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Vegetative Response to Meteorological Factors in a Desert Oasis Area Based on Principal Component Analysis

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Abstract: Based on the principal component analysis, we aimed to explore the mechanism for dynamics of oasis vegetation coverage on the basis of related meteorological factors. According to the six indicators including the annual precipitation, annual evaporation, average humidity, average wind speed, average temperature, and annual sunshine hour, two independent principal components such as annual evaporation and average temperature were extracted, with the cumulative variance contribution rate of 85.84%. The driving mechanism of meteorological drought in the whole desert oasis area was analyzed. The results showed that during the study period the annual evapotranspiration, average temperature, precipitation and humidity had greater influence on vegetation coverage dynamics than other two meteorological factors such as annual sunshine hours and wind speed. The partial correlation analysis indicated that the vegetative index was positively correlated with the average temperature (X_5) and average humidity (X_3) with the partial correlation coefficients and the correlation coefficient of 0.98, 0.977, and -0.901 respectively. However, the vegetative index was negatively correlated with the annual evaporation (X_2) with the coefficient of -0.901. Therefore, the present work supplemented the effects of evaporation and humidity on the vegetative index, and we proposed that when the external drought weather conditions was not under control effectively, the manual intervention would still be the first choice to improve the vegetation coverage, which was to provide theoretical gists for vegetation growth and ecological restoration in desert oasis area.

Keywords: deficit irrigation; water consumption patterns; yield and quality; water productivity; potato

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1. Introduction

Drought is commonly classified into two types: climatic drought and agricultural drought. The Minqin Oasis, located in the arid climate of northwest China, serves as an important ecological barrier in the region [1]. Due to a series of improper measures such as alterations to natural water systems, unreasonable allocation of water resources, over-extraction of groundwater, and the impact of global climate change, the natural hydrological cycle has been severely disrupted. As a result, river drying, sharp declines in groundwater levels, frequent sandstorms, and land degradation caused by desertification have become serious threats to human survival [2]. Under current conditions, the Minqin Oasis has become increasingly fragmented, with lower connectivity between its ecological patches. These structural changes and the consequent decline in ecosystem functions have had a direct and serious impact on human well-being [3,4].

It is crucial to emphasize recent findings indicating that temporal variations of drought indices exhibit different behaviors across time scales. Notably, shorter time scales show increased drought frequency but shorter duration, suggesting more frequent climatological fluctuations. In contrast, droughts on longer time scales occur less frequently but last longer. Understanding these temporal patterns is essential for grasping the dynamic nature of drought events [5,6]. Additionally, these insights urge the scientific community to conduct further research. Scholars have examined the relationship between meteorological drought and vegetation conditions using remote sensing vegetation indices [7]. Therefore, clarifying the factors that affect the size of the oasis and vegetation coverage is essential for mitigating desertification in the Minqin Oasis area.

Research on the relationship between meteorological factors and regional vegetation characteristics began in the 1980s and has gradually incorporated more complex meteorological variables. Early studies applied a systematic two-factor model based on runoff and precipitation to analyze oasis vegetation cover [8]. Later research on the Qaidam Basin using MODIS NDVI data identified meteorological parameters and groundwater depth as primary factors influencing vegetation dynamics [9]. Other studies modeled crop coefficients and investigated patterns of crop evapotranspiration using the normalized vegetation index, further analyzing their responses to meteorological variables [10]. The Monin-Obukhov similarity theory was also used to assess the spatial trends of sensible heat and momentum flux based on wind and temperature profiles, exploring vegetation patterns in Istanbul and their relationship to meteorological parameters [11]. In this study, we focus on the ecologically fragile zones of the Hexi Oasis and assess how various meteorological factors influence vegetation. Specifically, we take the Minqin Desert Oasis as an example, selecting meteorological variables and sensitivity indices relevant to drought. Using analytical techniques such as principal component analysis and partial correlation analysis, we aim to reveal the relationship between vegetation indices and key meteorological factors and to explore the development trends of vegetation coverage in desert oases.

2. Materials and Methods

2.1. Study Site Description

Minqin Oasis is located in the downstream region of the Shiyang River Basin in Gansu Province, northwestern China, between 38°03′ and 39°28′ N latitude and 101°49′ and 104°12′ E longitude (Figure 1). The study area covers approximately 1.6×10^6 hectares and is bordered on three sides by the Badain Jaran Desert and the Tengger Desert. The oasis exhibits a continental arid desert climate, characterized by frequent sandstorms, extremely low rainfall, an average annual sunshine duration of 3100 hours, and an average annual wind speed of 2.7 m/s. The mean annual effective precipitation is 127.7 mm, while the average annual evaporation reaches 2623 mm. The average annual temperature is 8.3 °C, with the lowest temperatures occurring in January, February, and December, and the highest temperatures observed from June to August.

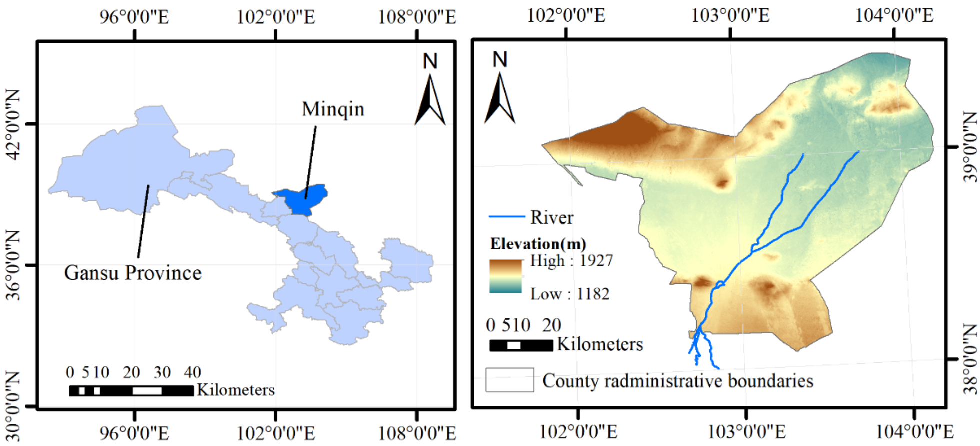

Figure 1. Overview Map of the Study Area.

2.2. Methodology

In Principal Component Analysis the composite index is converted into the principal component, a linear combination of the original variables [9]. When the first linear combination can not extract more information, the second one then should be considered until the extracted information retains almost the same as the original indicator. In addition, the contribution rate is introduced to show whether the selected principal component can reflect the degree of the original sample information and effectively describe the samples composed by multiple indicators or not. When the cumulative contribution rate is over 85%, and the newly selected principal component contains most of the information of the original variables, the principal component instead of the original variables can be used. The mathematical expression of principal component is as follows:

$$\begin{cases} Y_1 = u_{11}X_1 + u_{12}X_2 + \cdots + u_{1p}X_p \\ Y_2 = u_{21}X_1 + u_{22}X_2 + \cdots + u_{2p}X_p \\ \vdots \\ Y_p = u_{p1}X_1 + u_{p2}X_2 + \cdots + u_{pp}X_p \end{cases} \quad (1)$$

Where $Y_1 \sim Y_p$ representss the principal components, $X_1 \sim X_p$ are the standardized variables, and $u_{11} \sim u_{pp}$ standardize the eigenvector matrixes. In this study, the six indicators (X_1, X_2, X_3, X_4, X_5, and X_6) were respectively the annual precipitation, annual evaporation, average humidity, average wind speed, average temperature, and annual sunshine hours. The first step was the standardization as following:

$$X_{ij} = (Y_{ij} - \overline{Y}_j) / S_j \quad (2)$$

$$\overline{Y}_j = \frac{1}{m}\sum_{i=1}^{m} Y_{ij} \quad (3)$$

$$S_j^2 = \frac{1}{m-1}\sum_{i=1}^{m}(Y_{ij} - \overline{Y}_j)^2 \quad (4)$$

Where S_j^2 means the value of variance, and X_{ij} is the normalized value, using the Z-Score method to deal with the index [11].

The data were from the Gansu Minqin Desert Grassland Ecosystem National Field Observation Station. Shown in Table 1. The SPSS19.0 and Microsoft Office Excel 2016 were used in data processing.

Table 1. Meteorological Indicators and Their Standardization.

	Meteorological data						Standardized data					
Years	X_1	X_2	X_3	X_4	X_5	X_6	X_1	X_2	X_3	X_4	X_5	X_6
2007	227.0	1812.2	54.50	1.450	8.06	—	2.52669	0.76704	0.34556	0.63991	-0.41666	—
2008	133.4	1857.8	53.75	1.642	7.22	—	0.12642	1.01804	0.0348	1.13137	-1.41664	—
2009	105.7	1857.4	49.08	1.525	8.46	—	-0.58391	1.01584	-1.90018	0.83189	0.05952	—
2010	105.0	1902.4	52.50	1.758	8.34	3083.0	-0.60186	1.26354	-0.48313	1.42829	-0.08333	-1.75329
2011	138.7	1367.3	52.58	1.242	7.60	3166.6	0.26234	-1.68187	-0.44998	0.10751	-0.96427	-0.58100

2012	128.3	1495.9	53.17	1.000	7.85	3260.7	-0.00436	-0.97401	-0.20551	-0.51193	-0.66666	0.73852
2013	89.1	1716.1	52.25	1.058	9.07	3223.2	-1.0096	0.23807	-0.58671	-0.36347	0.7857	0.21268
2014	127.0	1559.7	54.42	1.025	8.45	3247.1	-0.0377	-0.62282	0.31242	-0.44794	0.04762	0.54781
2015	136.2	1583.3	56.83	0.675	8.68	3267.6	0.19823	-0.49292	1.31098	-1.34382	2.13092	0.83528

Note: X_1, X_2, X_3, X_4, X_5, and X_6 are the annual precipitation, annual evaporation, average humidity, average wind speed, average temperature, and annual sunshine hour, respectively. The same below.

The factor loading math was established using Varimax method for factor rotation. After rotating the factor load matrix concentrated at both ends, the main factors may be better explained in Table 2.

Table 2. Factor Load Matrix and Eigenvector Matrix.

Factor load matrix before and after rotation					**Eigenvector matrix**		
Index	Before rotation		After rotation		Index	Feature vector	
	1	2	1	2		t1	t2
X_1	0.641	-0.588	0.192	-0.849	X_1	0.347	-0.445
X_2	-0.608	0.759	-0.068	0.971	X_2	-0.329	0.575
X_3	0.833	0.337	0.877	-0.198	X_3	0.451	0.255
X_4	-0.950	-0.107	-0.842	0.454	X_4	-0.515	-0.081
X_5	0.504	0.834	0.889	0.398	X_5	0.273	0.631
X_6	0.879	0.042	0.746	-0.466	X_6	0.476	0.032

The principal components of the eigenvector matrix were maintained by transforming and calculating variable commands (shown in Table 2), resulting in the principal component expression and realization of principal component analysis. The principal component coefficient expressions were as following:

$$Y_1 = 0.347X_1 - 0.329X_2 + 0.451X_3 - 0.515X_4 + 0.273X_5 + 0.476X_6 \quad (5)$$

$$Y_2 = -0.445X_1 + 0.575X_2 + 0.255X_3 - 0.081X_4 + 0.631X_5 + 0.032X_6 \quad (6)$$

3. Results

3.1. Relationship between Vegetation Index and Meteorological Factors

Figure 2 is the inter-annual variation of the four influencing factors of climate drought. The temperature showed a single-peak curve, and the low temperature occurred in January, February and December, the winter freezing periods and basically without growth of vegetation. The temperature in March exceeded zero and the weather gradually became warmer but still relatively low, thus it was not suitable for vegetation growth yet. The Vegetation began to grow at the end of April to early May, while the maximum average temperature was recorded in July throughout the year. The temperature in September was close to that in May. This period coincided with the most vigorous growth of vegetation. As the temperature gradually dropped till the middle October, the growth rate began to decrease for preserving vegetative vitality, while the annual plant started to wither and die, with November becoming the transitional period. Evaporation varied similarly to temperature, with the maximum occurring in July and the minimum in January. The humidity values were high in January and February mostly due to the snowfall and snowmelt. After then, the precipitation decreased while the temperature rose quickly. The windy climate and strong evaporation in April and May resulted in the minimum humidity of the year and spring drought correspondingly. The rainfall was gradually increased after May and fluctuated widely. The maximum humidity occurred in September, which was related to rainfall and evaporation. The annual sunshine hours varied with fluctuations in elevation, water vapor, topography, and other factors, but the average annual sunshine remained at 3073.5 hours.

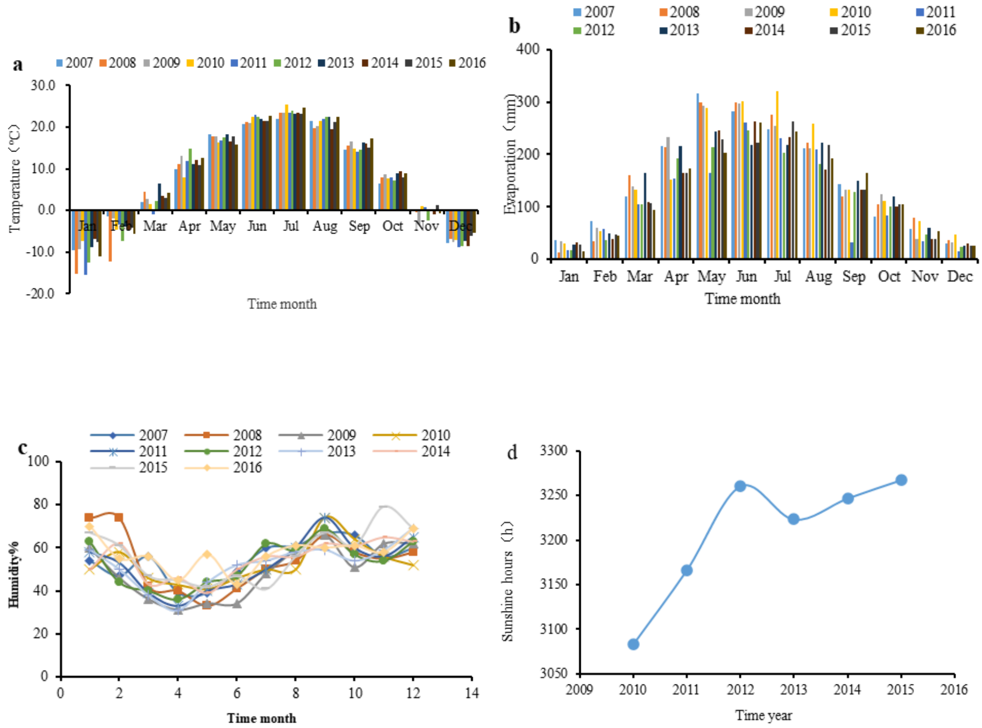

Figure 2. Inter-Annual Trend of Meteorological Factors.

The vegetation index (NDVI) was used to characterize the key indicators of plant growth. This study refers to the maximum value of Z_1 and the minimum value of Z_2 in the AFRISWIR2, as shown in Figure 3.

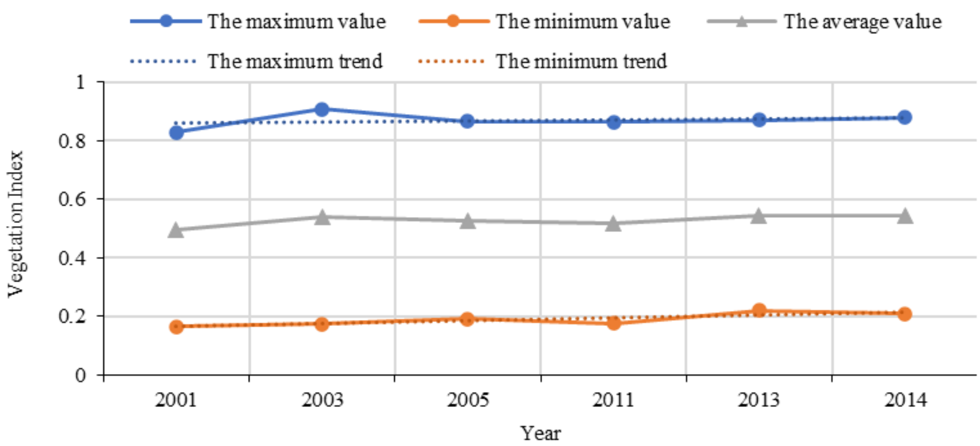

Figure 3. Dynamics of Vegetation Index in Minqin County, an Arid Oasis.

The partial correlation analysis method was used to eliminate the false correlation between various factors, which may effectively reveal the true relationship between the variables while controlling the linear influence of some other variables, identifying the disturbance variables and finding the implicit correlation. Under the control of other variables, the correlation analysis results between the maximum vegetation index of Minqin Oasis and various influencing factors were shown in Table 3.

Table 3. Correlation Analysis between the Maximum Vegetation Index and Influencing Factors.

Partial correlation analysis				Simple correlation analysis		
Control variables	Variable	Related to Z_1	Related to Z_2	Control variables	Related to Z_1	Related to Z_2
X_2,X_3,X_6	X_5	0.980	0.827	No	0.529	0.576
X_5,X_3,X_6	X_2	-0.901	-0.010	No	-0.367	-0.152
X_2,X_5,X_6	X_3	0.997	-0.906	No	0.668*	0.261
X_2,X_3,X_5	X_6	-0.041	-0.873	No	0.666	0.613

3.2. Main Driving Forces of Meteorological Drought Factors

Two principal components are extracted in Table 4, with the cumulative variance contribution rate of 85.844%. The average temperature was closely related to the component 1, while the component 2 was substantially correlated with the annual evaporation, indicating that the annual evaporation and average temperature change were the main driving forces of meteorological drought factors. The sum of the absolute values of the eigenvectors of each meteorological drought factor in Table 2 showed that X_2= X_5> X_1> X_3> X_6> X_4, that is, the influence was greater on annual evaporation, average temperature, precipitation and average humidity on climate droughts. The meteorological drought was less affected by wind speed and annual sunshine hours. The main component coefficients in equation (5) with X_3> X_1 while in equation (6) with X_5> X_2> X_3 were used to extract the driving factors affecting vegetation change, which may only play a macro-guiding role, however, can not effectively reflect the dynamic changes and effects of oasis vegetation Therefore, it is necessary to use partial correlation analysis to analyze the relationship between the impact factors and the changes of oasis vegetation. As seen from Figure 3, the maximum and minimum vegetation index changes showed a fluctuating growth pattern. Since 2007, we found that the maximum and minimum vegetation indexes gradually increased after the implementation of Key Governance Measures in the Shiyang River Basin due to the reduction of groundwater exploitation. Now, the groundwater level has been elevated in some areas, the ecological environment in Minqin Desert Oasis has been improved, and the Minqin Oasis area has also been slowly expanded gradually.

Table 4. Meteorological Factors in Explanation of the Total Variance.

	Meteorological data			Extracted square and load			Standardized weather data		
Ingredients	Total	Variance (%)	accumulation (%)	Total	Variance (%)	Accumulation (%)	Total	Variance (%)	accumulation (%)
1	3.406	56.761	56.761	3.406	56.761	56.761	2.866	47.772	47.772
2	1.745	29.083	85.844	1.745	29.083	85.844	2.284	38.072	85.844
3	0.723	12.049	97.893						
4	0.121	2.023	99.916						
5	0.005	0.084	100						
6	1.39E-16	2.32E-15	100						

3.3. Correlation Coefficients Analysis

From Table 4, the partial correlation analysis showed that the relationship between the variables and the dependent variables is clearer than that of simple correlation analysis, and there is no influence on unrelated variables. The partial correlation coefficients of dependent between the variable Z_1 and variables X_5, X_2, X_3, X_6 were 0.98, -0.901, 0.997, -0.041, respectively. The simple correlation coefficients between the dependent variable Z_1 and variables X_5, X_2, X_3, X_6 were 0.529, -0.367, 0.668 and 0.666 respectively. The partial correlation coefficients between Z_1 and X_5, X_3 were 0.98 and 0.997, indicating that there was a high correlation between the average temperature and the average humidity as well as the maximum vegetation index. The correlation was significant between Z_1 and X_3 at 0.005 level, demonstrating the significant effect of humidity on vegetation. Compared with X_6 year's data, the correlation coefficient of X_6 has a great contrast with that of X_6, which is due to the doping of other variables. Although the annual variations of sunshine hours may affect vegetation growth and distribution to a certain degree, the analysis results revealed that the effect was not accurate enough due to the partial data discontinuity. Therefore, the relationship between the annual sunshine hours and vegetation index could not be accurately described. In the follow-up study, a large number of annual sunshine hours data will be used to improve and vegetation coverage, the relationship between vegetation index. The partial and simple correlation coefficients between the variables Z_2 and X_5 were 0.827 and 0.576 respectively, reflecting the close relationship between the average temperature and the minimum vegetation index. Meanwhile, the simple correlations existed between the variable Z_2 and variables X_5, X_2, X_3, X_6, which was as the same as the partial correlation in the dependent variable Z_1, verifying the correctness of the partial correlation analysis. In addition, the precipitation of X_1 was also related to the vegetation index. However, the partial correlation analysis showed that the above correlation coefficient was lower than that of the other factors with the vegetation index because precipitation had a much more obvious hysteresis effect on vegetation growth than other climatic factors, but this did not mean that there was no relationship between precipitation and the vegetation index.

4. Conclusions

Dynamics in vegetation coverage and vegetation index were the result of the interaction of many factors. The results showed that the annual evaporation, average temperature, precipitation, and average humidity had a greater influence on vegetation coverage. There is an important connection between evaporation, humidity, and the oasis vegetation index, while the average temperature was positively correlated with vegetation coverage. Temperature is an important external factor affecting plant growth. Suitable temperature was conducive to plant germination and growth, promoting vigorous plant growth. The evaporation in arid regions was negatively correlated with vegetation coverage, accompanied by plant transpiration reduction. In addition, vegetation growth was directly affected by evaporation, thereby affecting vegetation coverage. Correlation analysis showed that annual evapotranspiration and average temperature changes were the main drivers of meteorological drought factors. Partial correlation analyses showed that average humidity and average temperatures were highly correlated with the maximum and minimum vegetation indices, respectively, and that precipitation was correlated with the magnitude of the vegetation index, indicating a significant lag effect of water volume on vegetation growth. The above analysis and conclusions will provide a theoretical reference for the recovery and growth of vegetation in regional desert oases.

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