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Effects of Wind Farm Construction on Soil Nutrients and Vegetation: A Case Study of Linxiang Wind Farm in Hunan Province

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Abstract: Amidst escalating global energy demands, the advancement and utilization of renewable energy sources have emerged as critical strategies for addressing environmental concerns and alleviating energy crises. Among them, wind power, as a renewable and clean energy source, has been widely applied and developed in China. However, the construction of wind farms may have some impact on vegetation cover and soil properties. This study aims to assess the impact of wind farm construction on vegetation cover and soil characteristics, thereby offering a scientific foundation for the sustainable management of wind farm development sites. The present study was carried out in the area of Jingzhushan wind farm in Linxiang City, Hunan Province, to examine the trends of the normalized difference vegetation index (NDVI), the fractional vegetation cover (FVC), and the indexes expressing the physicochemical properties of the soil in this area. The results showed the following: (1) The NDVI of the wind farm for the three periods was 0.742 in 2013, 0.770 in 2016, and 0.758 in 2023, respectively. According to the analysis of the index of FVC, it can be seen that the trend of the FVC of the study area for the three periods was basically the same as that of the NDVI. The average value of FVC was 0.754 in 2013, 0.791 in 2016, and 0.769 in 2023. This indicated that the vegetation cover in the early stage of wind farm construction (2013) was lower than that in the late stage of operation (2016, 2023), and it also suggested that the vegetation cover gradually recovered over time. (2) Compared with natural ecosystems, both altitude and wind farm construction significantly affected the organic carbon, the total nitrogen, the effective phosphorus, and the rapidly available potassium in the soil. At the same altitude, these four soil indicators in the area where the wind turbines were constructed had significantly lower levels compared with the control (CK), which indicated a decrease in soil fertility—the closer to the turbine construction area, the lower the levels of each indicator. In addition, soil pH did not change significantly during the construction of the wind farm. The analysis and comparison of various data showed that the construction and operation of wind farms can have an impact on local vegetation cover, and it had a significant negative impact on soil properties. Reasonable measures are needed to protect vegetation and soil to achieve the sustainable development of the ecological environment.

Keywords: wind farm construction; soil properties; normalized difference vegetation index (NDVI); fractional vegetation cover (FVC); sustainability

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1. Introduction

With the growing global demand for energy, the development and utilization of renewable energy sources are receiving increasing attention. As a clean and renewable energy source, wind power has become a key component of the energy strategy of many countries. In the context of achieving peak carbon and carbon neutral targets, wind power has great potential for development in China [1]. Wind power is a technology that converts wind energy into electrical energy [2], providing abundant power resources for human beings. Wind farms are mainly divided into two types: offshore wind farms and onshore wind farms. In China, onshore wind farms are usually built in areas such as high mountains, hills, or grasslands, which are sparsely populated, the ecological environment remains pristine, and natural resources are abundant [3]. However, the construction of wind farms may have a certain impact on the local ecological environment, especially on the vegetation coverage and soil properties. Therefore, measures need to be taken to optimize the construction and operation of wind farms in order to reduce the negative impact on the environment and achieve sustainable development.

With the large-scale construction of wind farms, the vegetation cover and soil properties around them tend to change. Firstly, the construction and operation of wind farms may destroy the original vegetation structure and change the moisture, temperature, and nutrient status of the soil, which in turn affects the activity of soil microorganisms and their interaction with plants; secondly, the construction of wind farms also leads to a series of environmental geological problems, such as foundation settlement and soil erosion, and these changes may further affect the nature of the soil; in addition, the construction of wind farms may also lead to a series of socio-economic problems. For example, the construction and operation of wind farms may affect the local land-use pattern and agricultural production, which in turn may affect the life and economic activities of local residents. All these issues may have an impact on the sustainable development of wind farms.

Research has demonstrated that wind farms affect the green cover of the ground by excavating the ground surface during the construction process through the construction of field stations and roads, which in turn removes the surface vegetation [4–7]. For example, it was found that after wind farms were installed in some peninsulas in Turkey, in all land cover categories, the most degraded areas were found to be within the facility areas (Aksoy et al., 2023) [8]. The changes in temperature and surface heat fluxes induced by a wind farm could lead to a global redistribution of cloudiness and precipitation patterns and result in changes in ground-level microclimatic conditions sufficient to significantly alter the plant–soil carbon cycle, with consequent impacts on ground-level vegetation (Armstrong et al., 2014) [9]. The remotely sensed data of wind farms in the United States have been analyzed, and it was found that because of the infrastructure, the normalized vegetation index (NDVI) of 59% of the wind farms decreased significantly compared to non-wind farm areas, and the effect of vegetation on NDVI was significant only in wind farms (Qin et al., 2022) [10]. Wind power facilities in northern Spain were investigated, and it was found that plant communities remain stable by maintaining low-intensity land use, whereas improvements in wind power sites may cause an increase in human activities, which may affect the long-term stability of plant communities (Fagúndez et al., 2008) [11]. In the relevant research progress in China, the construction period of the Xilingol League Greitengliang wind farm was studied, and it was found that it fragmented the habitat. During the period of wind farm operation, there was basically no effect on the vegetation, and only a weak effect was produced by affecting the animal habitat and food chain relationship (Zhang et al., 2012) [12]. The vegetation characteristics inside and outside the Huitengxile wind farm were investigated and showed that the wind farm had an obvious destructive effect on the surface morphology, biodiversity, aboveground biomass, and vegetation cover of the plant community and its surrounding areas, resulting in bare ground, lower vegetation cover, and a reduction in species diversity and even causing reverse succession (Liu et al., 2017) [13]. In comparison, the impacts of wind farms on regional vegetation in Inner Mongolia were complex and variable, and the influence of these impacts was multiplied by human activities, regional climate change, and other factors (Liu et al., 2023) [14].

Soil is one of the most complex ecosystem components on Earth; it is not only used as a habitat and survival site for many organisms, but it is also a source of nutrients for plant growth. Therefore, the study of soil properties is essential for the conservation and sustainable use of natural resources. It was predicted that wind turbine-induced microclimatic gradients would have an effect on soil moisture, water table height, peat depth, carbon content, nitrogen content, and C/N ratio (Armstrong et al., 2013) [15]. One study investigated the soil surrounding the construction of the Lianzhou wind farm and found that the use of heavy machinery and mechanical operations during the construction of the wind farm, as well as during the operation period, and the subsequent heavy pressure from the wind turbines had significantly affected the soil and damaged its physical structure (Xie et al., 2021) [16]. A study on the surface soils of desert grasslands in wind farms found that after nearly 10 years of natural recovery, except for phosphorus, there was little difference in nutrients in the surface soils of different disturbance zones (Chen et al., 2019) [17]. The operation of wind farms has a significant effect on soil nutrient content, but this effect is related to the distance from the wind farm and the duration of operation. Some soil nutrient contents may increase significantly with increasing radius of radiation from the center of the wind farm, and these nutrient contents will gradually increase with the duration of operation (Zhao et al., 2018; Xie et al., 2015) [18,19].

In summary, the impact of wind farm construction on vegetation cover and soil properties is a complex issue, involving ecological environment, geological environment, and socio-economic aspects. Therefore, in-depth study and exploration of the impact of wind farm construction on vegetation cover and soil properties and its mechanism are of great significance to guarantee the sustainable development of wind farms. At the same time, understanding and analyzing the relevant influence laws are crucial to the rational construction and operation of wind farms and the ecological sustainable development of wind farm areas. They also provide a scientific basis for environmental protection during the construction and operation of wind farms and help to realize the sustainable development of the wind power industry.

Consequently, this research focuses on the Linxiang wind farm in Hunan Province, examining the spatial and temporal effects of mountain wind farm development on soil characteristics and vegetation coverage. By leveraging soil physicochemical assessments, the normalized difference vegetation index (NDVI), and data on vegetation density and land-use transitions, this study endeavors to offer insights for a scientifically informed comprehension of the ecological ramifications and environmental implications associated with the construction of mountain wind farms.

2. Materials and Methods

2.1. Experimental Design

2.1.1. Overview of the Research Area

Yaopo Mountain wind farm is located in the northern suburb of Linxiang City, Hunan Province, belonging to the remnants of Mufu Mountain. The area has four distinct seasons, mild climate, and abundant rainfall [20]. The annual average wind speed is about 6.13 m/s. The effective ridge length within the wind farm site is 8.28 km, with a total area of about 11.36 km^2, and the altitude ranges from 200 m to 580 m [21]. The wind farm is equipped with large-impeller-diameter low-wind-speed-type permanent magnet generator (PMG) sets with an annual equivalent utilization time of up to 1900 h. The construction of the wind farm began in December 2013, with a total investment of USD 450 million and a total installed capacity of 50,000 kW with 25 units. There were 6 types of soils such as wattenschlick soil, tidal sand soil, red soil, yellow soil, mountain yellow-brown soil, and mountain meadow soil. The region's vegetation was diverse in type and had significant regional characteristics. There are large areas of Moso bamboo forests and *Pinus massoniana* forests below 800 m altitude, and above 800 m altitude there are secondary forests of *Castanopsis tibetana* Hance. There are *Symplocos paniculata* (Thunb.) Miq. forests and *Merremia hederacea* (Burm. F.) Hall. F. forests above 1200 m altitude [20]. On the whole, the original vegetation types in the study area are rich and the coverage is high.

2.1.2. Soil Collection and Sample Determination

Through data review and field investigation, and according to the mountain trend and wind turbine distribution in this study area, the wind farm in this area can be divided into three types according to altitude such as high altitude (400–500 m), medium altitude (300–400 m), and low altitude (200–300 m).

The soil samples were selected from the underlying surface area of the nine groups of wind turbines (see Figure 1), and the control samples (CK) were selected at a distance of 200 m from the area without construction interference. The altitudes corresponding to the soil samples from each wind turbine were shown in Table 1.

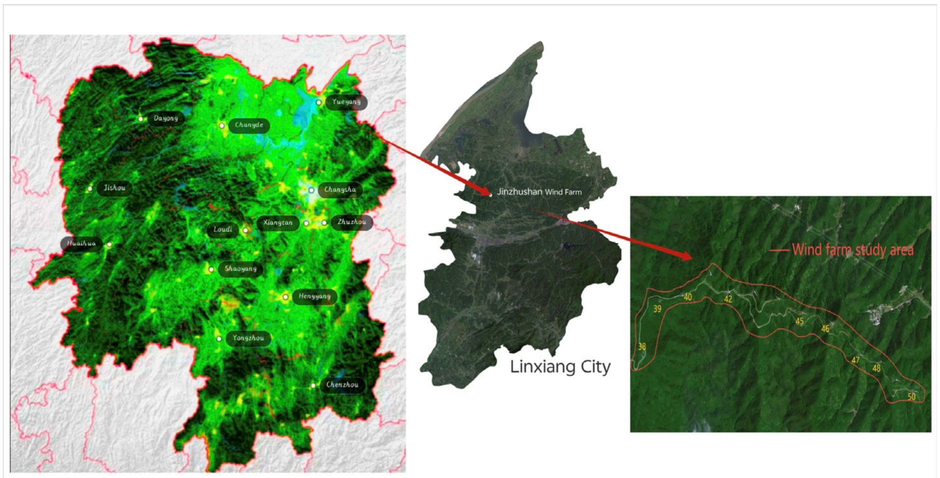

Figure 1. Distribution locations of wind turbines.

Table 1. The altitudes corresponding to the soil samples from each wind turbine.

The Number of Wind Turbine	High Altitude			Middle Altitude			Low Altitude		
	E38	**E39**	**E40**	**E42**	**E45**	**E46**	**E47**	**E48**	**E50**
Altitudes	446	442	425	356	334	332	244	224	260

Before sampling, the dead branches, stone particles, and pumice on the surface of the soil layer in the collection area were removed. The soil samples were collected by five-point method, and the soil depth was 0~20 cm. The soil samples were taken back to the laboratory and dried naturally, and 30 g soil samples were screened from each soil sample by 80-mesh earth sieve for later use.

The pH was determined by potentiometric method (soil/water ratio was 1:3); the soil organic carbon (SOC) content was determined by potassium dichromate oxidation spectrophotometry [22]. Soil total nitrogen (TN) and available phosphorus (TP) contents were determined by Kjeldahl method [23] and sodium bicarbonate extraction-molybdenum antimony spectrophotometry [24]. Rapidly available potassium was determined by ammonium acetate solution extraction method [25]. Each test was repeated three times. In addition, when collecting soil, the profile was dug near the sampling point, and the soil samples were collected by the ring knife method. The soil samples were placed in the oven at 105 °C in the laboratory to determine the soil bulk density and moisture content. In Table 2, the main instruments and equipment that were used in this experiment are listed.

Table 2. Instruments and equipment.

Instrument	Specification/Model	Manufacturer
Analytical balance	ME104E/02	Mettler-Toledo Instruments (Shanghai) Co., Ltd., Shanghai, China
Electric blast-drying oven	DHG-9070A	Tianjin Kenuoyi Electronic Technology Co., Ltd., Tianjin, China
Multi-head magnetic stirring apparatus	HJ-4A	Bonsee Technology (Shanghai) Co., Ltd., Shanghai, China
Ultraviolet–visible spectrophotometer	UV-1800	Shanghai Meipuda Instrument Co., Ltd., Shanghai, China
pH meter	BPH-7100	BELL Analytical Instruments (Dalian) Co., Ltd., Dalian, China
High-speed centrifuge	TG16-WS	Hunan Xiangyi Instrument Development Co., Ltd., Changsha, China
COD Elimination Instrument	DRB200	Hach Co., Ltd., Shanghai, China
Atomic absorption spectrometer	iCE™3300 AAS	Thermo Fisher Scientific Inc., Shanghai, China

2.1.3. Image Data Source

The satellite images of Landsat 8 OLI_TIRS (C2 L2) satellite digital products were selected [26,27]. The data were derived from the geographic data space cloud with a resolution of 30 m $\times$ 30 m. Compared with winter, the atmosphere in summer is more stable and the cloud layer is thinner, which has less influence on the study of vegetation coverage. Therefore, this study screened remote sensing images with cloud cover < 5% and date distribution in the three stages before, during, and after the construction and operation of wind farms. Finally, the data of September 2013, September 2016, and September 2023 were selected as the objects. Because the satellite images were derived from Landsat 8 OLI_TIRS (C2 L2) satellite digital product, the images have undergone atmospheric correction and radiation correction. Therefore, only these remote sensing images were cut and preprocessed to obtain the remote sensing image data of the study area with software ENVI 5.6.

2.1.4. Data Processing

The soil's physical and chemical data were statistically analyzed and plotted using Origin. One-way analysis of variance (one-way ANOVA) was used for significance analysis, and LSD was used for multiple comparisons to test the differences in the soil's physical and chemical properties among the components. The NDVI and the FVC were analyzed by ENVI5.6 software [28–30]. The calculation formulae were, respectively, as follows:

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

Note: NIR—Near-infrared band reflectance; R—Reflectance in the infrared band.

$$\text{FVC} = \frac{(\text{NDVI} - \text{NDVI}_{\text{soil}})}{(\text{NDVI}_{\text{Veg}} - \text{NDVI}_{\text{soil}})} \tag{2}$$

Note: $\text{NDVI}_{\text{soil}}$—Bare soil contribution information; NDVI_{Veg}—Green vegetation contribution information.

3. Results

3.1. Effects of Wind Farms on Soil Physicochemical Properties

3.1.1. Analysis of Soil Organic Carbon Content

Soil organic carbon (SOC) content serves as a pivotal measure for assessing soil health. It not only reflects the soil's fertility but also its capacity for ecological sustainability. In this study, the organic carbon content of soil samples from different altitude sampling sites of wind farms was detected as shown in Table 3.

Table 3. The soil properties of samples from different sites.

Site	Sample Corresponding to the Wind Turbine	Organic Carbon Content (%)	Total Nitrogen Content ($mg \cdot kg^{-1}$)	Available Phosphorus Content ($mg \cdot kg^{-1}$)	Rapidly Available Potassium Content ($mg \cdot kg^{-1}$)	pH
High altitude	CK1	1.50	448.36	38.80	179.56	6.87
	E38	1.06	364.54	36.25	118.24	6.63
	E39	1.02	350.31	33.70	145.80	6.78
	E40	1.00	308.52	26.56	120.35	6.66
Middle altitude	CK2	0.99	280.41	22.99	89.50	5.99
	E42	0.89	238.30	15.86	65.76	5.30
	E45	0.84	210.23	12.29	69.56	5.83
	E46	0.83	168.15	13.31	68.26	5.56
Low altitude	CK3	0.74	154.05	13.82	64.27	5.25
	E47	0.47	84.63	9.23	38.06	4.95
	E48	0.63	112.12	9.74	56.58	5.15
	E50	0.58	98.25	8.72	27.33	4.30

As shown in Figure 2, one-way ANOVA of the results of the organic carbon testing in the study area proved that altitude and wind farm construction have a significant effect ($p < 0.001$) on the organic carbon content in the soil.

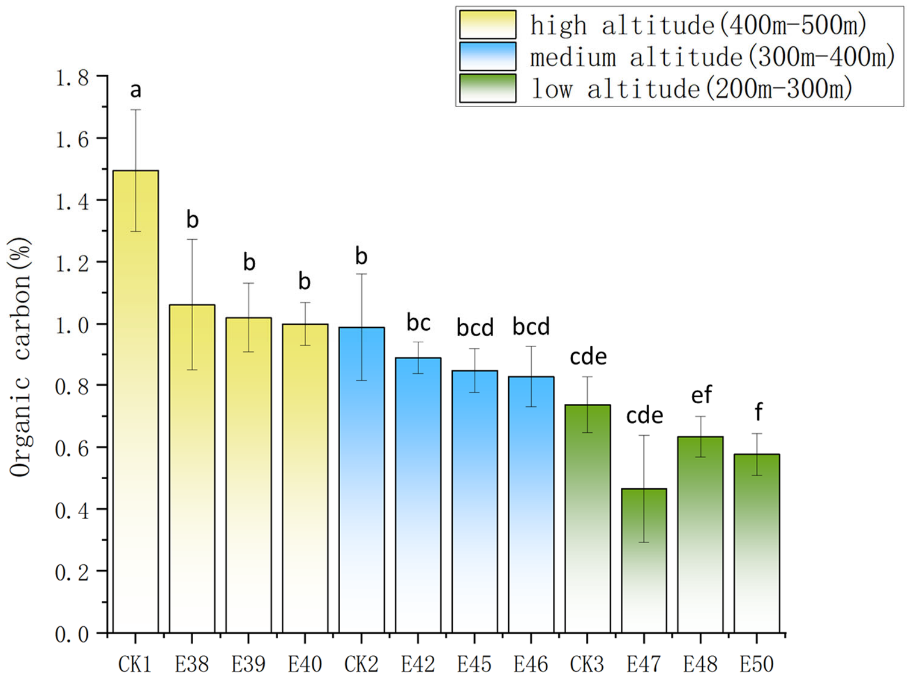

Figure 2. Influence of wind turbine construction on the soil organic carbon content. CK1, CK2, and CK3 were the blank controls of the areas without wind turbine construction in the three altitude areas. Different letters indicate significant differences between components ($p < 0.05$), and the same letters indicate insignificant differences between components ($p > 0.05$).

Due to the operation of the wind turbine, the airflow is disturbed and localized warming occurs. Localized warming increases soil microbial activity, which in turn promotes organic matter decomposition at the sampling sites at the base of the turbine. There is a positive relationship between organic matter and organic carbon content (som = soc × 1.724), as shown in Figure 2, which showed that the organic carbon content of soil samples from wind turbine site locations was significantly lower than that of soil samples from sites where no wind farms were constructed in all three altitude studies, except for the mid-altitude soil sample group.

With the increase in altitude and the decrease in temperature, this low temperature environment slows down the metabolism of plants and reduces the activity of soil bacteria. Therefore, the decomposition process of organic matter becomes relatively slow, resulting in an increase in organic matter content in the soil. At the same time, the soil ventilation conditions in high-altitude areas are worse than those in low-altitude areas, and there will be hypoxia. This environmental condition is not conducive to microbial decomposition of organic matter, which will promote the accumulation of organic matter in high-altitude soil. As shown in Figure 2, with the decrease in altitude, the content of organic carbon decreased.

3.1.2. Analysis of Soil Total Nitrogen Content

Total nitrogen content contains various forms of nitrogen in the soil, including inorganic forms of nitrogen and organic forms of nitrogen, and its content can be detected to better understand and evaluate the soil quality and soil fertility. In this study, the total nitrogen content of soil samples from wind farms at different altitude sampling locations is shown in Table 2.

As shown in Figure 3, one-way ANOVA of the total nitrogen test results in the study area showed $p < 0.001$ and significant difference between the control group and the CK group, which proved that the altitude and the construction of the wind farm have a significant effect on the total nitrogen content in the soil.

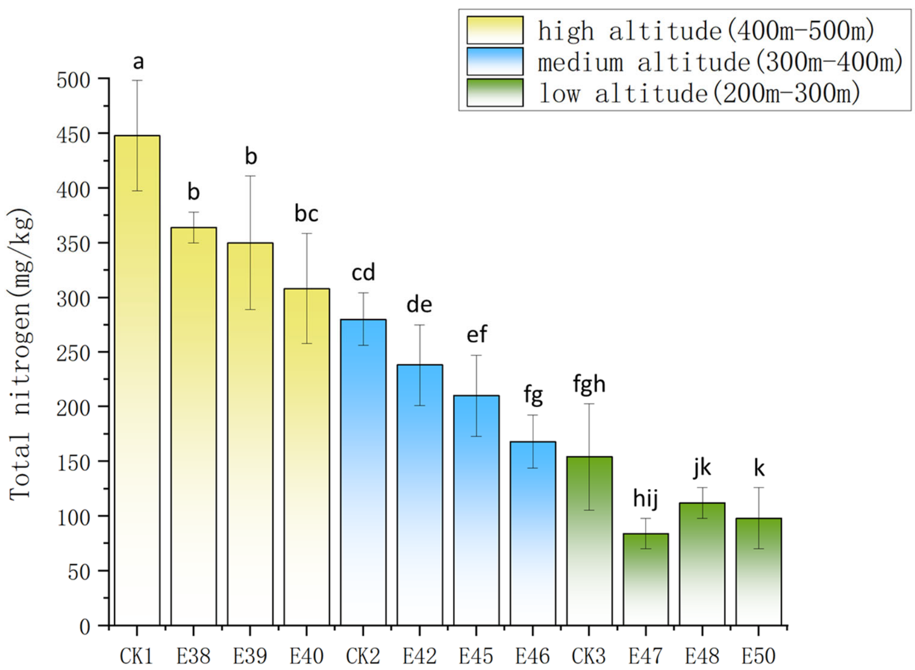

Figure 3. Influence of wind turbine construction on the soil total nitrogen content. CK1, CK2, and CK3 were the blank controls of the areas without wind turbine construction in the three altitude areas. Different letters indicate significant differences between components ($p < 0.05$), and the same letters indicate insignificant differences between components ($p > 0.05$).

The soil water storage capacity in high-altitude areas was stronger than that in low-altitude areas, and the microbial activity ability was weak, which was conducive to the accumulation of soil organic matter, so the total nitrogen content increases with the increase in altitude. As shown in this study, the change trend of total nitrogen content was high altitude > middle altitude > low altitude.

The pre-design and survey phase of wind farms and the later construction and operation phase may result in compaction of the underlying soil and a slow rate of positive community succession. Therefore, the soil nutrient loss was severe close to the center of the wind turbine base, while soil nutrient loss was less severe the further away from the turbine.

3.1.3. Analysis of Soil Available Phosphorus Content

Phosphorus is an indispensable nutrient element in the process of plant growth, and its content is an important index to evaluate and analyze soil phosphorus supply capacity. The detection of soil available phosphorus can comprehensively evaluate the soil phosphorus nutritional status and bioavailability, thus contributing to ecological sustainable development. In this study, the contents of the available phosphorus in the soil were tested and analyzed. The contents of the available phosphorus in soil samples at different altitude sampling points of the wind farms are shown in Table 2.

As shown in Figure 4, one-way ANOVA of the results of effective phosphorus testing in the study area proved that elevation and wind farm construction have a significant effect on effective phosphorus content in the soil ($p < 0.001$).

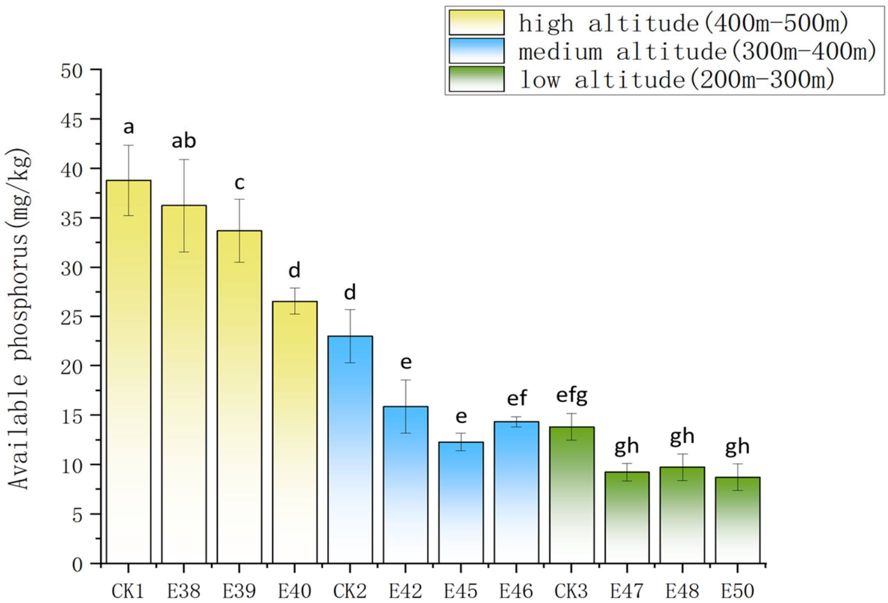

Figure 4. Influence of wind turbine construction on the soil available phosphorus content. CK1, CK2, and CK3 were the blank controls of the areas without wind turbine construction in the three altitude areas. Different letters indicate significant differences between components ($p < 0.05$), and the same letters indicate insignificant differences between components ($p > 0.05$).

In low-altitude areas, vegetation species are more abundant, soil microbial activity is strong, and the consumption of phosphorus in the soil is large. With the increase in altitude, low temperature will weaken the activity of vegetation and microorganisms and reduce the loss of phosphorus in the soil. Therefore, as shown in this study, as the altitude decreases, the available phosphorus content gradually decreases.

From Figure 4, it can be seen that at the same altitude, the available phosphorus content detected from the area without a wind farm (CK) to the base area of the wind farm showed a downward trend, but the change range was not large. It may be that phosphorus was a sedimentary element and its form in the soil was relatively stable. Although it was affected by the wind farm's local microclimate, temperature, humidity, and the underlying soil of the base, it was less affected than the rapidly available potassium. Therefore, at the same altitude, the content of available phosphorus in the area without a wind farm was gradually higher than that in the base area of the wind farm, but the change was smaller.

3.1.4. Analysis of Soil Rapidly Available Potassium Content

Most of the rapidly available potassium is exchangeable potassium, and water-soluble potassium accounts for a very small part. It is an element that is easily absorbed and utilized by crops in the soil, and it is also one of the important indicators of soil properties. The determination of its content can reflect the potassium supply capacity of the soil. In this study, the content of rapidly available potassium in soil was tested and analyzed. The rapidly available potassium content of soil samples at different altitude sampling points in the wind farm is shown in Table 2. Because there are many forms of potassium in the soil, and each form is in a dynamic equilibrium, as shown in Table 2, the content of rapidly available potassium in the measured soil samples was far more than the content of available phosphorus.

As shown in Figure 5, one-way ANOVA of the results of the rapidly available potassium tests in the study area proved that altitude and wind farm construction have a significant effect on the rapidly available potassium content in the soil ($p < 0.001$).

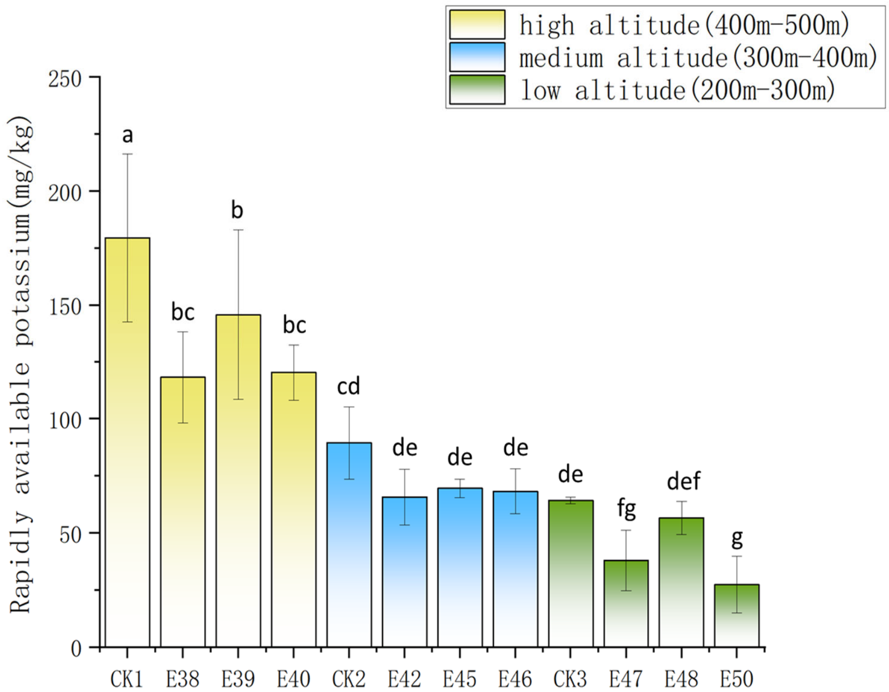

Figure 5. Influence of wind turbine construction on the soil rapidly available potassium content. CK1, CK2, and CK3 were the blank controls of the areas without wind turbine construction in the three altitude areas. Different letters indicate significant differences between components ($p < 0.05$), and the same letters indicate insignificant differences between components ($p > 0.05$).

As shown in Figure 5, the content of rapidly available potassium increased with the increase in altitude. At the same altitude, the content of rapidly available potassium in the area without a wind farm (control) was significantly higher than that in the area of the wind turbine base. Compared with the area without wind farm construction, the rapidly available potassium was more affected near the wind turbine base. The loss of rapidly available potassium was large, and the recovery was slow.

3.1.5. pH Analysis of Soil

Soil pH is one of the main factors affecting soil nutrient availability. In this study, the content of soil pH was tested and analyzed. The pH values of soil samples at different altitude sampling points of a wind farm are shown in Table 2. The soil in Hunan Province was acidic soil. As shown in Table 2, the soil in the study area was acidic as a whole, and the pH values of each sampling point were in the normal range.

One-way ANOVA was performed on the results of the pH tests in the study area, with $p < 0.001$, but the variability within the same group was not significant, and it proved that elevation had a significant effect on pH in the soil, whereas wind turbine construction had a lesser effect on it.

As shown in Figure 6, as the sampling altitude decreases, the pH value decreases. At the same altitude, the change in pH value was small between the soil samples without wind farm construction (control) and the soil samples on the base area of the wind farm.

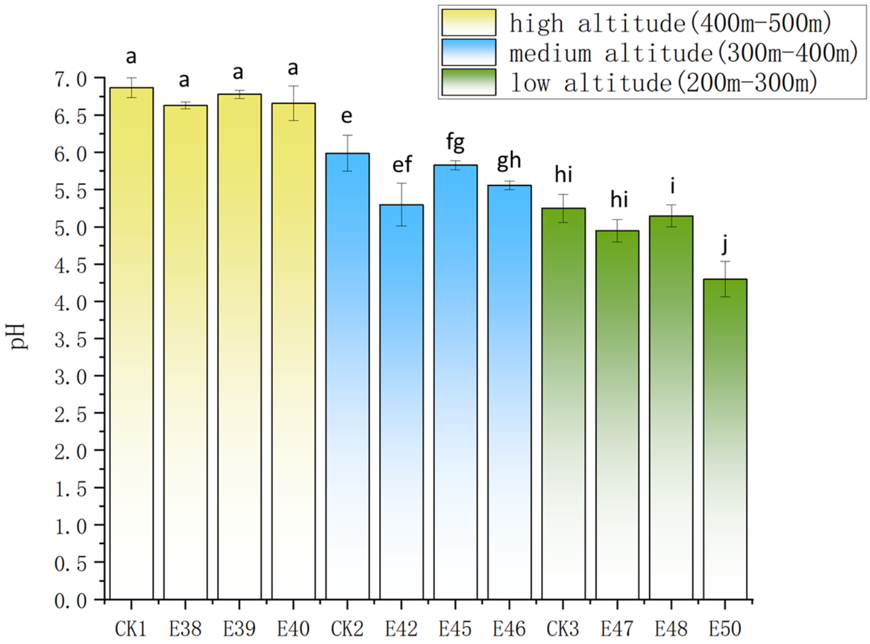

Figure 6. Influence of wind turbine construction on the soil pH. CK1, CK2, and CK3 were the blank controls of the areas without wind turbine construction in the three altitude areas. Different letters indicate significant differences between components ($p < 0.05$), and the same letters indicate insignificant differences between components ($p > 0.05$).

In the same climate zone, the mountain soil in this study area was in the high slope terrain, and the leaching effect was strong. Because the humus in the soil at high altitude decomposes slowly, the compounds formed by potassium were accumulated in the soil after decomposition, so the pH of the soil at high altitude was higher than that at low altitude.

3.2. Effects of Wind Farms on Vegetation Coverage

3.2.1. Analysis of Normalized Difference Vegetation Index (NDVI)

The remote sensing image of the wind farm area is shown in Figure 7.

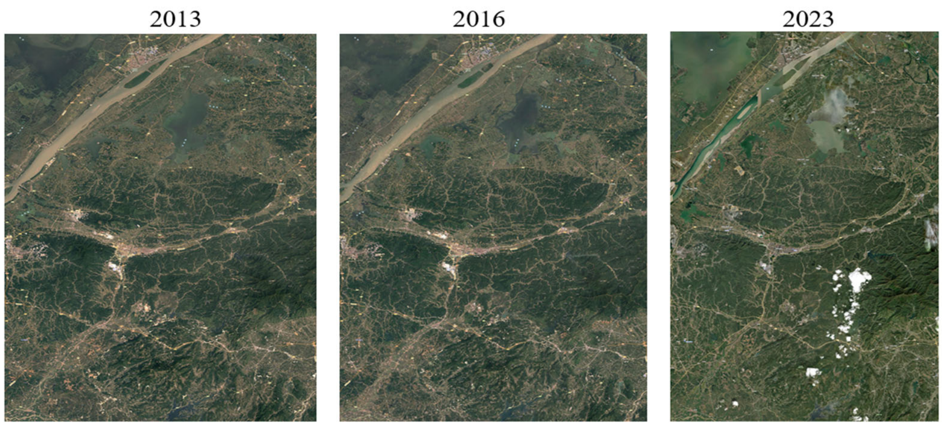

Figure 7. The remote sensing image of wind farm area.

The normalized difference vegetation index (NDVI) distribution map of the three periods of the wind farm was calculated by ENVI5.6 software (Figure 8). The average NDVI of the study area in 2013 was 0.742, the maximum value was 0.995, and the minimum value was −0.033. In 2016, the average NDVI of the study area was 0.770, the maximum value was 0.981, and the minimum value was −0.032. In 2023, the average NDVI of the study area was 0.758, the maximum value was 0.982, and the minimum value was 0.012. In 2016, the mean value of NDVI was the highest. In 2023, the maximum value of NDVI increased slightly, the minimum value decreased slightly, and the three values decreased in 2013. The values of the three periods were in the range of (−1, 1), and there was no need to eliminate outliers, which can be directly analyzed in the next step.

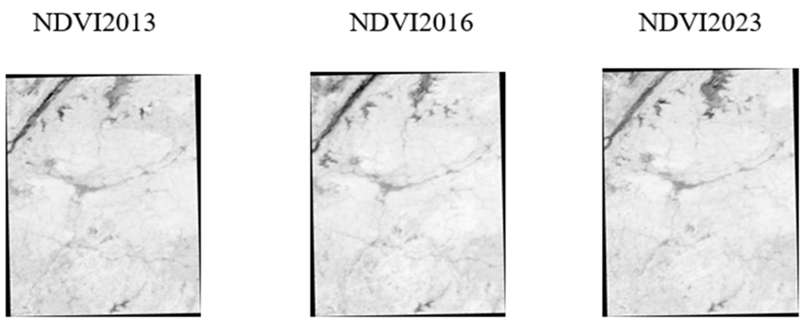

Figure 8. The NDVI images of the wind farm at three periods.

3.2.2. Analysis of Fractional Vegetation Coverage Index (FVC)

According to the calculation formula, the NDVI value with the cumulative number of pixels reaching 5% was selected as $NDVI_{soil}$, and the NDVI value with the cumulative number of pixels reaching 95% was $NDVI_{veg}$. The $NDVI_{soil}$ value and $NDVI_{veg}$ value of the study area in 2023 were 0.214 and 0.716, respectively, 0.294 and 0.727, respectively, in 2016, and 0.386 and 0.681, respectively, in 2013. Substituted into the calculation formula of FVC, calculated by ENVI5.6, and processed by ArcGIS10.7, the distribution map of the fractional vegetation coverage index in the three periods is shown in Figure 9.

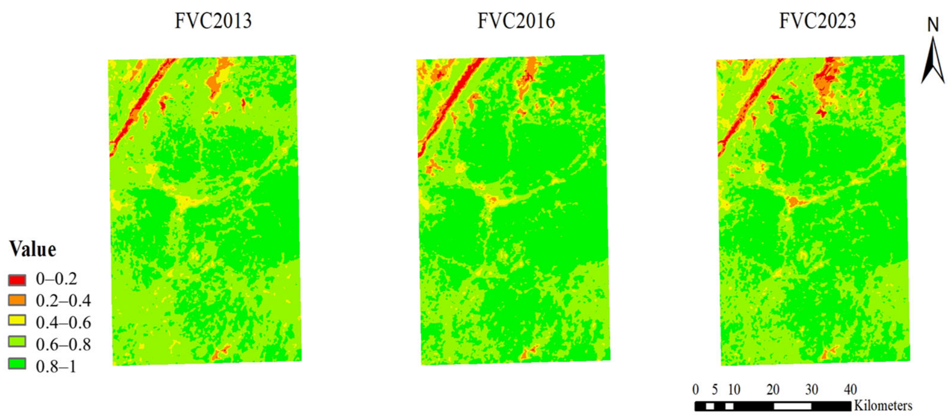

Figure 9. The FVC images of the wind farm at three periods.

According to the data analysis, the change trend of the FVC was basically consistent with the change trend of normalized difference vegetation index. The average vegetation coverage in 2013 was 0.754, the average vegetation coverage in 2016 was 0.791, and the average vegetation coverage in 2023 was 0.769, showing a trend of increasing first and then decreasing, but the overall coverage was high.

Data on the area of each land category in the study area for the three periods showed that changes in the area of each land category during the three periods were generally consistent with changes in vegetation cover (Table 4). The area of forested land increased from 2013 to 2016 and decreased from 2016 to 2023, but the overall range of change was smaller.

Table 4. The area of each category in three periods of wind farm.

Land Type	2013 Area (km^{-2})	2016 Area (km^{-2})	2023 Area (km^{-2})
Cultivated land	548.4429	551.34	549.4473
Woodland	933.4566	937.3869	935.109
Grassland	24.2658	24.4899	24.2937
Water area	157.6188	158.1642	157.6251
Construction land	54.6381	46.971	51.9219
Unutilized land	1.6128	1.683	1.638
Sum	1720.035	1720.035	1720.035

The main reason for this situation is that 2013 is the initial construction period of this study area. The development and excavation of construction roads, fan platforms, and the construction of solid waste placement sites and living sites affect and destroy the original vegetation, thus reducing vegetation coverage. With the passage of time, the vegetation gradually recovers, so the vegetation coverage in the middle of the operation in 2016 was higher than that in the early stage of construction in 2013. By 2023, it has experienced 10 years of vegetation restoration. However, due to the long recovery period of soil and vegetation, it is easy to be affected by many factors such as changes in air humidity, temperature, surface evaporation, and soil fertility caused by the construction and development of surrounding land and the operation of wind turbines during this period. As a result, the vegetation coverage in the later stage of operation in 2023 was higher than that in 2013, but there was a downward trend compared with 2016.

4. Discussion

The influence of soil properties and soil fertility changes: This study found that land excavation and compaction during wind farm construction significantly altered soil physicochemical properties, such as porosity and soil and water conservation capacity; the findings are consistent with those of Li G et al. (2016) [31] and Chai Y et al. (2014) [32]. In addition, the localized microclimate generated by wind farm operations influenced soil temperature and water evaporation, echoing the findings of Li Z. (2015) [33], and the studies of Armstrong A (2013) [15] and Xie JW (2021) [16], which also pointed out the effects of wind turbines on soil microclimate and physical structure, are in agreement with the soil physicochemical properties observed in this study.

The contents of organic carbon, total nitrogen, and quick-acting potassium contained in the soil samples from the area where the wind farm was constructed in this study were significantly lower than that of the soil samples from the area where no turbines were constructed, which is consistent with the findings of Yang D. et al. (2008) [34] regarding the accelerated decomposition of organic matter and nutrient loss due to construction activities. Since phosphorus exists in a more stable form than the other indicators, it is a little less affected, i.e., it has the same trend as organic carbon, total nitrogen, and quick-acting potassium but with smaller changes, which is consistent with the results of Xie Y. et al. (2015) [19] in their study of the effects of the Huitengxile wind farm on soil properties. And the changes in soil pH were not significant, indicating that the wind farm construction had limited effects on soil pH. Therefore, after the construction of mountain wind farms, the planting and replanting of plants suitable for native growth should be selected in conjunction with regulations related to soil and water conservation to ameliorate the unfavorable impacts on soil properties caused by disturbance.

Effect of altitude: this study also found that altitude had a significant effect on soil properties, with organic carbon, total nitrogen, effective phosphorus, and quick-acting potassium content of the soil increasing with increasing altitude, which may be related to factors such as temperature, biomass, evaporation, and leaching.

Dynamic change in vegetation cover: This study analyzed the vegetation cover of wind farms at different construction stages and found that the vegetation cover decreased at the beginning of wind farm construction and then gradually recovered, which is consistent with the findings of Zhang S. (2012) [12] and Liu J. (2017) [13]; the results of remote sensing analyses by Qin Y (2022) [10] also support the results of the findings on the impacts of wind farms on the vegetation cover in this study. However, this study further pointed out that vegetation cover may face a declining trend in the later stages of wind farm operation, emphasizing the importance of long-term monitoring and ecological restoration measures.

5. Conclusions

Evaluating the impact of wind farm construction on soil can help identify and quantify changes in soil quality, including soil structure, fertility, and biological activity, so that appropriate measures can be taken to protect the soil [16]. Secondly, evaluations can guide the adoption of appropriate measures, such as vegetation restoration and soil protection, which can help to protect and maintain the local ecological balance and reduce soil erosion. Thirdly, the health of agricultural soils directly affects the yield and quality of crops, and evaluating the potential impact of wind farms on soils can help ensure the sustainability of agricultural production [35]. In summary, the evaluation of the impact of wind farm construction on soil is of great significance for environmental protection, agricultural development, socio-economics, and policy making.

In this study, soil physicochemical properties and vegetation cover were systematically analyzed at Linxiang wind farm in Hunan Province to assess the impacts of wind farm construction on soil and ecological environment. It was found that wind farm construction had significant negative impacts on soil physicochemical properties and vegetation cover. Specifically, wind farm construction led to a decrease in soil organic carbon, total nitrogen, effective phosphorus, and quick-acting potassium content, changes that indicate a reduction in soil fertility. In addition, the construction and operation of wind farms altered the local microclimate of the soil, affecting soil temperature and water evapotranspiration, which in turn affected the physicochemical properties of the soil. Although wind farm construction had a small effect on soil pH, overall soil fertility decreased. Vegetation cover decreased in the early stages of wind farm construction due to construction activities but recovered over time and even reached high levels in mid-operation; however, it may have decreased in the later stages of operation due to a number of factors. In summary, the construction of wind farms had a certain impact on vegetation coverage and soil properties. It was necessary to take reasonable measures to protect and repair the ecological environment in order to achieve sustainable development of the wind power industry. Future research should consider the changes in biomass and biological species and increase the research of soil properties in the time dimension to improve the comprehensiveness and accuracy of the research. Meanwhile, the differences in the impacts of wind farm construction on soil and vegetation in different regions need to be further explored, and targeted ecological protection and restoration strategies need to be developed.

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