

Spatiotemporal Variation Characteristics and Attribution Analysis of Oasis Effects in the Hexi Region over the Past 20 Years: Postprint

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Abstract

The oasis effect plays an extremely important role in improving the climate of arid regions and supporting the self-maintenance and development of oasis systems. This study takes the Hexi region of Gansu Province as the research area, utilizes meteorological and remote sensing data, selects oasis effect intensity indicators, employs the Geographical Detector model, reveals the spatiotemporal variation characteristics of the oasis effect over the past 20 years, and analyzes the influencing factors of oasis effect intensity. The results show that: (1) During the period 2000-2020, the oasis effect intensity in the study area exhibited an increasing trend in spring, summer, and winter, while showing a decreasing trend in autumn. Daytime variations were similar to the corresponding seasonal changes but with greater intensity, with summer being the strongest (increase of 1.43 °C); nighttime variations in spring, summer, and autumn were similar to the corresponding seasons but with lower intensity. A weak oasis warm island effect occurred at night in autumn 2000 and winter 2010; (2) The area proportion of strong oasis effect (“cold island”) was largest in summer and exhibited minimal change, while the area proportion of oasis “warm island” effect was largest in winter, showing a year-by-year decreasing trend; (3) The oasis effect intensity in summer had a strong negative correlation with vegetation cover change in the oasis, with a correlation coefficient reaching -0.917. Climate and surface factors are the main controlling factors of oasis effect intensity in the Hexi region, surface albedo has the weakest influence, and the interaction between factors cannot be ignored.

Full Text

Characterization of Spatial and Temporal Changes in the Oasis Effect and Attribution Analysis of the Hexi Region in the Last 20 Years

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Abstract

The oasis effect is extremely important for improving the climate of arid areas and supporting the self-sustainability and development of oasis systems. This study takes the Hexi region of Gansu Province as the study area, selects indicators of oasis effect intensity using meteorological and remote sensing data, and adopts the geodetector model to reveal the spatial and temporal characteristics of the oasis effect over the past 20 years while analyzing the influencing factors of oasis effect intensity. The results show that: (1) From 2000 to 2020, the oasis effect intensity in the study area exhibited an increasing trend in spring, summer, and winter, and a decreasing trend in autumn. Daytime changes were similar to those of the corresponding seasons but with greater intensity, with the strongest effect in summer showing an increase of 1.43 °C. Nighttime changes in spring, summer, and autumn were similar to the corresponding seasons but with lower intensity, and a weak oasis warm island effect appeared during autumn nights in 2000 and winter nights in 2010. (2) The area proportion of strong oasis effect (“cold island”) was largest in summer and remained relatively stable, whereas the area proportion of oasis “warm island” effect was largest in winter and showed a decreasing trend year by year. (3) The intensity of the oasis effect in summer had a strong negative correlation with changes in oasis vegetation cover, with correlation coefficients reaching Climate and surface factors are the major controlling factors for the intensity of the oasis effect in the Hexi region. The effect of surface albedo is the weakest, and the interaction between factors should not be neglected.

Keywords: oasis effect; spatial and temporal variation; attribution; geographic detector; Hexi region

1. Introduction

Oases are unique and important ecological geographical units in arid regions, forming the foundation for human production and life and serving as crucial “regulators” for maintaining regional ecological stability. The series of unique microclimate characteristics exhibited by oasis ecosystems in their struggle against the forcing of arid climate environments are collectively referred to as the “oasis effect” [1]. Zhang Qiang and Hu Yinqiao [2] first proposed the oasis cold island effect in 2001, while domestic scholar Su Congxian et al. [3] proposed the formation mechanism of the oasis “cold island effect” through near-surface field observations in 1987. Subsequently, Bie Qiang et al. [4] revealed the dual characteristics of “cold island” and “warm island” effects in the Hexi oasis based on multi-source data.

Current research methods for oasis effects mainly include conventional methods and remote sensing technology. Conventional methods generally rely on ground measurements and spatial numerical simulations, using various meteorological data and mathematical methods to analyze oasis effects. Compared with conventional methods, remote sensing data are more convenient to obtain and offer higher spatiotemporal resolution, gradually becoming the main method for studying surface thermal environments and receiving widespread application. For example, Hao et al. [5] studied the cold island effect of oases in the Tarim Basin using remote sensing data and geostatistical methods, pointing out that the summer oasis “cold island effect” was strongest, followed by autumn. In the same year, Wu Zhaopeng et al. [6] used Landsat data to retrieve land surface temperature and studied the cold island effect of the Jinghe River Basin oasis in Xinjiang, demonstrating that oasis cropland, grassland, forest land, and water bodies positively influenced the oasis “cold island effect,” with precipitation being the main external factor affecting changes in the oasis cold island effect. Gao Yuan et al. [7] used remote sensing and meteorological data to study the cold island effect of the Shihezi oasis and its influencing factors, finding that normalized difference vegetation index (NDVI) had a significant negative correlation with land surface temperature, and socio-economic development was also an important factor affecting changes in the oasis cold island effect. Hao et al. [8] used soil moisture and multiple remote sensing data to study the upper limit and mechanism of the oasis effect in Xinjiang, concluding that soil moisture is the determining factor of the oasis effect in arid regions, controlling the difference in surface evapotranspiration between desert and oasis, thereby affecting the oasis effect. Bie Qiang [9] used MODIS LST and Albedo data to analyze influencing factors of the Hexi oasis effect, arguing that evapotranspiration (ET) is the main factor for the oasis “cold island effect” during the growing season, while albedo is the main factor for the oasis “warm island effect” in winter.

However, most current scholars focus their research on the oasis effect in summer, with fewer studies on other seasons. Investigating the characteristics of oasis effects across different seasons helps understand regional climate change. Al-

though scholars have analyzed the relationship between land cover, vegetation, landscape patterns, and oasis effects from different perspectives, many issues actually result from the interaction of multiple natural and socio-economic factors. Analyzing the interaction between factors and their relationship with the oasis effect helps reveal the mechanisms of oasis effects. Therefore, this paper takes the Hexi region as the study area, analyzes the spatial and temporal variation characteristics of oasis effects in different seasons, and uses the geodetector model to explore the main driving factors and their interactions, aiming to provide a scientific basis for ecological management and sustainable development of oasis cities in the Hexi region.

1.1 Study Area Overview The Hexi region is located in the hinterland of the Eurasian continent [Figure 1: see original paper]. It borders the Loess Plateau to the east, the Tarim Basin to the west, the Qinghai-Tibet Plateau to the south, and the Mongolian Plateau to the north. The Shiyang River, Heihe River, and Shule River are distributed sequentially from east to west. Administratively, it includes Wuwei, Jinchang, Zhangye, Jiuquan, and Jiayuguan cities. The Qilian Mountains' glacier meltwater nourishes the Hexi oasis. To study the thermal environment of the desert-oasis ecosystem and break through the limitations of single administrative divisions, this study removes the interference of the Qilian Mountains and takes the desert-oasis ecological unit in the Hexi region as the research object, using the surrounding desert as the background. The region's elevation ranges from 643 to 3900 m, with an annual average temperature of 5–9 °C, annual precipitation of 50–150 mm, and annual evaporation of 1500–3200 mm. The climate is arid, the soil is mostly sandy, and the oasis ecological environment faces serious threats [10].

1.2 Data Sources and Processing This study utilized MODIS Terra version 6 global land surface temperature product (MOD11A2) and MOD09A1 data to research the influencing factors of oasis effects in the Hexi region from 2000 to 2020. All data were resampled to 1000 m resolution. Surface albedo was calculated from MOD09A1. Aerosol optical depth (AOD) data were obtained from MCD19A2, and ozone (O_3) data from COPERNICUS/S5P/NRTI/L3_{O3} products. Population density data were sourced from Worldpop (<https://www.worldpop.org/>). Soil moisture and nighttime light data were obtained from the National Tibetan Plateau Data Center (<http://data.tpdac.ac.cn>). Temperature and precipitation data were monthly raster datasets from the National Tibetan Plateau Data Center. The annual average values of temperature, precipitation, and soil moisture at 10 cm depth were calculated. Oasis vector data were obtained from the National Cryosphere Desert Data Center (<http://www.ncdc.ac.cn>). Detailed data information and sources are shown in .

Land cover data were derived from the Global Land Cover Data Product Service website of the National Geomatics Center of China (<http://GlobeLand30>). The product resolution is 30 m. According to the definition of oasis structure

[11], cropland, grassland, shrubland, water bodies, and artificial surfaces were classified as oasis land cover types (wetlands were included in water bodies).

Based on previous research [4, 5, 7, 8] and data availability, influencing factors of the oasis effect were selected considering land cover, climate, and socio-economic factors, with air quality indicators included for the first time.

1.3 Methods

1.3.1 Oasis Effect Intensity Drawing on existing research [4, 5, 7, 8], this study calculates oasis effect intensity (OEI) using land cover data and MODIS LST to quantify the oasis effect intensity. The difference between the mean land surface temperature (LST) of oasis and bare land is defined as the oasis effect intensity. The oasis effect intensity characterizes the temperature difference between oasis and desert, where negative values indicate oasis cold island effect, positive values indicate oasis warm island effect, and larger absolute values indicate stronger cold island (or warm island) effects. The calculation formula is:

$$OEI = LST_{oasis} - LST_{bare}$$

where LST_{oasis} and LST_{bare} represent the mean LST values of oasis (cropland, grassland, shrubland, water bodies, and artificial surfaces) and bare land, respectively.

To further analyze the spatial variation of different oasis effect intensities and their area differences, the intensity is graded based on the mean LST of bare land [12]. The classification criteria are shown in .

1.3.2 Oasis Effect Footprint This study defines the area affected by the oasis effect as the oasis effect footprint, representing the spatial extent of oasis effect influence. To analyze the spatial variation of local oasis effects, an improved radius method is used to study the oasis effect footprint. The oasis centroid is extracted, and multi-ring buffers are established with the centroid as the origin. Each ring has an area equal to the initial ring area, and the ring radii are determined sequentially. The mean LST within each concentric ring is then extracted, and scatter plots of ring number versus mean LST are created. Due to irregular oasis boundaries, the rings also cover large areas of desert, allowing determination of the specific boundary where the oasis effect occurs. The specific discrimination method is: if there is an obvious inflection point in the scatter plot and the LST change after the inflection point becomes 平缓, the area within the ring corresponding to that point is defined as the oasis effect footprint. The ring radius calculation formula is:

$$r_i = \sqrt{i} \times r_1$$

where r_1 is the initial ring radius, r_i is the radius of the i -th ring, and S is the area of the initial ring and each ring, with i being the concentric ring sequence number.

1.3.3 Correlation Analysis Correlation analysis reveals the degree of closeness between geographical elements by calculating correlation coefficients [13]. This study uses correlation analysis to examine the relationship between oasis effect intensity and oasis vegetation cover changes. The formula is:

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}}$$

where r is the correlation coefficient between two elements, ranging from [-1, 1]. A positive value indicates positive correlation, and vice versa. The larger the absolute value, the closer the relationship. x_i and y_i are the values of the two variables in year i , \bar{x} and \bar{y} are the means of the two variables, and n is the study period length.

1.3.4 Geodetector Model Geodetector can detect spatial stratified heterogeneity to reveal its driving forces [14]. This study uses factor detection and interaction detection. Factor detection uses the q statistic to quantitatively analyze the explanatory power of each potential driving factor on the spatial stratified heterogeneity of oasis effect intensity in the Hexi region. The q value ranges from [0, 1], with larger values indicating greater influence on the oasis effect. The formula is:

$$q = 1 - \frac{\sum_{h=1}^L N_h \sigma_h^2}{N \sigma^2} = 1 - \frac{SSW}{SST}$$

where $h = 1, \dots, L$ are the strata of variable Y or factor X ; N_h and N are the number of units in stratum h and the entire region, respectively; σ_h^2 and σ^2 are the variances of Y values in stratum h and the entire region, respectively; SSW and SST are the sum of within-stratum variances and the total variance of the entire region, respectively.

Interaction detection is used to identify interactions between different factors, i.e., to assess the explanatory power when two factors act together on the dependent variable. The interaction relationships are divided into five categories [14].

2. Results and Analysis

2.1 Temporal Changes of Oasis Effect in Hexi Region from 2000 to 2020

2.1.1 Seasonal Variation Characteristics of Oasis Effect As shown in [Figure 2: see original paper], the oasis effect intensity in the Hexi oasis showed significant differences across seasons from 2000 to 2020. In all years and seasons, the oasis effect manifested as an oasis “cold island” effect, with the strongest intensity in summer, followed by spring and autumn, and the weakest in winter. During the study period, the oasis effect intensity in spring first decreased and then increased; in summer, it continuously increased from $-4.7\text{ }^{\circ}\text{C}$ to $-6.13\text{ }^{\circ}\text{C}$; in autumn, it first increased and then decreased; and in winter, it showed a slight increase, with oasis effect intensities of $-2.63\text{ }^{\circ}\text{C}$, $-1.74\text{ }^{\circ}\text{C}$, $-2.34\text{ }^{\circ}\text{C}$, and $-0.9\text{ }^{\circ}\text{C}$, respectively.

2.1.2 Diurnal Variation Characteristics of Oasis Effect The oasis effect exhibits different characteristics during daytime and nighttime [Figure 3: see original paper]. During the day, all seasons showed an oasis “cold island” effect with greater intensity, similar to the seasonal variation patterns. During the study period, daytime oasis effect intensity in all seasons showed an increasing trend, with small changes in spring and significant increases in summer. In autumn and winter, there was a slight enhancement but with small variation amplitude.

Compared with daytime, nighttime oasis effect intensity was lower. In spring, it first decreased and then increased; in summer, it showed an increasing trend; in autumn of 2000, it exhibited a weak oasis “warm island” effect, though the intensity was low at $0.005\text{ }^{\circ}\text{C}$; in winter of 2010, it showed an oasis “cold island” effect, and in 2020, it changed to a warm island effect, with an oasis effect intensity of $-0.36\text{ }^{\circ}\text{C}$. In winter, the oasis effect was weak.

2.2 Spatial Changes of Oasis Effect in Hexi Region from 2000 to 2020

2.2.1 Spatial Variation Characteristics of Oasis Effect The spatial distribution of seasonal oasis effect intensity in the Hexi region is shown in [Figure 4: see original paper]. The area proportion of strong oasis effect was largest in summer and smallest in winter, with spring and autumn in between. The area proportion of medium-intensity oasis effect was similar in spring, summer, and autumn, and smallest in winter. The area proportion of weak oasis effect was largest in autumn and smallest in summer. The area proportion of oasis warm island effect was largest in winter and similar in spring, summer, and autumn.

The area proportions and spatial distributions of the four oasis effect intensity levels showed little change. Strong oasis effects were mainly concentrated in the Zhangye oasis of the Heihe River Basin and the Wuwei oasis of the Shiyang River Basin. As shown in , during the study period, the area proportions of winter oasis warm island effect were 46.6%, 44.8%, and 38.5%, respectively, showing a decreasing trend year by year. This level was mainly distributed throughout the Shiyang River Basin and parts of the Zhangye oasis, possibly related to increased artificial surfaces and anthropogenic heat emissions in Zhangye and

Wuwei cities. In spring and autumn, oasis warm island effects existed within oasis interiors and surrounding sparse grassland areas, but the area proportions were small, increasing by 0.6% and 0.28% in spring and autumn, respectively.

2.2.2 Oasis Effect Footprint Taking the Minqin and Dunhuang oases as examples, oasis centroids were extracted, and concentric rings were made to cover the entire oasis. After multiple tests, the initial radius of concentric rings for Dunhuang oasis was determined to be 2.5 km with 15 rings, and for Minqin oasis, 3.5 km with 20 rings. As shown in [Figure 5: see original paper], the summer mean LST of Minqin oasis increased rapidly with increasing ring numbers, then decreased. When the ring number reached 11, it showed a significant increasing trend again. For Dunhuang oasis, the summer mean LST increased rapidly with increasing ring numbers, and when the ring number was 7, it increased slowly, with an inflection point appearing at ring 8, after which the change became 平缓.

Analysis of oasis internal structure showed that Minqin oasis had a small decrease at ring 11, but this point was not an inflection point. The reason was that there was a bare land patch within the northeast side of Minqin oasis, causing higher LST values in that ring, but when the ring exceeded 11 and passed through the upper part of the oasis, the mean LST decreased again. The inflection point appeared at ring 13, and after that, the change became 平缓. In 2020, the Minqin oasis footprint expanded to ring 15, indicating a certain expansion of the oasis effect range. In contrast, the Dunhuang oasis footprint showed no obvious change before and after, with the inflection point roughly at ring 8, indicating stable oasis ecological conditions.

2.3 Analysis of Influencing Factors

2.3.1 Impact of Land Cover Change To explore the impact of human activities on oases, land cover change in the Hexi oasis was studied based on GlobeLand 30 land cover data. As shown in [Figure 6: see original paper], from 2000 to 2010, human activities had a relatively small impact on the Hexi oasis, with artificial surfaces increasing by approximately 150 km². From 2010 to 2020, with rapid urban development, human activities dramatically affected oasis cover changes, with artificial surface area rapidly increasing to 2395 km², most significantly in Wuwei and Zhangye oases, mainly converted from cropland and bare land. Population growth and economic development brought about oasis expansion, with large areas of bare land converted to cropland, grassland, shrubland, and construction land, totaling 5348 km². Different oasis covers were converted among each other. Over the past 20 years, water bodies and cropland showed increasing trends, while desert showed a first-increasing then decreasing trend, with a total reduction of 4821 km². This indicates that environmental management around the Hexi oasis has achieved results, and the improved oasis ecological environment has positively contributed to enhanced oasis effects.

2.3.2 Response of Oasis Effect to Oasis Vegetation Cover Change As shown in [Figure 7: see original paper], based on land cover and oasis vector data, the oasis boundary and desert boundary were determined, and 20 km buffers were created outward to exclude mountainous areas. By calculating the annual mean NDVI of the buffer zones, the response relationship between oasis effect intensity and NDVI changes was investigated. Since oases can regulate regional climate in summer, creating comfortable living environments during high temperature days and extreme heat events, the oasis effect intensities of the entire Hexi oasis, Minqin oasis, and Zhangye oasis all showed increasing trends. As shown in [Figure 8: see original paper], from 2000 to 2020, the overall NDVI of the Hexi region showed an increasing trend. The multi-year average cold island effect intensity of Minqin oasis was relatively low at -7.4°C . Due to the good ecological environment of Zhangye oasis, it had a very strong cold island effect, with a multi-year average cold island effect intensity of -11.23°C , closely related to Zhangye's ecological wetland parks and ecological city construction.

By extracting summer NDVI of oases and analyzing the response relationship between oasis cold island effect intensity and NDVI changes, it was found that the vegetation cover in Minqin oasis area was low, with a multi-year average NDVI of 0.2. Low vegetation cover implies soil drought, severe water shortage, and land desertification, reducing the oasis's ability to resist desert climate. As shown in [Figure 8: see original paper], whether for the entire Hexi oasis or local oases (Zhangye and Wuwei), the curves of oasis effect intensity and NDVI changes showed strong correspondence. As NDVI changed, the cold island effect intensity changed accordingly, showing a significant negative correlation. The correlation coefficients between oasis effect intensity and oasis NDVI were $R^2 = 0.85$ ($p < 0.005$) and $R^2 = 0.68$ ($p < 0.005$), respectively. This indicates that green vegetation is one of the very important factors affecting the oasis cold island effect. Rational planning of oasis city structure and increasing urban green space are beneficial for enhancing the oasis effect.

Using interaction detection to test the interaction between the two driving factors, the results showed that the interaction between any two driving factors exhibited a two-factor enhancement relationship, and the interaction effect was greater than the explanatory power of single factors on the spatial stratified heterogeneity of desert-oasis effects. The interaction between temperature and other factors was most significant. The interaction q-value between temperature and NDVI was 0.68, reflecting that the combined effect of temperature and vegetation had the most significant impact on the oasis effect, followed by the interaction between temperature and land cover. The interaction between temperature and soil moisture, albedo, and other factors was significantly higher than the explanatory power of single factors.

As shown in , taking 2020 as an example, factor detection was used to quantitatively analyze the influence of driving factors on the oasis effect intensity in the Hexi region. Climate factors, vegetation cover, land cover type, and soil

moisture had significant impacts on oasis effect intensity. Precipitation affects surface runoff formation, determines land cover characteristics, and provides a good growth environment for vegetation, significantly enhancing the oasis effect. Surface albedo and socio-economic factors had smaller impacts on oasis effect intensity, possibly because the albedo difference between desert and oasis is not obvious at interannual scales and the overall urbanization level in the Hexi region is relatively low. Finally, the air quality indicator AOD had a certain impact on oasis effect intensity.

As shown in [Figure 9: see original paper], the interaction of oasis effect driving factors in 2020 demonstrated that the interaction between any two factors was significantly greater than the explanatory power of single factors, and the interaction types all showed two-factor enhancement. Among them, the interaction between temperature and vegetation was the largest.

3. Discussion

The study found that compared with urban heat island footprints [15], oasis effect footprints remained relatively stable during the 2000–2020 period. The main reasons are: first, compared with large cities with rapid economic development, oasis cities have slower population growth and fewer industrial industries, and the state emphasizes their continuous protection and construction; second, the overall oasis environment shows a deteriorating trend, causing oasis area not to expand or decrease rapidly, thus the area producing oasis effects does not expand or shrink quickly. For this phenomenon, constructing shelterbelts near the desert-oasis transition zone [16] and planting dominant species such as *Haloxylon ammodendron* [17] can resist desert wind-sand invasion [18], prevent soil erosion within the oasis area [19], maintain normal production and life, and achieve sustainable development of oasis cities.

The oasis effect is a unique climate phenomenon within the planetary boundary layer, with important ecological significance for oasis water saving and agricultural development. Studies have shown that due to different material composition, spatial structure, and water-heat characteristics between desert and oasis, oasis effects form local circulation [20]. Vegetation cover and human activities have significant impacts [21], and there is a response relationship between oasis area and summer oasis effect [22]. This paper analyzed the relationship between summer cold island effect intensity and vegetation cover changes within oases. Compared with oasis area, vegetation cover is more closely related to oasis effect, and the correlation coefficient R^2 reached 0.85. The NDVI of the Hexi oasis showed an increasing trend from 2000 to 2020, consistent with the research on vegetation change trends in the Hexi region by Lu Hui et al. [23].

Against the background of significant climate change in the Hexi region [24], this study quantitatively investigated influencing factors of the oasis effect. First, climate factors were found to be the main controlling factors. During the same

period, the Hexi region showed a potential trend of reverse desertification, also controlled by climate factors [25]. Second, this study found that the interaction between any two types of factors was enhanced, especially the significant enhancement between temperature and other factors. For example, AOD had small single-factor explanatory power, but its interaction with other factors significantly increased. Related studies have shown that gases such as NO_2 produced by human activities, influenced by meteorological conditions, are prone to photochemical reactions producing O_3 . Increased near-surface O_3 concentration can harm vegetation in oasis areas, thereby affecting vegetation cooling effects. This indicates that gases produced by human activities indirectly affect the oasis effect, and pollutant emissions should be reduced and the oasis city pollutant emission detection system should be improved. It also shows that the interaction between natural and socio-economic factors should not be ignored, and future research should further investigate the comprehensive impact of multiple factors on the oasis effect.

In oasis areas, desertification processes are controlled by groundwater changes under human activity influence [26]. In recent years, the groundwater level in the Hexi oasis plain has shown a continuous decreasing trend [27], mainly due to significantly increased agricultural irrigation water consumption. Long-term imbalance between groundwater extraction and recharge threatens regional ecological security and is not conducive to the exertion of oasis effects. Therefore, in oasis areas, groundwater should be reasonably exploited, the water resource allocation pattern should be improved, and high-quality development and protection of cropland should be focused on [28]. The long-term monitoring and regular evaluation of ecological construction and agricultural development in the Hexi Corridor should be strengthened [29]; ecological projects should be promoted, air quality should be improved, urban structure should be optimized [30], and the stability of oasis ecosystems in arid regions should be enhanced.

Previous studies have shown [31] that oases produce warm island phenomena in winter, with albedo being the main factor. This study found that a small number of areas also showed warm island phenomena in spring and autumn, mainly appearing in cities and surrounding areas, possibly related to increased artificial surfaces and anthropogenic heat emissions. Therefore, future work should focus on the formation mechanism and influencing factors of the oasis warm island effect to provide theoretical support for sustainable development of oasis cities.

4. Conclusions

This study takes the desert-oasis ecological geographical unit in the Hexi region as the research object, selects the geodetector model, and chooses climate, surface, and socio-economic driving factors to analyze the spatial and temporal variation characteristics and influencing mechanisms of the oasis effect in the

Hexi region. The main conclusions are as follows:

- 1) From 2000 to 2020, the seasonal variation characteristics of the oasis effect in the Hexi region showed significant differences. The intensity of oasis effect was generally in the order of summer > spring > autumn > winter, showing a continuous enhancement trend in spring, summer, and winter, with a slight weakening in autumn. Diurnal variations differed: daytime changes were similar to corresponding seasonal changes but with greater intensity; at night, a weak warm island effect appeared in the winter of 2010.
- 2) The area proportion of strong oasis effect was largest in summer, while the area proportion of oasis “warm island” effect was largest in winter, with the former remaining stable and the latter decreasing year by year during the study period.
- 3) The oasis effect footprint of Minqin and Dunhuang oases was studied. The Minqin oasis footprint expanded from ring 13 to ring 15, while the Dunhuang oasis footprint showed no obvious change before and after.
- 4) There was a significant negative correlation between oasis vegetation cover and oasis effect intensity. The correlation coefficients between oasis effect intensity and vegetation cover for the entire Hexi oasis and local oases (Zhangye and Wuwei) were $R^2 = 0.85$ ($p < 0.005$) and $R^2 = 0.68$ ($p < 0.005$), respectively.
- 5) Differentiation and factor detection showed that climate and surface factors are the main controlling factors for oasis effect intensity in the Hexi region. Interaction detection revealed that the interaction between any two factors was significantly greater than the explanatory power of single factors, and the interaction types all showed two-factor enhancement, with the interaction between temperature and vegetation being the largest.

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