Impacts of Off-Highway Vehicle Activity on Land Cover Change and Dune Dynamics:

Algodones Dunes, California

by

Suet Yi Cheung

A Thesis Presented in Partial Fulfillment

of the Requirements for the Degree

Master of Arts

Approved November 2018 by the
Graduate Supervisory Committee:

Ian J. Walker, Chair
Ronald I. Dorn
Soe W. Myint

ARIZONA STATE UNIVERSITY

December 2018

ABSTRACT

Use of off-highway vehicles (OHV) in natural landscapes is a popular outdoor activity around the world. Rapid-growing OHV activity causes impacts on vegetation and land cover within these landscapes and can be an important factor in land degradation and ecosystem change. The Algodones Dunes in southeastern California is one of the largest inland sand dune complexes in the United States and hosts many endangered species. This study examines changes in land cover and OHV activity within two OHV active sites in comparison to an adjoined protected area. The study also investigates potential associations between land cover changes, climate trends, and OHV activity over recent decades. Time-series analysis was used to investigate the spatial-temporal changes and trends in the land cover in the Algodones Dunes from 2001 to 2016. In addition, high-resolution aerial photographs were analyzed to determine spatial patterns of OHV usage in comparison to visitor estimation collected by the Bureau of Land Management and observed changes in land cover composition between the control site and OHVs areas.

A decreasing trend in Normalized Difference Vegetation Index over time indicates a decline in the amount of vegetation cover, which corresponds with an increasing trend in albedo and land surface temperature. Results also show a substantial difference in land cover between the control site and OHVs areas, which typically have a lower amount of vegetation cover, higher exposed sand surface, and increased anthropogenic features. Both climatic variations and OHV activity are statistically associated with land cover change in the dune field, although distinct causal mechanisms for the observed declines in vegetation cover could not be separated. The persistence of drought could inhibit vegetation growth and germination that, in turn, would hinder vegetation recovery in OHV areas. Meanwhile, repeated OHV driving has direct physical impacts on vegetation and landscape morphology, such as canopy destruction, root exposure, and increased aeolian sand transport. Active ecosystem protection and restoration is recommended to mitigate the response of declining vegetation cover and habitat loss to the impacts of OHV activity and climatic variability and allow natural recovery of re-establishement of nebkha dune ecosystems in the Algodones Dunes.

ACKNOWLEDGEMENT

First, I would like to express my gratitude to all committee members, Professor Ian J. Walker, Professor Ronald I. Dorn and Professor Soe W. Myint for the continuous support and encouragement of my master study and their insightful comments and suggestions on my thesis. I am also grateful to wildlife biologist, Mr. Camden Bruner, of the Bureau of Land Management for providing the GIS data and visitation data for the Algodones Dunes, and also for providing an interesting tour of the dune field.

I would like to acknowledge Dr. Robert Balling, a professor of School of Geographical Sciences and Urban Planning at Arizona State University, who provide useful advices on statistical and spatial analysis. I would like to thank Dr. Richard Inman, a research associate in conservation biogeography at Arizona State University, who provided useful literature on vegetation and ecosystems within the dunes for my research. I would also like to acknowledge Mr. Colin Marvin for assisting in digitizing the vehicle tracks during his spare time, even when he was sick.

I am also grateful to my friend, Miss Lu Zhao, who has supported me along the way, especially when I got some health issues during the last year of my master study. She always shows her supportive and happiness to me when I was in the hospital or clinic. She applied her knowledge on health and wellness to improve my health so that I can able to complete my master's degree. Lastly, I must express my profound gratitude to my parents for providing financial support and emotional encouragement throughout my master study and the process of researching.

TABLE OF CONTENTS

CHAPTER Page

List of Tables

List of Figures

Figure Page

Figure Page

Figure Page

CHAPTER

1 INTRODUCTION

1.1 Research Context

The use of off-highway vehicles (OHVs) in natural landscapes is one of the fastest growing recreational activities on public lands in the United States. OHVs include a variety of three or four-wheeled vehicles and motorcycles that are capable of traveling off-road over land, sand, ice, snow, desert surfaces, rangeland, or other natural landscapes (Davenport and Switalski, 2006). The vehicles were originally designed for military and commercial purposes; however, OHVs have since become popular for recreational purposes as they allow people to travel into more remote areas. Since the 1970s, OHVs have become increasingly popular for leisure and recreational activity. Between 1982 and 2003, the registration of OHVs increased rapidly in the United States from 3 million to 51 million (Adam et al., 1982; Groom et al., 2007; Cordell et al., 2008). In California, over roughly the same time interval, there has been a reported 90% increase in OHV registration between 1983 and 2000 (California State Department of Parks and Recreation, 2002; Van Dam and Van Dam, 2008). In 2016, 78% of total visitation on BLM public lands in California was OHV-related, which translates to 5.6 million visitors (California State Department of Parks and Recreation, 2017). Concerns with the growth of OHV activity include substantial ecological impacts on a wide range of ecosystems, including the removal of vegetation cover, increased root exposure, enhanced soil erosion, and reduction of native and/or endangered species (Groom et al., 2007; Al-Hurban, 2014).

Land degradation is a phenomenon described as the reduction of primary productivity of the land by accelerating ecological processes, such as soil erosion and leaching, with or without human disturbances (Blaikie and Brookfie, 2015). It consists of many components, such as the deterioration of soil quality and its nutrients, reduction of the vegetation cover and biological diversity, and the decline in available water (Stocking and Murnaghan, 2013). Climatic change and human population growth and activity pressures are two of the main causes of land degradation in a variety of different landscapes. Frequent and prolonged climatic events, such as El Niño or La Niña and associated droughts, affect vegetation growth and seed germination by reducing soil moisture and increase soil surface temperature (Nield and Baas, 2008; Thomas and Wiggs, 2008; McAuliffe and Hamerlynck, 2010; Ravi et al., 2010; Tsoar, 2013). Eventually, the impacts of such events can reduce primary productivity of the ecosystem, and causes declines in vegetation and biodiversity, resulting in land degradation and possible desertification.

Anthropogenic activities, such as farming, mining, and recreational activities, also lead to land degradation. Previous research identified that OHV activity mainly causes changes in land cover by reducing the amount of vegetation cover and increasing the soil exposure in the landscape (Webb et al., 1978; Lathrop ,1983; Lovich and Bainbridge, 1999; Misak et al., 2002; Davenport and Switalski, 2006; Groom et al., 2007; Olive and Marion, 2009; Al-Hurban, 2014). OHV activity also affects the natural ecosystem by reducing the number of vegetation and animal species by destroying their habitats (Stebbins, 1974;

Luckenbach and Bury, 1983; Davenport and Switalski, 2006; Van Dam and Van Dam, 2008). The most common finding of previous OHV research on soil properties is that the soil bulk density increases due to compaction from the heavy weight of OHVs. However, there is generally a lack of research that associates OHV activity with significant impacts on other soil properties, such as pH value and soil texture (Belnap, 1995; Goossens and Buck, 2009). Therefore, the term “land degradation” in this study will be focused specifically to refers to a reduction in the amount of vegetation cover associated with OHV recreational activities performed within the landscape.

Sand dunes and arid landscapes are among the most common environments for OHV traffic. Past research has shown that OHV activity cause significant reduction of the vegetation cover in arid environments either by destroying plants directly, or causing soil compaction (Stebbins, 1974; Webb et al., 1978; Lathrop ,1983; Luckenbach and Bury, 1983; Misak et al., 2002; Sack and Da Luz, 2003; Olive and Marion, 2009; Al-Hurban, 2014). Motorcycle racing is another OHV activity that has received some research attention. For instance, the El Cajon Motorcycle Club Race in 1972 in the Yuha Desert in western Imperial County, CA was associated with a reduction of vegetation by 23% after the race. Repeated OHV driving on a vegetated landscape results in breaking, crushing, and root exposure of the vegetation, and eventually, it leads to the death of vegetation cover and other disturbances within the landscape, such as change in soil bulk density and moisture infiltration. (Lathrop ,1983; Webb et al., 1978; Davenport and Switalski, 2006; Olive and Marion, 2009).

OHV activity is also associated with alteration of soil properties. Vehicles can compact soil substrates, reducing root growth, and disturbing seed germination (Lathrop, 1983; Stebbins, 1974; Misak et al., 2002; Davenport and Switalski, 2006). Vehicle compaction of the topsoil increase the soil bulk density and reduces the soil moisture and air availability to plant roots (Webb and Wilshire, 1980; Belnap, 1995). Soil penetration resistance is a measurement of soil shear stress, soil compressibility and soil friction using a penetrometer. Soil with higher penetration resistance indicates lower soil porosity of the soil and higher soil bulk density, which affect the ability of soil to retain water and air (Dexter et al., 2007). Moreover, the soil is susceptible to wind and water erosion when vegetation has been removed because active sediment transportation processes are more able to affect the stability of the sand dunes (Belnap, 1995; AL-Awadhi, 2013).

The Algodones Dunes, which hosts the Imperial Sand Dunes Recreation Area, is one of the most popular sand dune systems in California for intensive OHVs usage with over 1 million visitors a year and often more than 90,000 OHV drivers in the dune field during holidays (C. Bruner pers. comm., 2017). The use of OHVs in the dune field is associated with reduced vegetation cover, enhanced soil and wind erosion, and decreased presence of endangered species, such as perennial plant (*Astragalus magdalenae var. peirsonii*) and flat-tailed horned lizard (*Phrynosoma mcallii*) in areas open to OHV activity (Luckenbach and Bury, 1983; Groom et al., 2007; Van Dam and Van Dam, 2008). Generally, however, there is a lack of research investigating the temporal changes of vegetation cover in the dune field, both naturally and in response to anthropogenic disturbances, such as OHV activity. Desert sand dune ecosystems can be vulnerable to such disturbances as their recovery to the initial stages of land degradation (declines in vegetation cover and soil properties) can be long compared to forest settings (Lovich and Bainbridge, 1999; Dorothy and Silvino, 2003). Thus, more research is needed to investigate the spatial and temporal changes of vegetation cover in arid dune fields so as to better analyze and interpret the relationships between the use of OHVs and land cover changes that might lead to longer-term land degradation.

1.2 Purpose and Objectives

The main purpose of this research is to examine land cover and vegetation changes in the Algodones Dunes over recent decades and explore potential associations with OHV activity and climatic variability as potential mechanisms for land degradation. To accomplish this, some specific objectives are set as follows: (1) to investigate the changes of land cover in OHV active areas of the Algodones Dunes compared to an adjacent protected area using a decadal scale time-series of remotely sensed satellite imagery; (2) to identify and interpret the patterns of OHV activity and land cover change in the dune field by classifying high-resolution aerial photographs and digitizing vehicle tracks and vegetated areas; (3) to explore statistical associations between land cover change, OHV activity and climatic variations as potential mechanisms for land degradation.

1.3 Study Area

The Algodones Dunes field, located in the southeast corner of the Imperial County in California (Figure 1), is an elongated dune complex that is approximately 75 km long and 8 km wide (Sweet et al., 1988; Ewing et al., 2006). The dune field is bounded by the alluvial fan of the Chocolate Mountains and Cargo Muchacho Mountains in the east, and Coachella Chanel and East Mesa in the west (Figure 2). It composes of a variety of dune types, including linear dunes, barchan dunes, compound dunes, zibars and nebkha dunes (shrub-coppice dunes) (Nielson and Kocurek, 1986; Sweet et al., 1988; Groom et al., 2007; Derickson et al., 2008). It is an active dune field with an average southeasterly migration movement of 35 cm to 40 cm/year (Sharp, 1979).

The Algodones Dunes presently experience an arid, hot desert climate (BWh per the Köppen system). The summer temperature of the dune field often exceeds 45℃, while the winter temperature is mild which has an average temperature of 23℃. The annual rainfall average of the Algodones Dunes is 6.4 cm/year. The precipitation in the dune field occurs in summer as infrequent moderate thunderstorms and as winter storms (Norris and Norris, 1961; Smith, 1970; Groom et al., 2007). With the arid climate in the Algodones Dunes, a disperse vegetation pattern is observed dominated by a Creosote Bush Scrub community with Desert Microphyll Woodland and Desert Psammophytic Scrub communities found in the dune field (Luckenbach and Bury, 1983). Most of the vegetation is found along the boundary of the dune field as the canal and alluvial fans of the surrounded mountains and channels provide a water source for the vegetation growth.

The dune field attracts many ORV enthusiasts and visitors from around the country for OHV recreation on the dunes. The annual visitation of the Algodones Dunes was over 1 million people from 2002 to 2013, and Bureau of Land

Management (BLM) estimated the total number of OHVs in the dune field at around one-third of the annual visitation (C. Bruner pers. comm., 2017). To protect endemic and endangered species and restrict the OHV activity, BLM designated the portion of the dune field on the northern side of State Route 78 as North Algodones Dunes Wilderness (NADW) in 1994 (Figure 2). According to the 1994 California Desert Protection Act, all vehicles are prohibited in the NADW in order to preserve the natural habitats and protect the endangered or endemic species, such as Astragalus peirsonii (*Astragalus magdalenae var. peirsonii*), scarab beetle (*Pseudocotalpa andrewsi* and *Anomala hardyorum*), weevil (*Trigonoscuta rothi algodones*), andrenid bee (*Perdita glamis* and *Perdita algodones*), and flat-tailed horned lizard (*Phrynosoma mcallii*) (Groom et al., 2007; Van Dam and Van Dam, 2008). Meanwhile, most of the southern dune field is open for OHV activity or other recreational activities.

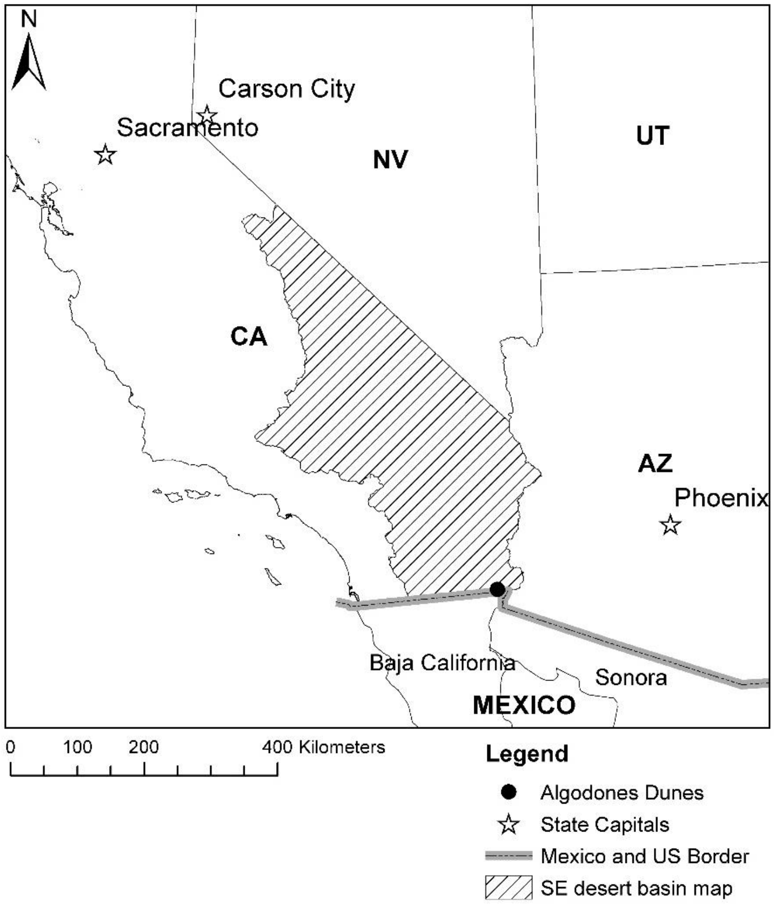


Figure 1 A map showing the location of the Algodones Dunes, and Southeast Desert Basin. Southeast Desert Basin is the area where NOAA obtains the long-term climatic data.

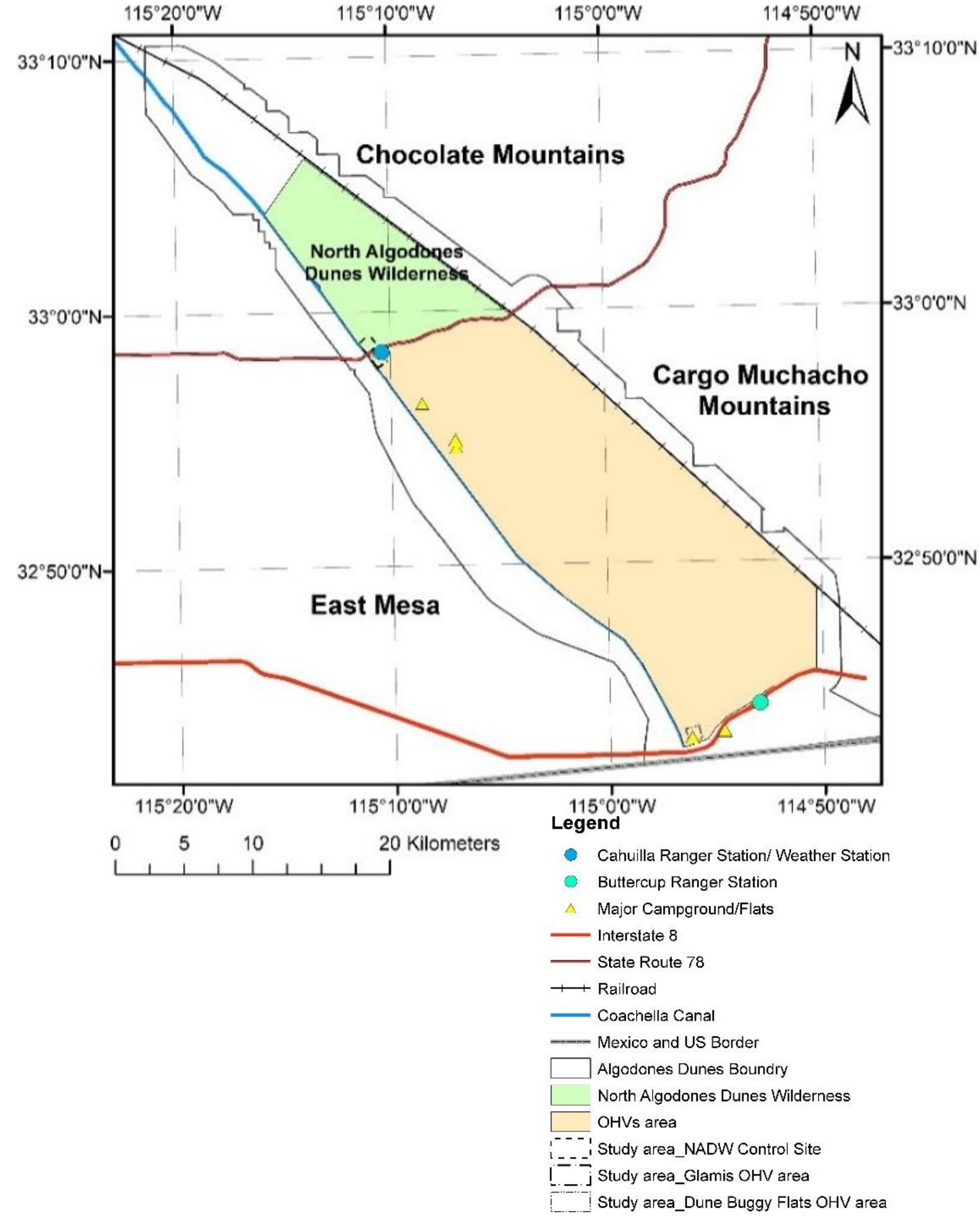
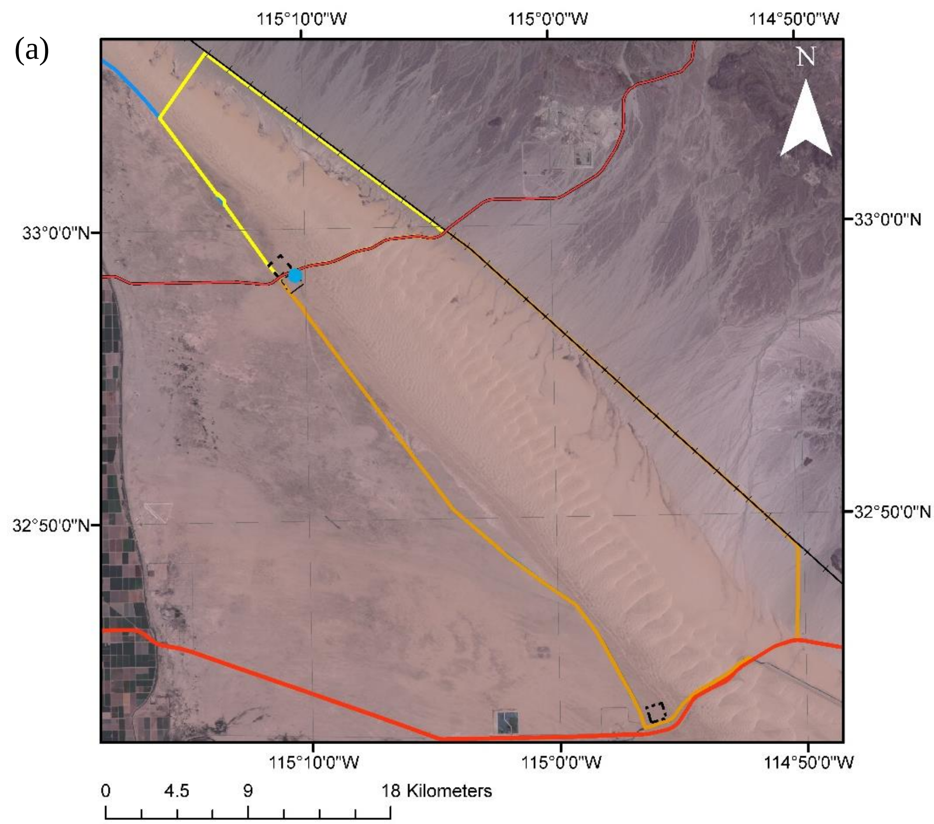


Figure 2A map showing the location of Algodones Dunes. The Algodones Dunes is bounded by the Chocolate Mountain in the east, Cahuilla Canal and a flat terrain named East Mesa in the west, and Interstate 8 and U.S. and Mexico Border in the south. The state route 78 is the road divides the dune field into the NADW (green) and ORVs open area (orange).

To investigate the land degradation phenomenon in the Algodones Dunes, the dune field is divided into two study areas: North Algodones Dunes Wilderness area (NADW) and the southern OHV accessible area (Figure 3a), in order to conduct a time-series analysis. The area of the NADW is 126 km^2 and all vehicles are prohibited in this area. The Imperial Sand Dunes Recreation Area covers a large proportion of the Algodones Dunes; however, there is limited OHV activity beyond the Coachella Canal in the west and past the Southern Pacific Railroad in the east due to difficulties with access to those areas. Also, the portion of the dune field to the south of Interstate 8 experiences less OHV activity because it is neighboring to the Mexico–United States border. Thus, two OHV areas were selected in this research for comparison with the NADW area to analyze the effects of OHV activity on land degradation in the Algodones Dunes. The total area of OHV area within the Algodones Dunes as bounded by State Route 78 on the north, Interstate 8 on the south, a railroad on the eastern edge of the dune field and the Coachella Canal on the west, is approximately 507.5 km^2 (Figure 3a).

Within this larger study region, three study areas of 1-km^2, named NADW control site, Glamis OHV area, and Dune Buggy Flats OHV area, were established to analyze the recreational impacts of OHVs on land degradation and change in vegetation cover in the dune field. These study areas were established in the eastern part of the dune field and along the Cahuilla Canal where most of the vegetation and nebkha dune area found in the dune field (Figure 3a). The NADW control site and Glamis OHV area are located adjacent to one another along State Route 78, while the Dune Buggy Flats OHV area is at the southern part of the dune field closed to Interstate 8. In the NADW control site, it is assumed that no OHV activity is taking place in this area as it is situated within a protected wilderness area; thus, it is presumed that this site represents natural environment and land cover without human disturbances. The Glamis OHV area allows the OHVs and other recreational activities (Figure 3b). There is a ranger station, a weather station and a road access for camping in the Glamis OHV area; thus, it attracts many people to conduct OHVs driving in this area. The Dune Buggy Flats OHV area is another popular OHV activity site because of the easy access from Interstate 8 (Figure 3c).

(a)



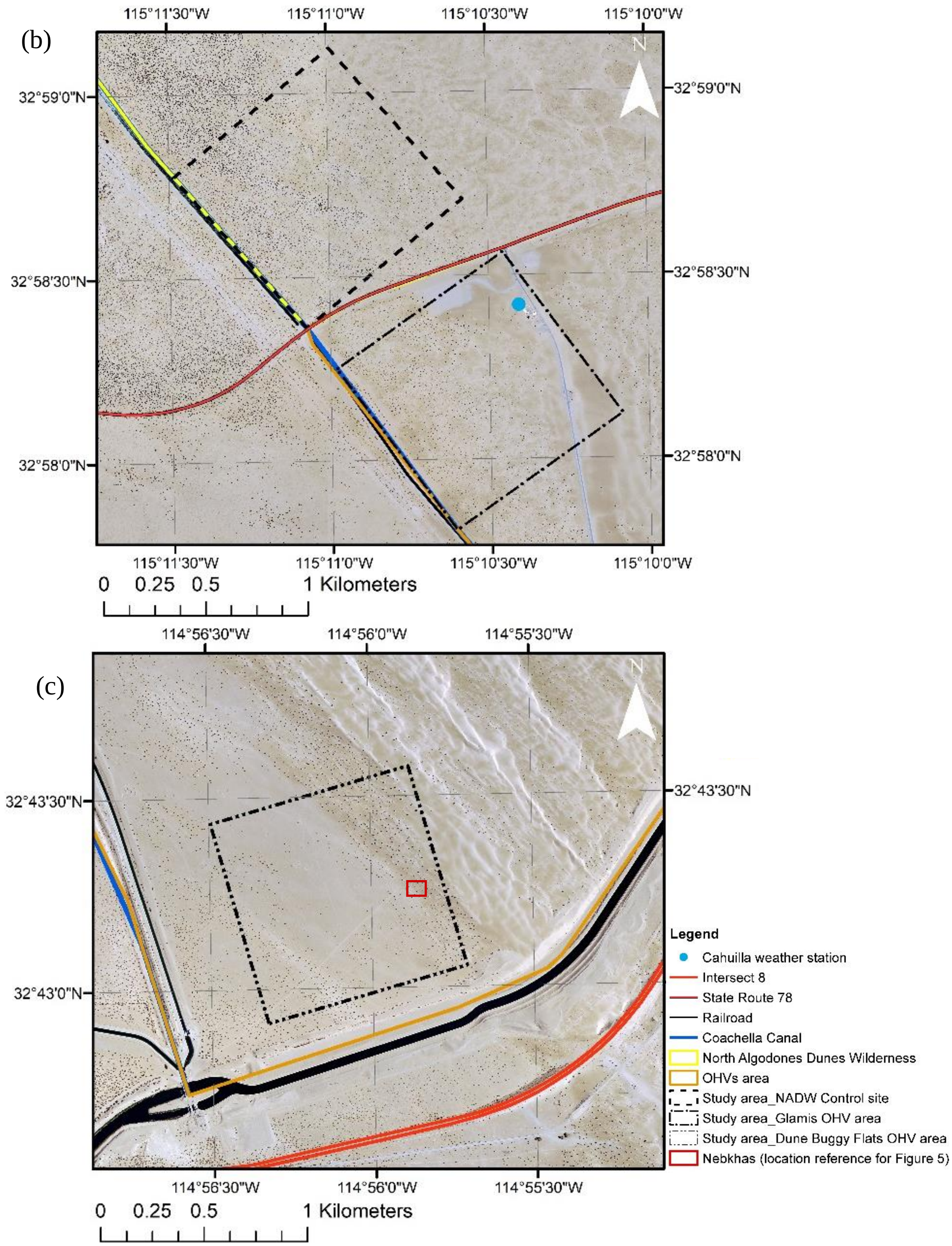


Figure 3a Study areas of the Algodones Dunes, Imperial County, California. The NADW and OHV area are designated to conduct the time-series analysis. Besides, three 1km x 1km study areas are established to study the recreational impacts of the OHVs activity in the dune field. Figure 3b: Control site is located at the northern side of the state route 78; Glamis is at the southern side of the State Route 78. Figure 3c: Buttercup is at the south-eastern part of the dune field. The location of the nebkha illustrating in Figure 5 is shown in Figure 3c.

2 LITERATURE REVIEW

2.1 Geomorphology of Algodones Dunes, California

The Algodones Dunes in southeastern California is one of the largest inland arid dune fields in North America. The dune field lies along the southeastern edge of the Cahuilla Basin, which includes the Imperial Valley and Coachella Valley. The terrain of the basin is generally flat with a low elevation. The Salton Sea situated with the distance of 70 km to the northwest of the dune field is currently the lowest part of the basin, and it has the surface elevation about of 75 m. The geology of the mountains around the basin is mainly composed of crystalline igneous and metamorphic rocks ranging in age from Precambrian to Tertiary (Norris and Norris, 1961). The Chocolate Mountains and Cargo Muchacho Mountains with the height of 823 m and 650 m, respectively, are positioned in the eastern boundary of the Cahuilla Basin. The Southern Pacific Railroad is built across the alluvial fans along the west flanks of these mountains and some funnel-shape drainage structures have been constructed under the railroad to manage overland flow and erosion of the railway and maintain water supply for dune vegetation. The Coachella Canal, built along the western edge of the dune field, also provides a localized water source to the vegetation located in the East Mesa, which is located in the west of the dune field.

A number of studies have researched the origin, formation and sediment source of the Algodones Dunes (Norris and Norris, 1961; Luckenbach and Bury, 1983; Sharp, 1987; Sweet et al., 1988; Strokes et al., 1997). Most studies suggest that the formation of the Lake Cahuilla is the critical factor causing the formation of the sand dunes and other shoreline features in the Cahuilla Basin (Water, 1983; Sharp, 1987; Sweet et al., 1988; Derickson et al., 2008). The lakes were formed when the Colorado River flowed into the Salton Trough instead of the Gulf of California. The sediments from the Colorado River were deposited within the lakes and formed a prominent shoreline positioned at 12 m in elevation of Lake Cahuilla, which is located at the East Mesa in the modern day (Water, 1983; Derickson et al., 2008). The sands and gravels were accreted along the shoreline and exposed to wave and wind actions. A study of aeolian activities in southern California (Johnson, 1977) revealed that the dominant wind in southern California is westerlies due to the interaction of the Pacific high and the Aleutian low. Therefore, when the wind in the Cahuilla Basin exceeds the shear threshold velocity, it transported the sediments toward the east and deposited along the mountain fronts, where the current Algodones Dunes situated.

The age of the Algodones Dunes remains to be firmly established. Thomas (1963) and Sweet et al. (1988) found that Lake Cahuilla was able to provide sand sediments for sediment transportation when the shoreline reaches 20 m to 50m in elevation of the Lake Cahuilla, and Hubbs et al. (1965) estimated the shoreline with 50 m in elevation is about 37,000 years old using a hydrodynamic model. Thus, the Algodones Dunes should be younger than 37,000. Strokes et al. (1997) calculated the age of the Lake Cahuilla using radiocarbon and optically stimulated luminescence (OSL). They found that the sediments from the 12 m shoreline dates range from 3,600 to 360 years, and the oldest OSL date of the aeolian deposits collected in the western part of the Algodones Dunes is around 3,100 years ago.

Another study conducted by Derickson et al. (2008) revealed that the OSL of the sediments in the East Mesa dates to 30,000 years, and the formation of the compound crescentic dunes should be dated at 15,000 to 18,000 years using pattern analysis, which study the interaction of bedforms that lead to pattern development in an aeolian dune field and predict the constructional trend of the dune by measuring dune spacing, crest length and defect density. The results also indicated that there is no new sediment influx from the dried Lake Cahuilla in the Algodones Dunes in the current circumstance.

The elongated dune field is composed of compound-complex crescentic dunes (Norris and Norris, 1961; Luckenbach and Bury, 1983; Kocurek and Nielson, 1986; Sweet *et al.*, 1988; Groom *et al.*, 2007). Small barchan and parabolic dunes occupy the eastern part of the dune field, and their orientation depends on the seasonal prevailing wind direction. The sand sheets near the alluvial fans shed by the Chocolate Mountains and Cargo Muchacho Mountains are covered with shrub vegetation, mud-cracked surface and shallow channels (Kocurek and Nielson, 1986). Some large compound dunes are found at the center of the dune field up to 80 m tall with the spacing of 50 m wide, and their orientation varies between northwest and northeast (Norris and Norris, 1961; Sweet et al., 1988). The linear dunes and zibars are observed in the western boundary of the dune field. The linear dunes with fine-grained size (median diameter approximately 0.15 mm) are range from 5 to 20 m in height, while the coarser grained (median diameter approximately 0.5 mm) zibars located at the interdune corridors between the linear dunes are about 3 m in height (Kocurek and Nielson, 1986; Derickson et al., 2008). Nebkha dunes in the Algodones Dunes were apparent in the 1970s (Smith, 1970) and are positioned at the western edge of the dune field where the sediment transportation is active, and the Coachella Canal provides a water source for the growth of shrub vegetation.

The Algodones Dunes are currently migrating toward the southeast. Sharp (1987) estimated that an average rate of movement of 35 to 40 cm/year by measuring the movement of intradune flats in the dune field. Subsequent research by Stroke et al. (1997), however, showed that the dunes are migrating at a rate of about 5 m a^{-1} using OSL dating of lee-face deposits of the dunes. This variation in migration rate relates partly to variations in the local wind regime in the Algodones Dunes and Cahuilla Basin. Wind data collected from the weather station near El Centro, CA and the Salton Sea region to the west of the Algodones Dunes show that the predominant wind of this region is westerly, west-northwesterly, and southwesterly, and the potential sand drift direction is in 80° (Long and Sharp, 1964; Smith, 1970). Sweet et al. (1988) illustrated the local wind and sand transport potential regime (Fryberger and Dean, 1979) of the Algodones Dunes using wind data obtained from a weather station located 3 km west of the southwestern boundary of the Algodones Dunes. They showed that the wind energy is low (111 vector units), and the resultant drift direction is 114°, which is closely aligned with the actual dune trend. Sweet et al. (1988) also indicated that there is a seasonal variation in wind speed and direction with the spring season (March through June) having the highest wind velocity and winds dominantly coming from the northwest and west. Summer winds (July through September) are the weakest and highly variable, while winter winds (October through February) are dominated by strong northerly and northwesterly. Thus, the sand drift potential and resulting surface sand transport patterns of the Algodones Dunes are not simple and most likely vary in different seasons.

2.2 Aeolian Processes and Dune Dynamics

Deserts are one of the major landscapes observed on the Earth's surface and they cover nearly one-third of the land's surface area. There are four major deserts in North America, including Chihuahuan Desert, Great Basin Desert, Mojave Desert, and Sonoran Desert. Typified by high temperatures and low precipitation, these arid environments are characterized by sparse vegetation cover and soils of limited pedogenic development. Windblown (aeolian) processes are common in desert landscapes where loose sand to clay-sized sediments are entrained, transported and redeposited by wind action (McTainsh et al., 2013). Bagnold (1941) identified that when the wind velocity is above a general threshold value of 6 m/s (measured at 10 m), aeolian sand transport and wind erosion may occur. The sediment is transported by creep, saltation and suspension depend on wind velocity and sediment particle size. It deposits when it loses the momentum from the wind by reaching a rough surface or reducing wind velocity. Therefore, the wind is an important factor in controlling the sediment transport processes and dunes dynamics in an arid environment.

Sand dunes are one of the depositional landforms resulting from aeolian processes. Wind regime, vegetation cover, and grain size are three major components controlling the formation of different dune types. Fryberger and Dean

(1979) describe the wind regime in the desert environment using drift potential (DP), resultant drift potential (RDP) and wind directional variability. DP and RDP are the sediment transport capacity of wind and the magnitude of net sediment transport trend calculated from annual or seasonal meteorological data of wind speed and wind direction. The wind directional variability is to characterize the wind regime in an environment using the ratio of RDP to DP. The value of wind directional variability smaller than 0.3 indicates a more complex wind regime, while the value greater than 0.8 reflects a unimodal wind. For instance, barchan dunes are developed when both sand supply and wind directional variability are low. Linear dunes or star dunes may appear when the wind directional variability increases.

Vegetation is another factor affecting the aeolian processes and dune formation. It alters the airflow over the surface and the erosive capacity of the wind. The impacts of vegetation on sediment transportation are covering the soil surface, extracting the momentum from the wind, and trapping the transporting sediments in the air (Tsoar, 2001; Okin, 2013). The trapping ability of the plant depends on the optical porosity, which is the fraction of a horizontal light beam that would pass through the vegetation canopy (Raupach et al., 2001; Gillies et al., 2014). When the optical porosity reaches approximately 0.2, the vegetation has the maximum trapping ability of the transporting sediments. With the protective cover from the vegetation, the shear stress is reduced due to the decrease in wind momentum. The sediments deposit and accumulate near the vegetation. Thus, vegetation in the arid environment possesses a function of stabilizing the sand dune by reducing the erosive capacity of wind and the amount of transporting sediment.

Nebkha, also known as shrub-coppice dunes, is a type of sand dunes that develop by trapping the transporting sediment within vegetation (Tengberg, 1995; Okin, 2013). Nebkha dunes cover about 5% of the world's land surface (Thomas et al., 2005), and are common in the southwestern United States (Langford, 2000; Parsons, 2003; Okin, 2013; Gillies et al., 2014). The morphology of nebkha is a mound-like accumulation of sand around vegetation with three segments, including windward, crest and leeward components (Figure 4) (Khalaf et al., 1995; Ardon et al., 2009). The windward slope of the nebkha often experience erosion from the wind action, and the crest is where vegetation traps the transporting sediment. A tail usually appears at the leeward of the nebkha where deposition occurs; thus, it can reflect the local wind regime of the landscape (Figure 4 and 5).

Nebkha are commonly found in the aeolian landscape with flat terrain, interdune areas or slacks of active dunes (Link et al., 1994; Hesp and McLachlan, 2000; Wang et al., 2006). The factors affecting the shape and size of the nebkha are the species of vegetation, sediment supply, local wind speed and direction, and topography of the landscape (Khalaf et al., 1995; Gillies et al., 2014). According to Tengberg (1995), there are three stages of the nebkha development, including growing, stabilizing, and degrading. A nebkha grows when the transporting sediments are trapped and deposited due to the growth of vegetation. Then, it increases the size and vegetation canopy in a steady state, and finally, it erodes due to the degenerated vegetation and sediment deposits. Without the presence of vegetation and nebkha dunes on the surface, it activates the process of sediment transportation and the migration of the dunes.

Figure 4 A photo shows a nebkha dune located at the southeastern of the Algodones Dunes. According to Tengberg's description of different stages of nebkha dunes (1995), the nebkha shown in the photo is at the growing stage as the vegetation canopy and the size of the nebkha are small. It clearly illustrates that wind actions caused the erosion on the windward side, while a small amount of sediment deposits (tail) on the leeward side of the dune.

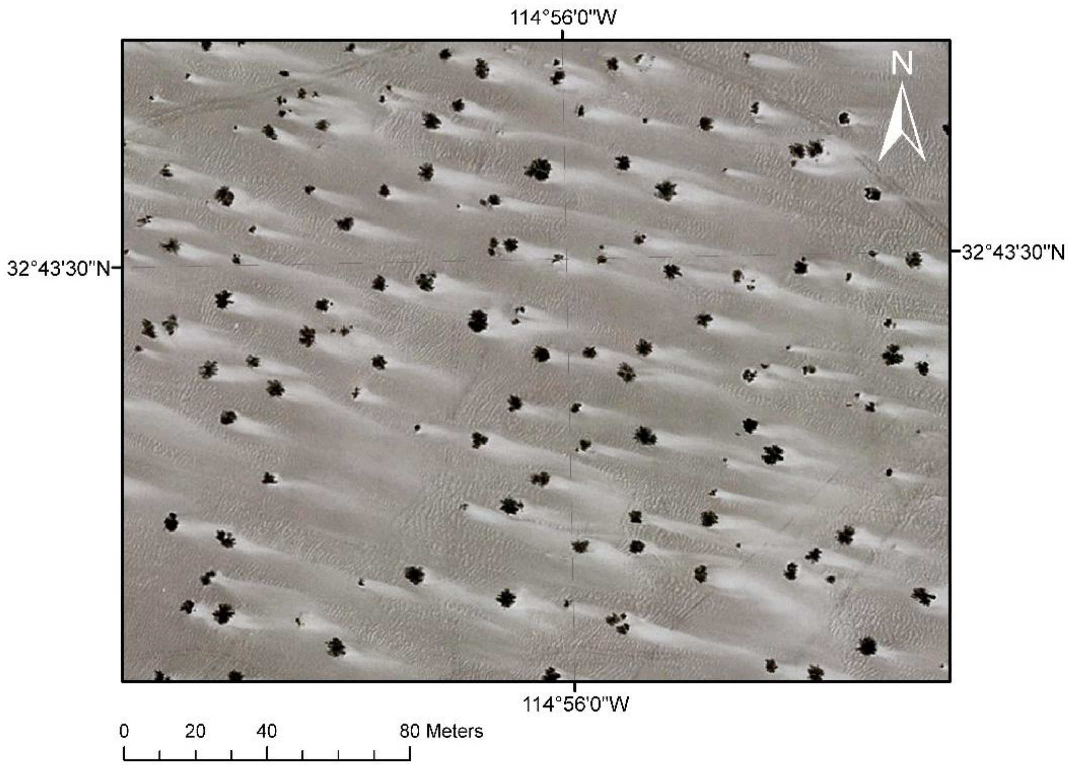


Figure 5 A high-resolution aerial photograph acquired in May 2011 shows a group of nebkha dunes located at the southern Algodones Dunes (See Figure 2 for the location where the photograph is taken). The direction of the nebkha tails reflects the local wind regime. All the nebkha tails points toward the east-south-east direction, which indicates the local dominant wind blows from the west to east.

2.3 Impacts of Off-highway Vehicles in Arid Environment

2.3.1 General impacts of OHVs

In general, OHV activity causes substantial impacts on soil and vegetation that have been identified in previous research (Stebbins, 1974; Webb et al., 1978; Luckenbach and Bury, 1983; Priskin, 2003; Sack and Da Luz, 2003; Davenport and Switalski, 2006; Groom et al., 2007; Goossens and Buck, 2009; Misak et al., 2002; Olive and Marion, 2009; Al-Hurban, 2014). For instance, OHVs traffic has been documented to notably to reduce vegetative cover, density, and diversity (Webb et al., 1978; Lathrop, 1983; Misak et al., 2002; Groom et al., 2007; Al-Hurban, 2014). Lathrop (1983) investigated the impacts of OHV activity on the number of perennial plants in Dove Springs, near the Jawbone Canyon, California. The research results showed that OHV activity caused a significant reduction in plant density of 46% on hillsides, while there was a 60% reduction in plant density in the pit areas. Another OHVs research conducted by Misak et al. (2002) in the Kabd area, located at the southwest of Kuwait City, found that the vegetation cover in the protected area was twice of the vegetation cover in the area opened to OHV activity.

Compared with other types of recreational activities, such as hiking and mountain biking, OHVs are more destructive to the landscape because they can disturb larger areas on a single trip and exert significantly more force to damage vegetation and soil surfaces. For instance, Lovich and Bainbridge (1999) revealed that the wheel tracks of a full-size OHV can damage around 5000 m^2 area of land when it travels every 6.44 km. The result indicated that the OHV activity can cause devastating impacts on vegetation and land cover compared with other types of recreational activities as it impacts a larger area than its track width. Experimental research by Gibson (1973) in the Mojave Desert found that 30% of creosote bushes *(Larrea divericata)* and 45% of the Mormon tea bushes *(Ephedra)* were deteriorated after an OHVs race that took place in Johnson Valley. Lathrop (1983) documented that the Barstow to Las Vegas Motorcycle Race in November 1974 caused devastating impacts on vegetation and soils. The mean vegetation density was reduced by 50%, and the number of vehicles and track depth increased by 140% after the pass of 3,000 vehicles.

Vehicles passes can also affect the growth of vegetation by compacting soil substrates, reducing root growth, and disturbing seed germination (Stebbins, 1974;

Lathrop, 1983; Misak et al., 2002; Davenport and Switalski, 2006). The weight of the four wheels off-road vehicle, for example sandrail with 500cc, is in a range from 360 kg to 680kg, and its speed can up to 130 km/hr. (Adam *et al.*, 1982; Goossens and Buck, 2009; Olive and Marion, 2009). The result is more substantial in desert regions because the typically loamy sands and coarse soils are more susceptible to displacement and compaction. Webb (1983) conducted an experimental research with a 175-cc motorcycle on the trails in Fremont Peak, CA in the western Mojave Desert. The study showed that the trails have a noticeable effect after 10, 100 and 200 passes. The width of the trail was nearly three times the width of the motorcycle tire, and the trail center was 10 m to 30 m lower than the adjacent undisturbed soil. He also recognized that the soil bulk density is positively correlated with the number of vehicle pass, and inversely related to the trail depth. Thus, the soils with high soil bulk density and penetration resistance increase in surface strength and decrease in infiltration rate which inhabits the root growth of desert plants and seed germination.

Soil erosion is another common phenomenon induced by OHV activity. Sack and deLuz (2003) found that the soil erosion rates of a site in Appalachia in southeastern Ohio State during the riding season is $0.11m^3/m^2$, which equates to over 200 kg of soil loss each year on a 60 m section of trail. The spinning of the vehicle wheels severely disrupts the topsoil and causes dust emission (Stebbins, 1974; Lovich and Bainbridge, 1999; Goossens and Buck, 2009); thus, the soils become more susceptible to wind erosion, especially in desert and dune fields where there are active aeolian processes. Once the soil surface layer is removed by the OHVs or wind, it results in plant root exposure which may affect the growth and nutrient uptake of plants. Moreover, the soil temperature increases after the removal of vegetation cover since the insolation can directly reach the soil surface without the shading and thermal insulation given by plant cover (Webb et al., 1978). Plant seed germination and plant growth may be prohibited due to high soil temperature and root exposure, and eventually, it reduces the amount of vegetation on the landscapes.

Belnap (1995) examined the OHVs and trampling impacts on soil properties and their effects on desertification in Arches National Park, north of Moab, Utah. He identified that soil bulk density in a recreational site with OHV activity was significantly higher than the protected site; however, there was no statistically significant differences in soil physical properties, such as pH value, soil texture, and chemical compositions, between the two sites. Increasing bulk density often results in lower water infiltration rate and increase the surface runoff (Webb and Wilshire, 1980). Reduced water availability affects the vegetation growth and its survival rate. Another major finding is that the nitrogen found in the leaf tissue in the protected site was 9% higher in the perennial shrub and 31% higher in the perennial forb in the recreational site. As nitrogen is one of the critical elements to maintain the primary productivity in arid and semi-arid ecosystems, the result indicated that the recreation activities disturbed the normal nitrogen cycle and affected the land productivity. Moreover, it takes a long period of time to recover the amount of soil nitrogen and vegetation cover to its initial stage; thus, those areas impacted by the recreational activities are susceptible to land degradation.

2.3.2 Effects of OHVs on Sand Dunes

Sand dunes, including coastal dunes and inland dunes, is one of popular landscape receiving excessive use of ORVs. There are several famous sand dunes allowing OHV activity, including St. Anthony Dune in Idaho, Syracuse Sand Dune Park in Kansas, Sand Mountain-Fallon in Nevada, Little Sahara Recreation Area in Utah, and Heber Dunes and Algodones Dunes in California (Brooks and Lair, 2005; California State Parks, 2018). However, there is a few OHVs research conducted in the sand dunes in the United States (Brodhead and Godfrey, 1977; Webb et al., 1978; Bury and Luckenbach, 1983; Belnap, 1995; Van Dam and Van Dam, 2008; Goossens and Buck, 2009).

Brodhead and Godfrey (1977) investigated the disruption of OHVs and dune vegetation recovery in Cape Cod National Seashore, Massachusetts using field-based measurement on the trails with different passes of vehicle. The major finding is the vegetation on the trail received a total of 675 vehicle passes had declined to 25% in the foredune and 15% in the dune, and it recovered to 59% and 32% after two-weeks recovery. Another trail with 270 vehicle passes had reduced in vegetation to 42% foredune and 34% in the dune and recovered to 99% and 45%. The results indicated that the trail with more OHV traffic caused a more substantial reduction of vegetation on the foredune and dune, and it had a slower rate of vegetation recovery than the trail with less vehicle passes. The reduction of vegetation cover on the foredune and dune leads to soil exposure and wind erosion, and it may re-activate the sediment transportation process when the prevailing wind exceed the threshold shear velocity. Eventually, the profile of the coastal landscape may be altered.

Plants play an important role in stabilizing the sand surface by reducing the shearing force of the wind at the surface available for sediment entrainment and transport. In addition, vegetation also acts as a supply-limiting factor in aeolian sand transport. They limit availability of sand to otherwise competent winds, by protecting and/or anchoring sediments. Related, vegetation also acts to promote deposition of aeolian sediments by extracting momentum from sediment-laden airflow and forming a catchment zone for sediment deposits. Desert vegetation is highly vulnerable to OHV activity because the soils in arid regions are compactible with slow infiltration rates. Once the vegetation gets damage, it may take a few decades for the vegetation to recover to the initial stage. OHV activity also threaten the seed germination of plant by the abrasion of the soil strata (Stebbins, 1974). Groom et al. (2007) found that the density of large-plants is low in the area allowed OHV activity because fewer small-plants can survive and grow to the larger size class rather than a significant reduction of the large-plants by the vehicles. Reducing the amount of the vegetation cover in an arid and semi-arid environment may lead to land degradation and desertification since the sand surface is more susceptible to wind when the vegetation has been removed (Belnap, 1995; AL-Awadhi, 2013).

Previous OHV literature has identified many substantial effects of OHV activity on vegetation, soils, and wildlife in an arid environment; therefore, mitigation the OHV effects and restoration of the OHV-impacted sites are important for protecting and restoring impacted landscapes as well as maintaining the ecosystem functions and services. However, some research evaluated the ecological recovery on the OHV-impacted landscapes revealed that revegetation or restoration of natural ecosystem in arid environment is difficult owing to severe weather conditions and infertile soils (Graves et al., 1975; Brodhead and Godfrey, 1977; Graves, 1978; Wallace et al., 1980; Webb and Wilshire, 1980; Kay and Graves, 1983; Ouren et al., 2007). Webb and Wilshire (1980) established a field-based study to analyze the soil and vegetation recovery in the Wahmonie ghost town in southwestern Nevada, which is part of the Mojave Desert. The results showed that the soil properties, such as soil texture, soil bulk density, and penetration resistance of the human-disturbed areas had recovered to its pre-disturbance stage measured in 1928, while there was a slow recovery rate of vegetation in the disturbed areas. The findings of the research indicated that vegetation in an arid environment takes a longer time to mitigate the impacts induced by human disturbances and return to its initial stage compared to forest setting (Lovich and Bainbridge, 1999; Dorothy and Silvino, 2003).

2.3.3 Empirical OHVs Studies in Algodones Dunes

OHV activity became a popular outdoor recreational activity of the United States since 1970s. With the growing demand of the outdoor activities, it experienced a rapid increase in OHV activity in 1990s. The total annual sale of OHVs in the United States increased dramatically from 368,600 in 1995 to 1,034,966 in 2006, and the estimate total number of OHVs rise from 2,920,000 in 1993 to 8,010,000 in 2003 (Cordell et al., 2008). The rapid growth of the number of OHVs combined with frequent and prolonged drought events cause the occurrence of land degradation, which leads to some management issues on the public land in the States.

Algodones Dunes as a largest sand dune field in the United States attracts lots of OHVs enthusiasts and visitors practicing OHVs in the dune field. However, there is only limited research has been conducted to study the impacts of OHVs on vegetation and wildlife in the dune field (Webb et al., 1978; Bury and Luckenbach, 1983; Van Dam and Van Dam, 2008; Goossens and Buck, 2009). Luckenbach and Bury (1983) identified that the NADW had 2.4 times more vegetation types and 10 times higher vegetation density than the dune field allowed the OHV activity. The vegetation was commonly destroyed by direct destruction, such as breaking and crushing, or plant root exposure. It showed a similar result with another research conducted by Groom et al. (2007). The vegetation density of the area open to OHV activity is 4 to 5 times fewer plants than the area restricted to OHVs. The results indicated the OHV activity altered the land cover by reducing the vegetation cover and increasing the soil surface. Without the vegetation as a protective layer, it may activate the aeolian sediment transportation processes, and affect the stability of the dune field.

The OHV activity also disturbs the natural habitat of the wildlife. The animal tracks, such as beetle, lizard and desert kangaroo rat, experienced a significant decrease in the areas frequently used for OHV activity in the Algodones Dunes (Luckenbach and Bury, 1983). For example, the desert kangaroo rat's track in the protected sites was five times than that in the OHV-impacted sites. Van Dam and Van Dam (2008) also found that the number of dune endemic Coleoptera in the OHV-impacted site is significantly lower than that in the NADW. OHV activity leads to the increase in soil bulk density and daytime soil surface temperature, and the removal of the dune vegetation. It resulted in the destruction of burrows system, which increased the mortality rate of the desert kangaroo rat and Coleoptera. It also caused a direct impact on the death and injury of lizards in the dune field by crushing and burying the lizards under the sand. Thus, OHV activity caused significant effects on the biota of the dune ecosystem in the Algodones Dunes.

Previous research indicated that the OHV activity caused a significant reduction in the amount of vegetation cover in the Algodones Dunes; however, most of them conducted a field-based study to calculate the vegetation types, amount, and density and estimate the ecological impacts induced by OHV activity. They neglect to identify the spatial and temporal trend of human-induced land degradation in the Algodones Dunes. Also, there is a weak evidence showing the relationship between the number of OHVs and the changes in land cover. Therefore, more research is needed to examine the spatial-temporal changes of the amount of vegetation cover and other land degradation indicators, such as albedo and surface temperature, as well as to analyze the OHVs usage and visitation pattern of the Algodones Dunes and its relationship with the land cover changes.

OHV activity causes significant impacts to the natural environment; however, the landscape itself also serves a critical function of providing opportunities for outdoor recreation to human. It is important to identify and mitigate the impacts of recreational activities so that it could be able to sustain its recreation and resource protection functions. This research might assist the Bureau of Land Management to implement some feasible management policies to control the amount of the OHV activity in order to mitigate those OHV impacts in the Algodones Dunes.

2.4 The Relationship Between the Climate Change and Vegetation Cover in Southwest United States

The effects of climate change on land degradation and vegetation growth are widely identified (Lavee et al., 1998; Nield and Baas, 2008; Thomas and Wiggs, 2008; Ravi et al., 2010; Tsoar, 2013). One impact of climate change is the alternation of hydrological conditions that change the soil moisture availability. As vegetation is sensitive to the change of climatic conditions, and soil nutrients and moisture content, the amount of vegetation on the landscape declines due to changes in extreme high temperatures, rainfall scarcity, or drought (Nield and Baas, 2008). Decreasing the amount of vegetation cover accelerates the soil, water, and wind erosion processes, and eventually, land degradation may occur.

According to World Meterological Organization (WMO) (1992), drought is generally described as sustained, extended deficiency in precipitation, which is less than 80% of its historical average based on a 30-year period of record. It can last less than five years but more than a few months in a region (Hugenholtz and Wolfe, 2005; Tsoar, 2013). The most significant effect of drought on land degradation is to reduce the amount of vegetation cover due to moisture stress. The longest drought event in the world occurred in the Negev desert in Israel from 1995 to 2009. This megadrought saw a reduction of rainfall by 38% (from 114 mm to 61 mm), which caused the wilting of 80% of the perennial shrubs in the dune field (Siegal et al., 2013). The decrease in vegetation cover leads to the exposure of soil surface and increased potential for soil and wind erosion. When wind speeds exceed the threshold shear velocity, it activates the sediment transportation and dune migration.

Some regional climatic events, such as the El Nino-Southern Oscillation (ENSO), are related to the occurrence of drought in the southwestern United States (McCabe and Dettinger, 1999; Woodhouse et al., 2010). ENSO describes as periodic variations in sea surface temperature and air pressure across the equatorial Pacific Ocean (NOAA, 2018). An ENSO consists of a warming phrase El Niño and cooling phrase La Niña. During an El Niño event, the ocean surface temperature of the tropical Pacific Ocean is warmer than normal. It decreases the air pressure gradient above the equatorial Pacific Ocean, thus, the easterly wind is weakened. El Niño usually causes severe drought to the western Pacific, while the eastern Pacific experience more precipitation due to the warm surface water. La Niña is an intensified condition than the neutral phrase. The ocean surface temperature is cooler than normal, and the easterly wind is strengthened. Therefore, La Niña leads to heavy precipitation in the western Pacific, while severe drought is resulted in the eastern Pacific. An El Niño or La Niña event typically can last nine to twelve months, however, it can be prolonged for few years.

The presence of an El Niño or La Niña event results in abnormal weather conditions in the southwest of the United States (Lindsey, 2011). During an El Niño event, the Southwest usually receives more precipitation during winter and early spring because a strong and humid subtropical jet stream is formed over the Pacific

Ocean and across the Southwest. La Niña event causes the shift of the jet stream northward, which reduces the amount of precipitations and brings drier weather conditions to the Southwest. A study of ENSO and its hydrological effects in the southwest United States (Cayan et al., 1999) reveales that the ENSO phrase alters the frequency of daily precipitation and larger precipitation events (> 90th percentile) in winter to early spring (October to April). The number of days with high precipitation increases during the El Niño event, in opposite, it decreases during the La Niña event. For instance, the frequency of daily precipitation at Prescott, AZ received three times more precipitation in the El Niño event than the La Niña event.

The occurrence of the La Niña over the Pacific Ocean leads to inadequate precipitation in the Southwest, which resulted in prolonged and severe droughts. There are four major drought events taken place in the Southwest in the recent two decades, including 2002 North American Drought, 2007-2009 California, 2010-2013 Southern United States Drought, and 2011-2017 California Droughts (National Integrated Drought Information System, 2018). A number of research studied the response of desert vegetation (mainly perennial vegetation) to the climate change in the southern California deserts (Lancaster 1997; Barrows and Murphy-Mariscal, 2012; Guida et al., 2013; Munson et al., 2016). McAuliffe and Hamerlynck (2010) studied the mortality of two perennial plants, *L. tridentate* and *Ambrosia* spp., in response to the 2002 North American Drought in the Sonoran and Mojave deserts. The research identified the Standardized Precipitation Index (SPI) of both deserts is deficit throughout the year of 2002, and the highest perennial plants mortality rate is located at the transition between the Sonoran and Mojave deserts. The severe drought caused the mortality of over 90% of *Ambrosia* spp. and 39% of *L. tridentate* in the Joshua Tree National Park, CA. The alteration of soil properties also causes the mortality of the plants. The reduction of soil moisture content and soils with surface pavement development affect the water and nutrient uptake of the plants; as a result, the plants reduced its size of canopy and withered.

Munson et al. (2016) analyzed the effects of cumulative drought on perennial vegetation in the Mojave Desert by comparing Moderate-Resolution Imaging Spectroradiometer Enhanced Vegetation Index (MODIS-EVI) and ground measurement on vegetation cover between 2000 and 2010. The research recognized that the precipitation of seven years between 2000 and 2010 is below the average annual precipitation of the Mojave Desert. The 10-years precipitation anomalies that ranged from -300 mm to +45 mm caused 30% reduction in vegetation cover of dominant shrub *L. tridentate* in the Death Valley National Park, 50% reduction at Joshua Tree National Park and Mojave National Preserve. The study identified that the loss of perennial vegetation was more significant in the areas with heavy visitation or wildfire, and the vegetation in the undistributed areas increased to a greater degree than the visitation-distributed areas.

Land degradation can be induced by both or either climate change or anthropic activities. Climatic events, such as droughts and ENSO, can cause devastating effects on land degradation because of the large coverage of the affected area, and it is difficult to control the occurrence and duration of the climatic events. While human-induced land degradation can also be destructive when the intensity of anthropic activities exceeds the carrying capacity of the land. It is critical to identify and analyze both long-term climatic variations and anthropic impacts on the landscape in order to study the impacts of OHVs on the arid environment.

3 METHODOLOGY AND DATA

3.1 Data Collection

3.1.1 MODerate-resolution Images (MODIS)

MODIS is one of the most widely used datasets for time-series analysis and land cover change study. Three variables are used in this research to investigate the land cover change in the Algodones Dunes, including normalized difference vegetation index (NDVI), albedo, and land surface temperature (LST). Three sets of MODIS products are used to detect the spatial and temporal trend of the variables, including MODIS NDVI 16-days composite imagery (MOD13A1), MODIS Land Surface Temperature 8-days composite imagery (MOD11A2), and MODIS BRDF/Albedo daily composite imagery (MOD43A3). The resolution of NDVI and albedo datasets is 500m, while LST dataset has a 1-km resolution. Both daytime and nighttime LST datasets are available in the MODIS Land Surface Temperature 8-days composite imagery (MOD11A2). The MODIS white-sky albedo for visible bands (0.3-0.7μm) is adopted to assess the human-induced land degradation in the recreational area of the dune field. In order to have a comprehensive coverage dataset for generating the annual and seasonal time-series analysis of those variables, the temporal extent of all datasets in this research is from 2001 to 2016.

Image processing has been done prior to the time-series analysis since the raw datasets cover the entirety of California. The pixels that are located in the NADW (protected area) and recreational area of the Algodones Dunes are extracted in the ArcMap software as two new images for the time-series analysis. In addition, the temporal granularity of each variable dataset is different and covers a short period of time, such as 16-days composites for NDVI datasets and daily composites for albedo dataset. In order to have a consistence temporal scale for all three variables, the annual and seasonal datasets are created by calculating the mean pixel value of every year from 2001 to 2016.

For seasonal time-series analysis in this research, the images obtained in the months of June and July are used for the summer time-series analysis as Algodones Dunes has the highest temperature and occurrence of precipitation event. The images obtained in November and December are used to analyze the analysis of winter season as they are the peak season of ORVs activities in the dune field. For example, MODIS NDVI 16 days composite dataset is converted to a seasonal dataset by calculating the mean pixel value of the images that obtained in June and July, and November and December for every year. The annual dataset is also generated by calculating the mean pixel value of every year. As a result, there are 32 images (16 each for summer and winter) for NDVI seasonal dataset and 16 images for NDVI annually dataset that are obtained from 2001 to 2016 in both protected area and recreational area.

3.1.2 High-resolution Aerial Photographs

The aerial photographs with high spatial resolution are used to illustrate the OHVs tracks pattern and study the effects of OHVs on the land cover change in the dune field. Table 1 shows the available high-resolution aerial photographs of the Algodones Dunes. The aerial photographs are mainly acquired from Digital Orthophoto Quadrangle (DOQ), National Agriculture Imagery Program (NAIP), and High Resolution Orthoimage, which are retrieved from the USGS EarthExplorer. These imagery datasets have 1 m resolution, except the High Resolution Orthoimage with 0.15 m resolution.

Three 1-km^2 study areas: I) the NADW control site, ii) the Glamis OHV area, and Iii) the Dune Buggy Flats OHV area (Figure 3). These sites were established in order to analyze the land cover change and the use of OHV activity in the dune field. The study areas are extracted from each available imagery in the ArcMap software prior to conduct image classification and vehicle track digitizing.

Table 1 Available high-resolution aerial photographs of the Algodones Dunes.

Imagery Dataset	Acquisition Date	Resolution	Number of Band
DOQ	15th Jun 1996	1m	3 (RGB)
DOQ	29th May 2002	1m	3 (RGB)
NAIP GEOTIFF	30th May 2005	1m	3 (RGB)
High Resolution Orthoimagery	25th May 2009	0.15m	3 (RGB)
High Resolution Orthoimagery	28th May 2011	0.15m	3 (RGB)
NAIP GEOTIFF	23rd Apr 2012	1m	4 (RGB+NIR)
NAIP GEOTIFF	6th Jun 2014	1m	4 (RGB+NIR)
NAIP GEOTIFF	24th Apr 2016	1m	4 (RGB+NIR)

3.1.3 Climatic Data

Local climatic data collected from the Cahuilla weather station (32.9736°N, 115.1735°W) is used to analyze the climatic variations causing land cover changes in the Algodones Dunes (Figure 2). The retrieved variables are hourly temperature, precipitation, wind speed, and wind direction. The temporal coverage is from 2001 to 2016. The annual temperature and precipitation are calculated by averaging all the available data collected from the weather station. The wind data from the weather station are used to calculate the annual and seasonal drift potential (DP), resultant drift potential (RDP), resultant drift direction (RDD), and wind directional variability using the Fryberger's model (Fryberger, 1979). The equation of the drift potential modified by Miot da Silva and Hesp (2010) is shown as follow:

$$Q \alpha V^2 (V - V_{\mathrm{t}}) * t \quad (1)$$

$$V_{\mathrm{t}} = 5.75(V * t) \log \frac{100}{d_{(\mathrm{mm})}} + (894(d_{\mathrm{mm}}) \quad (2)$$

where Q is the rate of sediment drift potential in 'vector units', V is averaged horizontal wind speed measured at 10 m height in knots, V_t is the threshold velocity at 10 m height. To obtain a more precise calculation of sand transporting potential of the local wind regime in the Algodones Dunes, this study categorized the unclassified wind direction data (in degree) into 16 equal 22.5° direction sectors and calculated the DP of each direction sector. Both wind rose and sand rose are generated in this study in order to illustrate the local wind regime of the Algodones Dunes. Sand rose is a circular diagram representing the DP in all 16 directions. The arm length and orientation of the arrow on the sand rose indicate the RDP and RDD, which reflect the intensity and orientation of the sediment transportation on the landscape.

The long-term climatic data, includes annual average temperature, annual rainfall, and Palmer Drought Severity Index, are retrieved from the NOAA National Centers for Environmental information (2018). Palmer Drought Severity Index is a measurement of the relative dryness of the region based on the temperature and rainfall. It is effectively quantifying the long-term droughts in a region. The value of 0 shows a normal condition. A wet condition is shown as positive value, and drought is indicated as negative value. The Algodones Dunes are located within the region of Southeast Desert Basin in California (Figure 1). The temporal coverage of the datasets are from 1895 to 2016. The Pearson's correlation coefficient (*p*-value<0.1) is used to analyze the relationship between the variables. The local and long-term climatic data is used to study the climatic variations of the dune field and the effects of those climatic variations on land cover changes in the Algodones Dunes.

3.1.4 Visitation Data

BLM collects the annual and seasonal visitation data of the Algodones dunes since 2002. They estimated the number of visitors by counting the vehicle entering the Algodones Dunes at the major entrance and multiplied the vehicle counter data by 3.5 which is the average occupancy per vehicle. The total visitation data is a proxy of the amount of OHV activity in the dune field. The minimum number of OHVs is the number of the vehicle entering the dune field, while the total visitation of the Algodones Dunes would be the maximum number of OHVs.

The annual and 12-months visitation data obtained in this research is provided by Camden Bruner, who is the wildlife biologist of BLM. It is used to identify the use of OHVs in the dune field and examine the associations between the pattern of OHV activity and land cover change in the dune field.

3.2 Data Analysis

3.2.1 MODIS images

Time-series Analysis

The MODIS images are imported into the Earth Trend Moduler of TerrSet Geospatial Monitoring and Modeling Software in order to analyze the time-series analysis for all the variables using Mann-Kendall test, also named as monotonic trend, which is a non-linear trend indicator that measures the degree to which a trend is consistently increasing or decreasing. The significance of the Mann-Kendall test is that *p*-value is less than 0.1. The outputs of the analysis are a *p*-value map and a map with calculated slope value of the variables in both protected area and recreational area.

The annual time-series analysis of NDVI, albedo, LST of the protected area and recreational area are compared to identify the impacts of ORVs on land cover change in the Algodones Dunes over time. The research also studied the seasonal time-series analysis of all the variables in the dune field in order to analyze the seasonal variations of land degradation between summer and winter. The assumption is that the amount of vegetation in the recreational area might decrease in winter due to the peak season of the OHV activity, while the precipitation event and lack of human disturbance in summer might lead to the recovery of the vegetation.

Pixels Trend Analysis

To conduct an impartial comparison between the protected area and recreational area, the pixels trend analysis of 30 randomly selected pixels in both areas are analyzed. The pixels which are statistically significant (p-value≤0.1) are divided into two categories depending on the threshold value of the variables. As there is limited vegetation in the arid environments, such as desert and sand dune, have a relatively low NDVI value and high surface reflectance. The NDVI value of the desert and barren soil is less than 0.15 (Nadal & Bréon, 1999; Meneses-Tovar, 2011; Kim, et al., 2013), and the albedo of the desert is in a range from 0.1 to 0.20 (Laity, 2008). Thus, four categories are generated, including NDVI less than or equal to 0.15, NDVI greater than 0.15, albedo less than or equal to 0.20, and albedo greater than 0.20, to study the pixels trend analysis of 30 randomly selected pixels in both areas. The mean value, average slope value and its standard deviation of each class in both areas are calculated so as to determine the impacts of ORVs on land cover change in the Algodones Dunes. A simple t-test is conducted to test the differences in mean value and average slope value of pixels between the protected area and recreational area.

Transects Study

To identify the differences of land surface temperature between protected area and recreational area, four transects are established across the state route 78 (Figure 6). Each transect with width interval of 2 km covers seven pixels in each area. The variables of land surface temperature, includes both daytime and nighttime LST, are analyzed in the transects study. The mean land surface temperature of the seven pixels in each area is calculated in order to compare the difference of the variables between the areas and identify the impacts of OHV activity on land cover change. A simple t-test is conducted to test the differences in mean value of pixels between the protected area and recreational area.

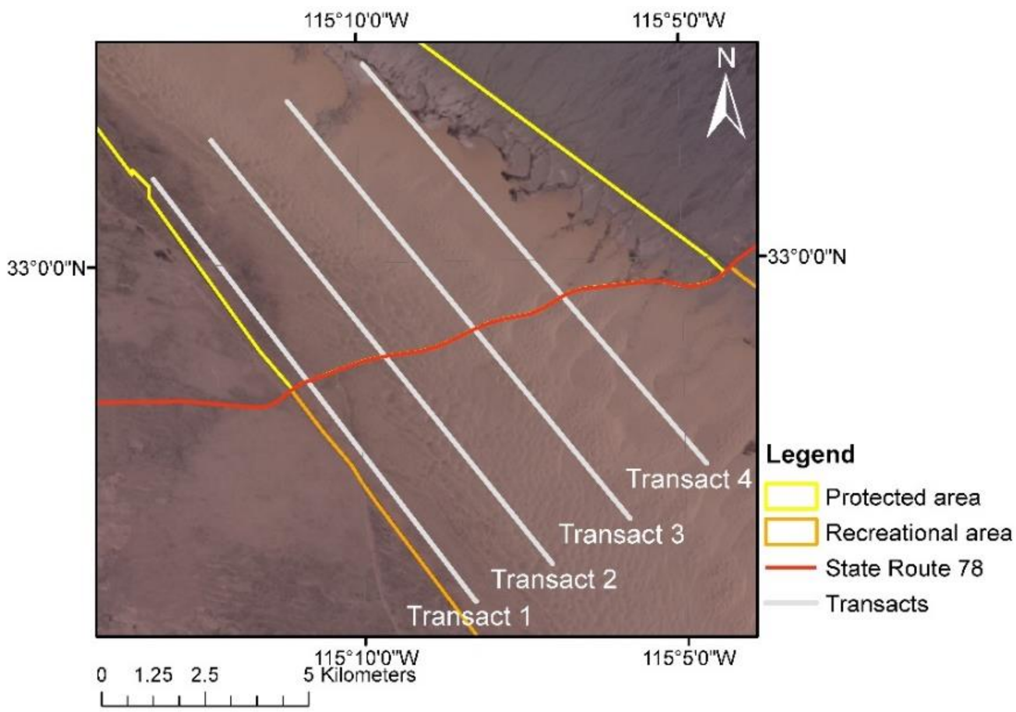


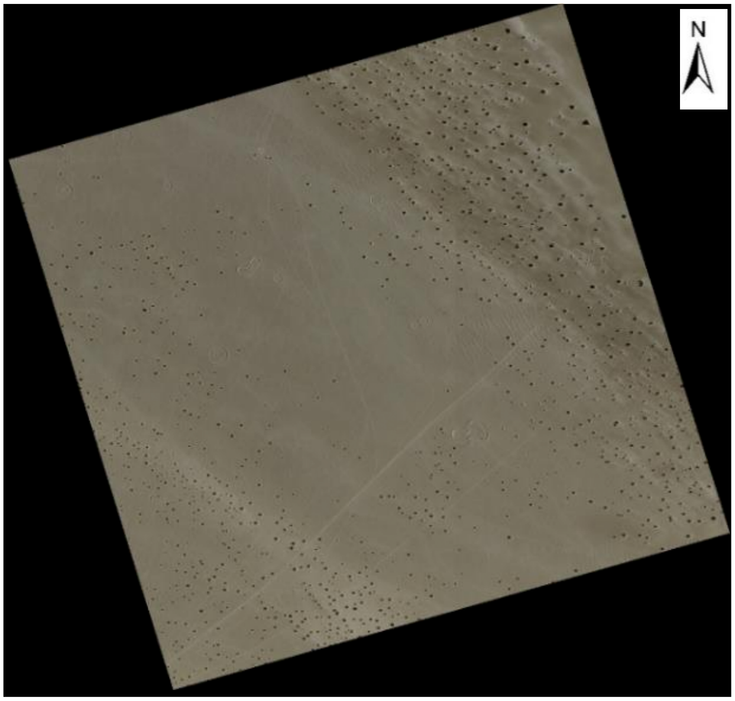
Figure 6 Four transects are established across the state route 78. Each transect is 13 km long with the width interval of 2 km. It consists of seven pixels in each protected area and recreational area.

3.2.2 Land Covers Classification and Vehicle Tracks Digitizing

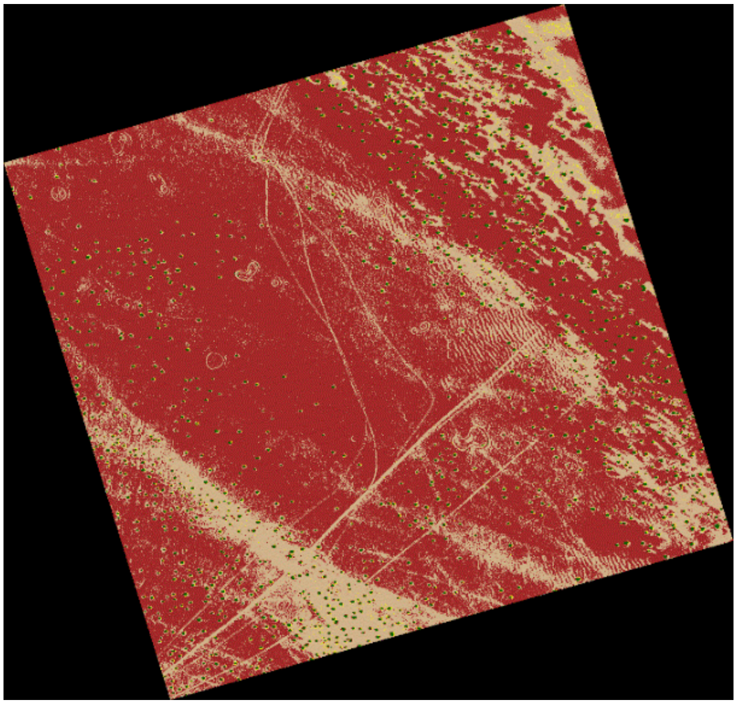
To examine the land cover change in the dune field, the high-resolution aerial photographs of the study areas are used to conduct unsupervised classification in the ERDAS Imagine software. It used the ISODATA algorithm, which computes the minimum spectral distance formula to form clusters, to perform the unsupervised classification. Four land cover classes are established in this analysis, including vegetation, soils with a brighter tone, soils with a dark tone, and anthropogenic features (Figure 7b). Soils with different particle size result in different soil colors on the remotely sensed data due to the variation of spectral reflectance (Baumgardber et al., 1986; Post et al., 2000). The soils with finer particle size have a higher spectral reflectance and cause a brighter tone on a satellites image or aerial photographs, while the coarse-grained soils have a darker tone on the image due to the low spectral reflectance (Stoner and Baumgardner, 1981; Jacquemoud et al., 1992). The anthropogenic features include buildings, roads, camping tracks, and OHVs. The total area of each class is calculated in order to illustrate the land cover change of the dune field over time.

The classification can only capture some of the vehicle tracks in the study area; therefore, manually digitizing the vehicle tracks is also conducted in ArcMap to calculate the length of the vehicle tracks in all three study areas. The major vehicle tracks can be recognized in the images with high spatial resolution. Those vehicle tracks have been digitized manually in the ArcMap 10.5 (Figure 7c). The total track length of OHV activity in each study areas is computed to analyze the use and pattern of OHV activity in the Algodones Dunes. A simple t-test (p-value$\leq$1) is conducted to test the statistical differences on different classes between the NADW control site and Glamis OHV area/ Dune Buggy Flats OHV area.

(a)



(b)



(c)

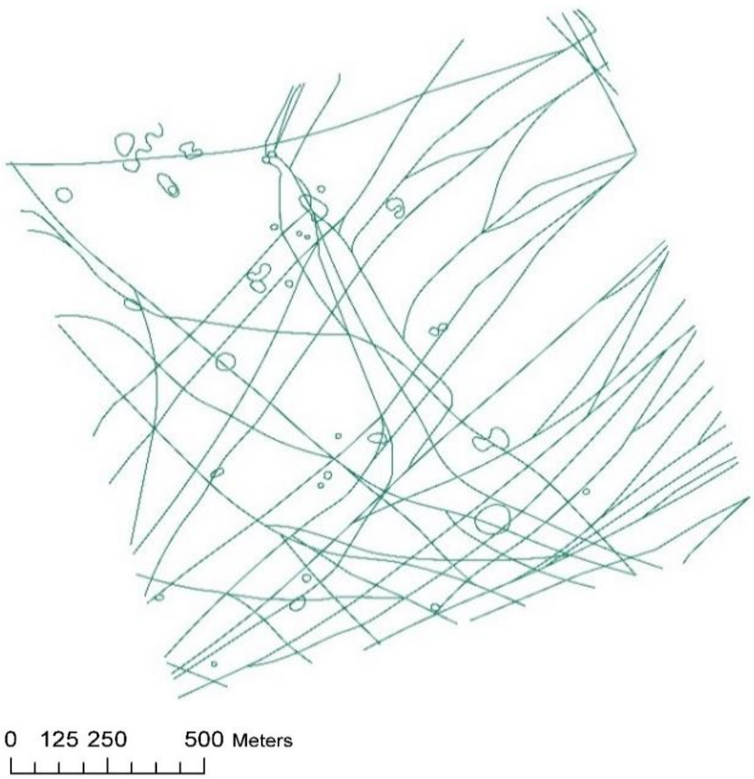


Figure 7 Data processing of the high-resolution aerial photographs. Figure a is a 1m-resolution aerial photograph acquired in June 2014 in the Buttercup study area. The classified image is shown as figure 7b. Figure 7c is the result of digitized vehicle tracks.

3.2.3 Statistical Analysis

To test the hypothesis that the OHV activity is the dominant cause leading to the differences on the land cover between the NADW and OHV area, a matrix is established to conduct the Pearson's correlation coefficient and multiple regression analysis. The matrix consists of the variables of the amount of area cover of each class in each study area, climatic variables retrieved from the Cahuilla weather station, Palmer Drought Severity Index of the Southeast Desert Basin from NOAA, and visitation data from the BLM, is established. As most of the remotely sensed data is acquired in April, May, and June, the climatic variables in this matrix are calculated as its corresponding month. The visitation data is also adjusted as the total number of visitations in three months prior to the acquisition of the images.

The Pearson's correlation coefficient is a common statistical test to measure the strength of the linear association between two variables. It is used to test the linear relationship between the local and long-term regional climatic variables, such as temperature, rainfall, and wind variables, and Palmer Drought Severity Index (PDSI), and between MODIS data, such annual mean NDVI and annual mean albedo, and total visitation. The significance of the correlation analysis is *p*-value less than or equal to 0.1.

Multiple regression analysis is adopted in the study in order to analyze the relationship between land cover change, climatic factors, and visitation data. The dependent variable of the analysis is the amount of vegetation cover in each study area. As there are only 8 years of available high-resolution aerial photographs, it reduced the sample size and limited the number of predictors in the analysis. The independent variables are drift potential, Palmer Drought Severity Index, total visitation, and the vehicle track length of the corresponding study area. The test result is significant when the *p*-value is less than or equal to 0.1.

4 RESULTS

4.1 Climatic Variations

4.1.1 Algodones Dunes

The Algodones Dunes experience a typical arid climate, which has a high annual average air temperature and low annual rainfall. The results of the local climatic data illustrated that there was an increase in the annual average air temperature during the study period (Figure 8a). The annual average temperature of the dune field between 2001 and 2016 was in a range from 24.06℃ to 25.54℃. The lowest annual average air temperature occurred in 2004 and 2010, and the air temperature increased steadily from 2010 to 2016. The results of the seasonal average air temperature illustrated that there is a substantial difference in average air temperature between summer and winter. The average air temperature of the dune field in summer generally exceeded 30℃, while the air temperature only reached 16℃ to 18℃ in winter. This is the same as the trend of the annual average air temperature. Both summer and winter average air temperature showed a slightly increasing trend between 2001 and 2016.

The annual total rainfall of the dune field was decreasing from 2001 to 2016 (Figure 8b). The annual rainfall was lower than 100 mm in most of the years. It had lower annual rainfall in 2004, 2007 and 2014, which are 24.89 mm, 26.67 mm and 19.56 mm respectively. The highest rainfall that the dune field received was 212.34 mm, which occurred in 2005. The results of the seasonal rainfall indicated that in most of the years, the rainfall that occurred in the winter season was higher than that in the summer season. The winter average rainfall between 2001 and 2016 was 23.81 mm, while summer average rainfall was 12.89 mm. In the summer season of 2002, 2013, and 2016, the dune field did not receive any rainfall. The results also revealed that there was an increasing trend of the total winter rainfall, and a decreasing trend of the total summer rainfall from 2001 to 2016.

According to Fryberger's (1979) classification of wind energy environments, the local wind regime of the Algodones Dunes is classified as lower wind-energy and intermediate obtuse to acute bimodal directional variability. The total DP of the dune field was in a range of 11 vector units and 21.07 vector units, and the RDP was between 4.99 vector units and 11.98 vector units (Figure 9a). The highest DP and RDP appeared in 2007. The results revealed that the winds of the Algodones Dunes have a lower energy to transport the sediments. The wind variability index of the dune field was between 0.37 to 0.67 (Figure 9b). It indicates that the variations in the sand drift direction are intermediate, which may have one to two dominant drift directions. The results of RDD reported the sand drift direction were mainly from 70° to 125° (Figure 9c), which are from east-north-east to southeast. The wind regime of the dune field was varied seasonally (See Appendix I). The seasonal sand roses showed that the sediment transportation is more active in the spring season as it has a higher DP (27.61 vector units), RDP (20.51 vector units) and wind variability index. The RDD was at 90°, which implies that the westerly wind is dominant in spring and the sand drifts toward the east. The sediment transportation is less active in the summer and autumn season due to the lower DP, RDP and wind variability index. The RDD of summer, autumn and winter were 22°, 121°, and 124° respectively, which mean southerly winds are dominant in summer, and it changes to north-westerly winds in autumn and winter.

The Palmer Drought Severity Index (PDSI) is a useful indicator to measure the dryness of the region based on air temperature and rainfall. There have been seven moderate droughts (PDSI $\leq$ -2), two severe droughts (PDSI $\leq$ -3), and two extreme droughts (PDSI ≤ -4) in the basin since 2001. The most severe drought event was recorded in 2007, which PDSI is -4.38 (Figure 8c). There was a prolonged drought that occurred from 2012 to 2016, which had three moderate droughts and two severe droughts. The highest positive value was recorded in 2005, which is 5.49. It indicated that the Southeast Desert Basin has an extremely high amount of moisture in 2005, which is matched with the results of the local climatic data that the Algodones Dunes received intense rainfall in the year of 2005. The correlations of the PDSI and local climatic variables are shown in Figure 10. There is a significant negative correlation between the PDSI and annual mean air temperature ($r = -0.846$, $p = 0.000$), and a positive correlation between the PDSI and annual total rainfall ($r = 0.846$, $p = 0.000$). The temperature and rainfall are two critical factors needed to calculate the PDSI; thus, they showed a strong association with the PDSI. However, the associations between PDSI and the wind variables is not statistically substantial. It implies that the occurrence and intensity of drought may not influence the aeolian activities in the dune field.

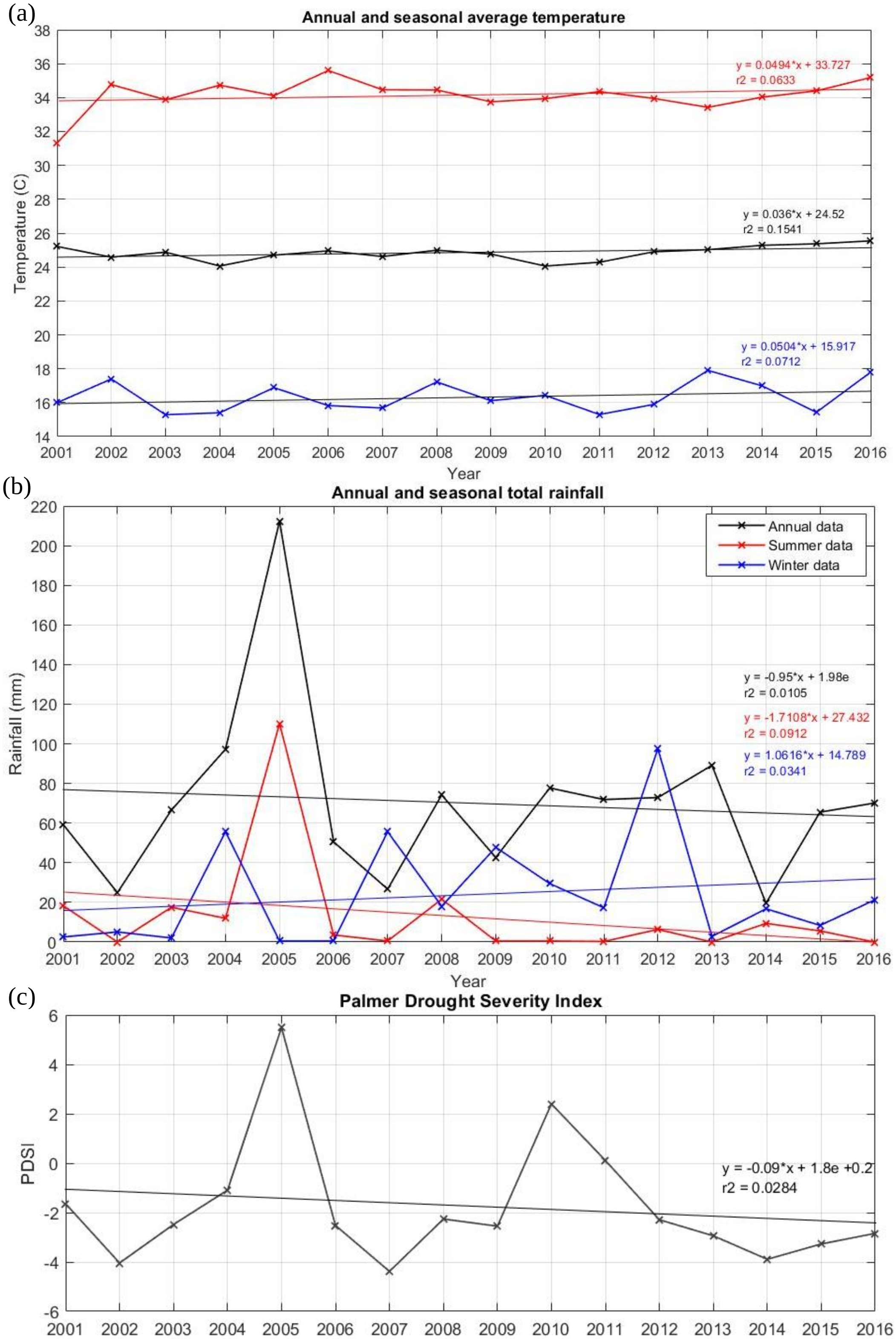


Figure 8 The annual and seasonal average temperature (a) and total rainfall (b) of the Algodones Dunes. Summer season includes the month of June, July, and August; winter season includes November, December, and January (following year). Figure 8c shows the Palmer Drought Severity Index of the Southwest Desert Basin from 2001 to 2016.

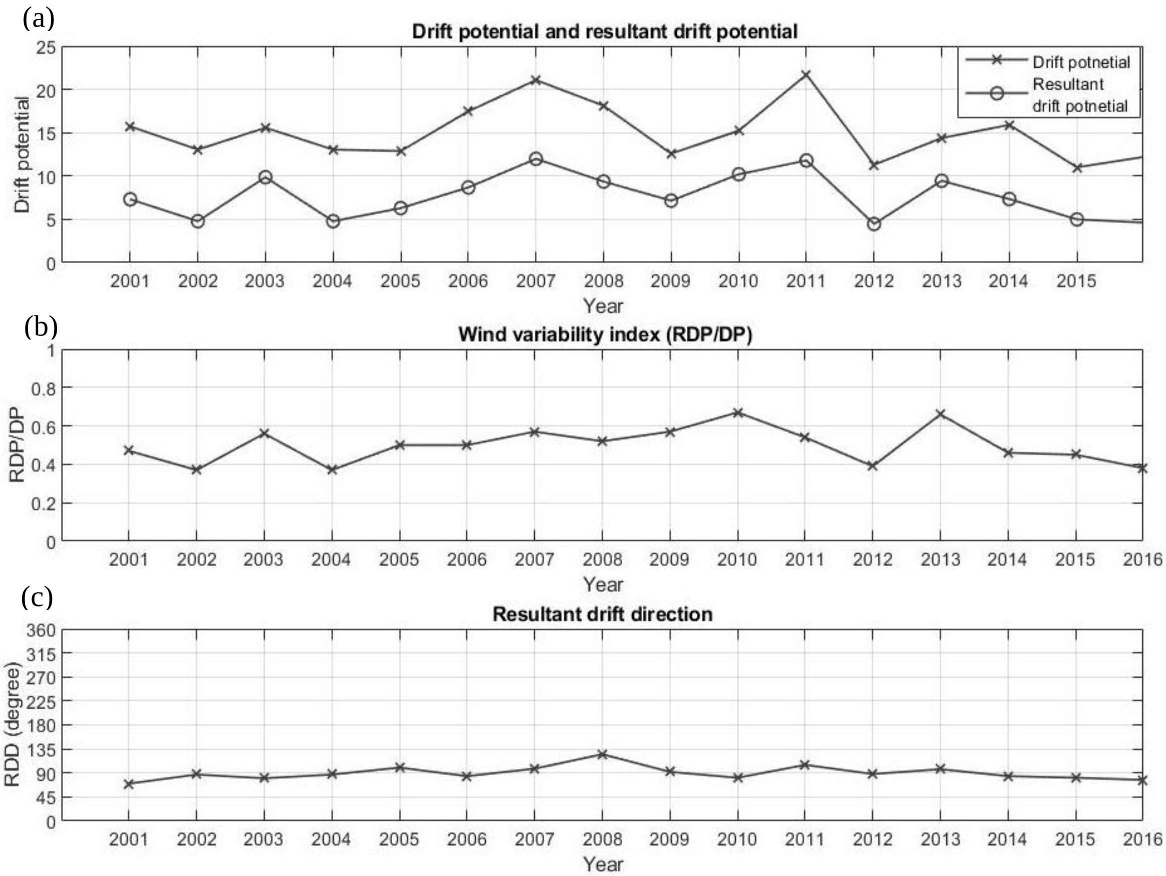


Figure 9 The annual DP, RDP (a), wind directional variability (RDP/DP) (b) and resultant drift degree (RDD) of the Algodones Dunes generated by the 16-years record hourly wind speed and direction data.

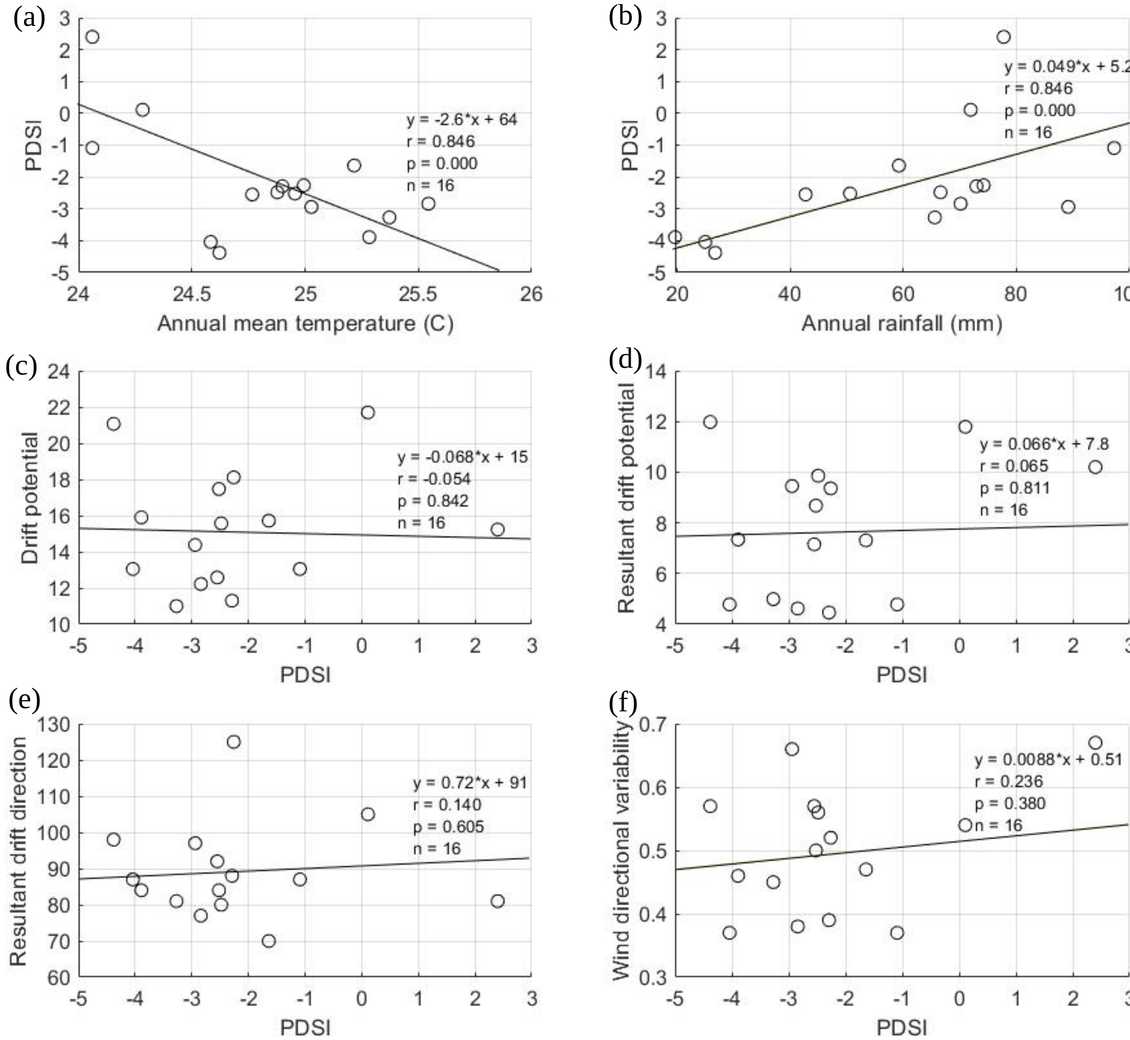


Figure 10 The results of the Pearson's correlation coefficient between Palmer Drought Severity Index (PDSI) and other variables, such as annual average temperature (a), annual rainfall (b), DP (c), RDP (d), RDD(e), and wind directional variability (RDP/DP) (f).

4.1.2 Long-term Regional Climatic Variations

The Southeast Desert Basin in California (Figure 1) also experienced a substantial increase in the annual average air temperature and a slight decline in the annual precipitation in the past century. The annual average air temperature of Southeast Desert Basin raised significantly from 17.33℃ in 1895 to 19.5℃ in 2016, which the temperature increased by 2.17℃ (Figure 11a). The results also illustrated that there were some temperature anomalies that occurred in the past century. In the year of 1934, 1981, 1996, 2003, 2007, 2012, 2014, 2015, and 2016, the annual average air temperature of the region exceeded 19℃. The highest annual average air temperature was 20℃ which occurred in 2014. The basin had an anomalous low annual average air temperature in 1912, 1944, 1998, which was 16.44℃, 16.78℃, and 17.28℃ respectively. The average annual rainfall of the southeast desert basin in California between 1895 and 2016 was 155.67 mm. The annual rainfall of the basin exceeded 300 mm in the year of 1941, 1978, and 1983, while the lowest annual rainfall occurred in 1953 with 49.78 mm (Figure 11b). A Pearson's correlation coefficient analysis is computed to assess the relationship between annual average air temperature and annual rainfall of the Southeast Desert Basin (Figure 12a). The results stated that there is a negative relationship between the two variables, $r = -0.185$, $p = 0.042$. It implies that the higher temperature in the region resulted in the increase of dryness in the region.

The mean PDSI of the Southeast Desert Basin between 1895 and 2016 was -0.45, which indicates that the basin experienced drought events with different intensity in the past century (Figure 11c). PDSI is inversely correlated with the annual average air temperature ($r = -0.473$, $p = 0.000$) (Figure 12b), and is positively correlated with annual rainfall ($r = 0.803$, $p = 0.000$) (Figure 12c). The results indicated that the dryness of the region increases when the air temperature rises and rainfall declines; thus, it increases the occurrence and intensity of the drought.

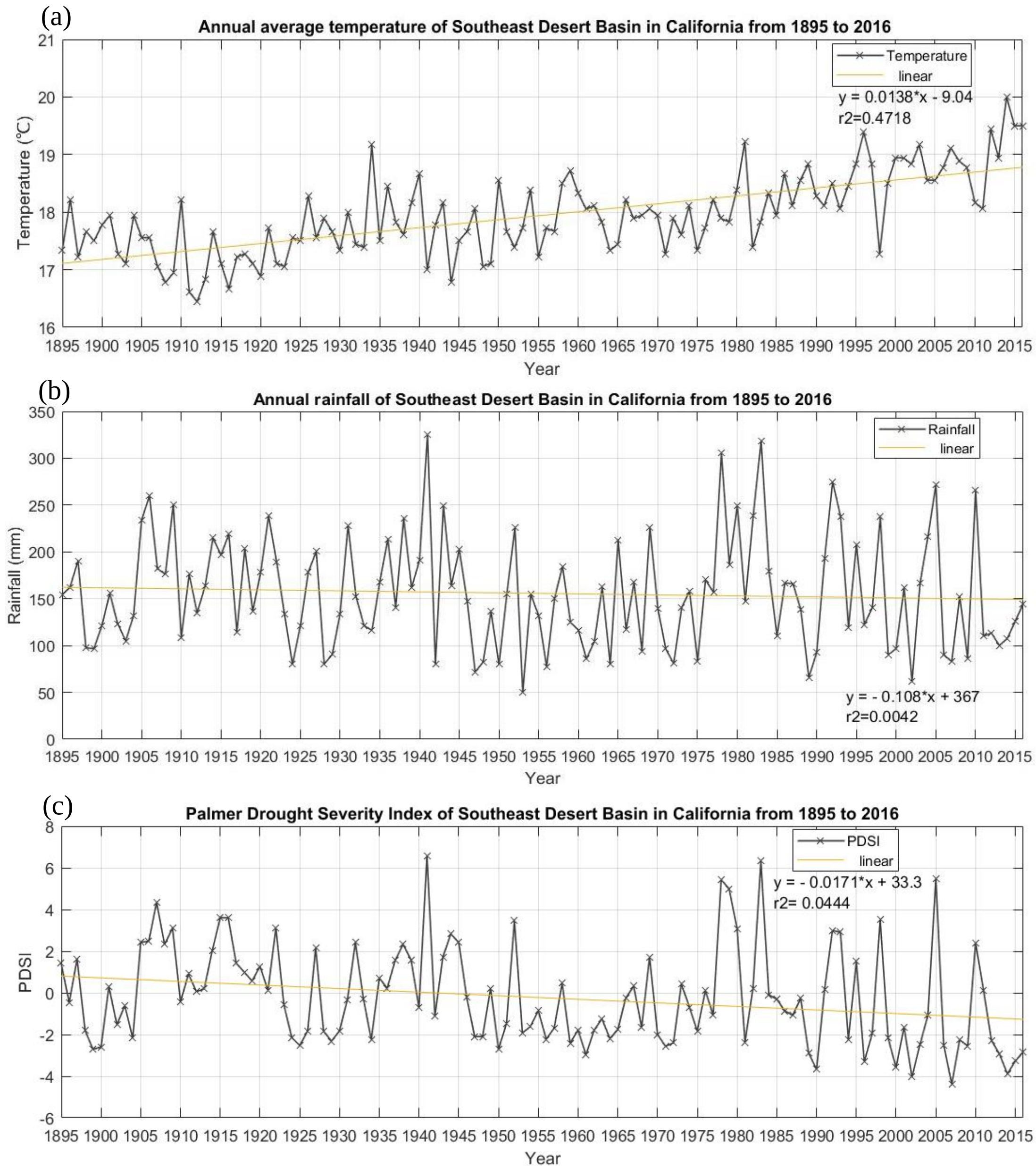


Figure 11 The annual average temperature(a), annual rainfall (b) and Palmer Drought Severity Index (c) of the Southeast Desert Basin in California from 1895 to 2016.

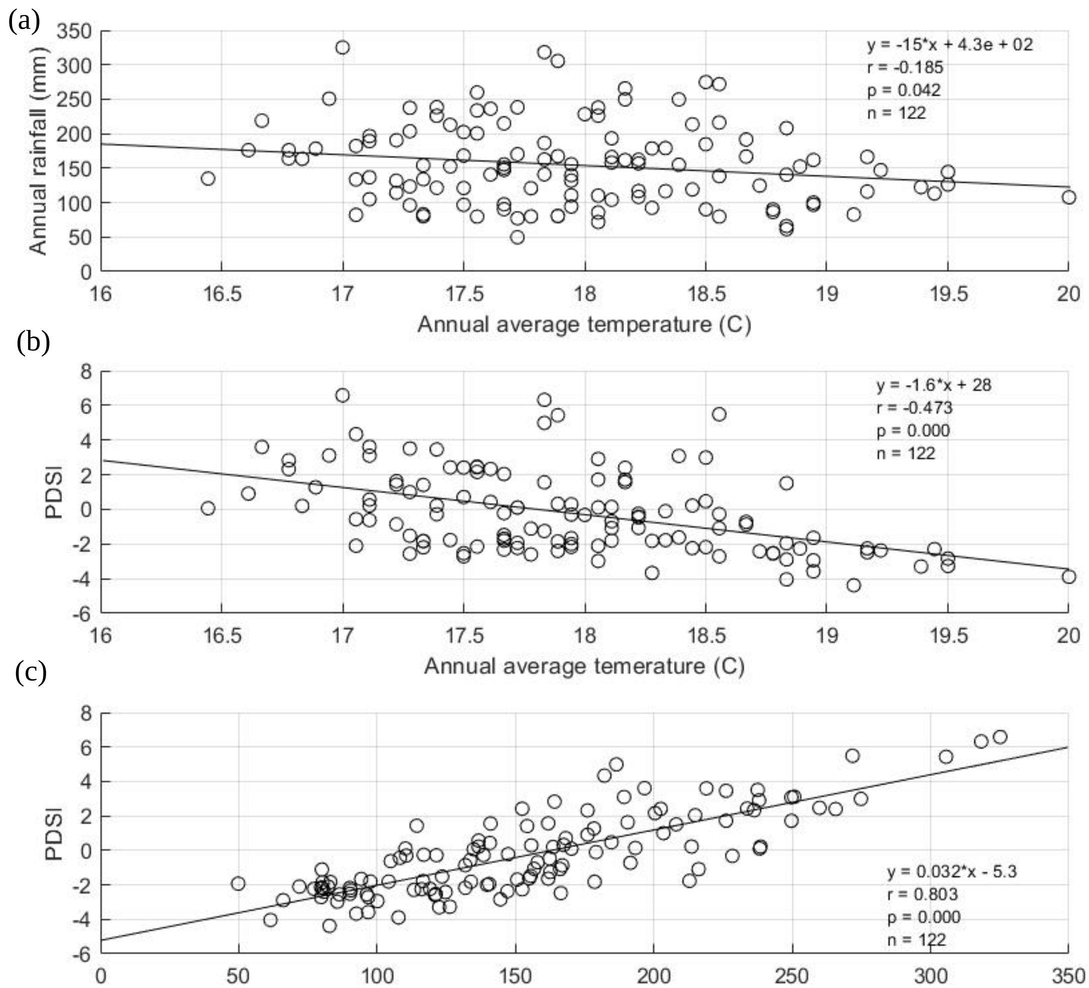


Figure 12 The results of the Pearson's correlation coefficient between annual average temperature and annual rainfall (a), between annual average temperature and PDSI (b), and between annual rainfall and PDSI (c).

4.2 Dune Visitation and OHV Tracks

The total visitation of the Algodones Dunes decreased significantly between 2002 and 2017, from 1.42 million in 2002 to 0.8 million in 2017 (Figure 13a). The maximum visitation appeared in 2005, which had 1.46 million people visit the dune field. There was a substantial decreasing trend of dune visitation since 2007, which dropped 45% between 2007 and 2017. Figure 13b illustrates the 12-months visitation of the Algodones Dunes. It showed that the Algodones Dunes received more visitation from late-October to mid-February, while there was less visitation during the summer season from March to September. Moreover, the number of visitations is mainly associated with the date of the holidays. Thanksgiving is the holiday that the dune field receives the maximum visitation throughout the year. During the week of Thanksgiving in 2014 and 2016, 127 thousand and 102 thousand people entered the dune field respectively. Other major holidays, such as New Years, President's day, Halloween, and Christmas also attract many visitations to the Algodones Dunes.

The results of digitalizing OHV tracks indicated that there are many OHV traffics in the Glamis OHV area and Dune Buggy Flats OHV area, while there were no any vehicle tracks identified in all the available aerial photographs in the NADW control site (Figure 14). Glamis OHV area is the study area that received the most OHV activity as its total track length of the OHV is higher than that in the Dune Buggy Flats OHV area in most of the years with available high-resolution aerial photographs. The average total track length of OHV activity across all the years in the Glamis OHV area was 40.88 km, which is higher than of 36.4 km in the Dune Buggy Flats OHV area over the same period of time. With the decreasing trend of annual visitation in the Algodones Dunes, Glamis OHV area also showed a similar pattern in the decline of the total length of OHV tracks in the area from 51.9 km in 2002 to 45.31 km in 2016. In the meantime, Dune Buggy Flats OHV area had an increasing trend of OHV track length, which raised rapidly from 21.48 km in 2002 to 56.95 km in 2011, and declined to 24.17 km in 2016.

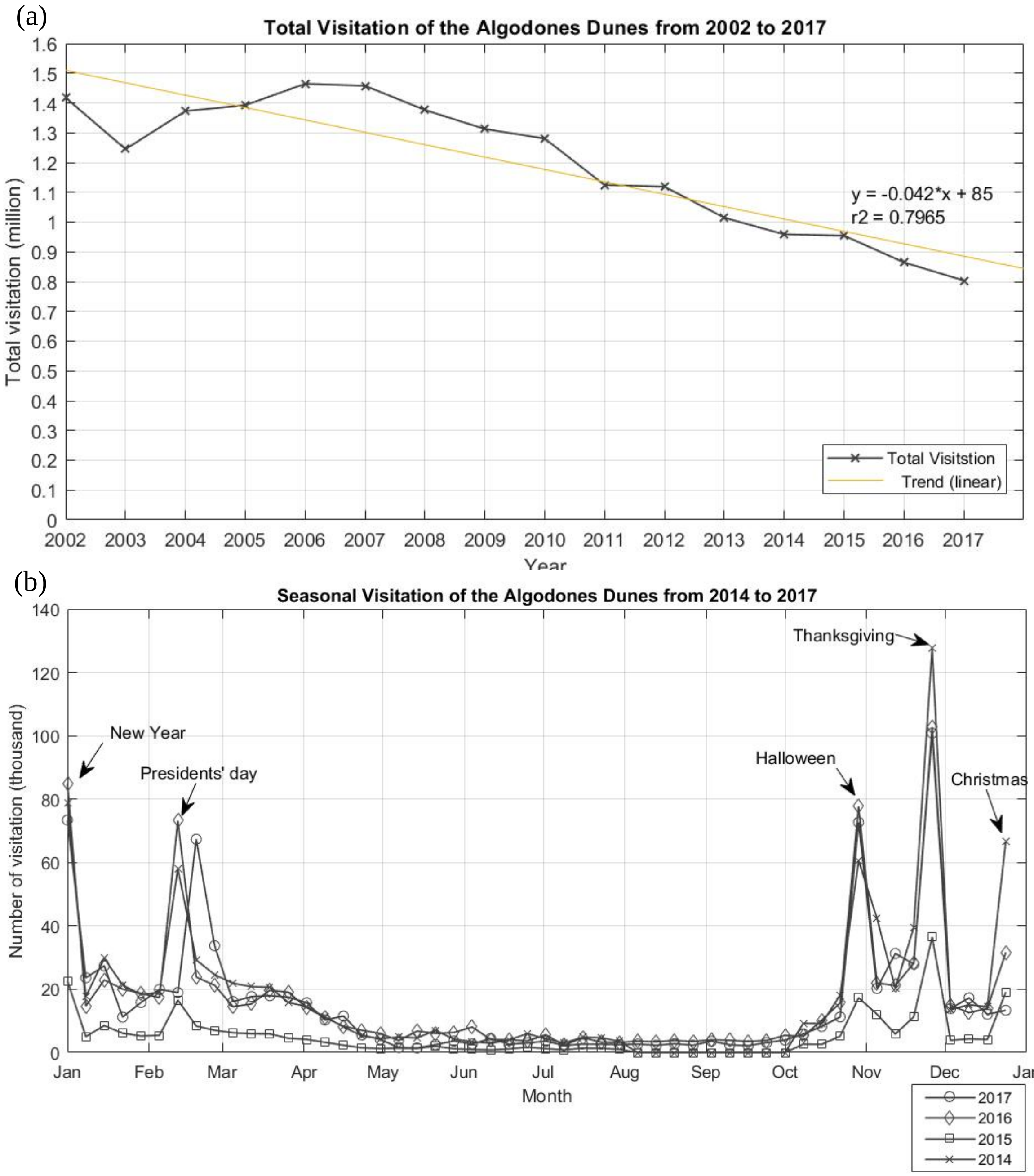


Figure 13 The graphs showing the annual visitation (a) and seasonal visitation (b) of the Algodones Dunes.

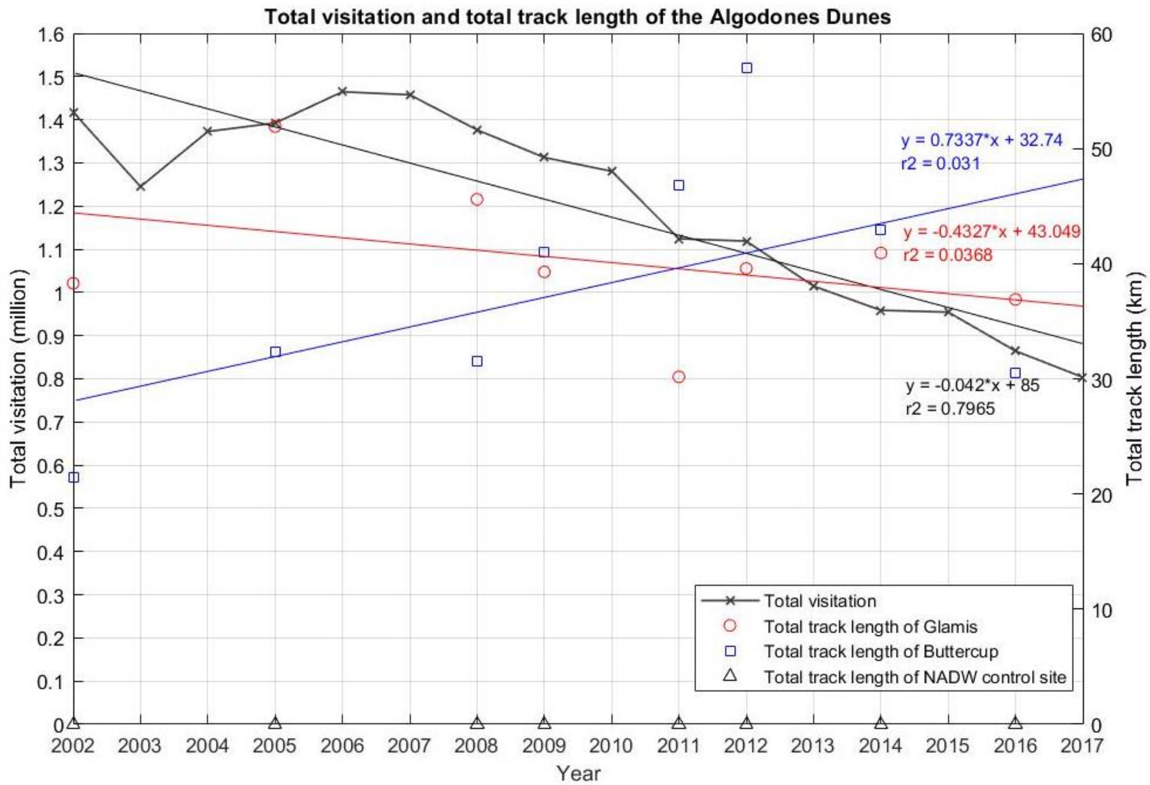


Figure 14 A graph illustrates the trend of the total visitation of the Algodones Dunes and the total track length of OHVs in the Glamis OHV area and Dune Buggy Flats OHV area.

4.3 Land Cover Changes

4.3.1 MODIS Time-series Analysis

Annual time-series analysis

The results of annual mean NDVI and albedo illustrate that there is a significant difference between the protected area and recreational area in the Algodones Dunes. The annual mean NDVI value of the protected area was substantially higher than the recreational area from 2001 to 2016 (Figure 15a). The average annual NDVI value of the protected area was 0.1045, which is higher than the recreational area with an average annual NDVI value of 0.0895. In general, both protected area and recreational area showed a decreasing NDVI trend from 2001 to 2016, which indicates that the vegetation cover of both areas has declined during the study period. The annual average NDVI decreased more significantly in the northern part of the dune field, and upper and lower part of the recreational area (Figure 16a), while most of the dune field experienced a substantial increase trend in both daytime and nighttime LST (Figure 16c and 16d). The highest annual mean NDVI value of dune field occurred in 2005, which was 0.1374 and 0.0987 in the protected area and recreational area respectively. Both areas had the lowest annual mean NDVI value in 2016, which was 0.0917 and 0.0847 respectively. The annual mean NDVI value of the protected area was lower than 0.1 in the year of 2002, 2012, 2015, and 2016. It implied that the amount of vegetation cover in the dune field decreases in those years due to the climatic variations.

Both protected area and recreational area have a high albedo rate due to the high spectral reflectance of the bare soil surface. The annual mean albedo of the protected area is substantially lower than the recreational area from 2001 to 2016 (Figure 15b). The average annual albedo of the protected area was 0.2293, which is lower than the recreational area with the value of 0.2507. The annual albedo trend showed that both protected area and recreational area have an increasing trend with the slope value of 0.3591 and 0.3808 respectively (Figure 15b and Appendix II). As the spectral reflectance of the soil surface is higher than that of vegetation, the results revealed that there is less soil exposure in the protected area than the recreational area, and both areas experienced an increase of soil exposure during the study period. The lowest annual mean albedo was 0.2083 in the protected area and 0.2372 in the recreational area that showed in 2005. The results of annual mean NDVI and albedo indicated that the dune field has the highest amount of vegetation cover in the year of 2005 as the increase of vegetation cover results in a higher NDVI value, and the presence of vegetation protects the soil surface and reduces the albedo rate.

The results of the Pearson's correlation showed that the OHV track length is positively correlated with the annual mean NDVI and negatively correlated with annual mean albedo in both Glamis OHV area and Dune Buggy Flats OHV area; however, the correlations are not statistically significant (Figure 17). The results only explained less than 20% of variance of the data.

The time-series analysis of the annual daytime and nighttime LST revealed that the protected area and recreational area shared a similar increasing trend from 2001 to 2016 (Figure 15c and 15d). The average annual daytime temperature of the protected area and recreational area were 41.79℃ and 41.71℃, while the average annual mean nighttime temperature of the protected area and recreational area were 17.97℃ and 17.88℃ respectively. The protected area has a slightly higher annual mean daytime and nighttime temperature than the recreational area; however, there are no any substantial differences in LST between the protected area and recreational area.

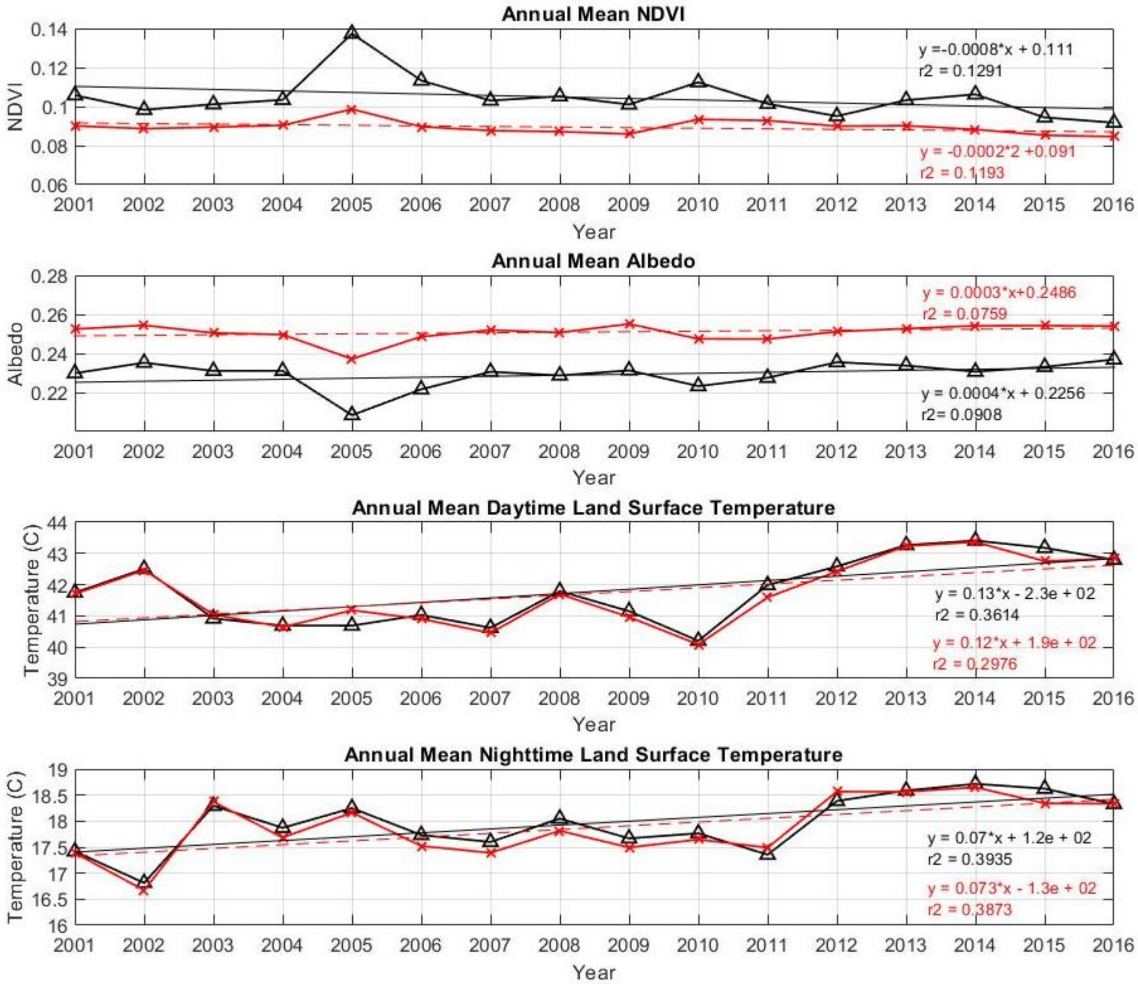
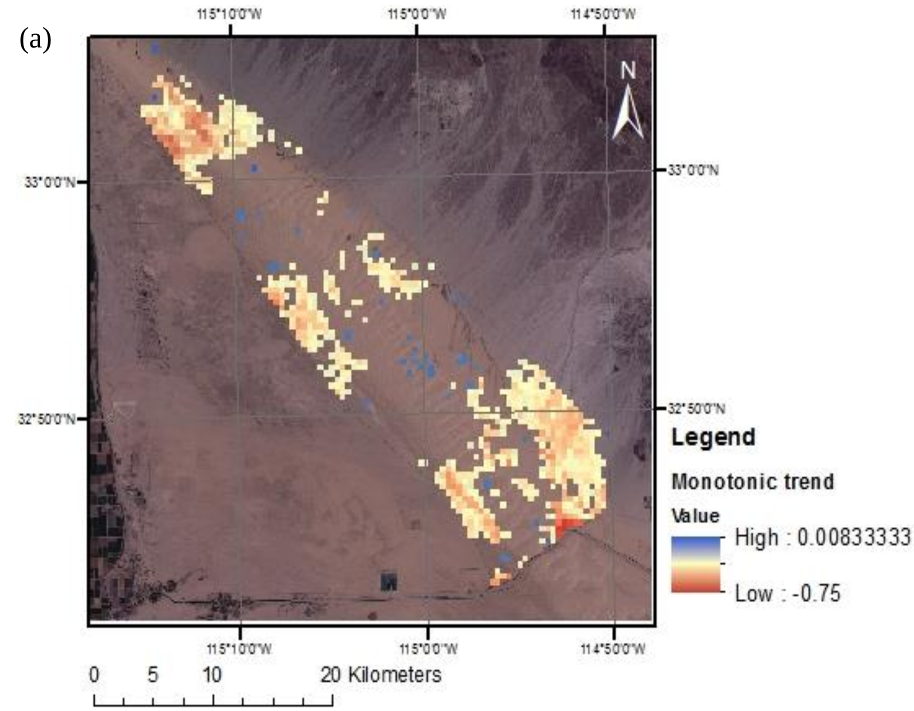
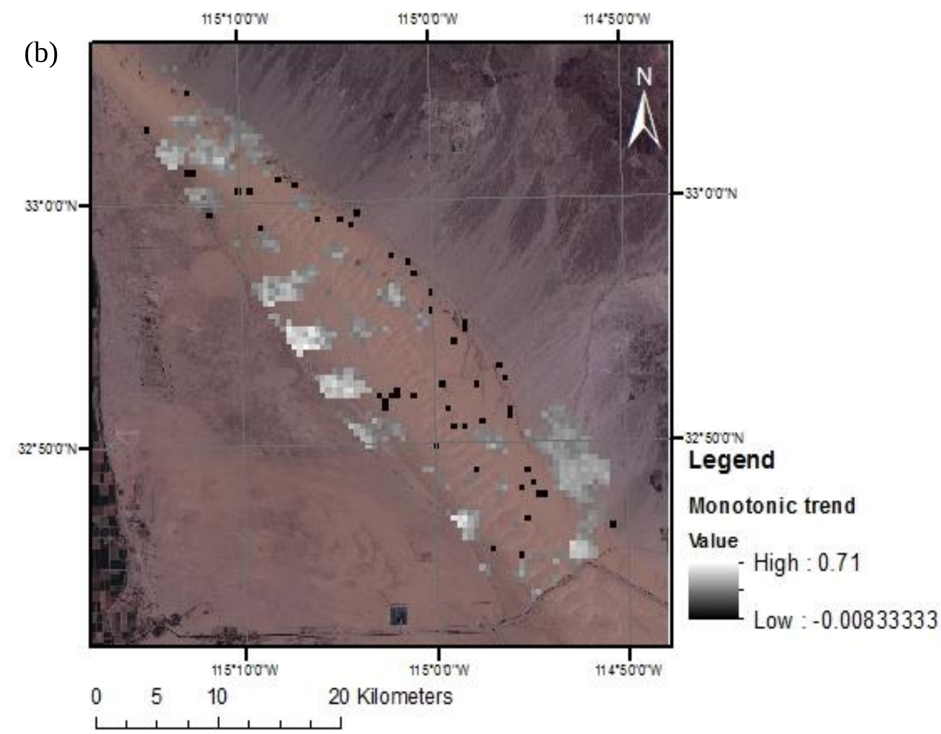


Figure 15 Annual mean value and trend of NDVI (a), albedo (b), daytime temperature (c) and nighttime temperature (d) of the protected area and recreational area in the Algodones Dunes from 2001 to 2016.

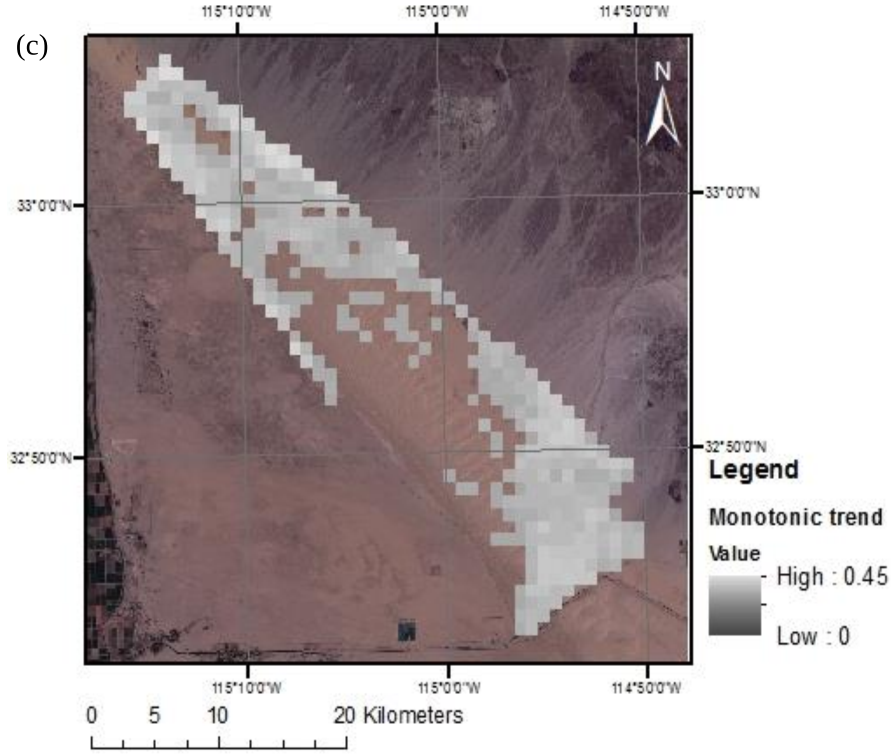
(a)


115°10'0"W
115°0'0"W
114°50'0"W
33°0'0"N
32°50'0"N
N
Legend
Monotonic trend
Value
High : 0.00833333
Low : -0.75
0 5 10 20 Kilometers

(b)


115°10'0"W
115°0'0"W
114°50'0"W
33°0'0"N
32°50'0"N
N
Legend
Monotonic trend
Value
High : 0.71
Low : -0.00833333
0 5 10 20 Kilometers

(c)



(d)

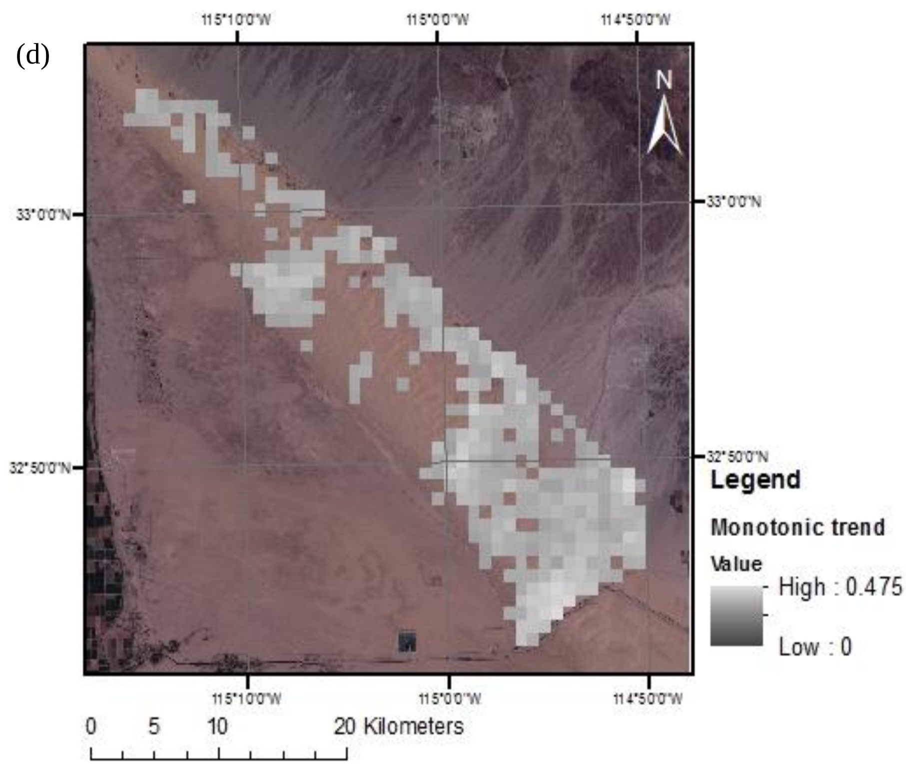


Figure 16 Maps showing the slope value of the pixels that is statistically significant ($p \leq 0.1$) with the variable of annual NDVI (a), albedo (b), daytime land surface temperature(c) and nighttime land surface temperature (d).

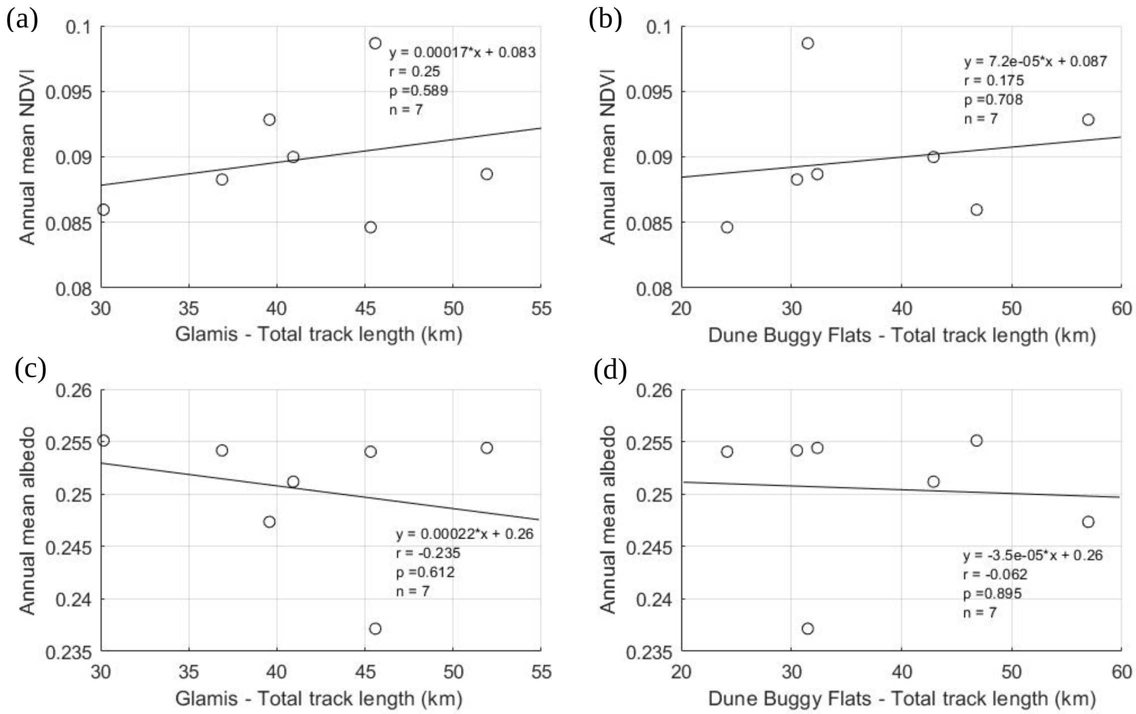


Figure 17 The results of the Pearson's correlation coefficient between annual mean NDVI of the recreational area and the total track length of Glamis OHV area (a) and Dune Buggy Flats OHV area (b), and between the annual mean albedo of the recreational area and the total track length of Glamis OHV area (c) and Dune Buggy Flats OHV area (d).

Seasonal Time-series Analysis

The seasonal time-series analysis of NDVI and albedo illustrates that the protected area has a higher NDVI and lower albedo than the recreational area in both summer and winter seasons from 2001 to 2016 (Figure 18a, 18b, 19a and 19b). It revealed that the protected area preserves more vegetation cover than the recreational area because of the restricted usage of ORVs activities in the protected area. Both areas experienced a decreasing trend in NDVI and increasing trend in albedo in both summer and winter seasons, which implies that the amount of vegetation cover was decreasing in both protected area and recreational area between 2001 and

2016. Moreover, both protected area and recreational area has a higher NDVI in winter than summer. The average winter NDVI of the protected area and recreational area were 0.1048 and 0.0896, while in summer, the average NDVI of the protected area and recreational area are 0.1002 and 0.0885. The results indicate that the vegetation in the dune field may primarily grow in the winter season rather than the summer season. Same as the results of the annual mean NDVI and albedo, the dune field had the highest NDVI value and lowest albedo rate in 2005 in both summer and winter seasons.

The summer daytime and nighttime LST time-series analysis revealed that the protected area had a slightly higher average mean daytime and nighttime temperature than the recreational area in most of the years from 2001 to 2016 (Figure 18c and 18d). The average summer mean daytime temperature of the protected area and recreational area were 56.48℃ and 56.01℃, while the average summer mean nighttime temperature of the protected area and recreational area were 28.98℃ and 28.57℃. And both protected area and recreational area experienced an increasing trend of summer daytime and nighttime LST between 2001 and 2016. For the winter daytime and nighttime LST, the results showed that there are no substantial differences between the protected area and recreational area (Figure 19c and 19d. The winter daytime temperature of the protected area and recreational area were 27.75℃ and 27.93℃, while the winter nighttime temperature of the protected area and recreational area were 8.29℃ and 8.38℃. The results of the seasonal LST indicated that there is substantial temperature difference between daytime and nighttime, and also between the summer and winter season in the Algodones Dunes.

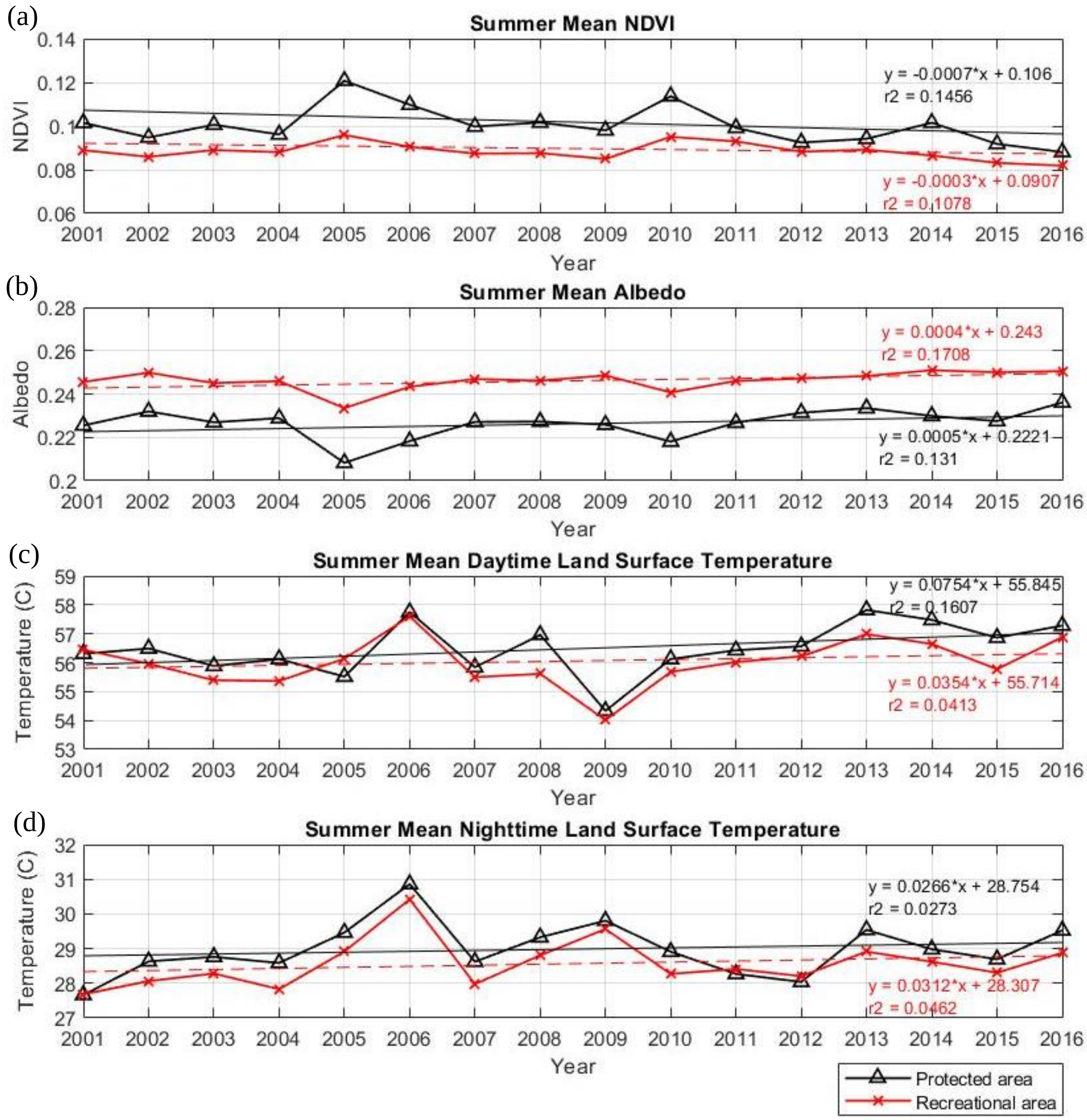


Figure 18 Summer mean value and trend of NDVI (a), albedo (b), daytime temperature (c) and nighttime temperature (d) of the protected area and recreational area in the Algodones Dunes from 2001 to 2016.

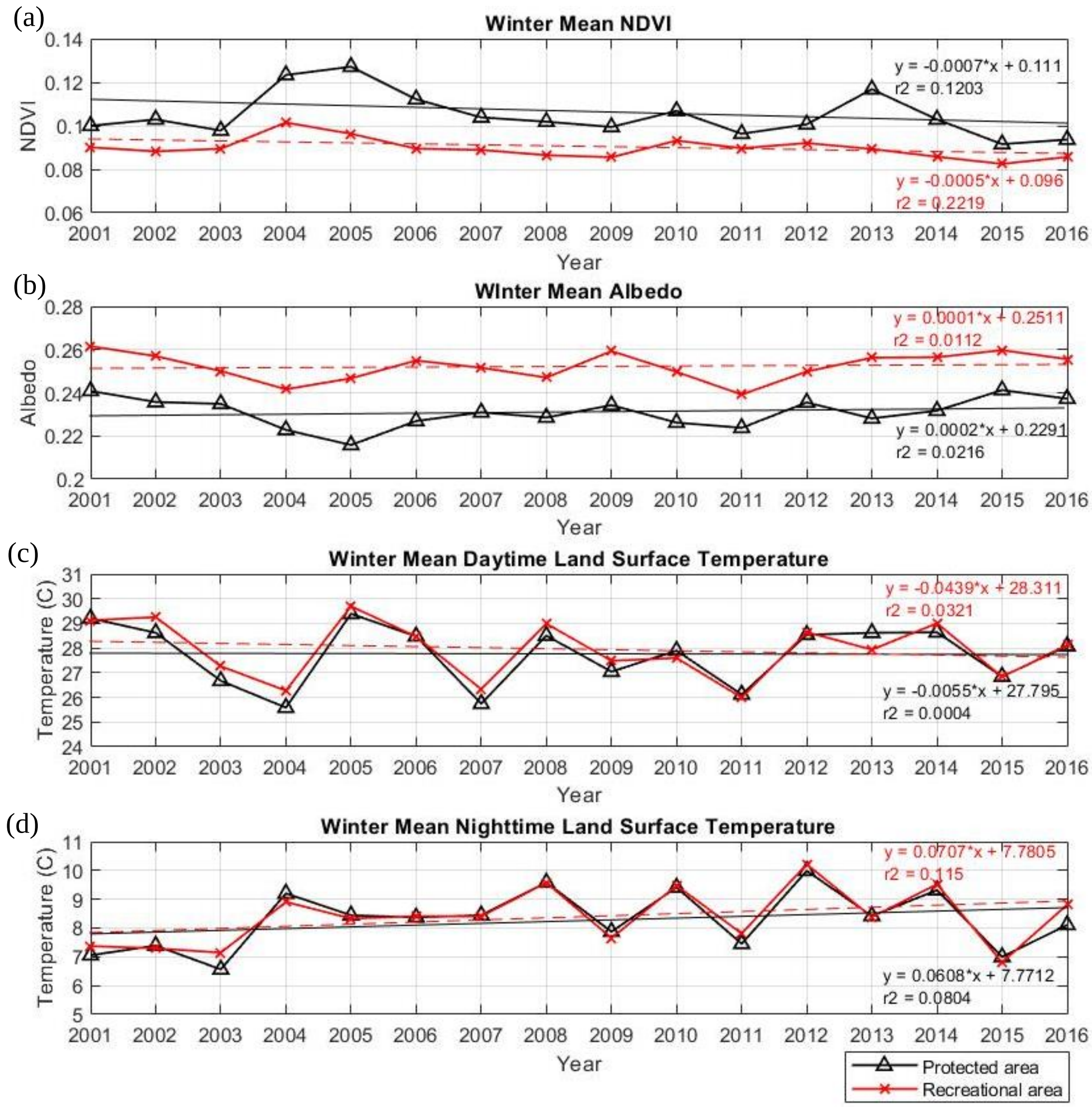


Figure 19 Winter mean value and trend of NDVI (a), albedo (b), daytime temperature (c) and nighttime temperature (d) of the protected area and recreational area in the Algodones Dunes from 2001 to 2016.

4.3.2 Pixels Trend Analysis

The trend analysis of the 30 randomly selected pixels reported that there is statistical difference in all NDVI categories between the protected area and recreational area at the significant level of 95% (Table 2). The mean NDVI value in the protected area was 0.1075, which is higher than 0.0947 in the recreational area, and also in the category of NDVI≤0.1 and NDVI>0.1, the mean NDVI value in the protected area is higher than that in the recreational area. It indicated that the protected area has more vegetation cover than the recreational area. The results of the analysis also showed that the vegetation cover in the recreational area was decreasing more substantially than the protected area as the average slope value of the pixels selected in the recreational area (-0.4520 ± 0.1718) is lower than that in the protected area (-0.4158 ± 0.1069). It also showed similar results in the category of NDVI≤0.1 and NDVI>0.1. The average slope value in the protected area and recreational area with NDVI value ≤0.1 were -0.3961 ± 0.1331 and -0.4033 ± 0.1743, and the average slope value in the protected area and recreational area with NDVI value >0.1 were -0.3921 ± 0.0626 and -0.4599 ± 0.1053.

The albedo of the dune field was increasing significantly from 2001 and 2016 as the pixels selected in both protected area and recreational area have a higher slope value, which is in a range of 0.3052 and 0.5479 (Table 3). The average slope value in the protected area and recreational area with albedo≤0.2 were 0.3555 ± 0.0504 and -0.5479 ± 0.0740, and the average slope value in the protected area and recreational area with albedo>0.2 were -0.3052 ± 0.1223 and -0.4271 ± 0.1654. It also indicated that the amount of vegetation cover in the dune field was declining during the study period. The results also revealed that the protected area has more vegetation cover than the recreation areas as the mean albedo of the protected area is slightly lower than the recreational area in all the albedo categories. In the category of albedo>0.2, the mean albedo of the recreational area (0.2470) was statistically different from that of the recreational area (0.2400) at the significant level of 90%.

Table 2 Annual NDVI trend analysis of 30 randomly selected pixels with p-value 0.1 in the protected area and recreational area in the Algodones Dunes.

Study area	Variables	NDVI	NDVI≤0.1	NDVI>0.1
Protected area	Mean	0.1075**	0.0907**	0.1227**
	Average slope value	-0.4158	-0.3961	-0.3921**
	Standard deviation of slope value	0.1069	0.1331	0.0626
Recreational area	Mean	0.0947**	0.0884**	0.1090**
	Average slope value	-0.4520	-0.4033	-0.4599**
	Standard deviation of slope value	0.1718	0.1743	0.1053

** statistical different between protected area and recreational area at a significance level ≤ 0.05

* statistical different between protected area and recreational area at a significance level ≤ 0.1

Table 3 Annual albedo trend analysis of 30 randomly selected pixels with p-value 0.1 in the protected area and recreational area in the Algodones Dunes.

Study area	Variables	Albedo	Albedo≤0.2	Albedo>0.2
Protected area	Mean	0.2190	0.1978	0.2400*
	Average slope value	0.3311**	0.3555**	0.3052**
	Standard deviation of slope value	0.1023	0.0504	0.1223
Recreational area	Mean	0.2303	0.1995	0.2470*
	Average slope value	0.4568**	0.5479**	0.4271**
	Standard deviation of slope value	0.1713	0.0740	0.1654

** statistical different between protected area and recreational area at a significance level ≤ 0.05

* statistical different between protected area and recreational area at a significance level ≤ 0.1

4.3.3 Transects Study

The MODIS time-series analysis does not reveal a significant difference in LST between the protected area and recreational area (Figure 15c and 15d, Appendix IV); however, the transects study showed different results (Figure 20 and 21). It illustrated that the mean daytime LST of the protected area is lower than that of the recreational area, and all transects, except the transect four in 2016, has a statistical difference in daytime LST between the protected area and recreational area in both years of 2001 and 2016 (Table 4). The mean daytime LST of the transects in 2001 was between 41.26℃ and 41.99℃ in the protected area, and between 41.46℃ and 42.43℃ in the recreational area. The differences are statistically significant between the areas at the significant level of 95%. In 2016, the mean daytime LST of the protected area was in a range of 42.24℃ and 43℃, which is generally lower than that of the recreational area (between 42.49℃ and 43.32℃). The transect three has the maximum differences in mean daytime LST, which is -0.55℃ in 2001 and -0.66℃ in 2016.

The results of nighttime LST transect study showed inverse results of the daytime LST. The mean nighttime LST of the protected area is generally higher than that of the recreational area (Figure 21 and Table 4). The protected area had the mean nighttime LST between 16.71℃ and 17.65℃ in 2001 and between 17.62℃ and 18.74℃ in 2016, while the recreational area was in a range of 16.61℃ and 17.68℃ in 2001 and a range of 17.6℃ and 18.62℃ in 2016. There is a statistical difference between the areas in the transect one and two in 2001, and transect one, two and three in 2016. The transect two has the maximum difference in mean nighttime LST, which is 0.33℃ in 2001 and 0.2℃ in 2016. The transect three shows a different result with other transect. The difference of the mean nighttime LST in the transect three is -0.12 ℃ in 2001 and -0.28℃ in 2016, which indicates that the protected area has a cooler nighttime temperature than the recreational area. The results of the transects study proved that there is a statistical difference in land cover between the protected area and recreational area, and the protected area has more vegetation cover than the recreational area as it has a lower mean daytime temperature and a higher mean nighttime temperature than the recreational area.

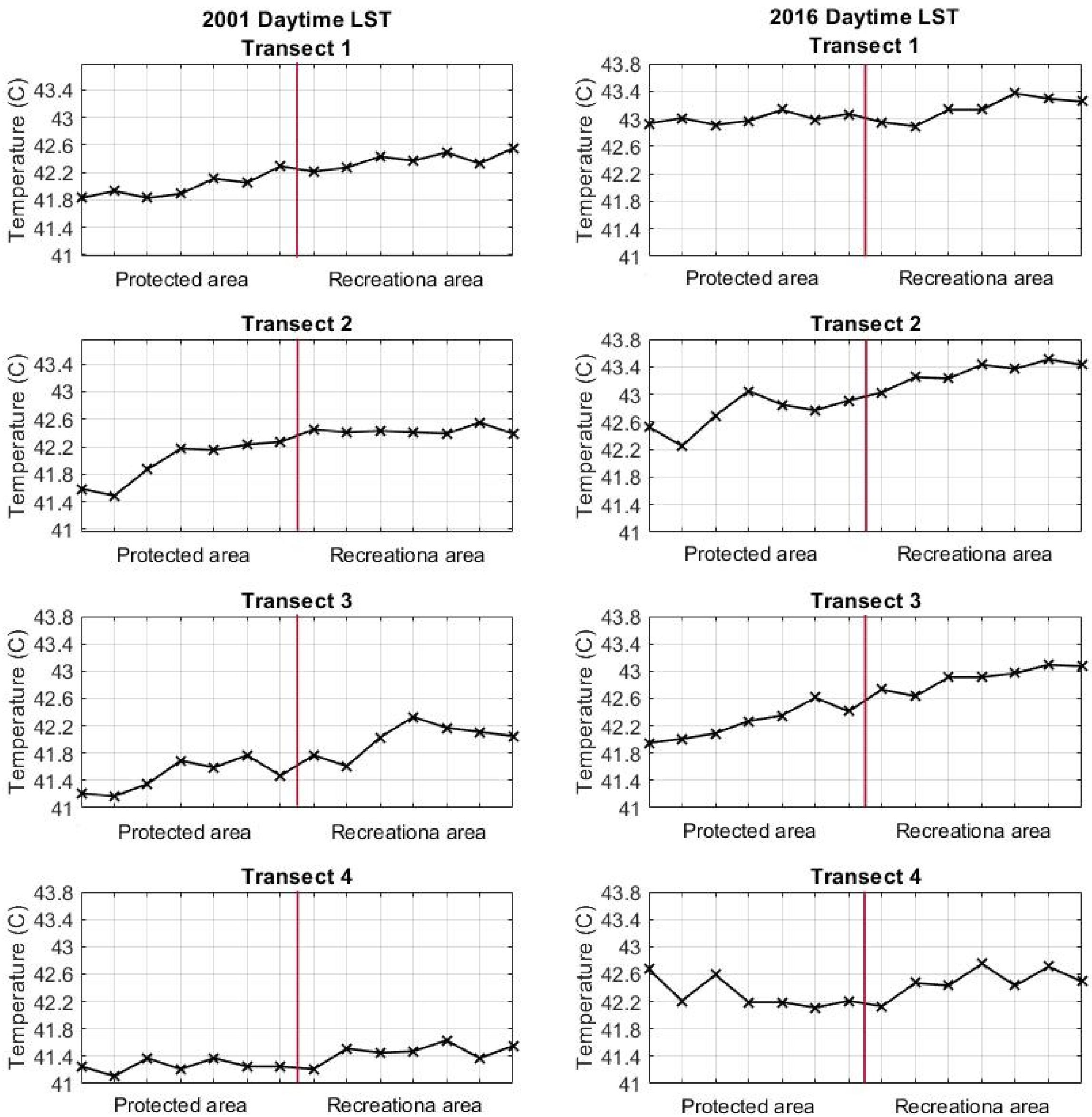


Figure 20 Graphs showing the daytime LST of the transects, which across the protected area and recreational area, in 2001 and 2016.

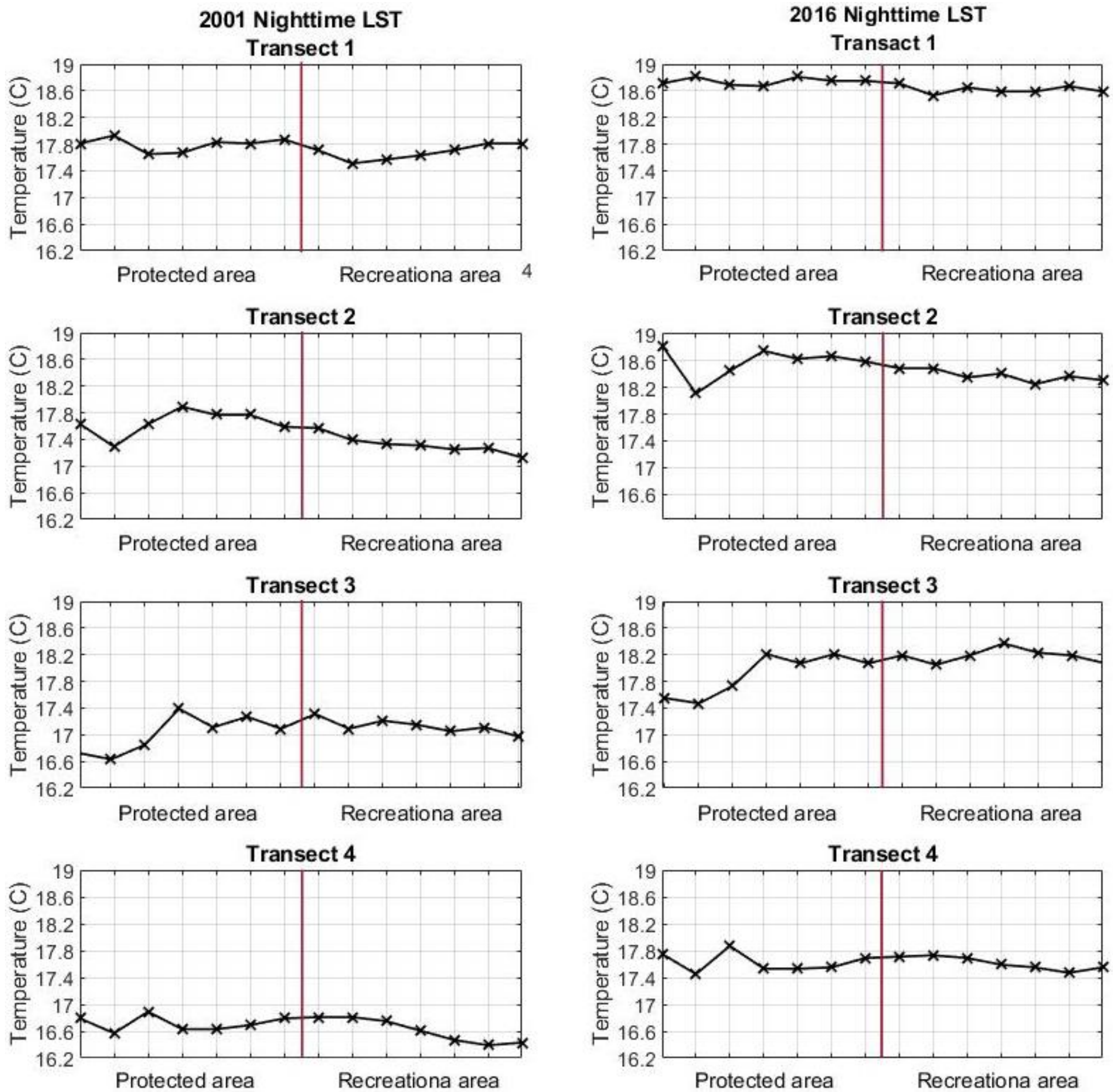


Figure 21 Graphs showing the nighttime LST of the transects in 2001 and 2016.

Table 4 The mean and standard deviation of daytime and nighttime LST of the transects in 2001 and 2016.

LST	Year	Transect	Protected area		Recreational area		Differences (°C)
			Mean Temperature (°C)	Standard deviation	Mean Temperature (°C)	Standard deviation	
Daytime	2001	One	41.99**	0.1571	42.38**	0.1115	-0.39
		Two	41.96**	0.2964	42.43**	0.0517	-0.47
		Three	41.46**	0.2153	42.01**	0.2260	-0.55
		Four	41.26**	0.0840	41.46**	0.1255	-0.2
	2016	One	43.00*	0.0716	43.14*	0.1631	-0.14
		Two	42.72**	0.2456	43.32**	0.1511	-0.6
		Three	42.24**	0.2198	42.90**	0.1567	-0.66
		Four	42.31	0.2059	42.49	0.1907	-0.18
Nighttime	2001	One	17.80*	0.0942	17.68*	0.1063	0.12
		Two	17.65**	0.1774	17.32**	0.1259	0.33
		Three	17.01	0.2610	17.13	0.1022	-0.12
		Four	16.71	0.1055	16.61	0.1690	0.1
	2016	One	18.74**	0.0511	18.62**	0.0564	0.12
		Two	18.58*	0.2203	18.38*	0.0827	0.2
		Three	17.90**	0.2894	18.18**	0.0984	-0.28
		Four	17.62	0.1384	17.61	0.0909	0.01

** statistical different between protected area and recreational area at a significance level ≤ 0.05

* statistical different between protected area and recreational area at a significance level ≤ 0.1

4.3.4 Land Cover Classification

The classification of the high-resolution aerial photographs illustrated more information about the composition of the land cover in each study area (Appendix V). Figure 21 shows the percentage of each land cover type in the study area of NADW control site, Glamis OHV area and Dune Buggy Flats OHV area, and the results of the statistical test are shown in Table 5.

The NADW control site has the highest amount of vegetation cover among all the study areas. Its mean vegetation cover was 11.99% ± 1.8838, which is higher than 3.93% ± 0.7198 in the Glamis OHV area and 1.60% ± 0.2868 in the Dune

Buggy Flats OHV area (Table 5). The difference in the amount of vegetation cover between the NADW control site and Glamis OHV area/ Dune Buggy Flats OHV area is statistically significant (p = 0.000). The results also revealed that there was an increasing trend of the amount of vegetation cover in the NAWD control site from 10.22% in 2008 to 15.17% in 2011; however, the Glamis OHV area and Dune Buggy Flats OHV area did not show a similar increasing trend of the amount of vegetation cover in the same period of time. The Glamis OHV area and Dune Buggy Flats OHV area have a low amount of vegetation cover; thus, the amount of soil cover in both areas is higher than the NADW control site. The average soil cover percentage of Glamis OHV area and Dune Buggy Flats OHV area was 95.16% ± 0.7981 and 98.38% ± 0.2935 respectively, while the NADW control site has the average soil cover percentage of 88.01% ±1.8838 (Table 5). There is a statistical difference in the amount of soil cover between the NADW control site and Glamis OHV area/ Dune Buggy Flats OHV area at the significant level of 95%. The results of the classification indicated that the OHV activity has a strong association with the reduction of the vegetation cover and the increase of soil exposure in the OHV areas.

Moreover, the Glamis OHV area has the highest amount of bright soil cover and lowest amount of dark soil cover among all the study area (Figure 22b and 22c), and the differences in both land cover types between the NADW control site and Glamis OHV area are substantial at the significant level of 95%. The results indicated that the OHVs activity causes the soil displacement and structure breakdown by shearing and pumping actions of the vehicle, and results in the increase in the amount of fine-grained sand particles and loose sediments, which has a higher spectral reflectance than the coarse-grained soils. As a result, the amount of soil with a brighter tone is higher in the OHV-disturbed study areas than the NADW control site.

The Glamis OHV area and Dune Buggy Flats OHV area are the major areas that received a lot of OHV activity in the dune field. There are many anthropogenic features, such as roads, ranger station, and park lots, constructed for providing services to the dune visitors and OHVs drivers. As a result, the number of anthropogenic features in the Glamis OHV area (0.91% ± 0.2511) and Dune Buggy Flats OHV area (0.0123% ± 0.0325) is higher than the NADW control site, which has no any anthropogenic features identified from the high-resolution aerial photographs (Table 5).

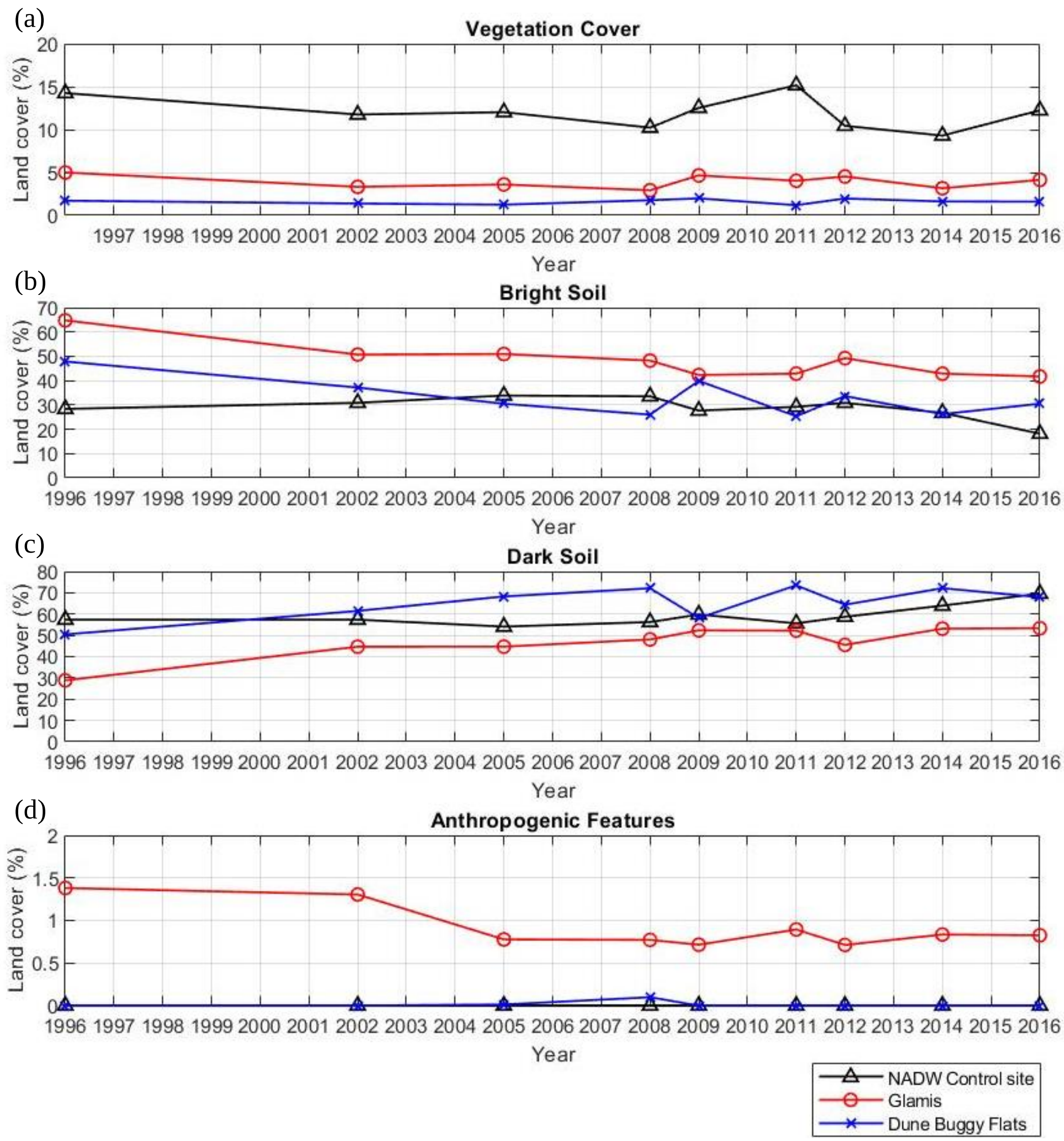


Figure 22 The results of the high-resolution aerial photographs classification. It shows the percentage of each class, includes vegetation cover (a), bright soil (b), dark soil (c), and anthropogenic features (d), in the study areas of NADW control site, Glamis OHV area and Dune Buggy Flats OHV area.

Table 5 The mean and standard deviation of each class in all study areas. The simple t-test is used to examine the difference of each class between the NADW control site and Glamis OHV area/Dune Buggy Flats OHV area.

Area	Vegetation (%)	Soil			Man-made features (%)
		Bright soil (%)	Dark soil (%)	Total (%)	
NADW control site	11.99 ±1.8838	28.81 ±4.6819	59.20 ±4.8111	88.01 ±1.8838	0
Glamis OHV area	3.93** ±0.7198	48.81** ±7.2733	46.98** ±7.7178	95.16** ±0.7981	0.91** ±0.2511
Dune Buggy Flats OHV area	1.60** ±0.2868	33.01 ±7.5099	65.37* ±7.6075	98.38** ±0.2935	0.0123 ±0.0325

** statistical different between NADW control site and Glamis OHV area/Dune Buggy Flats OHV area at a significance level ≤ 0.05

* statistical different between NADW control site and Glamis OHV area/Dune Buggy Flats OHV area at a significance level ≤ 0.1

4.4 Multiple Regression Analysis

The correlation and multiple regression are conducted to measure the linear association between the amount of vegetation cover and various independent variables, such as drift potential, PDSI, total visitation and the total length of vehicle tracks, in each study area. Table 6 summarizes the descriptive statistics and multiple regression analysis results. The results illustrated the amount of vegetation in the NADW control site is statistically correlated with the drift potential of the dune field (R^2 = 0.861, p = 0.000). The multiple regression model of the NADW control site explained 78% of variances of the data; however, the model is not statistically substantial at the significant level of 90%.

The multiple regression model with the same independent variables produced a statistically significant result in both Glamis OHV area and Dune Buggy Flats OHV area (Table 6). The regression result of the Glamis OHV area showed that the amount of vegetation cover in Glamis OHV area is positively correlated with the total visitation ($R^2 = 0.626$, $p = 0.061$). The model is statistically substantial at the significant level of 90%, and it explained 99.6% of variances. It predicted that the amount of vegetation cover in the Glamis OHV area is equal to 43884.18 + 181.57 (drift potential) – 190.88 (PDSI) + 0.103 (total visitation) – 0.763 (the length of vehicle tracks). The independent variables of drift potential, total visitation and the length of vehicle tracks are significant predicators of the amount of vegetation cover in the Glamis OHV area, and the Palmer Droughts Severity Index did not significantly contribute to the multiple regression model.

The multiple regression model of the Dune Buggy Flats OHV area showed that the amount of vegetation cover is statistically correlated with the independent variables of drift potential ($R^2 = - 0.631$) and PDSI ($R^2 = - 0.666$) at significant level of 90%. The model is statistically significant at the significant level of 90%, and it explained 99.2% of variances. The result also anticipates that the amount of vegetation cover in the Dune Buggy Flats OHV area is equal to 8895.76 – 231.84 (drift potential) – 397.31 (PDSI) + 0.019 (total visitation) + 0.22 (the length of vehicle tracks). All the independent variables are significant predicators of the amount of vegetation cover in the Dune Buggy Flats.

Table 6 Multiple regression analysis of the amount of vegetation cover in the study areas of NADW control site, Glamis OHV area and Dune Buggy Flats OHV area with the independent variables of drift potential, Palmer Drought Severity Index and the length of vehicle tracks in the corresponding study area.

Variable/Area		Mean	Standard deviation	NADW control site			Glamis OHV area			Dune Buggy Flats OHV area		
				Correlation	Multiple regression weights		Correlation	Multiple regression weights		Correlation	Multiple regression weights	
					B	β		B	β		B	β
Dependent variables Vegetation (m^2)	NADW control site	119509.17	20050.13	-	75840.99 (constant)	-	-	43884.18 (constant)	-	-	8895.76 (constant)	-
	Glamis OHV area	40310.83	5654.05	-	-	-	-	-	-	-	-	-
	Dune Buggy Flats OHV area	15982.67	3378.51	-	-	-	-	-	-	-	-	-
Independent variables	Drift Potential	25.1067	14.593	0.861**	1225.60	0.882	0.102	181.57*	0.469	-0.631*	-231.84**	-1.00
	Palmer Drought Severity Index	-0.9950	3.44	0.356	258.09	0.044	-0.215	-190.88	-0.116	-0.666*	-397.31*	-0.405
	Total visitation	213176.29	60610.71	-0.023	0.062	0.187	0.626*	0.103*	1.105	0.350	0.019*	0.335
	NADW control site _Vehicle tracks length (km)	0	0	0	0	0	-	-	-	-	-	-
	Glamis_ Vehicle tracks length (km)	39745.14	5768.94	-	-	-	-0.297	-0.763*	-0.778	-	-	-
	Dune Buggy Flats_Vehicle tracks length (km)	38808.03	12218.13	-	-	-	-	-	-	-0.026	0.22*	0.795
				$R^2 = 0.780$ $F(3, 2) = 2.362$ $p = 0.311$			$R^2 = 0.996$ $F(4, 1) = 65.136$ $p = 0.093$			$R^2 = 0.992$ $F(4, 1) = 149.675$ $p = 0.061$		

** statistical different between protected area and recreational area at a significance level ≤ 0.05

* statistical different between protected area and recreational area at a significance level ≤ 0.1

5 DISCUSSION

5.1 Effects of Climatic Change on Vegetation

5.1.1 Climatic Variations in the Algodones Dunes Region

The results of local climatic data and MODIS data indicated that some climatic variations occurred in the Algodones Dunes between 2001 and 2016, most notably an increase in air temperature. The average annual air temperature of the dune field increased +1.48℃ between 2010 and 2016 (Figure 8a), and the annual daytime and nighttime LST of both protected area and recreational area also showed an increasing trend over this period (Figure 15c and 15d). The temperature trends are similar to the long-term temperature trend of the Southeast Desert Basin, which showed that the air temperature of the region increases +0.1℃ per decade. Globally, according to the most recent report of the Intergovernmental Panel on Climate Change (IPCC) (2014), surface air temperatures warmed, on average, by about 0.72℃ between 1951 and 2012 and the southwest region of the United States showed an increasing trend of +1.5℃ over the period of 1901 to 2012, or approximately 0.13℃ per decade. Thus, it is clear that there is most likely a multi-decadal trend of increasing surface air temperature within the Algodones Dunes region.

The annual rainfall of the Algodones Dunes slightly decreased from 2001 to 2016, and the long-term regional data also shows a slight decline of the annual rainfall in the Southeast Desert Basin in the past century. However, the dune field received extremely high rainfall in the year of 2005 (Figure 8b). It is classified as moderately moist based on the classification of the Palmer Z-index. The high amount of precipitation in 2005 facilitated the growth of vegetation in the dune field that resulted in a higher NDVI annual value (Figure 15a) and a lower annual albedo (Figure 15b) in 2005 compared with other years.

As the OHV activity is mainly concentrated in winter, it assumed that the amount of vegetation cover is lower in the winter season. However, the results of the seasonal time-series analysis rejected the hypothesis. It found that the average winter NDVI of the protected area and recreational area is higher than the average summer NDVI in both area (Figure 18a and 19a). The results indicated that the amount of vegetation cover is higher in the winter season than the summer season. This observation can be explained by the temperature and rainfall pattern of the dune field.

The previous research has different interpretations on the rainfall pattern of the Algodones Dunes. Norris and Norris (1961) described the dune field receives most of the rainfall from infrequent heavy to torrential late summer showers and light winter precipitation. Groom et al. (2007) also have similar conclusions, which the rainfall of the dune field is mostly from heavy summer thunderstorms. However, there is a different observation from Smith (1970). It identified that the Algodones Dunes receives most of the rainfall from winter storms from October through March, and the rest from the summer thunderstorm. The result of this study is matched with Smith's findings. The rainfall occurred in winter season is higher than that in the summer season in most of the years between 2001 and 2016 (Figure 8b).

Despite the higher use of OHV activity in the winter season, the mild air temperature and the occurrence of the rainfall events facilitated vegetation growth in the dune field during the winter season. The average winter daytime LST of the protected area and recreational area are 27.75℃ and 27.93℃ respectively (Figure 19c), and the average air temperature in winter is 17.1℃ (Figure 8a). Ackerman (1979) conducted research on the seed germination and survival of the perennial plant species in the Mojave Desert. They study revealed that perennial plants could grow and germinate in the temperature range from 10℃ to 40℃, and the optimum temperature range of the perennial plants was between 23℃ and 29℃. The mild air temperatures during the winter are thus favorable for the perennial plants to grow and germinate in the dune field. Meanwhile, the average summer daytime LST of the dune field exceeded 56℃ (Figure 18c), and the air temperature of the dune field was 30℃ in summer (Figure 8a). The extremely high temperature in the summer season affects the seed germination and plant growth in the dune field; as a result, the amount of vegetation cover in the dune field is lower in the summer season than the winter season.

As the protected area and NADW control site prohibits the use of the vehicles and other recreational activity, the results of those areas represent the effects of climatic variations on the land cover change in the dune field. The time-series analysis and pixels trend analysis reported that the protected area also records a decreasing trend of the NDVI value (Figure 15a and Table 2) and an increasing trend of albedo rate (Figure 15b and Table 3). It indicates that the variation of the climatic conditions contributes to the land over change and decline in vegetation cover in the Algodones Dunes during the study period.

5.1.2 Response of Dune Vegetation to Droughts

The temperature change resulting from global warming may lead to the occurrence of extreme events in the different regions of the United States. The IPCC's report (2014) specified that the southwest of the United States might experience more intense drought events if the global warming is approximately 2°C above the pre-industrial period (IPCC, 2014). As the Southeast Desert Basin experienced an increase in temperature and insufficient rainfall in the past century, it leads to the occurrence of drought events over the region. Both temperature and rainfall are the two important factors determining the occurrence of drought; thus, they showed a significant association with the PDSI (Figure 10a, 10b, 12b, and 12c). The result of PDSI reveals that there were eleven drought events with different intensity that occurred in the Southeast Desert Basin between 2001 and 2016 (Figure 8c and 11c).

The Southeast Desert Basin experienced a prolonged drought event during the period of 2012 to 2016 (Figure 11c). During this period, the annual mean air temperature of the Algodones Dunes was between 25.28°C and 25.54°C, and the annual rainfall was in a range of 19.56 mm and 70.10 mm. Both variables are higher than its average value of the entire study period. For the results of the annual time-series analysis and pixels trend analysis, the protected area has a slightly decreasing trend in annual mean NDVI (Figure 15a) and an increasing trend in annual mean albedo (Figure 15b) during the period of the prolonged drought event. It indicated that the drought events that occurred during the study period caused a significant impact on land cover change by reducing the amount of vegetation cover.

Plants are sensitive to the changes in the climatic conditions by increasing its cover with high rainfall and decreasing in cover with low or insufficient rainfall. Most of the plant species observed in the Algodones Dunes, including Larrea tridentata (*Larrea tridentata*), brittlebush (*Encelia farinosa*), burrobush (*Ambrosia dumosa*), desert buckwheat (*Eriogonum deserticola*), desert dicoria (*Dicoria canescens*), are drought-tolerant perennial plants. These species possess unique structural and physiological attributes, such as deep roots and high water use efficiency, that help plant species to reduce their susceptibility to drought (Ehleringer and Cooper, 1988; Munson et al., 2015). However, the extreme and prolonged droughts event occurred in the past decades exceeds the capacity of the drought-tolerant plants to resist those extreme climatic conditions. A number of research found that the amount of the drought-tolerant plants cover in southwestern North America was decreasing in the past few decades (Hamerlynck et al., 2000; Hereford et al., 2006; McAuliffe and Hamerlynck, 2010; Munson et al., 2015; Munson et al., 2016). For example, Larrea tridentata (*Larrea tridentata*), which is one of the dominant plant species in the Algodones Dunes, reduced its cover by 50% at the Joshua Tree National Park and 15% at the Death Valley National Park due to the effects of the 2002 drought (McAuliffe and Hamerlynck, 2010; Munson et al., 2016).

The extreme and prolonged drought may cause the mortality of the plants due to the extreme water deficit, which is attributed to the intensive or sustained drought event and elevated temperatures (McDowell et al. 2008). The insufficient rainfall and high evapotranspiration resulted from the high temperature limit the soil moisture availability for plants growth and survival; thus, the plants may wilt or reduce their coverage. It may cause irreversible impacts on land cover in the arid environments. The desert vegetation is vulnerable to the impacts of climate changes or human disturbances as it takes a long time for plant recovery and seed establishment and germination (Lovich and Bainbridge, 1999; Dorothy and Silvino, 2003). Before the restoration of vegetation, the open soil surface resulted from the removal of vegetation cover is susceptible to soil and wind erosion, especially during the spring season. The results of the local wind regime indicated that the dune field has the highest total drift potential and resultant drift potential in spring (Appendix I). The reduction of vegetation cover leads to more soil exposure, which increases the sediment supply for sediment transportation in the Algodones Dunes. When the wind speeds of the dune field exceed the shear threshold velocity, it activates the sediment transportation processes. It may also accelerate the dune migration and cause land degradation if the vegetation is not able to grow and restore the landscapes.

5.2 OHV Activity Patterns in the Algodones Dunes

The Algodones Dunes attracted over 19 million visitors between 2002 and 2017, and has experienced a substantial decreasing trend in visitation since 2007 (Figure 13a). The results matched with the findings of a survey conducted by California State Department of Parks and Recreation (2014), which reported that the annual visitation of the State Vehicular Recreation Areas (SVRAs) in California increased from 2.8 million in 2002 to 4.1 million in 2006 and decreased rapidly to 2.7 million in 2012. The report suggested that the national economy and employment situations are the major reasons causing the decline in the number of visitations in SVRAs. The popularity of the OHV activity increased from 2002 to 2006 due to the growing economy; however, the United States entered into an economic recession in 2007. According to United States Census Bureau (2018), the mean income of people in the United States increased from $44,028 in 2002 to $45,725 in 2006 (normalized by 2017 currency) and dropped rapidly to $43,799 in 2008. California's Employment Development Department (2009) also stated that the job losses of the economic recession in 2007 were 15.2 million, which is one of the highest records in history.

People's wealth and economic well-being are one of the critical factors affecting their quality of living and recreational behavior (Scott, 2013). The economic recession experienced in the United States since 2007 has essentially affected affects the amount of extra income available for recreation due to job loss, unemployment, or a suite of other economic factors. In response, people may have changed their recreational behaviors and leisure activities. People with low-income or in poverty have a lower ability to participate in recreational activities because they have lower mobility of people to travel and access to recreational areas, such as national parks and SVRAs, due to the financial hardship (McLean and Hurd, 2015). Also, they have a lower capability to purchase or access to leisure amenities and commodities (Scott, 2013). For instance, many are not able to afford expansive OHVs, which can cost at least $5,000. Therefore, people may prefer other types of recreational activities that are less expansive and easily access, such as hiking or swimming, instead of OHV activity, especially during the economic turndown. It explains the decline in the number of total visitations since 2007 in the Algodones Dunes.

The visitation of the dune field is mostly concentrated in the winter season, which from late-October to mid-February (Figure 13b). One of the major reasons is that most of the holidays, such as Thanksgiving, Christmas, New Year and Presidents' Day, appear in the winter season. It attracts peoples to travel and participate in outdoor recreational activities because they have a longer vacation. Also, some special events, such as "Star Wars Invasion of Buttercup Valley" in February 2017 and "Discover the Desert—Star Wars Day" in February 2018, attracts a lot of people to visit and participate in OHV activity in the Algodones Dunes. Besides, the temperature of the dune field is another reason affecting the OHV pattern of the Algodones Dunes. The results of the MODIS LST show that the average daytime LST of the recreational area in the winter season was 27.93℃ (Figure 18c), which is lower than 56.01℃ in the summer season (Figure 17c). People prefer conducting OHV activity in comfort and mild temperature during the winter season. As a result, the visitation of dune field in winter is substantially higher than that in summer.

The length of measured vehicle tracks provides a proxy for the pattern and spatial extent of OHV activity in each study area. There are no vehicle tracks identified in the NADW control site in all the available high-resolution aerial photographs. This is in response to the 1994 California Desert Protection Act, which prohibits all vehicle traffic in the NADW. Both Glamis OHV area and Dune Buggy Flats OHV area are popular areas for OHV recreation in the dune field.

Glamis OHV area has the highest vehicle track length among all the study area (Figure 14) because it is a major camping ground in the dune field, and also it is near the Cahuilla ranger station. It attracts many visitors and OHV enthusiasts to camp and diving their OHVs in the Glamis OHV area; therefore, it received lots of OHV traffic in the area. Dune Buggy Flats at the southern part of the dune field also has a high use of OHV activity because it closes to the Interstate-8, which provide easy access for the visitors and OHV drivers. As the total visitation of the dune field was decreasing during the study period, it assumes that the total length of the vehicle tracks in the OHV area should be decline. The results reported that only the Glamis OHV area has a similar decreasing trend of the total vehicle track length; meanwhile the total length of the vehicle track in the Dune Buggy Flats was increasing between 2001 and 2016. However, the linear trend of both area explains only 3% of the variance of the data.

5.3 Overall Impacts of OHV Activity on Land Cover Change

As the total visitation of the dune field decreased in the 16 years, the amount of vegetation cover in the OHV area should be increased. However, the results of the research show that the amount of vegetation cover in all the study areas was decreasing between 2001 and 2016. Although the previous section identified that the reduction of vegetation cover in the dune field is attributed to the climatic variations and the occurrence of droughts, there are few observations indicated that the OHV activity also causes significant impacts on land cover changes in the Algodones Dunes.

The results show that there are substantial differences on the compositions of land cover between the NADW control site and the OHV areas. The time-series analysis and trend analysis illustrate that the recreational area has a lower mean NDVI (Figure 15a and Table 2) and a higher albedo rate that the protected area (Figure 15b and Table 3). It indicates that the amount of vegetation cover in the recreational area is substantially lower than that in the protected area. The result of the image classification also demonstrates a similar investigation. The average amount of vegetation cover in the Glamis OHV area and Dune Buggy Flats OHV area are 3.93% and 1.6% respectively, which are substantially lower than that of 11.99% in the NADW control site (Figure 22a and Table 5). It is matched with the findings of other OHV research conducted in the Algodones Dunes. Luckenbach and Bury (1983) and Groom et al. (2007) identified that the vegetation density of the OHV area is 5 to 10 times less than the wilderness area. It indicates that the use of the OHV activity is the major reason causing the differences in the amount of vegetation cover between the protected area and OHV areas. The OHV activity causes direct destructions on the vegetation cover by breaking, crushing or uprooting (Luckenbach and Bury, 1983; Al-Hurban, 2014). It also affects the vegetation growth and seed germination by compacting the soils, damaging the roots system, decreasing the nutrients uptakes, and weakening plant stability (Webb *et al.*, 1978; Davenport and Switalski, 2006). Therefore, the decline in the amount of vegetation cover is commonly resulted in the areas that allow OHV activity.

The land cover of the OHV areas is significantly different from the NADW control site; however, the study did not capture a rapidly decreasing in the amount of vegetation cover in the OHV areas. One of the explanations is that the OHV activity altered the land cover and caused land degradation since the 1970s when the OHV activity become popular leisure and recreational activity in the United States. Theoretically, the overall impacts of OHV activity on the environment is predicted to increase with the increased usage of the OHVs; however, Priskin (2003) specified that the first few passes of an ORV are sufficient to generate critical impacts on vegetation, and it makes little difference when more passes are adding after the first few passes. It suggested that the popularity of OHV activity in the 1970s cause severe land degradation and reduction of the amount of vegetation cover in the Algodones Dunes. In the 2000s, the land is already degraded in the dune field. The vegetation in the recreational area is sparse and small in size, so the current OHV activity is not sufficient to generate a significant damage to the vegetation. Unless it has an extremely high level of OHV usage, it shows a gently decreasing trend in the amount of vegetation cover and an increasing trend in the amount of soil cover in the OHV areas. It explained the observations that the OHV areas have the lower amount of vegetation cover, but it did not report a significant decreasing trend in the amount of vegetation cover between 2001 and 2016.

The slow-growing desert vegetation also leads to low vegetation cover observed in the OHV areas after the human disturbances. Compared with the forest ecosystems, the desert ecosystems have a slower recovery rate, which may take centuries to recover (Belnap 2003; Davenport and Switalski, 2006). Lovich and Bainbridge (1999) explained that the extreme climatic and environmental conditions, such as extremely high temperature, limited soil moisture availability, infertile soils, and high wind velocity, leads to the slow natural recovery of the desert vegetation. The OHV activity causes a significant reduction in the amount of vegetation cover in the OHV areas since the 1970s. There is no sufficient time for the vegetation in the dune field to recover to its initial stage. At the same time, the OHV activity is continuously taken place in the Algodones Dunes. The effects of trampling and compaction restrict the seed establishment and germination of desert vegetation for recovering the amount of vegetation on the landscape. The occurrence of droughts also inhabits the growth of vegetation as well as the recovery of the vegetation cover in the dune field. Therefore, there is a limit and sparse vegetation resulted in the OHV areas.

As there is less vegetation cover in the OHV areas, more soils are exposed to the surface. The results of the land cover classification indicated that the amount of soil cover in the Glamis OHV area and Dune Buggy Flats OHV area is significantly higher than that in the NADW control site (Table 5). Without the vegetation as a protective layer, the soil surface is susceptible to soil and wind erosion (Lovich and Bainbridge, 1999; Priskin, 2003; Van Dam and Van Dam, 2008). The soil exposure leads to the increase in the sediment supply for aeolian activities. The sediment transportation processes may activate when the wind speed exceeds the shear threshold velocity. Eventually, it may influence the stability of the dunes.

The presence of the vegetation is one of critical factor affecting the LST. The vegetation can protect the soil surface from direct thermal insulation during the day and reduce emission of longwave radiation during the night; thus, the landscape with more vegetation cover usually have a lower LST in the daytime and higher LST in the nighttime than the bared soil surface (Webb et al., 1978; Kleidon et al., 2000). The results of the transects study proved that there is a statistical difference in vegetation cover between the protected area and recreational area, and the protected area has more vegetation cover than the recreational area as it has a lower mean daytime temperature and a higher mean nighttime temperature than the recreational area.

Lastly, the OHV activity in the Algodones Dunes altered the natural morphology of the landscapes. The high-resolution aerial photographs illustrated that there are some circular vehicle tracks observed on the land surface of the OHV areas (Figure 23). When the riders repeatedly drive their OHV driving on the land surface or circulating the vegetation, the wheel spinning destroys the soil structure and cause soil rutting, which occurs when the strength of the soil is insufficient to support the vehicle load (Meadows et al, 2008). Eventually, it forms rut, which is a depressed vehicle track on the land surface. The formation of ruts around the vegetation in the dune field alters the morphology of the nebkha dunes. The OHV activity destroys the tail of the nebkha where the sediments deposit. The impacted nebkha shapes like a mound feature with a deep trench surround the vegetation (Figure 24). This type of OHV driving may affect the vegetation growth by reducing the vegetation canopy and damaging the root system. It may affect the formation of nebkha in the dune field as the presence of the vegetation is one of the main criteria forming the nebkha. Also, the loose sediments resulted from the soil rutting provide more sediment supply for aeolian sediment transportation. As a result, the OHV activity causes the change of land cover and the alternation of landscape morphology.

(a)

(b)

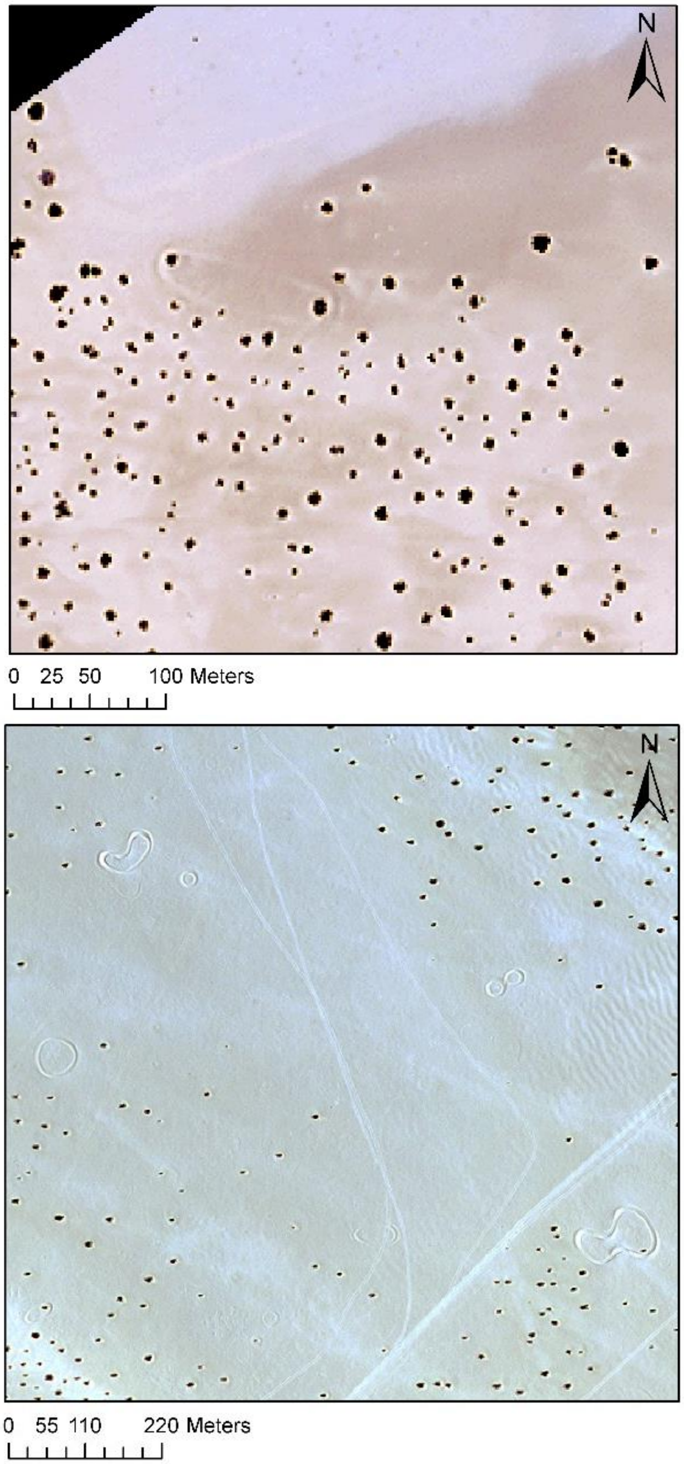


Figure 23 The high-resolution aerial photographs obtained in June 2014 illustrate that there are some ruts observed on the land surface or around the vegetation in the Glamis OHV area (a) and Dune Buggy Flats OHV area (b).

(a)

(b)

Figure 24 The photos showing the ruts, a depressed vehicle track, formed around the vegetation observed in the Dune Buggy Flats OHV area.

The research identified that both climatic variations and OHV activity are two major mechanisms affecting the land cover change in the Algodones Dunes. The results of the multiple regression analysis indicated that the change of land cover in different study areas was undergoing with different mechanisms (Table 6). The climatic variations are the only mechanism causing the reduction of vegetation cover in the NADW control site due to the prohibition of OHV activity in the NADW. The results of the NADW control site demonstrated the natural response of the vegetation to the climatic variations and drought events.

Both climatic variations and OHV activity simultaneously influence the land cover in both Glamis OHV area and Dune Buggy Flats OHV area; however, the results of the multiple regression analysis implied that there is different major mechanism influencing the amount of vegetation cover in each area. The OHV activity is the major factor causing the land cover change in the Glamis OHV area. There is a statistically significant association between the amount of vegetation cover and the total visitation. As mentioned, the Glamis OHV area is one of the major camping ground in the dune field that attracts many OHV enthusiasts to ride their vehicles in the area. As a result, the total length of vehicle tracks and total visitation are significant predictors anticipating the amount of vegetation cover in the Glamis OHV area. On the contrary, the drought is tended to be the dominant mechanism causing the land cover change in the Dune Buggy Flats OHV area as there is a statistically significant association between the amount of vegetation cover and PDSI. It implied that the OHV activity is not the only mechanism affecting the vegetation cover in the OHV area. The climatic variations also contributed to the land cover change in the dune field. It is essential for BLM, to identify the dominant mechanism causing the reduction of vegetation cover or the change of land cover in different parts of the dune field so as to restore the impacted landscape effectively.

6 CONCLUSIONS AND IMPLICATIONS

6.1 Summary of the Research

The objective of this research is to examine land cover and vegetation changes in the Algodones Dunes over recent decades and explore potential associations with OHV activity and climatic variability as potential mechanisms for land degradation in the dune field. The results of MODIS time-series analysis and land cover classification indicated that the amount of vegetation cover in both protected area and recreational area was declining from 2001 to 2016. As the protected area and NADW control site prohibits the use of the vehicles and other recreational activity, the results implied that the climatic variations contribute to the land over change and decline in vegetation cover in the Algodones Dunes during the study period. The occurrence of drought caused the decline in the vegetation cover due to the reduction of soil moisture availability for vegetation growth and seed germination.

The number of visitation of the Algodones Dunes was declining from 2002 to 2017, and a constant decreasing trend is recorded since 2007. One of possible factor causing decreasing visitation in the Algodones Dunes is the national economy and employment. The economic recession in 2007 reduced the employment rate and people’s income; as a result, they may have a lower ability to participate in recreational activities as well as the capability to purchase or access to leisure amenities and commodities.

The results of the research also indicated that the OHV activity cause substantial impacts on land cover change in the Algodones Dunes. The OHVs areas have a lower amount of vegetation cover and higher amount of soil cover than the NADW control site. It implied that the OHV activity caused significant effects of reducing the vegetation cover and altering the natural landscapes morphology of the dune field. Both climatic variations and OHV activity are statistically associated with land cover change in the dune field, although distinct causal mechanisms could not be separated. Desert ecosystem is more vulnerable than the forest ecosystem. The decline in amount of vegetation cover resulted from droughts or human disturbances may take a longer time for arid environments to restore the impacted landscape to its initial stage.

6.2 Management Implications

Based on the findings of this research, active ecosystem restoration with effective management planning and implementation, such as frequent revegetation and soil replacement, restriction or limitation of recreational activities in areas with heavy OHVs traffic, and the establishment of appropriate OHVs sites, are suggested to restore the OHV-impacted sites located in arid environments. It is also critical to conduct more research on the landscapes impacted by recreational activity in order to provide more information for governors or public land managers, such as Bureau of Land Management and California State Department of Parks and Recreation, to support their policy-making and carrying effective land management.

REFERENCES

Ackerman, T. L. (1979). Germination and survival of perennial plant species in the Mojave Desert. The Southwestern Naturalist, 399-408.

Adams, J. A., Endo, A. S., Stolzy, L. H., Rowlands, P. G., & Johnson, H. B. (1982). Controlled experiments on soil compaction produced by off-road vehicles in the Mojave Desert, California. Journal of Applied Ecology, 167-175.

Al-Awadhi, J. M. (2013). A case assessment of the mechanisms involved in Human-induced land degradation in northeastern Kuwait. Land Degradation & Development, 24(1), 2-11.

Al-Hurban, A. E. (2014). Effects of recent anthropogenic activities on the surface deposits of Kuwait. Arabian Journal of Geosciences, 7(2), 665-691.

Ardon, K., Tsoar, H., & Blumberg, D. G. (2009). Dynamics of nebkhas superimposed on a parabolic dune and their effect on the dune dynamics. Journal of Arid Environments, 73(11), 1014-1022.

Bagnold, R. (1941). The Physics of Blown Sand and Desert Dunes. London: Methuen.

Barrows, C. W., and M. L. Murphy-Mariscal. (2012). Modeling impacts of climate change on Joshua trees at their southern boundary: How scale impacts predictions. Biological Conservation 152:29–36.

Baumgardner, M. F., Silva, L. F., Biehl, L. L., & Stoner, E. R. (1986). Reflectance properties of soils. In Advances in agronomy (Vol. 38, pp. 1-44). Academic Press.

Belnap, J. (1995). Surface disturbances: their role in accelerating desertification. In Desertification in Developed Countries (pp. 39-57). Springer Netherlands. Blaikie, P., & Brookfield, H. (2015). Land degradation and society. Routledge.

Blaikie, P., & Brookfield, H. (2015). Land degradation and society. Routledge.

Brooks, M. L., & Lair, B. (2005). Ecological effects of vehicular routes in a desert ecosystem. Las Vegas, NV, USA: US Department of the Interior, Geological Survey, Western Ecological Research Center.

Brodhead, J. M., & Godfrey, P. J. (1977). Off road vehicle impact in Cape Cod National Seashore: disruption and recovery of dune vegetation. International Journal of Biometeorology, 21(3), 299-306.

Bruner, C. (2017). Personal Communication. A spreadsheet with the data of annual and seasonal visitation and estimated number of off-highway vehicles of the Algodones Dunes. Further question about the visitation data, please contact Camden Bruner, the Wildlife Biologist in Bureau of Land Management, via email cbruner@blm.gov.

Bury, R. B., & Luckenbach, R. A. (1983). Vehicular recreation in arid land dunes: biotic responses and management alternatives. In Environmental Effects of Off-Road Vehicles (pp. 207-221). Springer, New York, NY.

California State Department of Parks and Recreation. (2002). Taking the High Road: The Future of California's Off-highway Vehicle Recreation Program. Off-highway Motor Division, California State Parks, Sacramento, California.

California State Department of Parks and Recreation. (2014). Off-Highway Motor Vehicle Recreation Commission Program Report. Off-highway Motor Division, California State Parks, Sacramento, California.

California State Department of Parks and Recreation. (2017). Off-Highway Motor Vehicle Recreation Commission Program Report. Off-highway Motor Division, California State Parks, Sacramento, California.

California State Parks. (2018). State Vehicular Recreation Areas. Retrieved 11th September, 2018 from http://ohv.parks.ca.gov/?page_id=1170

Cayan, D. R., Redmond, K. T., & Riddle, L. G. (1999). ENSO and hydrologic extremes in the western United States. Journal of Climate, 12(9), 2881-2893.

Cordell, H. K., Betz, J. C., Green, T. G. & Stephens, B. (2008). Off-Highway Vehicle Recreation in theUnited States and its Regions and States: A National Report from the National Survey on Recreation and the Environment (NSRE). The National Survey on Recreation and the Environment.

Davenport, J., & Switalski, T. A. (2006). Environmental impacts of transport, related to tourism and leisure activities. In The ecology of transportation: Managing mobility for the environment (pp. 333-360). Springer Netherlands.

Dexter, A. R., Czyż, E. A., & Gaţe, O. P. (2007). A method for prediction of soil penetration resistance. Soil and Tillage Research, 93(2), 412-419.

Derickson, D., Kocurek, G., Ewing, R. C., & Bristow, C. (2008). Origin of a complex and spatially diverse dune-field pattern, Algodones, southeastern California. Geomorphology, 99(1), 186-204.

Dorothy S. & Silvino d. (2003) Sediment Flux and Compaction Trends on Off-Road Vehicle (ORV) and Other Trails in an Appalachian Forest Setting, Physical Geography, 24:6, 536-554.

Ehleringer, J. R., & Cooper, T. A. (1988). Correlations between carbon isotope ratio and microhabitat in desert plants. Oecologia, 76(4), 562-566.

Employment Development Department, State of California. (2009). A Labor Day Briefing for California, September 2009.

Ewing, R. C., Kocurek, G., & Lake, L. W. (2006). Pattern analysis of dune-field parameters. Earth Surface Processes and Landforms, 31(9), 1176-1191.

Fryberger, S.G. (1979). Dune forms and wind regime. In: McKee, E.D. (Ed.), A Study of Global Sand Seas, USGS Professional Paper, vol. 1052. US Geological Survey and United States National Aeronautics and Space Administration, Washington, DC, 137-169.

Fryberger, S. G., & Dean, G. (1979). Dune forms and wind regime. In A study of global sand seas (Vol. 1052, pp. 137-169). Washington DC: US Geological Survey Professional Paper.

Gibson, J. (1973). An initial study of the impact of desert motorcycle racing in the Mojave Desert. Research paper, Department of Biology, California State University, Full-erton.

Gillies, J. A., Nield, J. M., & Nickling, W. G. (2014). Wind speed and sediment transport recovery in the lee of a vegetated and denuded nebkha within a nebkha dune field. Aeolian Research, 12, 135-141.

Goossens, D., & Buck, B. (2009). Dust dynamics in off-road vehicle trails: measurements on 16 arid soil types, Nevada, USA. Journal of Environmental Management, 90(11), 3458-3469.

Graves, W.L. (1978). Revegetation of disturbed sites in the Mojave Desert with native shrubs: California Agriculture, p. 4–5.

Graves, W.L., Grant, B.L., and Williams, W.A. (1975). Seed treatment of Mojave Desert shrubs: Agronomy Journal, v. 67, p. 773–777.

Groom, J. D., McKinney, L. B., Ball, L. C., & Winchell, C. S. (2007). Quantifying off-highway vehicle impacts on density and survival of a threatened dune-endemic plant. Biological Conservation, 135(1), 119-134.

Guida, R. J., S. R. Abella, W. J. Smith Jr., H. Stephen, and C. L. Roberts. (2013). Climatic Change and Desert Vegetation Distribution: Assessing Thirty Years of Change in Southern Nevada's Mojave Desert. The Professional Geographer 66:311–322.

Hamerlynck, E. P., Huxman, T. E., Loik, M. E., & Smith, S. D. (2000). Effects of extreme high temperature, drought and elevated CO2 on photosynthesis of the Mojave Desert evergreen shrub, Larrea tridentata. Plant Ecology, 148(2), 183-193.

Hereford, R., Webb, R. H., & Longpre, C. I. (2006). Precipitation history and ecosystem response to multidecadal precipitation variability in the Mojave Desert region, 1893–2001. Journal of Arid Environments, 67, 13-34.

Hesp, P., & McLachlan, A. (2000). Morphology, dynamics, ecology and fauna of Arctotheca populifolia and Gazania rigens nabkha dunes. Journal of arid environments, 44(2), 155-172.

Hubbs, C. L., Bien, G. S., & Suess, H. E. (1965). La Jolla Natural Radiocarbon Measurements IV∗. Radiocarbon, 7, 66-117.

Hugenholtz, C. H., & Wolfe, S. A. (2005). Biogeomorphic model of dunefield activation and stabilization on the northern Great Plains. Geomorphology, 70(1-2), 53-70.

Intergovernmental Panel on Climate Change (IPCC). (2014). Climate Change 2014: Impacts, Adaptation, and Vulnerability, Part A Global and Sectoral Aspects ed C B Field et al (Cambridge: Cambridge University Press).

Jacquemoud, S., Baret, F., & Hanocq, J. F. (1992). Modeling spectral and bidirectional soil reflectance. Remote sensing of Environment, 41(2-3), 123-132.

Johnson, D. L. (1977). The Late Quaternary Climate of Coastal California: Evidence for an Ice Age Refugium 1. Quaternary Research, 8(2), 154-179.

Kay, B.L., and Graves, W.L. (1983) History of revegetation studies in the California deserts, in Webb, R.H., and Wilshire, H.G., eds., Environmental effects of off-road vehicles—Impacts and management in arid regions: New York, Springer-Verlag, p. 315–324.

Khalaf, F. I., Misak, R., & Al-Dousari, A. (1995). Sedimentological and morphological characteristics of some nabkha deposits in the northern coastal plain of Kuwait, Arabia. Journal of Arid Environments, 29(3), 267-292.

Kim, D., Chin, M., Bian, H., Tan, Q., Brown, M. E., Zheng, T., ... & Kucsera, T. (2013). The effect of the dynamic surface bareness on dust source function, emission, and distribution. Journal of Geophysical Research: Atmospheres, 118(2), 871-886.

Kleidon, A., Fraedrich, K., & Heimann, M. (2000). A green planet versus a desert world: Estimating the maximum effect of vegetation on the land surface climate. Climatic Change, 44(4), 471-493.

Kocurek, G., & Nielson, J. (1986). Conditions favourable for the formation of warm-climate aeolian sand sheets. Sedimentology, 33(6), 795-816.

Lancaster, N. (1997). Response of eolian geomorphic systems to minor climate change: examples from the southern Californian deserts. Geomorphology 19:333–347.

Langford, R. P. (2000). Nabkha (coppice dune) fields of south-central New Mexico, USA. Journal of Arid Environments, 46(1), 25-41.

Lathrop, E. W. (1983). The effect of vehicle use on desert vegetation. In Environmental Effects of Off-Road Vehicles (pp. 153-166). Springer, New York, NY.

Lavee, H., Imeson, A. C., & Sarah, P. (1998). The impact of climate change on geomorphology and desertification along a Mediterranean-arid transect. Land degradation & development, 9(5), 407-422.

Lindsey, R. (2011). Influence of El Niño and La Niña on Southwest Rainfall. National Oceanic and atmospheric administration. Retrieved 9th September, 2018 from https://www.climate.gov/news-features/event-tracker/influence-el-ni%C3%B1o-and-la-ni%C3%B1a-southwest-rainfall

Link, S. O., Waugh, W. J., Downs, J. L., Thiede, M. E., Chatters, J. C., & Gee, G. W. (1994). Effects of coppice dune topography and vegetation on soil water dynamics in a cold-desert ecosystem. Journal of Arid Environments, 27(3), 265-278.

Long, J. T., & Sharp, R. P. (1964). Barchan-dune movement in imperial valley, california. Geological Society of America Bulletin, 75(2), 149-156.

Lovich, J. E., & Bainbridge, D. (1999). Anthropogenic degradation of the southern California desert ecosystem and prospects for natural recovery and restoration. Environmental management, 24(3), 309-326.

Luckenbach, R. A., & Bury, R. B. (1983). Effects of off-road vehicles on the biota of the Algodones Dunes, Imperial County, California. Journal of Applied Ecology, 265-286.Merriam, R. (1969). Source of sand dunes of southeastern California and northwestern Sonora, Mexico. Geological Society of America Bulletin, 80(3), 531-534.

McAuliffe, J. R., & Hamerlynck, E. P. (2010). Perennial plant mortality in the Sonoran and Mojave deserts in response to severe, multi-year drought. Journal of Arid Environments, 74(8), 885-896.

McCabe, G. J., & Dettinger, M. D. (1999). Decadal variations in the strength of ENSO teleconnections with precipitation in the western United States. International Journal of Climatology, 19(13), 1399-1410.

McDowell, N., Pockman, W. T., Allen, C. D., Breshears, D. D., Cobb, N., Kolb, T., ... & Yepez, E. A. (2008). Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb to drought?. New phytologist, 178(4), 719-739.

McLean, D. D., & Hurd, A. R. (2015). Recreation and leisure in modern society.

McTainsh, G., Livingstone, I., & Strong, C. (2013). Fundamentals of aeolian sediment transport: aeolian sediments. Treatise on Geomorphology: volume 11, Aeolian Geomorphology, 23-42.

Meadows, D., Foltz, R. B., & Geehan, N. (2008). Effects of all-terrain vehicles on forested lands and grasslands. US Department of Agriculture, Forest Service, National Technology & Development Program, Recreation Management.

Meneses-Tovar, C. L. (2011). NDVI as indicator of degradation. Unasylva, 62(238), 39-46.Merriam, R. (1969). Source of sand dunes of southeastern California and northwestern Sonora, Mexico. Geological Society of America Bulletin, 80(3), 531-534.

Miot da Silva, G. and Hesp, P. (2010). Coastline orientation, aeolian sediment transport and foredune and dunefield dynamics of Moçambique Beach, Southern Brazil. Geomorphology (120), 258–278.

Misak RF, Al Awadhi JM, Omar SA, Shahid SA. (2002); Soil degradation in Kabad area, southwestern Kuwait City. Land Degradation & Development. 13(5): 403-415.

Munson, S. M., A. L. Long, C. S. A. Wallace, and R. H. Webb. (2016). Cumulative drought and land-use impacts on perennial vegetation across a North American dryland region. Applied Vegetation Science 19:430–441.

Munson, S. M., Webb, R. H., Housman, D. C., Veblen, K. E., Nussear, K. E., Beever, E. A., ... & Tallent, N. G. (2015). Long-term plant responses to climate are moderated by biophysical attributes in a North American desert. Journal of Ecology, 103(3), 657-668.

Nadal, F., & Bréon, F. M. (1999). Parameterization of surface polarized reflectance derived from POLDER spaceborne measurements. IEEE Transactions on Geoscience and Remote Sensing, 37(3), 1709-1718.

National Integrated Drought Information System. (2018). U.S. Drought Monitor - Western RCC. Retrieved 9th September, 2018 from https://www.drought.gov/drought/rcc/west

National Oceanic and atmospheric administration (NOAA). (2018). El Niño/Southern Oscillation (ENSO). Retrieved 8th September 2018 from https://www.ncdc.noaa.gov/teleconnections/enso/enso-tech.php

Nield, J. M., & Baas, A. C. (2008). The influence of different environmental and climatic conditions on vegetated aeolian dune landscape development and response. Global and Planetary Change, 64(1-2), 76-92.

Nielson, J., & Kocurek, G. (1986). Climbing zibars of the Algodones. Sedimentary Geology, 48(1), 1-15.

NOAA National Centers for Environmental information. (2018). Climate at a Glance: Global Time Series, published September 2018. Retrieved on September 21, 2018 from https://www.ncdc.noaa.gov/cag/

Norris, R. M., & Norris, K. S. (1961). Algodones dunes of southeastern California. Geological Society of America Bulletin, 72(4), 605-619.

Okin, G. S. (2013). Linked aeolian-vegetation systems. Treatise on geomorphology, 11, 428-439.

Olive, N. D., & Marion, J. L. (2009). The influence of use-related, environmental, and managerial factors on soil loss from recreational trails. Journal of environmental management, 90(3), 1483-1493.

Ouren, D. S., Haas, C., Melcher, C. P., Stewart, S. C., Ponds, P. D., Sexton, N. R., ... & Bowen, Z. H. (2007). Environmental effects of off-highway vehicles on Bureau of Land Management lands: A literature synthesis, annotated bibliographies, extensive bibliographies, and internet resources. US Geological Survey, Open-File Report, 1353, 225.

Parsons, A. J., Wainwright, J., Schlesinger, W. H., & Abrahams, A. D. (2003). The role of overland flow in sediment and nitrogen budgets of mesquite dunefields, southern New Mexico. Journal of Arid Environments, 53(1), 61-71.

Post, D. F., Fimbres, A., Matthias, A. D., Sano, E. E., Accioly, L., Batchily, A. K., & Ferreira, L. G. (2000). Predicting soil albedo from soil color and spectral reflectance data. Soil Science Society of America Journal, 64(3), 1027-1034.

Priskin, J. (2003). Physical impacts of four-wheel drive related tourism and recreation in a semi-arid, natural coastal environment. Ocean & Coastal Management, 46(1), 127-155.

Raupach, M. R., Woods, N., Dorr, G., Leys, J. F., & Cleugh, H. A. (2001). The entrapment of particles by windbreaks. Atmospheric environment, 35(20), 3373-3383.

Ravi, S., Breshears, D. D., Huxman, T. E., & D'Odorico, P. (2010). Land degradation in drylands: Interactions among hydrologic–aeolian erosion and vegetation dynamics. Geomorphology, 116(3-4), 236-245.

Sack, D., & Da Luz, S. (2003). Sediment flux and compaction trends on off-road vehicle (ORV) and other trails in an Appalachian forest setting. Physical Geography, 24(6), 536-554.

Scott, D. (2013). Economic inequality, poverty, and park and recreation delivery. Journal of Park and Recreation Administration, 31(4).

Sharp, R. P. (1979). Intradune flats of the Algodones chain, Imperial Valley, California. Geological Society of America Bulletin, 90(10), 908-916.

Siegal, Z., Tsoar, H., & Karnieli, A. (2013). Effects of prolonged drought on the vegetation cover of sand dunes in the NW Negev Desert: Field survey, remote sensing and conceptual modeling. Aeolian Research, 9, 161-173.

Smith, R.S.U. (1970). Migration and wind regime of small barchan dunes within the Algodones dune chain, Imperial County, California [M.S. thesis]: Tucson, University of Arizona, 125.

Stebbins, R. C. (1974). Off-Road and the Fragile Desert. American Biology Teacher, 36(4), 203-208.

Stocking, M. A., & Murnaghan, N. (2013). A handbook for the field assessment of land degradation. Routledge.

Stokes S., Kocurek G., Pye K., Winspear N.R. (1997). New evidence for the timing of aeolian sand supply to the Algodones dunefield and East Mesa area, southeastern California, USA. Palaeogeography, Palaeoclimatology, Palaeoecology 128: 63–75.

Stoner, E. R., & Baumgardner, M. F. (1981). Characteristic Variations in Reflectance of Surface Soils 1. Soil Science Society of America Journal, 45(6), 1161-1165.

Sweet, M. L., Nielson, J., Havholm, K., & Farrelley, J. (1988). Algodones dune field of southeastern California: case history of a migrating modern dune field. Sedimentology, 35(6), 939-952.

Tengberg, A. (1995). Nebkha dunes as indicators of wind erosion and land degradation in the Sahel zone of Burkina Faso. Journal of Arid Environments, 3(30), 265-282.

Thomas, D. S., Knight, M., & Wiggs, G. F. (2005). Remobilization of southern African desert dune systems by twenty-first century global warming. Nature, 435(7046), 1218.

Thomas, D. S., & Wiggs, G. F. (2008). Aeolian system responses to global change: challenges of scale, process and temporal integration. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group, 33(9), 1396-1418.

Thomas, R. G. (1963). The late Pleistocene 150 foot fresh water beach line of the Salton Sea area. Bulletin of the Southern California Academy of Sciences, 62(1), 9-18.

Tsoar, H. (2001). Types of aeolian sand dunes and their formation. In Geomorphological fluid mechanics. Springer, Berlin, Heidelberg, 403-429.

Tsoar, H. (2013). Critical Environments: Sand Dunes and Climate Change. Treatise on Geomorphology: volume 11, Aeolian Geomorphology, 414-425

United States Census Bureau. (2018). Historical Income Tables: People. Total CPS Population and Per Capita Income. Retrieved on October 17, 2018 from https://www.census.gov/data/tables/time-series/demo/income-poverty/historical-income-people.html

Van Dam, A. R., & Van Dam, M. H. (2008). Impact of off-road vehicle use on dune endemic Coleoptera. Annals of the Entomological Society of America, 101(2), 411-417.

Wallace, A., Romney, E.M., and Hunter, R.B. (1980). The challenge of a desert: revegetation of disturbed desert lands, in Woods, S.L., ed., Great Basin naturalist memoirs—Soil-plant-animal relationships bearing on revegetation and land reclamation in Nevada Deserts: Provo, Utah, Brigham Young University, 216–225.

Wang, X., Wang, T., Dong, Z., Liu, X., & Qian, G. (2006). Nebkha development and its significance to wind erosion and land degradation in semi-arid northern China. Journal of Arid Environments, 65(1), 129-141.

Waters, M. R. (1983). Late Holocene lacustrine chronology and archaeology of ancient Lake Cahuilla, California. Quaternary Research, 19(3), 373-387.

Webb, R. H. (1983). Compaction of desert soils by off-road vehicles. In Environmental effects of off-road vehicles. Springer, New York, NY,51-79.

Webb, R. H., Ragland, H. C., Godwin, W. H., & Jenkins, O. (1978). Environmental effects of soil property changes with off-road vehicle use. Environmental management, 2(3), 219-233.

Webb, R. H., & Wilshire, H. G. (1980). Recovery of soils and vegetation in a Mojave Desert ghost town, Nevada, USA. In Proceedings of 1980 symposium: a compilation of reports and papers presented at the fifth annual symposium of the Desert Tortoise Council, 22-24 March, 1980 in Riverside, California, 117. The Council.

Woodhouse, C. A., Meko, D. M., MacDonald, G. M., Stahle, D. W., & Cook, E. R. (2010). A 1,200-year perspective of 21st century drought in southwestern North America. Proceedings of the National Academy of Sciences, 107(50), 21283-21288.

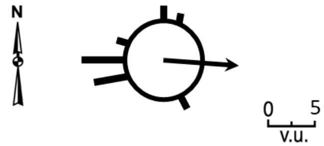
World Meteorological Organization. (1992). Monitoring, Assesment and Combat of Drought and Desertification, Ceneva, TD-No.55.

APPENDICES

APPENDIX I

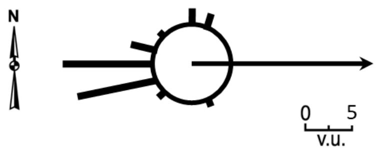
WIND ROSE AND SAND ROSE GENERATED BY THE 16-YEARS RECORD OF HOURLY WIND DATA FROM THE CAHUILLA WEATHER STATIO

2001-2016 Annual



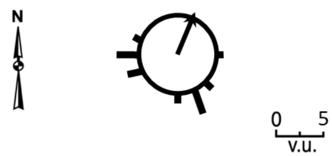
DP = 15.51 v.u.
RDP = 7.74
RDD = 92
RDP/DP =0.50

2001-2016 Spring (March-May)



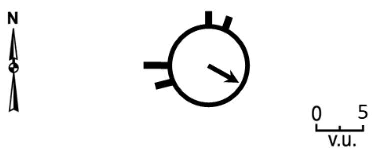
DP = 27.61 v.u.
RDP = 20.51
RDD = 90
RDP/DP = 0.74

2001-2016 Summer (June-Aug)



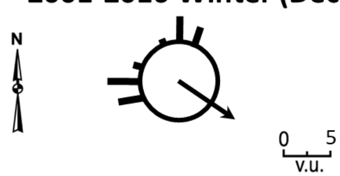
DP = 10.97 v.u.
RDP = 4.87
RDD = 22
RDP/DP = 0.44

2001-2016 Autumn (Sept-Nov)



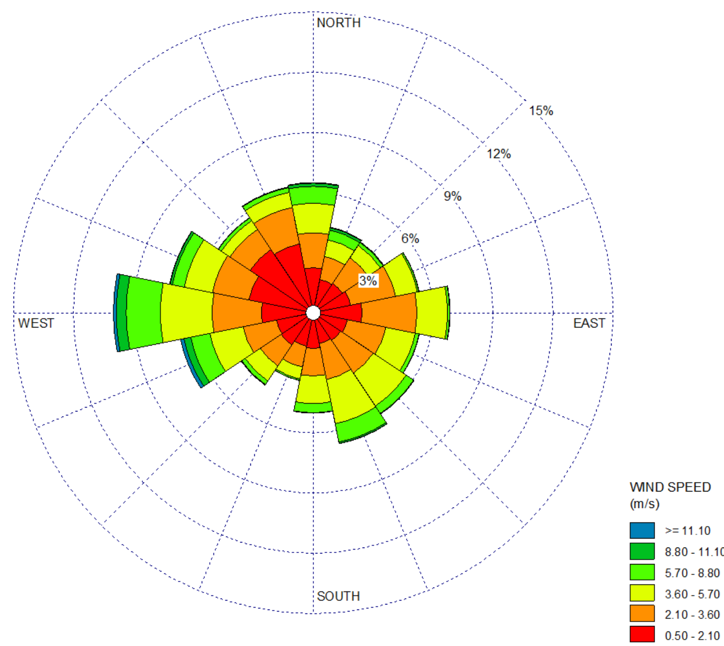
DP =10.84 v.u.
RDP = 4.08
RDD = 61
RDP/DP = 0.37

2001-2016 Winter (Dec-Feb)



DP = 13.07 v.u.
RDP = 6.70
RDD = 124
RDP/DP = 0.51

2001-2016 wind rose of the Cahuilla weather station



APPENDIX II

TREND ANALYSIS OF ANNUAL NDVI, LST, AND ALBEDO OF THE PROTECTED AREA AND RECREATIONAL AREA IN THE ALGODONES DUNES WITH THE SIGNIFICANCE LEVEL OF 90%.

Variables	Study areas	Total number of pixels	# of pixels with p-value≤0.1 (mean slope value)	% of +ve pixels	% of -ve pixels
NDVI	Protected area	503	204 (-0.4455)	1.47%	98.52%
	Recreational area	2030	630 (-0.3886)	3.65%	96.35%
Albedo	Protected area	503	150 (+0.3591)	97.34%	2.66%
	Recreational area	2030	502 (+0.3808)	96.22%	3.78%
LST (daytime)	Protected area	125	116 (+0.3746)	100%	0
	Recreational area	511	277 (+0.3504)	100%	0
LST (nighttime)	Protected area	125	43 (+0.3341)	100%	0
	Recreational area	511	305 (+0.3602)	100%	0

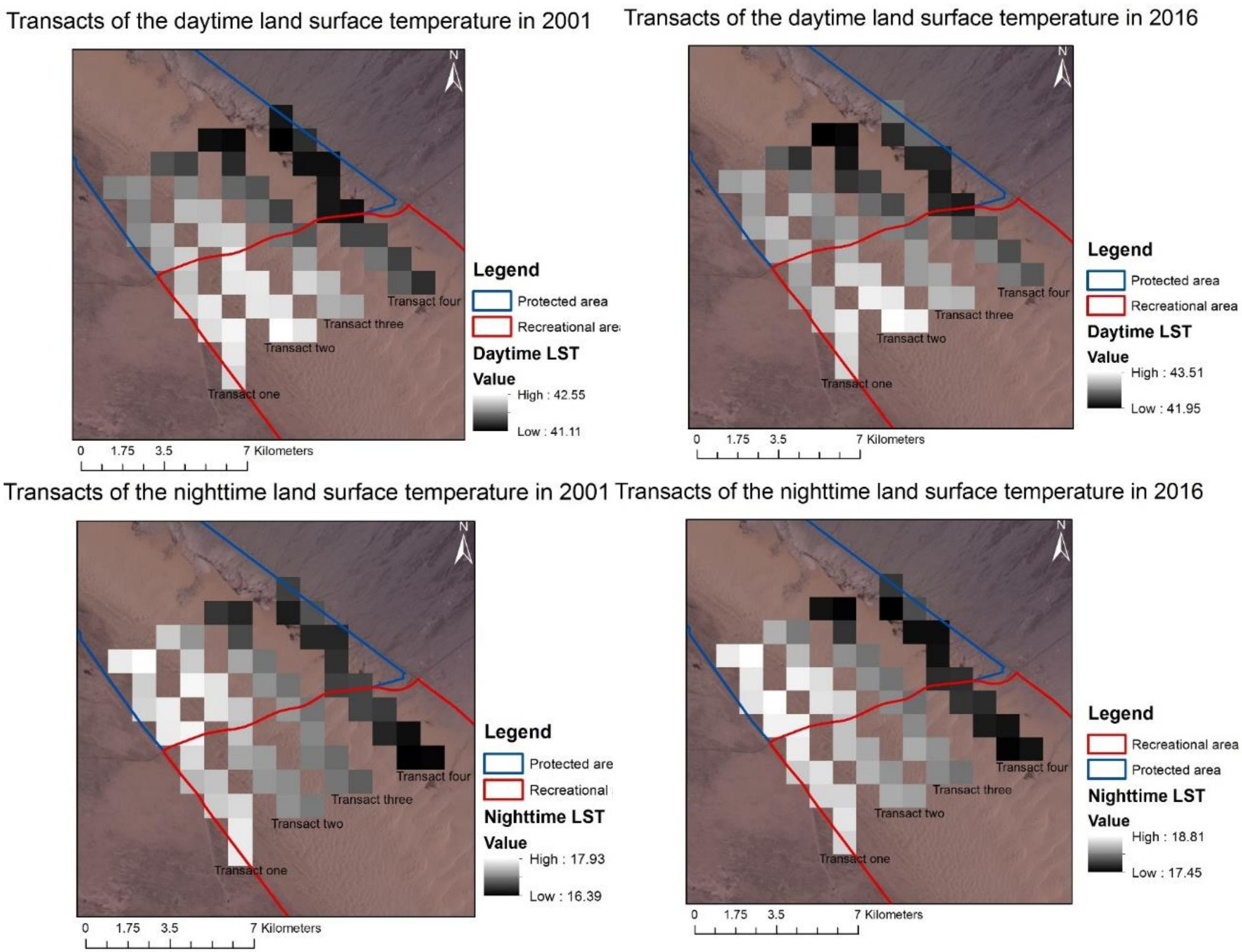
APPENDIX III

TREND ANALYSIS OF SEASONAL NDVI, LST, AND ALBEDO OF THE PROTECTED AREA AND RECREATIONAL AREA IN THE ALGODONES DUNES WITH THE SIGNIFICANCE LEVEL OF 90%.

Variables	Seasons	Study sites	Total number of pixels	# of pixels with p-value≤0.1 (mean slope value)	% of +ve pixels	% of -ve pixels
NDVI	Summer	Protected area	503	207 (-0.4214)	0.48%	99.52%
		Recreational area	2030	546 (-0.3734)	1.64%	98.36%
	Winter	Protected area	503	185 (-0.4023)	2.70%	97.30%
		Recreational area	2030	749 (-0.4173)	1.74%	98.26%
Albedo	Summer	Protected area	503	114 (+0.3797)	97.67%	2.33%
		Recreational area	2030	711 (+0.3899)	98.87%	1.13%
	Winter	Protected area	503	23 (+0.2449)	80.85%	19.15%
		Recreational area	2030	281 (+0.2184)	77.94%	22.06%
LST (daytime)	Summer	Protected area	125	31 (+0.3701)	100%	0
		Recreational area	511	33 (+0.2917)	93.93%	6.07%
	Winter	Protected area	125	7 (+0.0012)	71.42%	29.58%
		Recreational area	511	6 (+0.0028)	66.67%	33.33%
LST (nighttime)	Summer	Protected area	125	-	0	0
		Recreational area	511	91 (+0.3526)	100%	0
	Winter	Protected area	125	1 (+0.3167)	100%	0
		Recreational area	511	83 (+0.3398)	100%	0

APPENDIX IV

MAPS SHOWING THE RESULTS OF TRANSECT STUDY OF THE DAYTIME AND NIGHTTIME LAND SURFACE TEMPERATURE IN 2001 AND 2016.

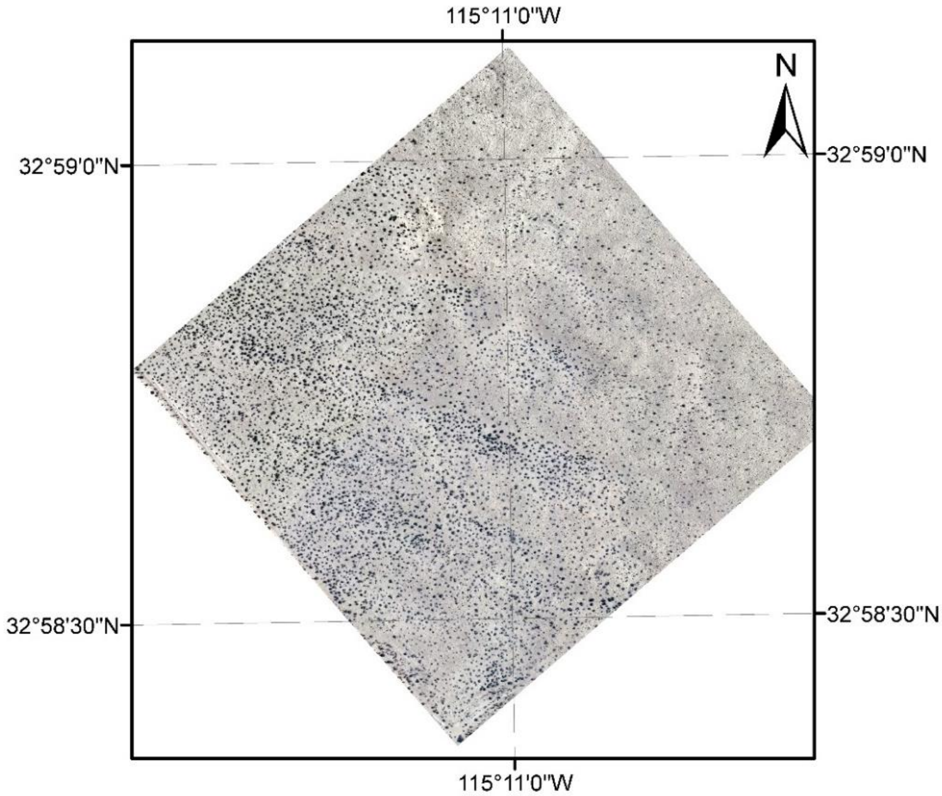


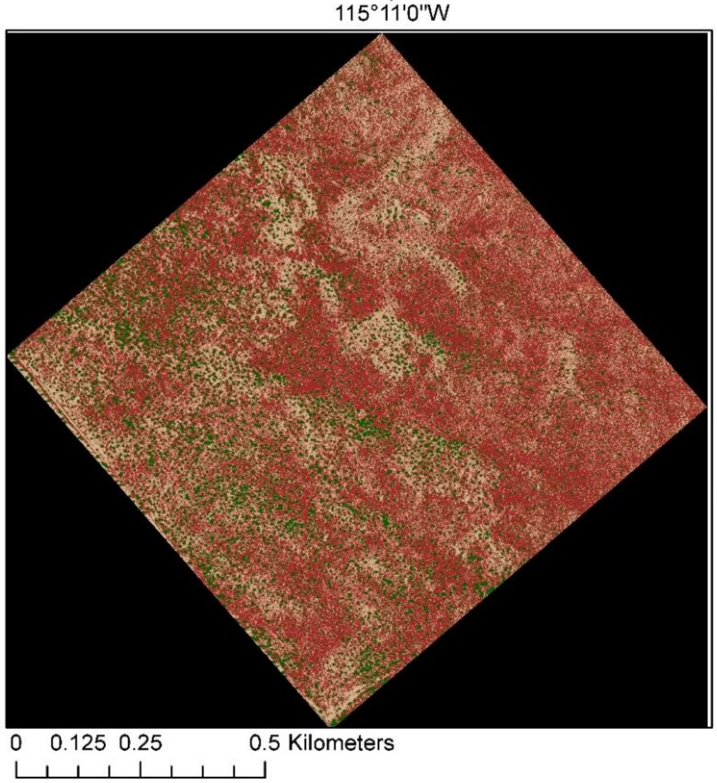
Transacts of the daytime land surface temperature in 2001
Transact one
Transact two
Transact three
Transact four
Legend
Protected area
Recreational are
Daytime LST
Value
High : 42.55
Low : 41.11
0 1.75 3.5 7 Kilometers
Transacts of the daytime land surface temperature in 2016
Transact one
Transact two
Transact three
Transact four
Legend
Protected area
Recreational area
Daytime LST
Value
High : 43.51
Low : 41.95
0 1.75 3.5 7 Kilometers
Transacts of the nighttime land surface temperature in 2001
Transact one
Transact two
Transact three
Transact four
Legend
Protected are
Recreational
Nighttime LST
Value
High : 17.93
Low : 16.39
0 1.75 3.5 7 Kilometers
Transacts of the nighttime land surface temperature in 2016
Transact one
Transact two
Transact three
Transact four
Legend
Recreational area
Protected area
Nighttime LST
Value
High : 18.81
Low : 17.45
0 1.75 3.5 7 Kilometers

APPENDIX V

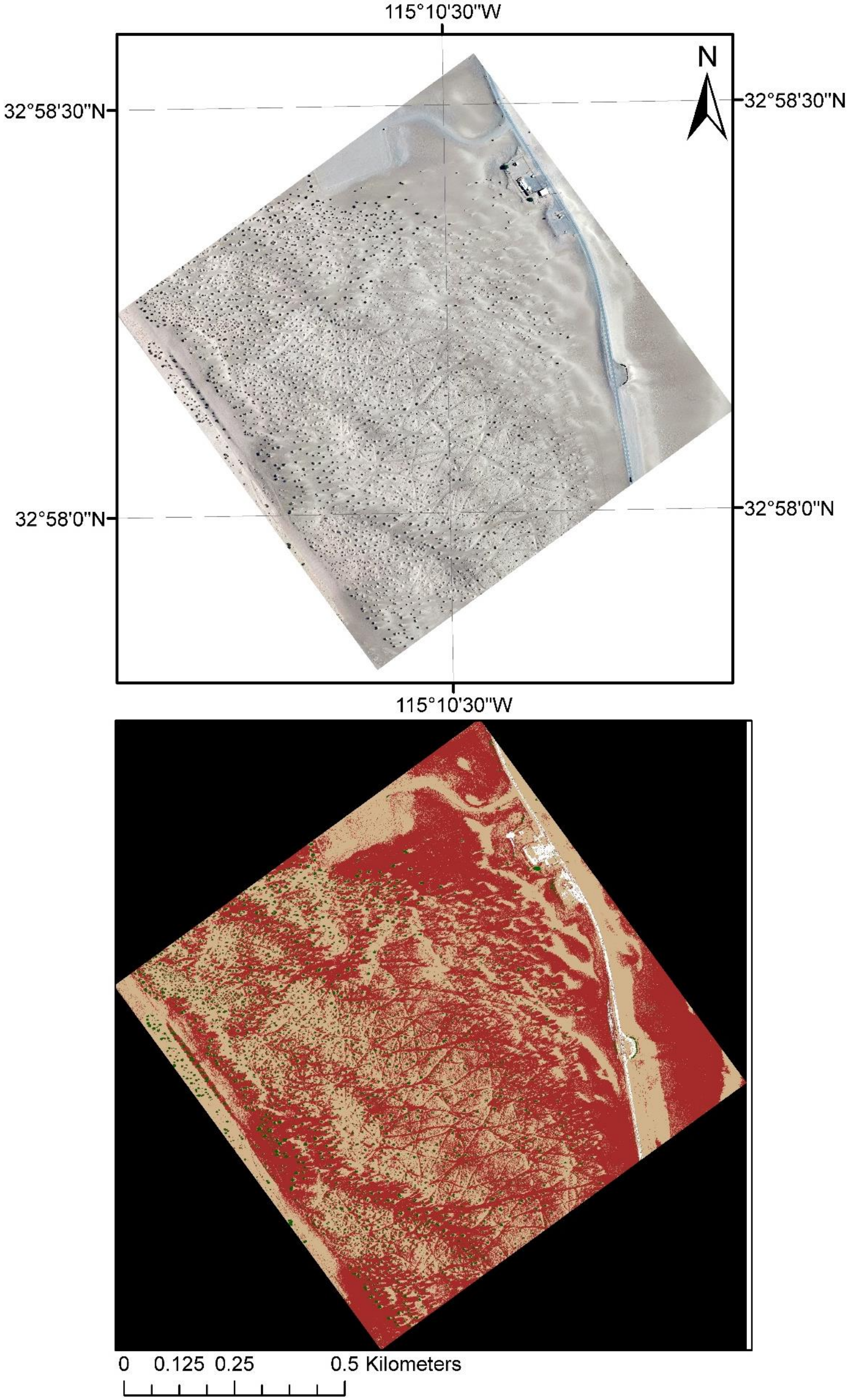
THE HIGH-RESOLUTION AERIAL PHOTOGRAPHS AND CLASSIFIED IMAGES RESULTED FROM UNSUPERVISED CLASSIFICATION OF THE IN THE NADW CONTROL SITE, GLAMIS OHV AREA, AND DUNE BUGGY FLATS OHV AREA.

NADW control site

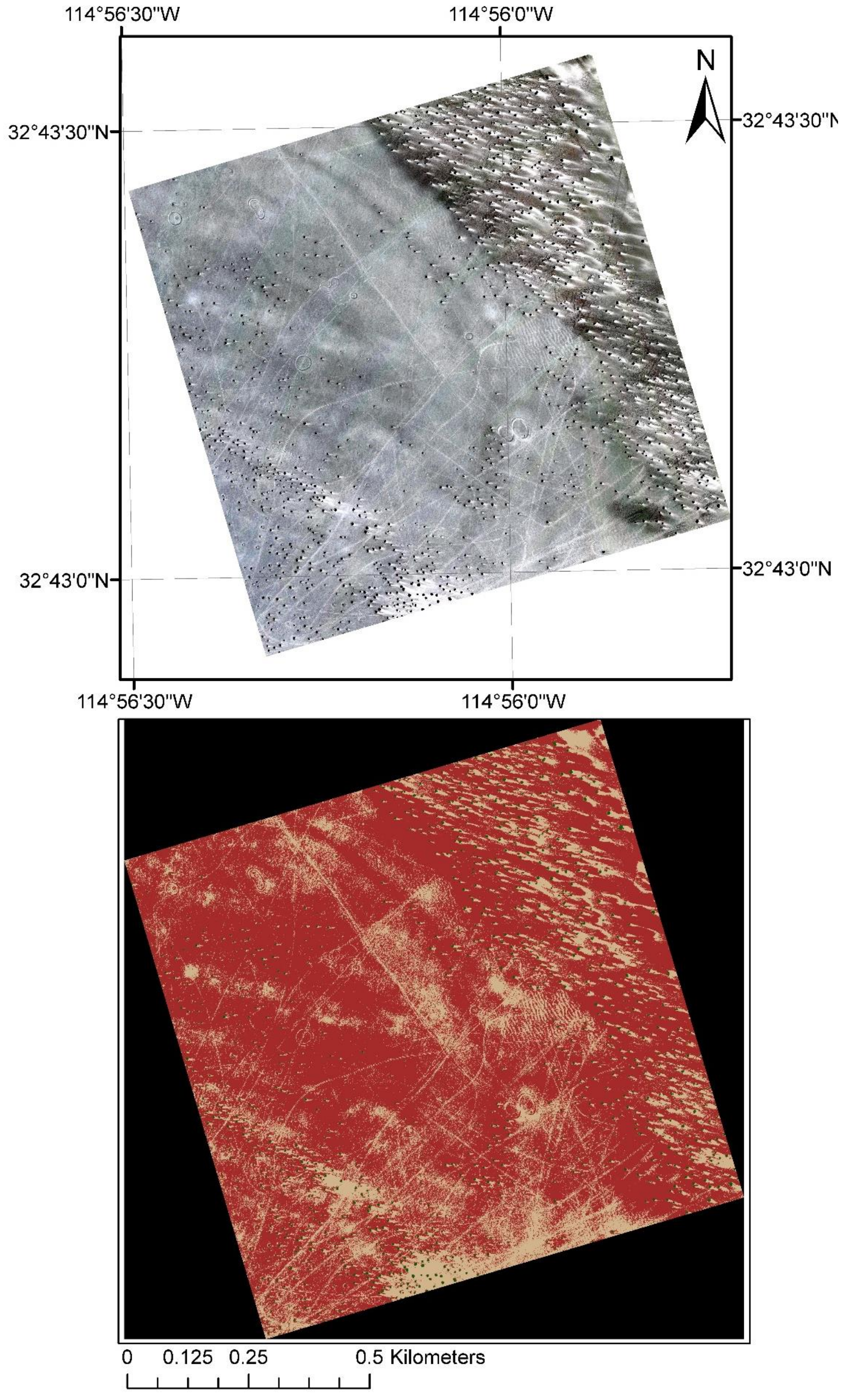




Glamis OHV area



Dune Buggy Flats OHV area



APPENDIX VI

THE TOTAL AREAS OF EACH CLASS IN THE NADW CONTROL SITE, GLAMIS OHV AREA, AND DUNE BUGGY FLATS OHV AREA.

NADW control site	Vegetation		Soil				Man-made features		Length of vehicle tracks
			Bright soil	Dark soil	Total				
	m²	%	m²	m²	m²	%	m²	%	m
1996/Jun	142,507	14.25	283,752	573,847	857,599	85.75	0	0.00	0.00
2002/May	117,562	11.75	308,735	573,809	882,544	88.25	0	0.00	0.00
2005/Jan	168,486	16.85	298,742	532,876	831,618	83.15	0	0.00	0.00
2005/May	120,300	12.03	338,728	541,077	879,805	87.97	0	0.00	0.00
2005/Aug	98,341	9.83	435,013	466,751	901,764	90.17	0	0.00	0.00
2008/Oct	102,233	10.22	335,418	562,453	897,871	89.78	0	0.00	0.00
2009/May	125,302	12.53	276,809	597,994	874,803	87.47	0	0.00	0.00
2011/May	151,674	15.17	292,095	556,336	848,431	84.83	0	0.00	0.00
2012/Apr	104,357	10.43	308,560	587,188	895,748	89.57	0	0.00	0.00
2014/Jun	92,992	9.30	267,500	639,613	907,113	90.70	0	0.00	0.00
2016/Apr	122,430	12.24	181,769	695,905	877,674	87.76	0	0.00	0.00

Glamis OHV area	Vegetation		Soil				Man-made features		Length of vehicle tracks
			Bright soil	Dark soil	Total				
	m²	%	m²	m²	m²	%	m²	%	m
1996/Jun	50,076	4.99	649,672	289,507	939,179	93.63	13,854	1.38	38291.91
2002/May	33,326	3.32	508,704	447,988	956,692	95.37	13,090	1.30	51908.54
2005/Jan	53,592	5.34	383,513	541,302	924,815	92.19	24,701	2.46	42896.14
2005/May	36,096	3.60	511,015	448,194	959,209	95.62	7,800	0.78	45583.05
2005/Aug	25,214	2.51	432,065	532,229	964,294	96.13	13,600	1.36	55575.15
2008/Oct	29,327	2.92	483,795	482,242	966,037	96.30	7,744	0.77	39286.73
2009/May	46,670	4.65	424,348	524,911	949,259	94.63	7,176	0.72	30169.20
2011/May	40,472	4.03	430,061	523,606	953,667	95.07	8,968	0.89	39579.94
2012/Apr	45,441	4.53	493,946	456,571	950,517	94.76	7,147	0.71	40928.95
2014/Jun	31,712	3.16	430,048	532,973	963,021	96.00	8,376	0.84	36891.94
2016/Apr	41,474	4.13	418,245	535,107	953,352	95.04	8,283	0.83	45317.76

Dune Buggy Flats OHV area	Vegetation		Soil				Man-made features		Length of vehicle tracks
			Bright soil	Dark soil	Total				
	m²	%	m²	m²	m²	%	m²	%	m
1996/Jun	17,091	1.71	478,671	504,613	983,284	98.29	0	0.00	21478.14
2002/May	13,798	1.38	371,634	614,941	986,575	98.62	0	0.00	32361.84
2005/Jan	24,972	2.50	306,718	641,531	948,249	94.79	27,150	2.71	26899.45
2005/May	12,447	1.24	304,891	682,908	987,799	98.74	129	0.01	31494.06
2005/Aug	18,728	1.87	452,221	529,417	981,638	98.13	0	0.00	28274.57
2008/Oct	17,665	1.77	260,267	721,456	981,723	98.14	983	0.10	40983.99
2009/May	19,756	1.97	398,956	581,663	980,619	98.03	0	0.00	46815.38
2011/May	11,871	1.19	253,590	734,910	988,500	98.81	0	0.00	56947.38
2012/Apr	19,640	1.96	336,433	644,302	980,735	98.04	0	0.00	42905.25
2014/Jun	16,208	1.62	262,388	721,779	984,167	98.38	0	0.00	30512.23
2016/Apr	15,974	1.60	305,143	679,253	984,396	98.40	0	0.00	24173.90

APPENDIX VII

ACCURACY ASSESSMENT OF THE IMAGE CLASSIFICATION CONDUCTED IN THE ERDAS IMAGINE SOFTWARE

Year/Month	Study area	Overall Accuracy	KAPPA statistics
1996/Jun	NADW control site	87%	0.8238
	Glamis OHV area	91%	0.8875
	Dune Buggy Flats OHV area	89%	0.8525
2002/May	NADW control site	89%	0.8517
	Glamis OHV area	96%	0.9500
	Dune Buggy Flats OHV area	91%	0.8794
2005/May	NADW control site	91%	0.8789
	Glamis OHV area	95%	0.9375
	Dune Buggy Flats OHV area	92.68%	0.9039
2009/May	NADW control site	91%	0.8790
	Glamis OHV area	94%	0.9250
	Dune Buggy Flats OHV area	96%	0.9464
2011/May	NADW control site	91%	0.8781
	Glamis OHV area	95%	0.9375
	Dune Buggy Flats OHV area	95%	0.9326
2012/Apr	NADW control site	92%	0.8923
	Glamis OHV area	95%	0.9375
	Dune Buggy Flats OHV area	93%	0.9056
2014/Jun	NADW control site	95%	0.9317
	Glamis OHV area	95%	0.9375
	Dune Buggy Flats OHV area	93%	0.9060
2016/Apr	NADW control site	90%	0.8644
	Glamis OHV area	95%	0.9375
	Dune Buggy Flats OHV area	91%	0.8792