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Impact of Photovoltaic Industry Development on Grassland Ecosystems

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Abstract: *As the global demand for renewable energy increases, the photovoltaic industry has developed rapidly. However, its large-scale construction in grassland ecosystems has caused potential threats to the ecological balance. Current problems include land use changes, reduced vegetation cover, and decreased biodiversity. This study conducts a field survey around a photovoltaic power station in Central Mongolia in a typical grassland area. Sample plots are set up to collect data on vegetation coverage, soil moisture, species diversity, etc., and high-resolution images are obtained by drone aerial photography. Secondly, remote sensing image data for 10 years before and after the construction of the photovoltaic power station are collected. Land use classification and change detection are carried out using ENVI and ArcGIS software, and key parameters such as vegetation index and soil moisture index are extracted. Then, meteorological data and the ecological model InVEST are combined to simulate the impact of photovoltaic power station construction on grassland ecosystem service functions. Finally, statistical analysis and spatial overlay methods are used to quantify the comprehensive impact of the photovoltaic industry on grassland ecosystems. The results show that the construction of photovoltaic power stations has led to an average decrease of 62.2% in vegetation coverage, a 27% decrease in the lowest value of soil moisture in the construction area, and a 70.8% decrease in species diversity index. The development of the photovoltaic industry has a significant negative impact on the grassland ecosystem, and ecological protection measures need to be taken in planning and construction to achieve a balance between renewable energy development and ecological protection.*

Keywords: *grassland ecosystem; photovoltaic industry development; remote sensing image; species diversity*

1. Introduction

With the rapid growth of global demand for renewable energy, the photovoltaic industry, as an important component of clean energy, has developed rapidly in recent years. However, the large-scale construction of photovoltaic power stations, especially in ecologically fragile grassland areas, poses a potential threat to the balance of the ecosystem. As an important carbon sink and water conservation area, grassland ecosystems have unique ecological functions and service values, but their fragility makes them easily disturbed by human activities. At present, the development of the photovoltaic industry has caused increasingly prominent problems such as land use change, reduced vegetation cover, and decreased biodiversity, and there is an urgent need to scientifically evaluate its ecological impact. Taking the Inner Mongolia grassland as an example, this region is an important ecological barrier in northern China and also a hot spot for the development of the photovoltaic industry. The health of its ecosystem is directly related to the ecological security of the region and even the whole country. Therefore, in-depth research on the impact of the development of the photovoltaic industry on the grassland ecosystem is not only of great scientific significance but also provides a practical basis for policy making.

This study adopts a multidisciplinary research method, combining field surveys, remote sensing data analysis and ecological model simulation to systematically evaluate the impact of photovoltaic power station construction on grassland ecosystems. By setting up fixed sample plots to collect vegetation coverage, soil moisture and species diversity data, and combining drone aerial photography and remote sensing image data, multi-dimensional and high-precision monitoring and analysis of the ecosystem is achieved. In addition, the InVEST model is used to simulate the impact of photovoltaic power station construction on carbon storage and water conservation functions. This comprehensive research method can not only comprehensively quantify the ecological impact of the photovoltaic industry but also provide a technical framework for reference for ecological assessments in similar areas.

The innovation of this study lies in that, firstly, by combining high-resolution UAV images with multi-source remote sensing data, high-precision dynamic monitoring of grassland ecosystems is achieved, which makes up for the lack of spatial coverage of traditional field surveys. Secondly, the InVEST model is applied to the ecological impact assessment of the photovoltaic industry for the first time, quantifying the impact of photovoltaic power station construction on grassland ecosystem service functions, providing a scientific basis for the formulation of ecological protection policies. Finally, through spatial overlay analysis and long-term trend prediction, the study reveals the multi-dimensional impact mechanism of photovoltaic industry development on grassland ecosystems, providing new ideas and methods for the balanced development of renewable energy development and ecological protection. These innovations make this study of great reference value in both theory and practice.

2. Related Work

Research on grassland ecosystems has gradually gained attention, involving multiple aspects such as biomass, environmental factors and ecological functions. Liu et al. [1] took the Xilin River Basin as the research area and measured the aboveground biomass of a typical grassland ecosystem from May to September 2020, as well as eight environmental factors in three categories, including meteorological factors, topographic factors and soil factors. They also quantitatively analyzed the relationship between aboveground biomass and various environmental factors using the geographic detector method. Lei et al. [2] took the Stipa brevisflower desert steppe as the object, quantified EMF based on the measurement of 11 ecosystem functions such as plant community biomass, soil organic carbon and multiple soil enzyme activities, and explored the effects of different grazing intensities on plant diversity and EMF. In order to protect the Ruoergai alpine wetland grassland, one of the most important water conservation areas in the upper reaches of the Yellow River, Miao et al. [3] constructed a comprehensive assessment system for the Ruoergai grassland ecosystem, quantitatively assessed its ecosystem service value and proposed corresponding protection measures. Wang et al. [4] used the eddy covariance system and meteorological gradient observation system observation data from the Xilinhot National Climate Observatory in Inner Mongolia from 2018 to 2021, combined with the Senti-nel-2 satellite data from January 1, 2018 to December 31, 2021, to analyze the changing patterns of the NEE and phenology of the Stipa krylovii grassland. Huang et al. [5] analyzed the advantages of UAV patrols in grasslands and found that UAV patrols are more efficient and cover larger areas, making them more suitable for monitoring grasslands in mountainous areas with complex terrain. At the same time, by accurately calculating the model and establishing a digital model of the growth and yield of various types of grassland plants, the accuracy of grassland yield assessment can be improved to a certain extent, providing a more reliable basis for protecting the diversity and stability of grassland ecosystems. Dudley et al. [6] outlined the key issues and steps needed to ensure that the decade creates positive outcomes for these important and biodiverse ecosystems. Liang et al. [7] conducted a sheep grazing experiment in a temperate grassland to test the effects of grazing on the temporal stability of productivity at different scales. He et al. [8] aimed to study the potential mechanisms of grazing effects on grassland C: N: P stoichiometry. Seabloom et al. [9] tracked the recovery of grasslands after 20 years of intense agricultural disturbance. Walker et al. [10] studied the responses of 128 components of subarctic grasslands to soil warming over 5-8 years or more than 50 years. These studies provide important scientific basis for grassland ecological protection and management, and help achieve sustainable development goals.

3. Methods

3.1 Research Area Selection

The research area of this paper is located in a typical grassland area in Inner Mongolia Autonomous Region, which is one of the important grassland ecosystems in northern China, with rich vegetation types and biodiversity. It is also a hot spot for the rapid development of the photovoltaic industry. The study area is centered on a large photovoltaic power station and covers the grassland ecosystem within a radius of 10 kilometers around the power station, with a total area of about 500 square kilometers.

The area has a temperate semi-arid climate, with an average annual precipitation of about 300 mm and an average annual temperature of 5°C. The vegetation is dominated by typical grassland plants such as Stipa and Leymus chinensis. The soil types are mainly chestnut-calcium soil and brown-calcium soil, which has strong ecological vulnerability. The reason for choosing this area as the research object is that it is typical and representative: On the one hand, the scale of photovoltaic power station construction in this area is large, with an installed capacity of more than 100 megawatts and an area of about 20 square kilometers, which has a significant impact on the surrounding grassland ecosystem. On the other hand, the ecosystem in this area is less disturbed by human activities and can better reflect the direct impact of the photovoltaic industry on natural grasslands[11]. Thirty fixed plots were set up in the study area, evenly distributed in the photovoltaic power station construction area, buffer zone (1-5 kilometers away from the power station) and control area (5-10 kilometers away from the power station) to ensure the spatial representativeness and comparability of the data. In addition, the area has long-term meteorological observation data and remote sensing image data, which provides reliable data support for the research.

3.2 Data Collection

During the data collection process, this paper systematically collects key ecological indicators such as vegetation coverage, soil moisture, and species diversity in the selected 30 fixed sample plots. Vegetation coverage is obtained by combining visual estimation and digital camera photography. A sample point of 1 square meter is set in each sample plot to record the vegetation coverage percentage; soil moisture is measured by randomly selecting 5 points in the sample plot using a TDR soil moisture meter, and the average value is taken as the soil moisture value of the sample plot; species diversity is calculated by identifying and counting all plant species in the sample plot, and the Shannon-Wiener diversity index [12] is calculated. At the same time, a DJI Phantom 4 RTK drone equipped with a multispectral camera is used to collect high-resolution images. The flight altitude is set to 100 meters and the resolution reaches 5 centimeters, covering all sample plots and surrounding areas, and obtaining data such as vegetation index (NDVI) and surface temperature. The drone aerial data is processed by Pix4D software to generate orthophotos and 3D models, and further extract vegetation coverage and surface feature information. All data collection work is carried out once before and after the construction of the photovoltaic power station to ensure the comparability of the data. Table 1 shows some of the collected data:

Table 1: Partial data display

Sample Plot Number	Vegetation Coverage (%)	Soil Moisture (m^3/m^3)	Species Diversity Index	NDVI
1	65	0.35	2.5	0.72
2	60	0.32	2.4	0.68
3	70	0.38	2.6	0.75
4	55	0.30	2.3	0.65
5	50	0.28	2.2	0.60

3.3 Remote Sensing Data Analysis

In the remote sensing data analysis part, this paper collected remote sensing image data 10 years before and after the construction of the photovoltaic power station, mainly from Landsat and MODIS satellites, with a time span from 2010 to 2020, and the spatial resolution is 30 meters and 250 meters, respectively, to ensure the continuity and high accuracy of the data. Landsat images are used for high-precision land use classification and change detection, while MODIS images are used for the extraction of vegetation index and soil moisture index over a large area. Data processing first uses ENVI software to perform radiation correction, atmospheric correction, and geometric correction to eliminate noise and errors in the image. ArcGIS software is then used to classify the land use of the corrected image. A supervised classification method is used to divide the land use types of the study area into categories such as grassland, bare land, and photovoltaic power station construction land. Change detection techniques (such as image difference method and post-classification comparison method) are used to analyze the changes in land use before and after the construction of the photovoltaic power station [13]. The extraction of the vegetation index (NDVI) and soil moisture index (TVDI) is based on the spectral characteristics of remote sensing images. The NDVI is obtained by calculating the reflectance difference ratio between the near-infrared band and the red band, and the

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TVDI is calculated by combining the land surface temperature (LST) and NDVI data using the temperature-vegetation index spatial relationship model [14].

3.4 Ecological Model Simulation

In the ecological model simulation part, the research team combines meteorological data (precipitation, temperature, wind speed) and the ecological model InVEST to simulate the impact of photovoltaic power station construction on grassland ecosystem service functions, focusing on the two core functions of carbon storage and water conservation. The InVEST model calculates the current status and changing trends of ecosystem service functions by inputting land use/cover data, meteorological data, soil type data, and vegetation parameters. First, based on the land use change data obtained from remote sensing data analysis, land use scenarios before and after the construction of the photovoltaic power station are set. Secondly, the changes in carbon storage and water conservation capacity of the grassland ecosystem in the next 20 years are simulated by combining meteorological station data and future climate scenarios output by the regional climate model [15]. The carbon storage module estimates carbon reserves through parameters such as vegetation biomass and soil organic carbon, while the water conservation module calculates the dynamic changes of precipitation, evapotranspiration, surface runoff and soil moisture based on the principle of water balance.

4. Results and Discussion

4.1 Comparative Analysis of Data Before and After the Construction of Photovoltaic Power Plants

The experiment first selects a typical grassland area in Inner Mongolia as the study area. With the photovoltaic power station as the center, it divides the area into a construction area, a buffer area (1-5 kilometers) and a control area (5-10 kilometers). Ten fixed sample plots are set up in each area to ensure the uniformity and representativeness of the spatial distribution. The experiment is divided into two phases: the first phase is to collect baseline data before the construction of the photovoltaic power station (2010-2015), including indicators such as vegetation coverage, soil moisture, and species diversity. At the same time, high-resolution images are obtained by drone aerial photography, and land use classification and ecological parameter extraction are carried out in combination with Landsat and MODIS remote sensing data. In the second phase, the same data collection and analysis process is repeated after the construction of the photovoltaic power station (2016-2020) to ensure the comparability of the data. During the experiment, vegetation coverage is obtained by visual estimation and digital camera photography in the sample plot, soil moisture is measured using a TDR soil moisture meter, species diversity is calculated by identifying and counting plant species in the sample plot to calculate the Shannon-Wiener index, and remote sensing data is processed and analyzed using ENVI and ArcGIS software.

4.2 Data Results

The average vegetation coverage of the 10 fixed plots in the five years before and after is calculated. In the first five years, since the photovoltaic power station is not built, only its individual vegetation coverage is calculated. In the last five years, the data of the buffer zone of the construction area and the control area are calculated. Figure 1 shows the vegetation coverage test results.

Data analysis shows that there has been a significant change in vegetation coverage before and after the construction of the photovoltaic power station: the average vegetation coverage of the 10 fixed sample plots before construction is 84.4%, while the average vegetation coverage of the construction area, buffer zone and control area after construction is 31.9%, 56.4% and 77.2%, respectively. The vegetation coverage in the construction area decreases most significantly, by 62.2%. This is mainly due to the direct occupation of grassland by the laying of photovoltaic panels and infrastructure construction, which leads to the removal or destruction of vegetation. Vegetation cover in the buffer zone decreases by 33.2%, which may be due to the indirect impact of construction activities, vehicle traffic and human disturbance on the surrounding ecosystem. Vegetation cover in the control area decreases by 8.5%, a smaller decline, mainly attributed to the combined effects of natural climate change and human activities such as grazing. Overall, the impact of photovoltaic power station construction on vegetation coverage has a significant spatial gradient effect, and the closer to the power station, the more significant the impact. This result reveals the direct and indirect impact of photovoltaic industry development on grassland ecosystems, and emphasizes the need to take ecological protection measures in the planning and construction of photovoltaic power stations, such as reasonable site selection, vegetation restoration and ecological compensation, to reduce the negative impact on grassland ecosystems.

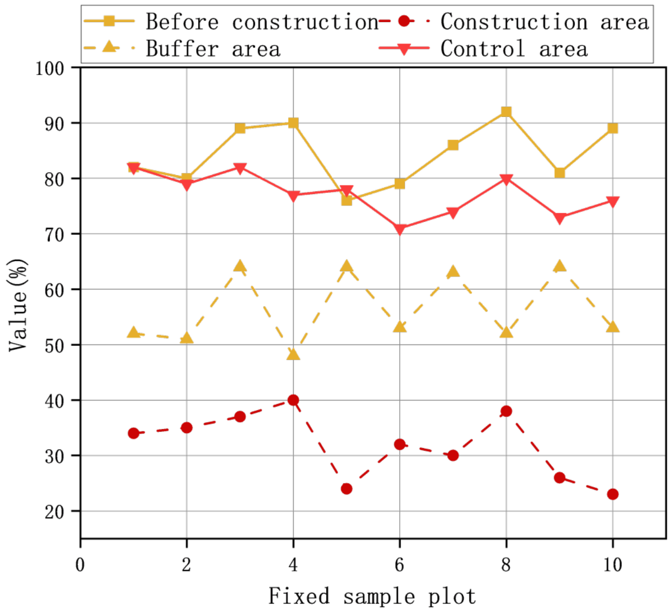

Figure 1: Vegetation Cover

Figure 2 shows the changes in soil moisture:

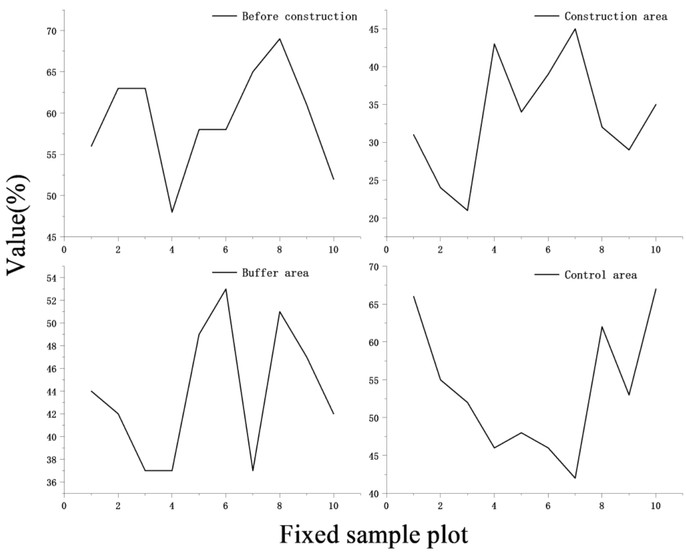

Figure 2: Soil moisture

The highest soil moisture value before construction is 69% (plot 8) and the lowest is 48% (plot 4), while after construction, the highest values in the construction area, buffer zone, and control zone are 45% (plot 7), 53% (plot 6), and 67% (plot 10), and the lowest values are 21% (plot 3), 37% (plots 3, 4, and 7), and 42% (plot 7), respectively. The maximum and minimum values of soil moisture in the construction area are significantly lower than before construction. The main reason is that the coverage of photovoltaic panels reduces surface water evaporation and precipitation infiltration. At the same time, infrastructure construction changes surface runoff and soil structure, resulting in a decrease in soil water retention capacity. The maximum and minimum values of soil moisture in the buffer zone are

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also lower than before construction, but the decrease is smaller, which may be due to the combined effects of construction activities and human disturbance on the destruction of soil structure and the reduction of vegetation cover. The maximum and minimum values of soil moisture in the control area are close to the pre-construction levels, but still decreases to a certain extent, which is mainly attributed to the long-term impact of natural climate change and human activities such as grazing. In general, the impact of photovoltaic power station construction on soil moisture has an obvious spatial gradient effect. The closer to the power station, the more significant the impact, and the greater the decrease in the maximum and minimum values. This further reveals the profound impact of the development of the photovoltaic industry on the hydrological processes of grassland ecosystems.

The Shannon-Wiener index is used to measure the species diversity of an ecosystem. The higher the value, the richer the species diversity. In actual calculations, the index is between 1 and 4. Figure 3 shows the results of changes in material diversity:

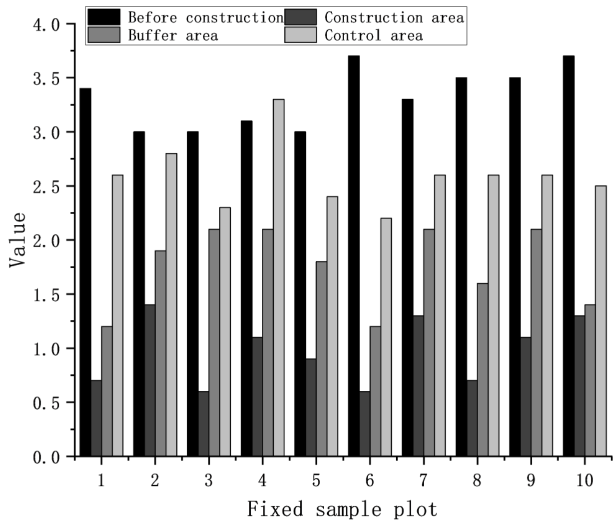

Figure 3: Species diversity

There are significant changes in species diversity before and after the construction of the photovoltaic power station. The average Shannon-Wiener index of the 10 fixed plots before construction is 3.32, indicating that the species diversity is high and the ecosystem is relatively stable. After construction, the average indexes of the construction area, buffer zone and control area are 0.97, 1.75 and 2.59, respectively. The species diversity in the construction area decreases most significantly, by 70.8%. This is mainly due to the direct destruction of vegetation habitats by the laying of photovoltaic panels and infrastructure construction, resulting in a sharp decrease in the number of species. The species diversity in the buffer zone decreases by 47.3%, while the species diversity in the control zone decreases by 22.0%, which is a relatively small decrease. This result reveals the profound impact of the development of the photovoltaic industry on the biodiversity of grassland ecosystems, and emphasizes the need to take ecological protection measures in the planning and construction of photovoltaic power stations to reduce the negative impact on the biodiversity of grassland ecosystems.

5. Conclusion

This study systematically evaluates the impact of photovoltaic industry development on grassland ecosystems through field surveys, remote sensing data analysis and ecological model simulation. The construction of photovoltaic power stations has had a significant negative impact on the vegetation coverage, soil moisture and species diversity of grassland ecosystems. These changes are mainly attributed to the direct and indirect damage to the ecosystem caused by the laying of photovoltaic panels, infrastructure construction and human interference. While the development of the photovoltaic industry promotes the use of renewable energy, it also creates considerable ecological pressure on the grassland ecosystem. It is urgent to take ecological protection measures in planning and construction to achieve a balance between renewable energy development and ecological protection.

In the future, as the global demand for renewable energy continues to grow, the expansion of the photovoltaic industry in grassland areas will be inevitable. Therefore, future research should further explore new models for the coordinated development of photovoltaic power stations and grassland ecosystems, such as developing an integrated "photovoltaic + ecological restoration" project, combining intelligent monitoring technology and ecological engineering methods to optimize the ecological impact of photovoltaic power stations.

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