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Assessing land degradation induced by recreational activities in the Algodones Dunes, California using MODIS satellite imagery

Suet-Yi Cheung[a,*], Ian J. Walker[b], Soe W. Myint[b], Ronald I. Dorn[b]

[a] Department of Park, Recreation and Tourism Management, North Carolina State University, Raleigh, NC, 27607, USA
[b] School of Geographical Science & Urban Planning, Arizona State University, Tempe, AZ, 85281, USA

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ABSTRACT

This research investigated spatial and temporal environmental changes associated with climatic variability and off-highway vehicle (OHV) activity in the Algodones Dunes, California, using time-series analysis of Moderate Resolution Imaging Spectroradiometer imagery from 2001 to 2016. We compared changes in land cover, surface albedo, and surface temperatures between the Imperial Sand Dunes Recreation Area (ISDRA) and areas with no OHV activity in the North Algodones Dunes Wilderness area (NADW). Both areas showed a decreasing normalized difference vegetation index (NDVI) and an increasing albedo from 2001 to 2016; however, ISDRA had a lower NDVI value and higher albedo compared to the adjacent NADW. Transects across these adjoining areas revealed substantial differences in daytime and nighttime land surface temperatures. ISDRA had an appreciably higher mean daytime temperature and a lower mean nighttime temperature compared to those within NADW. Results suggest direct association between increasing OHV activity and reduced vegetation cover, increased soil exposure, and higher daytime temperatures in the Algodones Dunes. We recommend enhanced monitoring of ecosystem and land use changes coupled with enhanced land use management to reduce the contributions of recreational OHV activity on land degradation and to maintain habitat for key species and ecosystems of interest in the dune field.

1. Introduction

Use of off-highway vehicles (OHVs) in natural landscapes is one of the fastest growing recreational activities in the United States. OHVs include a variety of motorized vehicles and motorcycles that are capable of traveling over land, sand, ice, snow, desert surfaces, rangeland, or other natural landscapes (Davenport and Switalski, 2006). OHVs have become increasingly popular for recreational purposes since the 1970s and have allowed people to travel into more remote areas. Between 1982 and 2003, the registration of OHVs increased rapidly in the United States from 3 million to 51 million (Groom et al., 2007; Cordell et al., 2008). In California, over roughly the same time interval, there was a 90% increase in OHV registration (Van Dam and Van Dam, 2008). By 2016, 78% of total visitation (5.6 million visitors) on public lands in California managed by the Bureau of Land Management (BLM) was OHV-related (California State Department of Parks and Recreation, 2017).

Concerns with the growth of OHV activity include substantial ecological impacts on a wide range of ecosystem structures and functions, including the destruction of vegetation cover, increased root exposure, enhanced soil erosion, and reduction of native or endangered species (Groom et al., 2007; Al-Hurban, 2014). In particular, much research has shown that OHV activity results in substantial impacts on soil ecosystems and vegetation. For example, intensive OHV use in vegetated landscapes results in physical breaking, crushing, and root exposure of vegetation and, eventually, death of plant cover (Stebbins, 1974; Lathrop, 1983; Luckenbach and Bury, 1983; Davenport and Switalski, 2006; Groom et al., 2007). In addition, soil ecosystems experience significant impacts with vehicular activity such as soil compaction, increased bulk density, and reduced moisture infiltration and soil water retention that, combined, reduce root growth, seed germination, and plant stability (Stebbins, 1974; Webb et al., 1978; Misak et al., 2002; Sack and Da Luz, 2003; Olive and Marion, 2009; Al-Hurban, 2014).

Sand dunes and arid landscapes are among the most common environments for OHV use, given the relative ease with which they can be accessed and ridden. Although biomass per unit land area might be lower than in forest ecosystems, plants play critical roles in arid ecosystems, particularly for protecting and stabilizing sand and soil surfaces

* Corresponding author.
E-mail address: scheung2@ncsu.edu (S.-Y. Cheung).

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against wind and water erosion and for providing habitat for many faunal species. Many semi-arid plant species are slow growing and/or vulnerable to soil disturbance or physical damage, so when exposed to OHV activities, they may take decades to recover to their initial state (Stebbins, 1974). In the early 1970s, an OHV race in Johnson Valley in the Mojave Desert resulted in the deterioration of 30% of the creosote bushes, 39% of the burroweed bushes, and 45% of the Mormon tea bushes (Gibson, 1973). Reducing the amount of the vegetation cover in arid and semi-arid environments is a form of land degradation and may lead to desertification as sand surfaces become more susceptible to wind and water erosion, as arid top soils become degraded, and as dune migration rates may change (Belnap, 1995; Al-Awadhi, 2013). In addition, soil temperatures may also increase after removal of vegetation cover as more insolation reaches the soil directly and there is less

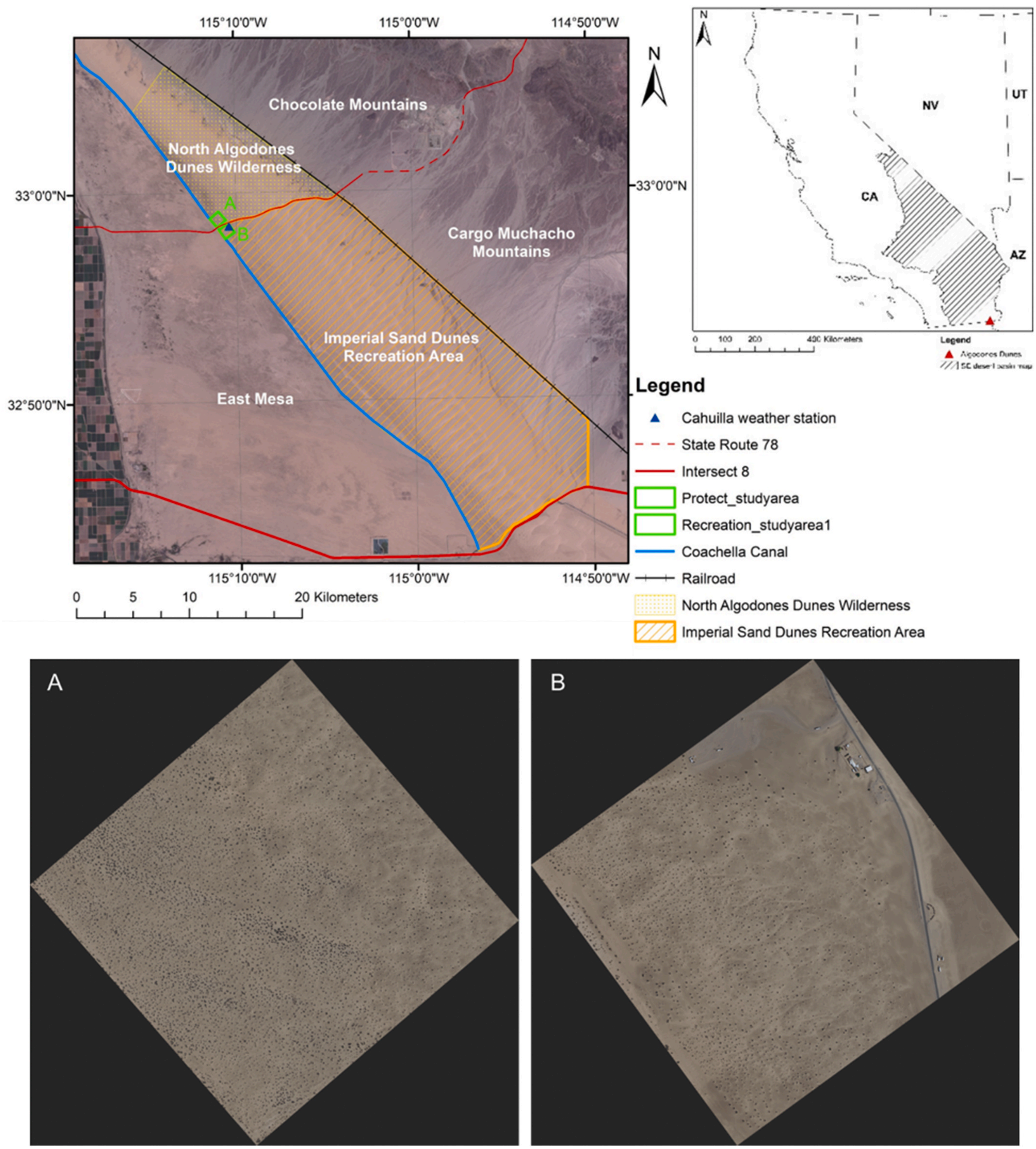

Fig. 1. The study areas of North Algodones Dunes Wilderness (NADW) and Imperial Sand Dunes Recreation Area (ISDRA) in the broader Algodones Dunes complex. High-resolution remotely sensed images took in Jun 2016 show the amount of vegetation cover and the level of human activities in a smaller sub-section of the NADW (A) and ISDRA (B).

thermal insulation provided by vegetation cover (Webb et al., 1978).

The Algodones Dunes, which hosts the Imperial Sand Dunes Recreation Area (ISDRA), is one of the most popular sand dune systems in California for OHV usage. The ISDRA sees over 1 million visitors a year and often more than 90,000 OHV drivers in the dune field during holidays (Camden Bruner, email to author, January 31, 2018). The use of OHVs in the dune field has resulted in reduced vegetation cover, enhanced soil and wind erosion, and, in turn, is associated with decreased presence of key endemic species, such as the fringe-toed lizard (*Uma notata*) and desert kangaroo rat (*Dipodomys desert*) (Luckenbach and Bury, 1983; Groom et al., 2007; Van Dam and Van Dam, 2008). Despite these observed impacts and associations, there is generally a lack of research on the spatial-temporal changes of vegetation cover in the Algodones Dunes in response to anthropogenic disturbances, such as OHV activity. In other landscapes, spatial-temporal approaches are commonly used to assess and monitor deforestation, forest degradation, urbanization, and the urban heat island effect (Verbesselt et al., 2010; Hansen et al., 2013; Wang et al., 2016; Wang and Myint, 2016). Given recent rises in recreational activities in semi-arid and arid landscapes, coupled with climatic variability (e.g., drought) and longer-term climate changes, it is essential to monitor and analyze the trends of land degradation in these areas using available remote sensing products and spatial-temporal approaches. In response, this paper addresses a distinct research gap related to the impacts of OHV activity in one of the most intensively used dune systems in North America.

This paper investigates the spatial-temporal changes in land cover (plants, bare soils) and regional climatic variability and change to explore associations with human-induced land degradation related to OHV use in the Algodones Dunes of southeastern California. Interpretations are referenced to an adjacent protected area, the North Algodones Dunes Wilderness Area (NADW) that has not seen OHV activity in at least 25 years by analyzing long-term and seasonal trends in key land cover variables, including normalized vegetation index (NDVI), albedo, and land surface temperature from 2001 to 2016.

2. Material and methods

2.1. Study area

The Algodones Dunes, located in the southeastern corner of Imperial County in California, is an elongated, compound dune (erg) 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 fans of the Chocolate Mountains and Cargo Muchacho Mountains in the east, and Coachella canal and East Mesa in the west (Fig. 1). The dune complex contains a variety of dune types, including: linear dunes, barchans, compound dunes, zibars, and nebkha dunes (shrub-coppice dunes) with some of the larger compound dunes reaching nearly 100 m in height (Nielson and Kocurek, 1986; Sweet et al., 1988; Groom et al., 2007; Derickson et al., 2008). Dunes in Algodones are very active with an average southeasterly migration of 35–40 cm per year (Sharp, 1979). The Algodones Dunes presently experience an arid, hot desert climate (BWh per the Köppen system) with summer temperatures exceeding 45 °C, while winter temperatures are milder, and the annual average temperature is 23 °C. Annual rainfall averages approximately 6.4 cm per year (Groom et al., 2007) and most precipitation in the Imperial Valley occurs either in summer as infrequent moderate thunderstorms or as occasional winter storms (Norris and Norris, 1961; Smith, 1970). This arid climate results in a typically dispersed vegetation pattern 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). Dominant plant species include creosote bush (*Larrea tridentate, Zygophyllaceae*), brittlebush (*Encelia farinose*, *Asteraceae*), burrobush (*Ambrosia dumosa*, *Asteraceae*), desert buckwheat (*Eriogonum deserticola, Polygonaceae*), and desert dicoria (*Dicoria canescens, Asteraceae*). Most of the vegetation is found along the boundary of the larger dune field as the canal and alluvial fan channels that border the dunes provide a water source for plant growth.

The ISDRA portion of the dune field attracts many OHV enthusiasts and visitors from around the United States for OHV recreation and camping. The average annual visitation to ISDRA was over 1 million people from 2002 to 2013 and the BLM estimated the total number of OHVs in the dune field at around one-third of the annual visitation (Camden Bruner, email to author, January 31, 2018). In accordance with the 1994 California Desert Protection Act, BLM designated the NADW portion of the dune field on the northern side of State Route 78 (Fig. 1) to preserve natural habitats and protect endemic and endangered species including Peirson's milkvetch (*Astragalus magdalenae var. peirsonii*), scarab beetles (*Pseudocotalpa andrewsi and Anomala hardyorum*), and the flat-tailed horned lizard (*Phrynosoma mcallii*) (Groom et al., 2007; Van Dam and Van Dam, 2008). Meanwhile, most of the southern portion of the dune field in ISDRA is open for OHVs and other recreational activities, including camping.

2.2. Data collection and processing

To investigate land cover changes related to OHV activity and land degradation in the Algodones Dunes, normalized difference vegetation index (NDVI), surface albedo, and land surface temperature (LST) are the three variables used in this research. The MODIS imagery datasets, including MODIS NDVI 16-days composite imagery (MOD13A1), MODIS BRDF/Albedo daily composite imagery (MOD43A3) and MODIS Land Surface Temperature 8-days composite imagery (MOD11A2), were downloaded from EarthExplorer managed by United States Geological Survey. The temporal extent of all datasets in this research is from 2001 to 2016 in order to have a comprehensive coverage dataset for generating the annual and seasonal time-series analysis of the variables. Both NDVI and albedo datasets have a 500-m spatial resolution, while the LST dataset includes daytime and nighttime land surface temperature images with a 1-km spatial resolution.

Image processing was done prior to the analyses. The pixels located in the study areas of NADW and ISDRA were extracted in the ArcMap software (ERSI, 2018). In addition, the temporal granularity of datasets were varied and covered a short period of time. In order to have a consistent temporal scale for all three variables, a new dataset was created for each variable by compiling all 16 images, wherein the pixels of each image show the mean value of the variable in one particular year. For the seasonal analysis, the images acquired in June and July were used for the summer time-series analysis which is when the Algodones Dunes has its highest temperatures, and the images obtained in November and December were used to characterize winter season temperatures. These winter months also correspond with the peak season of OHV activity in the dune field.

2.3. Time-series analyses

The time-series analyses were conducted using Earth Trend Modeler of TerrSet Geospatial Monitoring and Modeling Software. The significance level of the Mann-Kendall test was set 0.1, given the spatial coarseness of the dataset and the exploratory nature of this study. The annual time-series analyses of NDVI, albedo, LST of NADW and ISDRA were conducted to identify the impacts of OHV activity on land cover change in the Algodones Dunes over time. The seasonal time-series analyses were mainly used to analyze the seasonal variations of vegetation cover and OHV activity between summer and winter.

2.4. Transects of the land cover variables

Given the spatial variability of vegetation cover in the dune field and different areal extents of the NADW and ISDRA, four transects were established across State Route 78, which separates these regions, to provide an equal number of pixels in each region and allow systematic comparison of different variables (Fig. 2). The length of each transect is approximately 2 km. As the spatial resolution of the variables is varied, each transect covers 15 pixels in each area for NDVI and albedo datasets, and 8 pixels in each area for LST dataset. A simple *t*-test with the significance level of 90% was conducted to explore the differences in mean value of pixels between NADW and ISDRA.

2.5. Climatic variability and visitation data

Hourly air temperature and precipitation data measured at the Cahuilla weather station (Fig. 1) from 2001 to 2016 were used to characterize the climatic variations within the Algodones Dunes. Annual and seasonal averages for temperature and precipitation were calculated, with summer and winter averages determined from June and July, and November and December data, respectively.

BLM has collected visitation data at the Algodones dunes since 2002. They estimate the number of visitors by counting vehicles entering the dunes and multiplying the vehicle counter data by 3.5, which they estimate to be the average occupancy per vehicle (Camden Bruner, email to author, January 31, 2018). The total visitation data is thus a proxy for the amount of OHV activity in the dune field.

3. Results

3.1. Local climatic variations

The Algodones Dunes has a typical arid climate with a high annual average air temperature (from 24 to 25.5 °C) and low annual rainfall (<30 mm) between 2001 and 2016. Annual average temperatures have also increased steadily from 2010 to 2016 (Fig. 3A) with substantial seasonal variations ranging from >30 °C in summer to 15 °C–18 °C in winter. The annual total rainfall of the dune field decreased from 2001 to 2016 (Fig. 3B), with values ranging from <30 mm in 2002, 2007, 2009, 2013 and 2014, to >170 mm in 2005. Seasonally, winter receives higher rainfall than in summer, except in 2005, 2006 and 2015, and there were seven years that the dune field did not receive any precipitation in summer.

3.2. Visitation

The total visitation to the Algodones Dunes has decreased over time from 1.42 million in 2002 to 0.8 million in 2017 (Fig. 4A). The maximum visitation occurred in 2006 with 1.46 million people visiting the dune field. Since, a notable decreasing trend of visitation has occurred, dropping by approximately 45% between 2007 and 2017. The monthly averaged visitation data show that most visitation occurs from late-October to mid-February, while there are much fewer visitors during spring and summer seasons from March to September (Fig. 4B). Moreover, the number of visitations is strongly associated with established holidays. American Thanksgiving (in November) is the most popular holiday for visitors and other major holidays, such as Christmas and New Year (Dec–January), Halloween (October), and President's Day (February), also attract many visitors to the Algodones Dunes.

3.3. Annual time-series analysis

Both NADW and ISDRA show a similar decreasing trend in NDVI, which indicates that the vegetation cover within the transects that span the broader Algodones Dunes was generally declining from 2001 to 2016. However, there is a significant difference in mean NDVI value (Fig. 5A) and mean albedo (Fig. 5B) between two areas. The annual mean NDVI value of ISDRA (0.0895) was substantially lower than that of NADW (0.1045) during the study period, while ISDRA (0.2507) has substantially higher albedo rate than NADW (0.2293). Table 1 shows that both NADW and ISDRA show an increasing trend of albedo with average positive slope values of 0.3591 and 0.3808 respectively. The results of NDVI and albedo indicate that an increase in soil exposure and reflectivity of the soil surface occurred in both areas from 2001 to 2016, but that values in ISDRA were higher as more soil surface became exposed compared to within NADW.

The dune field transects had the highest mean NDVI and the lowest mean albedo in 2005. In this year, ISDRA had a mean NDVI value of 0.0987 and a mean albedo rate of 0.2372, while NADW had a mean NDVI value of 0.1374 and a mean albedo rate of 0.2083. This indicates that both regions within the dune field had the greatest amount of vegetation cover (highest NDVI value) during the study period in 2005, which in turn resulted in a greater amount of soil surface protected by vegetation cover (lowest albedo rates).

Both NADW and ISDRA regions show an increasing trend of annual mean daytime and nighttime LST from 2001 to 2016 (Fig. 5C and D). All transect pixels that had a significant change in land surface temperature also had a positive slope value, which indicates those areas have a significant increase in land surface temperature during the study period (Table 1). However, the differences in LST between NADW and ISDRA

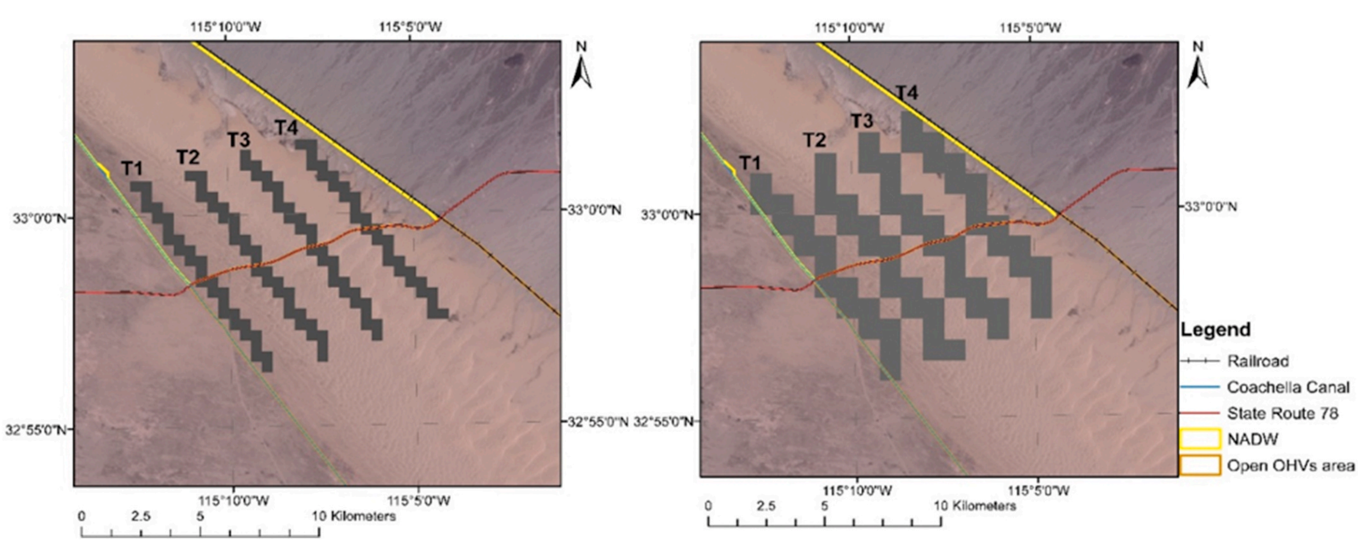

Fig. 2. MODIS pixel transects T1-T4 spanning the NADW and ISDRA (north and south of State Route 78, respectively). As NDVI and albedo datasets are of a higher spatial resolution than LST datasets, 15 pixels were selected for NDVI and albedo transects (left image) whereas only 8 pixels for each area were selected for the coarser datasets of daytime and nighttime temperatures (right image).

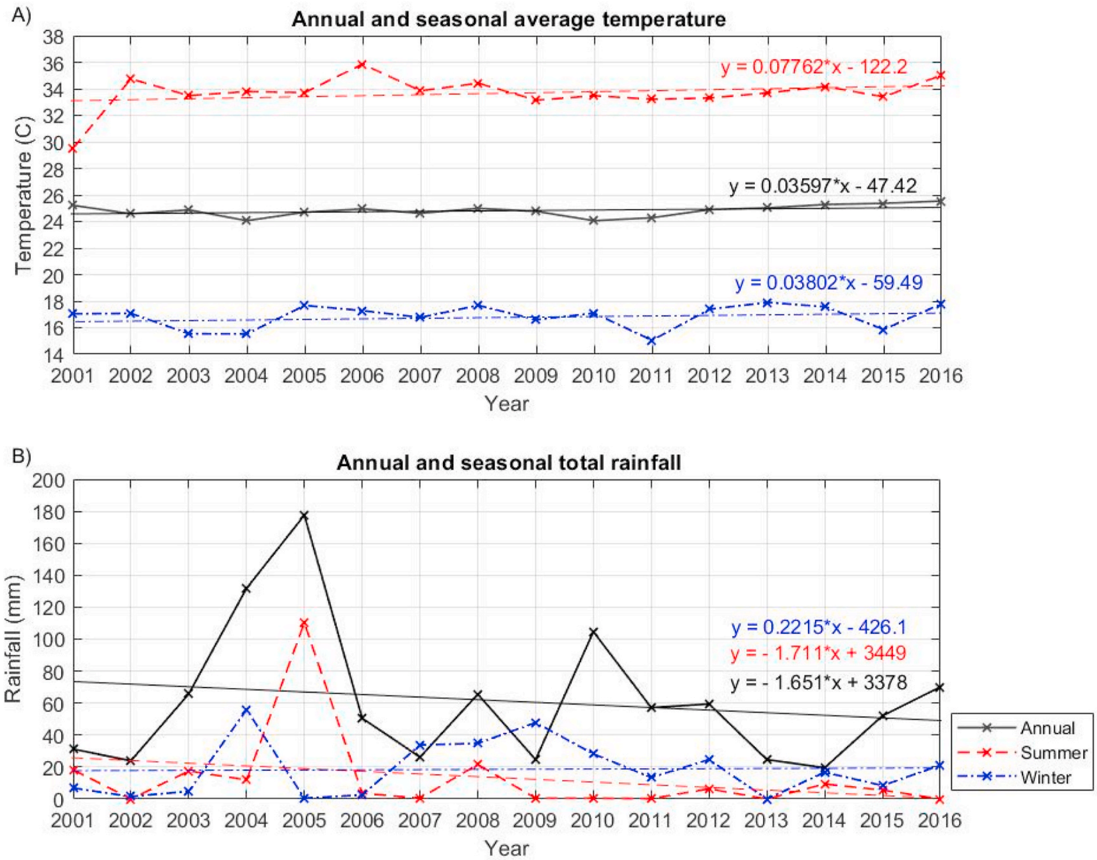

Fig. 3. Annual and seasonal average temperature (A) and total rainfall (B) within the Algodones Dunes from 2001 to 2016.

are not substantial in the annual time-series analysis.

3.4. Seasonal time-series analysis

The results of seasonal time-series also illustrates that both NADW and ISDRA have a decreasing trend of NDVI value and an increasing trend in albedo rate in both summer and winter seasons; however, the changes are not statistically significant (Fig. 6A, B, 7A, and 7B). Similar to the annual time-series analysis results, there are substantial difference in NDVI value and albedo rate between NADW and ISDRA in both summer and winter seasons. Both areas have a higher NDVI value and lower albedo in winter than summer. The average winter NDVI of ISDRA and NADW are 0.0896 and 0.1048 respectively, and the average summer NDVI of ISDRA and NADW are 0.0885 and 0.1002 respectively.

For summer daytime and nighttime LST, both areas experienced an increasing trend of LST between 2001 and 2016. ISDRA has a slightly lower summer average mean daytime and nighttime temperature than NADW in most of the years (Fig. 6C and D). The mean summer daytime temperature of NADW and ISDRA are 56.48 °C and 56.01 °C, while the mean summer nighttime temperature of NADW and ISDRA are 28.98 °C and 28.57 °C. The results of winter daytime and nighttime LST show that there are no substantial differences between NADW and ISDRA (Fig. 7C and D).

3.5. Transects of the land cover variables

The results of MODIS transects within the Algodones Dunes protected area and OHV-recreation area showed significant differences in all the variables between NADW and ISDRA (Table 2). These differences are most pronounced when comparing mean NDVI values. ISDRA has a substantially lower NDVI value and higher albedo rate than NADW, and transect one has the highest NDVI value and lowest albedo rate in both NADW and ISDRA. The results of daytime and nighttime LST in the transect study are different than the annual time-series analysis. The transect results indicate that ISDRA has substantially higher mean daytime temperature than NADW in all transects, except transect four. The mean daytime LST is between 41.6 °C and 42.62 °C in ISDRA, and between 41.53 °C and 42.4 °C in NADW. The results of nighttime LST illustrated inverse results of the daytime LST. The mean nighttime temperature of ISDRA is slightly lower than that of NADW in most of the transects. ISDRA has a mean nighttime temperature between 17.08 °C and 18.22 °C, while NADW ranges from 17.21 °C to 18.28 °C. The results of these transects of land cover variables indicate a statistical difference in land cover between NADW and ISDRA. As ISDRA has less vegetation cover than NADW, this results in a higher mean daytime temperature and a lower mean nighttime temperature in the OHV recreation areas.

4. Discussion

4.1. Spatial-temporal trends in vegetation cover

Seasonal time-series analysis of MODIS imagery of the Algodones Dunes indicates a distinct difference in vegetation cover (NDVI) between summer and winter in both protected (NADW) and OHV-use (ISDRA) study areas. Generally, vegetation cover is declining in both areas of the Algodones Dunes and this is apparent in both annual and seasonal (winter, summer) average trends in NDVI. Plant growth appears to occur mainly in the winter months, despite these also being times of increased OHV activity. One potential mechanism for this is the observed increase in land surface temperatures, which could encourage plant growth in winter, but conversely could inhibit growth during increasing heat stress in summer with increasing daytime LST trends and an average value exceeding 56 °C. Thus, although there is much less OHV activity in summer months, increasing daytime temperatures in the dune field are

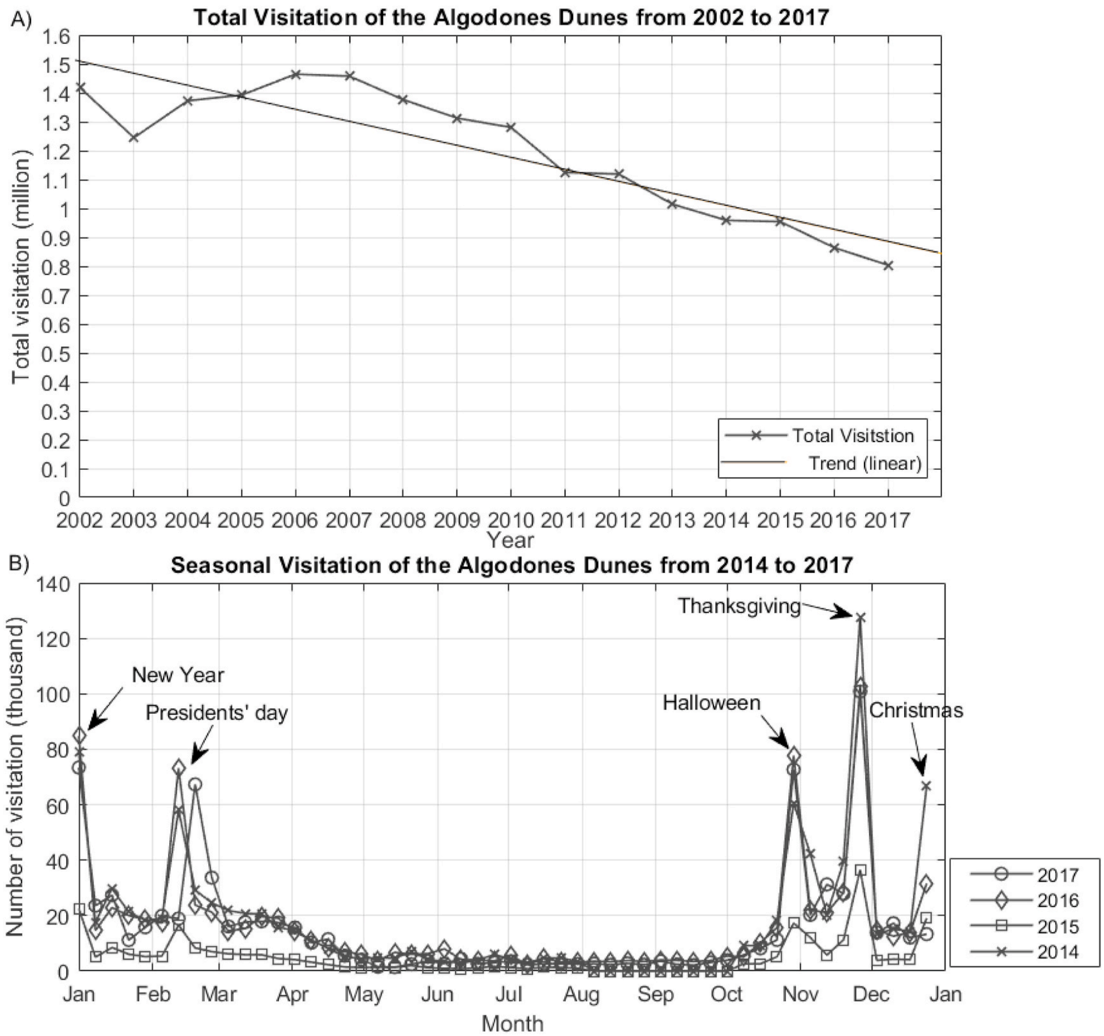

Fig. 4. Annual (A) and monthly-averaged (B) vistitation to the Algodones Dunes derived from BLM records from 2002 to 2016 and 2014–2017, respectively.

likely inhibiting plant growth and seed germination. In contrast, the trend in daytime LST in the winter is decreasing slightly and the average winter temperature is approximately 27 °C, which combined with ample water supply from the Coachella canal in the west and the washes from the Chocolate and Cargo Muchacho mountains in the east (Luckenbach and Bury, 1983), could readily promote seed germination and vegetation growth in low-lying areas.

The seasonal peak in vegetation growth during winter months also coincides with times of highest OHV activity. Despite more favorable conditions for plant growth, this is associated with concurrent declines in vegetation cover within the ISDRA. The peak season of OHV activity is between Hallowe'en (31 October) and New Year's Day (1 January). Desert vegetation is vulnerable to the disturbances generated by OHV traffic and related activities due to limited tolerance for physical damage, a very slow growth rate, and susceptibility of seed establishment and germination to trampling and compaction (Priskin, 2003). Once plants are damaged by OHV activity, it may take decades or centuries for recovery to initial conditions. Without sufficient time for plant recovery, land degradation from OHV activity has occurred in ISDRA even with declining rates of OHV activity over the 16-year observation period (Cheung, 2018).

NADW and ISDRA both show increasing trends for daytime and nighttime land surface temperature from 2001 to 2016. NADW generally has more vegetation cover and slightly higher daytime and nighttime LST than the ISDRA with less vegetation cover. This might seem contradictory to a common perception that a negative relationship should exist between vegetation cover and LST. Shrubby vegetation in desert environments is typically sparsely distributed and has much less leaf cover and vegetation biomass than in non-arid environments. Thus, the albedo of desert vegetation is significantly lower than surrounding desert sand dunes. Besides, evapotranspiration may not be considerably higher than bare sand surfaces so as to lower the LST. Myint et al. (2013) reported that even fully grown trees in a desert city are not capable of lowering nighttime LST. Areas with shrubby vegetation in the study area also tend to have biological soil crusts, more varied soil textures (e.g., sandy loam to clayey soils) vs. pure sand, and significantly lower albedo in comparison to the sand dune surfaces. Nevertheless, desert vegetation's evaporative cooling effect is weaker than the effect of albedo from the bare sand dune surfaces.

4.2. *Associations between OHV activity and land degradation*

Land surfaces in the Algodones Dunes have experienced land degradation by way of a decreasing amount of vegetation cover from 2001 to 2016. Generally, the results show that NDVI values within the ISDRA are significantly lower than that of NADW, which implies that ISDRA has a lower vegetation cover. These results support previous research that found that areas open to OHV activity had 4 to 5 times fewer plants than in the protected NADW, which was associated with the effects of OHVs reducing plant survival probability by 33% in the ISDRA (Groom et al., 2007).

The physical disturbances of OHV activity are believed to be the

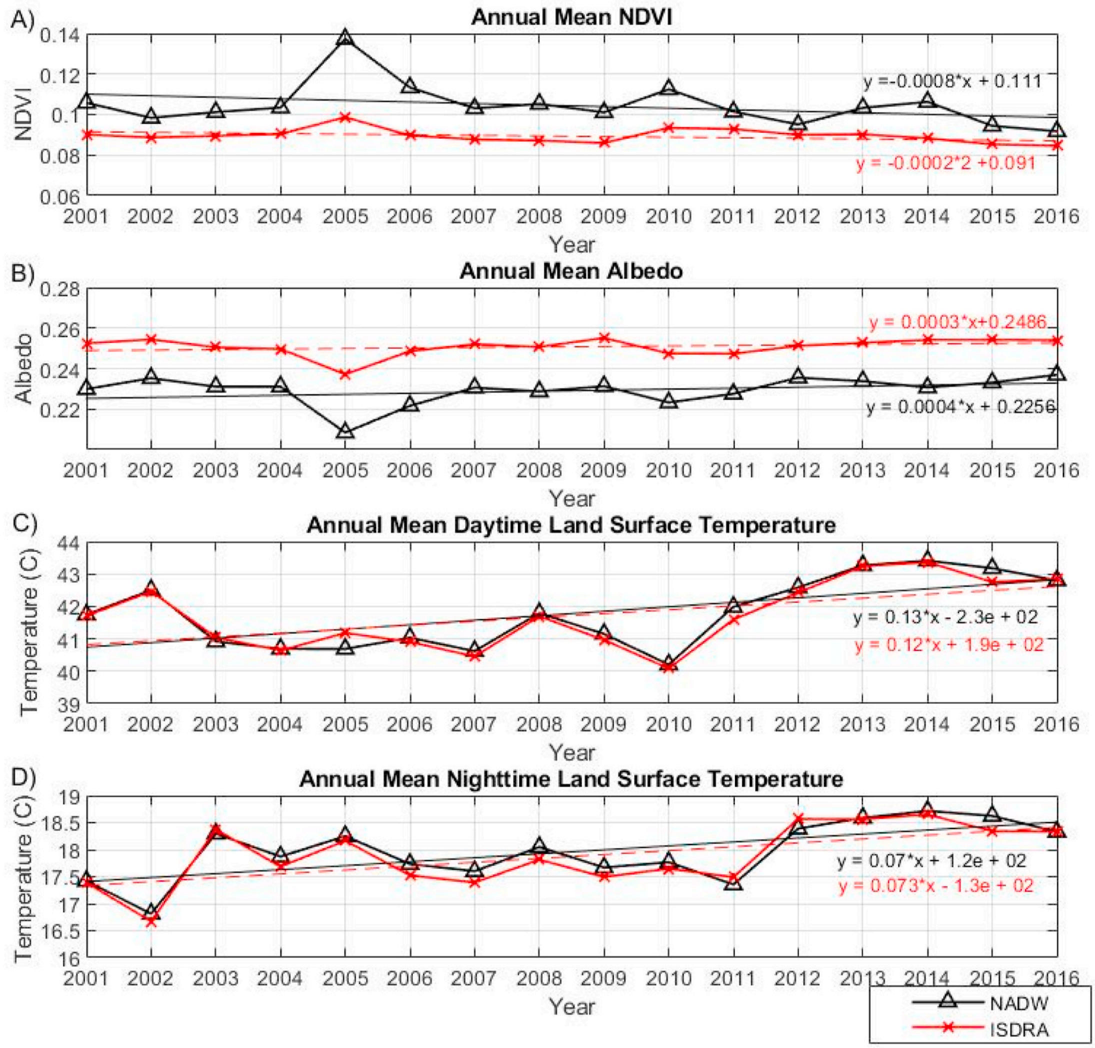

Fig. 5. Annual mean value trends in NDVI (A), albedo rate (B), daytime temperature (C), and nighttime temperature (D) from transects within NADW and ISDRA in the Algodones Dunes from 2001 to 2016.

Table 1
Time-series analysis of annual NDVI, albedo and LST of NAWD and ISDRA in the Algodones Dunes with the significant level of 90%.

Variables	Study areas	Total number of pixels	No. of pixels with $p \leq 0.1$ (mean slope value)	Percent of pixels with positive slope value	Percent of pixels with negative slope value
NDVI	NAWD	503	204 (−0.4455)	1.47	98.52
	ISDRA	2030	630 (−0.3886)	3.65	96.35
Albedo	NAWD	503	150 (+0.3591)	97.34	2.66
	ISDRA	2030	502 (+0.3808)	96.22	3.78
Daytime LST	NAWD	125	116 (+0.3746)	100	0
	ISDRA	511	277 (+0.3504)	100	0
Nighttime LST	NAWD	125	43 (+0.3341)	100	0
	ISDRA	511	305 (+0.3602)	100	0

predominant factor behind the differences in land cover between NADW and ISDRA. It is well documented that OHV activity causes significant negative impacts on vegetation growth and stability of sand dunes (Stebbins, 1974; Priskin, 2003; Davenport and Switalski, 2006; Goossens and Buck, 2009; Olive and Marion, 2009; Cabrera-Vega et al., 2013). When vehicles drive over or brush against vegetation this causes damage to, and reduction of, the plant canopy and root exposure can occur. In turn, this can eventually lead to uprooting and/or destruction of impacted plants (Stebbins, 1974). OHVs also indirect impact on vegetation growth by altering soil physical properties, such as increasing soil bulk density by compaction, soil erosion and displacement, and decreasing soil infiltration and moisture holding capacity that, collectively, negatively affect seed germination, root growth, and nutrient uptake (Davenport and Switalski, 2006; Cabrera-Vega et al., 2013). The net result is that OHV activity can substantially reduce vegetation cover and inhibit plant germination and recovery in natural landscapes, particularly if there are no traffic control or ecosystem restoration measures in place. Once the vegetation has been destroyed, soils are exposed and become more susceptible to water and wind erosion and further OHV impacts. In arid or semi-arid environments, such as the Algodones Dunes, reduced vegetation cover and OHV activity may also re-activate stabilized dunes, increase dune migration (Van Dam and Van Dam, 2008), and contribute to other land degradation processes such as topsoil loss, reduced soil productivity, or increased dust emissions and

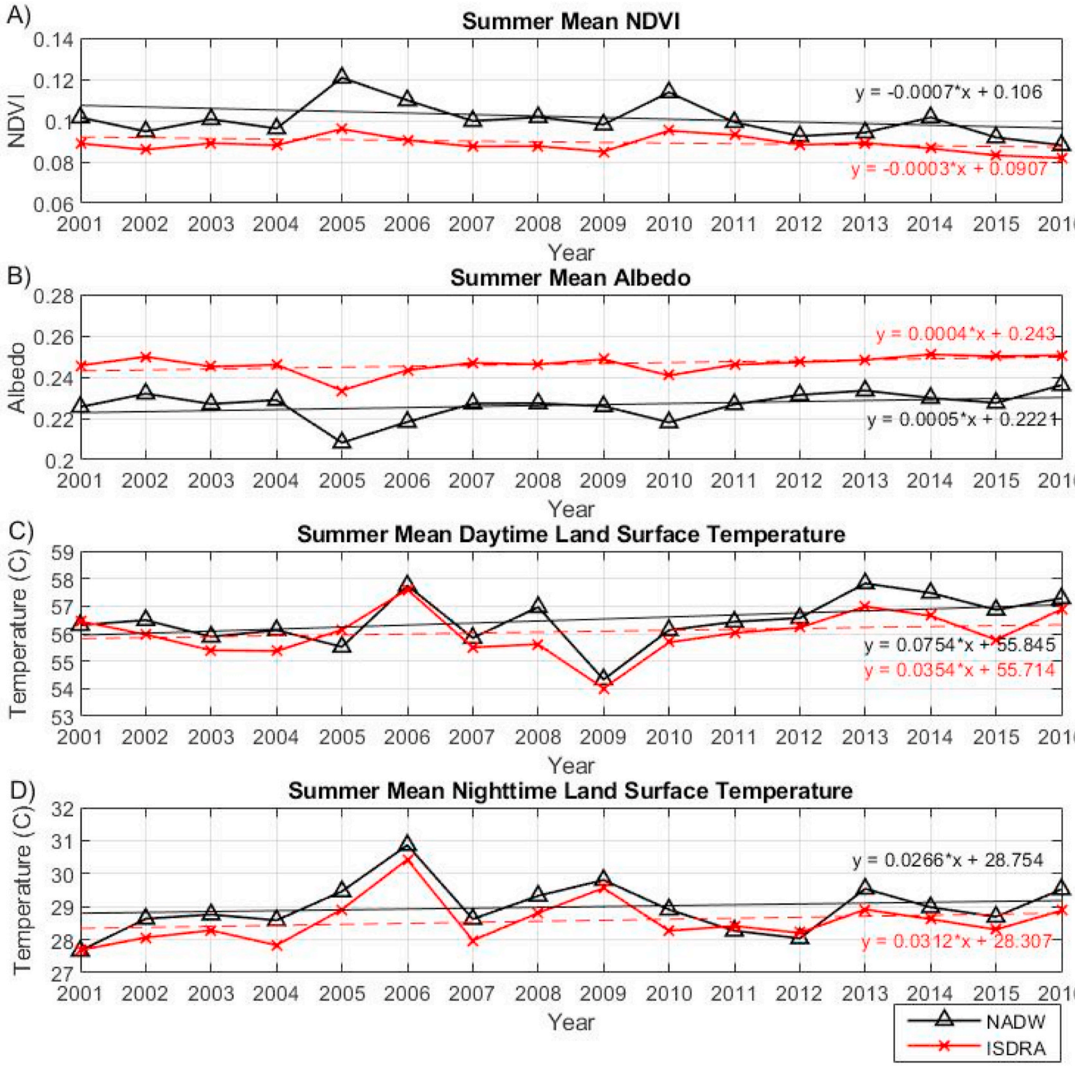

Fig. 6. Summer mean values and trends of NDVI (A), albedo (B), daytime temperature (C) and nighttime temperature (D) of NADW and ISDRA in the Algodones Dunes from 2001 to 2016.

reduced air quality concerns.

Both the projected NADW and ISDRA OHV-riding areas show a subtle decline in the amount of vegetation cover over the 16-year observation period, which could be partly related to climatic variations, such as drought or precipitation extremes that are common to desert environments. For instance, the extreme precipitation events in 2005 resulted in the highest value of NDVI and the lowest albedo in both areas during the study period (Fig. 5), which indicates that vegetation cover in the dune field can change notably in response to variations in precipitation or water supply. Also, the prolonged drought in California, which was particularly strong in 2012–2014 (Griffin and Anchukaitis, 2014), might also contribute to the decreasing NDVI trend in both NADW and ISDRA. Associated limits in water supply and increased land surface temperatures may also affect the vegetation growth and seed germination; however, most desert plant species are well-adapted to moisture deficits and temperature extremes. As NADW is undisturbed and has consistently maintained more vegetation cover than the ISDRA, the effects of the extreme weather events, such as extreme precipitation and drought are more pronounced in NADW than in the ISDRA where vegetation cover is less.

It is also important to note that OHV activity within the Algodones Dunes existed long before the study period began in 2001. OHV activity in the region dates back at least the 1970s and, thus, the impacts of associated land degradation were manifested in the landscape decades prior. The impacts can obviously increase over time with increased OHV ridership and/or spatial extent of activity; however, Priskin (2003) notes that it only takes the first few passes of an OHV to generate significant impacts and declines in vegetation and that subsequent passes make less of a difference after the initial damage is done. In other words, vegetation damage and land degradation signals in the Algodones Dunes are likely somewhat independent of fluctuations in visitorship numbers provided that OHV activity persists uncontrolled in the ISDRA. As above, it can take decades or longer for impacted ecosystems to recover from the initial phases and persistent impacts of OHV damage. The implication here is that appreciable damage to vegetation cover within ISDRA likely existed prior to 2001 and that this could explain the less steep trends in the degraded ISDRA relative to the protected NADW in the more recent observation period between 2001 and 2016.

5. Conclusion

Over the past few decades, off-highway vehicle use has become a fast-growing recreational activity in the United States. OHV impacts on different landscapes have been well-studied. However, most of the research lacks interpretation of spatial-temporal changes in vegetation cover and land surface temperatures associated with human-induced

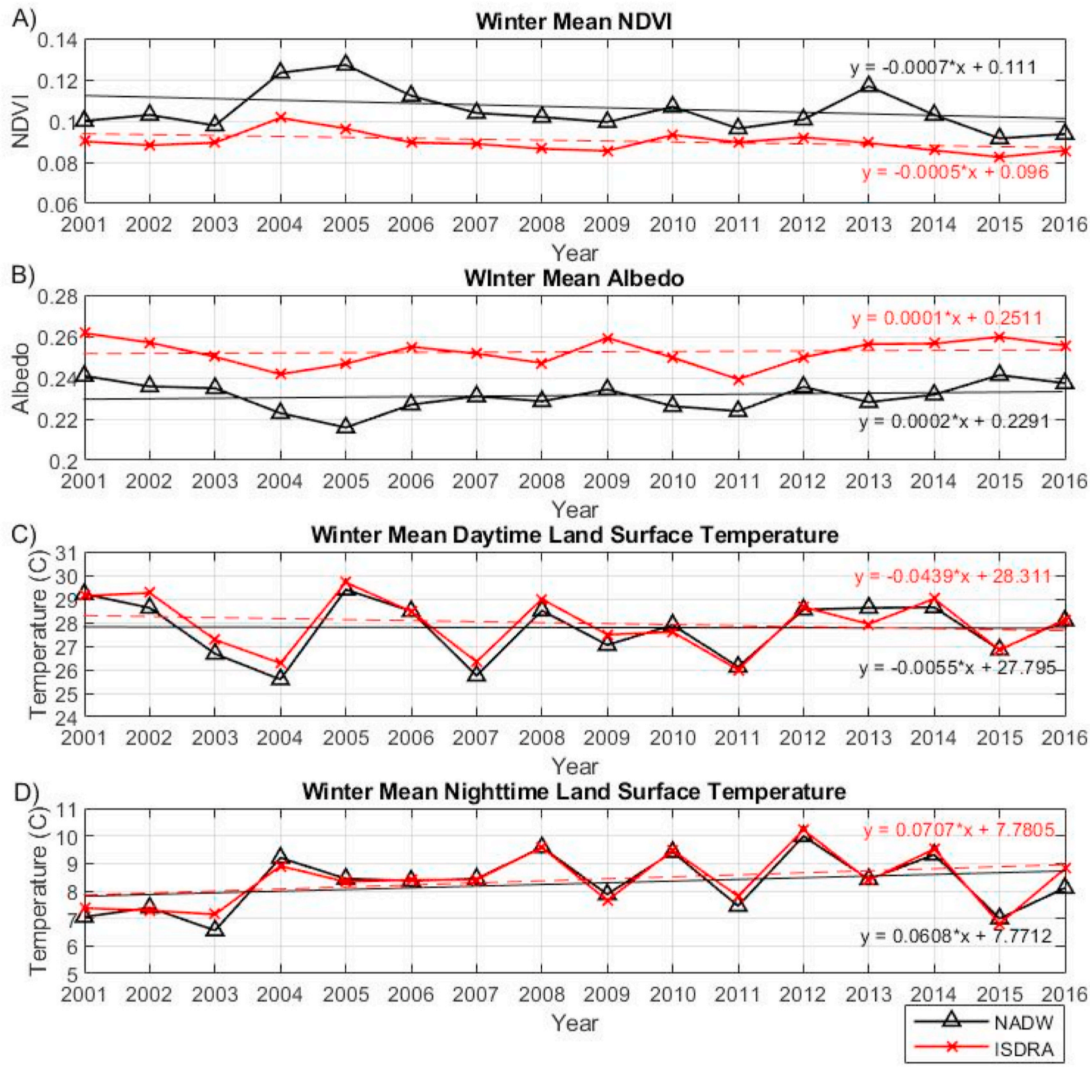

Fig. 7. Winter mean values and trends in NDVI (A), albedo (B), daytime temperature (C) and nighttime temperature (D) of NADW and ISDRA in the Algodones Dunes from 2001 to 2016.

Table 2
Statistical results of comparison of four transects between North Algodones Dunes Wilderness (NADW) and the Imperial Sand Dunes Recreation Area (ISDRA).

Transects	NDVI			Albedo			LST Daytime			LST Nighttime		
	NADW Mean	ISDRA Mean	Sig.	NADW Mean	ISDRA Mean	Sig.	NADW Mean	ISDRA Mean	Sig.	NADW Mean	ISDRA Mean	Sig.
T1	1356.13 ±151.1	994.8 ±73.08	<0.000	205 ±8.9	227 ±4.84	<0.000	42.40 ±0.110	42.53 ±0.075	0.017	18.28 ±0.141	18.22 ±0.064	0.263
T2	931.4 ±73.08	854.53 ±11.16	<0.000	249.27 ±2.58	251 ±3.05	0.104	42.15 ±0.246	42.62 ±0.085	<0.000	18.18 ±0.236	17.78 ±0.163	0.002
T3	928.27 ±8.73	858.73 ±9.99	<0.000	259.33 ±1.839	263 ±1.60	<0.000	41.53 ±0.213	42.09 ±0.201	<0.000	17.37 ±0.292	17.60 ±0.079	0.049
T4	1150.47 ±166.51	918.47 ±44.48	<0.000	224.87 ±16.82	258.13 ±4.03	<0.000	41.69 ±0.308	41.60 ±0.24	0.513	17.21 ±0.159	17.08 ±0.108	0.094

land degradation activities in arid and semi-arid environments. This study identifies associations between OHV activity, declines in NDVI, and increases in surface albedo and land surface temperature that are indicators of land degradation in the open-riding ISDRA portion of the Algodones Dunes, California, from 2001 to 2016. The ISDRA has a lower NDVI value and higher albedo than the adjacent NADW protected area, which suggests an association between OHV activity and concurrent reductions in vegetation cover and increasing soil exposure in the ISDRA. The winter peak season of OHV activity is also associated with a significant reduction of plant cover in the ISDRA, while high and increasing land surface temperature of the dune field in summer likely tends to inhibit plant growth, recovery, and seed germination.

Deserts in general, and dunes in particular, are fragile ecosystems whose vegetation communities are vulnerable to recreational impacts, such as OHV activity. Recovery of these ecosystems will likely be slowed by intense insolation, extreme and increasing temperatures, limited water supply, drought, and low soil fertility (Lovich and Bainbridge, 1999). The natural landscape of the Algodones Dunes provides both opportunities for outdoor recreation as well as preserves for many endangered and endemic species. This makes striking a balance between public recreation and natural conservation of endangered or endemic species a challenge. Given the findings of this research, it is essential that land management agencies (e.g., the Bureau of Land Management) continue to monitor, assess, and restore arid dune ecosystems in conjunction with effective management of the amount, timing, and locations of OHV activity. It is possible that the right balance of recreation and ecosystem protection and restoration can be found so as to preserve recreational value and activities within these special places. It is hoped that insights generated from this analysis will aid in the development of new policies and best management practices for ecosystem conservation and off-road recreation in the Algodones Dunes and similar sand dune landscapes.

CRediT authorship contribution statement

Suet-Yi Cheung: Conceptualization, Methodology, Software, Formal analysis, Writing - original draft, Writing - review & editing, Visualization. **Ian J. Walker:** Conceptualization, Writing - original draft, Writing - review & editing. **Soe W. Myint:** Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Ronald I. Dorn:** Resources, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Al-Awadhi, J.M., 2013. A case assessment of the mechanisms involved in human-induced land degradation in northeastern Kuwait. Land Degrad. Dev. 24, 2–11.
Al-Hurban, A.E., 2014. Effects of recent anthropogenic activities on the surface deposits of Kuwait. Arabian Journal of Geosciences 7, 665–691.
Belnap, J., 1995. Surface disturbances: their role in accelerating desertification. Environ. Monit. Assess. 37, 39–57.
Cabrera-Vega, L.L., Cruz-Avero, N., Hernández-Calvento, L., Hernández-Cordero, A.I., Fernández-Cabrera, E., 2013. Morphological changes in dunes as an indicator of anthropogenic interferences in arid dune fields. J. Coast Res. 65, 1271–1277.
California State Department of Parks and Recreation, 2017. Off-highway motor vehicle recreation commission program report. Off-highway Motor Division, California State Parks. Sacramento, CA. http://ohv.parks.ca.gov/pages/1140/files/OHMVR-Commission-2017-Program_Report-FINAL-Mar2017_web.pdf. (Accessed 18 January 2018).
Cheung, S.Y., 2018. Impacts of Off-Highway Vehicle Activity on Land Cover Change and Dune Dynamics: Algodones Dunes. M.A. thesis, School of Geographical Sciences & Urban Planning, Arizona State University, California. Tempe.
Cordell, H.K., Betz, J.C., Green, T.G., Stephens, B., 2008. Off-highway vehicle recreation in the United States and its regions and states: a national report from the national survey on recreation and the environment. The national survey on recreation and the environment. https://www.fs.fed.us/recreation/programs/ohv/IrisRec1rpt.%20pdf. (Accessed 4 April 2018).
Davenport, J., Switalski, T.A., 2006. Environmental Impacts of Transport Related to Tourism and Leisure Activities. In: Davenport, J., Davenport, J.L. (Eds.), The Ecology of Transportation: Managing Mobility for the Environment. Springer, Dordrecht, the Netherlands, pp. 333–360.
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, 186–204.
Environmental Systems Research Institute (ESRI), 2018. ArcMap 10.6 [Computer software]. https://www.esri.com/en-us/home.
Ewing, R.C., Kocurek, G., Lake, L.W., 2006. Pattern analysis of dune-field parameters. Earth Surf. Process. Landforms 3, 1176–1191.
Gibson, J., 1973. An Initial Study of the Impact of Desert Motorcycle Racing in the Mojave Desert. M.S. Thesis, Department of Biology, California State University, Fullerton.
Goossens, D., Buck, B., 2009. Dust dynamics in off-road vehicle trails: measurements on 16 arid soil types, Nevada, USA. J. Environ. Manag. 90, 3458–3469.
Griffin, D., Anchukaitis, K.J., 2014. How unusual is the 2012–2014 California drought? Geophys. Res. Lett. 41, 9017–9023.
Groom, J.D., McKinney, L.B., Ball, L.C., Winchell, C.W., 2007. Quantifying off-highway vehicle impacts on density and survival of a threatened dune-endemic plant. Biol. Conserv. 135, 19–34.
Hansen, M.C., Potapov, P.V., Moore, R., Hanche, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., et al., 2013. High-resolution global maps of 21st-century forest cover change. Science 342, 850–853.
Lathrop, E.W., 1983. The Effect of Vehicle Use on Desert Vegetation. In: Webb, R.H., Wilshire, H.G. (Eds.), Environmental Effects of Off-Road Vehicles. Springer, New York, NY, pp. 153–166.
Lovich, J.E., Bainbridge, D., 1999. Anthropogenic degradation of the southern California desert ecosystem and prospects for natural recovery and restoration. Environ. Manag. 24, 309–326.
Luckenbach, R.A., Bury, R.B., 1983. Effects of off-road vehicles on the biota of the Algodones dunes, imperial county, California. J. Appl. Ecol. 20, 265–286.
Misak, R.F., Al-Awadhi, J.M., Omar, S.A., Shahid, S.A., 2002. Soil degradation in Kabad area, southwestern Kuwait City. Land Degrad. Dev. 13, 403–415.
Myint, S.W., Wentz, E.A., Brazel, A.J., Quattrochi, D.A., 2013. The impact of distinct anthropogenic and vegetation features on urban warming. Landsc. Ecol. 28, 959–978.
Nielson, J., Kocurek, G., 1986. Climbing zibars of the Algodones. Sediment. Geol. 48, 1–15.
Norris, R.M., Norris, K.S., 1961. Algodones dunes of southeastern California. Geol. Soc. Am. Bull. 72, 605–619.
Olive, N.D., Marion, J.L., 2009. The influence of use-related, environmental, and managerial factors on soil loss from recreational trails. J. Environ. Manag. 90, 1483–1493.
Priskin, J., 2003. Physical impacts of four-wheel drive related tourism and recreation in a semi-arid, natural coastal environment. Ocean Coast Manag. 46, 127–155.
Sack, D., Da Luz, S., 2003. Sediment flux and compaction trends on off-road vehicle (ORV) and other trails in an Appalachian forest setting. Phys. Geogr. 24, 36–54.
Sharp, R.P., 1979. Intradune flats of the Algodones chain, Imperial Valley, California. Geol. Soc. Am. Bull. 90, 908–916.
Smith, R.S.U., 1970. Migration and Wind Regime of Small Barchan Dunes within the Algodones Dune Chain. Imperial County, California. M.S. thesis, University of Arizona, Tucson.
Stebbins, R.C., 1974. Off-road and the fragile desert. Am. Biol. Teach. 36, 203–208.
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, 939–952.
Van Dam, A.R., Van Dam, M.H., 2008. Impact of off-road vehicle use on dune endemic coleoptera. Ann. Entomol. Soc. Am. 101, 411–417.
Verbesselt, J., Hyndman, R., Newnham, G., Culvenor, D., 2010. Detecting trend and seasonal changes in satellite image time series. Rem. Sens. Environ. 114, 106–115.
Wang, C., Myint, S.W., 2016. Environmental concerns of deforestation in Myanmar 2001–2010. Rem. Sens. 8, 728.
Wang, C., Myint, S., Wang, Z., Song, J., 2016. Spatio-temporal modeling of the urban heat island in the Phoenix metropolitan area: land use change implications. Rem. Sens. 8, 185.
Webb, R.H., Ragland, H.C., Godwin, W.H., Jenkins, O., 1978. Environmental effects of soil property changes with off-road vehicle use. Environ. Manag. 2, 219–233.