CALIFORNIA STATE UNIVERSITY, NORTHRIDGE

Nebkha Morphology, Distribution and Stability
Black Rock Playa, Nevada

A thesis submitted in partial fulfillment of the requirements
For the degree of Master of Arts in Geography

By
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Dedication

This graduate thesis is whole heartedly dedicated to my beloved grandmother, Mary Louise Dobbs, to whom I owe my passion for the Earth. Mary Dobbs passed away on February 18, 2017, three months before I was to graduate with my bachelor’s degree in Geographic Information Science. While she is no longer with me, she has set a lasting impression on my life and is present in everything that I do. Without her, I would not have discovered my love for nature, and passion for learning, and would certainly not be where I am now – submitting a graduate thesis, and truly in love with what I do.

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Abstract

Nebkha Morphology, Distribution and Stability
Black Rock Playa, Nevada

By
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Master of Arts, Geography

The Black Rock Playa (BRP) is a remote, complex environment within the Black Rock Desert in northwestern Nevada. While the playa surface itself is entirely barren of vegetation, Greasewood (*Sarcobatus vermiculatus*) anchors nebkhas in the playa margins. This research examined two study sites and morphometrically characterized the BRP nebkhas, while also detailing the interrelationships between grain size, vegetation, groundwater, and local climate in relation to nebkha formation and stability. Nebkha morphometrics were delineated using photogrammetric techniques on UAV derived imagery within a GIS. The average nebkha dimensions were: area 60.23 m$^2$; length 8.54 m; width 8.0 m; height 1.4 m; height w/ vegetation 1.72 m; slope length 4.0 m; slope angle 20.5º, percent vegetation coverage of nebkha area 18.1%, and vegetation height 36.3 cm. The soil texture classification of the nebkhas was loam to silty clay loam. The fine sediment constituting the nebkha possibly aids in stabilization through *in situ* cementation. Nebkha vegetation was analyzed in relation to groundwater. Regional trends from wells surrounding the playa, paired with historic groundwater reports, indicate the water
table is less than 15.2 m beneath the playa surface. While greasewood roots do not tend to extend below 6 m, the healthy appearance of the greasewood and its reliance upon subsurface water sources suggests shallow groundwater levels. Local winds predominantly come from the SW or WSW at velocities 2.5 to 5.7 m/s\(^{-1}\) with gusts reaching up to 31 m/s\(^{-1}\). Overall this research concludes that the extent of the dune fields is strongly related to the distribution of greasewood, which anchors 100\% of the nebkhas in the region. The nebkhas have not migrated between 1982 and 2019 and the dune fields thus appear to be stable; however, the eastern study site shows some signs of degradation owing to anthropogenic impact associated with off-road vehicle use. A comparison of the BRP nebkhas to 20 other global dune fields concluded that the BRP was the only field to be anchored by greasewood. It also concluded that global nebkha populations vary considerably in size, height, sediment composition and vegetation, owing to the unique and limiting factors of the local environment.
Chapter 1: Introduction

The Black Rock Playa (BRP) in northwestern Nevada is one of the largest flat places on Earth, with a total relief of less than one meter across a 310 km² expanse (US BLM Black Rock Field Office, 2012). The unvegetated interior of the playa appears uniform in sediment color and texture. Local changes in relief owing to incised drainage channels and dunes stabilized by vegetation (nebkhas) occur in the ecotones between the playa margins and the nearby mountains. These vegetation-stabilized dunes, or nebkhas (Figure 1), are present in large fields along the western and eastern margins of the playa and have become of recent concern to local land managers and residents owing to the dunes perceived potential to migrate onto the playa.

Figure 1: Typical nebkha anchored by greasewood on the western shore of the Black Rock Playa, Nevada. Sean Robison (1.6m/5.25 ft.) for scale. Image was taken in May 2018 at the beginning of a drying period, hence the presence of salt encrustation and desiccation cracks. Variations in sediment color are owing to differences in moisture. (Image by author)

Nebkhas are typically products of aeolian deposition in environments with adequate sediment supply, vegetation, and active wind regimes, all of which are present within the Black Rock region. Many geomorphic characteristics of nebkhas are influenced by the vegetation that
anchors them, particularly the dune length and width, slope lengths, and crown heights (Lang et al., 2013) (Figure 2).

Figure 2: Diagram of typical coppice dune (aka nebkha) structure and morphology (Lang et al., 2013).

Environments suitable for nebkha formation and eventual steady state (Tsoar, 1985) range from sub-humid to arid, including coasts, deltas, grasslands, playas and deserts (Du, Yan, and Dong, 2010; Lang et al., 2013). They are global in distribution, occurring in China (Wang et al., 2008; Li et al., 2010), Australia (Hesp, 1981; Nield and Baas, 2007), Iceland (Mountney and Russell, 2009), the Middle East (Khalaf, Misak, and Al-Dousari, 1995; Al-Awadi and Al-Dousari, 2013), Africa (Nickling and Wolfe, 1994; El-Bana, Nijs, Khedr, 2003), and the American Southwest (Langford, 2000; Laity, 2003).

This research sought to describe and understand the processes responsible for the nebkha fields along the margins of the Black Rock Playa through a physical, spatial, and temporal lens by posing the following research questions: What are the morphometries of the BRP nebkhas and how do they compare with other nebkha fields globally? How does vegetation, groundwater,
grain size and climate affect the distribution and stability of the BRP nebkha field? Three clear objectives evolved during this research: (1) To characterize the morphometry of the Black Rock Playa nebkhas, using dimensional data such as dune length, width, area, height, vegetation height, slope length and slope angle; (2) To compare the BRP nebkhas to other global nebkha fields using data collected for this study; and (3) To analyze the interrelationships between vegetation, groundwater, sediment, and local climate in relation to nebkha formation and stability. This study focused on the distribution and stability of these features, which are dependent on sediment size and availability (determination of grain size), vegetation (an analysis of species, percent cover, height and relationship with dune stability and the role of groundwater dependence) and climate (wind speeds and directions). Above all, this study aimed to establish a baseline qualitative and quantitative dataset of the BRP dune field for future research.

**Significance of Research**

Dune systems are often good indicators of environmental change (Thomas and Leason, 2005). Expansion and contraction of arid regions and changes in local wind regimes can have significant effects on the magnitude and pattern of erosion and deposition, thus leading to destabilization or formation of dune fields (Li et al., 2014). Nebkhas provide valuable information for paleoenvironmental reconstruction. For example, Wang et al. (2008), Seifert et al. (2009), Wang et al. (2010), and Lang et al. (2013) found that by dating and analyzing the stratigraphy of nebkhas they were able to reconstruct historic periods of variable environmental conditions. Nebkhas also are sensitive to deteriorating vegetation health, which can result from changes in water availability and human impact (Laity, 2003; Tsoar, 2001). Laity (2003) found
that destabilization of Mojave Desert (CA) nebkhas was the result of vegetation death owing to local groundwater pumping, whereas Tsoar (2001), working along the coast of Israel, asserts that impacts on vegetation which stabilize dunes result from anthropogenic activity, wind velocity or low levels of annual precipitation (<50 mm). Thus, a study of the relationships between nebkhæ morphometries, vegetation, groundwater, and local climate at the Black Rock Playa is of scientific value in the larger concept of environmental change in a region impacted by anthropogenic activity.

The Black Rock Playa is subject to intense recreational use but has been little studied here. Common recreation for the playa includes land surfing, hosting the land speed record, rocket launching, and the annual Burning Man Festival. Impediment of these activities (i.e. changes in playa topography) have a significant potential of reducing regional economic benefit. An understanding of the physical features of the BRP related to recreation is essential to the land management community. The Bureau of Land Management (BLM) and local residents have expressed concern about the dune fields’ potential to migrate and change the characteristically flat topography of the playa, thereby impeding recreation opportunities (Mark Hall, personal communication, February 2018). The BLM is responsible for monitoring playa recreation and compliance with guidelines meant to preserve the current physical and ecological state of the playa, presenting a challenge when large recreational events, such as Burning Man, are hosted on the playa. Land managers must balance opportunity for multi-use recreation with preservation of a sensitive desert system. This often comes with unintended consequences, such as the potential activation of dune systems and degradation of the playa surface. These conflicts require a thorough and focused consideration of both natural and anthropogenic factors when determining how to balance multi-use conservation areas. This study contributes to these considerations while
underscoring the need for scientific data and analysis for the playa and its surrounding environment.

**Literature Review**

*Black Rock Playa*

Little is known about the morphological and spatial characteristics of dune systems found along the margins of the Black Rock Playa. Most studies have focused on a general assessment of playa topography, vegetation, climate, habitat, local geology, and archaeology (US BLM Black Rock Field Office, 2006, 2012, and 2019). These reports were generated in response to concerns regarding recreational use of the playa and, in particular, the Burning Man Festival which attracts approximately 70,000 participants each August. In the most recent BLM Environmental Impact Statement (EIS) reviewing Burning Man (2019), the agency acknowledged the existence of the peripheral nebkhas, terming them “adjacent mounds”, but largely focused on linear dunes located within the playa interior which are thought to have greater impact on the playa topography. One of the foundational papers on the Black Rock Playa was by Sinclair (1963), who performed a ground-water reconnaissance for Nevada. While noting such features as local mountain ranges and climate, mineral properties, ground-water levels, and water quality, the BRP nebkhas were not discussed. Sinclair noted that “Sand is notably lacking in the Black Rock Desert, although a few dunes, stabilized by vegetation, occur along the west flank of the Black Rock Range north of Double Hot Spring and to a lesser extent in an area north of Sulphur.” (1963, pg. 7).

The environmental setting of the BRP is well-documented with regard to temperature and precipitation and their relationship with playa wetting and desiccation. Adams and Sada (2014)
detailed geomorphic and fluvial characteristics of the playa, providing a critical perspective on how playa textures fluctuate annually with changes in aridity and temperature, thereby affecting the hardening and softening of soils that constitute the BRP dunes. Willden and Mabey (1961) documented the formation of desiccation cracks on the playa which may contribute to seasonal loosening of fine grained sediments available for wind transport. In 1961, these cracks were in a system 1.6–3.2 km (1–2 mi) wide, with individual fissures < 0.6 m (2 ft) wide and < 1.2 m (4 ft) deep. These features still are present today, which implies a prolonged drying trend on the order of at least six decades. More recently, in 2018 the NASA DEVELOP Black Rock Playa Team began research investigating the impact of Burning Man on the playa surface via a radar and climate analysis, concluding that after the 2017 festival there was a significant increase of dust at the Burning Man site that remained for at least two months later.

**Foundational Understanding and Research Methods of Vegetated Dunes**

Nebkhas are dunes formed around and stabilized by vegetation (Cooke, Warren, and Goudie, 1993); other common terms in the literature include coppice dune, hummock dune or nabkha (Laity, 2008). Nebkhas are studied widely not just for their morphology (Du et al. 2010; Li et al. 2014), but also to aid in understanding environmental changes in arid climates (Lang et al., 2013). Owing to the accumulative nature of nebkha formation, Lang et al. (2013) suggested that examination of nebkha stratigraphy, consisting of variable sediment sizes and vegetation litter, are valuable in dating and reconstructing environmental histories. Nebkhas generally are found in groups or fields and are dependent upon the relationship between adequate sediment supply, transport capacity, and vegetation capable of capturing entrained sediments (Tsoar, 2001; Laity, 2008). The foci of nebkha research varies and may include morphometrics (measures of
shape and size) or other factors such as vegetation, sediment size and sorting and the conditions of wind transport. There are many studies globally which have sought to compare nebkha fields in different environments (Hesp, 1981; Nickling and Wolfe, 1994; Khalaf et al., 1995; Langford, 2000; El-Bana et al., 2003; Laity, 2003; Tengberg and Chen, 1998, Nield and Baas, 2007; Wang et al., 2008; Mountney and Russell, 2009; Du et al., 2010; Li et al., 2010; Al-Awadhi and Al-Dousari, 2013; Lang, et al., 2013). Khalaf et al. (1995) and Al-Awadhi and Al-Dousari (2013) focused on coastal populations, in Kuwait. Mountney and Russell (2009) studied a unique nebkha field in Iceland which experienced frequent flooding, thus leading to an understanding of fluvial influences on erosion and deposition of nebkhas. Langford (2000) and Laity (2003) detailed nebkha populations within the southwestern United States with climates similar to that found on the BRP.

The type of vegetation anchoring a nebkha can affect the sediment trapping potential, formation, shape, and stability of the dune (Lancaster and Baas, 1998; Hesp and McLachlan, 2000; Dougill and Thomas, 2002). Hesp and McLachlan (2000) found that the horizontal growth of Gazania rigens resulted in narrow conical nebkhas, whereas nebkhas formed around Arctotheca populifolia were low and semi-circular in form. Lancaster and Baas (2005) assessed how sediment transport at Owens Lake, CA, was affected by salt grass (species present proximal to the BRP nebkha field), finding salt grass of 15% vertical coverage (a ratio of plant silhouette area and total surface area) was sufficient enough to increase surface roughness and significantly reduce sand transport. Dougill and Thomas (2002) compared nebkha morphometrics of three different vegetation species: Nebkhas with Gnidia caffra were the smallest nebkhas (avg. 0.44 m height), followed by Grewia flava (avg. 0.6 m height), with Acacia hebeclada forming the tallest nebkhas (1.35 m height). However, studies on greasewood (Sarcobatus vermiculatus), typical of
the BRP region, is lacking. Gillies et al., (2000) modelled the effects of greasewood on shear stress and drag coefficients relating to wind speed and determined that greasewood could reduce aeolian sediment transport with only a relatively low percentage of coverage.

Relationships between wind dynamics and sediment are critical to the understanding of nebkhas, as those factors influence nebkha formation and stability (Langford, 2000; Tsoar, 2001; Dougill and Thomas, 2002; Mountney and Russell, 2009; Du et al., 2010). Langford (2000) and Wu et al. (2008) detailed the typical sorting of sediment on nebkhas, with coarser sediment often found on the windward side and finer particles typically on the leeward side of a nebkha. Laity (2008) described how nebkha evolution and stabilization relies on sediment availability and particle size. Dougill and Thomas (2002) studied how interdune sediment size can contribute to nebkha formation, finding that larger grains transported via creep and saltation were effectively trapped by low shrubs with low horizontal growth. Tsoar (2008) noted that sand-based nebkhas have high infiltration rates and thus poor water retention owing to larger pore spaces. By contrast, nebkhas with finer grain sizes (silt and clay) have lower infiltration rates, higher levels of soil moisture, and are more cemented (Laity, 2008; Adams and Sada, 2014). These differences in sediment size also play a role in the potential instability or stability of the dune systems when disturbed by off-road vehicle use, vegetation clearance, or changes in the groundwater table.

Nebkha research commonly incorporates field observations and in situ data collection and may include morphometric (shape) data, sediment size and sorting, and vegetation indexing (Link et al., 1993; Nickling and Wolfe, 1994; Langford, 2000; Dougill and Thomas, 2002; El-Bana et al., 2003; Wang et al., 2008; Mountney and Russell, 2009; Wang et al., 2010; Yousefi, et al., 2019). Some studies have also examined groundwater and soil moisture to understand its role in vegetation health and dune stability (Link et al., 1993; Laity, 2003; Mountney and Russell,
Field studies have been supplemented by analyses of historical or contemporary imagery. For example, in Laity’s 2003 study of Mojave Desert, CA, nebkhas, historical imagery was utilized to infer the long-term transport of sand. By contrast, many studies have taken a conceptual approach to nebkha research, often using modelling techniques to understand the relationships between wind regimes, sediment, and vegetation (Tengberg and Chen, 1998; Tsoar, 2001; Mountney and Russell, 2009; Hesp and Smyth, 2016; Yousefi et al., 2019). In their 1998 study, Tengberg and Chen used morphometric nebkha data (height and length) to model nebkha development, concluding that nebkhas have three stages of development: growing, stabilizing, and degrading. Mountney and Russell (2009) produced a model that accounted for the various controls on construction, accumulation, and preservation of vegetated dunes in Iceland, finding that most of the dunes in their study were undergoing active construction and migration despite limited sediment availability and a high water table. Yousefi et al. (2019) used an AHP model to determine that Peganum was the most effective plant species (compared to Stipagrostis and Alhaji) at stabilizing moving sand in a case study of Samad-Abad, Sarakhs, Iran.

Aerial imagery has been widely used to derive accurate measurements of dune morphometric characteristics. For decades, satellite imagery provided areal coverage in poorly accessible regions while taking advantage of spectral capabilities, allowing researchers to study phenomena (inundation and vegetation presence and health) that is otherwise hard to discern with the visible spectrum (Thomas and Leason, 2005; Mountney and Russell, 2009; Adams and Sada, 2013). Thomas and Leason (2005) used Landsat 5 TM imagery to produce a dunefield surface cover index, which was later analyzed for areas susceptible to aeolian transport based on drought conditions, whereas Mountey and Russell (2009) used SPOT imagery to delineate dune size and shape in Iceland and Adams and Sada (2014) used satellite imagery to delineate
inundation extents on the BRP. Recently, the use of Unmanned Aerial Vehicles (UAVs) has augmented traditional photogrammetry (aerial and satellite photographs) to provide detailed imagery. Using Structure from Motion (SfM) measurements of three-dimensional features from a series of two-dimensional images has allowed detailed quantitative measurements of nebkhas. The accuracy of SfM products derived from UAVs is well documented (Barry and Coakley, 2013; Santise et al., 2014; Grenzdorffer, 2014). For example, Barry and Coakley (2013) found that XYZ data from an RTK GPS system compared to that collected by a UAV has demonstrated that the UAV derived spatial data achieved similar accuracies to those of an RTK GPS system. Santise et al. (2014) experimented with the use of Ground Control Points (GCPs), finding that implementation of small numbers of GCPs within an aerial survey adds to the vertical accuracy of UAV elevations.

**Study Area**

The Black Rock Playa (Figure 3), a remnant of Lake Lahontan, which occupied much of the Great Basin during the late Pleistocene, is located in the Black Rock Desert in northwestern Nevada (US BLM Black Rock Field Office, 2012; Adams and Sada, 2014). The playa sits at an elevation of 1,190 m, with relief of about 1 m over 310 km². The playa has “protected” status as part of the Black Rock Desert-High Rock Canyon Emigrant Trails National Conservation Area, which is federally managed by the Bureau of Land Management (BLM). Originating from locally eroded alluvial deposits, high-alkaline silt and clay sediments dominate the surface composition, incorporating small amounts of sand from the Quinn River and adjacent mountain drainage basins. Six generally north-trending, fault-block mountain ranges dominated by volcanics bound the playa, increasing the local relief by up to an additional 1,400 m.
Figure 3: Study area map depicting the Black Rock Playa, with surrounding geographic and geologic features.

The playa formed within an endorheic basin fed by local precipitation and two primary rivers: the Quinn River, which drains from the nearby Black Mountains; and Mud Meadow Creek, which drains into the northwestern portion of the playa, just west of the Black Rock Range (Figure 3). In the winter months, typically from November to March, the two rivers inundate lower elevations creating a shallow, ephemeral lake in the playa center. During these annual inundations the playa surface becomes muddy, making the central portions almost entirely inaccessible for recreation. When the annual lake recedes, typically between April and July, a hard, durable crust is formed, characterized by desiccation cracks of varying thicknesses and depths. This upper crust is eroded by off-road recreation or aeolian and fluvial processes to form a fine dust which then is entrained and deposited downwind.
The BRP is classified as semi-arid desert and is part of the Great Basin shrub-steppe eco-region. While the playa surface is devoid of vegetation, the margins and piedmonts are characterized by a desert-sagebrush environment. Various salt-tolerant brush species dominate, including shadscale (*Atriplex confertifolia*), greasewood (*Sarcobatus vermiculatus*), and invasive cheatgrass (*Bromus tectorum*). Owing to the semi-arid climate, vegetation in the Black Rock Playa region is largely dependent on sub-surface water sources.

*Local Climate*

The playa climate is typical of desert systems, with warm summers, cool winters and low levels of precipitation. Weather data was obtained from a combination of literature and original plotting of wind variables by the author. Data from the Gerlach, NV COOP station (ID 263090, elevation 1,215 m) (WRCC, 2019) show that from 1948 – 2016 the average summer temperature (June, July, August) is 31.4°C and the average winter temperature (December, January, February) is 6.3°C. The lowest levels of precipitation are typically received between July and October, averaging 7.6 mm, whereas the remaining months have an average precipitation of 20 mm. The NASA DEVELOP Black Rock Playa team (2018) performed an evaluation of drought conditions and found that for the past 20 years (1997 – 2017), temperatures and precipitation levels have remained relatively static, indicating that the BRP was not affected by drought conditions.

Wind was a primary weather element to help analyze the distribution and nature of nebkhas on the BRP. Wind data are available for Nov 2017 – Nov 2019 from the RAWS Black Rock Playa Station (RAWS id TT484; elevation 1,190 m) located on the interior of the playa.
east of Burning Man (WRCC 2019). Monthly wind summaries for wind speed, wind gusts, and wind direction were calculated from daily averages. The primary wind direction of the playa is southwest and west-southwest (Figure 4), with average wind speeds ranging from 2.5 m s\(^{-1}\) to 5.7 m s\(^{-1}\). There is minimal seasonal variation in the wind regime on the playa; between wet, winter months and dry, summer months, wind speeds only increase by about 1.5 m s\(^{-1}\). Wind gusts on the playa average 12.3 m s\(^{-1}\), however gusts ranging from 18 m s\(^{-1}\) up to 31 m s\(^{-1}\) are not uncommon (Figure 4). The strongest winds were recorded from the SW and WSW. Overall, Sinclair (1963) surmised that of climatic factors, wind was likely the strongest erosional force on the playa.
Research Sites

This study focused on two nebkha dune fields located on the margins of the western arm of the playa (in red, Figure 3). The western margin and the eastern margin were established as two separate research sites based on field observations of factors which were thought to influence the varying morphology of the dunes. The sites differed in the relative presence of drainage channels, moisture characteristics, the nature of anchoring vegetation, and impacts from recreation.
The western field site is the more accessible of the two sites. Dunes of the western field site are consistently round to elliptical in shape and are variable in size. The western site has dunes with drier sediment, fewer shallow surface runoff channels in the interdune areas, and more vegetation than the eastern site.

The eastern field site was often difficult to access owing to changes in playa moisture. Soil texture in the eastern dune field is much softer and more pliable than soils in the western dune field. This is assumed to be because of higher levels of moisture owing to runoff (as evidenced by several established drainage channels (<1.5 m depth) in the interdune area) and higher subsurface water levels (as evidenced by nearby hot springs). Additionally, there is widespread evidence of recreation, namely in the form of tire tracks, scattered debris, and fire pits within the dune field.
Chapter 2: Methods

In order to develop a thorough description of the BRP nebkhas, this study used (1) an Unmanned Aerial Vehicle (UAV) to obtain high resolution images of the dunes; (2) field sampling and laboratory analysis of dune sediments for size and sorting metrics; (3) identification of anchoring vegetation and percent cover on individual dunes; (4) regional groundwater data to examine influence on vegetation; and (5) historical imagery to delineate past dune field extents and potential dune field growth. Collectively, these methods not only aided in morphometrically characterizing the BRP nebkhas and offered insights into the morphological and behavioral characteristics of the dune fields, but also spoke to the larger question of anthropogenic and natural influences on dunes of the Black Rock Playa (BRP).

**Morphometrics of BRP Nebkhas**

This portion of the study focused on examining a moderate sample size of individual dunes from both study sites (n= 100) with the goal of digitally delineating dune morphometrics such as dune length, width, height, crown height, slope length, and slope angle. The dune fields were imaged using two DJI Phantom series UAVs which were piloted at varying altitudes using the flight program Drone Deploy (Table 1).

<table>
<thead>
<tr>
<th>Flight Date</th>
<th>Ortho</th>
<th>UAV model</th>
<th>Flight Altitude m (ft)</th>
<th>Flight Area hectares (acres)</th>
<th>Number of Images Collected</th>
</tr>
</thead>
<tbody>
<tr>
<td>27 May 2018</td>
<td>w1</td>
<td>Phantom 3 Pro</td>
<td>29.57 (97)</td>
<td>3.71 (9.16)</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td>w2</td>
<td>Phantom 3 Pro</td>
<td>29.57 (97)</td>
<td>4.76 (11.77)</td>
<td>540</td>
</tr>
<tr>
<td></td>
<td>w3</td>
<td>Phantom 3 Pro</td>
<td>29.57 (97)</td>
<td>1.38 (3.41)</td>
<td>130</td>
</tr>
<tr>
<td>22 June 2018</td>
<td>e1</td>
<td>Phantom 4 Pro</td>
<td>22.86 (75)</td>
<td>5.13 (12.69)</td>
<td>310</td>
</tr>
<tr>
<td></td>
<td>e2</td>
<td>Phantom 4 Pro</td>
<td>22.86 (75)</td>
<td>1.16 (2.88)</td>
<td>623</td>
</tr>
</tbody>
</table>

*Table 1: Specifications for the UAV flights and resulting orthoimages (orthos).*
The UAV flights produced hundreds of two-dimensional images geotagged with spatial information taken at nadir (90°) to the dune field. Post-flight processing was accomplished using Agisoft PhotoScan Pro (Agisoft LLC) and consisted of image alignment and dense-point cloud construction resulting in a single, cohesive Red-Green-Blue (RGB) orthomosaic for each flight. Ancillary to the spatially accurate orthomosaic was the production of a Digital Elevation Model (DEM); together the orthomosaic and DEM could then be input into a GIS for photogrammetric measurements.

The orthomosaiced image for each sample area was manipulated in ESRI’s ArcMap 10.5/10.6 (ESRI, 2011) to collect dune dimensions (Figure 5).

![Image](image.png)

_Figure 5: Diagram of general GIS workflow. Image 1 (from left) shows 3-inch contour layer used to delineate the dune boundary in Image 2. Image 3 is an example of the dune length and width measurements, based on the geographic center (yellow dot). The established height of the dune is marked by the green triangle. Image 4 depicts the vegetation polygons. (North is at the top of each image; width of each image is approximately 7.4 m) (Images by author)_

Owing to the large number (>1,000) of dunes present within the imagery, a sample population of dunes was established using a combination of logical determination and random sampling to ensure the dunes could be delineated reasonably for measurement while minimizing bias. All dunes within the orthomosaic were evaluated based on their potential for accurate delineation; this was based on visual cues such as playa color, shading indicative of slope, shape,
and the use of a 7.62 cm (3 in) contour data set derived from the DEM. Delimitation of dune boundaries proved difficult owing to the merged and severely eroded nature of some features – for many of the dunes it was difficult to discern if they were two features that had grown in close proximity and merged, or if they had started as a larger feature that had been eroded in between the anchoring plants. The sample size was further limited to 20 dunes per orthoimage based on a random selection of the eligible dunes using the GIS. Sample dunes then were outlined, thus creating a constraining polygon for the individual dune measurements, further resulting in a master layer that would house all attribute data for the dunes.

Dune measurements were executed based on features created using the ArcMap Editor toolbar. Total area of the dunes (area_sqm) was calculated using the Calculate Geometry function. Dune height is a critical measurement when analyzing dune morphology, however when studying nebkhas, the height of the dune with and without vegetation must be considered. To determine the height of the dunes independent of the anchoring vegetation (ht_noc_m), the DEM, contour line layer, and visual cues from the orthomosaic were used. For dunes that were classified as multipart, multiple heights were cataloged. A polyline layer was created to house dune length and width dimensions based on the geographic center of the dune. Dune length (length_m) was derived from the windward and leeward slopes of the dune, as dictated by the prevailing southwest wind direction, with dune width (width_m) derived from a line perpendicular to the dune length. Lastly, measurements pertaining to the windward and leeward slopes were calculated using geometric and angular expressions based on the dune height and base. These calculations resulted in windward and leeward slope lengths (ww_sl_m, lw_sl_m) and windward and leeward slope angles (ww_slopea_m, lw_slopea_m). Dunes with multiple heights (compound nebkhas) resulted in slope length and slope angle measurements associated
with each height. All dune characteristics then were assessed within a descriptive and inferential statistical analysis to discover patterns within the dataset.

Factors Affecting Nebkha Distribution and Stability on the BRP

Grain Size Determination

Dune particle size was determined by sieve analysis of collected sediment samples. Grain size initially was assumed to be primarily silt and clay (<.062 mm) based on geologic literature and field observations. A total of 24 samples were collected from 4 different dunes, two from each research site. Samples were dried to extract any residual moisture and then disaggregated using a mortar and pestle to ensure true size prior to sieving (Figure 6).

Figure 6: Image of aggregated sediment sample from the Black Rock Playa. This sample was taken from a vegetated dune at the surface on the western shore.

Samples were processed using a Sepor sieve shaker with an American Society for Testing and Material (ASTM) Standard No 10 (2.00 mm) sieve, which demarcated the coarsest threshold of the aggregate category sand. Of the original 24 samples collected, 18 were then processed
using a hydrometer bath to determine particle size. The analysis was fraught with problems owing to equipment limitations, leading to procedural changes and human error that were later deemed unacceptable by ASTM standards. It was decided to test the hydrometer results by sending two samples to the Desert Research Institute (DRI) for analysis on a Malvern 3000 Laser Particle Analyzer; further sampling of the remaining 22 samples was abandoned owing to financial constraints. Results produced from the DRI analyses grouped the sediment into percent sand, percent silt, and percent clay, and provided a USDA soil texture classification (US Department of Agriculture, n.d.).

Assessment of Vegetation and Groundwater

Dune vegetation was measured by a combination of in situ field observations and measurements using a GIS. Using the high-resolution UAV imagery, DEM, and dune contour layers, various vegetation characteristics could be derived. Using a zonal statistics function with a focus on the minimum, maximum, and range values of the DEM the height of the dunes including the anchoring vegetation was delineated (ht_wcrn_m). Crown height – the height of the vegetation rooted within the dune (avg_ch_cm) – was taken as an average of three measurements owing to the variability in plant growth on the dune surface. Digitization of the vegetation on the dune provided a means to calculate vegetation area as a percent of total dune area (vegarea_sqm; pctCanopy). In situ identification of species within and adjacent to the dune field were obtained with assistance from the BLM Black Rock Field Office Biologist, Brian McMillan (Brian McMillan, personal communication, June 23, 2018). Properties of each species such as root depth and water requirements were further investigated using secondary sources to understand relationships between dunes and local playa hydrology. Sources for collecting species

Groundwater levels (meters below the surface) were compiled from various reports and well measurements, though these data for the Black Rock Playa are extremely limited – thus historic reports and well measurements close to the playa were relied upon to construct local and regional trends. Historical groundwater levels from 1962 (Sinclair, 1963) and 1947 – 2004 (USGS, 2006) were obtained from groundwater reports by the USGS and State of Nevada. A separate dataset of groundwater levels ranging from various years between 1963 and 2019 from four measurement sites were obtained from the USGS National Water Information System (USGS, n.d.) (Figure 7). Owing to the scarcity of groundwater data in the region, none of the measurement sites were on the playa; instead sites within approximately 40 km (25 mi.) of the playa were chosen and used to construct regional trends of groundwater levels to infer if the groundwater had risen or sunk during the 56-year period. These trends were then applied to the playa measurements from the reports (Sinclair, 1963; USGS, 2006) to estimate recent groundwater levels, which, in turn, were compared with nebkha vegetation root depths to help determine general vegetation health.
Historical Imagery and Delineation of Past Dune Field Extents

A historical imagery analysis was incorporated into study methodology owing to its potential value in estimating the relative age of the dunes and topographic change within the dune field over time. A set of color infrared (IR) aerial images of the playa from 1982 was acquired from the BLM field office in Winnemucca, NV (Figure 8).
Each available image was scanned in the field office and manipulated via cropping and file format transformations to be compatible with an orthoimage analysis, resulting in a total of 104 images available for stitching. All cropped .jpg imagery was loaded into Agisoft Pro and run through a process of alignment and orthomosaic construction. The resulting orthoimage then was assessed for shoreline extent and position based on visual cues such as color, textures, and positioning based on fixed coordinate points. The points then were re-used within Google Earth (Google Inc., 2019) for the years 2003 and 2016 - 2019, which provided insight to any movement or changes of the dune field. Additionally, areas in which obvious changes in dune field extents had occurred between 1982 and present imagery were identified as Areas of Interest (AOIs) and further examined.
Chapter 3: Data and Results

Morphometrics of BRP Nebkhas

Delineation of the BRP nebkha morphometrics included collection of high-resolution imagery, extraction of nebkha geometries via a GIS, and statistical analyses involving descriptive statistics, correlations and regression analysis. The image processing performed within Agisoft PhotoScan produced five spatially accurate orthoimages that were the basis of the GIS measurements (Figure 9).
Figure 9: Resulting orthoimages from all imagery collected at the two sample areas within the BRP. Location map (A). Image (B) constituted the western sample, area approximately 590m in width; The bottom two orthoimages (C) constituted the eastern sample area, approximately 560m in width.

The dunes of the western shoreline study area were examined using three orthoimages with an average resolution of 1.35 cm per pixel, while two orthoimages comprised the eastern shoreline with an average resolution of 0.92 mm per pixel. Using the GIS data acquired via the photogrammetric measurements, several descriptive statistics were calculated.

<table>
<thead>
<tr>
<th>Dune Dimensions</th>
<th>Dune Area (Sq m)</th>
<th>Dune Length (m)</th>
<th>Dune Width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>west site</td>
<td>east site</td>
<td>west site</td>
</tr>
<tr>
<td>Minimum</td>
<td>9.70</td>
<td>8.83</td>
<td>3.57</td>
</tr>
<tr>
<td>Maximum</td>
<td>190.69</td>
<td>197.80</td>
<td>18.51</td>
</tr>
<tr>
<td>Average</td>
<td>61.74</td>
<td>58.72</td>
<td>8.50</td>
</tr>
</tbody>
</table>

Table 2: Descriptive statistics derived from GIS analysis using dune area, length, and width.
Figure 10: Histogram showing the distribution of nebkha area.

Table 2 displays results of the GIS analysis pertaining to the dimensions of the BRP nebkhas. Nebkha area ($m^2$) within both sites was representative of a right-skewed distribution (Figure 10), meaning that most nebkha areas were less than the average. Average nebkha areas were 61.4 $m^2$ for the western field and 58.72 $m^2$ for the eastern field, although the means likely were overestimated by the outliers of very large dunes ($>100$ $m^2$ as seen in the right tail of Figure 10). The smallest dune area within the western dune field was 9.70 $m^2$ whereas the smallest dune area within the eastern dune field was 8.83 $m^2$. Most of the dune field population (86.6% of west dunes; 77.5% of east dunes) had a nebkha area smaller than 100 $m^2$. Eight of the sampled nebkhas within the western site (13.3%) and five nebkhas (8.3%) within the eastern site had dune areas between 100 $m^2$ and 200 $m^2$ respectively.

Comparisons of nebkha lengths and widths are shown in Figure 11. The distributions for lengths and widths did not vary much between the two research sites; most nebkhas (west 66.7%,
east 77.5% had lengths and widths between 4 m and 12 m. The smallest dune lengths observed were 3.57 m (west) and 6.02 m (east), while the largest lengths observed were 18.51 m (west) and 20.54 m (east); the mean lengths of the west and east areas were 8.50 m and 8.59 m, respectively.

The relationship between length and width was tested for correlation under the assumption that the two variables would be positively related. The correlation coefficient for the lengths and widths of the BRP nebkhas was 0.73, which represented a relatively strong, positive

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**Figure 11**: Nebkha lengths and widths, separated by research site for comparison. The y-axis shows how many nebkhas are within different length and width ranges (x-axis).

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The relationship between length and width was tested for correlation under the assumption that the two variables would be positively related. The correlation coefficient for the lengths and widths of the BRP nebkhas was 0.73, which represented a relatively strong, positive
relationship. This significant relationship indicated that as one dimension (length or width) increased, the other dimension (length or width) also would increase, prompting further testing with a univariate regression. This tested the prediction that as nebkhas grow, they will grow relatively proportionately – in other words, as the dune length increased, so would dune width. This model returned an R-squared value of 54%. The residuals plot (Figure 12) shows where the model over- and under-predicted the dune width values based on a unit increase in dune length values. Overall this model was deemed statistically significant based on the low P-Value of 3.49E-18 being less than the confidence interval of 95%.

<table>
<thead>
<tr>
<th>Independent variable (x)</th>
<th>Dune Length (Length m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dependent variable (y)</td>
<td>Dune Width (Width m)</td>
</tr>
<tr>
<td>R Square</td>
<td>54% - Relatively Weak</td>
</tr>
<tr>
<td>Significance</td>
<td>3.49E-18</td>
</tr>
</tbody>
</table>

*Figure 12: Results from the univariate regression which tested the relationship between dune length and width.*

Eccentricity is a measure of shape—rounded or elliptical. The measurement is based on an equation factoring in the semi-major and semi-minor axis of a feature – in this case half the length and half the width of the dune. The results range from 0 – 1; values closer to 0 are more round, whereas values closer to 1 are more elliptical in shape (Figure 13).
Figure 13: Example of eccentricity of dunes. The dune on the left had an eccentricity of 0.04, meaning it is nearly round. The dune on the right had an eccentricity value of 0.64, meaning it is much more elliptical in shape.

Figure 14 shows the frequencies of eccentricity for both the western and the eastern dunes. Of the entire sample, 61 dunes (61%) had an eccentricity value of less than 0.5, indicating that those dunes are more round than elliptical in shape. The eastern shoreline has a small number of dunes in the range 0.8 – 0.99, indicating that they are very close to elliptical in shape, meaning that one axis of the dunes is more elongated than the others. However, the highest frequency of dunes has an eccentricity of 0.3- 0.4, indicating a rounded form.
Figure 14: Sample eccentricity values, separated by research site.

Table 3: Descriptive statistics for the various heights of the dunes both with and without vegetation.

Dune heights, as seen in Table 3, primarily were derived using a DEM and factored in both the height of the dune itself and the height of the dune including the anchoring vegetation (Height w/ Crown). Nebkha height without the vegetation ranged from 0.58 m to 3.58 tall in the western site with an average height of 1.32 m, whereas nebkhas in the eastern site ranged from 0.59 m to 3.22 m tall, with an average height of 1.48 m. When factoring greasewood into the height of the nebkhas, the average height increased by 25.8% (west) and 19.6% (east). Eighty-four percent of nebkhas had a height with crown between 0.61 m and 2.4 m; of the remaining 16% of nebkhas, 1% had a height with crown shorter than 0.61 m, and 15% ranged from 2.4 m to
4.13 m vegetation area and crown height variables were tested with the assumption that they would express a positive correlation. The result returned a weak value of 0.16, indicating that the relationship between vegetation area and crown height was negligible. A second correlation was used to test the relationship between dune area and dune height (without the vegetation), operating under the hypothesis that as the dune area increased, so would the dune height – In other words, the dunes would grow somewhat proportionately in height and area. The correlation result returned a 0.74 – a moderately strong, positive correlation. This result was indicative that there may be an inferential relationship between the two variables and that they needed to be tested further within a univariate regression. The R-squared value for this regression was 55% (Figure 15); the residuals plot for this relationship shows that this model tended to overpredict dune height values. This regression expressed high statistical significance, based on the low P-Value of 1.42E-18 and a confidence interval of 95%.

![Image](image_url)

*Figure 15: Univariate regression testing the relationship between dune area and height without crown.*
Table 4: Results table from the GIS analysis, separated by shoreline, displaying descriptive statistics specific to the slope lengths within the path of the primary playa wind direction.

Slope characteristics (length and angle) are frequently studied in dune research as indicators of wind dynamics and stability. Windward and leeward slope lengths for each dune, based on the primary wind direction of the playa, were calculated using the Pythagorean theorem. The results in Table 4 show the basic morphometrics of the BRP nebkha slope lengths and angles, separated by research site. Dune slope lengths ranged from 0.96 m to 4.0 m long in the western site and ranged from 1.44 m to 4.65 m in the eastern site. Nebkhas are frequently described as having an extended “tail”, or leeward slope length, with steeper windward slopes and more gradual leeward slope angles (Khalaf et al., 1995; Du et al., 2010; Al-Awdhi and Al-Dousari, 2013; Li et al., 2014) (Figure 16). On average, leeward slopes were 26.18% longer than windward slope lengths, and windward slope angles were an average of 10.52% steeper than leeward slope lengths.
Figure 16: Illustration from Al-Awadhi and Al-Dousari (2013) that depicts one type of shape (tear-drop) commonly found in nebkha fields. This tear-drop shape is characterized by a longer leeward slope.

Dune slope angles, as described in Table 4, were calculated using an angular expression as a function of the dune heights and lengths. Windward slope angles varied between 9.42° and 42.25°, whereas leeward slope angles varied between 7.56° and 44.74°. The relationship between both slope angle and slope length vs vegetation area were separately tested. It was hypothesized that owing to the generally stabilizing nature of vegetation there would be a significant relationship with either the slope angle or the slope length of the dune. However, three of the four correlation results returned were very weak (<0.32), therefore inferring that the variables were not significantly related. There was a slight positive correlation relationship (0.40) identified between the windward slope length and the vegetation area, inferring that as the windward slope length increased the vegetation area increased as well.
Factors Affecting Nebkha Distribution and Stability on the BRP

Grain Size Determination

The process of determining grain size of BRP nebkhas proved challenging owing to the dominant presence of silt and clay. Despite adequate drying and mechanical and chemical (sodium hexametaphosphate) disaggregation of the sediment prior to the initial dry sieving, the sediment would consistently stick to itself and reaggregate during shaking, producing false data of sand-sized particles. No sand grains were observed during a visual inspection of sediment; upon handling, these reaggregated clumps would disaggregate again and crush into a fine powder under minimal pressure, leading to the assumption that most, if not all, of the nebkha sediment was silt or clay. Ultimately, laser particle analysis was required to verify relative percent sand, silt, and clay presence. Samples used for particle size testing were collected from (1) west shore, vegetated dune, windward slope, 0.7 m depth sediment, and (2) east shore, unvegetated dune, leeward slope, surface sediment. Results of the particle size analyses yielded a breakdown of sediment percentages based on a range of particle diameters in microns (µm) and classified into ranges that were representative of Wentworth’s aggregate classes--sand, silt, and clay (Table 5).

<table>
<thead>
<tr>
<th>Sample</th>
<th>% Sand (2,000 - 63 µm)</th>
<th>% Silt (63 - 2 µm)</th>
<th>% Clay (&lt;2 µm)</th>
<th>ΣSum</th>
<th>USDA Soil Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 West Veg WW Bottom</td>
<td>15.73</td>
<td>48.45</td>
<td>35.17</td>
<td>99.4</td>
<td>Silty Clay Loam</td>
</tr>
<tr>
<td>2 East UNV LW Top</td>
<td>45.29</td>
<td>41.76</td>
<td>12.96</td>
<td>100.0</td>
<td>Loam</td>
</tr>
</tbody>
</table>

*Table 5: Results of sediment particle size from the Laser Particle Size Analysis (Desert Research Institute, Nevada). The first sediment sample was collected at 0.7m depth on the windward slope of a vegetated dune at the western site, whereas the second sediment sample was collected from the surface (0m depth) of the leeward slope of an unvegetated dune at the eastern site.*

The results suggest that there may be significant differences in the composition of the dunes, but the sampling methodology was inadequate for any firm conclusions to be drawn. The
sample from the western shoreline at 0.7 m depth was composed primarily of silt and clay (84%), with only a small portion (16%) of sand present. The dunes on the eastern shoreline (surface sample) had a high proportion of sand (45%) and silt (42%) and a small percentage of clay (13%). The results, as well as field observations, suggest that the nebkhas are silt-clay dunes (as opposed to sand dunes). It is possible that the high percentages of fines at depth represents the long-term infiltration of silt and clay into the interstices of the sand under conditions of dune stability. However, significantly more sampling would be necessary to understand the sedimentology and sediment history of the dunes.

Assessment of Vegetation and Groundwater

Vegetation on the BRP is typically characterized by populations of native grasses and salt tolerant shrubs. Within the Black Rock Basin, greasewood (*Sarcobatus vermiculatus*) (Figure 17), four-wing saltbush (*Atriplex confertifolia*), seepweed (*Suaeda nigra*), and inland salt grass (*Distichlis spicata*) are widespread. Other species seen within the piedmont adjacent to the dune field include spiny horsebrush (*Tetradymia spinosa*), bottlebrush squirreltail (*Elymus elymoides*), budsage (*Artemisia spinescens*), Great Basin wild rye (*Leymus cinereus*), snakeweed (*Gutierrezia sarothrae*), and cheat grass (*Bromus tectorum*). All species listed are native to the North American west with exception of cheat grass, which is invasive and is listed as a noxious weed within the Western Intermountain Region. The vegetation of the BPR is especially well-suited for the arid nature of the region with each species having a high tolerance for alkaline soils and drought conditions. Vegetation along the playa periphery tends to be halophilic, exhibiting a high tolerance to saline substrates. Several of the species above, including greasewood,
seepweed, four-wing saltbush and spiny horsebrush, are known to thrive in fine and/or loamy soils.

![Greasewood](image)

**Figure 17**: Greasewood (*Sarcobatus vermiculatus*) – the vegetation that dominates and anchors the BRP dune field. The left image shows needles approximately <2.5 cm in length, the right image is greasewood on a dune (width of greasewood bush is approximately 1m). (Photo by author)

The dunes of the BRP were almost entirely populated by greasewood, a species of semi-arid regions adapted to a seasonally high groundwater table and alkaline flats. The roots of the greasewood plant grow to depths of 1.5 m to 6.1 m and extend laterally from 0.9 m to 3.7 m. Greasewood exhibits a low water requirement and generally grows rapidly to a height of approximately 1.0 – 1.5 m. GIS analysis to determine vegetation area (coverage) and descriptive statistics showing average crown height, coverage, and percent vegetation cover are presented in Table 6.
Table 6: Results table from the GIS analysis, separated by shoreline, displaying descriptive statistics specific to the vegetation anchoring the dune. The Vegetation Area (m²) field denotes the total area of all the vegetation anchoring the dune. Percent Vegetation Cover denotes the vegetation area as a percentage of the total area of the dune.

<table>
<thead>
<tr>
<th></th>
<th>Average Crown Height (cm)</th>
<th>Vegetation Area (sq m)</th>
<th>Percent Vegetation Cover</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>west site</td>
<td>east site</td>
<td>west site</td>
</tr>
<tr>
<td>Minimum</td>
<td>5.54</td>
<td>5.58</td>
<td>2.53</td>
</tr>
<tr>
<td>Maximum</td>
<td>45.38</td>
<td>134.63</td>
<td>45.64</td>
</tr>
<tr>
<td>Average</td>
<td>17.84</td>
<td>54.85</td>
<td>15.45</td>
</tr>
</tbody>
</table>

It was assumed that as dune area increased, so would vegetation area—there would be a positive relationship between the two variables. When tested for correlation a value of 0.58 was returned, signifying a moderately strong positive relationship between dune area and vegetation area. This confirmed that generally as dune area increases, vegetation area increases as well or vice versa. This was further tested using regression analysis. The regression returned an $R^2 = 33\%$, indicating overall this was a weak model (Figure 18). This was reinforced by the residuals plot, depicting that most data values were over or under predicted. The P-Value for this regression was $3.93E-10$; based on a confidence interval of 95%, the P-Value shows that the 33% R Squared value was statistically significant, overall indicating that there are additional factors which may influence the positive correlation between dune area and dune vegetation.

Figure 18: Results from the univariate regression that tested the relationship between dune area and vegetation area.
The role of vegetation in the morphometry and stabilization of the dunes is significant. The western dunes had significantly more vegetation - of the 100 sample dunes, 35% of dunes on the eastern shoreline (14 dunes) had no vegetation, whereas only 8% of dunes on the western shoreline (5 dunes) had no vegetation. Overall, the average vegetation area of the western nebkhas was 12% higher than the average vegetation average of the eastern nebkhas. Figure 19 shows the distributions of average crown height separated by research site. The majority of western nebkha crown heights (78%) were smaller than 30 cm; the remaining 22% of western nebkhas had a crown height between 30 and 60 cm. The crown heights of the eastern nebkhas were much more distributed in size; 58% had a crown height between 5.58 cm and 90 cm. The tallest crown height observed was 135 cm on the eastern dune field; 8% of eastern nebkhas were taller than 90 cm. These results characterized the crown of the vegetation, however the interrelationships between vegetation and subsurface water is of equal importance.

The depth to the water table plays a major role in nebkha stability, in so far as groundwater provides the most important source of water for anchoring greasewood plants.
Published reports suggest shallow depths to the groundwater table near the playa (<25 m). Sinclair (1963, pg. 15) observed “In August 1962 the depth to water beneath the playa was nowhere greater than 10 feet…The area of the floor of the Black Rock Desert beneath which water levels are less than 5 feet may be as much as 200,000 acres.” Owing to the scarcity of groundwater data for this region, the 2006 USGS report relied heavily upon greasewood as an indicator of shallow groundwater levels when field measurements were not available. The USGS 2006 report estimated that “81% of areas in Nevada with greasewood is where depth to water is less than 50 ft, 10% (dictum ‘of areas’) is where depth to water is 50 to 100 ft, and 9% (dictum ‘of areas’) is where depth to water is greater than 100 ft” (USGS, 2006, pg. 13). Unfortunately, no details within the report were given to further specify the location of sample areas used to approximate groundwater levels.

Owing to the absence of recent well measurements for groundwater depth at the playa, four wells proximal to the playa (<40 km) were used to estimate general groundwater trends for the region (Figure 20). Both Rabbithole Well and Maudes Well showed an overall positive trend during the period (1963 - 2019), implying that the groundwater table had risen closer to the surface. The earliest observation for Maudes Well within the dataset was 6.36 m below the surface in 1963, whereas the most recent record was a depth of 5.92 m in 2019 – a decrease in depth to water below surface of 0.44 m. Rabbithole Well in 1989 had an observed depth of 52.97 m below the playa surface, decreasing 0.14 m to its most recent reading of 52.83 m in 2019. Rabbithole Mine appeared to have relatively consistent increases and decreases throughout the recorded time period, with a starting depth of 11.46 m in 2011 and 11.50 m in 2019. This resulted in a negligible .04 m increase in depth to water and an overall invariable trendline. The biggest difference in groundwater trends was observed at the N35 E24 32DDCC2 site, just west
of the playa at Fly Ranch. Depth to water levels in 1973 were 1.54 m, whereas depths in 2019 were 5.44 m, showing that the groundwater table surface had decreased 3.9 m in 46 years.
Figure 20: Graphs depicting the trendlines for various groundwater field measurement sites near the BRP. (Compiled from USGS 2019)

Historical Imagery and Delineation of Past Dune Field Extents

Aerial infrared imagery of the BRP captured in 1982 provided a means for a historical imagery comparison. The historical aerial imagery consisted of a total of 11 flight paths, with each path containing 6 – 16 images, for a total of 118 images, although the imagery set did have some missing prints. Owing to the number of images missing within the various flight paths, the resulting orthoimage had some holes. Missing data (holes in the imagery) were primarily located in the center of the playa; this is a typical result within orthomosaic construction when working with surfaces having very similar characteristics from one image to another - in this case, a consistently flat, textureless playa surface. Data were successfully replaced using a function within ArcMap in which pieces of the original images were inserted into the incomplete orthomosaic using georeferencing, thus resolving any missing data issues.
The orthoimage of the 1982 imagery (Figure 21) was placed into ArcMap for photogrammetric measurements. Google Earth imagery from 2019 and various previous years were compared with the 1982 measurements to identify areas of change in the <37-year period. To ensure accuracy of comparisons, the orthoimage was projected to the same projection as Google Earth (WGS 1984 Web Mercator Auxiliary Sphere). Using prominent and static physical features along the shoreline interior, and texture and color cues to mark the edge of the dune field, 18 reference points were overlaid on the orthoimage (Figure 22, below). Reference points were placed in sets of two so that the distance from the shoreline interior to the dune field extent could be approximated, and later compared with Google Earth measurements to detect movement or changes of the dune field. Reference points were transferred into Google Earth
using XY coordinates derived from ArcMap. Using a ruler tool within each software, the distance between reference points was recorded (in meters) and compared.

Reference points 1 through 10 and 15 thru 18 were located on the western shoreline, proximal to the western sample area. Reference point set 11 – 12 was located on the western shoreline, far north of the western sample area near the northern portion of the playa (north of the Burning Man site). Reference points 13 – 14 were located on the eastern shoreline, close to the eastern sample area, just west of Trego Hot Springs. Based on the measurements made between the two pieces of software and sets of imagery, shrinkage or growth of the dune field was limited to less than 4 meters (Table 7). The set of reference points with the largest discrepancy in measurements was points 11 – 12, whereas the smallest difference observed was between points 3 – 4.

Figure 22: Sample image showing locations of 14 of the 18 reference points used to approximate dune field extents from imagery of various years.
Table 7: Results from measuring the distance between reference points to determine dune field extents from 1982 IR and 2017 Google Earth imagery.

<table>
<thead>
<tr>
<th>Reference Point</th>
<th>ArcMap: 1982 Distance (m)</th>
<th>Google Earth: 2017 Distance (m)</th>
<th>Difference (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 2</td>
<td>222.9</td>
<td>222.6</td>
<td>-0.3</td>
</tr>
<tr>
<td>3 - 4</td>
<td>261.6</td>
<td>261.7</td>
<td>0.1</td>
</tr>
<tr>
<td>5 - 6</td>
<td>273.4</td>
<td>274.1</td>
<td>0.7</td>
</tr>
<tr>
<td>7 - 8</td>
<td>304</td>
<td>305.8</td>
<td>1.8</td>
</tr>
<tr>
<td>9 - 10</td>
<td>94.8</td>
<td>96.8</td>
<td>2.0</td>
</tr>
<tr>
<td>11 - 12</td>
<td>3288.7</td>
<td>3292.7</td>
<td>4.0</td>
</tr>
<tr>
<td>13 - 14</td>
<td>381.9</td>
<td>380.4</td>
<td>-1.6</td>
</tr>
<tr>
<td>15 - 16</td>
<td>95.4</td>
<td>97.5</td>
<td>2.1</td>
</tr>
<tr>
<td>17 - 18</td>
<td>104.8</td>
<td>106.4</td>
<td>1.6</td>
</tr>
</tbody>
</table>

In addition to the use and comparison of reference points between 1982 and 2016-2019 imagery, four polygons encompassing Areas of Interest (AOIs) were established within ArcMap and Google Earth (Figure 23). This method provided visual comparison of shoreline changes, such as increases or decreases in dune field or vegetation growth when photogrammetric measurements were not feasible.
Figure 23: Areas of Interest (AOIs) Index Map (top) with comparison of AOIs 1 (bottom left) and 2 (bottom right) within the western sample depicting change from 1982-2017. (North is at top of images; width of AOI 1 is ~ 547m, width of AOI 2 is ~ 424m).
Figure 23 illustrates the temporal changes of the first (left) and second (right) AOIs, located on the western shoreline within the western sample area. Using visual cues such as color, texture, and shape, the time series above indicates that the dune field maintained its position and extent within the 35-year period. In each of the images, from 1982 to 2003 to 2017, the general shape of the outer extent of the dune field is mostly consistent, with changes primarily being in color, which in this case is interpreted to be from lighting and playa moisture variability.

![Figure 23: Comparison of Areas of Interest (AOIs) 3 (left) and 4 (right) near the western shoreline depicting change from 1982 – 2017.](image)

Figure 24: Comparison of Areas of Interest (AOIs) 3 (left) and 4 (right) near the eastern shoreline depicting change from 1982 – 2017. The linear feature running southwest to northeast is the Western Pacific railroad. (North is at the top of each image; width of AOI 3 is ~2,210m; width of AOI 4 is ~1,610m).

The second time series is of AOIs 3 (left) and 4 (right), located on the eastern shore of the playa proximal to Trego Hot Springs (Figure 24). AOI 3 is located within the eastern sample

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area, whereas AOI 4 is located slightly northeast. The time series of AOI 4 is mostly unchanged – playa color, texture, and extent appeared to have remained relatively stable. The most prominent change from all four AOIs was observed in AOI 3 where it was clearly shown that vegetation growth expanded within the 35-year period. Most growth was to the southeast towards the railroad tracks, with some growth observed eastward.
Chapter 4: Discussion of Analyses
Morphometrics of BRP Nebkhas

The nebkhas along the edge of the Black Rock Playa represent a dune field that has not been studied previously, thus eliciting the need for a thorough analysis of the physical characteristics of these features. Many researchers tend to understand nebkhas through classification, basing categories on elements such as dune form (McKee, 1979; Cooke et al., 1993), field patterns (Laity, 2008) and migration (Pye and Tsoar, 1990; Tsoar, 2001). McKee (1979) originally classified nebkhas based on their forms, stating that they can be simple, compound or complex: simple dunes are individual and spatially independent of other dunes, compound dunes are two or more of the same dune type that have coalesced or superimposed one another, and complex dunes are coalesced or superimposed dunes or two or more dune types. The nebkhas on the Black Rock Playa can be classified as a mixture of simple and compound (Figure 25). Nebkhas that initially were thought to be compound were likely simple (spatially independent) dunes at one time that eventually grew into one another owing to proximity. McKee (1979) also asserted that simple dunes are typically ‘small’ with spacing between one crest to another being between 10 m and 500 m. The wavelength distance between nebkhas in the BRP was well within McKee’s 10 – 500 m definition of simple dunes.
Figure 25: Samples of simple and compound nebkha dunes from the western site.

Dune field patterns are similarly classified (Laity, 2008) as simple or complex; a simple pattern is characterized by dunes of similar shape, size, orientation, with dune type primarily reflective of local winds, whereas a complex dune field pattern is numerous patterns observed and superimposed within a single field. The BRP dune fields are representative of a simple dune field pattern, in which most nebkhas are hemispherical in shape, similar in size, and a product of the local aeolian environment. Tsoar (2001) notes a classification schema (Figure 26) in which dunes are generally classified by accumulation and then by movement. The classifications for
accumulation are: (1) owing to topography (excluding vegetation), (2) in open terrain primarily by bed roughness, and (3) owing to vegetation. Obviously, the nebkhas on the Black Rock Playa are inherently in the third category (accumulation owing to vegetation). Tsoar further classifies these dunes based on activity and movement, stating that there are three types based on wind variability: (1) migrating (2) elongating and (3) accumulating. The BRP nebkhas best fit the accumulating classification, by definition of having “little to no net advancement or elongation” (Tsoar 2001 p. 407).

*Figure 26: Classification schema of dune types based on dune genesis, adapted from Tsoar 2001.*
Table 8: Global comparison of nebkha fields, compiled in part by Du et al. (2010) and Lang et al. (2013).

Global studies of nebkha fields have enhanced our understanding of their morphometries and factors controlling dune formation and stability (Table 8). This thesis is the first evaluation of nebkhas on the Black Rock Playa in Nevada. Out of the 21 nebkha fields compared (Table 8), the BRP nebkhas are the only ones to be anchored by greasewood (Sarcobatus vermiculatus); In
the other dune studies, 10% of nebkhas were anchored by *Prosopis glandulosa*, 24% were anchored by various *Nitraria* species, 29% were anchored by various *Tamarix* species, while the remaining 33% were anchored by other species.

The tallest nebkhas (>8 m) studied to date are found in China (Tengger Desert). Those of the BRP are relatively low in height (0.5 – 4.13 m) - resembled heights also observed in New Mexico (0.2 – 4.3 m), Iceland (<5 m), and the Tengger Desert nebkhas (0.1 – 3.6 m). The morphometric dimensions (lengths and widths) of the BRP nebkhas were similar to those measured in Iceland, Kuwait, and of the finer sediment nebkhas of the Ala Shan Plateau in China. The sediment constituting the BRP nebkhas (silty clay loam) most closely resembled the sediment classification of nebkhas found in eastern Washington, USA, (silt loam) and Mali, Africa (silty-clay loam). Differences in climates across all regions studied were primarily regarding annual rainfall; 57% of the areas with data available had less rainfall than that measured at the BRP.

Overall, the global comparison of nebkhaha morphology proved difficult. This in part was due to differences in the variables assessed and their classifications within each study area and that the various nebkhaha populations shared multiple, overlapping similarities or differences. It is clear from this comparison is that nebkhaha morphometrics, anchoring vegetation, soil substrates and other natural factors widely vary globally. However, this in of itself presented an important consideration that although the above authors studied the same geomorphic feature, the nebkhahas were each differently influenced by the natural properties unique to the area being studied. For example, comparisons between precipitation levels and grain size can offer insights to sediment transport and availability. In areas with relatively high precipitation (>150 mm), grain sizes are typically larger (fine – coarse sand) (ex. Iceland; Molopo Basin, Africa; Huade County, China).
However, there are areas with relatively lower precipitation that also had larger grain sizes (Tengger Desert, China), thus indicating the variability in global sediment availability. While nebkhas are typically a product of arid / semi-arid environments (76% of the above studied), it is recognized that nebkhas also form in areas with high precipitation owing to marine climate or latitude (Iceland; Kuwait).

**Factors Affecting Nebkha Distribution and Stability on the BRP**

This study offered insights regarding the distribution and morphological characteristics of the nebkhas on the BRP. Dunes are a depositional feature largely formed and controlled by aeolian processes; nebkhas are strongly influenced by local vegetation, sediment availability and type, and wind regime. The particle size analysis suggests that the dunes of the BRP are composed primarily of silt, with substantial quantities of sand and clay present. Fine particles likely are derived from the playa, deposited as dust on the nebkha surface, particularly during the summer months when there are high levels of recreation (including Burning Man) on the desiccated surface. Annual flooding of the Quinn River and the subsequent formation of an ephemeral lake on the interior of the playa probably contributes both sand and finer sediments, potentially allowing growth of the dune field over time. However, the results from the historical imagery analysis comparing dune field positions over an approximate 35-year period indicated negligible changes to the dune field, at least for the scale that could be observed using such images. The 2018 NASA DEVELOP white paper also concluded that the dune field extent from 2006 to 2017 remained relatively static. An analysis of nebkha accumulation on a very fine scale (mm level) was not within the scope of this thesis.
There are several elements within the playa system thought to contribute to the [static] distribution of the dune field. The material of the dunes was found to be composed, in part, of clay. When clay is exposed to moisture and then dried, it undergoes cementation in which desiccation cracks and a hard surface is produced (often termed desert concrete). The desiccation cracks and precipitated salt found on the BRP nebkhas and interdune areas are evidence of capillary rise, which is promoted by fine-grained sediments (as opposed to sand). *In situ* field observations confirmed that the surface of the dunes fluctuated between a dry, concreted crust, to a softer, malleable mud in areas where more moisture was present. In either instance, the fine particles constituting the dune become more difficult to transport, thus supporting the assertion that the dunes on the BRP are relatively stable in nature. Dune instability begets dune field growth or migration, neither of which was observed within this study.

Vegetation was hypothesized to be a significant controlling factor while investigating the BRP dune distribution and morphological behavior. Several observations within the data were made relating to vegetation in an attempt to constrain the mechanisms underpinning the BRP dune field distribution. One primary observation from the data was the piedmont slopes that transition to playa had varying vegetation species and densities compared to those within the playa periphery or interior. The piedmont slopes east and south of the main highway had several species present: bottlebrush squirreltail, Great Basin wild rye, seepweed and fourwing saltbush, among others. As the topography transitioned into playa, greasewood quickly became the dominant species, in most instances being the only vegetation species present with the exception of a few patches of inland salt grass (Figure 27).
Figure 27: Image showing the transition from the densely and variably populated piedmont slopes to the dune field, dominated solely by greasewood, to the playa, entirely devoid of vegetation (North is at the top of the image; width of delineated area is ~ 620m). (Image from Google Earth)

The dune fields along the playa edge marked a transition zone of vegetation in which population density and species variability decreased with proximity to the playa surface. Greasewood was the only species observed to anchor the dunes. As a phreatophyte, it was assumed that groundwater would be the primary control on the location of greasewood, and thereby dunes. While the results of the groundwater analysis did not provide actual, current values of levels beneath the playa, it was useful in constructing regional trends and estimating changes in levels at the playa. Groundwater levels at the site N35 E24 32DDCC2 decreased by 3.9 m in 46 years, which was the most drastic change observed within the groundwater data. This drop of groundwater table levels is suspected to be due to pumping for Burning Man Operations – Site N35 E24 32DDCC2 is located near Fly Ranch, a property owned by Burning Man Project. In aerial imagery lush green agricultural fields can be seen within Fly Ranch, and BLM Land
Manager Mark Hall has noted that Burning Man often pumps from within the property to provide water for Burning Man participants, thus explaining the isolated instance of dramatic groundwater level changes. Aside from N35 E24 32DDCC1 site, all other sites measured within this study had negligible variations in groundwater levels. Sinclair (1963) reported that groundwater was less than 3 m below the playa surface. While measurements in the three other groundwater sites were lower than 3 m below the surface (Rabbithole Mine = 11.5m; Rabbithole Well = 52.83m; Maudes Well = 5.92m), the general trends show that the sites generally remained at the same levels, if not increasing slightly. Thus, it was estimated that groundwater levels below the playa remained relatively consistent within the 35-year time period and that the local greasewood had sufficient access to a water source. This estimate was supplemented by field observations in which seemingly healthy greasewood anchored the dune fields. It would be valuable future research to understand better the nature of groundwater levels and greasewood distribution in the playa region.

Langford (2000) notes that nebkhas are generally convex in shape with steep slopes that engulf and surround vegetation for stabilization. A 1995 study by Wiggs et al. (1995) observed that vegetation cover threshold of 14% was necessary for coppice dune development. Of the 100 sampled dunes, the GIS identified that approximately 80% of dunes had a vegetation cover of 14% or greater. Of the remaining twenty percent, in situ field investigations confirmed several instances in which dunes remained anchored by dead vegetation and the remaining root system. The field observations of dead vegetation implied that there was vegetation present for the formation of the dunes, but for various reasons (likely climatic or anthropogenic) the vegetation did not survive. One recurring observation within this study via aerial imagery and in situ field observations was that vegetation appeared to be concentrated on the windward (western) slopes.
of the dunes (Figure 28). Of all the dunes with vegetation, almost 89% had more vegetation on
the windward slope than on the leeward slope.

![Image](image.jpg)

*Figure 28: UAV image showing several examples within the western research site in which vegetation was observed to be primarily on the windward slope of the dunes. The dominant southwest wind direction for the playa is depicted by the grey arrow (North is at the top of the image; width of image is ~ 99m) (Image by author).*

Referring back to the foundational concept that dunes are a depositional product of aeolian processes, this pattern appeared to make morphological sense. As the dominant southwest winds transport the fine-grained sediment, it is trapped on the greasewood within the dune fields. This produces a positive feedback in which the dune begins to grow and continues growing as more aeolian-driven deposition occurs. Field observations of the dune field witnessed what appeared to be erosional degradation on the leeward slopes of the dunes. The leeward slopes often showed signs of dead vegetation through exposed root systems. Several sets of rills also were witnessed consistently on the leeward slopes of the dunes, indicating that the leeward slopes were subject to fluvial erosion. With healthy vegetation present on windward slopes but
not often present on leeward slopes, and the presence of rills, it was clear that the leeward slopes are subject to higher frequencies of erosion, although the exact mechanics of the erosion were not confirmed in the field. However, the presence of the rills suggests stability induced by fine particles coupled with surface salts resulting from capillary rise in moisture from the subsurface. These features normally are not present in dunes dominated by sand-sized particles.

The vegetation differences between the windward and leeward slopes leads to a discussion regarding the stability and nature of the dune slopes. Of the total sample population, 73% of dunes demonstrated a steeper slope angle on the windward slopes of the dunes, and 72% of slopes demonstrated a longer slope length for the leeward slopes. This slope morphology is consistent with Lang’s 2013 diagram of coppice dune characteristics of steeper, shorter windward slopes paired with lower, longer leeward slopes. However, it should be noted that the length of leeward slopes is influenced by sediment size. Nebkhas formed of silt or clay will be less likely to develop longer leeward slopes whereas nebkhas of sand will form and behave more like dunes composed primarily of sand, which typically have an elongated leeward slope. The angle of repose for loamy soils, or silt/clay soils (when moist) is 40°-50°. Of the total sample, only one dune had a slope greater than the angle of repose, overall signifying that the slopes generally are stabilized. This is consistent with the fact that vegetation present on slopes tends to stabilize a slope rather than contribute to the erosion of it. The elongated slopes observed in the 72% of dunes are assumed to be a product of aeolian erosion.

The regressions performed with GIS sought to predict how various dependent variables would increase or decrease based on a change contributed by an independent variable. The relationship between dune area and vegetation area was found to have a positive correlation, which meant that as one area increased, so did the other. Thus, this relationship was tested within
a univariate regression in an attempt to discover if a growth in vegetation area would result in a growth of dune area. The model returned an overall weak result (33%), indicating that while the two areas are positively related, factors other than vegetation influenced the growth of the dune. The results from the regression between dune area and dune height (Figure 15) were relatively weak (55%) but indicated that dune growth in height and area are significantly related. The last relationship tested was of dune length and width, which was testing the assumption that the dunes would grow rather symmetrically. The relationship was positive, showing that as the dune length increased, so did the dune width. When tested in a regression analysis, the relationship between the dune length and dune width produced an R value of 0.54 (54%) (Figure 12), however the significant, positive relationship was reinforced within another analysis. The eccentricity calculations performed on the dune length and width (Figure 14) measured how round or elliptical the dune was: values closer to 0 were rounder in shape whereas values closer to 1 were deemed more elliptical in shape. The results of the eccentricity calculations showed that 77% of dunes were rounder in shape than elliptical, overall reinforcing the similarity in values of dune lengths and dune widths.

Many of the metrics detailed within this discussion focused on individual features of the dunes. Taking a broader focus, there were several observed differences between western dunes and eastern dunes (Figure 29).
On average, the dunes in the western dune field had over twice the vegetation coverage of those in the eastern dune field (w = 26%; e = 11%). Additionally, of the 60 dunes measured in the western field, 91% had vegetation, whereas only 65% of the dunes had vegetation on the eastern dunes. Dunes in the eastern field had more dead roots exposed, suggesting that at one time the eastern dunes had more vegetation (Figure 30A). They were also generally softer with a crust that deflated easily under minimal pressure, whereas dunes in the western field had a dry, hard, unyielding crust. The softer sediment experienced in the eastern field was determined to be due to increased moisture on the eastern playa margin in the forms of higher groundwater and increased surface run off. The eastern dune field is nearby Trego Hot Springs, a popular
geothermal site for recreationists. Additionally, within the historical imagery analysis AOI 3 (within the eastern sample area Figure 24) experienced the most change from 1982 to 2019 in the form of increased vegetation growth. No other AOI experienced this increase in vegetation growth; the growth experienced at AOI 3 again is suspected to be due to the increased water supply, however, it was unverified with this dataset. This theory is supported by the prominence of established surface channels formed within the eastern dune field (Figure 30B). Field observations placed the channels at approximately 1.0-1.5m (3.0-4.9 ft) deep, with several distributaries noted. These channels also are speculated (though not confirmed) to contribute to the larger sand particles present in the eastern field. The eastern dunes had higher quantities of large particles (>silt). The surface channels present within the eastern dune field were suspected to be the source of this larger sediment by carrying sand and larger particles from nearby exposed bedrock and deposited them in the eastern dune field where the channel flow dissipates.

One last observational difference between eastern and western research sites was that dunes at the eastern site experienced more anthropogenic erosion and degradation than dunes at the western site. Several sets of vehicle tire tracks and abandoned vehicle equipment were observed within the eastern dune area during field work (Figure 30C), whereas the western dune field and interdune area was observed to be relatively undisturbed. Therefore, it is assumed that differences in dune morphology seen at the eastern site versus the western site primarily are due to differences in water supply and exposure to anthropogenic activity.
Figure 30: Images illustrating significant characteristics that differentiate the east dune field: (A) dead root systems, (B) prominent surface channels, and (C) tire tracks indicative of anthropogenically driven erosion (Width of image A is ~ 4m; width of image B is ~ 11.5m; length of tire tracks in image C ~2m). (Image by author).
Chapter 5: Conclusions

The Black Rock Playa in Nevada is home to an extensive nebkha dune field, heavily populated and anchored by greasewood, which heretofore has not been studied. This research, through field observations, Unmanned Aerial Vehicle (UAV) imagery, GIS-based digital measurements, statistics, lab analysis, and secondary source evaluation, established a baseline dataset of nebkha geometries and morphologies for this remote area while addressing two key research questions. The first question sought to morphometrically characterize the BRP nebkhas and compare them to global populations, while the second question aimed to explore the distribution and morphological behavior of the nebkha fields. Several objectives were established to address the research question, including delineation of nebkha dimensions, determining sediment size, analyzing vegetation and groundwater relationships, and exploring the role of local climate in nebkha morphology.

To answer the first research question and to describe the morphometric characteristics of the nebkhas, an innovative technical approach was used. UAV imagery was captured and input into a GIS to delimit and quantify dune characteristics, including shape, height, slope length, slope angle, and vegetation measurements. The BRP nebkhas ranged in size from 8.83 m$^2$ to 197.80 m$^2$, with an average area of 60.23 m$^2$. Most nebkha lengths and widths (west field 67% and east field 78%) are between 4 m and 12 m. The nebkhas are primarily round in shape – of the entire sample 61% of the dunes had an eccentricity value of less than 0.5, indicating that they were more round than elliptical in shape. Nebkha height was measured both to the top of the dune surface and to the top of the anchoring vegetation (height w/ crown). Heights varied between 0.60 m and 4.13 m; when including vegetation into the height measurement the average heights increased by 26% (western field) and 20% (eastern field). On average the leeward slope
lengths of the nebkhas were 26% longer than the windward slope lengths, whereas windward
slope angles were an average of 11% steeper than the leeward slope angles. Overall the BRP
nebkhas were identified as repositories for sediment (Tsoar, 2001), simple and compound in
form (McKee, 1979), and within a simple dune field (Laity, 2008). When compared to other
studied dune populations worldwide, the BRP nebkhas were the only dune field to be anchored
by greasewood.

The second research question was much more complex in nature and sought to gain a
basic understanding of the BRP dune distribution and behavior. This question was paired with a
single hypothesis, that the dune field distribution and morphology would be influenced largely
by vegetation (and groundwater). Methods used to answer this question included data derived
from the GIS analysis and particle size analysis, paired with a vegetation indexing, groundwater
and climate review based on secondary sources, and a historical imagery analysis. A paired
vegetation and groundwater assessment was performed, owing to the reliance of desert
vegetation on subsurface water. The dune field appears to be constrained in extent to locations
where greasewood prospers. While groundwater levels seem to support a larger range for
greasewood populations, the plants are constrained to the playa margins. This implies that there
are factors other than groundwater that control the general distribution of the dune field. The
sediment constituting the nebkhas was analyzed based on size. It was concluded that the BRP
nebkhas were largely a product of aeolian erosion and deposition, owing to the small particle size
and high wind speeds, however it was speculated that dunes in the eastern dune field also were
subject to periods of fluvial and anthropogenic erosion as well. The historical imagery analysis
provided evidence that the dune field largely maintained its position and extent over the 35-year
historical study period, implying that this is a relatively stable dune field. It also confirmed that
the dunes are at least 35 years old, as they were present in imagery from 1982. Lastly, comparisons between the western and eastern field sites showed that the eastern dune fields were subject to more moisture, although the effects of this were not fully investigated within this study. Additionally, the eastern study site experiences more impact from anthropogenic recreation, which contributes to the degradation of the dune field.

This thesis established a preliminary dataset for two selected areas of dunes at Black Rock Playa, examining differences in vegetation, sediment size, and water availability. It provides data that can be used to continue research on the BRP in efforts to preserve the natural environment of the Black Rock Desert. While this thesis provided insight into the morphology of the BRP nebkhas, it was preliminary in nature. More research is needed on sediment supply and availability, nebkha age, the role of playa deflation, and the role of local wind dynamics.
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