Quantification of driving factors on NDVI in oasis-desert ecotone using geographical detector method

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Abstract: Within oasis-desert ecotone regions, the normalized difference vegetation index (NDVI) is an important parameter for evaluating the growth of vegetation. An accurate quantitative study between NDVI and environmental and anthropogenic factors is critical for understand the driving factors of vegetation growth in oasis-desert ecotone. In 2016, four periods Landsat 8 OLI_TIRS images, relevant climatological parameters data (air temperature, air relative humidity, wind velocity and accumulated temperature), land cover type data and soil data were selected as proxies. In order to quantify the explanatory power for NDVI spatial and temporal distribution in the southern edge of Dunhuang City and northern side of the Mingsha Mountain, the geographical detector model was used to explain the potential influences of factors versus the spatial distribution of NDVI, and each explanatory variable's relative importance can be calculated. The factor detector results disclose that the spatial distribution of NDVI is primarily dominated by land cover type. The risk detector results show that, high NDVI region is located within woodland. The mean value of NDVI displays an increase and then decrease trend with air temperature increase. With the increase of wind velocity and decrease of air relative humidity, the NDVI value shows a decrease trend. The interactive q values between the two factors are higher than any q value of separated factors. Results also indicate that the strongest interactive effects of NDVI are different in distinct seasons. Consequently, anthropogenic activity is more important than environmental factors on NDVI in oasis-desert ecotone. We also demonstrate that air relative humidity rather than air temperature have played a greater role in NDVI spatial distribution.

Keywords: Influence factors; Normalized difference vegetation index; Geographical detector; Oasis-desert ecotone

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Introduction

In China, as the cornerstone of human survival and economic prosperity, oases support more than 90% of the population and over 95% social wealth although they take up less than 4%-5% of the total area of arid regions (Wang et al. 2015; Zhang et al. 2015). Oasis-desert ecotone is a narrow belt located between desert ecosystem and oasis ecosystem, which is subject to the dual effect by the two ecosystems (Zhang et al. 2016a). As the most typical and specific nature landscape in arid areas, it is also plays a buffering role in the process of shifting sand encroachment. However, the oasis-desert ecotone is very sensitive to climate change and anthropogenic disturbance (Reynolds et al. 2010a). As an ecological fragile area, it is affected by adjacent environmental condition and has enormous effects on oasis's ecosystems. Therefore, exploring the transport of atmosphere, energy, water vapor and heat exchange is practically essential for understanding the regional climate effects, supporting oasis sustainability (Li et al. 2016; Zhang et al. 2004).

In recent decades, enormous researches have been made in studying the sand dust storm and meteorological elements, such as wind velocity, precipitation, air temperature, air relative humidity and wind-blown sand environment in arid and semi-arid area (Fan et al. 2006; Hupy 2004; Li et al. 2007; Reynolds et al. 2010b; Zou et al. 1999). Land degradation and land cover changes of desert oasis ecosystems have chiefly focused on the land/vegetation processes and climatic change (Bakr et al. 2010; Schulz et al. 2010; Tsegaye et al. 2010). For instance, Mao et al. (2014) indicated that the average wind velocity decreased significantly from the shifting-sand frontier to the inner oasis which was mainly attributable to the vegetation coverage. The characteristics of wind-blown sand and dynamical environment exhibited remarkable spatial and temporal variations, which chiefly depended on the regional landform and season (Zhang et al. 2012; Zhang et al. 2013). The spatial and temporal dynamic of soil water content has obvious seasonal characteristics because of vegetation cover and soil physical features in desert-oasis ecotone (Zhao et al. 2005). However, these findings have not accurately examined each driving factor or interactive impacts of factors on stability of desert-oasis ecotone quantitatively. The dominant factors influencing oasis-desert ecosystems include natural factors of vegetation, soil, hydrology, meteorological, energy, biological activities and terrain, and anthropogenic factors of land cover, agriculture, tourism, graze, and industrial behaviors (Su et al. 2007; Ma et al. 2010; Huang et al. 2015). Therefore, quantitative analysis of the principal influencing factors in desert-oasis ecotone is necessary.

Undoubtedly, vegetation in oasis-desert ecotone plays an important role in preventing wind-sand encroachment (Zhao et al. 2008). As a sensitive index in the research of ecosystems and global change (Salim et al. 2008), NDVI (The normalized difference vegetation index) is the most suitable indicator to reflect the growth and vegetation coverage. Many scholars have used NDVI to elaborate the response between vegetation and climatic factors in agricultural and ecological research (Cui et al. 2010; Luo et al. 2016; Wang et al. 2003; Wardlow et al. 2008).

The purpose of this study attempts to elucidate the relationship between variations of seasonal NDVI and the change of hydrothermal condition or human activities in detail in such extreme region of China. The geographical detector method (Wang et al. 2010) was used to assess each important factor and their interactions of NDVI in Dunhuang oasis-desert ecotone. The results in this study would clarify the main influence factors of NDVI and provide scientific foundation for maintaining stability and sustainable development of oasis in arid region.

1 Materials and Methods

1.1 Study location

The experiment was conducted in Dunhuang County and the total area is 31,200 km^2, including 1400 km^2 of oasis area. Dunhuang is the intersection of the Gansu, Qinghai and Xinjiang province with an average altitude below 1200 m. The study area is surrounded by the Guazhou County to the east and the Mingsha Mountain to the south, where the Kumtagh Desert and the South Lake Oasis located in the west side of the city. The climate in this area is dominated by arid desert continental climate in warm temperate zone with very low precipitation of 39.9 mm, high evaporation of 2486 mm and strong winds. Accompanied by significant temperature difference between day and night, the dominant wind direction is southwest and northwest with annual strong windy day over 20 days (Qu et al. 2001; Wang et al. 2005).

The six observation points are located at the southern edge of Dunhuang City and northern side of the Mingsha Mountain, with a total area of 17 km² (Figure 1; E94°35′9.13″~94°35′26.65″, N40°03′43.79″~40°04′27.67″). The study area perennially suffers from aeolian disaster and regional surface soil is mainly composed of aeolian sand and a small amount of gravel. Mingsha Mountain is the extension area of Kumtagh Desert, which is approximately 40 km long from southwest to northeast and 15 km width from southeast to northwest. The aeolian landforms in the megadune is mainly dominated by pyramidal dune and linear dune (Zhang et al. 2016b). Additionally, natural and artificial vegetation is exhibited in the form of *Haloxylon ammodendron* as constructive species and *Nitraria as* accompanying species. Meanwhile, herbaceous plants are widely but sparsely distributed in this area, such as *Agriophyllum squarrosum* and so on.

1.2 Data sources

In this study, the seasonal average NDVI value were calculated based on four periods Landsat 8 OLI_TIRS images, which were obtained from Geospatial Data Cloud site, Computer Network Information Center, Chinese Academy of Sciences (http://www.gscloud.cn).

The NDVI is most applied to reflect the growth condition and coverage of vegetation, which is acquired by using the following equation:

$$\text{NDVI} = \frac{NIR-R}{NIR+R} \quad (1)$$

Where, NIR is the reflectance in the near infrared (Band 5) and *R* is the reflectance in the red (Band 4).

Digital elevation model (DEM) was also from the Geospatial Data Cloud site, Computer Network Information Center, Chinese Academy of Sciences (http://www.gscloud.cn). The air temperature, air relative humidity and wind velocity were monitored by HOBO self-recording anemometers at intervals of 10 min and height of 2 m above the ground. The accumulated temperature was calculated as the sum of daily average temperature, whose temperature value is more than 10 ℃. Inverse distance weighted method was used for spatial interpolation. Land cover type dataset derived from vectorization of Google images with three bands and verified on-site to ensure its accuracy (Figure 2).

1.3 Analysis method

The geographical detector method was first proposed by Wang et al. (2010) which is aimed to assess the effect of different environmental factors on risks of health, which was based on four geographical detectors: risk detector, factor detector, ecological detector and interaction detector. Many researches used this model to

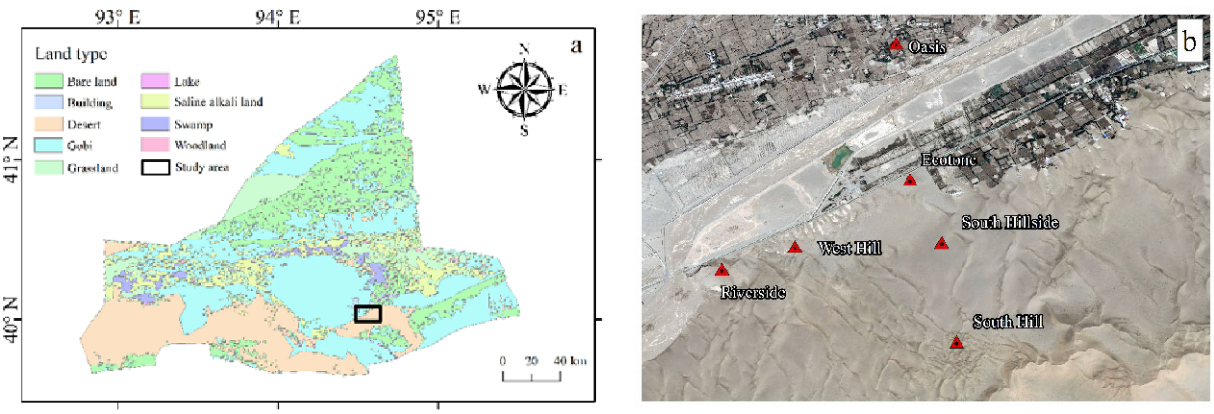

Figure 1 Location of study area (a) and monitoring stations (red triangles) (b). **Note:** This map is downloaded from the standard map service website of the National Bureau of Surveying and Mapping Geographic Information.

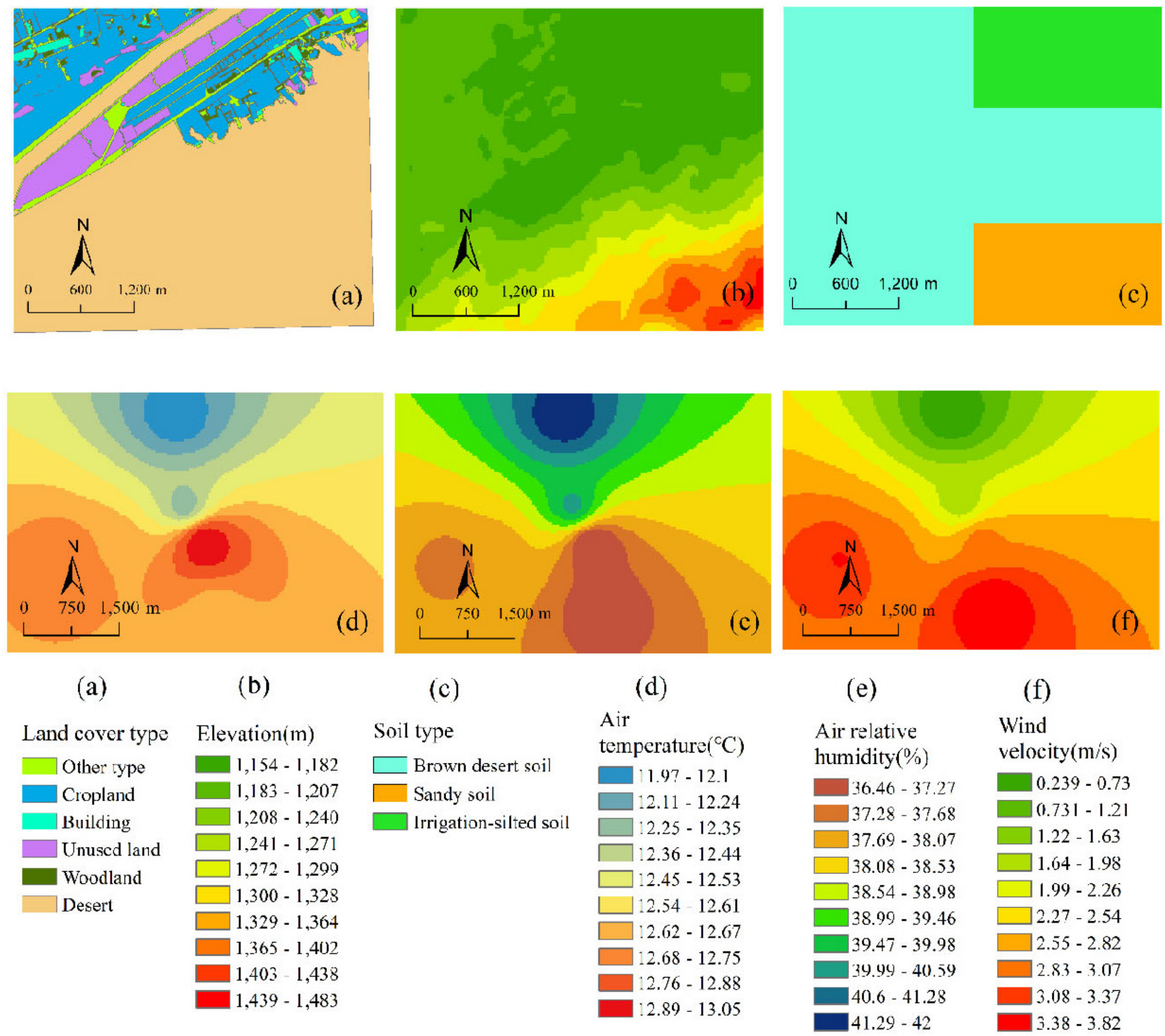

Figure 2 The spatial distribution of explanatory variables and its strata (based on annual mean values).

analyze the influences of various factors and its interaction on some particular disease or geography, such as

neural tube defects (Wang et al. 2010), schistosomiasis (Yi et al. 2017), hand – foot – mouth disease (Huang et al. 2014), typhoid and paratyphoid fever (Wang et al. 2013) and aeolian desertification (Du et al. 2016). In this article, the spatial heterogeneity of NDVI is influenced by many factors. The model was used to explore the potential influences factors versus the spatial distribution of NDVI and to identify each explanatory variable's relative importance. Each explanatory variable was divided into several strata by using natural breaks method (Figure 3). If an explanatory variable X controls or dominates the cause of spatial distribution of NDVI, the spatial distribution of NDVI should be similar to that of X, that is, factor X can explain the pattern of NDVI completely. The degree of spatial association between layers X and stratified heterogeneity of NDVI can be measured by the q-statistic (Factor detector), whose mathematical formula is:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} \qquad (2)$$

where σ^2 is population variance of NDVI; σ_h^2 is the variance of stratum h; N the is number of total samples in the whole study area and was stratified into L strata; N_h is number of sample units in strata h.

The value of the q-statistic is within the range [0,1]. If q value tends towards 1 ($\sigma_h^2 = 0$), which means factor X can completely explain the distribution of NDVI. On the contrary, if explanatory variable *X* is unrelated to the distribution of NDVI at all, the value of the *q*-statistic is close to 0 (Wang et al. 2016).

The risk detector is used to judge whether there is a significant difference by comparing the mean values between two strata, which is tested with *t*-statistics.

The interactive detector can identify the interactions of multiple risk factors on NDVI, namely assessing whether the mutual action of factors $X1$ and $X2$ could enhance or weaken the explanatory power to NDVI, which hinges on the relationship between $q\ (X1 \cap X2)$ and $q\ (X1)$ or $q\ (X2)$ (Table 1).

The ecological detector is used to compare whether the effects of the two factors $X1$ and $X2$ have significantly differences on the spatial distribution of NDVI, testing with *F*-statistics.

2 Results

2.1 Factor detector

The *q* value revealed the explanatory degree of each factor for NDVI in oasis-desert ecotone, Dunhuang (Table 2). The spatial distribution of NDVI was dominated as follows: in spring, among the 7 selected factors, the land cover type (0.47), and air relative humidity (0.32) were more significant than other factors. In summer, land cover type (0.66) > air temperature (0.41) and air relative humidity (0.41) > wind velocity (0.37) > accumulated temperature (0.33). In autumn, land cover type (0.58) has the strongest explanatory power to NDVI, followed by air relative humidity (0.38), wind velocity (0.34) and air temperature (0.32). In winter, land cover type (0.61), wind velocity (0.41), relative humidity (0.37) and temperature (0.31) have stronger influence in controlling the spatial heterogeneity of NDVI. These results reveal that land cover type has the greatest impact on NDVI during the whole year. It means that there is a similar spatial pattern between two of them. Moreover, the second contributing factor indicates that seasonal variations of environmental and anthropogenic factors caused the seasonal NDVI spatial distribution (e.g., the air relative humidity is more important than air temperature in the first three seasons).

2.2 Risk detector

The areas potential risk can be identified in the determinant strata. According to *q*-statistic, land cover type has the greatest impact on NDVI. Thus, this factor was selected as an example in detail analysis. The potential determinants of NDVI were significantly different among various land cover types. The mean NDVI value of woodland was higher than other land cover types in four seasons, especially in summer. Desert has the lowest NDVI value (Table 3). Table 4 compared

Table 1 Types of interaction between two covariates (Wang et al. 2010; Zhang et al. 2018; Wang et al. 2018)

Interaction	Description
Weaken, nonlinear	$q\ (X1 \cap X2) < \text{Min}\ (q\ (X1), q\ (X2))$
Weaken, univariate	$\text{Min}\ (q\ (X1), q\ (X2)) < q\ (X1 \cap X2) < \text{Max}\ (q\ (X1), q\ (X2))$
Enhance, bivariate	$q\ (X1 \cap X2) > \text{Max}\ (q\ (X1), q\ (X2))$
Independent	$q\ (X1 \cap X2) = q\ (X1) + q\ (X2)$
Enhance, nonlinear	$q\ (X1 \cap X2) > q\ (X1) + q\ (X2)$

Table 2 The value of *q*-statistic by season

Factors	*X1*	*X2*	*X3*	*X4*	*X5*	*X6*	*X7*
Spring	0.47	0.08	0.32	0.29	0.12	0.14	0.02
Summer	0.66	0.41	0.41	0.37	0.17	0.12	0.33
Autumn	0.58	0.32	0.38	0.34	0.13	0.13	0.22
Winter	0.61	0.30	0.37	0.41	0.17	0.14	-

Note: *X1* land cover type, *X2* air temperature, *X3* air relative humidity, *X4* wind velocity, *X5* elevation, *X6* soil type, *X7* accumulated temperature.

Table 3 The mean NDVI value for each land type by season

Season	Desert	Cropland	Woodland	Unused land	Others
Spring	0.05	0.18	0.31	0.05	0.15
Summer	0.07	0.52	0.63	0.09	0.30
Autumn	0.05	0.19	0.28	0.06	0.14
Winter	0.09	0.22	0.30	0.10	0.17

Table 4 Statistically significant differences of risk factors between the land type in spring

Strata	Desert	Cropland	Woodland	Unused land	Others
Desert					
Cropland	Y				
Woodland	Y	Y			
Unused land	N	Y	Y		
Others	Y	Y	Y	Y	

Note: Y means the risk difference between the two strata is significant with the confidence of 95%, and N stands for not.

whether there were the significant differences between subareas which generated by land cover type. The results showed that the mean NDVI in the desert and unused land were significantly lower than that of other land types at 95% confidence intervals in spring. For other seasons, the mean NDVI within any two land cover types were significantly different.

2.3 Interactive detector

The interaction detector aimed to check whether two determinants of NDVI work independently or not. The results are tabulated in Table 5 by season.

In spring, the *q* values of land cover type and air temperature were 0.47 and 0.08, respectively. However, their interactive value (0.54) was greater than either of *q* value, and interactive effect belonged to the types of bivariate enhancement. The interactive *q* values of land cover type and air relative humidity, wind velocity, elevation, accumulated temperature were 0.54, 0.53, 0.48, 0.47, respectively. The interactive result was also bivariate enhancement, that is to say $q\ (X1 \cap X2) > \mathrm{Max}\ (q\ (X1),\ q\ (X2))$. Whereas the interactive effect between air temperature and air relative humidity, wind velocity, elevation, accumulated temperature were found to belong to nonlinear enhancement to increase the interpretation of NDVI ($q\ (X2 \cap X3) > q\ (X2) + q\ (X3)$, $q\ (X2 \cap X4) > q\ (X2) + q\ (X4)$, $q\ (X2 \cap X5) > q\ (X2) + q\ (X5)$).

In summer, the interaction of each factor has a stronger explanation to NDVI by comparing other seasons. This means that the interplay of selected factors has greater effects in summer than other seasons for NDVI. In general, land cover ∩ air temperature, land cover ∩ air relative humidity and land cover ∩ wind velocity were primary influence factors on NDVI in Dunhuang oasis-desert ecotone.

These findings revealed that the interactive *q* values between two factors were higher than any *q* value of independent factors, and most of the interactive results belonged to bivariate enhancement.

2.4 Ecological detector

Is a determinant factor more significant than another one in controlling the spatial distribution of NDVI? Table 6 showed that between any factors of land cover type, air relative humidity, wind velocity, elevation and accumulated temperature in spring. There was no statistically significant difference for affecting the spatial distribution of NDVI. However, air temperature and air relative humidity, wind velocity, elevation were significantly different for NDVI distribution.

Table 5 Interactive seasonal *q* values of explanatory variables for normalized difference vegetation index (NDVI)

Season		*X1*	*X2*	*X3*	*X4*	*X5*	*X6*	*X7*
Spring	*X1*	0.47						
	X2	0.54	0.08					
	X3	0.54	0.47	0.32				
	X4	0.53	0.43	0.34	0.29			
	X5	0.48	0.32	0.31	0.35	0.12		
	X6	0.50	0.30	0.36	0.35	0.17	0.14	
	X7	0.47	0.11	0.33	0.30	0.13	0.15	0.02
Summer	*X1*	0.66						
	X2	0.73	0.41					
	X3	0.72	0.44	0.41				
	X4	0.74	0.49	0.47	0.37			
	X5	0.66	0.46	0.45	0.42	0.17		
	X6	0.66	0.42	0.41	0.38	0.17	0.01	
	X7	0.76	0.61	0.59	0.56	0.44	0.34	0.33
Autumn	*X1*	0.57						
	X2	0.63	0.32					
	X3	0.64	0.38	0.38				
	X4	0.63	0.41	0.42	0.34			
	X6	0.58	0.36	0.41	0.37	0.13		
	X6	0.59	0.36	0.42	0.39	0.17	0.13	
	X7	0.59	0.47	0.49	0.49	0.34	0.34	0.22
Winter	*X1*	0.61						
	X2	0.68	0.31					
	X3	0.66	0.53	0.37				
	X4	0.67	0.52	0.56	0.41			
	X5	0.62	0.36	0.42	0.46	0.17		
	X6	0.63	0.36	0.38	0.46	0.22	0.14	
	X7	-	-	-	-	-		-

Note: *X1* land cover type, *X2* air temperature, *X3* air relative humidity, *X4* wind velocity, *X5* elevation, *X6* soil type, *X7* accumulated temperature.

Table 6 Statistically significant differences of risk factors in spring

Factors	*X1*	*X2*	*X3*	*X4*	*X5*	*X6*	*X7*
X1							
X2	N						
X3	N	Y					
X4	N	Y	N				
X5	N	Y	N	N			
X6	N	Y	N	N	Y		
X7	N	N	N	N	N	Y	

Note: Y means the risk difference between the two strata is significant with the confidence of 95%, and N stands for not.

Besides, the detection results were also quite different in different seasons. For example, in summer, only wind velocity and air relative humidity were statistically significant. Whereas in autumn and winter, air temperature with wind velocity and air relative humidity were significantly different to influence the spatial distribution of NDVI.

3 Discussion

In our study, four geographical detectors were used to find the chiefly influential factors and the spatial distribution feature of NDVI. It is also quantitatively analyzed the degree of interactive effect between selected factors in controlling the seasonal attributes of NDVI in oasis-desert ecotone, Dunhuang.

The precipitation, surface water, and groundwater play important roles in vegetation growth, and anthropogenic activities control almost all the surface hydrologic, even part of groundwater (Jolly et al. 1996; Mensforth et al. 1994; Zhao et al. 2014). Most of the previous studies focused on the response of groundwater depth to vegetation distribution. In the oasis-desert ecotone of Hexi corridor, there was no significant effects on vegetation productivity, while the hydrologic processes varied noticeably (Zhao et al. 2014). Actually, most surface and near-surface water would vaporize into the air due to strong evaporation. However, this phenomenon was often neglected in the research of vegetation growth in arid and semi-arid regions. Few studies have analyzed the effects of temporal and spatial variation of air relative humidity on vegetation distribution in oasis-desert ecotone. This paper demonstrated that air relative humidity had a strong effect on NDVI and seasonal explanatory power are 32%, 41%, 38% and 37%, respectively (Table 2). Additionally, according to the interactive detector results, land cover type integrating with air relative humidity had the strongest explanatory power on NDVI in spring and autumn, followed by summer and winter. With temperature raising in spring, the large amount of water is required for vegetation growth, and it is strictly controlled by precipitation recharge, whereas the study area has low precipitation in spring (less than 20 mm). In summer, abundant precipitation, diurnal alternation and different properties of underlying surfaces causing dominant factor have changed. The top factors influencing the NDVI are land cover type, air temperature, air relative humidity, wind velocity and accumulated temperature. Fundamentally, the spatial difference of air temperature between desert and oasis is the main reason for a strong wind field within the local area. Thus, the interaction of wind velocity and other factors is more powerful for NDVI in summer. On one hand, the change of wind speed affects plant growth rate and leaf shapes, leading to leaf thickness increased, stem elongation and leaf area decreased, also affects cell synthesis. Wind-induced friction between plant leaves can abrade the waxy layer on the upper surface of leaves, resulting in epidermal conductivity and water loss increased (Cleugh et al. 1998; Grace. 1988). When wind speed exceeds the plant tolerance, it can lead plant leaves tearing, peeling, abrasion, and vegetation lodging (Van et al. 1991; Knight et al. 1992; Daudet et al. 1999). Wind-blown sand may also abrade plant tissues (Cleugh et al. 1998; Grace. 1988; Van et al. 1991; Armbrust et al. 1982; Pitcairn et al. 1986; Rosenberg et al. 1966), strong wind or continuous wind might damage plant, reduce transpiration rate and net photosynthetic rate (Zhang et al. 2013). On the other hand, appropriate wind speed can improve plant growth and enhance the primary productivity, even increase the number and length of plant roots (Stokes et al. 1995; Liu et al. 2008). For seasonal variations, the risk detector showed that the larger the air relative humidity, the higher the NDVI, which imply that greater air relative humidity has a positive effect on vegetation growth in oasis-desert ecotone. On the contrary, the greater the wind velocity, the lower the NDVI (Figure 3).

The results of NDVI and climatological parameters showed that the temperature has a strong impact on NDVI changes (Gao et al. 2001), and more remarkable than precipitation (Luo et al. 2016). Previous analysis also indicated that higher temperature exhibits negative effects on NDVI in arid and semi-arid area (Barber et al. 2000), which were consistent with our conclusion. The risk detector disclosed that the value of NDVI witnessed an increased and then downward trend with air temperature increasing in spring. But compared

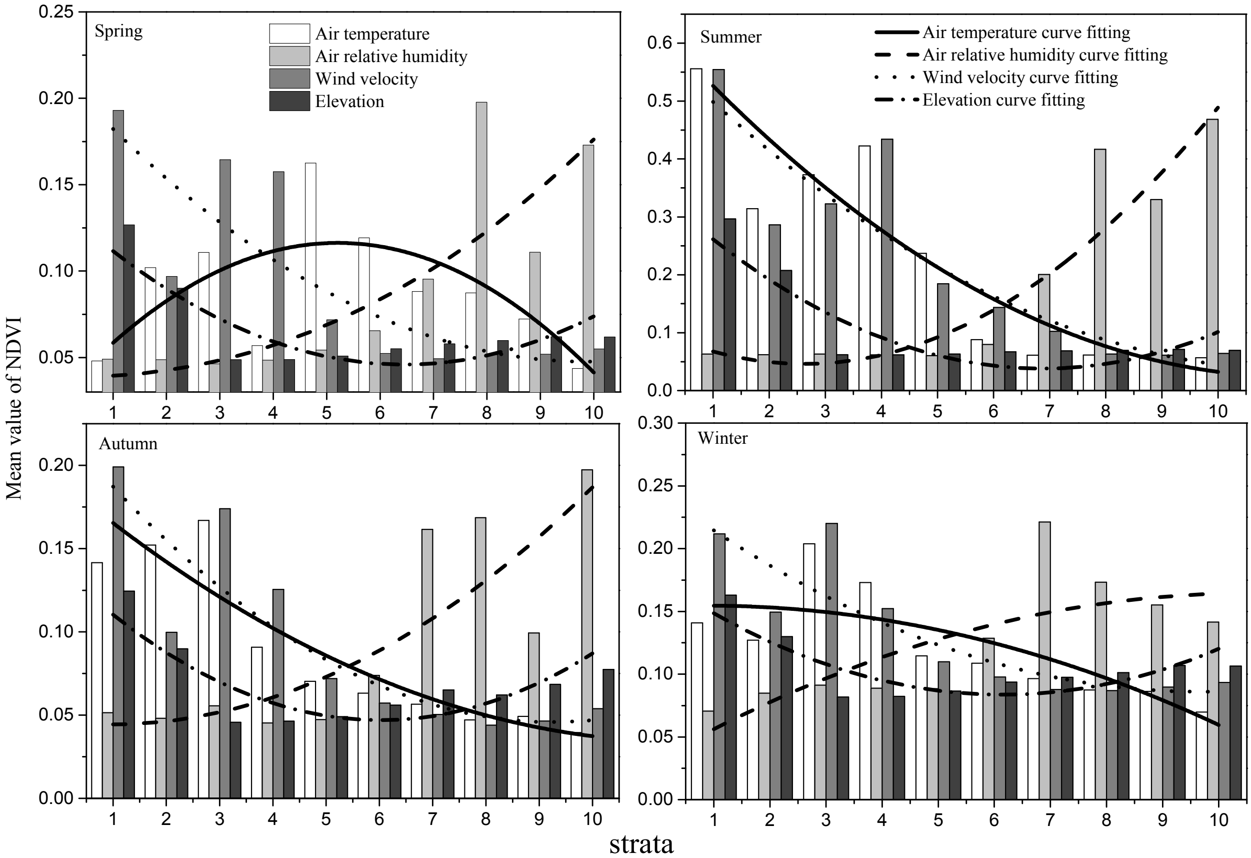

Figure 3 The results of risk detector and corresponding curve fitting by season. Natural breakpoint method was used to calculate strata of various factors, and different season has diverse strata value. From 1 to 10, it means that the value of selected factors were increased.

with other seasons, too high or too low the temperature, the lower the NDVI.

According to our research, the influence of elevation was weak to NDVI distribution. When interacting with land cover type, to some degree, they contribute more strongly impact on spatial heterogeneity of NDVI. However, there was study finding that elevation and land cover type obviously influence the correlation coefficients between NDVI and climatological parameters (Gao et al. 2001). As the mainly dominant factors, the risk detection results of land cover type uncovered that the woodland was higher than that of other types of land. Especially in summer, average NDVI value of woodland (0.63) and cropland (0.52) were higher than that the rest of seasons. Besides, the significance test showed that only desert and unused land did not have significant differences in spring (Table 4). Generally, classical statistical methods are difficult to identify interactions for multiple influence factors. Therefore, the interaction detector used in this study can reflect the degree of mixed interaction effect (Yi et al. 2017). Our results of interaction between land cover type and air temperature was more powerful for NDVI in spring and summer, strongest in winter.

Overall, vegetation coverage plays a practical significance role for preventing aeolian disaster. The higher NDVI value indicates the better vegetation growth. For various seasons, different influencing factors can provide effective method for vegetation restoration and oasis stability.

4 Conclusions

This study applied geographical detector model to assess the influential factors of NDVI in oasis-desert ecotone. The results reflected that the land cover type, air temperature, air relative humidity and wind velocity were the significative factors to explain the spatial distribution of NDVI. Land cover type was the strongest influence factor and explanatory power were 0.47, 0.66, 0.58, and 0.61 by season, respectively. Relatively, the degree of explanatory of elevation and soil type were much smaller than other factors. For seasonal variations, the air relative humidity had more explanatory power in summer and autumn than in spring and winter, wind velocity had a stronger effect in winter. The distribution curve between NDVI and air temperature was similar to parabola, and displayed an increase and then downward trend with air temperature increasing. The NDVI value decreased with the increase of wind velocity and decrease of air relative humidity. Each explanatory variable enhances and bivariate or enhance and nonlinear other single effect when they were taken together. The top interactive relationships influencing NDVI were land cover type and air relative humidity in spring and autumn, land cover type and accumulated temperature in summer, land cover type and air temperature in winter. Consequently, anthropogenic activity was the strongest effect on NDVI in oasis-desert ecotone followed by meteorological elements and terrain.

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