae richness. Several studies support a positive response in grass diversity with grazing. As with the forb response, though, it is rarely simple, with important covariates, such as productivity, playing an important role (e.g., Bakker et al. 2003). At GRSA the factors that interact with ungulate use and facilitate release of forbs (with the possible exception of Asteraceae) or increases in grass diversity will require more research to understand.

Rhizomatous to non-rhizomatous cover ratio

When its covariance with precipitation and soil water deficit is controlled for, the ratio of rhizomatous to non-rhizomatous absolute cover becomes the metric with the second highest correlation with total disturbance in MMI 1 (Figure 58). Although the pattern is complex, with some outliers, sites with greater total disturbance have a higher cover of taxa with rhizomes relative to those without. Rhizomes are modified subterranean stems that grow laterally that can send out roots and shoots from their nodes. They are important for vegetative reproduction and for the storage of starches, proteins, and other nutrients. They may confer a level of adaptation to competition or disturbance through the spread and regeneration of rhizome fragments, and to grazing through protection afforded by the ground-level position of meristems characteristic of grasses (Taylor et al. 1990).

Endemic taxa importance and richness

Finally, two metrics within our endemism, or conservation value, category revealed marginal but important patterns

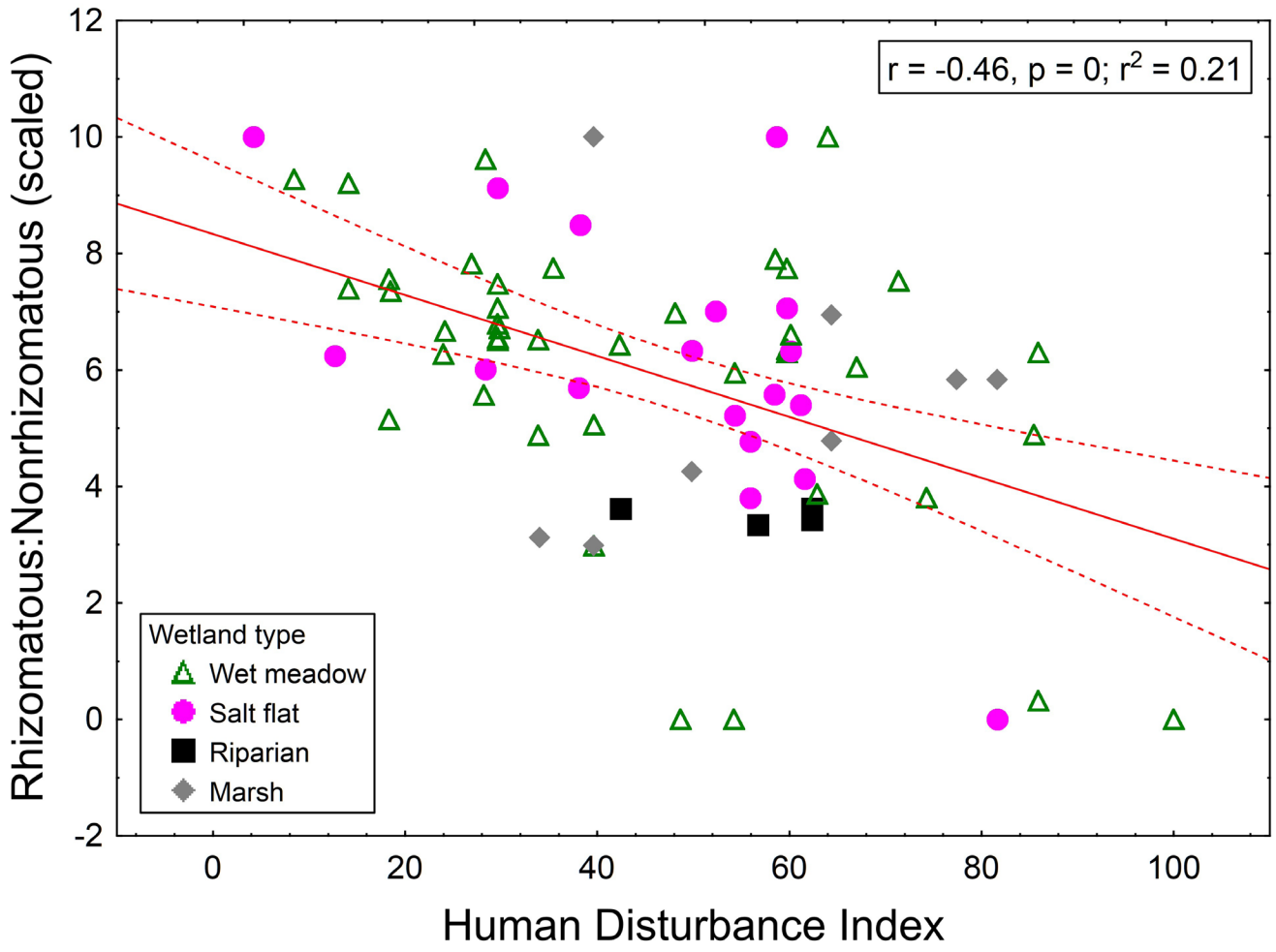


Figure 58. Bivariate relationship between the ratio of rhizomatous to non-rhizomatous taxa and Human Disturbance Index (HDI) at sandsheet wetland sites, Great Sand Dunes National Park and Preserve, 2010. Response values are quadrisection transformed and scaled by relevant environmental gradients (see Table 34).

with disturbance. Our measure of the importance (a metric of weighted cover) of state ranked endemic taxa showed a small increase with total disturbance. At first this seems counterintuitive. However, this pattern is due to two taxa, *Cleome multicaulis* and *Polygonum persicaria*, recognized by CNHP and GRSA as taxa with high conservation value yet that have a strong preference for disturbed sites (Figure 59). At the same time we see a decrease in the richness of globally ranked endemic taxa with total disturbance. This is a complex response that likely requires a proportional odds model to better understand given its ordinal response. It is likely that while the importance (weighted cover) of these taxa increases (the first metric), the probability that they occur (richness) decreases with total disturbance.

3.8.3.2 Multimetric Index 2: ungulate use

The conceptual model behind MMI 2 is shown in Figure 60. The model includes the same five covariates as MMI 1, plus HDI. As noted above it is appropriate to remove the joint effect of HDI on UUI and on candidate metrics by including it as a covariate (Schoolmaster et al. 2013a, b) given the structural relationship between UUI and HDI. As with MMI 1, we must make some assumptions about the relationship between UUI, soil chemistry, and groundwater hydrology. UUI at least conceptually would seem to have an influence on these and thus there could be loss of signal by including them as covariates. Predictive models for soil conductivity and depth to water did not include UUI. However, the Elk Index was positively associated with depth to water (see Table 32). We interpret this as hydrology driving elk numbers and thus believe we should include this pathway in MMI 2. If there is some small loss of signal by using either of these covariates, we feel this is necessary given the strong role soil chemistry and groundwater hydrology can play in wetland vegetation composition.

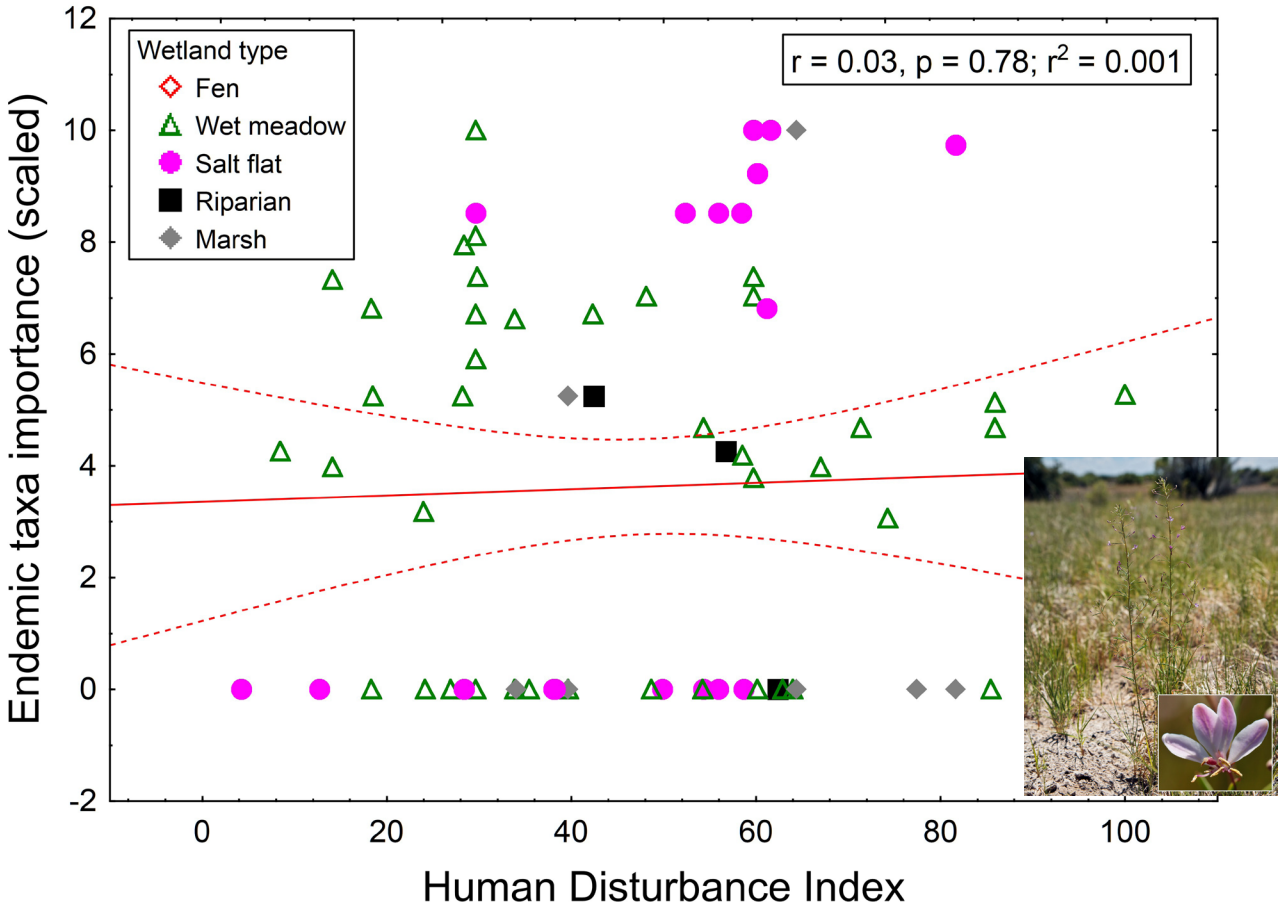
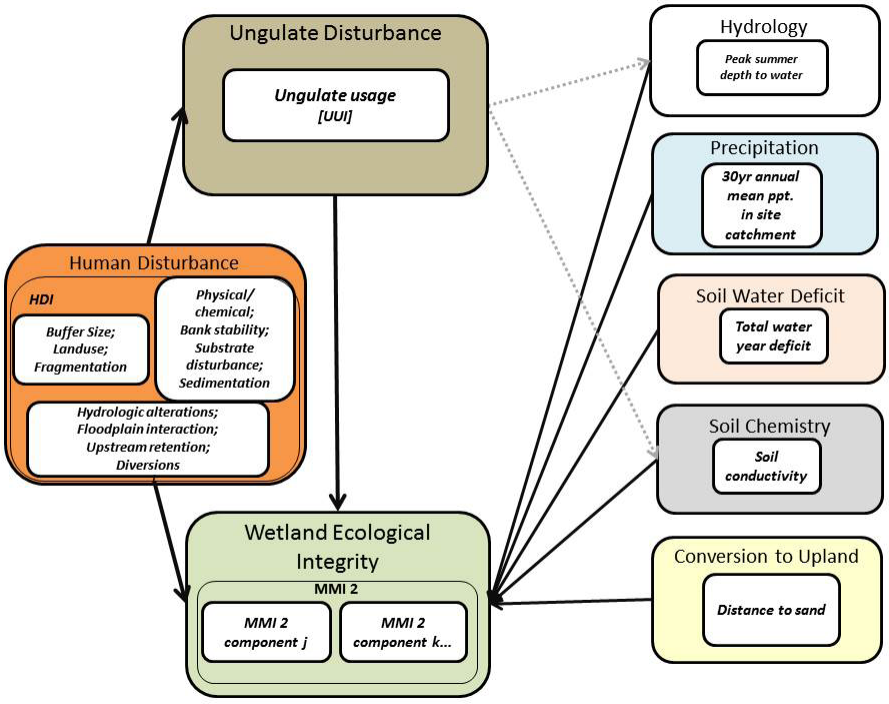


Figure 59. Bivariate relationship between the importance of endemic taxa and Human Disturbance Index (HDI) at sandsheet wetland sites, Great Sand Dunes National Park and Preserve, 2010. Response values are quadrisection transformed and scaled by relevant environmental gradients (see Table 34). Inset shows *Cleome multicaulis* in a disturbed site near the park. Image courtesy Colorado Natural History Program.

Figure 60. Conceptual model for Multimetric Index (MMI 2) at Great Sand Dunes National Park and Preserve. Covariates included in model are shown with solid boxes/arrows, with the assumed or demonstrated causal direction of a relationship indicated by the head of an arrow. Dotted arrows indicate possible causal connections that we assume play a minor role.



The final MMI 2 was selected from seven statistically equivalent (similar correlation with HDI and low and similar AIC scores) models based on a comparison of the interpretability of the component metrics. The model includes five metrics (Table 36) and has a correlation with HDI of -0.83 with an R2 of 0.69 (Figure 61). The correlation between MMI 2 and UUI is markedly stronger than any individual component metric, confirming the statistical (and ecological) advantage of an MMI. Most metrics had at least one meaningful pattern with a covariate, and adjustment improved the signal in nearly all cases. This suggests that adjustment for these environmental gradients improved MMI 2.

3.8.3.2.1 Application of assessment points

Predicted condition classes in the distribution of MMI 2 using negligible, minor, moderate, and major disturbance assessment points are given in Table 37 and shown graphically in Figure 61. We include 95% prediction intervals around these estimates in Table 37. A prediction interval accounts for both the uncertainty in knowing the value of the population mean, plus data scatter. They provide conservative estimates of each predicted assessment point in MMI 2 and GRSA resource management may choose to use these in place of the actual percentile based value.

Importantly, even though there are interesting patterns with some component metrics suggesting positive effects of ungulate habitat use (see below), the final MMI 2 shows a strong negative relationship with increasing ungulate disturbance. In other words, while some elements of wetland vegetation communities at GRSA react favorably to bison and elk usage, as a whole integrity is lower where UUI is highest.

In 2010, 17 sites on the sandsheet were in a pristine reference condition state as defined by a UUI of zero. Eight of these had the expected UUI score of zero. All these sites were within the lower bounds on the prediction interval around the pristine reference assessment point, suggesting that given the statistical challenge of predicting novel single site values, these sites could very well also be in a pristine reference state. Another five sites were in pristine reference, but with non-zero UUI scores. These sites either reveal error in the model or perhaps alternate non-zero upper bounds to UUI (around a score of 30), suggestive of a level of sustainable ungulate use that can still result in high ecological integrity. Eight of the pristine reference sites were also in reference condition within the MMI 1 model, suggesting that they were also relatively intact or resistant to human disturbances. An additional five sites also had a UUI value of zero but were below the pristine reference condition and within the reference or intermediate condition classes. Twenty-seven sites of various wetland types spread across the sandsheet were in a reference condition. Fifteen of these had minor disturbance levels, three were moderately disturbed, yet nine had major disturbances, again perhaps indicating some error in the model or sites that were under performing. Seventeen sites were classified as non-reference—most of which had corresponding major levels of ungulate disturbance. The fourteen intermediate integrity sites generally had moderate or minor disturbances. Finally, MMI 2 clearly reflected the separation between condition classes (Figure 62).

3.8.3.2.2 Spatial patterns

The spatial pattern of multimetric MMI 2 is shown in Figure 63. It resembles the general pattern seen with HDI and UUI. This is important as it supports a structural relationship between these drivers and ecological response. In general, lower MMI 2 estimates of integrity occur along the Big Spring Creek corridor and near ranching infrastructure in the bison pasture. Remote sites outside the bison fence near the westernmost extent of the main dune field and in the extreme north portion of the park boundary had higher integrity. In contrast to MMI 1, sites east of the visitor center had higher integrity, likely because of the reduced levels of ungulate use in these wetlands.

3.8.3.2.3 Population scale

Design-based summaries infer MMI 2 results to all salt flat–wet meadow wetlands on the sandsheet. As with MMI 1, we must assume that MMI 2, built for all wetland types on the sandsheet, can be applied to salty meadows alone.

Roughly 31% (with a 95% confidence interval of 20–42%) of the salty meadow on the sandsheet in 2010 was in a non-reference condition, with MMI 2 scores under 3.57 (Figure 64). Around 38% (27–49%) was in a reference state, and around 8% was in a pristine reference condition (2–14%). The remainder (around 23%) was in an intermediate condition.

As with MMI 1, this is a somewhat surprising amount of non-reference condition wetland for a national park like GRSA. It likely reflects use of the sandsheet for historical cattle grazing, and more recently, bison ranching, as well as the often large elk herds that use these wetlands. However a larger percentage of the salty meadow wetlands on the sandsheet were in a reference state than seen with MMI 1, suggesting that, in general, the effects of ungulate disturbance alone are less detrimental than HDI, or total disturbance.

Table 36. Final component metrics of Multimetric Index 2 (MMI 2) for Great Sand Dunes National Park and Preserve. Correlation with disturbance (Human Disturbance Index—HDI) is given before and after scaling and adjustment by the five covariates listed. Intercept and coefficients are given for each adjustment equation. * p < 0.05, ** p < 0.01, *** p < 0.001.

Category	Metric Name	r (raw)	r (adjusted, scaled)	Intercept	Depth to groundwater	Precipitation (30 year mean)	Soil conductance	Distance to sand	Total soil water deficit	HDI
Conservatism	Tolerant cover	0.09	-0.45***	23.09	0.13	-0.79	0	0	0	0.65
Taxonomic composition	Cyperaceae cover (relative)	-0.32**	-0.70***	0.93	0	-0.01	0	0	0	0.01
Life form	Native forb cover (absolute)	0.47***	0.47***	2.76	0	0	0	0	0	0
Life form	Woody cover (absolute)	-0.30*	-0.34**	-0.02	0	0.07	0	0	0	0
Salt tolerance	Cover weighted mean halophyte score	0.05	0.53***	-0.83	-0.01	0.06	0.32	4.47E-04	0	-0.05

Table 37. Multimetric Index (MMI 2) of ecological integrity assessment points and condition classes based on ungulate use (UUI) for salty meadows on the Great Sand Dunes National Park and Preserve sandsheet. Moderate disturbance and intermediate ecological integrity are between the minor/reference and major/non-reference assessment points. LPI = Lower prediction interval, UPI = upper prediction interval, and SE = standard error.

HDI disturbance class	MMI 1 ecological integrity class	SE	LPI	UPI
Negligible ~0	Pristine reference >6.95	0.19	5.03	8.86
Minor <57	Reference >4.63	0.12	2.74	6.52
Major >83	Non-reference <3.57	0.17	1.66	5.47

3.8.3.2.4 Interpreting MMI 2: patterns with component metrics

The component metrics in MMI 2 integrate the suite of underlying ecological processes and/or response to ungulate disturbance in the sandsheet wetlands of GRSA. Interpreting each allows insight into the model. However, an MMI is ultimately intended as a stand-alone predictive tool—it has statistical and ecological properties as a whole that exceed its parts.

Conservatism

The absolute cover of tolerant taxa, or those species with a C score of 3 or less (Rocchio 2007a, b), was one of the more prominent component metrics of MMI 2. However, its pattern was counter intuitive and opposite that within MMI 1. The cover of taxa tolerant of disturbance decreased with ungulate disturbance (Figure 65). In general, sites with high ungulate use and low MMI 2 scores had low cover of taxa with high C scores. Sites with low UUI and high MMI 2 often had higher cover of tolerant taxa like *Agrostis gigantea* or *Pyrrocoma lanceolate*.

This is an interesting pattern. The adjustment of tolerant cover within MMI 2 included a correction for a strong negative relationship with precipitation (tolerant taxa prefer drier sites) and a strong positive effect of HDI. The positive pattern with HDI is what drives this variable's inclusion in MMI 1 (see Figure 54). With this effect removed in MMI 2, the residual pattern is negative. This suggests that some level of ungulate disturbance may actually reduce the suitability of a site for tolerant taxa. In other words, while ungulate disturbance clearly reduces overall ecological integrity, there may be select components of a wetland's condition that are improved with some level of ungulate habitat use.

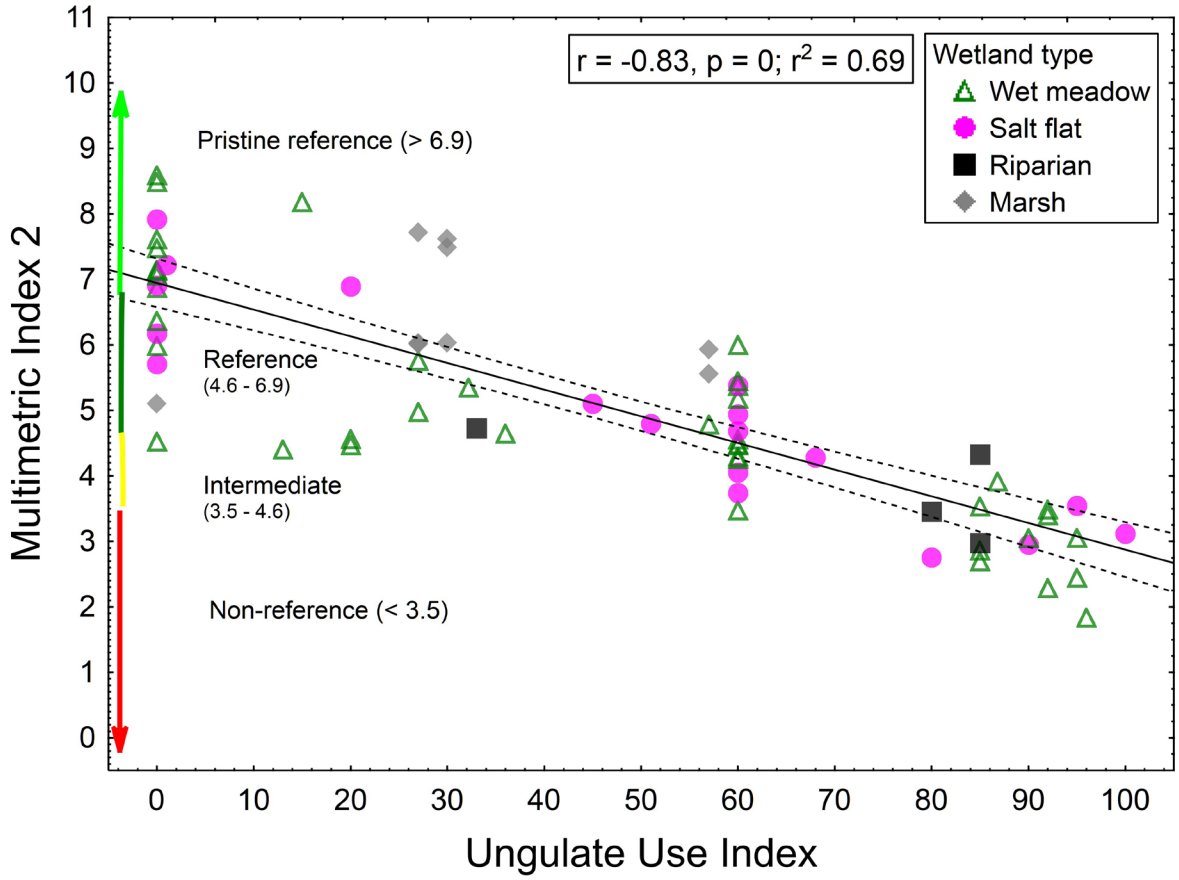


Figure 61. Bivariate relationship between Multimetric Index 2 (MMI 2) and Ungulate Use Index (UUI), Great Sand Dunes National Park and Preserve, 2010. Linear fit and its 95% confidence intervals area indicated by black solid and dashed lines, respectively. Point symbology derived from wetland type. Vertical lines along the X axis partition MMI 2 scores for each site into pristine reference (MMI 2 > 6.9), reference (MMI 2: 4.6–6.9), intermediate (MMI 2: 3.5–4.6), and non-reference (MMI 1 < 3.5) classes based on predicted response at negligible disturbance (UUI = 0), minor disturbance (UUI < 57), intermediate (UUI: 57–83), and major disturbance (UUI > 83) levels. See also Table 34 and Table 35.

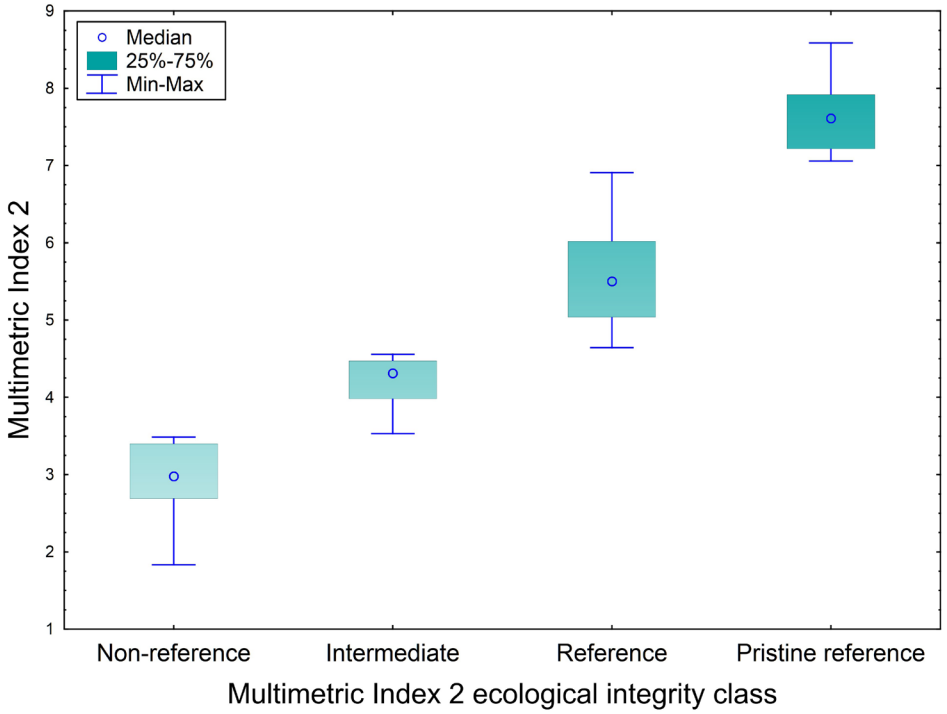


Figure 62. Box plot of Multimetric Index 2 (MMI 2) by ecological integrity class for Great Sand Dunes National Park and Preserve. Overall Kruskal-Wallis test was strongly significant (H (3, N=72) = 64.99, p = 0). Post hoc paired comparisons (Siegel and Castellan 1988) showed differences between all contrasts except intermediate and non-reference. Data for tests include all sites.

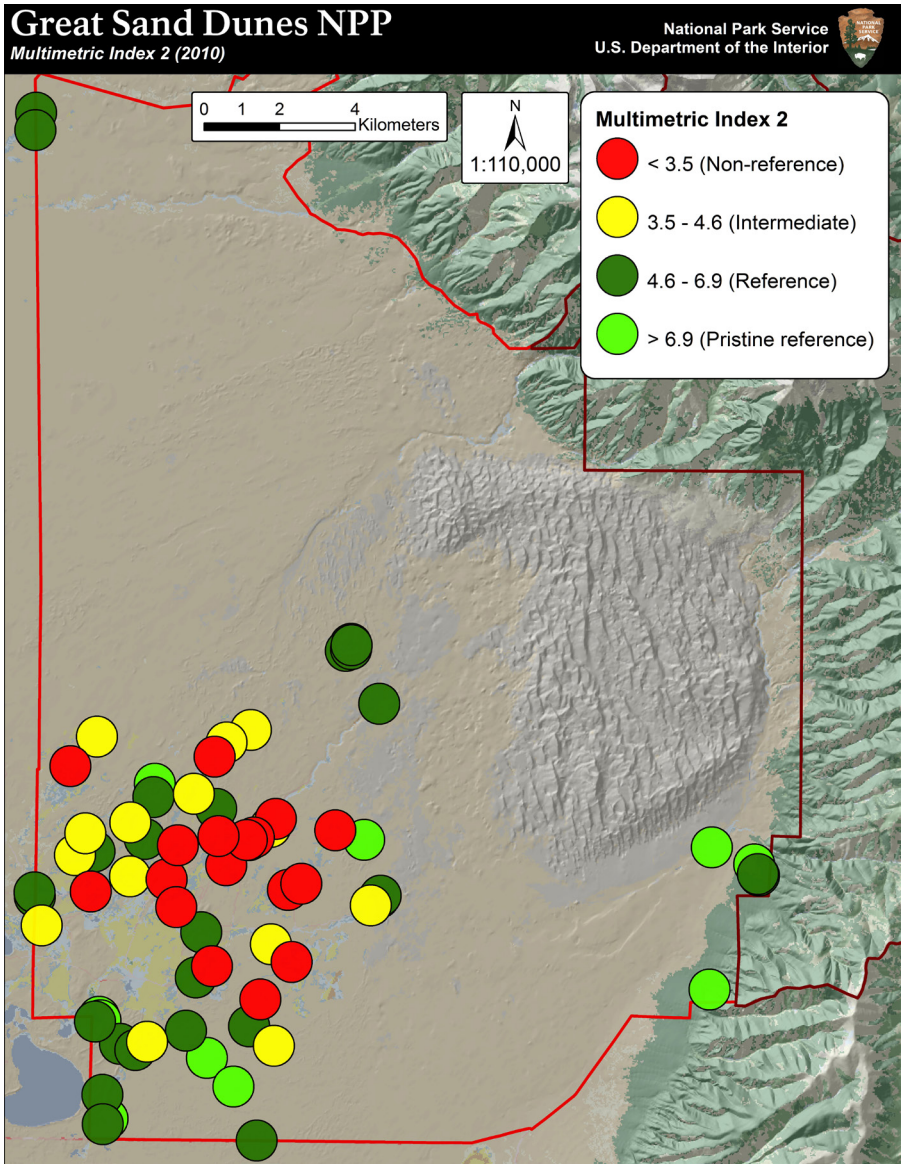


Figure 63. Map of Multimetric Index 2 in Great Sand Dunes National Park and Preserve, 2010. Classes are based on assessment points predicted from a model of MMI 2 and UUI at the >75th percentile for major disturbance (red dots) and the <50th percentile for minor disturbance (dark green dots). A moderate disturbance class falls in between these values (yellow dots). For the negligible disturbance class we use the predicted MMI 2 value at UUI = 0 (light green dots).

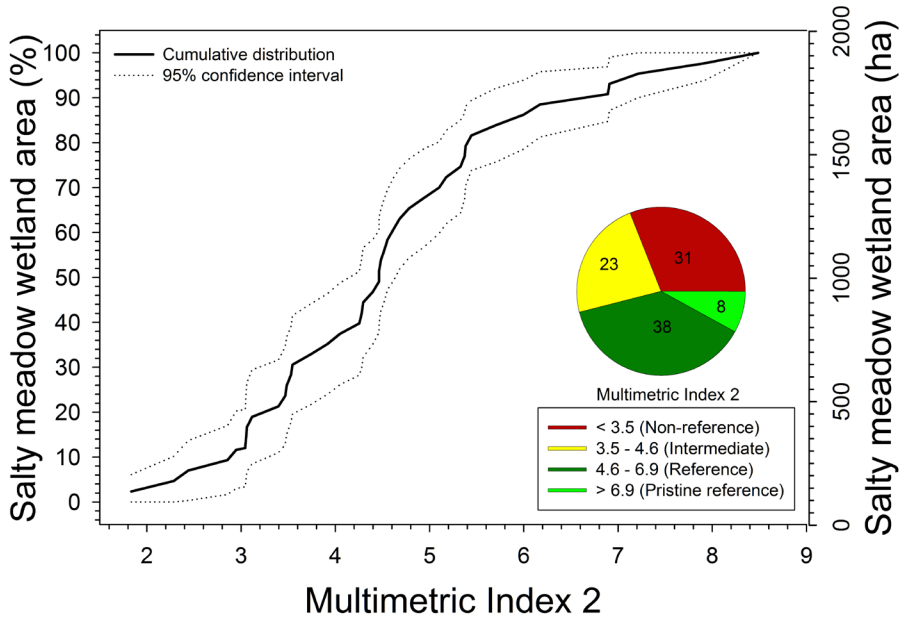


Figure 64. Cumulative distribution function (CDF) of Multimetric Index 2 (MMI 2) for the population of salt flat and meadow sandsheet wetlands at Great Sand Dunes National Park and Preserve, 2010. The left y-axis gives the percent of salty meadow wetlands on the sandsheet and the right y-axis shows the actual estimated area of wetland. A 95% confidence interval (dotted lines) around the percent values (heavy line) is also shown. Pie chart shows the percentage of the total area in each condition class as light green (pristine reference), dark green (reference), yellow (intermediate), and red (non-reference). Pie charts do not include a confidence for each estimate in these classes so they should be used with caution.

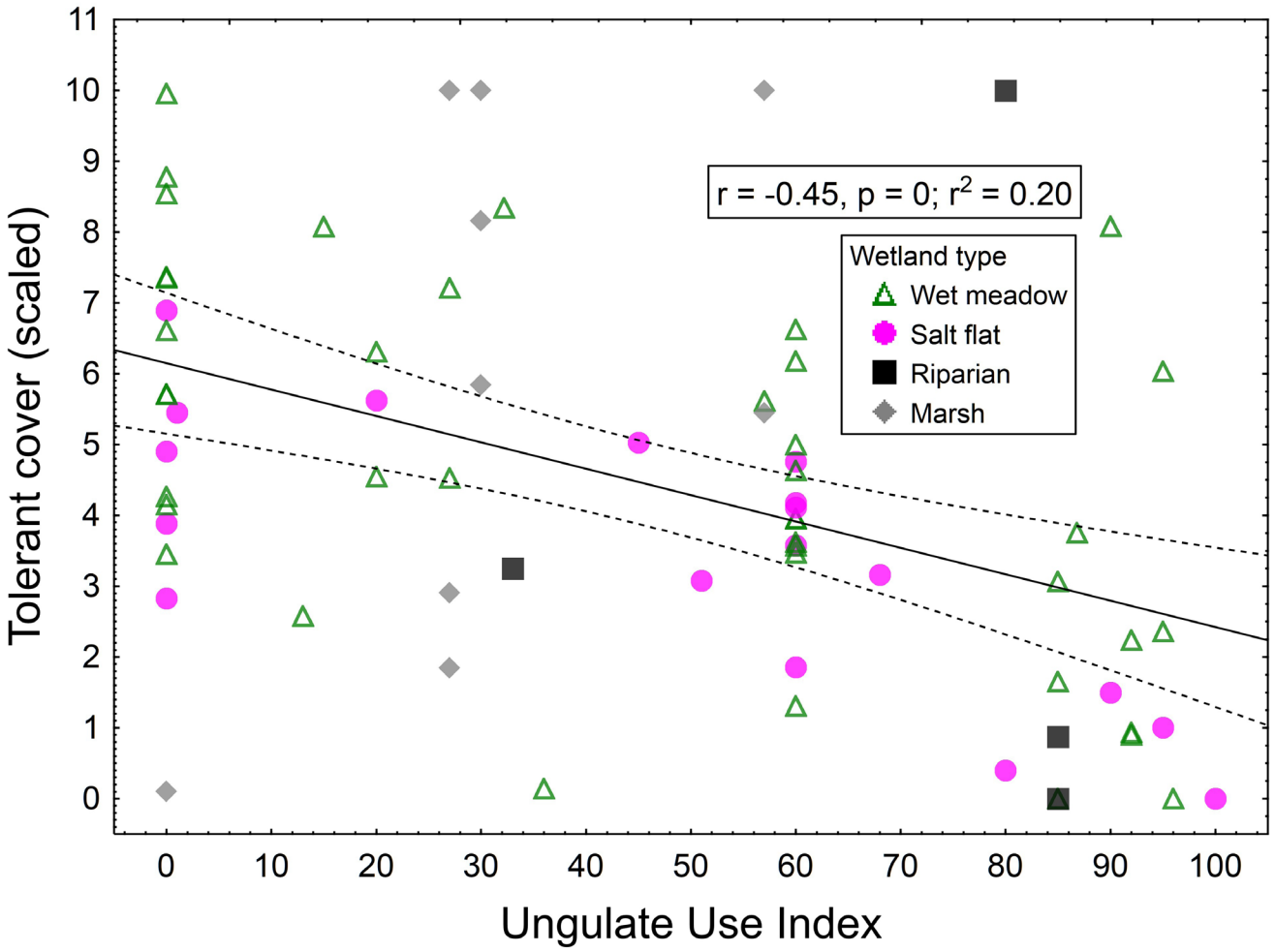


Figure 65. Bivariate relationship between tolerant taxa cover and Ungulate Use Index (UUI) at sandsheet wetland sites, Great Sand Dunes National Park and Preserve, 2010. Response values are quadrisection transformed and scaled by relevant environmental gradients (see Table 36).

Sedge cover

The relative cover of taxa in the sedge family (Cyperaceae) was reduced with increasing ungulate disturbance (Figure 66). Common Cyperaceae on the sandsheet include Carex praegracilis, Carex simulate, and Amphiscirpus nevadensis. Most members of this family are specific in their habitat requirements and many are sensitive to high levels of grazing (i.e., Holmquist et al. 2013).

Native forb cover

Simialr to MMI 1, the relative cover of native forbs (note the response in MMI 1 was across all forbs) had a surprising pattern with UUI, with higher relative cover of taxa like *Cleome multicaulis* in sites with greater total disturbance and lower integrity (Figure 67). Browse may remove palatable species, especially woody taxa, which can affect light regimes or other limiting factors for forbs (Royo et al. 2010; Bakker et al. 2003).

Woody cover

While the bivariate fit was somewhat weak, the absolute cover of woody taxa did marginally decrease with UUI (Figure 68). As with MMI 1, the pattern is seen more across select riparian and wet meadow sites where woody species are more of an important component of the vegetation. It is likely that if we had more of these sites in the model, we would expect the relationship to be stronger given the well documented effect of browsers, like elk, on willow and cottonwood (Zeigenfuss et al. 2002; Schoenecker 2012).

Cover weighted mean halophyte score

Finally, with a series of adjustments for nearly all environmental covariates, our index of halophyte importance was the last component metric in MMI 2. Sites with more ungulate disturbance tended to have more halophytes (Figure 69). Common halophytes at GRSA included *Distichlis stricta*, *Spartina gracilis*, and *Sporobolus*—all of which tolerate high

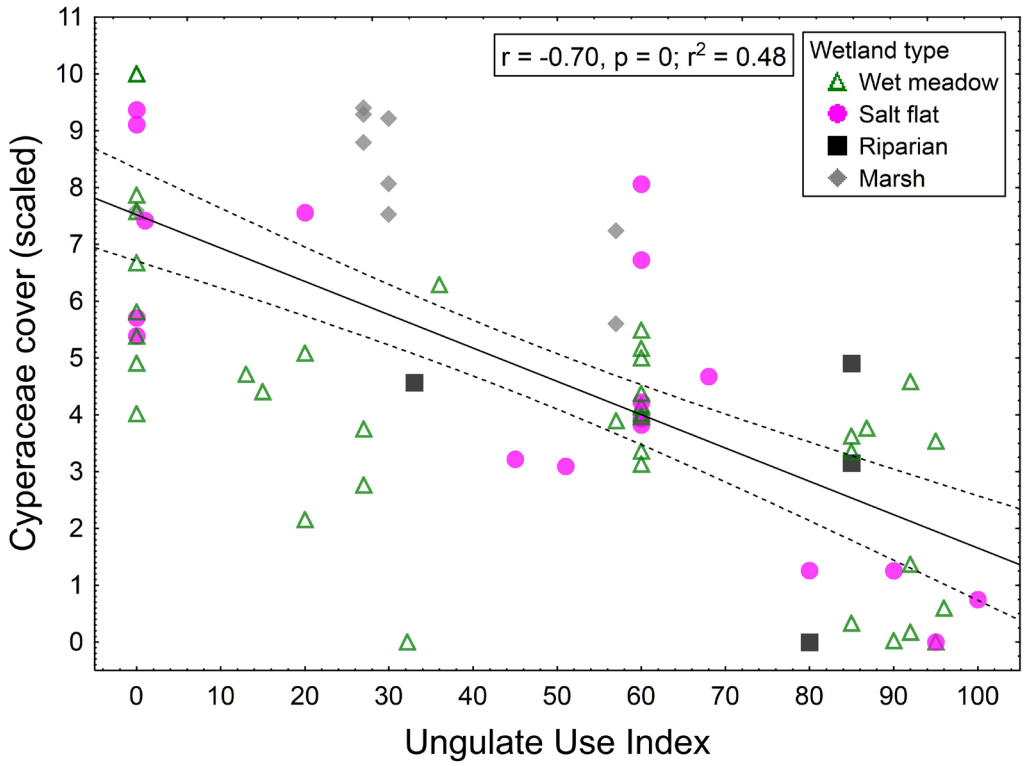


Figure 66. Bivariate relationship between Cyperaceae cover and Ungulate Use Index (UUI) at sandsheet wetland sites, Great Sand Dunes National Park and Preserve, 2010. Response values are quadrisection transformed and scaled by relevant environmental gradients (see Table 36).

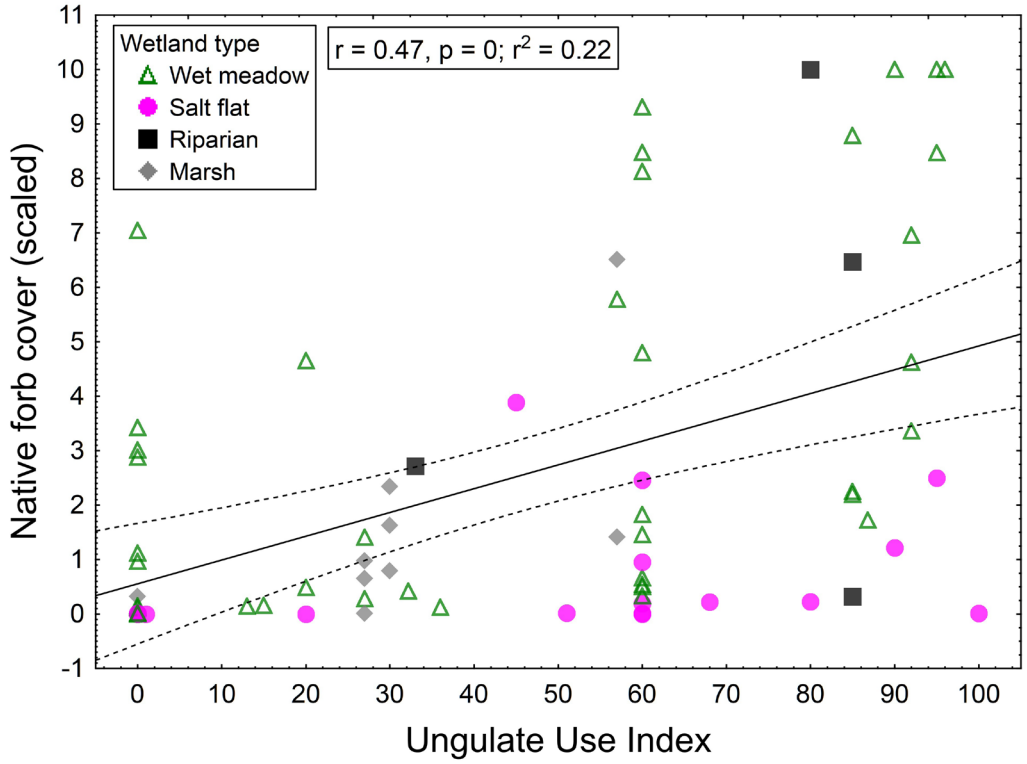


Figure 67. Bivariate relationship between native forb cover and Ungulate Use Index (UUI) at sandsheet wetland sites, Great Sand Dunes National Park and Preserve, 2010. Response values are quadrisection transformed and scaled by relevant environmental gradients (see Table 36).

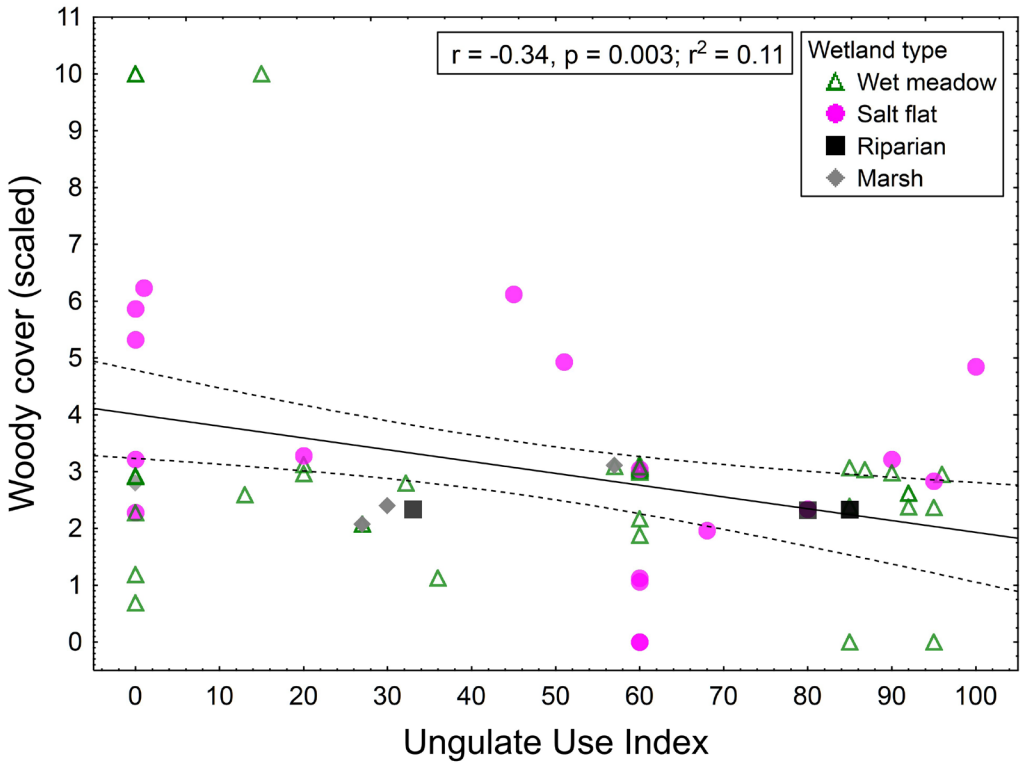


Figure 68. Bivariate relationship between woody cover and Ungulate Use Index (UUI) at sandsheet wetland sites, Great Sand Dunes National Park and Preserve, 2010. Response values are quadrisection transformed and scaled by relevant environmental gradients (see Table 36).

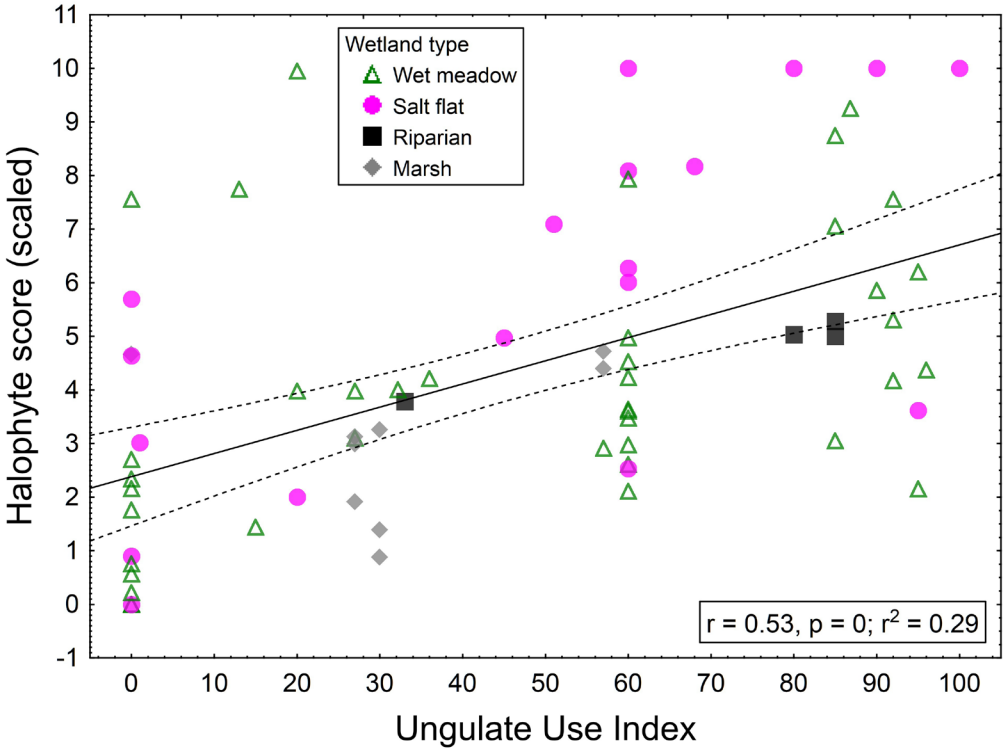


Figure 69. Bivariate relationship between halophyte index and Ungulate Use Index (UUI) at sandsheet wetland sites, Great Sand Dunes National Park and Preserve, 2010. Response values are quadrisection transformed and scaled by relevant environmental gradients (see Table 36).

levels of salinity in wetland soils and groundwater. One of the covariates controlled for in this metric was soil conductivity (used as an index to salinity). Therefore, the relationship between halophytes and UUI is largely independent of the substrate conditions that favor halophytes. It is possible that higher ungulate use may actually be driving some of the reduction in these taxa. While many halophytes are not palatable, others are (Reimold et al. 1975; Gihad and Shaer 1994; Tesfa et al. 2009). In particular, *Sporobolus airoides*, which is a valuable forage species in arid and semiarid regions, produces abundant herbage utilized by livestock and wildlife (Johnson 2000).

3.8.3.3 Trend in MMI 1 and 2 at sandsheet sentinel sites: 2010–2014

We estimate trend in MMI 1 and 2 at sentinel sites on the sandsheet from 2010 to 2014. We use linear mixed-effects models that specifically address trend estimation for correlated data. We treat year as a random effect to estimate the variation of any linear trend over time. Given the way each MMI was constructed by including (or removing) the effect of environmental gradients, we do not include covariates in these models. Following Heard et al. (2012), we model HDI and UUI both logged and untransformed. The logged response allows a test of the net change over the five year interval, while the untransformed response looks at an annual change or effect. Note that the variance in both MMIs across years was homogenous in Brown-Forsythe and Levene tests.

Table 38 gives summary statistics by year. Importantly, while these models are statistically well constructed, five years is likely too short a period to detect significant ecological change given the complexity of this system and the time frames over which system components (past cattle grazing, elk populations and use, climate, long-lived perennial plants, etc.) respond to the environment. Future iterations of these models will likely be more revealing and valuable. The area has a long history of changes in disturbance and it will take more years of data to understand whether any trend is relevant over the long term.

3.8.3.3.1 MMI 1

MMI 1 had a significant increasing trend at sandsheet sentinel sites, both on an annual basis and net over a five year period from 2010 to 2014 (Figure 70, see Appendix G for the full models). The models had high approximate R2 (correlation between the fitted and the observed values) of around 0.70, suggesting that much of the variance in MMI 1 across years at these sites was explained. The net change calculated from the coefficient of the logged response was a 4.3% increase in MMI 1. Both models also had a significant site term, suggesting that the trend in MMI 1 varied by sentinel site, with the smallest increase occurring at the Big Spring Creek Terminus sites.

We saw a decrease in HDI—the primary driver of MMI 1—at these same sites (see Figure 26). While this is only at the three sentinel complexes and over a short time period, our results suggest that increasing wetland ecological integrity tracked this decrease. This is useful qualitative support that MMI 1 responds to disturbance and is suggestive of improving conditions at select sites. We will continue to investigate this as we add sample events.

Table 38. Summary statistics for Multimetric Index 1 (MMI 1) and Multimetric Index 2 (MMI 2) for sandsheet sentinel sites at Great Sand Dunes National Park and Preserve from 2010 to 2014. LCB/UCB are lower and upper 95% confidence interval boundaries around the mean, respectively.

Index	Year	N	Mean index score	LCB	UCB	Standard deviation	Variance	Standard error
MMI 1	2010	7	4.88	4.39	5.37	0.53	0.28	0.20
	2011	5	4.86	4.26	5.46	0.48	0.23	0.22
	2012	5	5.42	5.02	5.82	0.32	0.10	0.14
	2013	5	5.53	4.94	6.12	0.48	0.23	0.21
	2014	5	6.27	5.81	6.72	0.37	0.14	0.17
	All Years	27	5.35	5.09	5.62	0.67	0.45	0.13
MMI 2	2010	7	3.73	3.01	4.45	0.78	0.61	0.29
	2011	5	3.74	2.81	4.67	0.75	0.56	0.34
	2012	5	3.81	3.00	4.62	0.65	0.42	0.29
	2013	5	4.07	2.92	5.21	0.92	0.85	0.41
	2014	5	3.96	2.38	5.55	1.28	1.63	0.57
	All Years	27	3.85	3.52	4.18	0.83	0.69	0.16

Figure 70 includes sites in reference and non-reference conditions. In 2010 several sites were near or above the reference threshold, with one close to pristine reference condition. By 2014 more sites were above these thresholds and several had moved into an intermediate integrity class (improved).

3.8.3.3.2 MMI 2

MMI 2 increased at our sandsheet sentinel sites, both on an annual basis and net over a five year period from 2010 to 2014 (Figure 71, see Appendix G for the full models). However, the trend was not significant and was relatively low. The models had high approximate R2 (correlation between the fitted and the observed values) of around 0.67, suggesting that much of the variance in MMI 2 across years at these sites was explained. The net change calculated from the coefficient of the logged response was a 1.8% in MMI 2. Both models also had a significant site term, suggesting that the trend in MMI 2 varied by sentinel site, with the smallest increase occurring at the Big Spring Creek sites. We saw an increase in UUI at these same sites (see Figure 27) and thus might have expected MMI 2 to decrease in response to its primary driver. This different result may be due to small sample size, a short time period of interest, or issues with the model. We will continue to investigate this as we add sample events. In 2010 several sites were near or above the reference threshold. By 2014 more sites were above this threshold (improving), with a few close to pristine reference condition.

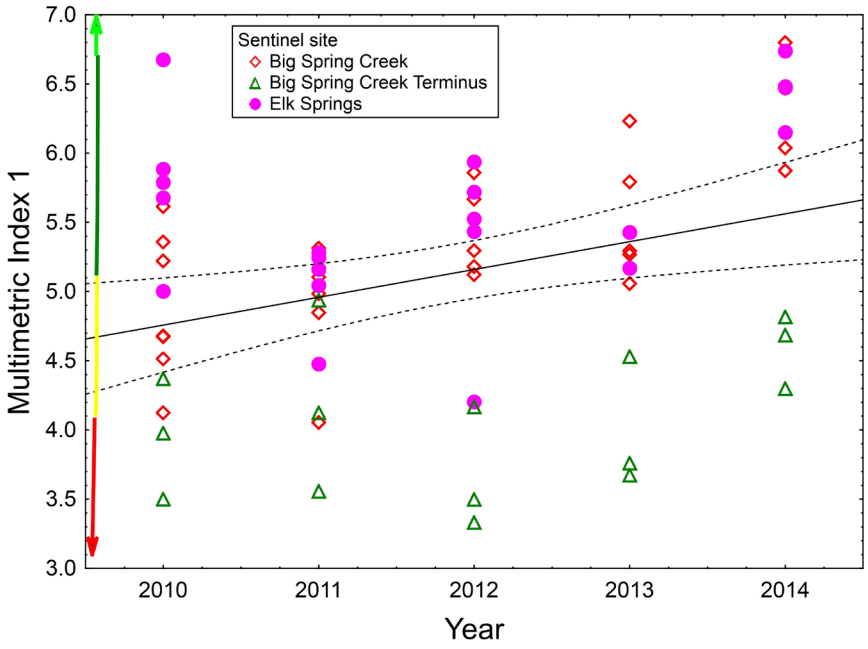


Figure 70. Multimetric Index 1 (MMI 1) at sandsheet sentinel sites by year for Great Sand Dunes National Park and Preserve, 2010 to 2014. Points (representing unique sites) within a year may overlap. Pristine reference, reference, intermediate, and non-reference condition classes are shown along the Y axis, with light green, dark green, yellow, and red vertical arrows, respectively. See the full model in Appendix G.

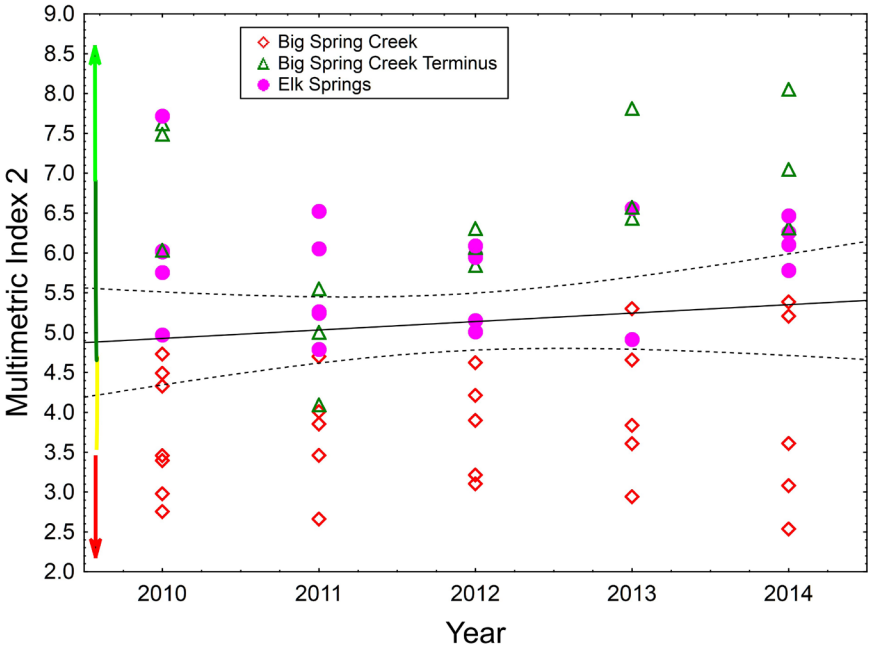


Figure 71. Multimetric Index 2 (MMI 2) at sandsheet sentinel sites by year for Great Sand Dunes National Park and Preserve, 2010 to 2014. Points (representing unique sites) within a year may overlap. Pristine reference, reference, intermediate, and non-reference condition classes are shown along the Y axis with light green, dark green, yellow, and red vertical arrows, respectively. See the full model in Appendix G.

4 Management applications and future directions

4.1 Management applications

A fundamental goal of Network long-term inventory and monitoring is to provide park managers with data and information useful for protecting and managing park resources. GRSA managers must ultimately decide if and how they will use Network wetland monitoring data and information, but we provide some suggestions for consideration here.

First (and at the very least), our estimates of wetland ecological integrity and the suite of bioassessment models serve as baselines for understanding the current status and future changes/trends in wetlands in GRSA. This provides a useful (and largely heretofore missing) broad scale ecological perspective on wetlands in the park, where impacts from climate change, nutrient deposition, and landscape level disturbances are likely occurring. In addition, this basic information can help GRSA management report on and meet basic regulatory requirements (e.g., under GPRA (Government Performance and Results Act) and the Clean Water Act).

The new GRSA enabling legislation was passed in 2000 and acquisition of land is ongoing. These areas have a long and varied history of human use. For example, the Baca Ranch was utilized for cattle grazing from the early 1900s through 2003. Park managers could use our wetland ecological integrity data to monitor the condition and (hopefully) recovery of wetlands in these areas (with different environmental histories) through time. (Note that the Network sampling design, additional sampling, and some field method modification might be needed to do this.)

GRSA may soon be the primary manager for natural resources within the authorized boundary of the park on the sandsheet, long used for ranching and other human purposes. Understanding how human disturbance and ungulate use may have impacted wetland condition is important given these new management needs. Moreover, the developing Ungulate Management Plan (UMP) also reflects the park's new responsibilities relative to how ungulates will be managed across the landscape.

MMI models (and other parkwide monitoring results) can be used to document the condition of individual wetlands. That information could be used by park managers to prioritize wetlands for restoration (e.g., a highly degraded wetland) or protection (e.g., fencing a wetland that has very high ecological integrity and/or significance).

Our data can be used to quantify the importance of various "stressors" and "drivers" of wetland health (e.g., ungulate use, groundwater hydrology, etc.). This has been done with data similar to ours at ROMO (NPS 2007a). This understanding and analytical method can be used to guide NPS wetland protection and restoration actions and is particularly well suited to an adaptive management and monitoring effort. This can be done at the wetland site scale (e.g., by estimating site specific MMI scores to understand the effectiveness of a restoration project at an individual wetland) and at the park scale (e.g., within the framework of a parkwide restoration plan).

Specific metrics, when interpreted in the context of the larger Wetland Ecological Integrity (WEI) dataset, can also enhance general understanding of wetland ecology. However, as the specificity of application increases, the models' precision may become a concern and additional tools should be brought to bear to enhance understanding of site level wetland ecology. We have begun to implement such approaches (i.e., enhanced monitoring of ungulate use) to better inform ungulate management planning at GRSA (Figure 72).

Finally, WEI results should also help park staff understand and communicate to the public about the important wetland resources in GRSA. They allow interpretation of specific wetlands in the context of the broader resource as well as provide a unique perspective across the park as a whole.

4.2 Future wetland ecological integrity monitoring in Great Sand Dunes National Park and Preserve

This effort has been, and will continue to be, a cooperative undertaking between Network staff, wetland scientists, especially from Colorado State University (including the Colorado Natural Heritage Program), USGS, and most importantly, GRSA resource managers and biologists. Our results represent the efforts of many dedicated scientists and resource managers over many years. We believe these results are valid, representative, and useful for understanding and managing wetlands in the park. As we continue to work with park managers to monitor and understand wetland dynamics and ecological integrity in GRSA, we will adapt our approach and methods to park planning and management needs.



Figure 72. Elk herd at Sand Creek (top) and bison herd near the Medano Ranch headquarters (bottom) as captured by wildlife motion detection cameras in 2016 at Great Sand Dunes National Park and Preserve.

5 Glossary

Assessment point – a point along a continuum of indicator values where scientists and managers have together agreed to assess or document the status or trend of a resource relative to program goals, natural variation, or potential concerns.

Biological assessment – using biological community indicators to assess the health or ecological integrity of an ecosystem

Condition classes

Reference condition – "good" condition: intact, healthy, having high ecological integrity (used in bioassessment or, in rare cases, where there is a clear functional ecological understanding of the relationship between an indicator and a stressor or impact). Primarily influenced by natural drivers.

Non-reference condition – "bad" condition: not intact (e.g., missing some ecological component(s)), unhealthy, having low ecological integrity (used in bioassessment or, in rare cases, where there is a clear functional ecological understanding of the relationship between an indicator and a stressor or impact). Primarily influenced by anthropogenic drivers.

Intermediate condition – condition between reference and non-reference condition.

Least disturbed condition (LDC) – an LDC reference condition allows a degree of physical, chemical, and biological alteration (caused by anthropogenic stress or "natural drivers" that are outside the range of natural variability (e.g., human-caused rapid climate change).

Minimally disturbed condition (MDC) – an MDC reference condition is a "pristine" state with little to no human footprint beyond very diffuse background impacts.

Depth-to-water – the water level (expressed in cm below ground level) as measured in shallow groundwater wells installed by the Network. Some wells are measured manually at peak growing season (usually), while others are measured continuously by pressure transducer loggers.

Driver – environmental factor that influences (or causes a response in) a community or ecosystem. A driver is a natural factor (as opposed to a human or anthropogenic factor) that is within the "natural range of variability."

Ecological integrity – Ecological integrity is the capacity to support and maintain a balanced, integrated, and adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of natural habitats of the region.

Gradient site – sampled once or multiple times to characterize wetland condition under a gradient of (primarily) human disturbance; either under stress or in an unstressed pristine condition; results cannot be inferred to other wetlands without complex modelling or assumptions.

GMP impact terms

Negligible – a negligible impact is barely detectable and/or would result in no measurable or perceptible changes to wetlands. Negligible impact corresponds to a zero level in HDI and UUI.

Minor – a minor impact is where an impact is slight but detectable and/or would result in small but measurable changes in wetlands and/or wetlands hydrology and the effects would be localized.

Moderate – a moderate impact is readily apparent and/or would result in easily detectable changes to wetlands and/or wetlands hydrology and the effects would be localized.

Major – a major impact is severely adverse and would result in appreciable changes to wetlands and/or wetlands hydrology, with the effects often regionally important.

HDI – Human Disturbance Index – an index of various field and remotely sensed indicators of human caused disturbance, such as agricultural use, roads, trails, etc.

High elevation wetlands – wetlands in the mountains in the preserve.

In-situ water chemistry – water chemistry indicators such as electric conductivity or pH measured in the field.

Multimetric Index (MMI) – a GRSA wetland index constructed of multiple indicators selected in a statistical modeling exercise designed to include only the most relevant, parsimonious set of wetland health (ecological integrity) indicators.

Response measures – wetland (or other) indicators that "respond" to natural (e.g., drought) and human (e.g., agricultural development) drivers and stressors.

Sandsheet wetlands – wetlands on the "sandsheet" in the park.

Sentinel site – targeted or hand-picked sites sampled (usually annually) to help understand wetland dynamics or impor-

tant for management purposes; results cannot be inferred to other wetlands without complex modelling or assumptions.

Survey – random probabilistic sampling of a resource (i.e., wetlands) at intervals (e.g., every 10 years) such that results provide inference to the entire resource.

Status - a "snap shot" evaluation of an indicator over a well-defined and concise range in time

Stressor – environmental factor that influences (or causes a response in) a community or ecosystem. A stressor is a human influence or a natural factor that, because of human action, is outside the "natural range of variability."

Trend - a non-cyclic, directional change in a response measure that can be with or without pattern.

UUI – Ungulate Use Index – an index of various field and remotely sensed indicators of excessive (outside the natural range of variability) ungulate use or disturbance.

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Appendix A: Great Sand Dunes National Park and Preserve Wetland Ecological Integrity Sample Sites

Table A-1. Great Sand Dunes National Park and Preserve Wetlands Ecological Integrity survey sites (48) on the sandsheet with type, complex area, and catchment area, and the number of full sample events in 2010. Two fen, seven wet meadow, and 11 marsh sites selected by the survey but treated as sentinel or gradient sites are given in Table A-2 and Table A-3. For wetland type: Slt = Salt flat, Mdw = wet meadow.

Site ID	Site name	Wetland type	Complex area (ha)	Catchment area (km^2)	Lat	Lon	Number full visits (2010)
101	Medano Ranch Boundary	Slt	3.375	4.370	37.663	-105.660	1
102	Medano Ranch East Twin Lakes	Slt	31.607	0.160	37.689	-105.682	2
103	Medano Ranch Closed Basin Well	Slt	3.555	1.216	37.676	-105.667	1
104	Medano Ranch Little Spring Creek	Mdw	7.426	12.928	37.710	-105.656	2
105	Medano Ranch Lower	Slt	4.349	0.943	37.683	-105.675	1
106	Medano Ranch West South Ditch 2	Slt	17.354	12.502	37.697	-105.659	1
107	Medano Ranch South Ditch 2	Mdw	48.428	135.455	37.706	-105.650	1
108	Medano Ranch House	Mdw	4.034	83.086	37.719	-105.685	2
109	Medano Ranch South Ditch 1	Slt	4.993	137.266	37.702	-105.679	1
110	Twin Lakes North Ditch	Mdw	4.450	46.518	37.685	-105.697	1
111	Upper Big Spring Crk interdunal swale	Mdw	0.296	0.945	37.719	-105.626	2
112	Middle Sand Crk Medano Sand Creek Ditch	Mdw	0.466	0.863	37.745	-105.692	2
113	Medano Ranch East Dollar Lake	Slt	5.653	2.338	37.722	-105.710	1
114	Medano Ranch Head Lake	Slt	0.280	118.839	37.714	-105.725	1
115	Big Spring Crk Below Main Culvert	Mdw	4.887	81.237	37.736	-105.672	1
116	Middle Sand Creek Low	Mdw	0.327	0.671	37.736	-105.712	1
117	Middle Sand Creek Low Ditch	Mdw	4.220	1.123	37.731	-105.715	1
118	Elk Springs West	Mdw	0.819	51.298	37.780	-105.634	2
119	San Luis Lake East	Slt	1.735	0.706	37.674	-105.706	1
120	Twin Lakes North East	Slt	0.081	0.055	37.686	-105.701	1
121	Twin Lakes Barren	Slt	0.284	0.132	37.681	-105.704	1
122	Twin Lakes North	Slt	1.147	46.292	37.687	-105.693	1
123	San Luis Lake South	Slt	2.023	69.949	37.667	-105.706	1
124	Little Spring Creek North	Mdw	2.711	0.159	37.735	-105.628	1
125	Spring Creek Ranch Rd North Mid	Mdw	0.691	9.990	37.723	-105.651	1
126	Spring Creek Ranch Rd North Up	Mdw	2.635	10.043	37.725	-105.647	1

Table A-1 (*continued*). Great Sand Dunes National Park and Preserve Wetlands Ecological Integrity survey sites (48) on the sandsheet with type, complex area, and catchment area, and the number of full sample events in 2010. Two fen, seven wet meadow, and 11 marsh sites selected by the survey but treated as sentinel or gradient sites are given in Table A-2 and Table A-3. For wetland type: Slt = Salt flat, Mdw = wet meadow.

Site ID	Site name	Wetland type	Complex area (ha)	Catchment area (km^2)	Lat	Lon	Number full visits (2010)
127	Medano Ranch Ditch Housing	Slt	2.340	13.718	37.713	-105.677	1
128	Middle Sand Creek Up	Mdw	0.650	0.588	37.761	-105.663	2
129	Middle Sand Creek Low Mid	Mdw	3.247	0.848	37.755	-105.673	1
130	Middle Sand Creek Mid Mid	Mdw	1.713	0.843	37.758	-105.670	1
131	Middle Sand Creek Low	Mdw	1.798	2.242	37.746	-105.680	1
132	North of Big Spring Crk Ditch	Slt	17.784	0.566	37.742	-105.673	1
133	Big Spring Crk Medano Sand Creek Ditch	Mdw	0.889	105.884	37.734	-105.684	1
134	Big Spring Crk Los Ojos Ditch	Mdw	6.092	0.285	37.729	-105.670	1
135	Hosa House North	Mdw	6.559	82.079	37.725	-105.688	1
136	Sand Creek North Mid	Mdw	1.866	10.240	37.752	-105.717	1
137	Sand Creek North Up	Mdw	19.174	9.640	37.759	-105.709	1
138	Medano Ranch Lower Sand Creek 1	Mdw	11.939	1.181	37.739	-105.699	1
139	Medano Ranch Lower Sand Creek 2	Mdw	13.319	0.608	37.735	-105.694	1
140	Medano Ranch East South Ditch 1	Slt	3.283	1.117	37.705	-105.674	1
141	Medano Ranch South Ditch 1 West	Mdw	9.071	48.617	37.705	-105.694	1
142	Lower Sand Creek	Mdw	1.941	2.243	37.732	-105.709	1
143	Hosa House West	Mdw	43.002	1.042	37.726	-105.699	1
144	Medano Ranch South Mid	Slt	14.225	25.841	37.686	-105.655	1
145	Medano Ranch Middle	Slt	1.329	26.140	37.690	-105.663	1
146	Baca Ranch North	Mdw	1.634	0.998	37.904	-105.729	1
147	Baca Ranch South	Mdw	0.560	0.526	37.908	-105.729	1
148	King Well	Mdw	1.923	0.618	37.737	-105.637	1

A-2. Great Sand Dunes National Park and Preserve Wetlands Ecological Integrity sentinel sites (21) with key site selection criteria and full sample events from 2010 to 2014. Plots in bold are inside an ungulate exclosure. *Site selected by the survey design but treated as a sentinel site. For site type: Mdw = wet meadow, Rip = riparian, Slt = salt flat, Msh = marsh.

Complex name	Complex size	Elev. zone	General topography	Park region	Disturbance regime(s)	Historical monitoring	Resource management issues	Site ID	Type	Lat	Lon	# Full events (2010–2014)
Upper Sand Creek Lake (4 sites as of 2015)	Small (2.1 ha)	High (3590 m)	Flat subalpine fen and wet meadow; complex topography	High elev.	Human: little to no historical use; light to medium current use Natural: medium elk use	No historical wetland monitoring	Ungulate management (hunting, habitat use), visitor interpretation	254*	Fen	37.943	-105.542	4
								255	Fen	37.942	-105.543	5
								256	Mdw	37.943	-105.541	5
								257	Fen	37.941	-105.542	5
Upper Sand Creek Trail (4 sites as of 2015)	Small (2.6 ha)	High (3433 m)	Flat subalpine fen and wet meadow	High elev.	Human: little to no historical use; light to medium current use Natural: medium elk use	No historical wetland monitoring	Ungulate management (hunting, habitat use), visitor interpretation	258	Fen	37.941	-105.529	4
								259	Fen	37.941	-105.529	5
								260*	Fen	37.941	-105.528	4
								261	Fen	37.941	-105.527	5
Big Spring Creek (5 sites as of 2015)	Medium to large (43.6 ha)	Low (2312 m)	Riparian corridor with adjacent salt flat wetland	Sand-sheet	Human: heavy historical use; medium to heavy current use Natural: heavy bison and elk use	Relatively recent groundwater and vegetation monitoring	Ungulate management (ranching, habitat use), restoration of hydrologic dynamics, visitor interpretation	**202**	Rip	37.735	-105.662	6
								203	Rip	37.738	-105.657	6
								209	Slt	37.735	-105.664	5
								210	Rip	37.740	-105.655	5
								211	Rip	37.735	-105.663	5
Big Spring Creek Terminus (3 sites as of 2014)	Large (169.8 ha)	Low (2296 m)	Flat, large marsh	Sand-sheet	Human: heavy historical use; medium to heavy current use Natural: heavy bison and elk use	Relatively recent groundwater and vegetation monitoring	Ungulate management (ranching, habitat use), restoration of hydrologic dynamics, visitor interpretation	214*	Msh	37.692	-105.708	5
								215*	Msh	37.692	-105.707	5
								216*	Msh	37.691	-105.709	5
Elk Springs (5 sites as of 2014)	Small (2.3 ha)	Low (2312 m)	Isolated interdunal area with complex topography	Sand-sheet	Human: light to medium historical and current use Natural: medium elk and some bison use	Relatively recent groundwater and vegetation monitoring	Maintenance and restoration of hydrologic dynamics, visitor interpretation	204*	Msh	37.782	-105.633	4
								205*	Msh	37.782	-105.633	4
								206*	Mdw	37.782	-105.633	4
								207*	Mdw	37.781	-105.633	5
								208*	Msh	37.781	-105.633	4

Table A-3. Great Sand Dunes National Park and Preserve Wetlands Ecological Integrity gradient sites (14), with key attributes and number of full sample events in 2010. *Site selected by the survey design but treated as a gradient site. Wetland type: Mdw = wet meadow, Msh = marsh.

Site ID	Site name	Wetland type	Complex area (ha)	Catchment area (km^2)	Lat	Lon	Number full visits (2010)
201	Visitors Center below Horse Barn	Mdw	6.952	0.628	37.730	-105.511	2
212	Middle Sand Creek Non Exclosure	Mdw	4.241	0.765	37.748	-105.691	1
213	Denton Spring	Mdw	0.552	0.811	37.747	-105.691	1
250*	Horse Barn Lower	Mdw	0.284	0.142	37.700	-105.524	2
251*	Medano Island Mosca confluence	Mdw	0.581	0.404	37.728	-105.510	1
252*	Horse Barn Upper	Mdw	12.270	110.101	37.734	-105.524	1
262*	Mitchell Pond 1	Mdw	0.581	0.398	37.727	-105.510	1
300*	San Luis Lake Mid	Mdw	0.423	15.844	37.832	-105.587	1
301*	Little Spring Crk swale	Mdw	5.318	69.796	37.668	-105.705	1
302	Little Spring Crk swale	Mdw	0.414	0.839	37.721	-105.624	1
303*	Dollar Lake South	Mdw	0.414	0.835	37.722	-105.623	1
304*	Dollar Lake West	Msh	8.475	3.110	37.722	-105.727	1
305*	Indian Spring	Msh	8.475	3.105	37.721	-105.727	1
306*	Visitors Center below Horse Barn	Msh	0.363	0.733	37.768	-105.624	1

Appendix B: Auxiliary Data

For references in this appendix please see the literature cited section that follows the main narrative.

Climate

NPS (2009, 2010) and Colwell et al. (2012) suggest understanding changing climatic conditions should be incoporated in how parks like GRSA are managed into the future. As our data are intended to help in the management of GRSA's wetland resources, we include climate in our analyses of monitoring data. Future work will continue to enhance this effort.

We use climate data from ~800-m grid cells from the Parameter-elevation Relationships on Independent Slopes Model (PRISM, PRISM Climate Group 2015; Daly et al. 2008). PRISM data are derived using an interpolation method that reflects the current state of knowledge of spatial climate patterns. A climate–elevation regression for each digital cell is generated from nearby climate station data that incorporates location, elevation, coastal proximity, topographic orientation, vertical atmospheric layer, topographic position, and orographic effectiveness of the terrain into how station data are assigned to each data point over time. Monthly temperature and precipitation were obtained for all WEI points from 1895 to 2014 using PRISM data (PRISM Climate Group 2015; Daly et al. 2008). We also use data from the National Weather Service station (COOP ID 53541) to summarize general patterns over time for the sandsheet portion of the park. PRISM data have the advantage of reflecting, even over the smaller spatial extent of the GRSA sandsheet, variation in climate due to space.

Deposition

Deposition of nitrogen (N) and other nutrients can increase productivity, eutrophication, and acidification of freshwaters, and lead to hypoxia and loss of biodiversity (Vitousek et al. 1997; Baron et al. 2011). Figure B-1 shows a map of average wet deposition in and around GRSA over a 10 year period. Deposition is modeled using PRISM climate data and National Atmospheric Deposition Program (NADP) station measured N deposition—see Baron et al. (2011) for details.

Landscape composition

Similar to the impacts of climate on park resources, the composition of landscapes in and around parks matters greatly to park resource management (Hansen et al. 2014). Intensification of anthropogenic landuse leads to the conversion of natural habitat and fragmentation of remaining natural areas in and around parks. It can also increase edge zones, reduce core areas, and change runoff of water, sediments, and nutrients (Monahan and Gross 2012).

We use a variety of landscape data sources. Most important perhaps is a vegetation map (Salas et al. 2011) produced from 2006 1:12,000-scale infrared aerial photography, 2006 National Agricultural Imagery Program (NAIP) imagery, and ground-truthing from over 800 points to interpret the complex patterns of vegetation and landuse at GRSA. While most map unit types in the vegetation map were natural, six anthropogenic landuse types were included. The vegetation map has a final accuracy of 73.7% (estimated from over 1,500 accuracy assessment points) and a minimum mapping unit of 0.5 ha that provided high resolution to resolve spatial patterns. It was also large and extended well beyond the boundaries of GRSA proper, covering several management units from a variety of government and private agencies.

Another important data source was the National Land Cover Database (NLCD; Fry et al. 2011; Homer et al. 2015). These data are the definitive Landsat-based, 30-meter resolution, land cover database for the Nation. NLCD provides spatial reference and descriptive data for characteristics of the land surface such as thematic class (for example, urban, agriculture, and forest), percent impervious surface, and percent tree canopy cover. We used NLCD data where the vegetation map was unavailable. All types were crosswalked between the vegetation map and NLCD to a common map unit.

Several data layers were obtained from the park (A. Valdez, NPS). These included a high resolution roads and trails layer, the locaion of sand dunes and escape dunes, wells, ditches, and structures. Most of these layers were created from heads up digitizing of imagery or from ground truthed GPS data. Details on these data are available upon request.

Trails and other disturbance features

NPS (2013) developed a series of landuse and land cover disturbance data layers from aerial and satellite 2012 and 2013 NAIP imagery. Linear and areal anthropogenic disturbance features were hand digitized across the sandsheet (Figure B-2 shows linear features only). One of the more prominent features included was ungulate trails. The lack of a heavy woody canopy and the aridity of the soils made these readily

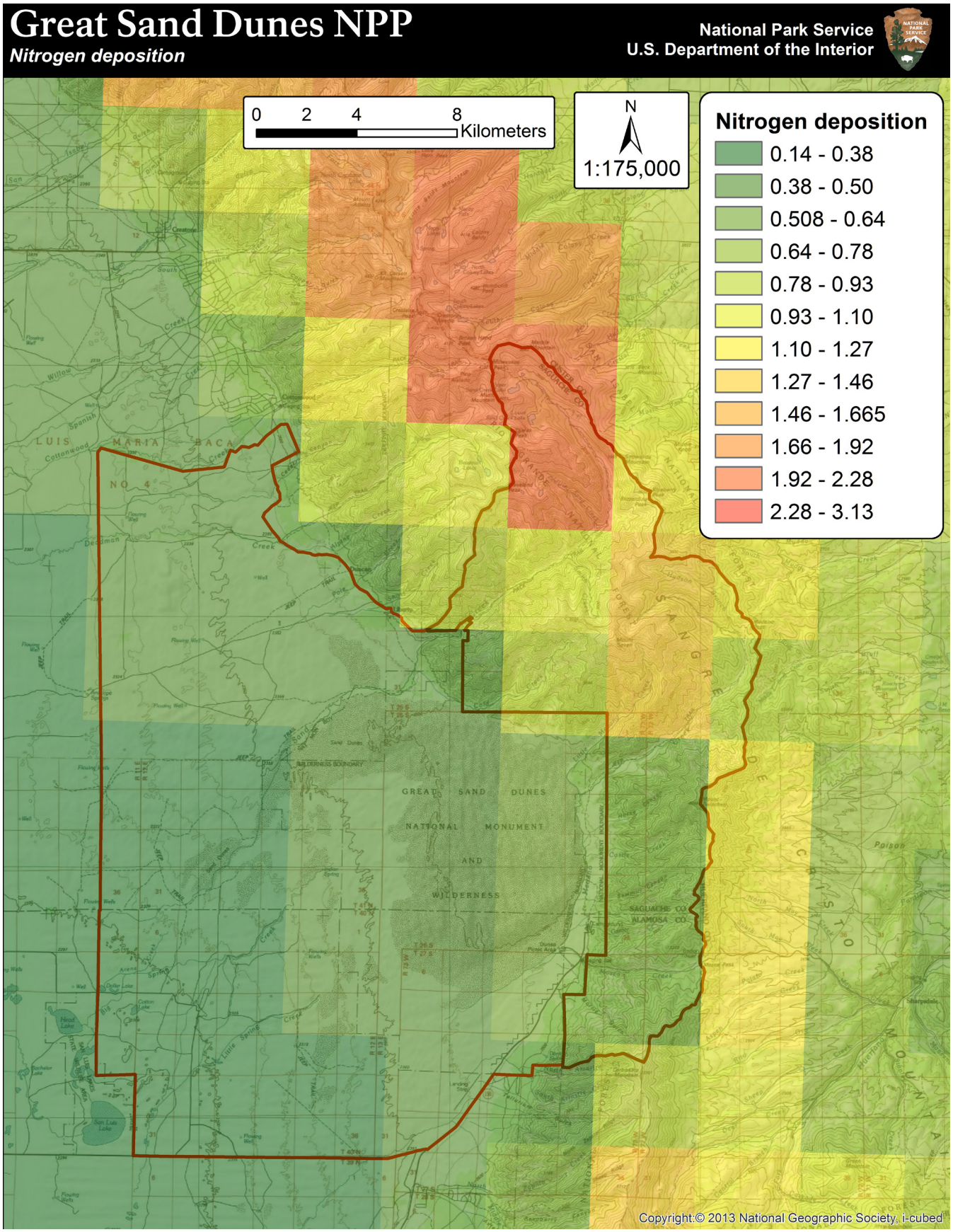


Figure B-1. Nitrogen deposition (mm of N per square meter and year) in Great Sand Dunes National Park and Preserve, 1997–2006. Background imagery courtesy National Geographic Society.

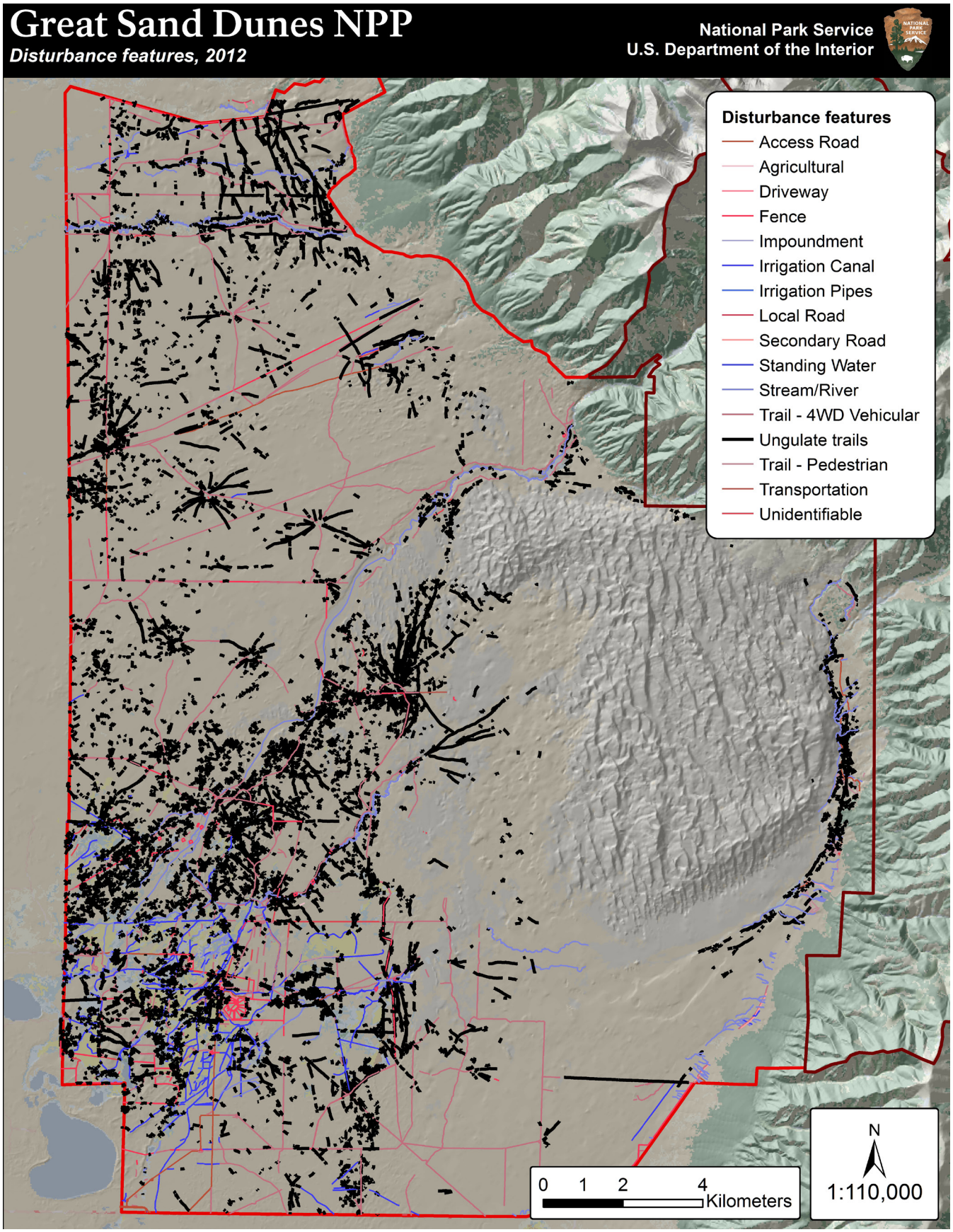


Figure B-2. Linear (including trails) and point disturbance features across the Great Sand Dunes National Park and Preserve sandsheet, 2010. Brown lines in the Figure are roads and trails.

visible. Over 14,230 trail segments were mapped at around 1150 km in total length. Around 23% of the total assessed area was double evaluated, with these quality assessments adjusting attribution and topology. These rules were applied to all other features. Final variance across analysts and line segments was low.

Bison and elk range/count (USGS)

Wockner at el. (2015) developed bison and elk ranges across the sandsheet with VHF and GPS radio collar data collected from 2005 to 2007 using flight, ground, and satellite based methods. Individual locations were used to calculate 90% kernel home range estimates (see Figure B-3 as an example for elk). Those estimates were then stacked in a GIS to yield relative density maps per 30m cell. These densities are relative concentrations of animals and only an index to actual counts. Seasonal variability of range use was very low (high overlap of range use occurred in all seasons); therefore, seasonal polygons together were merged to create unified ranges.

Productivity (USGS)

Production (pounds per acre) values by vegetation type were generated by Wockner at el. (2015) using the vegetation map and forage-production estimates by vegetation type derived from USGS field measurements. Where possible, these were compared to Natural Resources Conservation Service (NRCS 2015) forage production estimates mapped at relatively fine scale SSURGO (Soil Survey Geographic Database) data. The sandsheet had SSURGO data available, with 213,492 ha, or 64% of the study area mapped. Production in high elevation areas was represented using statewide coarse-scale production estimates (STATSGO). The alpine production estimate included data from a study conducted in central Colorado (Walker et al. 1994). Production values were generated for 1 acre pixels that were resampled to 30m.

Metrics

Data from the above sources were summarized in various metrics. Many are self-explanatory (i.e., distance to closest sand dune), yet others require brief summaries, as follows.

Climate

We used four metrics to characterize a range of lag times and seasonal patterns in precipitation. In three cases these were simple sums or means across the monthly PRISM values at a site over a given time interval. For the 30 year mean, we averaged annual precipitation across all cells in a site's catchment from 1980 to 2010.

Water balance

Stephenson (1990) presents support for several parameters that follow from the interaction of precipitation, temperature, and local site conditions on vegetation (Figure B-4). Thoma et al. (2016) show that measures can help explain pattern in vegetation within NPS Northern Colorado Plateau Network parks. Metrics include evapotranspiration (actual, AET, and potential, PET) and deficit (D)—we refer to this group of variables collectively as measures of "water balance." We calculate three water balance metrics from monthly PRISM (PRISM Climate Group 2015) data for the water year of a sample event. Potential evapotranspiration is the amount of water that could be evapotranspired with available energy if water availability was unlimited to a short grass. Actual evapotranspiration is the monthly upward loss of water from soil via transpiration and evaporation, which as limited by stored soil moisture. Finally, deficit is the amount of additional water vegetation would use if it were available, calculated as the difference between monthly PET and AET. It is a measure of absolute drought that is independent of the actual vegetation of the site. Soil water storage data are from SSURGO and STATSGO (NRCS 2015). All calculations were conducted using a toolset graciously provided by D. Thoma (NPS).

Deposition

We averaged N deposition values over each site's catchment. For some catchments, the native grid cell size or resolution of the data was not sufficient to spatially discriminate a catchment—in these cases we artificially reduce the N deposition raster size and use area weighted mean values of N deposition value for these small catchments.

Landscape composition

Most GIS derived indices were fairly simple (i.e., distance to a feature) and generated using standard procedures within a GIS. For interior wetland we used the Analytical Tools Interface for Landscape Assessments (ATtILA) (Ebert and Wade 2000; Riitters et al. 2000) modeling package. Interior wetland is defined as a cell with at least 90% of its bordering cells as wetland. This was calculated within the ATtILA package using a moving window model over a 9x9 cell search area.

Landscape integrity (CNHP)

The Colorado Natural History Program (CNHP) Landscape Disturbance Index (LDI; Lemly et al. 2011) was derived statewide by CNHP following Brown and Vivas (2005; see Figure 17 in results) from 2010 NLCD data. The LDI includes several mappable types of human disturbance, such as

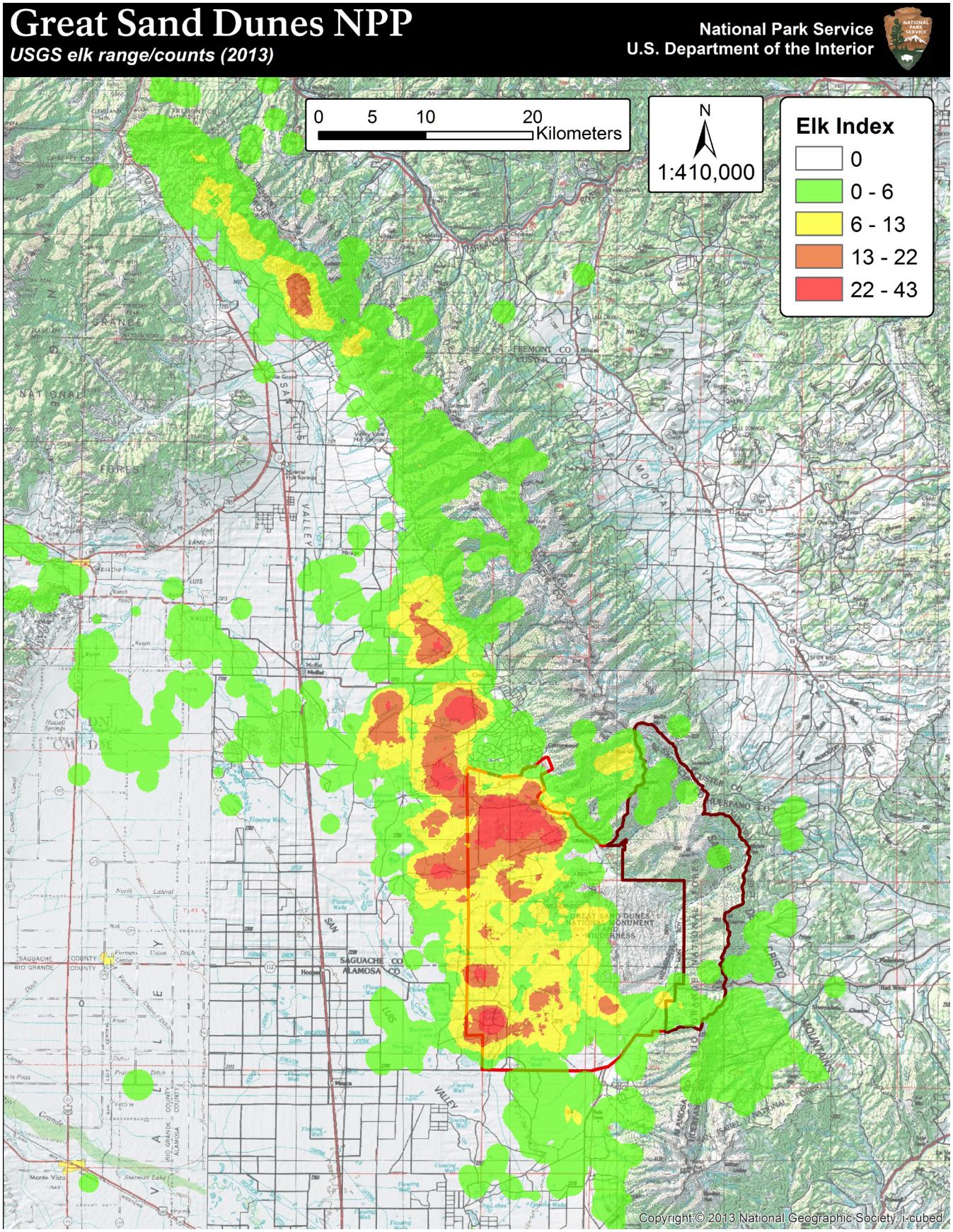


Figure B-3. Elk range/counts (2013) in and around Great Sand Dunes National Park and Preserve, from U.S. Geological Survey data.

roads and urban areas in a weighted and normalized index of disturbance. Its algorithm accounts for the decrease in magnitude of anthropogenic effects with distance from the source of disturbance (Theobald et al. 1997) with a cutoff or limit to the effect distance. The form of the decay curve varies with disturbance type and was developed and refined by CNHP in discussions with partners (including NPS) engaged in conservation management.

To attach LDI values to each WEI site at GRSA, we determined that the best model based on patterns within with WEI condition metrics and our other disturbance indices was the 2008 statewide version and the best scale at which to summarize values was a 1 km buffer around each site. Interestingly the statewide LDI model performed better than a custom GRSA model. Summarization of LDI across a buffer removes some of the complex distance weighting used in the CNHP model, but point based treatments of LDI did not show a strong pattern with WEI condition metrics nor other disturbance indices.

Bison, elk, production and trails indices

Our Elk and Bison Indices used the total number of overlapping elk or bison ranges from Wockner et al. (2015) within each 30m grid cell within the park as source data. We constructed a Bison Index as the total count of overlapping ranges within a 100m buffer around each WEI site. For elk we used total number of overlapping ranges across a 1 km buffer. We chose these two different scales based on qualitative patterns in the spatial scales of bison or elk data. Bison were more clumped in their distribution, whereas elk counts tended to be spread across a larger area. We also examined the covariance between various scales and summarization methods for these data with UUI and selected those that resulted in the highest correlations with UUI. Note that the Bison Index is, by definition, zero for sites outside of 100m from the bison fence.

To create a Trail Index and a production metric, we followed similar logic. Our analyses suggested the best Trail Index to be the total length of trails, corrected for area, with a 100m buffer around each site. Our analyses also suggested that the best index of productivity was the point scale value for the associated grid cell. For trails this seemed to visually match the scale at which trails seemed to be meaningfully associated with a feature, such as a wetland or stock tank.

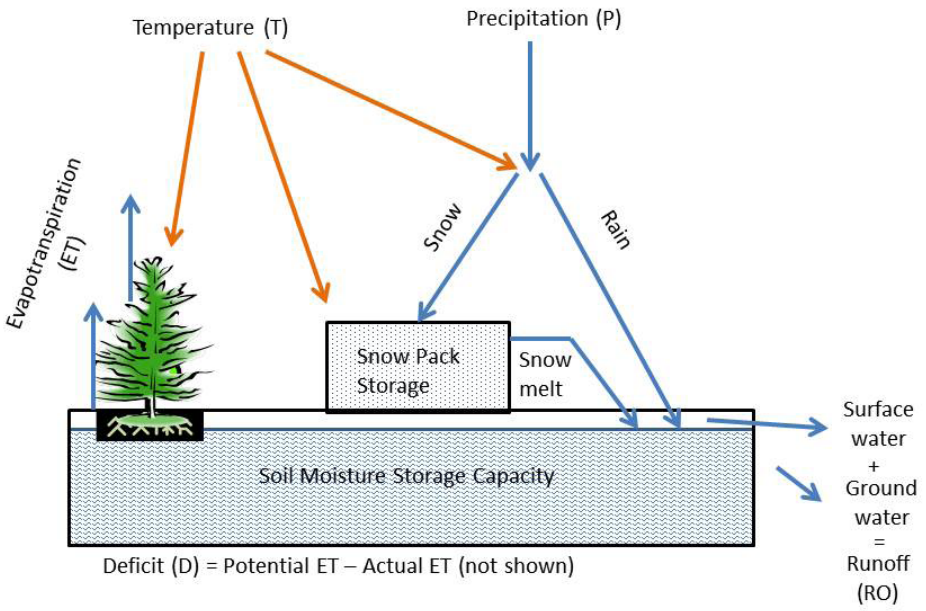


Figure B-4. Conceptual relationships behind water balance metrics. Graphic courtesy of D. Thoma, NPS.

Appendix C: Detailed Analysis Methods

For references in this appendix please see the literature cited section that follows the main narrative.

The following sections present summaries of how GRSA data were analyzed and interpreted. We present general overviews of analytical strategies in Schweiger et al. (2015). However, this report is the first time we have detailed our modeling so there is more content here. We group the narrative by the general type of analysis rather than the order of objectives, but do link each analysis back to relevant motivating objective.

Note for sites with replicates within 2010, most analyses use the sample event where phenology was nearest to peak, the crew consisted of the best trained botanists, and the groundwater table was at its lowest (thus vegetation most stressed). These events are referred to in this document as the "best" sample event. Replicate events at sites may be used in select analyses, such as power models, estimates of precision, and as test data for bioassessment models.

To meet WEI objectives we analyze quality assured data and metrics derived from measures using models or statistical procedures. Ideal metrics describe characteristics that change in predictable ways with wetland condition (Barbour et al. 1999). In some cases, the process of generating metrics is involved and requires several years of data and research to complete. Schweiger et al. (2015) presents more detail on metrics used in WEI analyses at GRSA.

All code for the more involved predictive and trend models, MMIs, and design based analysis is available upon request from the Network and will appear in a future revision of the WEI protocol as detailed standard operating procedures (SOPs).

Status

We define status as a "snap shot" evaluation of a WEI response over a well-defined and relatively concise range in time (Olsen et al. 1999). It is estimated using a variety of tools for all WEI variables.

Model based descriptive statistics

Objective four (determine the status for select sites in a suite of response measures) requires analyses that estimate the status of select wetland responses at site scales. We use traditional or model-based analyses that summarize data as means and various measures of the variance around a mean. Results are presented in simple tables and a variety of Figures. For select responses we use "bubble plots" or maps of a response at our sites in GRSA. In some cases, tabular results are grouped by important factors like wetland type or sample design. Importantly, model-based results, including both simple descriptive statistics as well as more complex predictive models, apply only to the sites included in an analysis.

Understanding status: exploratory models

Objective seven (relate spatial and temporal patterns in select wetland responses to important ecological and anthropogenic drivers) requires more complex analyses that facilitate understanding of ecological and statistical connections among WEI responses, drivers of wetland condition, and important covariates that influence these patterns. To address this we develop exploratory linear models of select responses, focusing on independent variables (also referred to as drivers or predictors) that might best help us understand patterns in a response and that therefore might aid in wetland management. Importantly, these models apply only to the sampled sites and we make no inference to unsampled wetlands in GRSA. However, given our representative sample design, we expect the results to be broadly generalizable.

We keep these models as simple as possible by assuming all independent variables are fixed effects and we omit interaction terms. Given limitations in sample size and period of record, we do not consider these models to be predictive. Rather they are (examples) of explorations into potentially important connections amongst key estimates of a wetland response. While these models are in essence descriptive and limited in predicting novel data, they are useful in that they reveal patterns and connections that might assist the park in improving or protecting wetland condition. Future work may support complementary predictive models, with more rigorous confirmation via techniques such as cross validation.

We tested each candidate variable for the assumptions of linear models and transformed as needed. We selected candidate independent variables for each model using a series of steps. First, we developed an initial list based on inclusion of interpretable variables from across the classes of responses measured in WEI monitoring. Second, we used variables that were not confounded with one another based on checks for multicollinearity, choosing the most interpretable variable from pairs or sets of highly correlated variables. We then conducted forwards and backwards stepwise selection based

on Akaike Information Criterion (AIC) values using the R library MASS and the stepAIC() function (Venables and Ripley 2002). Final models were constructed by hand based on the stepwise output, followed by additional rounds of expert opinion for culling or re-including independent variables based on a variable's interpretation and change in AIC value of the candidate model. While stepwise procedures have been criticized (i.e., Zuur et al. 2010), our approach is not entirely automated and we feel that the use of AIC coupled with interpretations of the ecological relationships among a response and a candidate predictor(s) was justified. Note that we did use and do report p values for secondary support in variable selection. While this is a subject of much debate, we felt it appropriate for our exploratory purposes (*sensu* Murtaugh 2014). Models were built using the lm() function within the stats library in R version 3.2.3 (Chambers 1992; R Development Team 2014).

To assist in the interpretation of the final model we estimated the relative contributions of each of the predictors to a model's total explanatory value. We used a classic, but recently much improved, approach (Grömping 2006) implemented within the R library relaimpo of averaging sequential sums of squares over orderings of regressors (Lindeman et al. 1980; Kruskall 1987). This produces estimates of each predictor's importance relative to the total amount of explained variance expressed as a simple percentage. These estimates consider both direct effects (i.e., correlations with the response) and the predictor's effect when combined with the other variables in the regression equation. Furthermore, the method averages over all possible orderings of predictors in a model, thereby dealing with multicollinearity (Grömping 2006).

Finally, we use conditional plots of partial residuals to visualize these models (Larsen and McCleary 1972; Breheny and Burchett 2013). A partial residual plot is a graphical technique that shows the relationship between a given independent variable and the response variable, given that other independent variables are also in the model. The plot shows the value of the variable on the x-axis and the change in response on the y-axis, holding all other variables constant (by default, median for numeric variables and most common category for factors).

Understanding status: clustering, indicator species, and ordination of vegetation data

To further address objectives four (determine the status for select sites in a suite of response measures) and seven (relate spatial and temporal patterns in select wetland responses to important ecological and anthropogenic drivers) for wetland vegetation, we use exploratory and descriptive multivariate classification and ordination techniques. These models examine relationships between vegetation composition patterns and the underlying environmental gradients that might be influencing these patterns. They support interpretation of how vegetation communities are structured relative to environmental gradients or anthropogenic disturbance and are very useful as setup to successive bioassessment models. We use 2010 best sample data from all design types and do not statistically infer results to unsampled sites. We used only species level identifications. Our ordinations are an analysis of status with no explicit incorporation of time—future work may include temporal ordinations.

We first conducted cluster analysis to assess our *a priori* classification of wetland type. We follow McCune and Grace (2002) and apply hierarchical agglomerative cluster analysis using a space-conserving Ward's method with a Euclidean distance measure on relative species abundance. Because rare species often obscure clustering of sites, species that occurred in fewer than three plots were removed to better isolate community structure and minimize chaining. Methods from Beals (1984) were used to minimize chaining stemming from the large number of zero values in the species matrix. Percentages of floristic similarity and resulting branching on the dendrogram were used to assess community groups and outliers. Clustering utilized PC-ORD v.5.10 (McCune and Mefford 2006).

We identify species most representative of wetland types using Dufrêne and Legendre's (1997) method of indicator species analysis. Higher Indicator values (IV) suggest fidelity of a species to a particular wetland type, with an IV of 100 indicating that the given species was always present in that wetland type and exclusive of all other types. Statistical significance for each IV value was tested using a Monte Carlo randomization method with 5k permutations.

We then conducted ordination to better understand how select environmental gradients map on to multivariate space. We used Sorenson (Bray-Curtis) distance matrices calculated from relative abundances. Species occurring in less than three plots were first removed. Data were standardized using the decostand method in vegan with a log base 10 transformation (Anderson et al. 2006). Based on an examination of the distance matrices, a parametric ordination method of principal coordinates analyses (PCoA) was used with the "extended distance" method to deal with samples with low similarity (De'ath 1999). An ordination technique other than nonmetric multidimensional scaling (NMDS) was deemed

suitable because the extended distance adjustment provides a reasonable solution to the zero-truncation problem commonly found in community matrices and allowed a parametric model where the axes have defined meaning. All models were conducted with the R package vegan (Oksanen et al. 2016).

We chose environmental variables to include in an ordination based on likely relationships with wetland vegetation structure. Variables were included in the ordination plots based on Bonferroni corrected p values for the R2 of the variable with a PCoA axis that were less than 0.05. The goodness of fit (p value) was calculated using 9999 permutations of the models.

Bioassessment: multimetric indices

Bioassessment is, generally speaking, the use of biologically based response measures to assess and monitor natural systems (Barbour et al. 2000). We use the approach to further meet objective four (determine the status for select sites in a suite of response measures) as a synthetic way to estimate wetland status (Schweiger et al. 2015). We use a multimetric index (MMI; classically known as an index of biotic integrity or IBI) as our primary way of estimating ecological integrity. MMIs synthesize data from multiple levels of biological organization with the goal of deriving a single index that reflects the overall effects of disturbance on wetland integrity. Importantly, at GRSA we use both human disturbance (Human Disturbance Index, HDI) and ungulate disturbance (Ungulate Use Index, UUI) to create two MMIs that reflect these sources of disturbance in the park. The UUI was constructed and used at the request of park managers to help inform the Ungulate Management Plan (UMP) effort.

Schoolmaster et al. (2012) and Schoolmaster et al. (2013a, b) refine the theory behind MMIs and present the methods we used in detail. Key features of the approach include:

1. Control of potentially confounding influences of environmental covariates using a strategy based on causal graphical models (key in wilderness parks like GRSA where wetland condition can vary markedly along natural gradients).
2. Use of the complete data set to adjust for environmental gradients, simultaneously considering the effects of disturbance and environmental covariates on metrics in a single model, not a series of residualized adjustments as in other methods that require an *a priori* classification of sites into reference and non-reference.
3. A statistically optimal number of metrics are in a final MMI.
4. Accounting for correlations among candidate component metrics and their impacts on the performance of the MMI.
5. Incorporation of metrics in final MMI index only if they improve the performance of the model—this process depends nonlinearly on the signal of the disturbance gradient, the noise (error) of the metric, and the correlation of the metric errors.
6. Use of an information-theoretic model selection approach to assemble and select the final MMI—this evaluates all possible combinations of component metrics and guarantees a statistically best model for any empirical data set.

Overall, this modeling approach requires fewer assumptions and is more efficient with the given information than classic methods; thus, it represents an important advance for creating synthetic bioassessments of system response.

A summary of the steps used to create an MMI follows (Figure C-1; Schoolmaster et al. (2012) and Schoolmaster et al. (2013a, b)):

1. Develop conceptual graphical model of the relationships amongst disturbance, metrics, and environmental covariates. These can be based on ecological knowledge and/or other models of patterns in the data.
2. Assemble disturbance indices (i.e., HDI or UUI).
3. Assemble set of candidate vegetation metrics.
4. Evaluate all possible vegetation metrics for interpretability (expert opinion), completeness (remove any with missing and/or 0 values below a threshold of 25%), and multicollinearity (remove one from pairs with a $r > 0.95$, choosing those that are more interpretable).
5. Construct MMI:
    a. Reflect metrics that are positively correlated with disturbance to ensure each metric (and final MMI) is negatively correlated with disturbance.
    b. Adjust metrics for important covariates using an approach that uses all available data to model metrics as a function of known gradients and disturbance simultaneously.
    c. Scale metrics from 1 to 10 (Blocksom 2003).
    d. Select an initial metric (m1) to include in the MMI. This selection can be made arbitrarily since all metrics will eventually be used as an initial metric.
    e. Add m1 to each of the rest of the metrics, mj, site-by-site.

f. For each mj, find which combination m1 + mj with the strongest negative correlation with disturbance. Select that one.

g. Record the correlation (or other statistic) of the relationship between the assembled index with disturbance.

h. Add the index to each of the remaining metrics mj ,site-by-site.

i. Find the combination of index + mj that has the strongest negative correlation with disturbance. Select this as a MMI based on AIC scores.

   i. Near equivalent (statistically the same) models are reported, such that final selection may also be based on the metrics included in each.

   ii. A model averaging approach is also used that creates a MMI as a matrix product of all equivalent MMIs and their AIC scores as weights. Component metrics within this model are the combined list from all near equivalent MMIs.

Design based status

For objectives one and two (determine population scale status in wetland area and a suite of response measures) we use data from survey sites and design-based analyses that provide inference to an extensive target population of the park's wetlands. Design-based analyses are well specified (Horvitz and Thompson 1952; Overton and Stehman 1996; Stevens 1997) and are the foundation of long-established analyses used in socioeconomics, politics, medicine, and other fields. While beyond our scope here, in summary, design-based analyses use the inclusion probabilities (or sampling weights) from the design to extrapolate results or provide inference to unsampled elements of the target population. Results from design-based analyses apply (with the precision given in a confidence interval or standard error about an estimate) to all sandsheet salt flat–wet meadows in GRSA in 2010. We report design-based results for most core WEI responses in tables and plots (using a cumulative distribution function; CDF). CDFs include a confidence interval around the distribution of probabilities as estimates of the uncertainty in population scale inference (Stevens 1997).

For the assessment of population scale results (objective three) where assessment points are known, we estimate and graphically show the proportion and/or real unit-based extent of a wetland response that is above or below the assessment point and interpret these patterns using ecological theory and NPS management guidance. This process is well suited to Figures created from CDFs as we can locate the proportion and/or real unit-based percentage of the response that is above or below the assessment point on these plots. We also use simple pie charts to illustrate the

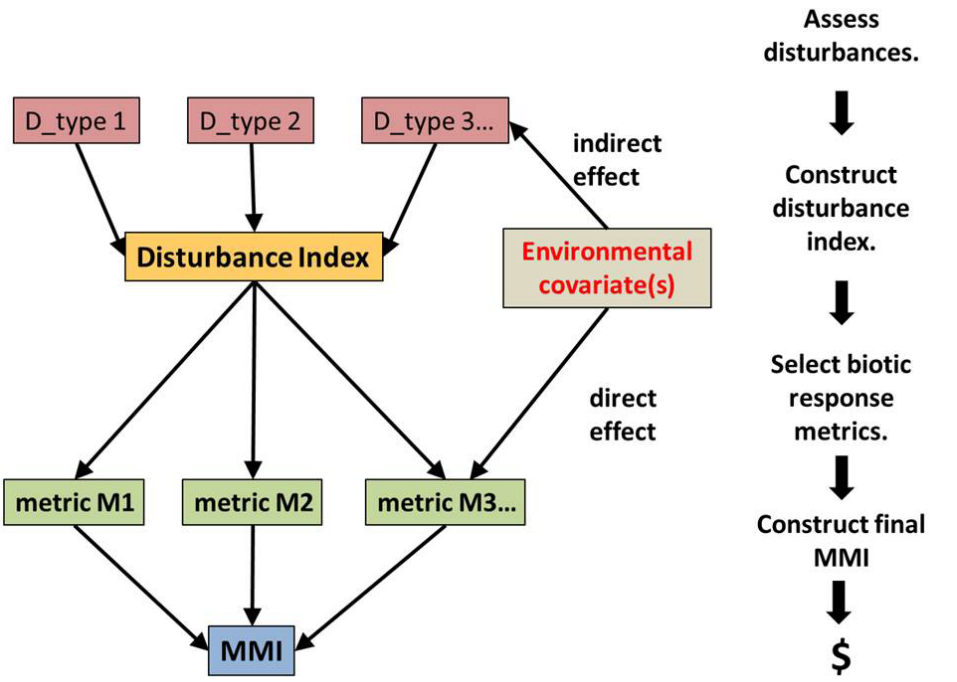


Figure C-1. General flowchart for creating an MMI.

proportion of a population in an assessment class, although these limit the inclusion of estimates of the variance around a value and should be used with caution.

For population scale status (objective two), we use design-based analysis. This is a less familiar approach than model-based analyses; however, it is a central component of any Network protocol that includes a population scale perspective and survey designs such as wetland monitoring at GRSA.

Design-based inference uses a suite of algorithms detailed in Horvitz and Thompson (1952) and Diaz-Ramos et al. (1996) and implemented in the R library spsurvey (Kincaid and Olsen 2015). We report population means, 95% confidence intervals to the means, and standard errors (vs. a standard deviation, as our interest is in how we expect results to vary from a population mean). Confidence intervals and standard errors are based on estimates of variance that take advantage of the properties of a GRTS (Generalized Random Tessellation Stratified) design. Known as a local neighborhood variance (Stevens and Olsen 2003, 2004), it provides estimates 20 to 60% smaller (i.e., more precise) than traditional survey-design variance estimators.

Wetland extent estimation details

To estimate wetland extent for all types across the entirety of GRSA, we use the most current remotely sensed data (see Table 6) and its interpretation from Salas et al. (2011) as modified in our development of the survey design sample frame (Schweiger et al. 2015). Our edits included reclassifications and adjustments to patch boundaries based on detailed examination of imagery and incorporation of site level data. In total we made 305 substantive edits to the 586 (52%) polygons in the sample frame. We summarize final area within the three most relevant wetland classification systems (WEI, the Vegetation Map, and Ecological Systems; Table C-1) by sandsheet and high elevation sites. Because the three systems do not crosswalk one to one with one another, there is some duplication within the table. We use WEI type as the primary structure in Table 6.

We also estimate extent for salt flats and wet meadows on the sandsheet using design-based methods. Source data for these analyses were the mean percent of the 100 m2 area around each of the 302 evaluated 2nd stage design points that was a WEI wetland type (excluding fens, which do not occur on the sandsheet), upland, or water (Table 7). This approach takes advantage of the site level assessment of wetland type inferred to all sandsheet wetland using properties of the survey design (Table 8).

To estimate site specific wetland extent for sentinel site complexes, we use Salas et al. (2011) as modified by (Schweiger et al. 2015). Future work should include more detailed complex level delineation and/or focused updates of remotely sensed data to better understand how the area of these important wetlands is changing through time.

Table C-1. Wetland extent by wetland type at Great Sand Dunes National Park and Preserve, 2010. Results derived following Salas et al. (2011) using 1:12k imagery hand and auto digitized with park-specific map unit names cross walked to Ecological Systems and Wetland Ecological Integrity (WEI) wetland types. Site location code: high = high elevation.

Trend

Trend in episodic data: mixed effect models

Objective five (determine the long-term trend in the condition of select wetland responses at specific sentinel sites or complexes) requires analyses that estimate trend in WEI responses collected annually at sentinel sites. Our approach follows work by the NPS Sierra Nevada Inventory and Monitoring Network (Heard et al. 2012), especially the statistical tools developed by L. Starcevich.

We construct linear mixed-effects models using a restricted maximum likelihood approach (REML; VanLeeuwen et al. 1996) that specifically address trend estimation for correlated data (i.e., the correlations across time that naturally occur in repeated measures ecological data). These models are parametric and we therefore first test and correct for the assumptions of independent and normally distributed errors with equal variance using histograms and Q-Q plots of residuals. Mixed models allow effects to be considered either "fixed" or "random." Fixed effects contribute to the mean of the outcome and random effects contribute to its variance. Following Heard et al. (2012) and Piepho and Ogutu (2002), we model sites as fixed and years as random effects. The designation of terms as either fixed or random is an important and complex process; however, Piepho and Ogutu (2002) develop methods that, for REML, allow site as we use it to be fixed or random based on the type of design used. GRSA sentinel sites were selected by a targeted (vs. random) design and so the proper form for the site effect is fixed. We treat years as a random variable given that we only have a small sample of all possible years and thus we assume the years included in our models are realized values of a truly random variable. Moreover, Piepho and Ogutu (2002) recommend modeling the site intercept as fixed so that convergence problems are avoided and because this optimizes test power

when residual variance is large. For select responses we use the single year (2010) exploratory models (see above) to select a limited set of covariates and include these in each model as additional fixed effects. Because we have an interest in measuring net trend over time as a percent change (i.e., what is the total percent change from 2010 to 2014), we use both a logged and untransformed version of each response. We use Satterthwaite degrees of freedom (Piepho and Ogutu 2002) for the tests of trend and confidence interval construction. Finally, because mixed models do not generate a model R2, yet this is a very useful metric of the model's quality, we approximate this using the correlation between fitted and observed values (Xu 2003). We implement the mixed models in the R library lmerTest (Kuznetsova et al. 2013) which references the R library lme (Bates et al. 2014).

Trend in continuous time series data: generalized additive mixed model

Objective five also requires models that estimate trend in the hydrologic regime collected daily at sentinel sites. Groundwater hydrology time series data typically exhibit strong periodicity and often nonlinear patterns of change. Methods such as simple regression assume linear trends and have no provision to deal with serial autocorrelation. These models may therefore provide a poor fit to time series data. To estimate trend in daily mean depth to water (DTW) from 2010 to 2014 at our sentinel site wells, we therefore used a generalized additive model (GAM; Wood 2011) in which smooth functions were used for select predictor(s), and an autocorrelation-moving average model applied to account for temporal structure in the DTW data (Box et al. 1994). We structured the DTW data as the daily average for spring to fall periods within each year where nearby climate stations and field visits suggested the well was not covered in snow (snow confuses the pressure transducers in the loggers and makes DTW data unreliable). We fit various GAM models to estimate these daily data to estimate the pattern of within-year variation, and then tested for across-year variation (trend). Models that used one smooth form for all sites versus individual smooths by site were compared via AIC. We used the mgcv library in R for the gam with the corARMA function from the nlme library to test for autocorrelation. All models were constructed following guidance from T. Philippi (NPS). Given limited data and incomplete understanding of the drivers of site level hydrologic regimes, they should be considered draft.

Table C-1. Wetland extent by wetland type at Great Sand Dunes National Park and Preserve, 2010. Results derived following Salas et al. (2011) using 1:12k imagery hand and auto digitized with park-specific map unit names cross walked to Ecological Systems and Wetland Ecological Integrity (WEI) wetland types. Site location code: high = high elevation.

Site location	WEI type	VegMap	Ecological systems	Count	Total (ha)	Mean patch size (ha)	SD patch size (ha)	% of total wetland area	% of total GRSA area
high	fen	–	–	5	1.47	0.29	0.12	0.04	0.002
high	fen	Alpine - Upper Subalpine Herbaceous Wetland Alliances	Rocky Mountain Alpine-Montane Wet Meadow	4	3.74	0.94	1.00	0.11	0.006
high	fen Total	–	–	9	5.21	0.58	0.74	0.15	0.009
high	riparian	–	–	3	8.21	2.74	0.50	0.24	0.014
high	riparian	Alpine - Upper Subalpine Herbaceous Wetland Alliances	Rocky Mountain Alpine-Montane Wet Meadow	2	2.41	1.21	0.59	0.07	0.004
high	riparian	Montane Riparian Shrubland Alliances	Rocky Mountain Subalpine-Montane Riparian Shrubland	5	35.68	7.14	12.09	1.04	0.059
high	riparian	Montane-Lower Subalpine Wetland Alliances	Rocky Mountain Alpine-Montane Wet Meadow	8	9.87	1.23	0.74	0.29	0.016
high	riparian	Narrowleaf Cottonwood Sand Dune Woodland Association	Inter-Mountain Basins Active and Stabilized Dune	1	3.47	3.47	0.00	0.10	0.006
high	riparian	Narrowleaf Cottonwood Temporarily Flooded Woodland Alliance	Rocky Mountain Lower Montane-Foothill Riparian Woodland and Shrubland	18	165.90	9.22	15.70	4.82	0.274
high	riparian	Subalpine Riparian Forest Alliances	Rocky Mountain Subalpine-Montane Riparian Woodland	21	89.03	4.24	4.22	2.59	0.147
high	riparian	Subalpine-Alpine Riparian Shrubland Alliances	Rocky Mountain Subalpine-Montane Riparian Shrubland	1	0.74	0.74	0.00	0.02	0.001
high	riparian Total	–	–	59	315.31	5.34	10.14	9.17	0.521
high	wet meadow	–	–	5	2.53	0.51	0.49	0.07	0.004
high	wet meadow	Alpine - Upper Subalpine Herbaceous Wetland Alliances	Rocky Mountain Alpine-Montane Wet Meadow	25	81.68	3.27	6.12	2.37	0.135
high	wet meadow	Subalpine Riparian Forest Alliances	Rocky Mountain Subalpine-Montane Riparian Woodland	1	2.62	2.62	0.00	0.08	0.004
high	wet meadow	Subalpine-Alpine Riparian Shrubland Alliances	Rocky Mountain Subalpine-Montane Riparian Shrubland	16	77.71	4.86	6.14	2.26	0.128
high	wet meadow	Winterfat Dwarf-shrubland Alliance	–	2	2.62	1.31	0.30	0.08	0.004
high	wet meadow Total	–	–	49	167.17	3.41	5.76	4.86	0.276

Table C-1 (*continued*). Wetland extent by wetland type at Great Sand Dunes National Park and Preserve, 2010. Results derived following Salas et al. (2011) using 1:12k imagery hand and auto digitized with park-specific map unit names cross walked to Ecological Systems and Wetland Ecological Integrity (WEI) wetland types. Site location code: high = high elevation.

Site location	WEI type	VegMap	Ecological systems	Count	Total (ha)	Mean patch size (ha)	SD patch size (ha)	% of total wetland area	% of total GRSA area
high Total		–	–	117	487.69	4.17	8.23	14.18	0.806
sandsheet	marsh	–	–	1	0.23	0.23	0.00	0.01	0.000
sandsheet	marsh	Emergent Marsh Alliances	Inter-Mountain Basins Alkaline Closed Depression, NA Arid West Emergent Marsh	1	3.04	3.04	0.00	0.09	0.005
sandsheet	marsh	–	North American Arid West Emergent Marsh	19	311.99	16.42	37.52	9.07	0.516
sandsheet	marsh	Playa Alliances	Inter-Mountain Basins Playa	1	1.55	1.55	0.00	0.04	0.003
sandsheet	marsh	San Luis Valley Mesic Meadow Alliances	Inter-Mountain Basins Alkaline Closed Depression	7	40.15	5.74	2.85	1.17	0.066
sandsheet	marsh	San Luis Valley Mesic Meadow Alliances, Emergent Marsh Alliances	Inter-Mountain Basins Alkaline Closed Depression, NA Arid West Emergent Marsh	1	15.69	15.69	0.00	0.46	0.026
sandsheet	marsh	–	North American Arid West Emergent Marsh, IM Basins Alkaline Closed Depression	1	22.85	22.85	0.00	0.66	0.038
sandsheet	marsh	Water	–	3	26.28	8.76	5.99	0.76	0.043
sandsheet	marsh Total	–	–	34	421.78	12.41	28.72	12.26	0.697
sandsheet	riparian	Coyote Willow Temporarily Flooded Shrubland Alliances	Rocky Mountain Lower Montane-Foothill Riparian Woodland and Shrubland	9	13.47	1.50	1.21	0.39	0.022
sandsheet	riparian	Emergent Marsh Alliances	North American Arid West Emergent Marsh	4	58.03	14.51	17.04	1.69	0.096
sandsheet	riparian	Narrowleaf Cottonwood Sand Dune Woodland Association	Inter-Mountain Basins Active and Stabilized Dune	28	23.95	0.86	0.62	0.70	0.040
sandsheet	riparian	Narrowleaf Cottonwood Temporarily Flooded Woodland Alliance	Rocky Mountain Lower Montane-Foothill Riparian Woodland and Shrubland	49	233.84	4.77	8.98	6.80	0.386
sandsheet	riparian	San Luis Valley Mesic Meadow Alliances	Inter-Mountain Basins Alkaline Closed Depression	2	1.71	0.86	0.24	0.05	0.003
sandsheet	riparian Total	–	–	92	331.00	3.60	8.04	9.62	0.547
sandsheet	salt flat	–	–	12	18.95	1.58	1.62	0.55	0.031
sandsheet	salt flat	–	Inter-Mountain Basins Semi-Desert Grassland, Inter-Mountain Basins Playa	1	1.56	1.56	0.00	0.05	0.003

Table C-1 (*continued*). Wetland extent by wetland type at Great Sand Dunes National Park and Preserve, 2010. Results derived following Salas et al. (2011) using 1:12k imagery hand and auto digitized with park-specific map unit names cross walked to Ecological Systems and Wetland Ecological Integrity (WEI) wetland types. Site location code: high = high elevation.

Site location	WEI type	VegMap	Ecological systems	Count	Total (ha)	Mean patch size (ha)	SD patch size (ha)	% of total wetland area	% of total GRSA area
sandsheet	salt flat	–	Upland other	9	5.99	0.67	1.20	0.17	0.010
sandsheet	salt flat	Alluvial Flat Herbaceous Alliance	Inter-Mountain Basins Playa	1	12.18	12.18	0.00	0.35	0.020
sandsheet	salt flat	Alluvial Flat Herbaceous Alliances	Inter-Mountain Basins Semi-Desert Grassland	49	198.86	4.06	5.79	5.78	0.329
sandsheet	salt flat	Alluvial Flat Herbaceous Alliances, Playa Alliances	Inter-Mountain Basins Playa, Inter-Mountain Basins Semi-Desert Grassland	1	10.49	10.49	0.00	0.30	0.017
sandsheet	salt flat	Alluvial Flat Herbaceous Alliances, San Luis Valley Mesic Meadow Alliances	Inter-Mountain Basins Semi-Desert Grassland and Alkaline Closed Depression	1	19.17	19.17	0.00	0.56	0.032
sandsheet	salt flat	Emergent Marsh Alliances	North American Arid West Emergent Marsh	1	1.88	1.88	0.00	0.05	0.003
sandsheet	salt flat	Greasewood Alliance	–	1	2.72	2.72	0.00	0.08	0.004
sandsheet	salt flat	Greasewood Flat Shrubland and Steppe Alliance	–	1	0.79	0.79	0.00	0.02	0.001
sandsheet	salt flat	Playa Alliances	Inter-Mountain Basins Playa	24	112.84	4.70	6.05	3.28	0.187
sandsheet	salt flat	Playa Alliances, Alluvial Flat Herbaceous Alliances	Inter-Mountain Basins Semi-Desert Grassland, Inter-Mountain Basins Playa	1	7.64	7.64	0.00	0.22	0.013
sandsheet	salt flat	San Luis Valley Mesic Meadow Alliances	Inter-Mountain Basins Alkaline Closed Depression	14	129.52	9.25	12.61	3.76	0.214
sandsheet	salt flat	San Luis Valley Mesic Meadow Alliances, Alluvial Flat Herbaceous Alliances	Inter-Mountain Basins Semi-Desert Grassland, Alkaline Closed Depression	1	8.02	8.02	0.00	0.23	0.013
sandsheet	salt flat	San Luis Valley Mesic Meadow Alliances, Playa Alliances	Inter-Mountain Basins Playa, Inter-Mountain Basins Alkaline Closed Depression	1	31.61	31.61	0.00	0.92	0.052
sandsheet	salt flat	Sandsheet Rabbitbrush	–	1	0.33	0.33	0.00	0.01	0.001
sandsheet	salt flat Total	–	–	119	562.56	4.73	7.37	16.35	0.930
sandsheet	wet meadow	–	–	17	78.82	4.64	11.26	2.29	0.130
sandsheet	wet meadow	–	Upland other	1	0.17	0.17	0.00	0.00	0.000
sandsheet	wet meadow	Alluvial Flat Herbaceous Alliances	Inter-Mountain Basins Semi-Desert Grassland	27	105.04	3.89	3.77	3.05	0.174

Table C-1 (*continued*). Wetland extent by wetland type at Great Sand Dunes National Park and Preserve, 2010. Results derived following Salas et al. (2011) using 1:12k imagery hand and auto digitized with park-specific map unit names cross walked to Ecological Systems and Wetland Ecological Integrity (WEI) wetland types. Site location code: high = high elevation.

Site location	WEI type	VegMap	Ecological systems	Count	Total (ha)	Mean patch size (ha)	SD patch size (ha)	% of total wetland area	% of total GRSA area
sandsheet	wet meadow	Alluvial Flat Herbaceous Alliances, San Luis Valley Mesic Meadow Alliances	Inter-Mountain Basins Alkaline Closed Depression, Basins Semi-Desert Grassland	2	4.15	2.07	0.93	0.12	0.007
sandsheet	wet meadow	Emergent Marsh Alliances	North American Arid West Emergent Marsh	10	11.71	1.17	0.91	0.34	0.019
sandsheet	wet meadow	Interdunal Swale Wetland Alliances	Inter-Mountain Basins Interdunal Swale Wetland	33	25.15	0.76	0.79	0.73	0.042
sandsheet	wet meadow	San Luis Valley Mesic Meadow Alliances	Inter-Mountain Basins Alkaline Closed Depression	122	1252.07	10.26	30.19	36.39	2.069
sandsheet	wet meadow	–	Inter-Mountain Basins Alkaline Closed Depression, NA Arid West Emergent Marsh	1	10.45	10.45	0.00	0.30	0.017
sandsheet	wet meadow	–	Inter-Mountain Basins Alkaline Closed Depression, San Luis Valley Mesic Meadow	1	83.68	83.68	0.00	2.43	0.138
sandsheet	wet meadow	San Luis Valley Mesic Meadow Alliances, Alluvial Flat Herbaceous Alliances	Inter-Mountain Basins Alkaline Closed Depression	1	4.99	4.99	0.00	0.15	0.008
sandsheet	wet meadow	–	Inter-Mountain Basins Alkaline Closed Depression, IMB Semi-Desert Grassland	3	30.15	10.05	2.76	0.88	0.050
sandsheet	wet meadow	–	Inter-Mountain Basins Semi-Desert Grassland, IMB Alkaline Closed Depression	1	6.94	6.94	0.00	0.20	0.011
sandsheet	wet meadow	San Luis Valley Mesic Meadow Alliances, Emergent Marsh Alliances	Inter-Mountain Basins Alkaline Closed Depression, NA Arid West Emergent Marsh	3	23.29	7.76	4.53	0.68	0.038
sandsheet	wet meadow	Sandsheet Rabbitbrush	–	1	0.19	0.19	0.00	0.01	0.000
sandsheet	wet meadow	Water	–	1	0.42	0.42	0.00	0.01	0.001
sandsheet	wet meadow Total	–	–	224	1637.23	7.31	23.45	47.59	2.706
sandsheet Total		–	–	469	2952.57	6.30	18.82	85.82	4.880
Grand Total	–	–	–	586	3440.27	5.87	17.26	100.00	5.686

Appendix D: Vegetation Metrics

A key initial step in the development of an MMI is the computation of vegetation metrics representing various aspects of the wetland vegetation community. Metrics are direct and purposefully one-dimensional assays of vegetation composition and structure. They have significant explanatory power in and of themselves and we present and interpret several throughout this report.

Details of metric calculation are in Schweiger et al. (2015). We generated 187 metrics representing 11 groups: floristic quality/conservatism, duration, ground cover, life form composition, nativity/invasiveness, endemism (perhaps better thought of as "conservation value"), noxiousness, taxonomic diversity, taxonomic composition, wetland status, and salt tolerance.

Table D-1. Example vegetation metrics and expected direction of change with increasing human disturbance.

Metric group	Metric name	Direction of change with increasing disturbance
Conservatism	Absolute Cover Intolerant	decrease
	Absolute Cover Tolerant	increase
	C Cover Weighted All	decrease
	C Cover Weighted Native	decrease
	C Mean	decrease
	C Mean Native	decrease
	Percent of Spp. Intolerant	increase
	Percent of Spp. Tolerant	decrease
	Floristic Quality Index (FQI)	decrease
	FQI Cover Weighted	decrease
	FQI Cover Weighted Native	decrease
	Floristic Quality Index Native	decrease
	Floristic Quality Index Adjusted	decrease
	FQI Adjusted Cover Weighted	decrease
	Percent Cover Intolerant	decrease
	Percent Cover Tolerant	decrease
	Rel. Proportion Tolerant To Intolerant Absolute Cover	increase
Duration	Absolute Cover Annual	increase
	Rel. Proportion Annual To Perennial Absolute Cover	increase
	Absolute Cover Perennial	decrease
	Percent Abs Cover Annual	increase
	Percent Absolute Cover Perennial	decrease
Ground cover	Total Basal Area	decrease
	Total Cover	decrease
	Total Bare Ground	increase
Lifeform	Absolute Cover Forb	decrease
	Absolute Cover Graminoid	decrease
	Absolute Cover Rhizomatous	increase
	Absolute Cover Shrub	decrease
	Absolute Cover Woody	decrease
	Percent Forb	decrease
	Percent Graminoid	decrease
	Percent Rhizomatous	decrease
	Rel. Proportion Rhizomatous To Non Rhizomatous Cover	decrease

Table D-1 (*continued*). Example vegetation metrics and expected direction of change with increasing human disturbance.

Metric group	Metric name	Direction of change with increasing disturbance
Nativity	Rel. Proportion Annual To Perennial Native Abs. Cover	increase
	Absolute Cover Annual And Native	decrease
	Absolute Cover Dominant Native	decrease
	Rel. Proportion Native Forb To Graminoid Abs. Cover	increase
	Absolute Cover Forb Native	decrease
	Absolute Cover Gram Native	decrease
	Absolute Cover Invasive	increase
	Absolute Cover Native	decrease
	Absolute Cover Perennial Native	decrease
	Absolute Cover Shrub Native	decrease
	Absolute Cover Woody Native	decrease
	Invasive Richness	increase
	Percent of Spp. Native Forbs	decrease
	Percent of Spp. Non Native	increase
	Cover Weighted Mean Invasive	increase
	Cover Weighted Mean Invasive I Rank	increase
	Cover Weighted Mean Invasive Noxious	increase
	Mean Invasiveness	increase
	Mean Invasive I Rank	increase
	Mean Invasive Noxious	increase
	Percent Annual Native	decrease
	Percent Dominant Native	increase
	Percent Forb Native	decrease
	Percent Graminoid Native	decrease
	Percent Invasive	increase
	Percent Non Native	increase
	Percent Perennial Native	decrease
	Percent Shrub Native	increase
	Percent Woody Native	increase
	Rel. Proportion Annual To Perennial Native Total Cover	increase
	Rel. Proportion Native Forb To Graminoid Total Cover	increase
	Rel. Proportion Native To Total Cover	increase
Endemism	Mean state element occurrence rank score	decrease
	Mean global element occurrence rank score	decrease
	Mean cover weighted state element occurrence rank score	decrease
	Mean cover weighted global element occurrence rank score	decrease
Noxiousness	Mean state noxious score	increase
	Mean cover state noxious score	increase
Taxomomic status	Absolute Cover Asteraceae	increase
	Absolute Cover Brassicaceae	decrease
	Absolute Cover Bryophyte	decrease
	Absolute Cover Carex	decrease
	Rel. Proportion Cyperaceae To Cyperaceae And Poaceae Absolute Cover	decrease
	Absolute Cover Cyperaceae	decrease

Table D-1 (*continued*). Example vegetation metrics and expected direction of change with increasing human disturbance.

Metric group	Metric name	Direction of change with increasing disturbance
Taxonomic status (continued)	Absolute Cover Poaceae	increase
	Absolute Cover Salicaceae	decrease
	Absolute Cover Salix	decrease
	Absolute Cover Sphagnum	decrease
	Percent Carex	decrease
	Percent Cyperaceae	decrease
	Percent Poaceae	increase
	Percent Salicaceae	decrease
	Percent Salix	decrease
	Percent Sphagnum	decrease
	Percent Asteraceae	increase
	Percent Brassicaceae	increase
	Percent Bryophyte	decrease
	Rel. Proportion Cyperaceae To Cyperaceae	decrease
Wetland status	Absolute Cover Hydrophytes	decrease
	Relative Cover Hydrophytes	decrease
	Percent Hydrophytes	decrease
	Wet Indicator Mean	decrease
	Wet Indicator Native	decrease
	Wet Indicator Total	decrease
	Wet Rich Native	decrease
	Wet Rich Total	decrease
	Wet Score Weighted	decrease
Taxonomic diversity	Richness	decrease
	Richness Asteraceae	decrease
	Richness Bryophytes	decrease
	Richness Cyperaceae	decrease
	Richness Poaceae	increase
	Richness Salicaceae	decrease
	Simpson Diversity	decrease
	Simpson Diversity Native	decrease
Salt tolerance	Absolute cover no salt tolerance	increase?
	Absolute cover low salt tolerance	increase?
	Absolute cover medium salt tolerance	decrease?
	Absolute cover halophyte (high salt tolerance)	decrease?
	Halophyte: no salt tolerance	increase?
	Percent halophyte	increase?
	Percent no salt tolerance	decrease?
	Mean salt tolerance score	increase?
	Mean cover weighted salt tolerance score	increase?

Appendix E: EPA Disturbance Scores

Candidate reference sites are selected based on the expected impact of large scale disturbances (EPA, in review). Stressor gradients at candidate wetland sites are examined in a GIS based on three criteria: (1) presence of anthropogenic impact (hydrologic modifications, forestry activities, agricultural development, recreational development, residential and urban development, and industrial development); (2) presence/absence of roads and trails within a 1-km radius buffer; and (3) distance from the site to the nearest ditch, edge of human landuse, or roads/trails. Sites are scored from 0 to 3 based on the proximity/intensity of the disturbance within each of these 11 classes. The maximum score for a most disturbed site is 33. EPA (in review) defines a reference site as having a score of 11 or less. When we applied these to GRSA WEI sandsheet sites, all sites were classified as having minor stress and thus in a reference condition.

Well num	Site alias	Hydro	Forestry	Agr	Recreation	Residential	Industrial	Road Trail	Distance	Ref Score
101	Medano Ranch Boundary	1	0	0	0	0	0	3	3	**7**
102	Medano Ranch East Twin Lakes	0	0	0	0	0	0	2	1	**3**
103	Medano Ranch Closed Basin Well	1	0	0	0	0	0	2	1	**4**
104	Medano Ranch Little Spring Creek	2	0	0	0	0	0	2	2	**6**
105	Medano Ranch Lower	1	0	0	0	0	0	2	1	**4**
106	Medano Ranch West South Ditch 2	1	0	0	0	0	0	0	0	**1**
107	Medano Ranch South Ditch 2	3	0	0	0	0	0	2	3	**8**
108	Medano Ranch House	3	0	0	0	1	0	2	3	**9**
109	Medano Ranch South Ditch 1	3	0	0	0	0	0	2	3	**8**
110	Twin Lakes North Ditch	2	0	0	0	0	0	0	3	**5**
111	Upper Big Spring Crk interdunal swale	0	0	0	0	0	0	2	2	**4**
112	Middle Sand Crk Medano Sand Creek Ditch	0	0	0	0	0	0	0	3	**3**
113	Medano Ranch East Dollar Lake	1	0	0	0	0	0	2	3	**6**
114	Medano Ranch Head Lake	2	0	0	0	0	0	2	1	**5**
115	Big Spring Crk Below Main Culvert	2	0	0	0	0	0	2	1	**5**
116	Middle Sand Creek Low Low	1	0	0	0	0	0	0	1	**2**
117	Middle Sand Creek Low Ditch	1	0	0	0	0	0	2	1	**4**
118	Elk Springs West	1	0	0	0	0	0	2	3	**6**
119	San Luis Lake East	0	0	0	0	0	0	0	0	**0**
120	Twin Lakes North East	0	0	0	0	0	0	0	1	**1**
121	Twin Lakes Barren		0	0	0	0	0	0	1	**1**
122	Twin Lakes North	2	0	0	0	0	0	2	2	**6**
123	San Luis Lake South	2	0	0	0	0	0	3	1	**6**
124	Little Spring Creek North	0	0	0	0	0	0	2	1	**3**
125	Spring Creek Ranch Rd North Mid	1	0	0	0	0	0	0	2	**3**
126	Spring Creek Ranch Rd North Up	1	0	0	0	0	0	0	1	**2**
127	Medano Ranch Ditch Housing	2	0	0	0	1	0	2	3	**8**
128	Middle Sand Creek Up	0	0	0	0	0	0	0	0	**0**
129	Middle Sand Creek Low Mid	0	0	0	0	0	0	0	0	**0**
130	Middle Sand Creek Mid Mid	0	0	0	0	0	0	0	0	**0**
131	Middle Sand Creek Low	1	0	0	0	0	0	0	0	**1**
132	North of Big Spring Crk Ditch	0	0	0	0	0	0	2	1	**3**
133	Big Spring Crk Medano Sand Creek Ditch	3	0	0	0	0	0	0	3	**6**

Appendix E (*continued*)

Well num	Site alias	Hydro	Forestry	Agr	Recreation	Residential	Industrial	Road Trail	Distance	Ref Score
134	Big Spring Crk Los Ojos Ditch	1	0	0	0	0	0	2	3	**6**
135	Hosa House North	2	0	0	0	0	0	2	3	**7**
136	Sand Creek North Mid	2	0	0	0	0	0	0	3	**5**
137	Sand Creek North Up	0	0	0	0	0	0	0	0	**0**
138	Medano Ranch Lower Sand Creek 1	0	0	0	0	0	0	0	1	**1**
139	Medano Ranch Lower Sand Creek 2	0	0	0	0	0	0	0	1	**1**
140	Medano Ranch East South Ditch 1	1	0	0	0	0	0	2	3	**6**
141	Medano Ranch South Ditch 1 West	0	0	0	0	0	2	1	3	
142	Lower Sand Creek	0	0	0	0	0	0	0	1	**1**
143	Hosa House West	2	0	0	0	0	0	2	1	**5**
144	Medano Ranch South Mid	2	0	0	0	0	0	2	1	**5**
145	Medano Ranch Middle	2	0	0	0	0	0	0	0	**2**
146	Baca Ranch North	0	0	0	0	0	0	2	1	**3**
147	Baca Ranch South	0	0	0	0	0	0	2	1	**3**
148	King Well	2	0	0	0	0	0	2	1	**5**
201	Visitors Center below Horse Barn	1	0	0	1	1	0	3	1	**7**
202	Big Spring Creek Exclosure 1	1	0	0	0	0	0	2	3	**6**
203	Big Spring Creek Exclosure 2	1	0	0	0	0	0	2	3	**6**
204	Middle Sand Creek Elk Springs 1	1	0	0	0	0	0	2	3	**6**
205	Elk Springs Middle Marsh	1	0	0	0	0	0	2	3	**6**
206	Elk Springs North	1	0	0	0	0	0	2	3	**6**
207	Elk Springs South	1	0	0	0	0	0	2	3	**6**
208	Elk Springs Edge Marsh	0	0	0	0	0	0	2	3	**5**
209	Big Spring Creek	1	0	0	0	0	0	2	3	**6**
210	Big Spring Creek Paired Exclosure 2	1	0	0	0	0	0	2	3	**6**
211	Big Spring Creek Paired Exclosure 1	1	0	0	0	0	0	2	3	**6**
212	Middle Sand Creek Non Exclosure	1	0	0	0	0	0	0	1	**2**
213	Middle Sand Creek Exclosure	0	0	0	0	0	0	1	1	
214	Big Spring Creek Terminus 1	2	0	0	0	0	0	0	0	**2**
215	Big Spring Creek Terminus 2	2	0	0	0	0	0	0	0	**2**
216	Big Spring Creek Terminus 3	2	0	0	0	0	0	0	0	**2**
250	Denton Spring	1	0	0	1	0	0	2	3	**7**
251	Horse Barn Lower	1	0	0	1	1	0	3	3	**9**
252	Medano Island Mosca confluence	2	0	0	1	0	0	3	1	**7**
254	Upper Sand Crk Lake Mid	0	0	0	1	0	0	1	2	**4**
255	Upper Sand Crk Lake West	0	0	0	1	0	0	1	1	**3**
256	Upper Sand Crk Lake North	0	0	0	1	0	0	1	3	**5**
257	Upper Sand Crk Lake South	0	0	0	1	0	0	1	1	**3**
258	Upper Sand Crk Trail North	0	0	0	1	0	0	1	3	**5**
259	Upper Sand Crk Trail South	0	0	0	1	0	0	1	3	**5**
260	Upper Sand Crk Trail Mid	0	0	0	1	0	0	1	3	**5**
261	Upper Sand Crk Trail East	0	0	0	1	0	0	1	3	**5**
262	Horse Barn Upper	1	0	0	1	1	0	3	3	**9**

Appendix E (*continued*)

Well num	Site alias	Hydro	Forestry	Agr	Recreation	Residential	Industrial	Road Trail	Distance	Ref Score
300	Mitchell Pond 1	1	0	0	1	0	0	2	3	**7**
301	San Luis Lake Mid	2	0	0	0	0	0	3	1	**6**
302	Little Spring Crk swale	0	0	0	0	0	0	2	1	**3**
303	Little Spring Crk swale	0	0	0	0	0	0	2	1	**3**
304	Dollar Lake South	3	0	0	0	0	0	2	3	**8**
305	Dollar Lake West	3	0	0	0	0	0	2	3	**8**
306	Indian Spring	1	0	0	0	0	0	2	1	**4**

Appendix F: Example Disturbance at Specific Sites

For references in this appendix please see the literature cited section that follows the main narrative.

We present several specific examples of disturbance at sample sites from the sandsheet. Our intention is to illustrate with site level photos and more focused graphics connections between our indices and real anthropogenic and natural disturbances. We also point out possible inconsistencies in the data that might be explained by measurement scale or be driven by real idiosyncratic factors at a site.

Site 133 (Figure F-1) near the terminus of Big Spring Creek on the Medano Ranch (just north of the main ranch house) had the highest HDI score measured in 2010 (100). The complex contained several fences and diversions and other structures used for ranching. The UUI score was also very high, at 85. While the site is inside the bison fence, its Bison Index was lower than might be expected (65). However, this may be an artifact of the scale at which this index was summarized (from a 100m buffer), as bison counts were very high in the area to the south of the site. A mid-level LDI score of 43.8 suggests that more of the anthropogenic footprint at the site was local. Finally, a lower Trail Index indicates that relatively fewer trails were found in imagery within 100m of the site—interesting given the high UUI and suggestive of the complex interpretation of ungulate trail density near wetlands.

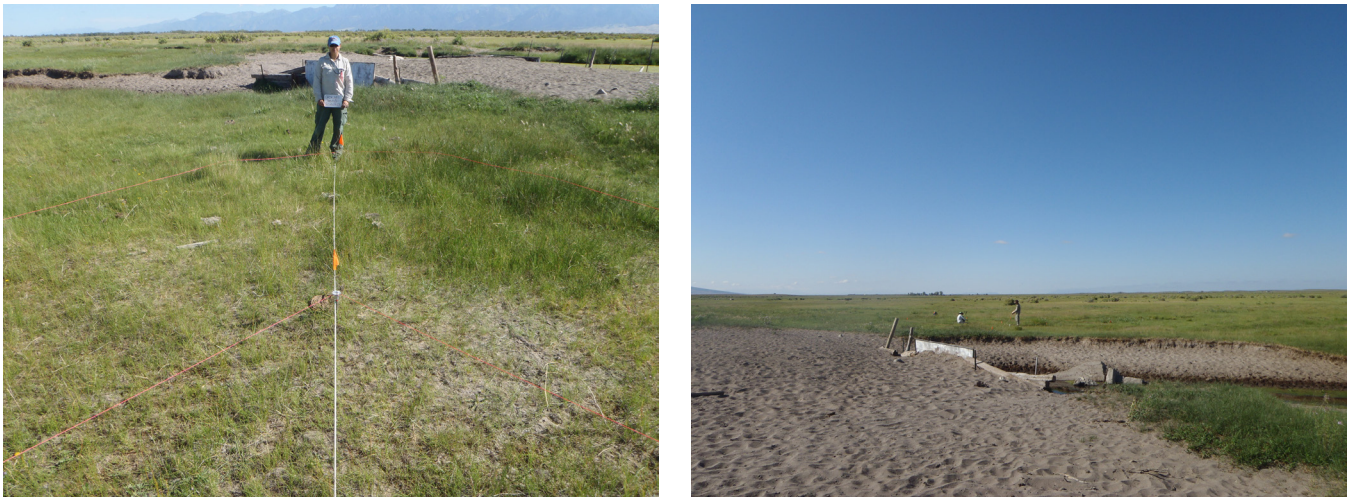


Figure F-1. Two views of site 133 near the terminus of Big Spring Creek on the Medano Ranch at Great Sand Dunes National Park and Preserve. This site had the highest Human Disturbance Index (HDI) score measured in 2010. (NPS/J. JOHNSON)

Site 146 (Figure F-2) near Deadman Creek in the northwest corner of the park in 2010 had a low HDI score (8.5), with little to no evidence of human use and a Bison Index of zero (or null as it was outside the bison fence). The site had a high Elk Index (90.8), but a zero UUI score, likely reflecting the difference in scales of these two metrics of ungulate use (the Elk Index is summarized across 1km while the UUI focuses on the wetland complex only). A low to mid-level LDI score of 31.2 suggests that there was more anthropogenic disturbance at some distance from the site. Finally, a null Trail Index indicates that trails did not occur near the site, which matches the pattern with UUI and the Elk Index.



Figure F-2. Site 146 looking east near Deadman Creek in the northwest corner of Great Sand Dunes National Park and Preserve in 2010. This site had a very low Human Disturbance Index (HDI) score but a high Elk Index (some old ungulate droppings are evident in the second image foreground). (NPS/J. JOHNSON)

Site 128 (Figure F-3) in between Sand and Big Spring Creeks in the escape dunes to the west of the main dune field had a relatively low HDI (12.7) and LDI (17.8), suggesting that there was little human footprint on the site or in the surrounding area. The site had a mid-level Elk Index (45.6), but a low Bison Index (4.4), which makes sense given its location near the edge of the bison paddock. Finally, the Trail Index was also generally low (23.3), indicating few trails in the immediate area. There was a prominent trail running through the site itself and this trail is seen in the imagery used to create the Trail Index (Figure F-3—good ground truth data!).

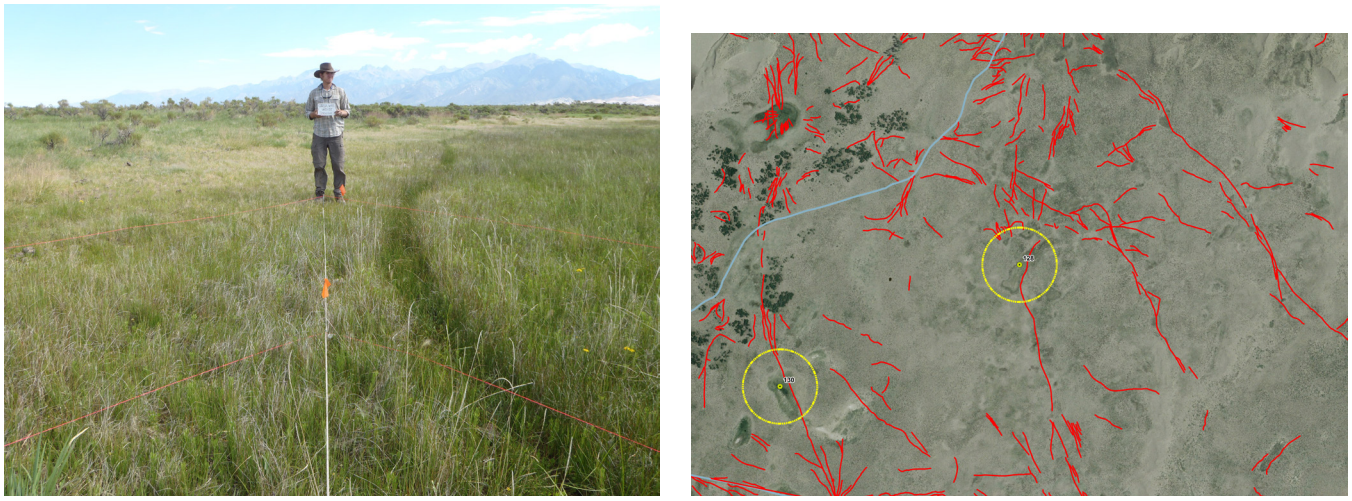


Figure F-3. Site 128 in between Sand and Big Spring Creeks in the escape dunes to the west of the main dune at Great Sand Dunes National Park and Preserve in 2010. The site had relatively low human disturbance and a medium to low ungulate usage. Note the trail passing through the site in both images (the second image shows the 100m buffer over which the individual trails (red lines) are summarized, with site 128 nearer the middle of the image). (NPS/J. JOHNSON)

Finally, site 136 (Figure F-4) near Sand and Arena Creeks, north of Dollar Lake, had a high HDI (71.4) and mid-level LDI (39.5), suggesting that there was intensive human use of the site that dropped off somewhat away from the wetland. The site had a very high UUI (96), Bison Index (90.1), and Trail Index (98.7), indicating intensive ungulate use at all scales.

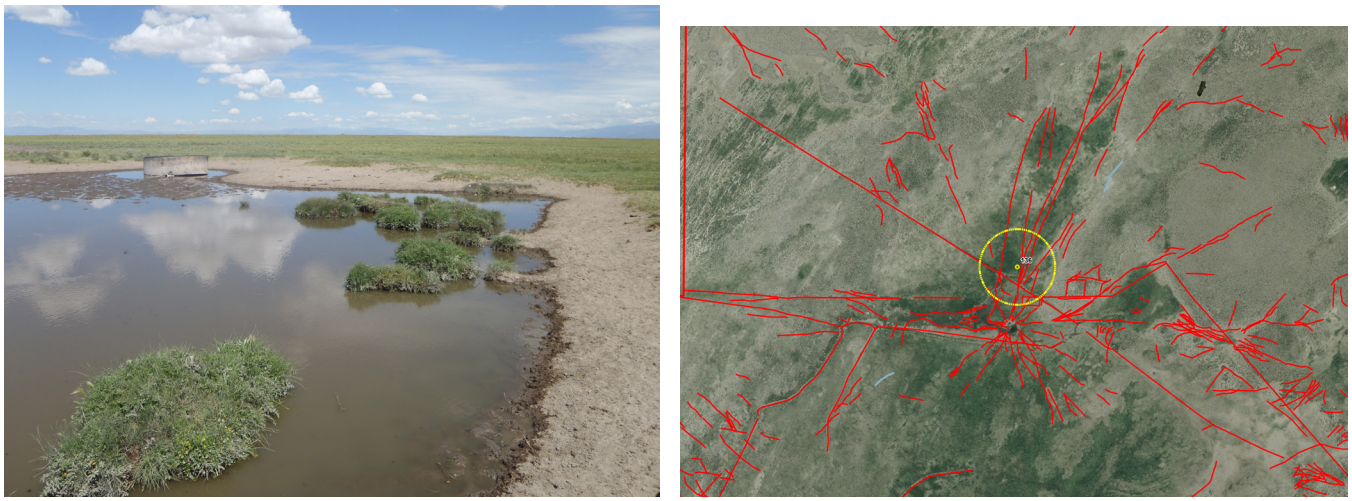


Figure F-4. Site 136 near Sand and Arena Creeks, north of Dollar Lake at Great Sand Dunes National Park and Preserve in 2010. The site had higher human disturbance, and, consistent across scales, very high ungulate usage, with trails passing through the site to a nearby open water feature. The first image shows the area adjacent to the site and the second image shows the 100m buffer over which the individual trails (red lines) are summarized. (NPS/J. JOHNSON)

Appendix G: Exploratory and Trend Model Result Details

For references in this appendix please see the literature cited section that follows the main narrative.

The following presents detailed output for exploratory and trend models.

Exploring Human Disturbance Index (HDI)

```
FINAL Call:

lm(formula = hdi ~ +env$UUI + env$elk.index + env$bison.index +
    env$ppt_sum_monsoon2008to2010 + env$elev + env$hydro + env$landuse +
    env$nonnat_dist + env$ldi + soil_ph + log_zn + log_co3 +
    mean_ph, data = env)

Residuals:
     Min       1Q   Median       3Q      Max
-10.4566  -2.5434   0.0809   2.3959  10.6229

Coefficients:
                               Estimate Std. Error t value Pr(>|t|)
(Intercept)                  354.310538 102.931982   3.442  0.00109 **
env$UUI                        0.125109   0.038688   3.234  0.00203 **
env$elk.index                 -0.132418   0.026397  -5.016 5.47e-06 ***
env$bison.index               -0.098089   0.032181  -3.048  0.00349 **
env$ppt_sum_monsoon2008to2010  0.372821   0.116383   3.203  0.00222 **
env$elev                      -0.147659   0.050440  -2.927  0.00490 **
env$hydro                      0.304759   0.012593  24.201  < 2e-16 ***
env$landuse                   -0.264591   0.050236  -5.267 2.20e-06 ***
env$nonnat_dist               -0.003533   0.001318  -2.681  0.00959 **
env$ldi                       -0.057644   0.025023  -2.304  0.02491 *
soil_ph                        2.810314   0.928692   3.026  0.00371 **
log_zn                        17.348125   5.001068   3.469  0.00100 **
log_co3                       -1.711753   0.851822  -2.010  0.04923 *
mean_ph                       -4.480687   0.818406  -5.475 1.02e-06 ***
---

Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 4.133 on 57 degrees of freedom
  (3 observations deleted due to missingness)
Multiple R2:  0.9685,    Adjusted R2:  0.9613
```

```
F-statistic: 134.8 on 13 and 57 DF,  p value: < 2.2e-16

Relative importance metrics:

                                      lmg        last        first
env$UUI                        0.10745544 0.014039505 1.489377e-01
env$elk.index                  0.01010799 0.033783510 2.455149e-04
env$bison.index                0.04883604 0.012472875 9.132846e-02
env$ppt_sum_monsoon2008to2010  0.01394531 0.013776451 1.870324e-06
env$elev                       0.01306912 0.011504993 2.126354e-03
env$hydro                      0.49836394 0.786297915 3.530680e-01
env$landuse                    0.15995862 0.037242073 1.981263e-01
env$nonnat_dist                0.02532755 0.009647872 3.098933e-02
env$ldi                        0.02619828 0.007124590 3.240911e-02
soil_ph                        0.01975296 0.012293671 3.367602e-02
log_zn                         0.01181475 0.016154544 1.366756e-02
log_co3                        0.05355556 0.005421248 8.894516e-02
mean_ph                        0.01161444 0.040240754 6.478616e-03
```

Exploring Ungulate Use Index (UUI)

```
Call:
lm(formula = UUI ~ factor(env$wettype) + env$hdi + env$elk.index +
    env$productivity_point + env$ppt_sum_2010 + env$sand_dist +
    env$elev + env$landuse, data = env)

Residuals:
     Min       1Q   Median       3Q      Max
-27.6367  -6.2190  -0.4622   7.2501  23.8133

Coefficients:
                            Estimate Std. Error t value Pr(>|t|)
(Intercept)                -5.604e+02  2.353e+02  -2.382  0.02037 *
factor(env$wettype)[T.M]    2.229e+01  5.257e+00   4.241 7.69e-05 ***
factor(env$wettype)[T.R]    2.475e+01  7.781e+00   3.181  0.00231 **
factor(env$wettype)[T.S]    3.509e+01  6.181e+00   5.677 4.04e-07 ***
env$hdi                     2.366e-01  1.059e-01   2.234  0.02914 *
env$elk.index               2.282e-01  8.643e-02   2.640  0.01051 *
env$productivity_point      1.641e-02  5.834e-03   2.813  0.00660 **
env$ppt_sum_2010           -5.978e-01  2.149e-01  -2.781  0.00719 **
env$sand_dist              -3.427e-03  1.334e-03  -2.570  0.01264 *
env$elev                    3.058e-01  1.116e-01   2.741  0.00801 **
```

```
env$landuse              -9.509e-01  9.099e-02 -10.451 3.21e-15 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 11.32 on 61 degrees of freedom
  (2 observations deleted due to missingness)
Multiple R2:  0.9038,    Adjusted R2:  0.888
F-statistic:  57.3 on 10 and 61 DF,  p value: < 2.2e-16

Relative importance metrics:

                              lmg       last        first
factor(env$wettype)    0.06806747 0.17613617 0.0306426705
env$hdi                0.16959010 0.02724577 0.1937802014
env$elk.index          0.03360237 0.03803822 0.0341511563
env$productivity_point 0.11409289 0.04318429 0.1538360493
env$ppt_sum_2010       0.05205473 0.04222686 0.0763780300
env$sand_dist          0.01744264 0.03603622 0.0002371347
env$elev               0.03760287 0.04102016 0.0617976540
env$landuse            0.50754693 0.59611229 0.4491771037
```

Trend in HDI at sentinel sites

Logged, net change:

```
Linear mixed model fit by REML
t-tests use  Satterthwaite approximations to degrees of freedom ['lmerMod']
Formula: log(hdi) ~ wyear + sentinelname + hydro + landuse + UUI + (1 |      year)
   Data: env

REML criterion at convergence: -89.9

Scaled residuals:
     Min       1Q   Median       3Q      Max
-2.46387 -0.49295  0.04334  0.60234  1.23166

Random effects:
 Groups   Name        Variance Std.Dev.
 year     (Intercept) 0.004554 0.06748
```

```
 Residual             0.005010 0.07078
Number of obs: 63, groups:  year, 5

Fixed effects:
                                            Estimate Std. Error         df t value Pr(>|t|)
(Intercept)                                3.5683054  0.0868632 16.3100000  41.080  < 2e-16 ***
wyear                                     -0.0828041  0.0225633  3.1000000  -3.670   0.0332 *
sentinelname[T.Big Spring Creek Terminus] -0.2403455  0.1341828 53.3600000  -1.791   0.0789 .
sentinelname[T.Elk Springs]               -0.0695046  0.0373481 55.2500000  -1.861   0.0681 .
hydro                                      0.0078517  0.0016134 53.3100000   4.867 1.05e-05 ***
landuse                                    0.0002789  0.0008893 55.6700000   0.314   0.7550
UUI                                        0.0030357  0.0004847 55.2800000   6.263 5.91e-08 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Analysis of Random effects Table:
     Chi.sq Chi.DF p.value
year   17.8      1   2e-05 ***

> R2.corr.mer(m6)
[1] 0.9408187

Not logged, annual change:


Linear mixed model fit by REML
t-tests use  Satterthwaite approximations to degrees of freedom ['lmerMod']
Formula: hdi ~ wyear + sentinelname + hydro + landuse + UUI + (1 | year)
   Data: env

REML criterion at convergence: 348.6

Scaled residuals:
     Min       1Q   Median       3Q      Max
-2.33690 -0.47471  0.00091  0.75604  1.57854

Random effects:
 Groups   Name        Variance Std.Dev.
 year     (Intercept)  8.083   2.843
 Residual             12.817   3.580
Number of obs: 63, groups:  year, 5
```

```
Fixed effects:
                                                Estimate Std. Error         df t value Pr(>|t|)
(Intercept)                                    3.511e+01  4.137e+00  2.194e+01   8.486 2.24e-08 ***
wyear                                         -3.535e+00  9.723e-01  3.130e+00  -3.636   0.0334 *
sentinelname[T.Big Spring Creek Terminus] -1.012e+01  6.783e+00  5.347e+01  -1.492   0.1414
sentinelname[T.Elk Springs]                -2.445e+00  1.880e+00  5.568e+01  -1.301   0.1986
hydro                                          3.929e-01  8.157e-02  5.342e+01   4.817 1.25e-05 ***
landuse                                        2.004e-04  4.467e-02  5.598e+01   0.004   0.9964
UUI                                            1.209e-01  2.439e-02  5.574e+01   4.957 7.06e-06 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlation of Fixed Effects:
            (Intr) wyear  s[TSCT s[T.ES hydro  landus
wyear       -0.341
snt[T.BSCT]  0.518 -0.026
sntnl[T.ES] -0.105  0.043 -0.186
hydro       -0.564  0.017 -0.984  0.239
landuse     -0.518 -0.153 -0.082 -0.581  0.099
UUI         -0.436 -0.165  0.140  0.271 -0.099  0.301

Analysis of Random effects Table:
     Chi.sq Chi.DF p.value
year   12.3      1   5e-04 ***

> R2.corr.mer(m7)
[1] 0.9380793
```

Trend in UUI at sentinel sites

Logged, net change:

```
> summary(m8)
Linear mixed model fit by REML
t-tests use  Satterthwaite approximations to degrees of freedom ['lmerMod']
Formula: log(UUI) ~ wyear + sentinelname + hdi + landuse + (1 | year)
   Data: env

REML criterion at convergence: 164.2
```

```
Scaled residuals:
     Min       1Q   Median       3Q      Max
-1.89773 -0.45761  0.04548  0.64203  1.55336

Random effects:
 Groups   Name        Variance Std.Dev.
 year     (Intercept) 0.4429   0.6655
 Residual             0.5432   0.7371
Number of obs: 63, groups:  year, 5

Fixed effects:
                                          Estimate Std. Error        df t value Pr(>|t|)
(Intercept)                               2.104991   1.291781 41.820000   1.630  0.11071
wyear                                     0.237051   0.227938  3.420000   1.040  0.36620
sentinelname[T.Big Spring Creek Terminus] -1.373087   0.468633 54.920000  -2.930  0.00493 **
sentinelname[T.Elk Springs]               -0.229712   0.389694 56.330000  -0.589  0.55791
hdi                                        0.054326   0.019749 55.250000   2.751  0.00802 **
landuse                                   -0.024665   0.008954 56.980000  -2.755  0.00787 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

> rand(m8)
Analysis of Random effects Table:
     Chi.sq Chi.DF p.value
year   17.8      1   3e-05 ***

> R2.corr.mer(m8)
[1] 0.6962271

> summary(m9)
Linear mixed model fit by REML
t-tests use  Satterthwaite approximations to degrees of freedom ['lmerMod']
Formula: UUI ~ wyear + sentinelname + hdi + landuse + (1 | year)
   Data: env

REML criterion at convergence: 518.9

Scaled residuals:
     Min       1Q   Median       3Q      Max
-1.92398 -0.67017  0.00205  0.50182  1.88267

Random effects:
```

```
 Groups   Name        Variance Std.Dev.
 year     (Intercept) 204.8    14.31
 Residual             275.2    16.59
Number of obs: 63, groups:  year, 5

Fixed effects:
                                          Estimate Std. Error       df t value Pr(>|t|)
(Intercept)                               -34.9809    28.8553  43.0400  -1.212   0.2320
wyear                                      12.2591     4.9353   3.3100   2.484   0.0811 .
sentinelname[T.Big Spring Creek Terminus] -54.3074    10.5432  54.9000  -5.151 3.62e-06 ***
sentinelname[T.Elk Springs]                -7.2030     8.7601  56.4200  -0.822   0.4144
hdi                                         2.0696     0.4442  55.2700   4.659 2.04e-05 ***
landuse                                    -0.3684     0.2011  57.0000  -1.832   0.0722 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

> rand(m9)
Analysis of Random effects Table:
     Chi.sq Chi.DF p.value
year   13.7      1   2e-04 ***

> R2.corr.mer(m9)
[1] 0.7515304
```

Exploring peak season soil total carbon

```
Call:
lm(formula = log_totalc_perc ~ log_om_40cm + soil_ph + log_zn +
    log_soil_ec + log_na + log_totaln_perc + env$sum_pet + env$elk.index +
    env$ppt_30yrnormal_sum + env$sand_dist + env$ldi + env$nonnat_catch,
    data = env)

Residuals:
      Min        1Q    Median        3Q       Max
-0.189662 -0.046475 -0.008292  0.049690  0.184089

Coefficients:
                      Estimate Std. Error t value Pr(>|t|)
(Intercept)           5.557e-01  3.200e-01   1.737 0.087673 .
log_om_40cm           1.537e-01  4.094e-02   3.754 0.000400 ***
soil_ph              -6.780e-02  1.693e-02  -4.004 0.000176 ***
```

```
log_zn                  -3.579e-01  1.243e-01  -2.880 0.005532 **
log_soil_ec              1.844e-01  6.837e-02   2.698 0.009088 **
log_na                   1.284e-01  3.153e-02   4.074 0.000140 ***
log_totaln_perc          3.924e+00  2.612e-01  15.022  < 2e-16 ***
env$sum_pet             -1.678e-03  6.300e-04  -2.663 0.009957 **
env$elk.index            1.227e-03  6.058e-04   2.025 0.047396 *
env$ppt_30yrnormal_sum   6.085e-05  1.801e-05   3.379 0.001296 **
env$sand_dist           -4.168e-05  1.525e-05  -2.733 0.008268 **
env$ldi                  3.176e-03  8.844e-04   3.592 0.000671 ***
env$nonnat_catch         9.174e-02  3.471e-02   2.643 0.010503 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.08515 on 59 degrees of freedom
  (2 observations deleted due to missingness)
Multiple R2:  0.9251,    Adjusted R2:  0.9099
F-statistic: 60.74 on 12 and 59 DF,  p value: < 2.2e-16


Relative importance metrics:

                              lmg       last        first
log_om_40cm             0.112869685 0.04169918 1.199713e-01
soil_ph                 0.091129892 0.04744955 1.155698e-01
log_zn                  0.141402123 0.02454876 2.122609e-01
log_soil_ec             0.009092574 0.02153759 1.074738e-03
log_na                  0.032281042 0.04911295 4.731511e-04
log_totaln_perc         0.517443652 0.66778996 4.385975e-01
env$sum_pet             0.011584306 0.02099277 1.105978e-02
env$elk.index           0.007412612 0.01213561 8.546915e-05
env$ppt_30yrnormal_sum 0.045858878 0.03377981 7.319666e-02
env$sand_dist           0.007590756 0.02210494 1.319795e-03
env$ldi                 0.008597535 0.03817371 1.287767e-05
env$nonnat_catch        0.014736945 0.02067517 2.637808e-02
```

Exploring peak season groundwater *in situ* specific conductance

```
Call:
lm(formula = log_mean_sc ~ +soil_ph + log_cu + mg + log_soil_ec +
    log_totaln_perc + log_totalc_perc + factor(env$wettype) +
    env$bison.index + env$ppt_sum_2008to2010 + env$ppt_30yrnormal_sum +
    env$ldi, data = env)
```

```
Residuals:
     Min       1Q   Median       3Q      Max
-0.29673 -0.11098 -0.00520  0.08431  0.44191

Coefficients:
                           Estimate Std. Error t value Pr(>|t|)
(Intercept)                1.8882216  0.4489140   4.206 9.28e-05 ***
soil_ph                    0.0682364  0.0281146   2.427 0.018405 *
log_cu                     0.3246022  0.1761956   1.842 0.070637 .
mg                         0.0004488  0.0002129   2.107 0.039498 *
log_soil_ec                0.4146480  0.1319783   3.142 0.002663 **
log_totaln_perc            1.7567903  0.9451001   1.859 0.068215 .
log_totalc_perc           -0.7830303  0.1992059  -3.931 0.000232 ***
factor(env$wettype)[T.M] -0.2599249  0.0845178  -3.075 0.003226 **
factor(env$wettype)[T.R] -0.1291174  0.1181667  -1.093 0.279135
factor(env$wettype)[T.S]  0.0054418  0.1057609   0.051 0.959144
env$bison.index           -0.0048549  0.0011139  -4.359 5.53e-05 ***
env$ppt_sum_2008to2010    -0.0033859  0.0018124  -1.868 0.066885 .
env$ppt_30yrnormal_sum     0.0002891  0.0001671   1.731 0.088914 .
env$ldi                    0.0053054  0.0012168   4.360 5.50e-05 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.1744 on 57 degrees of freedom
  (3 observations deleted due to missingness)
Multiple R2:  0.7997,    Adjusted R2:  0.754
F-statistic: 17.51 on 13 and 57 DF,  p value: 2.402e-15

Relative importance metrics:

                              lmg       last      first
factor(env$wettype)    0.22761634 0.18341548 0.21589597
soil_ph                0.08229754 0.05529292 0.11420739
log_cu                 0.02199260 0.03185778 0.02064519
mg                     0.01982714 0.04168471 0.03090121
log_soil_ec            0.14285738 0.09265234 0.15827105
log_totaln_perc        0.04573044 0.03243297 0.07994465
log_totalc_perc        0.07068274 0.14502914 0.06928216
env$bison.index        0.22950208 0.17831099 0.16202376
env$ppt_sum_2008to2010 0.02739724 0.03275855 0.03619525
env$ppt_30yrnormal_sum 0.03495908 0.02811584 0.04880945
```

```
env$ldi                0.09713742 0.17844928 0.06382391
```

Trend in specific conductance at sentinel sites

SC not logged

```
> summary(m12)
Linear mixed model fit by REML
t-tests use  Satterthwaite approximations to degrees of freedom ['lmerMod']
Formula: log_mean_sc ~ wyear + sentinelname + mean_ph + ldi + (1 | year)
   Data: env

REML criterion at convergence: 40.4

Scaled residuals:
    Min      1Q  Median      3Q     Max
-1.5244 -0.6434 -0.1054  0.4764  3.9937

Random effects:
 Groups   Name        Variance Std.Dev.
 year     (Intercept) 0.009101 0.0954
 Residual             0.079144 0.2813
Number of obs: 57, groups:  year, 5

Fixed effects:
                                    Estimate Std. Error       df t value Pr(>|t|)
(Intercept)                          0.19297    0.70186 49.80000   0.275  0.78450
wyear                               -0.02988    0.04207  3.56000  -0.710  0.52121
sentinelname[T.Big Spring Creek Terminus] -0.91078    0.62914 48.29000  -1.448  0.15417
sentinelname[T.Elk Springs]          1.34325    0.68682 48.31000   1.956  0.05629 .
mean_ph                              0.14522    0.04991 48.88000   2.909  0.00544 **
ldi                                  0.02870    0.01668 48.34000   1.720  0.09185 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Analysis of Random effects Table:
     Chi.sq Chi.DF p.value
year   1.26      1     0.3

> summary(lmfit)$r.squared
[1] 0.4034472
```

correlation approximate R2 correlation between the fitted and the observed values

```
                                                                    logged pseudo R2:
                                                                            0.4034472
logged for net trend

> summary(m13)
Linear mixed model fit by REML
t-tests use  Satterthwaite approximations to degrees of freedom ['lmerMod']
Formula: log(env2$log_mean_sc) ~ env2$wyear + env2$sentinelname + env2$mean_ph +      env2$ldi + (1 |
env2$year)
   Data: env2

REML criterion at convergence: -69.1

Scaled residuals:
    Min      1Q  Median      3Q     Max
-1.7084 -0.6752 -0.0793  0.5031  3.5175

Random effects:
 Groups    Name        Variance  Std.Dev.
 env2$year (Intercept) 0.0009453 0.03074
 Residual              0.0092853 0.09636
Number of obs: 57, groups:  env2$year, 5

Fixed effects:
                                                Estimate Std. Error        df t value Pr(>|t|)
(Intercept)                                     0.082660   0.240248 49.730000   0.344  0.73225
env2$wyear                                     -0.011968   0.013975  3.600000  -0.856  0.44505
env2$sentinelname[T.Big Spring Creek Terminus] -0.335544   0.215488 48.320000  -1.557  0.12597
env2$sentinelname[T.Elk Springs]                0.520591   0.235241 48.340000   2.213  0.03165 *
env2$mean_ph                                    0.047255   0.017092 48.940000   2.765  0.00801 **
env2$ldi                                        0.011047   0.005715 48.370000   1.933  0.05908 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

> rand(m13)
Analysis of Random effects Table:
          Chi.sq Chi.DF p.value
env2$year   1.04      1     0.3

> summary(lmfit)$r.squared
[1] 0.4218859
```

correlation approximate R2 correlation between the fitted and the observed values
logged pseudo R2:
0.4218859

-0.012
% change over 5 years NOT SIG
-1.1968

Trend in pH at sentinel sites

ph NOT logged

```
> summary(m10)
Linear mixed model fit by REML
t-tests use  Satterthwaite approximations to degrees of freedom ['lmerMod']
Formula: mean_ph ~ wyear + sentinelname + mean_sc + hdi + UUI + (1 | year)
   Data: env

REML criterion at convergence: 166.1

Scaled residuals:
     Min       1Q   Median       3Q      Max
-2.07694 -0.55800 -0.00095  0.56901  1.76919

Random effects:
 Groups   Name        Variance Std.Dev.
 year     (Intercept) 0.03908  0.1977
 Residual             0.58140  0.7625
Number of obs: 57, groups:  year, 5

Fixed effects:
                                          Estimate Std. Error         df t value Pr(>|t|)
(Intercept)                             8.045e+00  1.142e+00  4.338e+01   7.045 1.06e-08 ***
wyear                                   1.348e-01  1.247e-01  4.490e+00   1.081  0.33419
sentinelname[T.Big Spring Creek Terminus] 1.568e+00  5.725e-01  3.583e+01   2.738  0.00956 **
sentinelname[T.Elk Springs]             -7.731e-01  3.292e-01  4.937e+01  -2.349  0.02288 *
mean_sc                                 1.713e-04  4.937e-05  4.971e+01   3.470  0.00109 **
hdi                                     -2.998e-02  2.375e-02  4.330e+01  -1.262  0.21362
UUI                                     6.609e-03  5.875e-03  1.637e+01   1.125  0.27686
```

```
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

> rand(m10)
Analysis of Random effects Table:
     Chi.sq Chi.DF p.value
year  0.373      1     0.5

correlation approximate R2 correlation between the fitted and the observed values
logged pseudo R2:
0.6092679

0.135
% change over 5 years NOT SIG
13.48
```

Ph Logged – note had to drop the nas

```
logged for change over 5 years

Linear mixed model fit by REML
t-tests use  Satterthwaite approximations to degrees of freedom ['lmerMod']
Formula: log(env2$mean_ph) ~ +env2$wyear + env2$sentinelname + env2$mean_sc +      env2$hdi + env2$UUI + (1 |
env2$year)
   Data: env2

REML criterion at convergence: -39.1

Scaled residuals:
     Min       1Q   Median       3Q      Max
-2.22372 -0.66625  0.04665  0.61966  1.65449

Random effects:
 Groups    Name        Variance  Std.Dev.
 env2$year (Intercept) 0.0007801 0.02793
 Residual              0.0095601 0.09778
Number of obs: 57, groups:  env2$year, 5

Fixed effects:
                                            Estimate Std. Error         df t value Pr(>|t|)
(Intercept)                                2.126e+00  1.473e-01  4.391e+01  14.437  < 2e-16 ***
env2$wyear                                 1.540e-02  1.650e-02  4.490e+00   0.933  0.39805
```

```
env2$sentinelname[T.Big Spring Creek Terminus]
2.068e-01  7.398e-02  3.740e+01   2.795  0.00814 **
env2$sentinelname[T.Elk Springs]
-1.182e-01  4.234e-02  4.959e+01  -2.791  0.00744 **
env2$mean_sc
1.892e-05  6.340e-06  4.960e+01   2.984  0.00441 **
env2$hdi
-4.602e-03  3.063e-03  4.424e+01  -1.503  0.14004
env2$UUI
7.672e-04  7.646e-04  1.768e+01   1.003  0.32924
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.'
0.1 ' ' 1


Analysis of Random effects Table:
          Chi.sq Chi.DF p.value
env2$year  0.515      1     0.5

correlation approximate R2 correlation between the
fitted and the observed values
logged pseudo R2:
0.6092679

0.002
% change over 5 years NOT SIG
0.154
```

Exploring peak season depth to water (DTW)

```
Call:
lm(formula = dtwgh_mean ~ factor(env$wettype) + env$elk.index +
    env$productivity_point + env$ppt_sum_monsoon2008to2010 +
    env$hydro + env$nonnat_dist + env$ndepbaron_mean + log_mn +
    mg + log_soil_ec, data = env)

Residuals:
    Min      1Q  Median      3Q     Max
-49.930 -13.862  -0.105  13.987  57.268

Coefficients:
                                Estimate Std. Error t value Pr(>|t|)
```

```
(Intercept)                    -2.966e+02  3.329e+01  -8.911 1.61e-12 ***
factor(env$wettype)[T.M]       -6.287e+01  1.002e+01  -6.275 4.51e-08 ***
factor(env$wettype)[T.R]        1.425e+01  1.471e+01   0.969 0.336747
factor(env$wettype)[T.S]       -2.834e+01  1.185e+01  -2.392 0.019985 *
env$elk.index                   5.554e-01  1.500e-01   3.702 0.000472 ***
env$productivity_point          3.175e-02  1.166e-02   2.723 0.008502 **
env$ppt_sum_monsoon2008to2010   1.195e+00  1.794e-01   6.659 1.02e-08 ***
env$hydro                      -3.767e-01  7.787e-02  -4.837 9.81e-06 ***
env$nonnat_dist                 2.203e-02  6.647e-03   3.314 0.001575 **
env$ndepbaron_mean              2.493e+01  7.976e+00   3.126 0.002753 **
log_mn                          6.744e+01  1.265e+01   5.329 1.62e-06 ***
mg                             -7.070e-02  2.397e-02  -2.949 0.004564 **
log_soil_ec                    -5.732e+01  1.425e+01  -4.021 0.000167 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 22.33 on 59 degrees of freedom
  (2 observations deleted due to missingness)
Multiple R2:  0.7944,    Adjusted R2:  0.7526
F-statistic:    19 on 12 and 59 DF,  p value: 5.394e-16

Relative importance metrics:

                                       lmg       last        first
factor(env$wettype)            0.29289647 0.28806534 0.3096151260
env$elk.index                  0.02198108 0.05991608 0.0027956682
env$productivity_point         0.02112589 0.03240132 0.0156348205
env$ppt_sum_monsoon2008to2010  0.21659731 0.19380756 0.2247820307
env$hydro                      0.06034630 0.10228195 0.0172123068
env$nonnat_dist                0.02415730 0.04800746 0.0001415012
env$ndepbaron_mean             0.06847304 0.04269952 0.0698065345
log_mn                         0.18248057 0.12413527 0.2147948883
mg                             0.02097162 0.03801147 0.0070491158
log_soil_ec                    0.09097042 0.07067405 0.1381680080
```

Trend in Multimetric Index 1 (MMI 1) at sentinel sites

Logged, net change:

```
> summary(m1) logged
Linear mixed model fit by REML
t-tests use  Satterthwaite approximations to degrees of freedom ['lmerMod']
Formula: log(mmi_1) ~ wyear + (sentinelname) + (1 | year)
   Data: env

REML criterion at convergence: -84.1

Scaled residuals:
     Min       1Q   Median       3Q      Max
-2.54020 -0.63205  0.06423  0.60721  2.58306

Random effects:
 Groups   Name        Variance Std.Dev.
 year     (Intercept) 0.002479 0.04979
 Residual             0.010363 0.10180
Number of obs: 63, groups:  year, 5

Fixed effects:
                                          Estimate Std. Error       df t value Pr(>|t|)
(Intercept)                                1.58659    0.04639  3.51000  34.204 1.48e-05 ***
wyear                                      0.04374    0.01813  2.95000   2.413   0.0963 .
sentinelname[T.Big Spring Creek Terminus] -0.27528    0.03283 56.07000  -8.386 1.78e-11 ***
sentinelname[T.Elk Springs]                0.04865    0.02979 56.44000   1.633   0.1080
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlation of Fixed Effects:
            (Intr) wyear  s[TSCT
wyear       -0.768
snt[T.BSCT] -0.239 -0.019
sntnl[T.ES] -0.291  0.017  0.393
> anova(m1)
Analysis of Variance Table of type III  with  Satterthwaite
approximation for degrees of freedom
              Sum Sq Mean Sq NumDF  DenDF F.value    Pr(>F)
wyear        0.06033 0.06033     1  2.949   5.822   0.09626 .
sentinelname 1.02644 0.51322     2 56.271  49.523 3.928e-13 ***
```

```
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
> rand(m1)
Analysis of Random effects Table:
     Chi.sq Chi.DF p.value
year   4.23      1    0.04 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
> R2.corr.mer(m1)
[1] 0.6957301
```

0.044
% change over 5 years
4.374

Not Logged, annual change:

```
> summary(m2)
Linear mixed model fit by REML
t-tests use  Satterthwaite approximations to degrees of freedom ['lmerMod']
Formula: mmi_1 ~ wyear + sentinelname + (1 | year)
   Data: env

REML criterion at convergence: 105

Scaled residuals:
     Min       1Q   Median       3Q      Max
-2.55964 -0.58370 -0.05069  0.67319  2.55721

Random effects:
 Groups   Name        Variance Std.Dev.
 year     (Intercept) 0.07656  0.2767
 Residual             0.25322  0.5032
Number of obs: 63, groups:  year, 5

Fixed effects:
                                        Estimate Std. Error       df t value Pr(>|t|)
(Intercept)                              4.90927    0.24934  3.42000  19.689 0.000123 ***
wyear                                    0.23185    0.09812  2.95000   2.363 0.100565
sentinelname[T.Big Spring Creek Terminus] -1.29190    0.16227 56.05000  -7.961  8.9e-11 ***
sentinelname[T.Elk Springs]               0.26180    0.14729 56.37000   1.777 0.080884 .
```

```
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlation of Fixed Effects:
            (Intr) wyear  s[TSCT
wyear       -0.776
snt[T.BSCT] -0.220 -0.017
sntnl[T.ES] -0.268  0.016  0.393
> anova(m2)
Analysis of Variance Table of type III  with  Satterthwaite
approximation for degrees of freedom
              Sum Sq Mean Sq NumDF  DenDF F.value    Pr(>F)
wyear         1.4136  1.4136     1  2.952   5.583    0.1006
sentinelname 23.2554 11.6277     2 56.224  45.919 1.508e-12 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
> rand(m2)
Analysis of Random effects Table:
     Chi.sq Chi.DF p.value
year   5.69      1    0.02 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
> # anova(m2, ddf="lme4")
> # if(requireNamespace("pbkrtest", quietly = TRUE))
> #   anova(m2, ddf = "Kenward-Roger")
>
> R2.corr.mer(m2)
[1] 0.6940723
```

Trend in Multimetric Index 2 (MMI 2) at sentinel sites

```
> summary(m4) logged
Linear mixed model fit by REML
t-tests use  Satterthwaite approximations to degrees of freedom ['lmerMod']
Formula: log(mmi_2) ~ wyear + (sentinelname) + (1 | year)
   Data: env

REML criterion at convergence: -20.9

Scaled residuals:
     Min       1Q   Median       3Q      Max
```

```
-2.45257 -0.49527  0.02508  0.62055  1.76848

Random effects:
 Groups   Name        Variance Std.Dev.
 year     (Intercept) 0.001161 0.03408
 Residual             0.031840 0.17844
Number of obs: 63, groups:  year, 5

Fixed effects:
                                     Estimate Std. Error       df t value Pr(>|t|)
(Intercept)                           1.29038    0.05223  4.78000  24.705 3.13e-06 ***
wyear                                 0.01852    0.01906  3.09000   0.972    0.401
sentinelnameBig Spring Creek Terminus 0.51684    0.05752 56.39000   8.985 1.79e-12 ***
sentinelnameElk Springs               0.43612    0.05205 57.20000   8.379 1.58e-11 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlation of Fixed Effects:
            (Intr) wyear  snBSCT
wyear       -0.694
sntnlnmBSCT -0.371 -0.033
sntnlnmElkS -0.451  0.025  0.393
> anova(m4)
Analysis of Variance Table of type III  with  Satterthwaite
approximation for degrees of freedom
             Sum Sq Mean Sq NumDF  DenDF F.value    Pr(>F)
wyear        0.0301 0.03006     1  3.087   0.944    0.4011
sentinelname 3.4545 1.72725     2 56.829  54.248 6.639e-14 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
> rand(m4)
Analysis of Random effects Table:
     Chi.sq Chi.DF p.value
year  0.252      1     0.6
> R2.corr.mer(m4)
[1] 0.6578209



0.019
% change over 5 years
1.852
```

```
> summary(m5)
Linear mixed model fit by REML
t-tests use  Satterthwaite approximations to degrees of freedom ['lmerMod']
Formula: mmi_2 ~ wyear + sentinelname + (1 | year)
   Data: env

REML criterion at convergence: 161.4

Scaled residuals:
     Min       1Q   Median       3Q      Max
-2.39355 -0.62567 -0.05276  0.61162  2.21538

Random effects:
 Groups   Name        Variance Std.Dev.
 year     (Intercept) 0.0736   0.2713
 Residual             0.6827   0.8263
Number of obs: 63, groups:  year, 5

Fixed effects:
                                     Estimate Std. Error      df t value Pr(>|t|)
(Intercept)                            3.6444     0.2964  4.1000  12.296 0.000217 ***
wyear                                  0.1037     0.1126  3.0900   0.921 0.423280
sentinelnameBig Spring Creek Terminus  2.5632     0.2664 56.2700   9.621 1.73e-13 ***
sentinelnameElk Springs                2.0248     0.2415 56.8400   8.386 1.61e-11 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlation of Fixed Effects:
            (Intr) wyear  snBSCT
wyear       -0.737
sntnlnmBSCT -0.303 -0.025
sntnlnmElkS -0.369  0.021  0.393
> anova(m5)
Analysis of Variance Table of type III  with  Satterthwaite
approximation for degrees of freedom
             Sum Sq Mean Sq NumDF  DenDF F.value    Pr(>F)
wyear         0.579   0.579     1  3.085   0.848    0.4233
sentinelname 80.313  40.157     2 56.580  58.819 1.521e-14 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
> rand(m5)
```

```
Analysis of Random effects Table:
     Chi.sq Chi.DF p.value
year   1.51      1     0.2
> # anova(m2, ddf="lme4")
> # if(requireNamespace("pbkrtest", quietly = TRUE))
> #   anova(m2, ddf = "Kenward-Roger")
>
> R2.corr.mer(m5)
[1] 0.683837
```

Exploring Soil sodium adsorption ratio (SAR)

```
SAR
Call:
lm(formula = log_sar ~ soil_ph + log_k + ca + log_soil_ec + log_na +
    log_totaln_perc + c_n_ratio + env$UUI + env$trail.index +
    env$elk.index + env$ppt_sum_monsoon2008to2010 + env$elev +
    env$nonnat_dist + env$ldi, data = env)

Residuals:
     Min       1Q   Median       3Q      Max
-0.61909 -0.10905 -0.02029  0.10406  0.59666

Coefficients:
                              Estimate Std. Error t value Pr(>|t|)
(Intercept)                  1.007e+01  5.340e+00   1.886 0.064369 .
soil_ph                      2.163e-01  3.255e-02   6.645 1.24e-08 ***
log_k                       -3.630e-01  1.333e-01  -2.724 0.008558 **
ca                          -2.084e-04  3.249e-05  -6.414 3.00e-08 ***
log_soil_ec                  1.534e+00  1.664e-01   9.219 6.78e-13 ***
log_na                       2.270e-01  8.233e-02   2.757 0.007831 **
log_totaln_perc              1.969e+00  6.016e-01   3.274 0.001807 **
c_n_ratio                    5.944e-03  2.904e-03   2.047 0.045314 *
env$UUI                      1.498e-03  8.396e-04   1.784 0.079777 .
env$trail.index              3.110e-03  1.188e-03   2.617 0.011327 *
env$elk.index               -2.734e-03  1.406e-03  -1.944 0.056837 .
env$ppt_sum_monsoon2008to2010  1.411e-02  5.872e-03   2.402 0.019566 *
env$elev                    -5.641e-03  2.611e-03  -2.161 0.034907 *
env$nonnat_dist              1.102e-04  5.586e-05   1.973 0.053313 .
env$ldi                      4.096e-03  1.171e-03   3.498 0.000915 ***
---
```

```
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.1905 on 57 degrees of freedom
  (2 observations deleted due to missingness)
Multiple R2:  0.9331,    Adjusted R2:  0.9167  F-statistic: 56.77 on 14 and 57 DF,  p value: < 2.2e-16
F-statistic: 56.77 on 14 and 57 DF,  p value: < 2.2e-16


Relative importance metrics:

                                       lmg       last        first
soil_ph                        0.162545247 0.18355058 0.1561093806
log_k                          0.106172168 0.03082894 0.1377462278
ca                             0.055451875 0.17097237 0.0381303543
log_soil_ec                    0.262314122 0.35325816 0.2056921019
log_na                         0.144452950 0.03158320 0.1646369121
log_totaln_perc                0.031025794 0.04454370 0.0425164826
c_n_ratio                      0.163183569 0.01740968 0.1743787637
env$UUI                        0.007239133 0.01322528 0.0032875524
env$trail.index                0.009205120 0.02847276 0.0086000581
env$elk.index                  0.006673152 0.01570714 0.0000332831
env$ppt_sum_monsoon2008to2010 0.013788352 0.02398896 0.0219661900
env$elev                       0.015410856 0.01941038 0.0248782549
env$nonnat_dist                0.012853402 0.01618466 0.0145482801
env$ldi                        0.009684259 0.05086417 0.0074761583
```

Exploring Soil Total Percent Carbon

```
Call:
lm(formula = log_totalc_perc ~ log_om_40cm + soil_ph + log_zn +
    log_soil_ec + log_na + log_totaln_perc + env$sum_pet + env$elk.index +
    env$ppt_30yrnormal_sum + env$sand_dist + env$ldi + env$nonnat_catch,
    data = env)

Residuals:
      Min        1Q    Median        3Q       Max
-0.189662 -0.046475 -0.008292  0.049690  0.184089

Coefficients:
                         Estimate Std. Error t value Pr(>|t|)
(Intercept)             5.557e-01  3.200e-01   1.737 0.087673 .
```

```
log_om_40cm              1.537e-01  4.094e-02   3.754 0.000400 ***
soil_ph                 -6.780e-02  1.693e-02  -4.004 0.000176 ***
log_zn                  -3.579e-01  1.243e-01  -2.880 0.005532 **
log_soil_ec              1.844e-01  6.837e-02   2.698 0.009088 **
log_na                   1.284e-01  3.153e-02   4.074 0.000140 ***
log_totaln_perc          3.924e+00  2.612e-01  15.022  < 2e-16 ***
env$sum_pet             -1.678e-03  6.300e-04  -2.663 0.009957 **
env$elk.index            1.227e-03  6.058e-04   2.025 0.047396 *
env$ppt_30yrnormal_sum   6.085e-05  1.801e-05   3.379 0.001296 **
env$sand_dist           -4.168e-05  1.525e-05  -2.733 0.008268 **
env$ldi                  3.176e-03  8.844e-04   3.592 0.000671 ***
env$nonnat_catch         9.174e-02  3.471e-02   2.643 0.010503 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.08515 on 59 degrees of freedom
  (2 observations deleted due to missingness)
Multiple R2:  0.9251,    Adjusted R2:  0.9099
F-statistic: 60.74 on 12 and 59 DF,  p value: < 2.2e-16


Relative importance metrics:

                              lmg       last        first
log_om_40cm             0.112869685 0.04169918 1.199713e-01
soil_ph                 0.091129892 0.04744955 1.155698e-01
log_zn                  0.141402123 0.02454876 2.122609e-01
log_soil_ec             0.009092574 0.02153759 1.074738e-03
log_na                  0.032281042 0.04911295 4.731511e-04
log_totaln_perc         0.517443652 0.66778996 4.385975e-01
env$sum_pet             0.011584306 0.02099277 1.105978e-02
env$elk.index           0.007412612 0.01213561 8.546915e-05
env$ppt_30yrnormal_sum  0.045858878 0.03377981 7.319666e-02
env$sand_dist           0.007590756 0.02210494 1.319795e-03
env$ldi                 0.008597535 0.03817371 1.287767e-05
env$nonnat_catch        0.014736945 0.02067517 2.637808e-02
```

Appendix H: Soil Chemistry

Summary of soil chemistry for all sandsheet sites in 2010. LCL/UCL are lower and upper 95% confidence intervals. Standard error is for the mean. This appendix gives means and measures of dispersion for each response by site type (high elevation vs. sandsheet) and wetland type.

Site type	Metric	Valid N	Mean	LCL	UCL	Min	Max	Std. dev.	Std. error
All sites	pH	82	7.61	7.27	7.94	4.36	10.40	1.53	0.17
	Specific conductance (µS/cm)	82	1704	1060	2420	192	18720	310	341
	Potassium (mg/kg)	82	1052.26	812.19	1292.34	57.80	4449.00	1092.62	120.66
	Zinc (mg/kg)	82	0.87	0.46	1.28	0.01	10.76	1.88	0.21
	Iron (mg/kg)	82	163.82	88.82	238.81	0.62	1699.00	341.32	37.69
	Manganese(mg/kg)	82	5.16	4.09	6.22	0.68	25.99	4.83	0.53
	Copper (mg/kg)	82	6.21	2.30	10.13	0.39	128.40	17.82	1.97
	Calcium (mg/kg)	82	2016.71	1804.45	2228.96	538.00	4686.00	966.00	106.68
	Magensium (mg/kg)	82	249.22	216.87	281.58	3.88	667.80	147.26	16.26
	Sodium (mg/kg)	82	355.19	242.21	468.18	4.90	2376.00	514.21	56.79
	Sodium (%)	80	48.36	-0.48	97.20	0.09	1566.50	219.46	24.54
	Sodium adsorption ratio	82	49.21	2.40	96.02	0.14	1515.13	213.04	23.53
	Sulfate (mg/kg)	82	188.86	95.96	281.76	0.24	2703.00	422.81	46.69
	Carbonate (mg/kg)	75	364.75	239.69	489.81	0.10	2410.00	543.56	62.76
	Bicarbonate (mg/kg)	75	152.63	126.36	178.91	0.10	528.00	114.20	13.19
	Cation exchange capacity (meq/100g)	82	16.41	15.01	17.80	4.95	33.89	6.36	0.70
	Total nitrogen %	82	0.35	0.22	0.47	0.00	2.42	0.57	0.06
	Total carbon %	82	4.90	3.25	6.56	0.13	33.25	7.55	0.83
	Carbon to nitrogen ratio	82	19.18	16.32	22.04	5.00	73.40	13.00	1.44
	Peat thickness (cm)	82	10.93	3.80	18.06	0.00	165.00	32.46	3.58
	Organic matter at 40 cm %	80	7.57	4.86	10.28	0.67	62.05	12.17	1.36
	Organic matter at 5-20 cm %	81	8.25	5.98	10.52	0.51	42.80	10.26	1.14
	Ammonium (mg/kg)	82	62.85	-2.36	128.05	0.01	2577.90	296.74	32.77
	Nitrate (mg/kg)	82	7.98	2.29	13.68	0.45	187.50	25.90	2.86
	Phosphorous (mg/kg)	82	6.49	4.94	8.04	0.60	49.90	7.07	0.78
Sandsheet sites	pH	74	7.90	7.60	8.20	4.36	10.40	1.30	0.15
	Specific conductance (µS/cm)	74	1.86	1.11	2.61	0.19	18.72	3.24	0.38
	Potassium (mg/kg)	74	1152.61	896.75	1408.48	88.73	4449.00	1104.37	128.38
	Zinc (mg/kg)	74	0.42	0.23	0.62	0.01	4.51	0.82	0.10
	Iron (mg/kg)	74	70.20	34.66	105.74	0.62	1019.00	153.39	17.83
	Manganese(mg/kg)	74	4.83	3.75	5.90	0.68	25.99	4.64	0.54
	Copper (mg/kg)	74	1.72	1.31	2.12	0.39	8.96	1.74	0.20
	Calcium (mg/kg)	74	2011.64	1796.05	2227.22	538.00	4686.00	930.54	108.17
	Magensium (mg/kg)	74	255.30	220.13	290.47	3.88	667.80	151.82	17.65
	Sodium (mg/kg)	74	392.78	270.47	515.09	15.31	2376.00	527.93	61.37
	Sodium (%)	72	53.70	-0.56	107.95	0.22	1566.50	230.87	27.21
	Sodium adsorption ratio	74	54.49	2.65	106.34	0.27	1515.13	223.76	26.01
	Sulfate (mg/kg)	74	147.76	51.04	244.48	0.24	2703.00	417.47	48.53
	Carbonate (mg/kg)	74	337.11	223.28	450.95	0.10	2170.00	491.35	57.12
	Bicarbonate (mg/kg)	74	153.68	127.13	180.24	0.10	528.00	114.62	13.32

Appendix H (*continued*)

Site type	Metric	Valid N	Mean	LCL	UCL	Min	Max	Std. dev.	Std. error
Sandsheet sites (cont'd)	Cation exchange capacity (meq/100g)	74	16.85	15.43	18.27	4.95	33.89	6.14	0.71
	Total nitrogen %	74	0.18	0.13	0.22	0.00	0.96	0.20	0.02
	Total carbon %	74	2.70	2.06	3.34	0.13	11.78	2.76	0.32
	Carbon to nitrogen ratio	74	19.81	16.67	22.95	5.00	73.40	13.54	1.57
	Peat thickness (cm)	74	1.80	0.15	3.45	0.00	40.00	7.12	0.83
	Organic matter at 40 cm %	72	4.36	3.21	5.51	0.67	31.34	4.88	0.58
	Organic matter at 5–20 cm %	73	5.30	4.19	6.41	0.51	21.46	4.76	0.56
	Ammonium (mg/kg)	74	8.46	6.58	10.34	0.01	44.40	8.10	0.94
	Nitrate (mg/kg)	74	4.28	1.07	7.48	0.45	118.30	13.82	1.61
	Phosphorous (mg/kg)	74	6.47	4.79	8.15	0.60	49.90	7.25	0.84
HIgh sites	pH	8	4.92	4.51	5.34	4.43	6.02	0.50	0.18
	Specific conductance (µS/cm)	8	0.56	0.35	0.78	0.20	1.00	0.26	0.09
	Potassium (mg/kg)	8	124.03	71.22	176.83	57.80	228.00	63.16	22.33
	Zinc (mg/kg)	8	4.97	2.03	7.90	0.73	10.76	3.51	1.24
	Iron (mg/kg)	8	1029.76	702.68	1356.84	576.90	1699.00	391.24	138.32
	Manganese(mg/kg)	8	8.20	3.31	13.09	2.45	18.58	5.85	2.07
	Copper (mg/kg)	8	47.79	15.92	79.66	9.60	128.40	38.12	13.48
	Calcium (mg/kg)	8	2063.63	952.92	3174.33	844.00	4158.00	1328.56	469.72
	Magensium (mg/kg)	8	193.00	125.35	260.65	134.00	361.00	80.92	28.61
	Sodium (mg/kg)	8	7.50	4.49	10.51	4.90	15.50	3.60	1.27
	Sodium (%)	8	0.31	0.20	0.43	0.09	0.48	0.14	0.05
	Sodium adsorption ratio	8	0.33	0.21	0.44	0.14	0.52	0.14	0.05
	Sulfate (mg/kg)	8	569.00	350.91	787.09	114.00	875.00	260.86	92.23
	Carbonate (mg/kg)	1	2410.00	–	–	2410.00	2410.00	–	–
	Bicarbonate (mg/kg)	1	75.00	–	–	75.00	75.00	–	–
	Cation exchange capacity (meq/100g)	8	12.33	6.21	18.44	5.60	24.10	7.32	2.59
	Total nitrogen %	8	1.91	1.44	2.37	0.97	2.42	0.56	0.20
	Total carbon %	8	25.29	19.17	31.40	12.46	33.25	7.31	2.59
	Carbon to nitrogen ratio	8	13.32	12.53	14.11	11.61	14.40	0.95	0.33
	Peat thickness (cm)	8	95.38	52.50	138.25	12.00	165.00	51.29	18.13
	Organic matter at 40 cm %	8	36.48	20.41	52.55	9.84	62.05	19.22	6.80
	Organic matter at 5–20 cm %	8	35.20	29.30	41.10	21.30	42.80	7.05	2.49
	Ammonium (mg/kg)	8	565.91	-132.42	1264.24	18.70	2577.90	835.30	295.32
	Nitrate (mg/kg)	8	42.29	-12.42	97.00	2.30	187.50	65.44	23.14
	Phosphorous (mg/kg)	8	6.70	2.14	11.26	2.40	17.20	5.46	1.93
Low salt flats	pH	19	9.00	8.55	9.46	7.61	10.40	0.95	0.22
	Specific conductance (µS/cm)	19	4.86	2.27	7.44	0.30	18.72	5.36	1.23
	Potassium (mg/kg)	19	2428.79	1828.49	3029.09	475.90	4449.00	1245.48	285.73
	Zinc (mg/kg)	19	0.10	0.06	0.14	0.01	0.30	0.07	0.02
	Iron (mg/kg)	19	2.49	1.79	3.19	0.62	5.32	1.45	0.33
	Manganese(mg/kg)	19	2.27	1.62	2.91	0.68	4.71	1.34	0.31
	Copper (mg/kg)	19	0.79	0.65	0.92	0.47	1.58	0.28	0.06
	Calcium (mg/kg)	19	1594.70	1279.49	1909.91	538.00	3225.00	653.98	150.03

Appendix H (*continued*)

Site type	Metric	Valid N	Mean	LCL	UCL	Min	Max	Std. dev.	Std. error
Low salt flats (cont'd)	Magnesium (mg/kg)	19	130.89	83.98	177.80	3.88	305.50	97.32	22.33
	Sodium (mg/kg)	19	890.06	597.46	1182.67	47.07	2217.00	607.08	139.27
	Sodium (%)	18	203.13	-14.21	420.46	0.72	1566.50	437.04	103.01
	Sodium adsorption ratio	19	201.36	1.26	401.45	0.77	1515.13	415.15	95.24
	Sulfate (mg/kg)	19	302.89	-2.20	607.98	2.62	2703.00	632.98	145.22
	Carbonate (mg/kg)	19	735.03	389.37	1080.68	32.70	2170.00	717.15	164.52
	Bicarbonate (mg/kg)	19	126.82	64.73	188.92	17.60	355.00	128.83	29.56
	Cation exchange capacity (meq/100g)	19	19.16	16.76	21.56	12.48	33.89	4.98	1.14
	Total nitrogen %	19	0.05	0.02	0.08	0.01	0.25	0.06	0.01
	Total carbon %	19	1.61	0.80	2.43	0.41	7.56	1.69	0.39
	Carbon to nitrogen ratio	19	36.52	28.89	44.15	15.17	73.40	15.83	3.63
	Peat thickness (cm)	19	0.00	–	–	0.00	0.00	0.00	0.00
	Organic matter at 40 cm %	18	5.13	3.15	7.11	1.26	17.25	3.98	0.94
	Organic matter at 5–20 cm %	19	2.32	1.53	3.11	0.71	7.83	1.64	0.38
	Ammonium (mg/kg)	19	3.48	1.90	5.07	0.01	13.90	3.29	0.76
	Nitrate (mg/kg)	19	3.65	1.10	6.20	0.65	24.30	5.29	1.21
	Phosphorous (mg/kg)	19	7.40	4.64	10.16	1.50	21.80	5.72	1.31
Low wet meadows	pH	42	7.78	7.47	8.08	5.03	9.59	0.98	0.15
	Specific conductance (µS/cm)	42	0.83	0.65	1.02	0.19	2.76	0.59	0.09
	Potassium (mg/kg)	42	668.53	513.31	823.76	88.73	2309.00	498.12	76.86
	Zinc (mg/kg)	42	0.39	0.15	0.63	0.01	3.99	0.76	0.12
	Iron (mg/kg)	42	52.26	27.72	76.80	1.74	301.80	78.75	12.15
	Manganese(mg/kg)	42	4.81	3.62	6.00	1.00	15.17	3.82	0.59
	Copper (mg/kg)	42	2.03	1.38	2.68	0.39	8.96	2.08	0.32
	Calcium (mg/kg)	42	2283.00	1968.96	2597.03	611.00	4686.00	1007.74	155.50
	Magnesium (mg/kg)	42	298.64	252.43	344.85	59.43	667.80	148.29	22.88
	Sodium (mg/kg)	42	235.90	107.37	364.43	15.31	2376.00	412.46	63.64
	Sodium (%)	41	4.16	2.44	5.87	0.22	21.25	5.44	0.85
	Sodium adsorption ratio	42	4.11	2.49	5.73	0.27	20.64	5.20	0.80
	Sulfate (mg/kg)	42	44.28	14.49	74.07	0.24	569.10	95.59	14.75
	Carbonate (mg/kg)	42	217.50	134.41	300.60	0.10	1240.00	266.65	41.14
	Bicarbonate (mg/kg)	42	178.90	145.30	212.49	0.10	528.00	107.81	16.64
	Cation exchange capacity (meq/100g)	42	16.64	14.58	18.71	4.95	28.68	6.63	1.02
	Total nitrogen %	42	0.20	0.13	0.26	0.00	0.92	0.20	0.03
	Total carbon %	42	2.90	2.01	3.80	0.13	11.78	2.88	0.44
	Carbon to nitrogen ratio	42	14.75	12.85	16.65	5.00	36.19	6.08	0.94
	Peat thickness (cm)	42	1.31	-0.73	3.35	0.00	40.00	6.54	1.01
	Organic matter at 40 cm %	41	3.60	2.61	4.58	0.67	12.63	3.11	0.49
	Organic matter at 5–20 cm %	41	5.86	4.47	7.25	0.51	20.64	4.40	0.69
	Ammonium (mg/kg)	42	8.47	6.55	10.39	0.01	27.60	6.16	0.95
	Nitrate (mg/kg)	42	2.39	1.72	3.05	0.64	11.00	2.14	0.33
	Phosphorous (mg/kg)	42	6.45	3.79	9.10	0.60	49.90	8.52	1.31

Appendix H (*continued*)

Site type	Metric	Valid N	Mean	LCL	UCL	Min	Max	Std. dev.	Std. error
Low riparian	pH	4	6.55	4.71	8.38	5.32	7.87	1.15	0.58
	Specific conductance (µS/cm)	4	0.51	0.14	0.87	0.20	0.76	0.23	0.12
	Potassium (mg/kg)	4	636.08	174.37	1097.78	385.60	970.00	290.16	145.08
	Zinc (mg/kg)	4	0.82	-0.29	1.92	0.15	1.78	0.69	0.35
	Iron (mg/kg)	4	270.98	-139.66	681.62	38.51	627.90	258.07	129.03
	Manganese(mg/kg)	4	9.29	-0.02	18.60	5.08	17.54	5.85	2.93
	Copper (mg/kg)	4	1.75	0.80	2.70	0.91	2.31	0.60	0.30
	Calcium (mg/kg)	4	1882.38	353.47	3411.28	966.50	3167.00	960.84	480.42
	Magnesium (mg/kg)	4	263.90	67.21	460.59	141.40	435.90	123.61	61.80
	Sodium (mg/kg)	4	120.40	-7.97	248.77	44.03	221.30	80.67	40.34
	Sodium (%)	4	1.87	0.39	3.35	1.00	3.19	0.93	0.47
	Sodium adsorption ratio	4	1.83	0.46	3.20	1.13	3.08	0.86	0.43
	Sulfate (mg/kg)	4	34.98	-12.40	82.36	6.63	67.05	29.78	14.89
	Carbonate (mg/kg)	4	10.75	-9.56	31.06	0.10	25.60	12.77	6.38
	Bicarbonate (mg/kg)	4	112.55	-77.13	302.23	10.50	244.00	119.20	59.60
	Cation exchange capacity (meq/100g)	4	13.77	3.39	24.14	8.33	22.92	6.52	3.26
	Total nitrogen %	4	0.34	0.01	0.68	0.11	0.59	0.21	0.11
	Total carbon %	4	4.95	-0.09	10.00	1.23	8.12	3.17	1.58
	Carbon to nitrogen ratio	4	13.90	10.95	16.85	11.43	15.83	1.85	0.93
	Peat thickness (cm)	4	5.00	-10.91	20.91	0.00	20.00	10.00	5.00
	Organic matter at 40 cm %	4	10.55	-11.82	32.92	1.02	31.34	14.06	7.03
	Organic matter at 5–20 cm %	4	9.20	-3.83	22.22	3.34	21.22	8.19	4.09
	Ammonium (mg/kg)	4	21.00	-0.41	42.41	6.70	35.00	13.46	6.73
	Nitrate (mg/kg)	4	1.51	-1.67	4.68	0.45	4.50	2.00	1.00
	Phosphorous (mg/kg)	4	4.08	-0.94	9.09	0.90	8.10	3.15	1.58
Low marsh	pH	9	6.74	5.52	7.95	4.36	9.14	1.58	0.53
	Specific conductance (µS/cm)	9	0.95	0.46	1.44	0.35	2.40	0.64	0.21
	Potassium (mg/kg)	9	947.08	156.95	1737.20	173.50	3522.00	1027.91	342.64
	Zinc (mg/kg)	9	1.09	-0.04	2.22	0.13	4.51	1.47	0.49
	Iron (mg/kg)	9	207.63	-40.22	455.47	5.29	1019.00	322.43	107.48
	Manganese(mg/kg)	9	8.34	2.13	14.55	2.04	25.99	8.08	2.69
	Copper (mg/kg)	9	2.21	1.04	3.39	0.81	6.11	1.53	0.51
	Calcium (mg/kg)	9	1682.92	1162.24	2203.60	748.50	2636.00	677.38	225.79
	Magnesium (mg/kg)	9	311.86	202.22	421.49	175.00	625.00	142.62	47.54
	Sodium (mg/kg)	9	196.16	37.57	354.75	24.77	636.40	206.32	68.77
	Sodium (%)	9	3.54	-0.26	7.35	0.61	15.91	4.95	1.65
	Sodium adsorption ratio	9	2.97	-0.80	6.74	0.50	15.95	4.90	1.63
	Sulfate (mg/kg)	9	353.32	-176.11	882.76	6.63	2110.00	688.77	229.59
	Carbonate (mg/kg)	9	200.31	-103.24	503.86	0.10	1190.00	394.90	131.63
	Bicarbonate (mg/kg)	9	111.00	35.35	186.65	0.10	252.00	98.42	32.81
	Cation exchange capacity (meq/100g)	9	14.29	10.69	17.90	6.73	20.24	4.69	1.56
	Total nitrogen %	9	0.28	0.06	0.50	0.04	0.96	0.28	0.09

Appendix H (*continued*)

Site type	Metric	Valid N	Mean	LCL	UCL	Min	Max	Std. dev.	Std. error
Low marsh (cont'd)	Total carbon %	9	3.05	0.49	5.61	0.34	11.10	3.33	1.11
	Carbon to nitrogen ratio	9	10.78	8.19	13.37	7.57	18.45	3.37	1.12
	Peat thickness (cm)	9	6.44	-3.50	16.39	0.00	33.00	12.94	4.31
	Organic matter at 40 cm %	9	3.54	-0.75	7.83	0.78	17.91	5.58	1.86
	Organic matter at 5–20 cm %	9	7.30	2.36	12.24	1.31	21.46	6.43	2.14
	Ammonium (mg/kg)	9	13.36	4.00	22.72	3.20	44.40	12.18	4.06
	Nitrate (mg/kg)	9	15.65	-13.99	45.28	0.48	118.30	38.56	12.85
	Phosphorous (mg/kg)	9	5.64	1.83	9.46	0.60	14.90	4.96	1.65
	Total carbon %	9	3.05	0.49	5.61	0.34	11.10	3.33	1.11
	Carbon to nitrogen ratio	9	10.78	8.19	13.37	7.57	18.45	3.37	1.12
	Peat thickness (cm)	9	6.44	-3.50	16.39	0.00	33.00	12.94	4.31
	Organic matter at 40 cm %	9	3.54	-0.75	7.83	0.78	17.91	5.58	1.86
	Organic matter at 5–20 cm %	9	7.30	2.36	12.24	1.31	21.46	6.43	2.14
	Ammonium (mg/kg)	9	13.36	4.00	22.72	3.20	44.40	12.18	4.06
	Nitrate (mg/kg)	9	15.65	-13.99	45.28	0.48	118.30	38.56	12.85
	Phosphorous (mg/kg)	9	5.64	1.83	9.46	0.60	14.90	4.96	1.65

Appendix I: Sandsheet Sentinel Site 2010–2014 Hydrographs

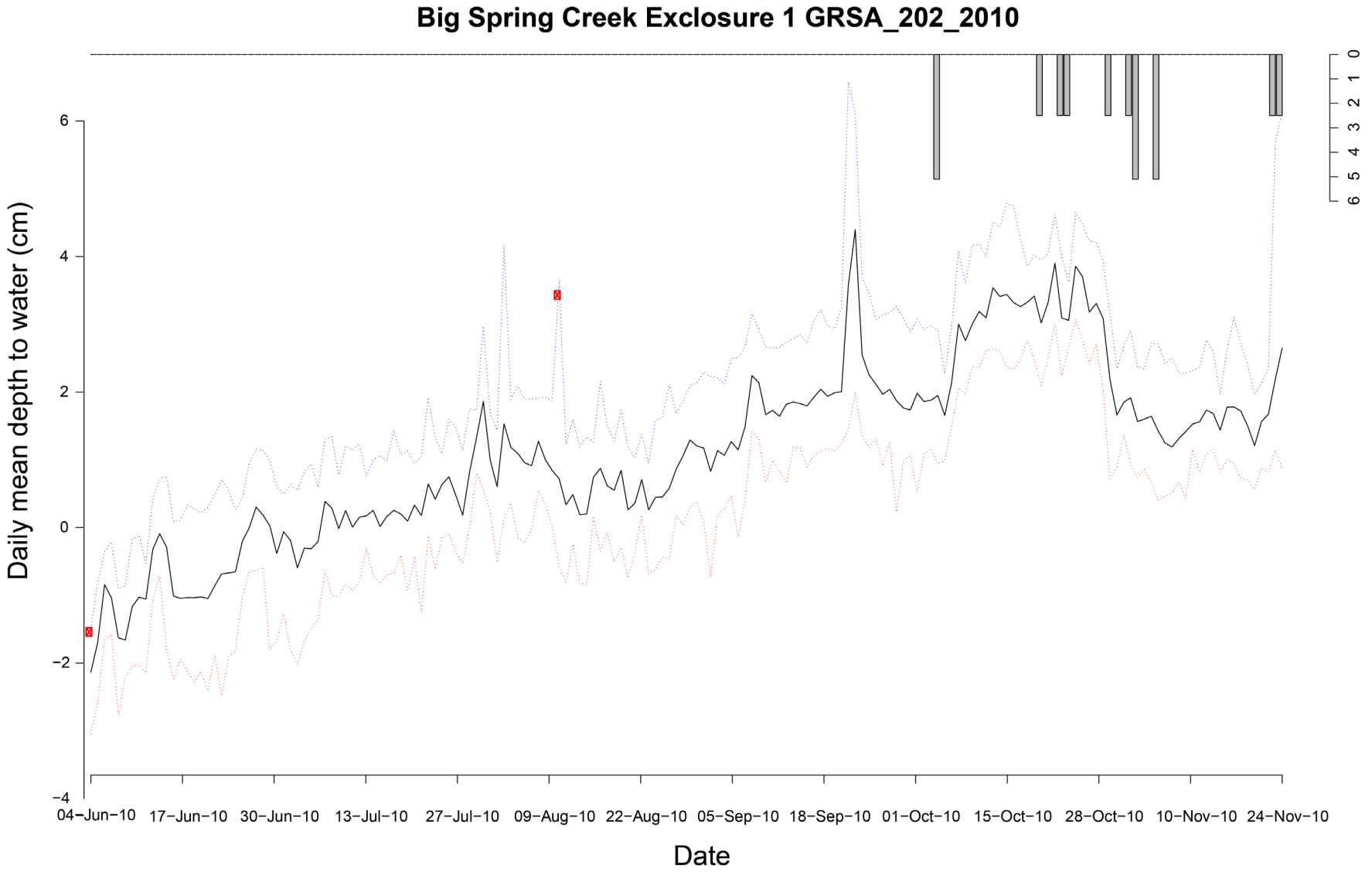


Figure I-1. 2010 hydrographs with precipitation climogram for snow free period at site 202 Big Spring Creek, Exclosure 1, in Great Sand Dunes National Park and Preserve. Ground elevation is at 0 on the y axis. Black line is the daily mean depth to water (DTW) (cm relative to ground level, with negative values indicating a water table below ground), with blue and red lines the maxima and minima. Red dots are episodic hand readings. Climogram shows daily precipitation (cm), with higher values shown by longer bars.

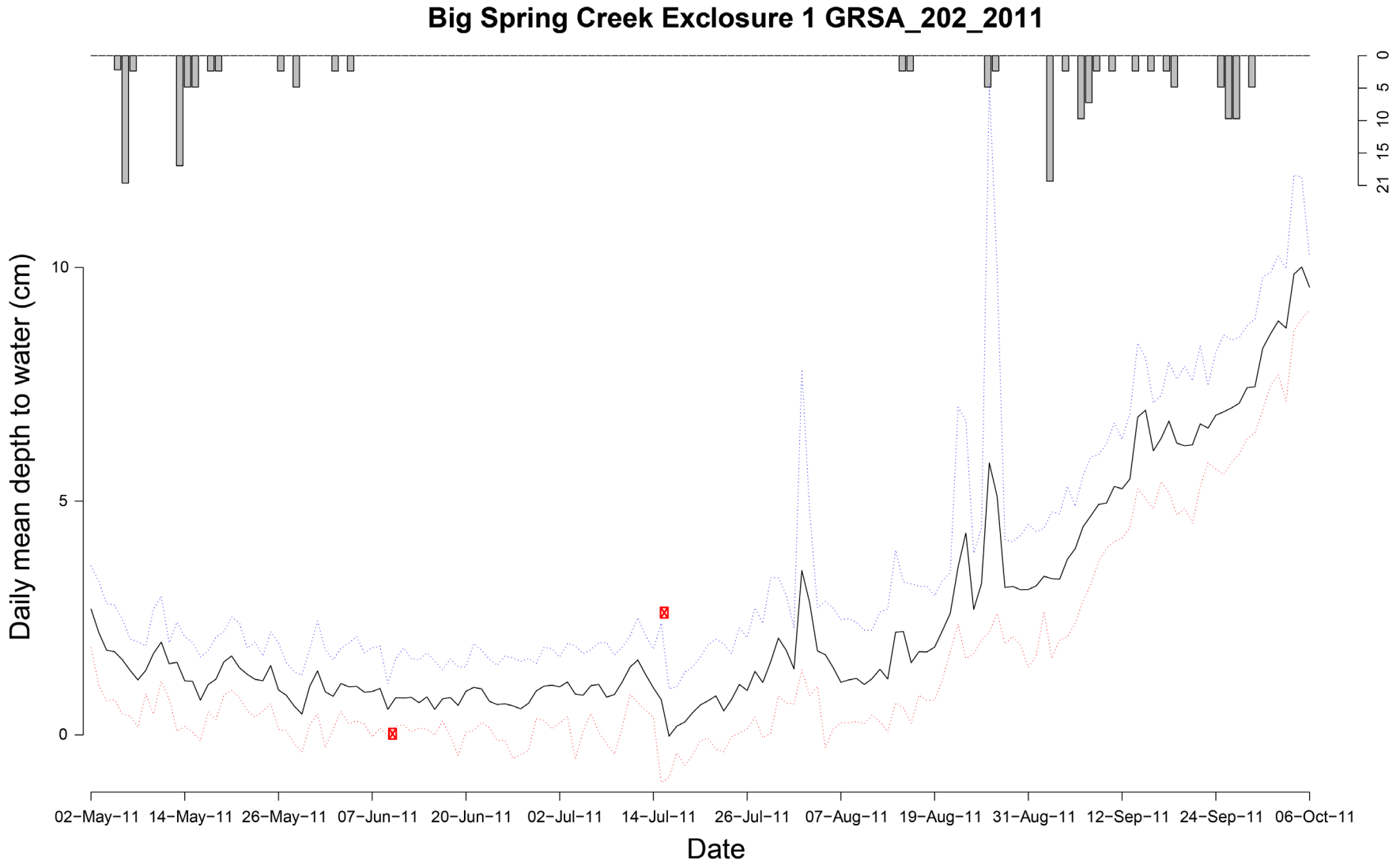


Figure I-2. 2011 hydrograph with precipitation climogram for snow free period at site 202 Big Spring Creek, Exclosure 1, in Great Sand Dunes National Park and Preserve. Ground elevation is at 0 on the y axis. Black line is the daily mean depth to water (DTW) (cm relative to ground level, with negative values indicating a water table below ground), with blue and red lines the maxima and minima. Red dots are episodic hand readings. Climogram shows daily precipitation (cm), with higher values shown by longer bars.

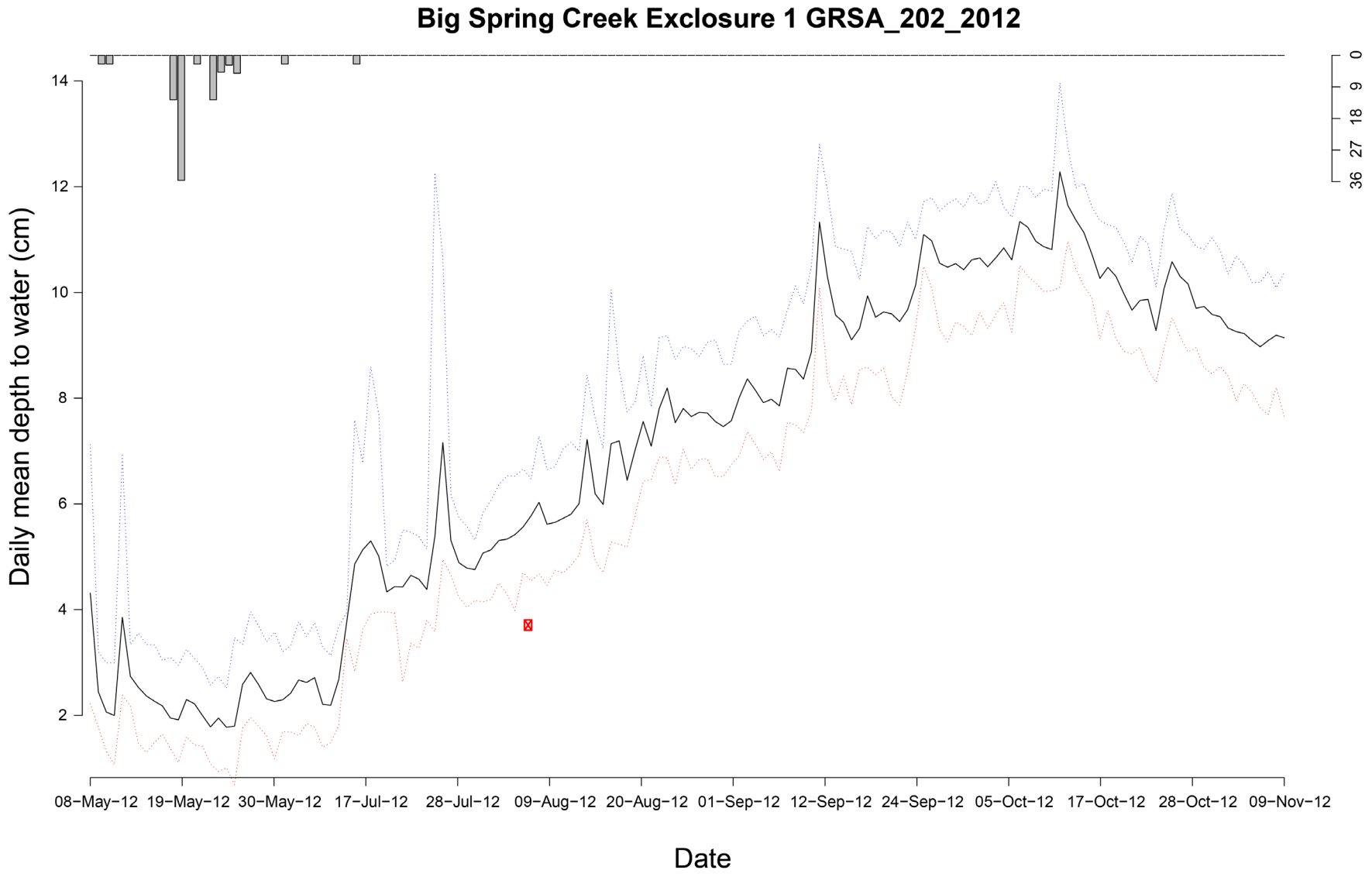


Figure I-3. 2012 hydrograph with precipitation climogram for snow free period at site 202 Big Spring Creek, Exclosure 1, in Great Sand Dunes National Park and Preserve. Ground elevation is at 0 on the y axis. Black line is the daily mean depth to water (DTW) (cm relative to ground level, with negative values indicating a water table below ground), with blue and red lines the maxima and minima. Red dots are episodic hand readings. Climogram shows daily precipitation (cm), with higher values shown by longer bars.

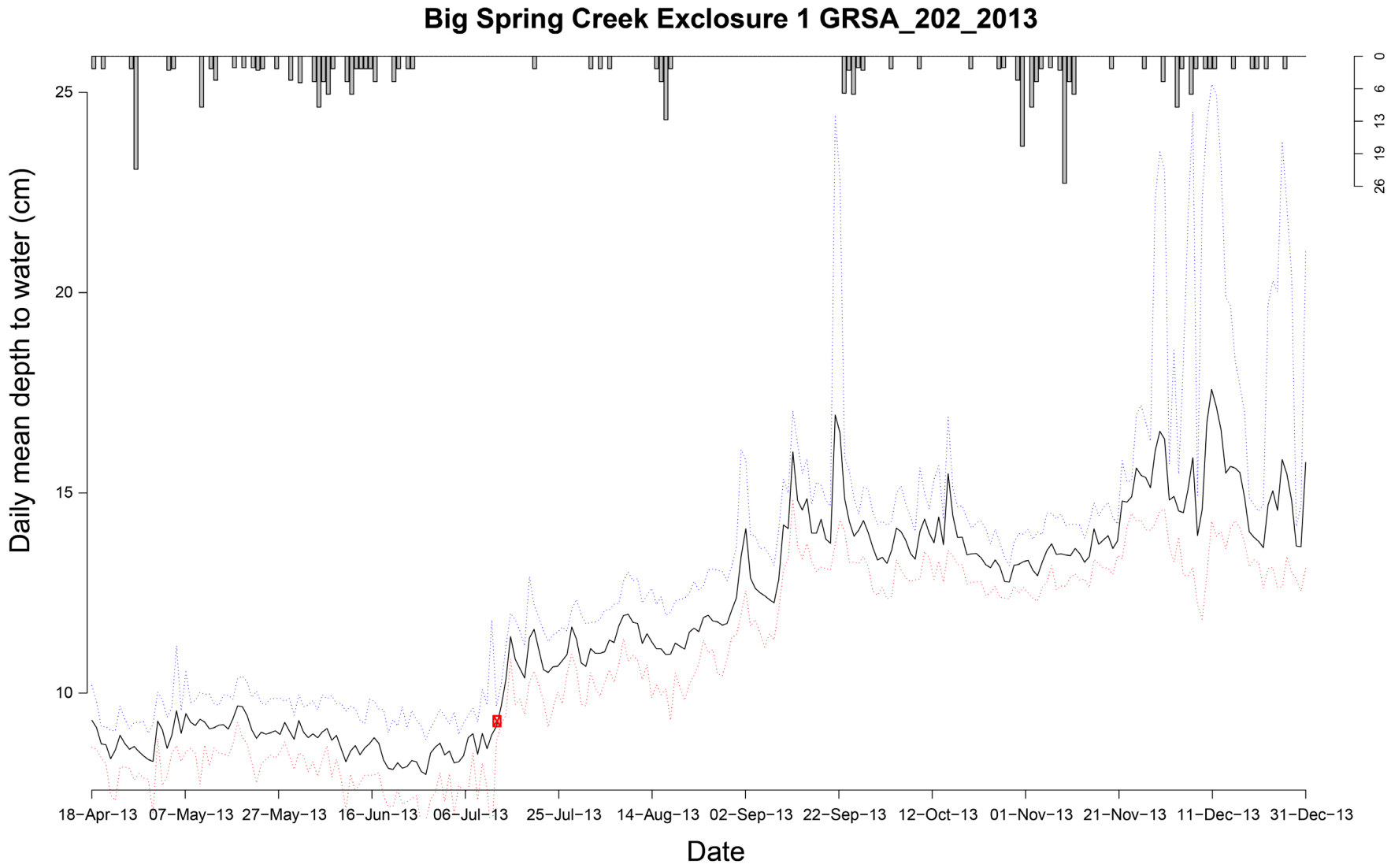


Figure I-4. 2013 hydrograph with precipitation climogram for snow free period at site 202 Big Spring Creek, Exclosure 1, in Great Sand Dunes National Park and Preserve. Ground elevation is at 0 on the y axis. Black line is the daily mean depth to water (DTW) (cm relative to ground level, with negative values indicating a water table below ground), with blue and red lines the maxima and minima. Red dots are episodic hand readings. Climogram shows daily precipitation (cm), with higher values shown by longer bars.

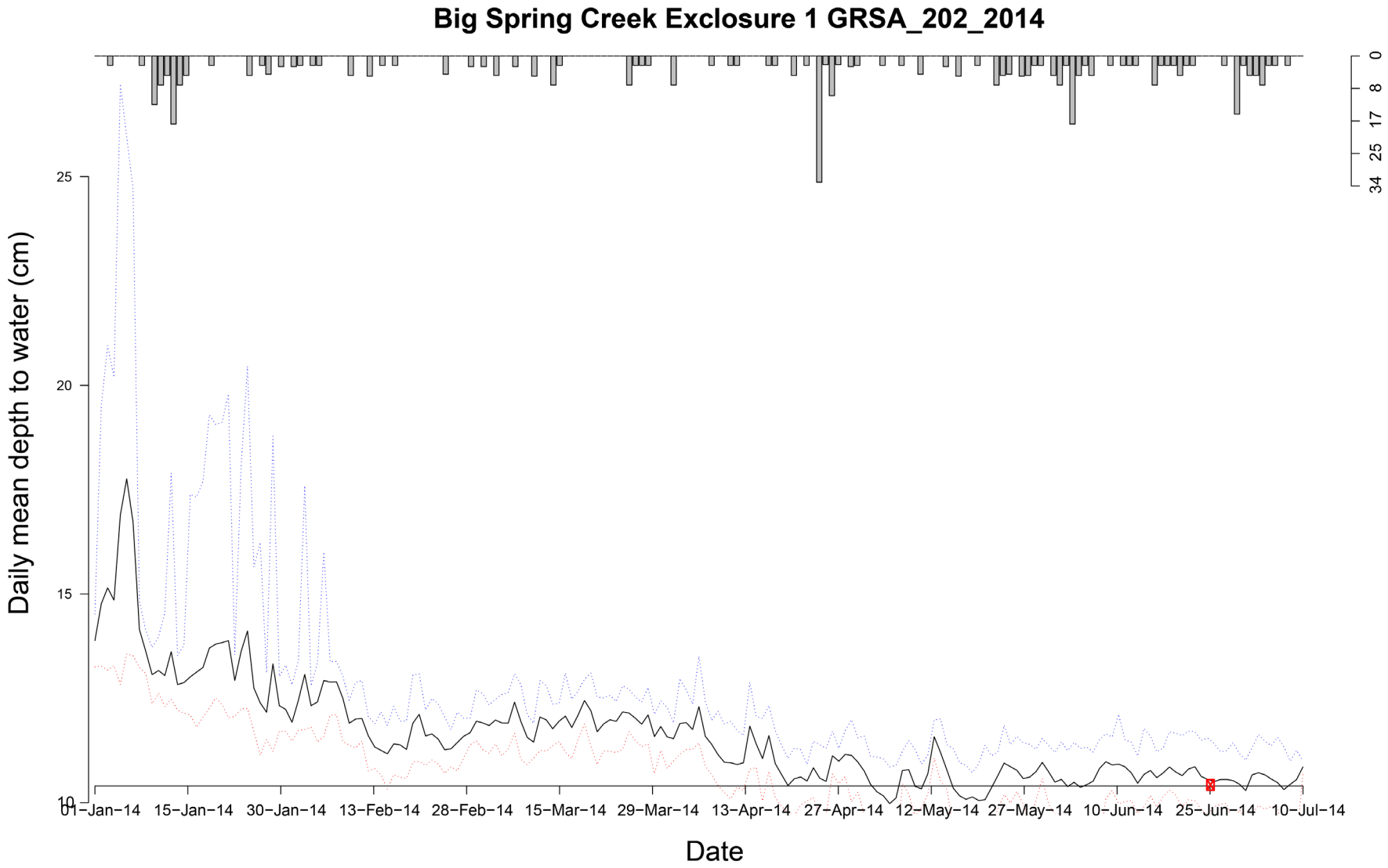


Figure I-5. 2014 hydrograph with precipitation climogram for snow free period at site 202 Big Spring Creek, Exclosure 1, in Great Sand Dunes National Park and Preserve. Ground elevation is at 0 on the y axis. Black line is the daily mean depth to water (DTW) (cm relative to ground level, with negative values indicating a water table below ground), with blue and red lines the maxima and minima. Red dots are episodic hand readings. Climogram shows daily precipitation (cm), with higher values shown by longer bars.

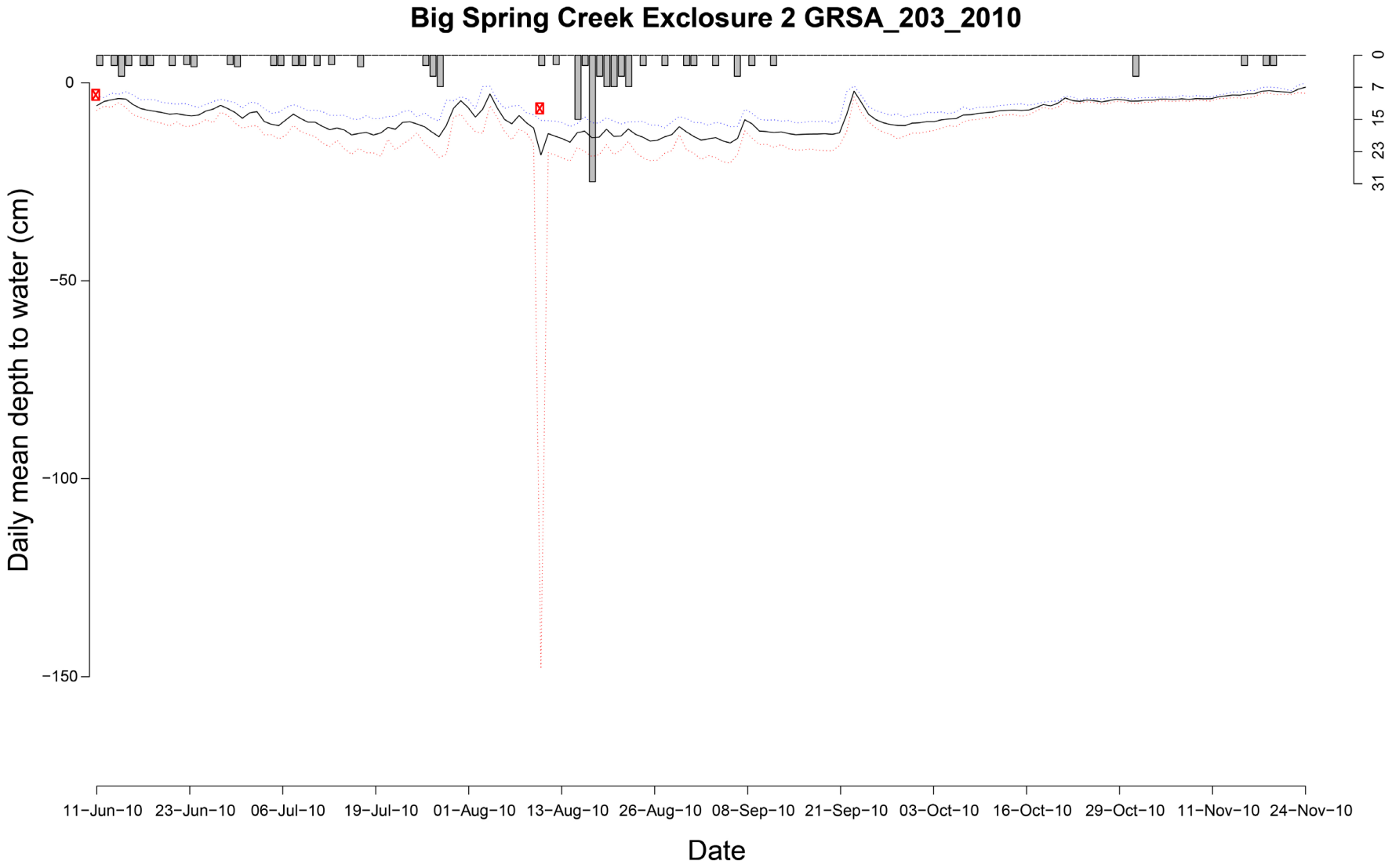


Figure I-6. 2010 hydrograph with precipitation climogram for snow free period at site 203 Big Spring Creek, Exclosure 2, in Great Sand Dunes National Park and Preserve. Ground elevation is at 0 on the y axis. Black line is the daily mean depth to water (DTW) (cm relative to ground level, with negative values indicating a water table below ground), with blue and red lines the maxima and minima. Red dots are episodic hand readings. Climogram shows daily precipitation (cm), with higher values shown by longer bars. Note that due to the timing of logger installations, 2010 data started after snow melt-off.

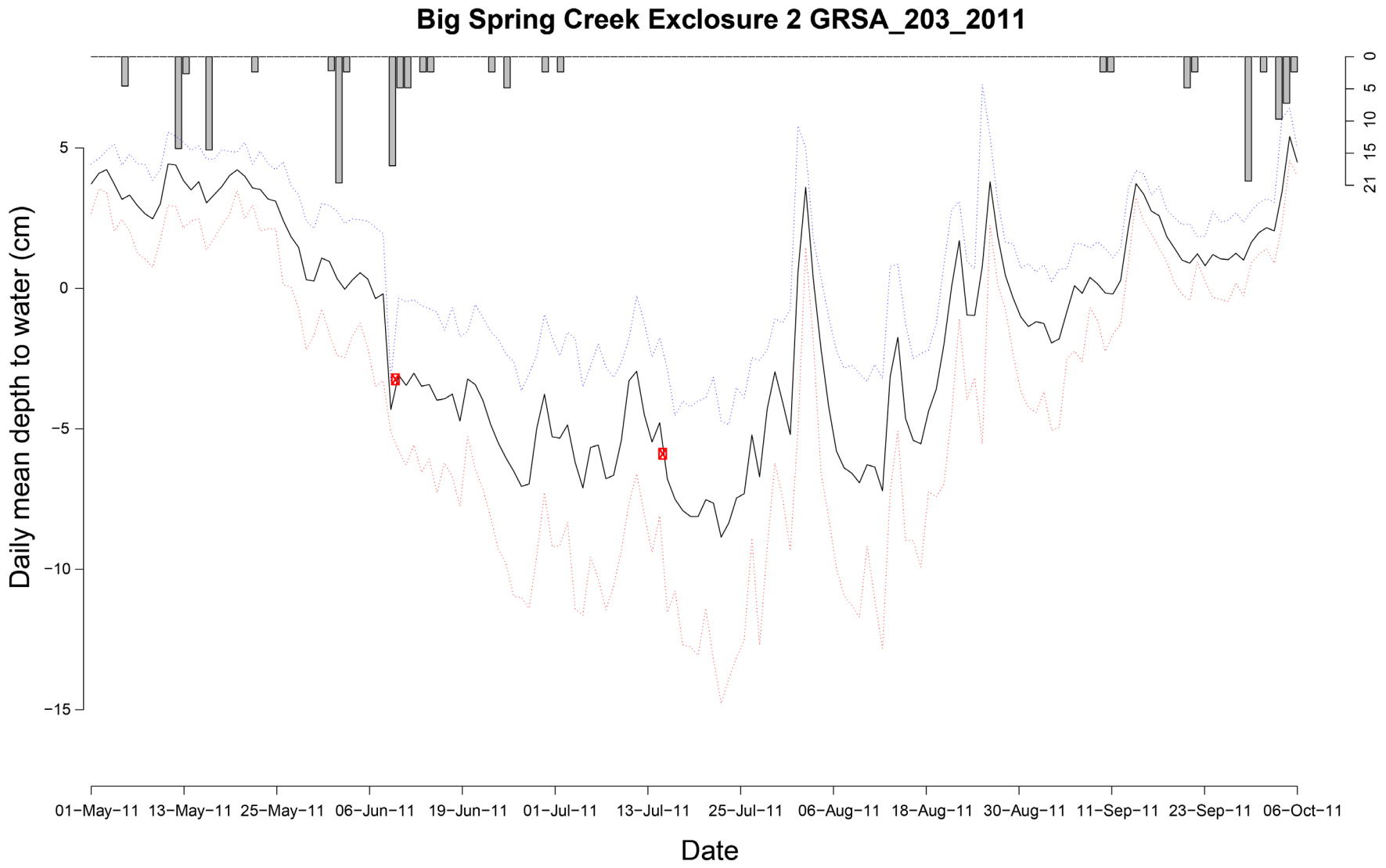


Figure I-7. 2011 hydrograph with precipitation climogram for snow free period at site 203 Big Spring Creek, Exclosure 2, in Great Sand Dunes National Park and Preserve. Ground elevation is at 0 on the y axis. Black line is the daily mean depth to water (DTW) (cm relative to ground level, with negative values indicating a water table below ground), with blue and red lines the maxima and minima. Red dots are episodic hand readings. Climogram shows daily precipitation (cm), with higher values shown by longer bars.

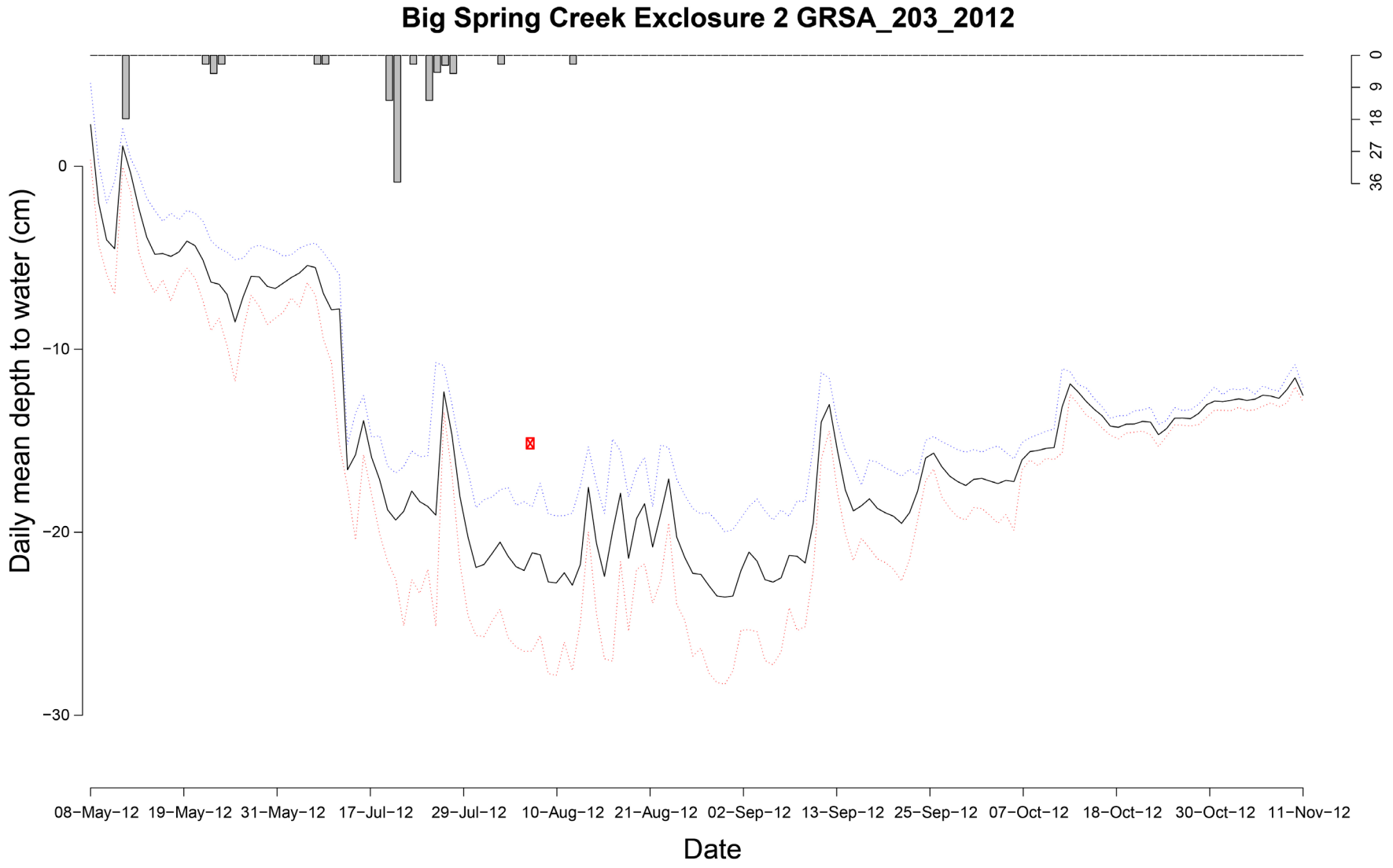


Figure I-8. 2012 hydrograph with precipitation climogram for snow free period at site 203 Big Spring Creek, Exclosure 2, in Great Sand Dunes National Park and Preserve. Ground elevation is at 0 on the y axis. Black line is the daily mean depth to water (DTW) (cm relative to ground level, with negative values indicating a water table below ground), with blue and red lines the maxima and minima. Red dots are episodic hand readings. Climogram shows daily precipitation (cm), with higher values shown by longer bars.

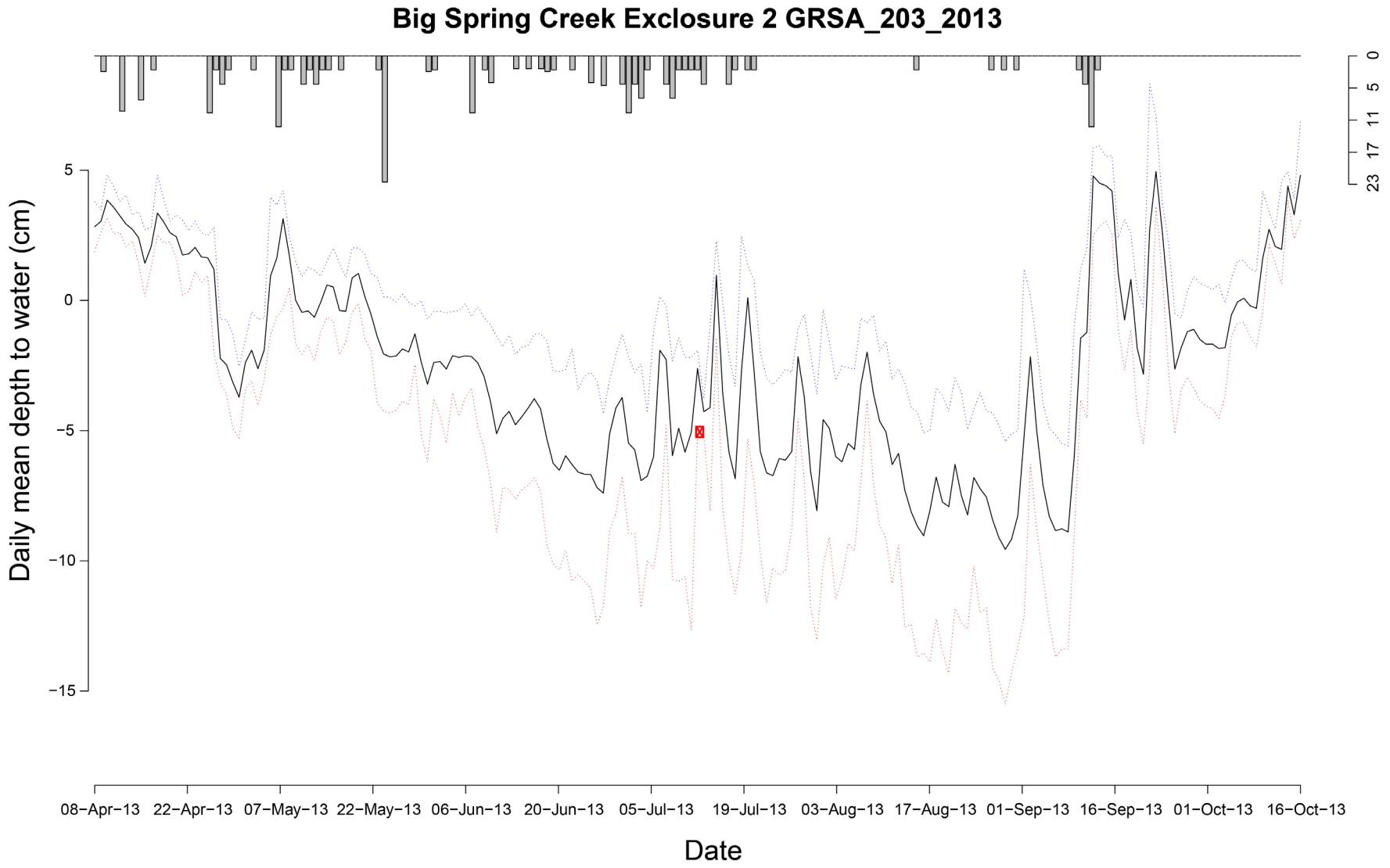


Figure I-9. 2013 hydrograph with precipitation climogram for snow free period at site 203 Big Spring Creek, Exclosure 2, in Great Sand Dunes National Park and Preserve. Ground elevation is at 0 on the y axis. Black line is the daily mean depth to water (DTW) (cm relative to ground level, with negative values indicating a water table below ground), with blue and red lines the maxima and minima. Red dots are episodic hand readings. Climogram shows daily precipitation (cm), with higher values shown by longer bars.

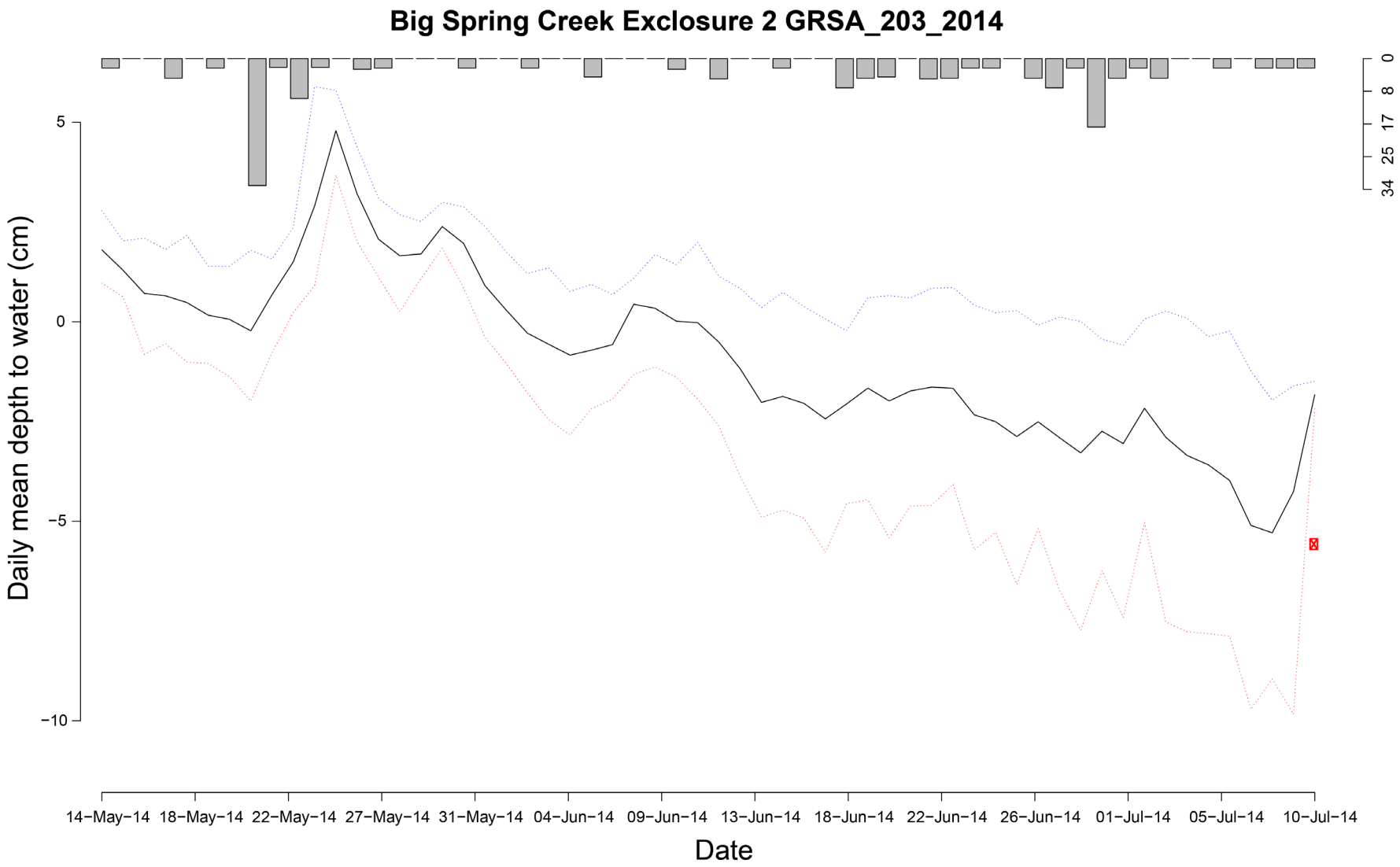


Figure I-10. 2014 hydrograph with precipitation climogram for snow free period at site 203 Big Spring Creek, Exclosure 2, in Great Sand Dunes National Park and Preserve. Ground elevation is at 0 on the y axis. Black line is the daily mean depth to water (DTW) (cm relative to ground level, with negative values indicating a water table below ground), with blue and red lines the maxima and minima. Red dots are episodic hand readings. Climogram shows daily precipitation (cm), with higher values shown by longer bars.

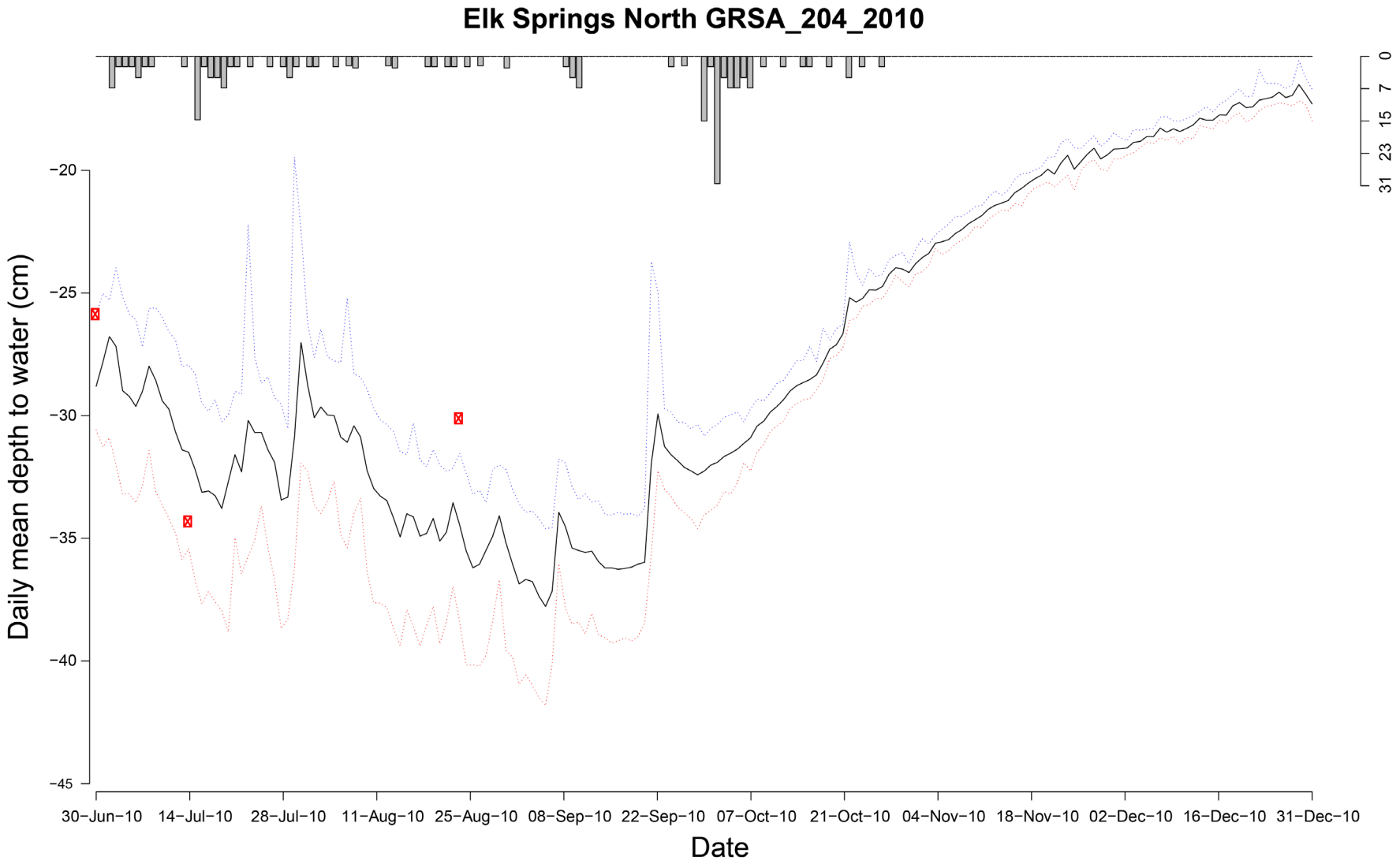


Figure I-11. 2010 hydrograph with precipitation climogram for snow free period at site 204 Elk Springs North, in Great Sand Dunes National Park and Preserve. Ground elevation is at 0 on the y axis. Black line is the daily mean depth to water (DTW) (cm relative to ground level, with negative values indicating a water table below ground), with blue and red lines the maxima and minima. Red dots are episodic hand readings. Climogram shows daily precipitation (cm), with higher values shown by longer bars.

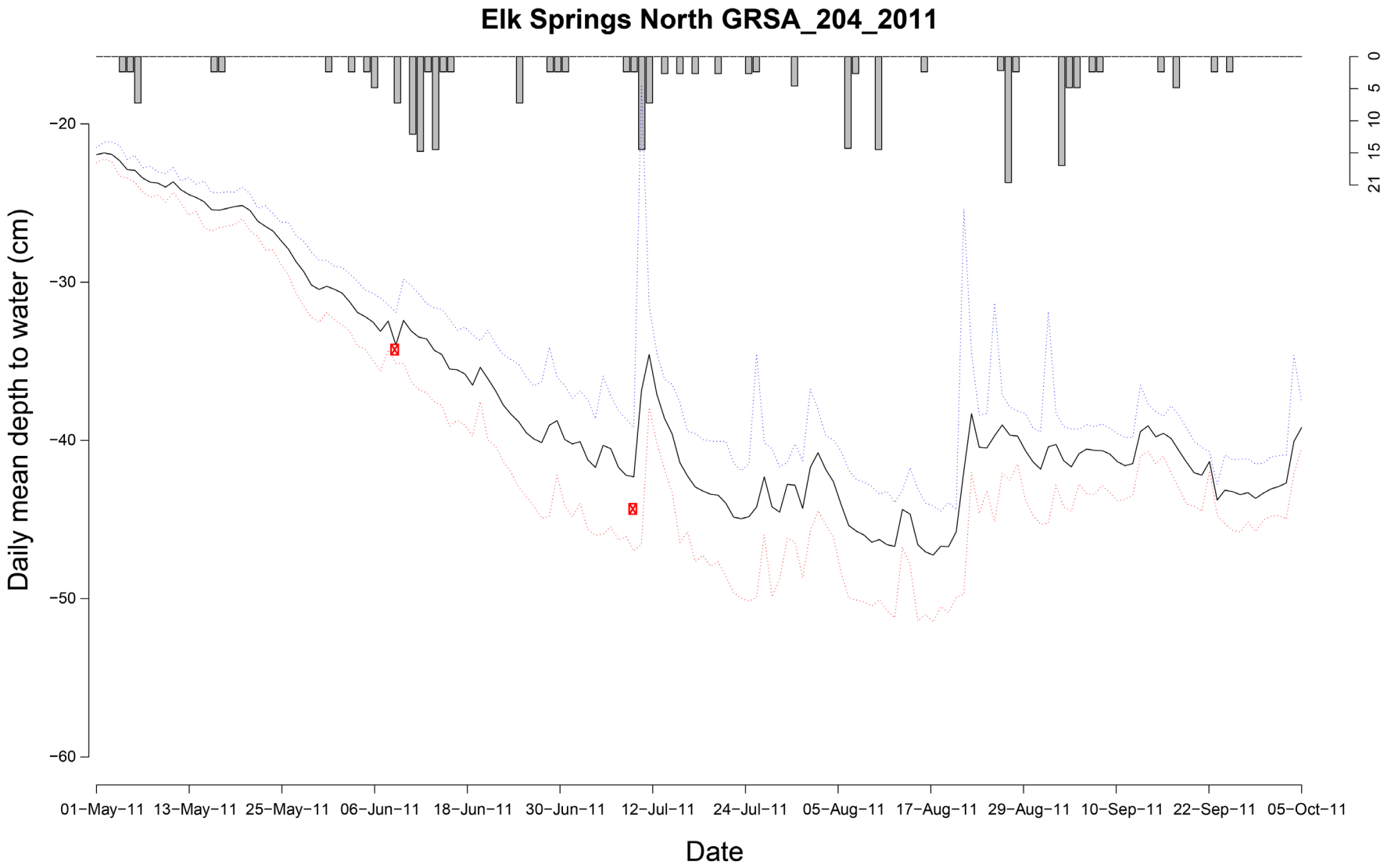


Figure I-12. 2011 hydrograph with precipitation climogram for snow free period at site 204 Elk Springs North, in Great Sand Dunes National Park and Preserve. Ground elevation is at 0 on the y axis. Black line is the daily mean depth to water (DTW) (cm relative to ground level, with negative values indicating a water table below ground), with blue and red lines the maxima and minima. Red dots are episodic hand readings. Climogram shows daily precipitation (cm), with higher values shown by longer bars.

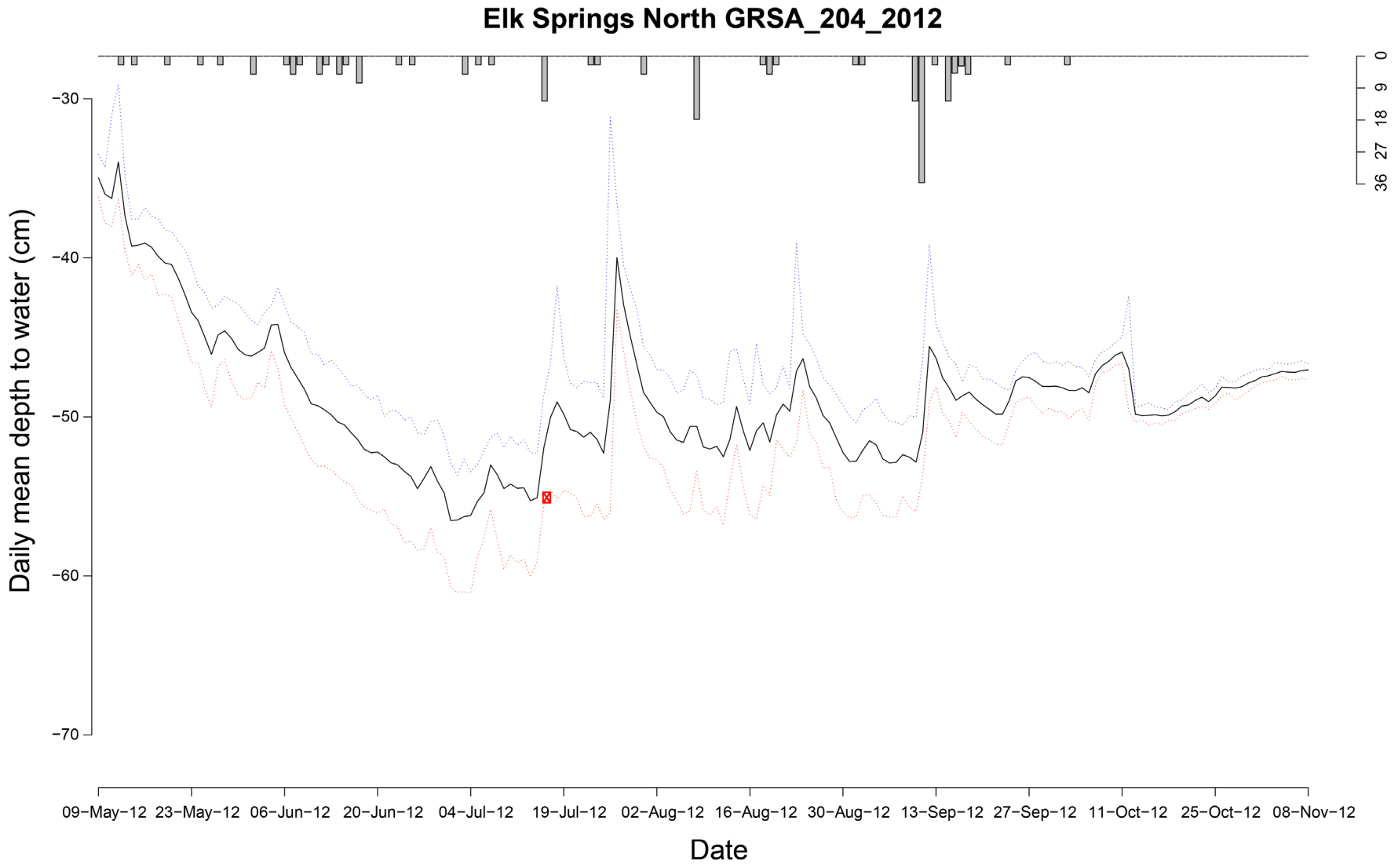


Figure I-13. 2012 hydrograph with precipitation climogram for snow free period at site 204 Elk Springs North, in Great Sand Dunes National Park and Preserve. Ground elevation is at 0 on the y axis. Black line is the daily mean depth to water (DTW) (cm relative to ground level, with negative values indicating a water table below ground), with blue and red lines the maxima and minima. Red dots are episodic hand readings. Climogram shows daily precipitation (cm), with higher values shown by longer bars.

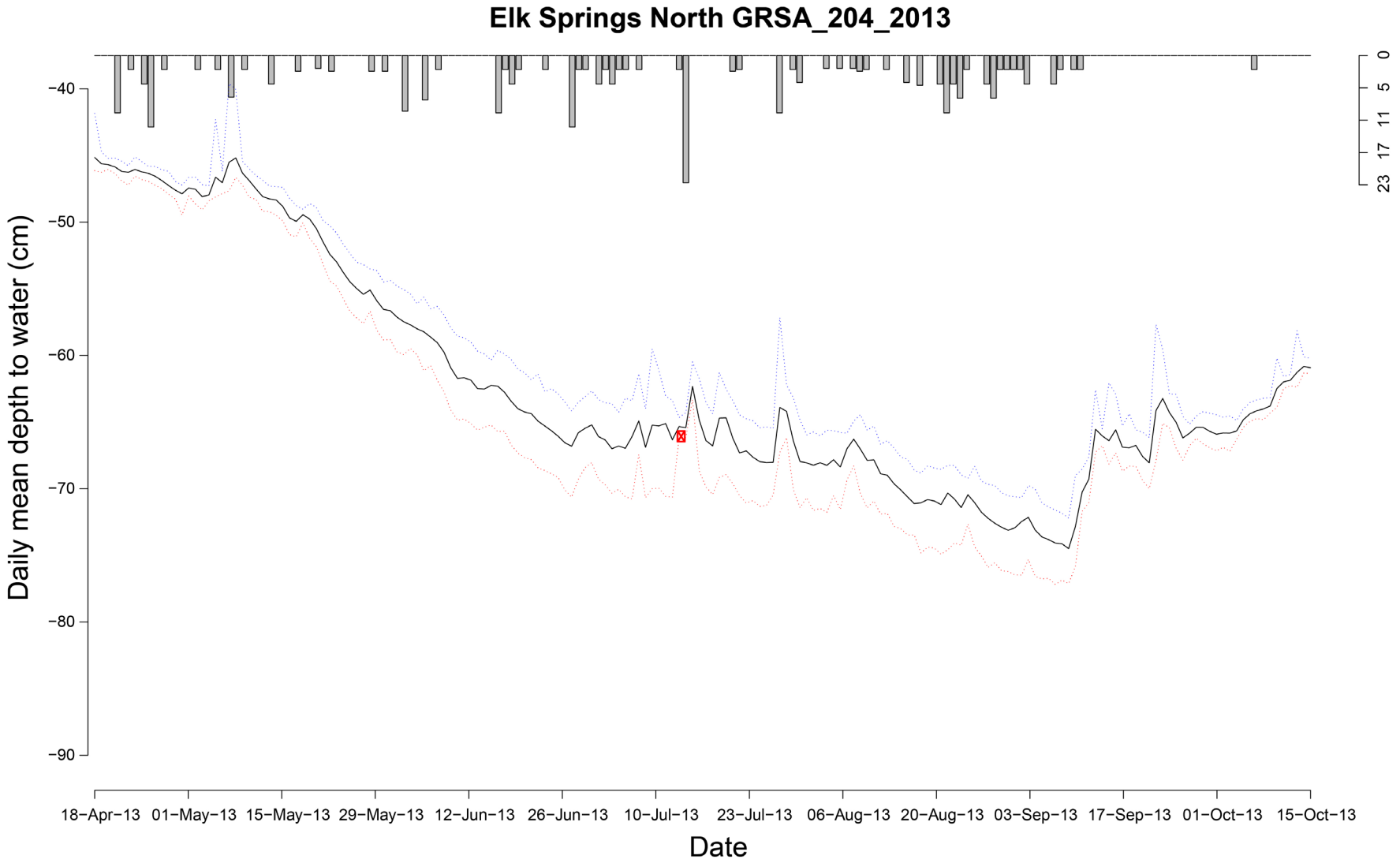


Figure I-14. 2013 hydrograph with precipitation climogram for snow free period at site 204 Elk Springs North, in Great Sand Dunes National Park and Preserve. Ground elevation is at 0 on the y axis. Black line is the daily mean depth to water (DTW) (cm relative to ground level, with negative values indicating a water table below ground), with blue and red lines the maxima and minima. Red dots are episodic hand readings. Climogram shows daily precipitation (cm), with higher values shown by longer bars.

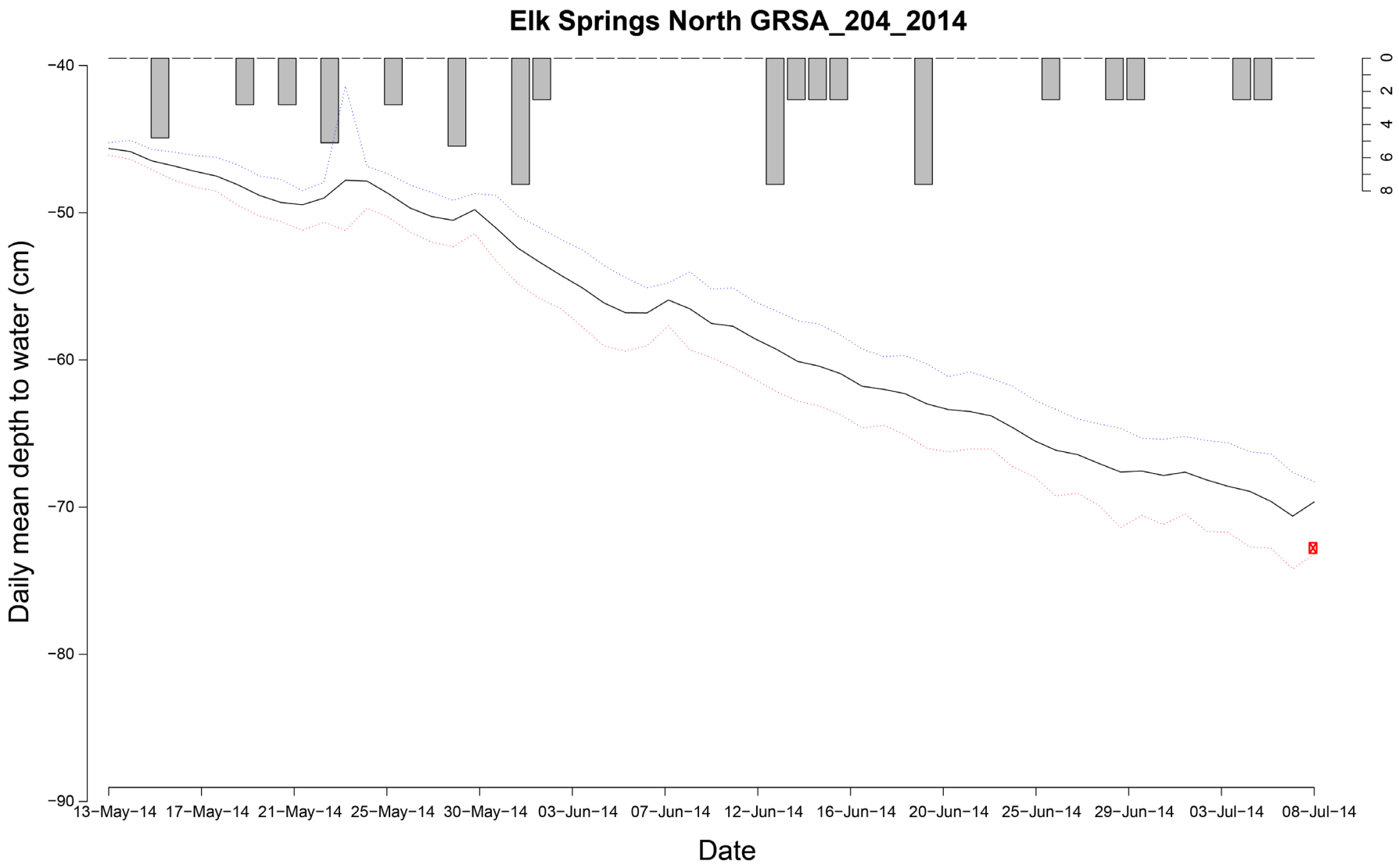


Figure I-15. 2014 hydrograph with precipitation climogram for snow free period at site 204 Elk Springs North, in Great Sand Dunes National Park and Preserve. Ground elevation is at 0 on the y axis. Black line is the daily mean depth to water (DTW) (cm relative to ground level, with negative values indicating a water table below ground), with blue and red lines the maxima and minima. Red dots are episodic hand readings. Climogram shows daily precipitation (cm), with higher values shown by longer bars.

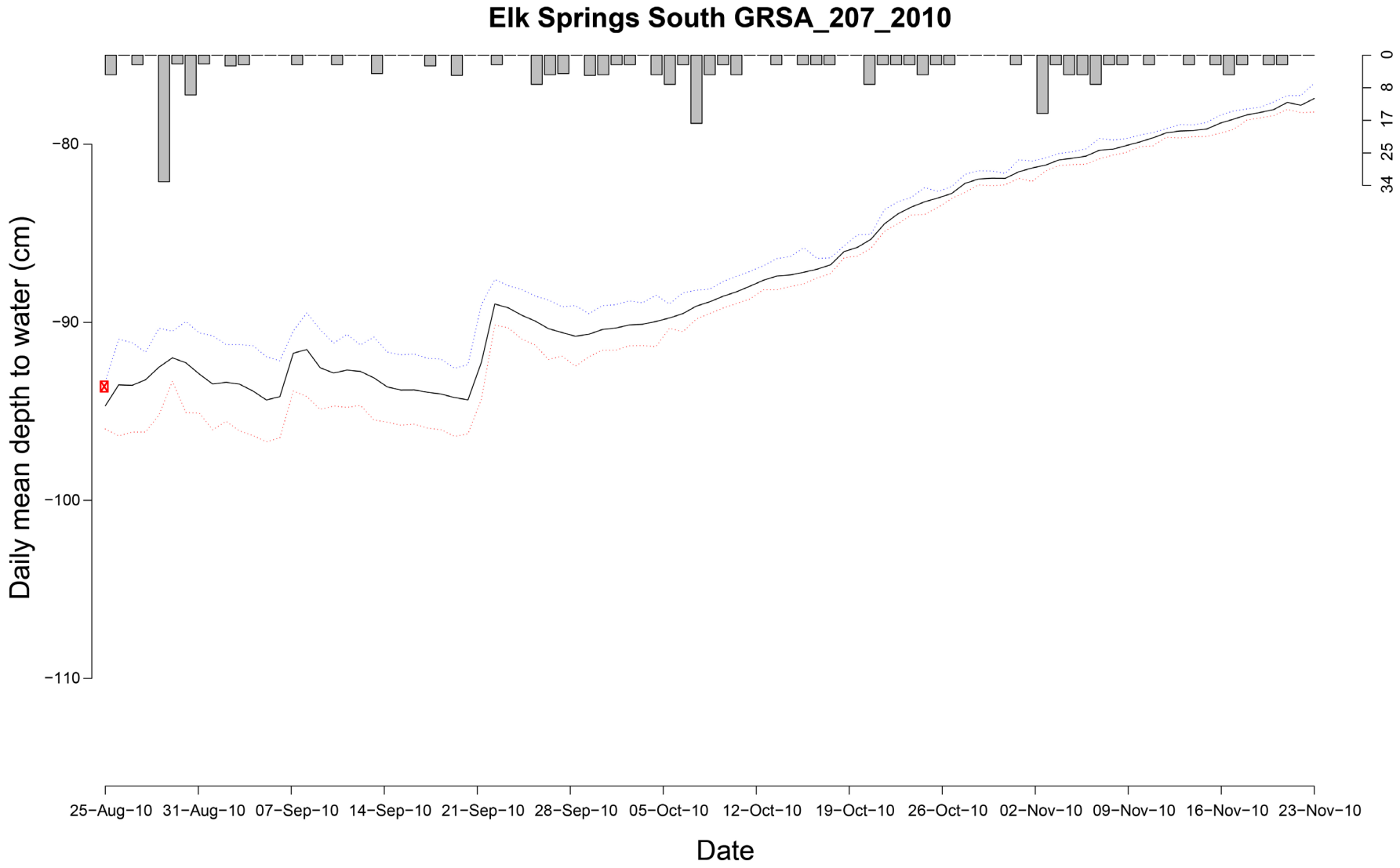


Figure I-16. 2010 hydrograph with precipitation climogram for snow free period at site 207 Elk Springs South, in Great Sand Dunes National Park and Preserve. Ground elevation is at 0 on the y axis. Black line is the daily mean depth to water (DTW) (cm relative to ground level, with negative values indicating a water table below ground), with blue and red lines the maxima and minima. Red dots are episodic hand readings. Climogram shows daily precipitation (cm), with higher values shown by longer bars.

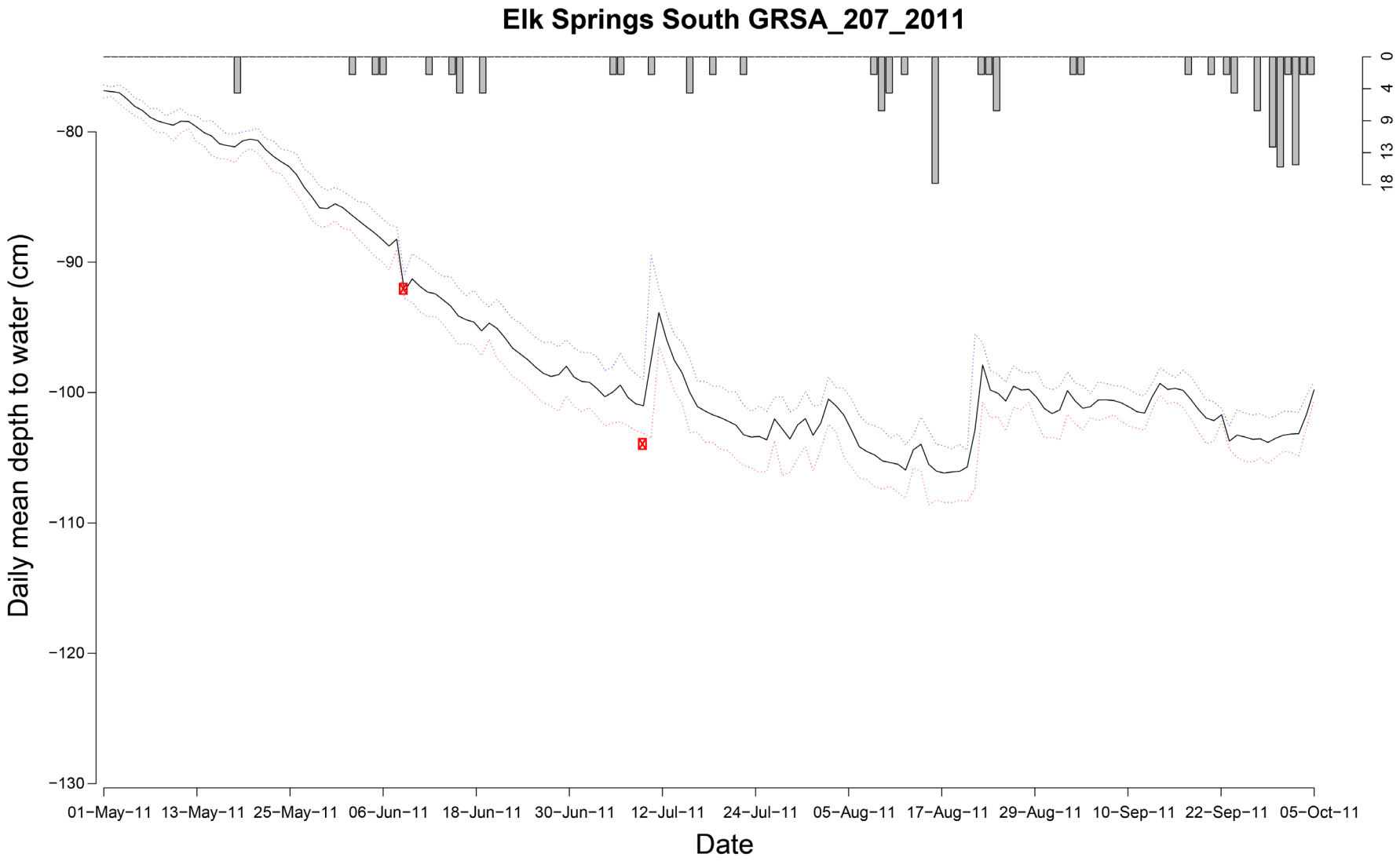


Figure I-17. 2011 hydrograph with precipitation climogram for snow free period at site 207 Elk Springs South, in Great Sand Dunes National Park and Preserve. Ground elevation is at 0 on the y axis. Black line is the daily mean depth to water (DTW) (cm relative to ground level, with negative values indicating a water table below ground), with blue and red lines the maxima and minima. Red dots are episodic hand readings. Climogram shows daily precipitation (cm), with higher values shown by longer bars.

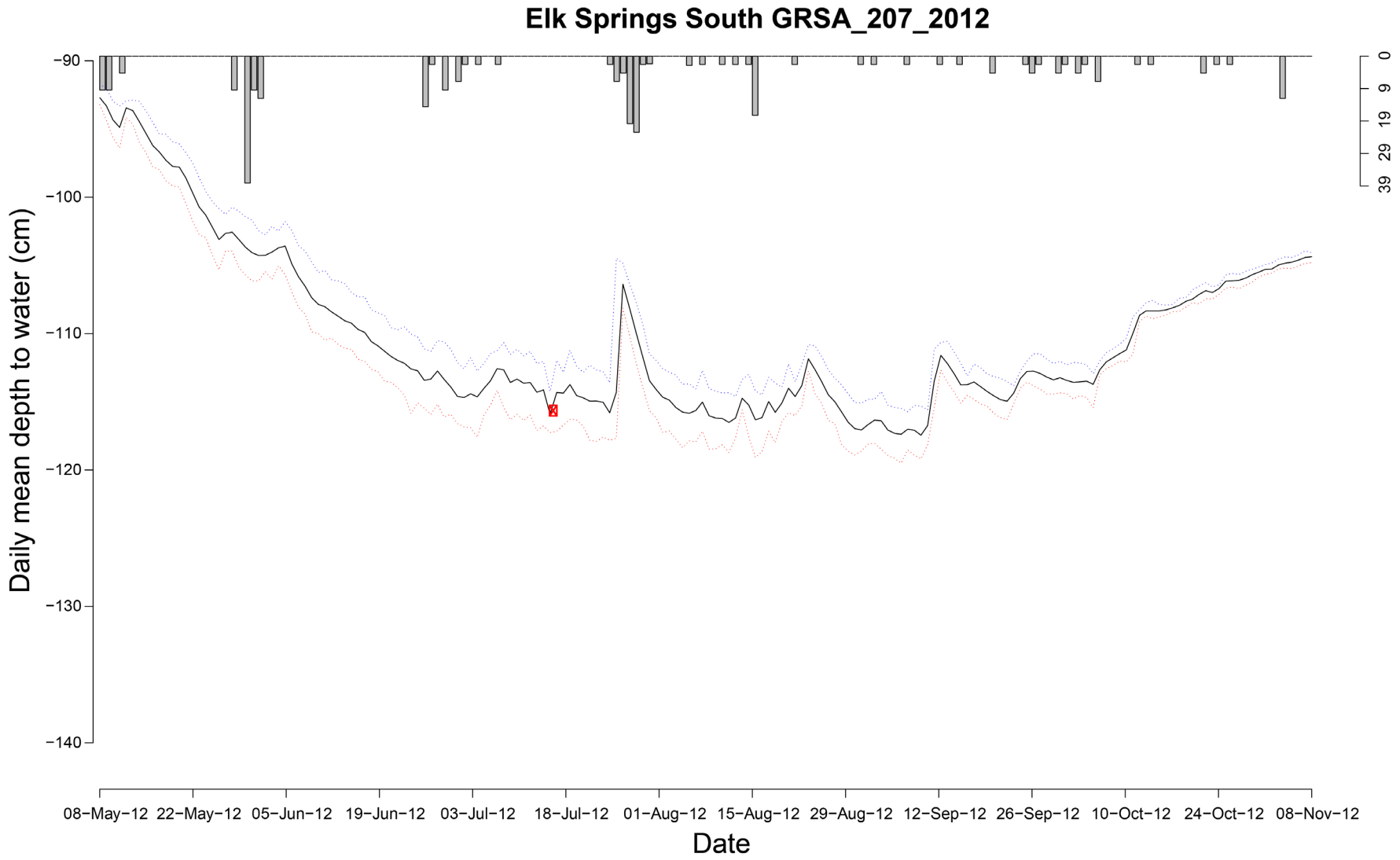


Figure I-18. 2012 hydrograph with precipitation climogram for snow free period at site 207 Elk Springs South, in Great Sand Dunes National Park and Preserve. Ground elevation is at 0 on the y axis. Black line is the daily mean depth to water (DTW) (cm relative to ground level, with negative values indicating a water table below ground), with blue and red lines the maxima and minima. Red dots are episodic hand readings. Climogram shows daily precipitation (cm), with higher values shown by longer bars.

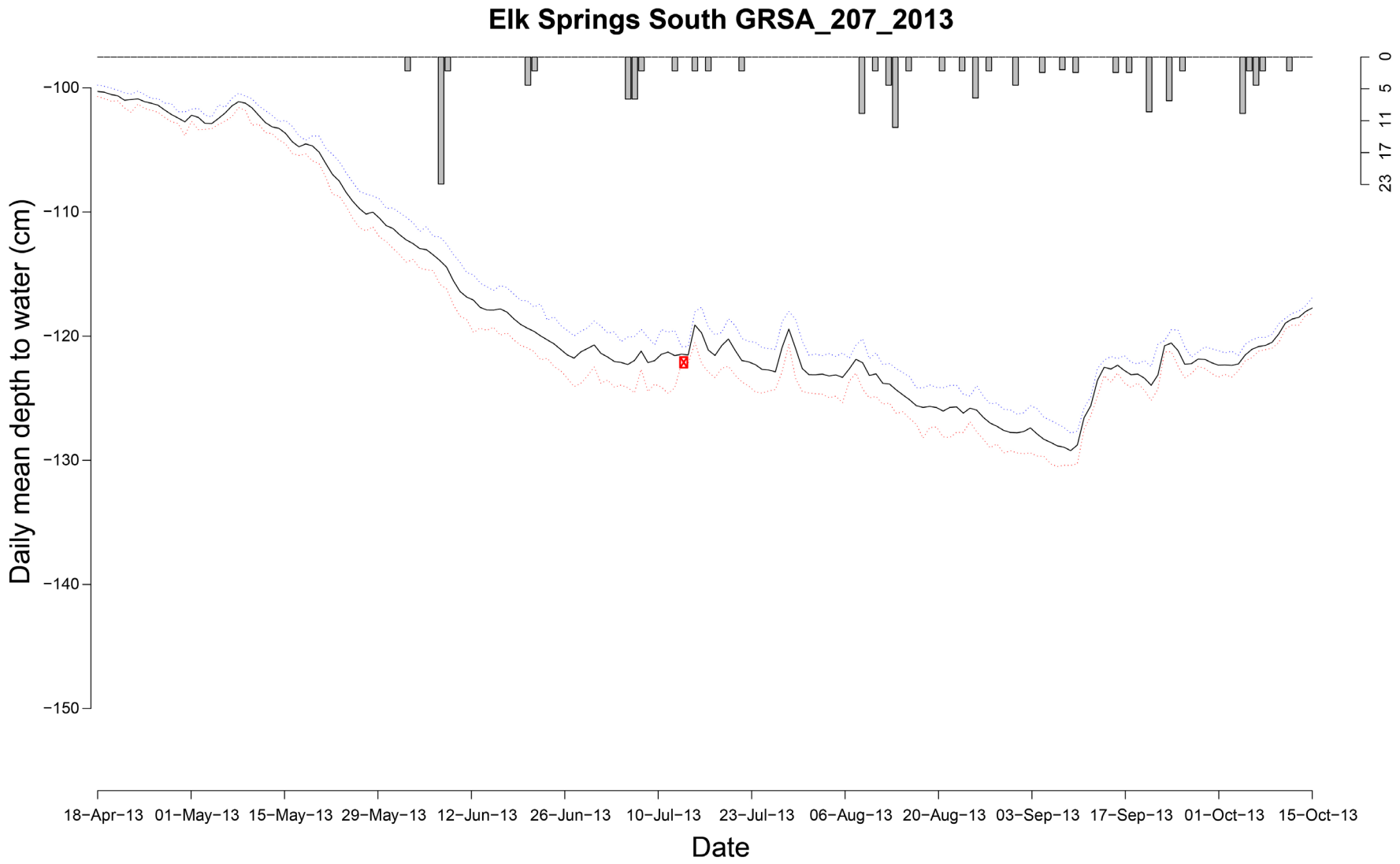


Figure I-19. 2013 hydrograph with precipitation climogram for snow free period at site 207 Elk Springs South, in Great Sand Dunes National Park and Preserve. Ground elevation is at 0 on the y axis. Black line is the daily mean depth to water (DTW) (cm relative to ground level, with negative values indicating a water table below ground), with blue and red lines the maxima and minima. Red dots are episodic hand readings. Climogram shows daily precipitation (cm), with higher values shown by longer bars.

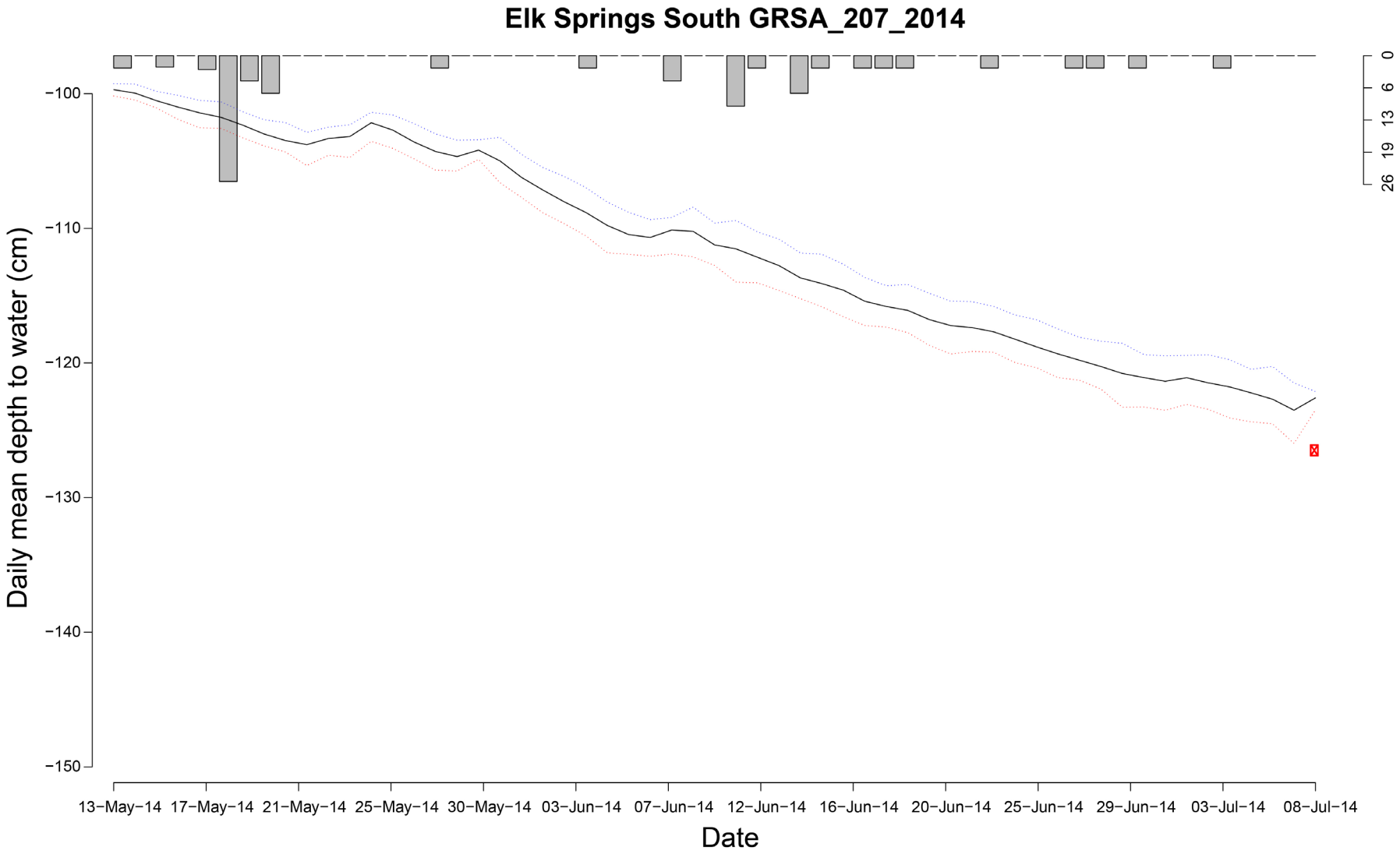


Figure I-20. 2014 hydrograph with precipitation climogram for snow free period at site 207 Elk Springs South, in Great Sand Dunes National Park and Preserve. Ground elevation is at 0 on the y axis. Black line is the daily mean depth to water (DTW) (cm relative to ground level, with negative values indicating a water table below ground), with blue and red lines the maxima and minima. Red dots are episodic hand readings. Climogram shows daily precipitation (cm), with higher values shown by longer bars.

Appendix J: Taxa List

Complete list of taxa documented at Great Sand Dunes National Park and Preserve in 2010–2014. For an explanation of C (conservatism) and invasiveness (I-rank scores) see main narrative, section 2.4.1.2. Nomenclature follows Weber and Wittmann (2001) (see literature cited section of main narrative).

Family	Taxa	Common name	C Score	I Score	Freq.	Mean relative cover	Mean absolute cover
Alismataceae	*Alisma gramineum*	narrowleaf water plantain	4	–	5	0.037	3.670
	Sagittaria cuneata	arumleaf arrowhead	6	–	4	0.011	1.360
Alliaceae	*Allium geyeri*	Geyer's onion	5	–	6	0.004	0.113
Alsinaceae	*Spergularia*	sandspurry	–	–	2	0.000	0.050
	Spergularia media	media sandspurry	0	2	2	0.025	2.900
	Stellaria	starwort	–	–	6	0.000	0.050
	Stellaria crassifolia	fleshy starwort	7	–	2	0.004	0.340
	Stellaria longifolia	longleaf starwort	7	–	2	0.014	1.120
	Stellaria longipes	longstalk starwort	8	–	1	0.000	0.050
Amblystegiaceae	*Amblystegium varium*	amblystegium moss	8	–	12	0.007	0.192
	Calliergon richardsonii	Richardson's calliergon moss	8	–	18	0.014	1.830
	Calliergonella lindbergii	–	8	–	5	0.000	0.050
	Campylium stellatum	star campylium moss	8	–	16	0.002	0.043
	Cratoneuron filicinum	cratoneuron moss	8	–	5	0.000	0.050
	Drepanocladus	drepanocladus moss	–	–	2	0.004	0.233
	Drepanocladus aduncus	drepanocladus moss	8	–	7	0.004	0.147
	Warnstorfia exannulata	warnstorfia moss	8	–	37	0.014	1.116
Anacardiaceae	*Rhus aromatica ssp. trilobata*	skunkbush sumac	5	–	1	0.004	1.000
Apiaceae	*Conioselinum scopulorum*	Rocky Mountain hemlockparsley	7	–	22	0.026	2.985
	Oxypolis fendleri	Fendler's cowbane	7	–	21	0.005	0.707
Asteraceae	*Achillea lanulosa*	western yarrow	4	–	12	0.005	0.462
	Agoseris glauca	pale agoseris	6	–	1	0.000	0.050
	Almutaster pauciflorus	alkali marsh aster	4	–	27	0.006	0.573
	Antennaria	pussytoes	–	–	2	0.000	0.050
	Antennaria corymbosa	flat-top pussytoes	5	–	7	0.001	0.186
	Antennaria rosea	rosy pussytoes	5	–	3	0.002	0.208
	Artemisia biennis	biennial wormwood	0	3	12	0.044	2.249
	Artemisia bigelovii	Bigelow sage	7	–	1	0.054	4.841
	Artemisia frigida	prairie sagewort	4	–	2	0.003	0.525
	Artemisia ludoviciana	white sagebrush	4	–	1	0.000	0.050
	Aster foliaceus	alpine leafybract aster	5	–	1	0.000	0.050
	Aster lanceolatus ssp. hesperius	white panicle aster	5	–	11	0.006	0.391
	Asteraceae	–	–	–	16	0.005	0.349
	Breea arvensis	Canada thistle	0	7	34	0.032	2.057
	Chrysothamnus nauseosus ssp. nauseosus	rubber rabbitbrush	3	–	10	0.037	0.496
	Erigeron peregrinus ssp. callianthemus	subalpine fleabane	7	–	13	0.000	0.111
	Gnaphalium palustre	western marsh cudweed	5	–	5	0.001	0.176
	Helianthus nuttallii	Nuttall's sunflower	3	–	2	0.003	1.025

Appendix J (*continued*)

Family	Taxa	Common name	C Score	I Score	Freq.	Mean relative cover	Mean absolute cover
Asteraceae (cont'd)	*Heterotheca villosa*	hairy false goldenaster	3	–	1	0.000	0.050
	Lactuca serriola	prickly lettuce	0	1	4	0.005	1.762
	Lactuca tatarica ssp. *pulchella*	blue lettuce	3	–	17	0.016	1.020
	Packera	ragwort	–	–	6	0.002	0.453
	Packera crocata	saffron ragwort	6	–	8	0.002	0.280
	Packera dimorphophylla	splitleaf groundsel	6	–	3	0.002	0.378
	Packera pseudaurea	falsegold groundsel	7	–	2	0.003	1.025
	Packera tridenticulata	threetooth ragwort	7	–	2	0.001	0.050
	Psilochenia runcinata	fiddleleaf hawksbeard	6	–	59	0.087	5.735
	Pyrrocoma lanceolata	–	–	–	32	0.116	3.576
	Senecio triangularis	arrowleaf ragwort	7	–	12	0.015	2.629
	Solidago	goldenrod	–	–	1	0.002	0.366
	Sonchus uliginosus	moist sowthistle	0	3	4	0.068	3.929
	Taraxacum officinale	common dandelion	0	3	26	0.006	0.489
	Tragopogon dubius ssp. *major*	yellow salsify	0	2	1	0.000	0.050
	Trimorpha lonchophylla	shortray fleabane	5	–	7	0.003	0.276
	Virgulaster ascendens	western aster	6	–	3	0.000	0.050
	Virgulus ericoides	white heath aster	4	–	6	0.110	6.131
	Virgulus falcatus	white prairie aster	4	–	5	0.009	0.912
Aulacomniaceae	*Aulacomnium palustre*	aulacomnium moss	8	–	15	0.017	1.794
Bartramiaceae	*Philonotis fontana*	philonotis moss	6	–	10	0.012	2.222
Boraginaceae	*Cryptantha crassisepala*	thicksepal cryptantha	3	–	1	0.000	0.050
	Cryptantha fendleri	sanddune cryptantha	3	–	2	0.000	0.050
	Mertensia ciliata	tall fringed bluebells	7	–	4	0.003	1.525
	Plagiobothrys scouleri ssp. *penicillata*	sleeping popcornflower	3	–	4	0.001	0.129
Brachytheciaceae	*Brachythecium*	brachythecium moss	–	–	2	0.000	0.025
	Brachythecium latifolium	–	6	–	1	0.002	0.194
	Brachythecium nelsonii	Nelson's brachythecium moss	6	–	1	0.000	0.050
	Tomentypnum nitens	tomentypnum moss	8	–	18	0.001	0.175
Brassicaceae	*Boechera*	rockcress	–	–	1	0.000	0.050
	Brassicaceae	–	–	–	1	0.008	0.440
	Cardaria chalepensis	lenspod whitetop	0	8	1	0.001	0.050
	Cardaria latifolia	broadleaved pepperweed	0	8	5	0.012	0.436
	Descurainia	tansymustard	–	–	1	0.001	0.050
	Descurainia sophia	herb sophia	0	4	1	0.003	0.366
	Draba	draba	–	–	1	0.001	0.050
	Draba albertina	slender draba	5	–	4	0.008	1.685
	Erysimum capitatum	sanddune wallflower	5	–	1	0.000	0.050
	Nasturtium officinale	watercress	0	4	4	0.002	0.371
	Rorippa alpina	alpine yellowcress	6	–	1	0.000	0.050
	Rorippa sinuata	spreading yellowcress	4	–	1	0.000	0.050
	Rorippa teres	bluntleaf yellowcress	5	–	2	0.002	0.145

Appendix J (*continued*)

Family	Taxa	Common name	C Score	I Score	Freq.	Mean relative cover	Mean absolute cover
Bryaceae	*Bryum knowltonii*	Knowlton's bryum moss	7	–	1	0.000	0.050
	Ptychostomum	–	–	–	2	0.004	0.193
	Ptychostomum pallescens	–	8	–	1	0.000	0.050
	Ptychostomum pseudotriquetrum	–	8	–	42	0.005	0.427
Capparaceae	*Cleome*	spiderflower	–	–	1	0.003	0.050
	Cleome multicaulis	slender spiderflower	4	–	50	0.051	3.249
	Cleome serrulata	Rocky Mountain beeplant	2	–	8	0.001	0.188
Chenopodiaceae	*Bassia sieversiana*	burningbush	0	2	2	0.000	0.050
	Chenopodium	goosefoot	–	–	4	0.003	1.406
	Chenopodium album	lambsquarters	0	2	4	0.002	0.129
	Chenopodium leptophyllum	narrowleaf goosefoot	5	–	9	0.004	0.461
	Chenopodium rubrum	red goosefoot	2	–	19	0.052	3.136
	Salsola australis	prickly Russian thistle	0	7	6	0.040	2.067
	Sarcobatus vermiculatus	greasewood	4	–	11	0.082	0.985
	Suaeda calceoliformis	Pursh seepweed	3	–	30	0.011	0.439
Climaciaceae	*Climacium dendroides*	tree climacium moss	6	–	10	0.005	0.658
Crassulaceae	*Clementsia rhodantha*	redpod stonecrop	8	–	33	0.047	3.942
Cupressaceae	*Sabina scopulorum*	Rocky Mountain juniper	5	–	2	0.008	1.500
Cyperaceae	*Amphiscirpus nevadensis*	Nevada bulrush	7	–	33	0.158	3.441
	Carex	sedge	–	–	6	0.068	8.025
	Carex aquatilis	water sedge	6	–	11	0.086	8.969
	Carex aurea	golden sedge	7	–	4	0.001	0.109
	Carex canescens	silvery sedge	8	–	16	0.028	3.683
	Carex festivella	smallwing sedge	5	–	2	0.016	1.692
	Carex lanuginosa	woolly sedge	6	–	10	0.077	5.625
	Carex nebrascensis	Nebraska sedge	5	–	28	0.293	18.701
	Carex norvegica	Norway sedge	8	–	2	0.000	0.050
	Carex nova	black sedge	10	–	13	0.009	0.865
	Carex praegracilis		–	–	62	0.072	5.064
	Carex saxatilis ssp. *laxa*	rock sedge	8	–	20	0.096	7.139
	Carex scopulorum	mountain sedge	7	–	35	0.214	15.198
	Carex simulata	analogue sedge	6	–	43	0.100	7.673
	Carex utriculata		–	–	42	0.177	12.484
	Eleocharis	spikerush	–	–	4	0.039	1.285
	Eleocharis acicularis	needle spikerush	5	–	2	0.011	1.011
	Eleocharis macrostachya	pale spikerush	3	–	28	0.278	21.666
	Eleocharis quinqueflora	fewflower spikerush	8	–	24	0.026	2.243
	Eriophorum angustifolium	tall cottongrass	9	–	23	0.021	1.261
	Schoenoplectus lacustris ssp. *acutus*	hardstem bulrush	3	–	5	0.195	14.938
	Schoenoplectus lacustris ssp. *creber*	softstem bulrush	3	–	8	0.143	7.826
	Schoenoplectus pungens	common threesquare	4	–	27	0.104	3.864

Appendix J (*continued*)

Family	Taxa	Common name	C Score	I Score	Freq.	Mean relative cover	Mean absolute cover
Equisetaceae	Equisetum arvense	field horsetail	4	–	2	0.001	0.050
	Hippochaete laevigata	smooth horsetail	4	–	22	0.006	0.319
Ericaceae	Vaccinium	blueberry	–	–	1	0.001	0.050
	Vaccinium cespitosum	dwarf bilberry	7	–	2	0.001	0.050
Euphorbiaceae	Chamaesyce	sandmat	–	–	1	0.002	0.366
	Chamaesyce glyptosperma	ribseed sandmat	2	–	2	0.057	2.525
	Chamaesyce serpyllifolia	thymeleaf sandmat	0	3	3	0.016	0.960
Fabaceae	Astragalus bodinii	Bodin's milkvetch	7	–	25	0.059	4.123
	Glycyrrhiza lepidota	American licorice	3	–	4	0.028	1.264
	Thermopsis montana	mountain goldenbanner	6	–	1	0.000	0.050
	Trifolium	clover	–	–	1	0.000	0.050
	Trifolium repens	white clover	0	4	3	0.006	0.502
Gentianaceae	Gentianella strictiflora	autumn dwarf gentian	3	–	5	0.001	0.113
	Pneumonanthe affinis	pleated gentian	8	–	3	0.001	0.155
	Swertia perennis	felwort	8	–	29	0.050	4.474
Grossulariaceae	Ribes	currant	–	–	2	0.002	0.208
Helleboraceae	Aconitum columbianum	Columbian monkshood	8	–	6	0.005	1.080
	Psychrophila leptosepala	white marsh marigold	7	–	33	0.064	5.645
	Trollius albiflorus	American globeflower	8	–	11	0.002	0.431
Hippuridaceae	Hippuris vulgaris	common mare's-tail	6	–	5	0.002	0.245
Iridaceae	Iris missouriensis	Rocky Mountain iris	4	–	27	0.037	2.733
	Sisyrinchium demissum	stiff blue-eyed grass	7	–	8	0.000	0.050
	Sisyrinchium montanum	strict blue-eyed grass	6	–	1	0.000	0.050
Juncaceae	Juncus arcticus ssp. ater	mountain rush	4	–	97	0.217	11.442
	Juncus drummondii	Drummond's rush	6	–	7	0.001	0.366
	Juncus longistylis	longstyle rush	6	–	3	0.000	0.050
	Juncus parryi	Parry's rush	7	–	1	0.000	0.050
	Juncus triglumis	three-hulled rush	10	–	6	0.005	0.384
	Luzula parviflora	smallflowered woodrush	7	–	7	0.001	0.186
Juncaginaceae	Triglochin concinna	–	6	–	39	0.039	0.839
	Triglochin maritima	seaside arrowgrass	6	–	19	0.016	1.020
	Triglochin palustris	marsh arrowgrass	7	–	1	0.002	1.000
Lamiaceae	Lycopus asper	rough bugleweed	5	–	2	0.189	10.250
	Mentha arvensis	wild mint	4	–	6	0.036	4.034
Lemnaceae	Lemna minor	common duckweed	2	–	10	0.041	4.366
Lentibulariaceae	Utricularia minor	lesser bladderwort	9	–	1	0.000	0.050
Malvaceae	Sidalcea neomexicana	salt spring checkerbloom	5	–	3	0.003	0.583
Mniaceae	Plagiomnium ellipticum	elliptic plagiomnium moss	8	–	12	0.002	0.158
Onagraceae	Epilobium	willowherb	–	–	11	0.002	0.720
	Epilobium anagallidifolium	pimpernel willowherb	6	–	7	0.002	0.236
	Epilobium ciliatum	fringed willowherb	4	–	13	0.031	2.591
	Epilobium hornemannii	Hornemann's willowherb	6	–	3	0.001	0.155
	Epilobium lactiflorum	milkflower willowherb	7	–	2	0.004	0.335

Appendix J (*continued*)

Family	Taxa	Common name	C Score	I Score	Freq.	Mean relative cover	Mean absolute cover
Onagraceae (cont'd)	*Epilobium leptocarpum*	slenderfruit willowherb	4	–	1	0.001	0.050
	Epilobium leptophyllum	bog willowherb	8	–	3	0.009	0.243
	Gayophytum	groundsmoke	–	–	2	0.001	0.050
Orchidaceae	*Spiranthes*	lady's tresses	–	–	3	0.000	0.050
	Spiranthes romanzoffiana	hooded lady's tresses	7	–	4	0.000	0.050
Pinaceae	*Picea engelmannii*	Engelmann spruce	5	–	20	0.013	1.743
Plantaginaceae	*Plantago eriopoda*	redwool plantain	5	–	6	0.003	0.478
Poaceae	*Achnatherum hymenoides*	Indian ricegrass	5	–	1	0.000	0.050
	Agrostis	bentgrass	–	–	1	0.007	1.000
	Agrostis gigantea	–	–	–	8	0.074	3.278
	Agrostis scabra	rough bentgrass	4	–	7	0.001	0.329
	Agrostis variabilis	mountain bentgrass	4	–	2	0.000	0.050
	Alopecurus aequalis	shortawn foxtail	4	–	1	0.005	0.683
	Bromopsis inermis	smooth brome	0	7	1	0.382	19.666
	Calamagrostis canadensis	bluejoint	6	–	37	0.056	7.436
	Calamagrostis stricta	slimstem reedgrass	7	–	12	0.078	3.575
	Catabrosa aquatica	water whorlgrass	7	–	2	0.001	0.525
	Critesion jubatum	foxtail barley	2	–	72	0.037	2.894
	Danthonia intermedia	timber oatgrass	8	–	13	0.057	5.283
	Deschampsia cespitosa	tufted hairgrass	4	–	37	0.016	1.808
	Distichlis stricta	saltgrass	4	–	61	0.213	6.328
	Elymus trachycaulus	slender wheatgrass	4	–	36	0.035	2.377
	Elytrigia repens	quackgrass	0	7	1	0.000	0.050
	Glyceria elata	fowl mannagrass	6	–	3	0.009	4.139
	Glyceria grandis	American mannagrass	6	–	2	0.005	3.000
	Hesperostipa comata	needle and thread	6	–	1	0.006	1.000
	Hordeum	barley	–	–	2	0.008	1.163
	Koeleria macrantha	prairie Junegrass	6	–	4	0.001	0.129
	Leymus triticoides	beardless wildrye	5	–	3	0.005	1.700
	Muhlenbergia asperifolia	scratchgrass	4	–	65	0.093	6.033
	Muhlenbergia richardsonis	mat muhly	8	–	17	0.049	3.408
	Panicum capillare	witchgrass	0	4	5	0.035	1.500
	Pascopyrum smithii	western wheatgrass	5	–	32	0.065	3.034
	Phleum commutatum	alpine timothy	6	–	25	0.003	0.547
	Phleum pratense	timothy	0	5	1	0.000	0.050
	Poa alpina	alpine bluegrass	7	–	4	0.004	0.830
	Poa glaucifolia	plains bluegrass	5	–	22	0.006	0.438
	Poa juncifolia	Sandberg bluegrass	6	–	4	0.050	2.465
	Poa palustris	fowl bluegrass	6	–	1	0.002	0.366
	Poa pratensis	Kentucky bluegrass	0	5	12	0.070	3.988
	Poaceae	–	–	–	7	0.006	0.514
	Podagrostis thurberiana	alpine bentgrass	8	–	15	0.002	0.311

Appendix J (*continued*)

Family	Taxa	Common name	C Score	I Score	Freq.	Mean relative cover	Mean absolute cover
Poaceae (cont'd)	Puccinellia airoides	Nuttall's alkaligrass	6	–	14	0.008	1.006
	Spartina gracilis	alkali cordgrass	7	–	33	0.082	1.113
	Sphenopholis obtusata	prairie wedgescale	5	–	9	0.030	2.626
	Sporobolus airoides	alkali sacaton	5	–	14	0.050	2.229
	Trisetum wolfii	Wolf's trisetum	7	–	14	0.004	0.641
Polygonaceae	Bistorta bistortoides	American bistort	7	–	14	0.007	1.468
	Bistorta vivipara	alpine bistort	8	–	21	0.005	0.529
	Persicaria coccinea	longroot smartweed	2	–	12	0.032	2.933
	Persicaria maculata	spotted ladysthumb	0	4	4	0.125	9.687
	Persicaria pensylvanica	Pennsylvania smartweed	1	–	5	0.056	3.942
	Polygonum arenastrum	oval-leaf knotweed	0	2	3	0.008	0.750
	Polygonum douglasii	Douglas' knotweed	3	–	2	0.264	8.025
	Rumex	dock	–	–	1	0.000	0.050
	Rumex aquaticus ssp. occidentalis	western dock	5	–	1	0.000	0.050
	Rumex stenophyllus	narrowleaf dock	0	4	1	0.003	0.208
Polytrichaceae	Polytrichum juniperinum	juniper polytrichum moss	7	–	5	0.001	0.122
	Polytrichum strictum	polytrichum moss	6	–	10	0.003	0.322
Portulacaceae	Portulaca oleracea	little hogweed	0	3	2	0.000	0.050
Potamogetonaceae	Potamogeton gramineus	variableleaf pondweed	4	–	3	0.002	0.683
	Potamogeton vaginatus	sheathed pondweed	7	–	1	0.002	1.000
Primulaceae	Dodecatheon pulchellum	darkthroat shootingstar	8	–	7	0.002	0.324
	Glaux maritima var. angustifolia	sea milkwort	7	–	18	0.056	6.594
Ranunculaceae	Batrachium longirostre	longbeak buttercup	4	–	2	0.000	0.050
	Halerpestes cymbalaria ssp. saximontana	alkali buttercup	4	–	42	0.004	0.383
	Hecatonia scelerata	cursed buttercup	1	–	3	0.014	1.878
	Ranunculaceae	–	–	–	1	0.000	0.050
Rosaceae	Argentina anserina var. concolor	silverweed cinquefoil	3	–	81	0.078	7.022
	Fragaria vesca ssp. bracteata	woodland strawberry	5	–	2	0.000	0.050
	Pentaphylloides floribunda	shrubby cinquefoil	4	–	5	0.000	0.050
	Potentilla	cinquefoil	–	–	1	0.000	0.050
	Potentilla diversifolia	varileaf cinquefoil	6	–	30	0.014	1.631
	Potentilla plattensis	Platte River cinquefoil	7	–	18	0.008	0.587
	Rosa woodsii	Woods' rose	5	–	2	0.030	0.863
Rubiaceae	Galium trifidum ssp. subbiflorum	threepetal bedstraw	7	–	5	0.002	0.296
Salicaceae	Populus angustifolia	narrowleaf cottonwood	5	–	1	0.363	12.333
	Populus tremuloides	quaking aspen	5	–	2	0.007	0.525
	Salix	willow	–	–	3	0.003	0.367
	Salix exigua	narrowleaf willow	3	–	2	0.101	7.525
	Salix lucida ssp. caudata	greenleaf willow	8	–	1	0.041	8.000
	Salix planifolia	diamondleaf willow	7	–	33	0.263	27.825
Scapaniaceae	Scapania	leafy liverwort	–	–	5	0.001	0.122
	Scapania cuspiduligera	–	5	–	5	0.000	0.050
	Scapania undulata	–	5	–	5	0.000	0.050

Appendix J (*continued*)

Family	Taxa	Common name	C Score	I Score	Freq.	Mean relative cover	Mean absolute cover
Scrophulariaceae	Castilleja occidentalis	western Indian paintbrush	8	–	12	0.001	0.132
	Castilleja sulphurea	sulphur Indian paintbrush	7	–	1	0.000	0.050
	Mimulus glabratus	roundleaf monkeyflower	5	–	5	0.000	0.050
	Mimulus guttatus	seep monkeyflower	8	–	1	0.000	0.050
	Orthocarpus luteus	yellow owl's-clover	6	–	7	0.008	0.607
	Pedicularis groenlandica	elephanthead lousewort	8	–	35	0.025	2.008
	Veronica americana	American speedwell	6	–	8	0.048	5.779
	Veronica catenata	water speedwell	1	–	1	0.000	0.050
	Veronica nutans	American alpine speedwell	7	–	23	0.007	0.759
Valerianaceae	Valeriana edulis	tobacco root	7	–	1	0.001	0.050
Violaceae	Viola	violet	–	–	19	0.039	3.420
	Viola adunca	hookedspur violet	6	–	1	0.000	0.050
	Viola labradorica	alpine violet	9	–	1	0.000	0.050
	Viola macloskeyi ssp. pallens	smooth white violet	5	–	9	0.024	1.197
	Viola renifolia var. brainerdii	white violet	7	–	7	0.038	3.124
	Viola scopulorum	Canadian white violet	7	–	1	0.011	2.016
Zannichelliaceae	Zannichellia palustris	horned pondweed	2	–	3	0.014	1.472

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