sustainability

MDPI

Article

Spatial Differentiation and Influencing Factors of Available Potassium in Cultivated Soil in Mountainous Areas of Northwestern Hubei Province, China

Zhengxiang Wu [1,2,3,4], Yong Zhou [2,*] and Lei Xu [3,4]

[1] Key Laboratory of Natural Disaster and Remote Sensing of Henan Province, Nanyang Normal University, Nanyang 473061, China; 20131138@nynu.edu.cn
[2] Hubei Provincial Key Laboratory of Geographical Process Analysis and Simulation, Central China Normal University, Wuhan 430079, China
[3] Rural Revitalization Institute, Nanyang Normal University, Nanyang 473061, China; hedaxl@163.com
[4] Nanyang Development Strategy Institute, Nanyang Normal University, Nanyang 473061, China
* Correspondence: yzhou@mail.ccnu.edu.cn

Abstract: This research was conducted based on 701 soil sampling points in cultivated land (0–20 cm) in Shiyan, a mountainous area in northwest Hubei Province, China. The methods of classical statistics, geostatistics, and geodetector were used to explore the spatial differentiation characteristics and influencing factors of soil available potassium (AK) in cultivated land in Shiyan. The results showed that the soil AK content in the study area ranged from 17.00 to 350.00 mg/kg, with an average value of 118.95 mg/kg and a coefficient of variation of 54.06%, exhibiting moderate variability. The spatial structure was well fitted by a spherical model; the block gold effect was 0.027, indicating strong spatial autocorrelation; and spatial variation was mainly caused by structural factors. The spatial differentiation characteristics of the soil AK content are obvious; overall, there was a spatial distribution pattern of high in the northeast and low in the southwest. The factor detection results show that soil pH plays a dominant role in the spatial variation in soil AK in the study area, followed by parent material and annual average temperature. The interaction detection results show that each environmental factor exhibits non-linear or dual factor enhancement between factors, with soil pH slope ranking first in explanatory power. The explanatory power of the interaction between soil pH, parent materials, annual average temperature, and other factors dominates. In the process of the fine management of soil AK in cultivated land in the study area, when considering the influence of dominant factors, the impact of the interaction of various factors on the spatial variation in soil AK should also be taken into account. This study could provide a theoretical reference for improving the soil and farmland improvement, improving farmland quality in this area.

Keywords: northwest mountainous area of Hubei Province; soil available potassium; spatial differentiation; geostatistics; geodetector

check for updates

Citation: Wu, Z.; Zhou, Y.; Xu, L. Spatial Differentiation and Influencing Factors of Available Potassium in Cultivated Soil in Mountainous Areas of Northwestern Hubei Province, China. *Sustainability* **2024**, *16*, 7311. https://doi.org/10.3390/su16177311

Academic Editor: Maria De Nobili

Received: 7 June 2024
Revised: 22 August 2024
Accepted: 24 August 2024
Published: 26 August 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Potassium is one of the three essential nutrients for plant growth and development and is known as the quality element and stress resistance element for plants [1]. In recent years, with the continuous growth in China's grain production and the intensity of cultivated land use, crops have taken away a large amount of potassium [1]. In addition, due to irrational land use by farmers and failure to apply potassium fertilizer, the problem of potassium deficiency in farmland in China has become increasingly serious [2]. The lack of potassium in cultivated soil not only affects the sustainable use of cultivated land resources but also directly affects the yield and quality of crops. In the long run, it will further affect the sustainable development of regional agriculture. As the form of potassium that can be directly absorbed by plants, soil available potassium (AK) is an important indicator of

soil potassium supply capacity [3] and an indispensable nutrient element that participates in plant biochemical processes throughout the whole life cycle [2]. Its supply and crop nutrient demand in space are not coordinated, which has been one of the key factors limiting the efficient use of fertilizer [4]. Therefore, it is of great significance to explore the spatial differentiation characteristics and influencing factors of regional soil AK to aid the scientific formulation of fertilization programs, the protection of ecological security, regional planting planning, the sustainable use of soil, improvements in cultivated land quality, and national food security [5–7].

With the development of precision agriculture and soil testing formula technology, research on the heterogeneity of soil AK is also deepening. Many researchers have used a combination of geostatistics and GIS technology to reveal the spatial variability of soil AK and its spatiotemporal variability characteristics [8] from the perspectives of terrain [9], land use [10–12], watershed [13], scale [14], and spatial distribution prediction [15], and have achieved rich results. The research shows that the spatial heterogeneity of soil AK is closely related to regional natural factors (terrain, climate, soil parent materials) and human factors, which provides a scientific basis for the precise management of the content of soil AK in the region. From the relevant literature, at present, it appears that researchers mostly use correlation analysis, classical regression models, boosted regression tree methods, analysis of variance, canonical redundancy analysis, and other traditional methods to explore the factors affecting the spatial distribution pattern of soil AK, mainly based on the degree of influence of a single factor [16,17]. There is still limited research on how the interaction of factors affects the AK distribution in cultivated land. Geodetectors serve as powerful tools for detecting potential spatial correlations between variables [18]. Originally used for studying endemic diseases and their related geographical impact factors [19], in recent years they have been applied in environmental [20], societal [21], and economic research [22] and have achieved good research results. Geodetectors could overcome the shortcomings of traditional methods and further comprehensively reveal the explanatory power of influencing factors on the spatial differentiation of soil nutrients. Therefore, this paper uses the geostatistics method, combined with a geographical detector model, to analyze the spatial differentiation characteristics and mechanism of soil AK more comprehensively and objectively. Our research also expands the practical application field of geographical detectors.

The study area is a typical mountainous agricultural region in China, with a relatively low quality of cultivated land and a small per capita cultivated land area. With construction, agricultural structure adjustment, and ecological conversion, the trend of cultivated land reduction is difficult to reverse. Due to the excessive cultivation of land resources, the environment has been damaged: water and soil losses have been serious, and the quality of cultivated land has changed greatly, which has seriously affected food production. This study considers Shiyan, a mountainous area in northwestern Hubei Province, as the research area. Through field investigation, data collection, and sampling analysis by the research team, and on the basis of 3S technology, combined with geostatistics and geographical detectors, the spatial variation in AK in the cultivated land of Shiyan and its influencing factors were studied. The findings of this research can provide a theoretical reference not only for soil improvement in cultivated land but also for improving the quality of cultivated land and promoting agricultural production in the research area.

2. Research Methods and Data Sources

2.1. Overview of the Study Area

Shiyan is located in the northwest mountainous area of the Hubei Province, 109°29′–111°16′ E and 31°30′–33°16′ N, with a total area of about 23,680 km^2. The city is high in the north and south and low in the middle, inclined from southwest to northeast, with an altitude of 83–2571 m. The study area belongs to the north subtropical semi-humid climate, with an annual precipitation of about 870 mm and a mean annual temperature of 15.4 °C. The soil parent materials in the area are mainly river and lake alluvial deposits,

red sandstone alluvium, quartzite weathering products, argillaceous weathering products, carbonate weathering products, and Quaternary old alluvium. The various soil parent materials staggered. The main soil types are yellow-brown soil and paddy soil. The main crops are corn, wheat, and rice.

2.2. Data Source and Processing

2.2.1. Sampling Point Data

The data were from the sampling results of cultivated land quality evaluation in every county of Shiyan (urban area not included) in 2017, and the sampling points were arranged based on the principles of representativeness and uniformity. We used GPS to locate and collect 0–20 cm cultivated land samples. Each soil sample was mixed with a "plum blossom"- or "S"-shaped procedure according to the size of the plot. Each soil sample was taken away in 1 kg bags for analysis [23]. A total of 701 samples were taken (Figure 1), and we recorded surface environmental information such as the cropping system, land use mode, topsoil depth, etc. of the sampled fields in detail. In the later stages, there were more than 40 items in total, including the supplementary soil type and soil parent material information of the relevant sample points of the second soil survey soil map. After the soil sample was air-dried, sieved, and mixed, the pH value of the soil sample was determined by a 2.5:1 water and soil ratio extraction using the pH meter method. The soil organic matter was determined using the oil bath heating potassium dichromate oxidation volumetric method, and the content of AK was determined using the ammonium acetate extraction and flame photometric method.

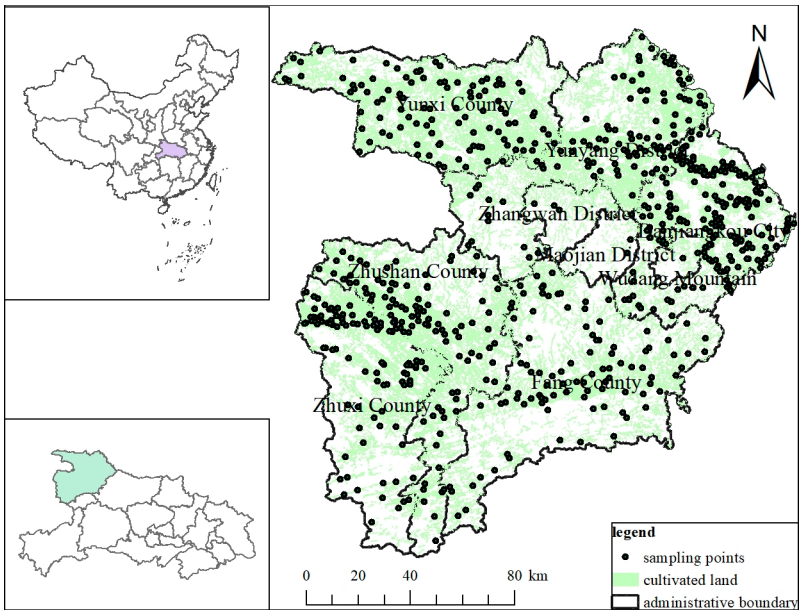


Figure 1. Geographical location of study area and distribution of sampling sites.

2.2.2. Impact Factor Data

Based on the existing relevant results [24,25], we selected the natural factors (terrain, climate, soil) and human factors that are most closely related to the spatial variability in AK in cultivated soil on this scale. The selected factors were as follows: elevation (X1), slope (X2), mean annual temperature (X3), annual precipitation (X4), soil parent materials (X5), soil type (X6), soil pH (X7), cropping system (X8), and topsoil depth (X9). Among them, the temperature and precipitation data were from the China Meteorological Science Data Sharing Service Network; the DEM data came from the geospatial data cloud, at a resolution of 30 m; and ArcGIS 10.7 software was used to extract the altitude and slope data.

2.2.3. Geodetector

The geodetector model is composed of four sub-models—factor detector, interaction detector, risk detector, and ecological detector—and is a powerful tool for detecting the potential spatial correlation between variables [18]. It was initially used to study endemic diseases and their related geographical impact factors [19]; in recent years, it has also been used to study the driving factors of the spatial variability of soil nutrients [26]. In this paper, a geographical detector was used to quantitatively study the influence of different factors on the spatial distribution of soil AK in the study area. The interaction detector was used to explore the impact of the interaction of different influencing factors on the spatial differentiation of soil AK. The specific calculation method is detailed in [26].

2.3. Data Preprocessing

SPSS24.0 was used for descriptive statistical analysis and one-way ANOVA. Semi-variance analysis and theoretical model fitting were carried out using GS+9.0. The sample distribution map and ordinary Kriging interpolation were completed in ArcGIS 10.7. According to the requirements of geodetectors for input variables, the data of soil type, soil parent materials, and cropping system were classified according to the category. The data of elevation, slope, temperature, precipitation, soil pH, and topsoil depth were discretized and divided into five categories according to the natural breakpoint method.

3. Results

3.1. Statistical Characteristics of Soil AK

According to the classification standard of the second soil survey [27], the soil AK was classified in this study. See Table 1 for details. The soil AK at I-VI levels in the study area was 9.99%, 16.55%, 28.10%, 34.09%, 9.84%, and 1.43%, respectively. The III and IV levels accounted for 62.20% of the total. The variation range of soil AK was 17.00–350.00 mg/kg, with an average value of 118.95 mg/kg, which is moderate and can basically meet the growth needs of local corn, wheat, rice, and other crops. However, considering the environmental background of soil and water loss in the study area, it is necessary to pay attention to soil potassium conservation. The coefficient of variation was 54.06%, representing moderate variation. The skewness was 1.08, and the kurtosis was 1.10 (Table 2), which is close to a normal distribution after logarithmic conversion, meeting the requirements of geostatistical analysis.

Table 1. Classification standard for soil AK and frequency distribution of each class.

Rating	Range (mg/kg)	Sampling Number	Proportion (%)
I (very rich)	350.00–200.00	70	9.99
II (rich)	150.00–200.00	116	16.55
III (moderate)	100.00–150.00	197	28.10
IV (low)	50.00–100.00	239	34.09
V (very low)	30.00–50.00	69	9.84
VI (extremely low)	15.00–30.00	10	1.43
AK average value	118.95		

Table 2. Statistical characteristic values of soil AK.

Sample Points	Minimum (mg/kg)	Maximum (mg/kg)	Mean (mg/kg)	SD (mg/kg)	C.V. (%)	Skewness	Kurtosis
701	17.00	350.00	118.95	64.30	54.06	1.08	1.10

3.2. Spatial Variation in Soil AK

Fitting the semi-variance function model with high accuracy is the key to spatial variability analysis. We used GS$^+$9.0 software to fit the semi-variance function of soil AK in

the study area (Table 3). According to the principle of R^2 maximum, RSS minimum, and giving priority to RSS [28,29], we selected the spherical model as the best fitting model. The nugget coefficient was 0.027, which is far less than 0.25, indicating that the soil AK has a strong spatial correlation, which is mainly the result of natural factors and less affected by human activities. It shows that there is a strong environmental correlation between the soil potassium supply and the background environment in the study area, which is similar to the previous research results [26]. Therefore, we can take measures to improve the fertility of soil potassium in accordance with local conditions.

Table 3. Theoretical model and parameters of semi-variance function for soil AK.

Model	Nugget	Sill	Nugget Coefficient	Range (m)	R^2	RSS
Spherical	0.0081	0.2952	0.027	7500	0.549	2.821×10^{-3}
Exponential	0.0262	0.2944	0.089	8400	0.499	3.123×10^{-3}
Gaussian	0.0458	0.2946	0.156	6409	0.546	2.825×10^{-3}
Linear	0.2908	0.2908	0.000	102,158	0.000	2.82×10^{-3}

3.3. Spatial Distribution Characteristics of Soil AK

The spatial distribution of soil AK was interpolated using ordinary Kriging (Figure 2). Figure 2 shows that the largest distribution area of AK was between 50 and 150 mg/kg, which is mainly in the moderate and low levels, in line with the general statistical results. High-value areas were concentrated in the northeast, with a small number in the southeast. They mainly included Zhangwan District, Maojian District, the north of Yunyang District, the north of Danjiangkou City, the middle of Yunxi County, and the southeast of Fang County; low-value areas were mainly distributed in the western region and Danjiangkou City, including the central part of Yunxi County, Zhushan County, Zhuxi County, the eastern part of Fang County, and the Danjiangkou Reservoir in Danjiangkou City. The overall spatial distribution pattern was high in the northeast and low in the southwest.

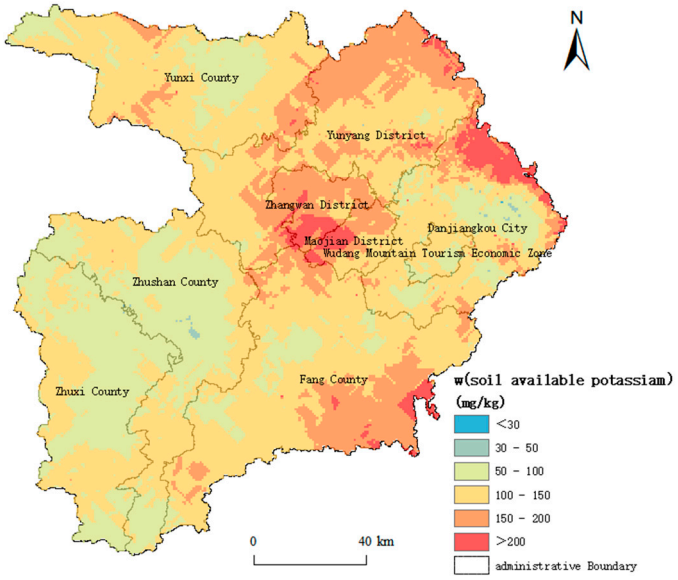


Figure 2. Spatial distributions of soil AK in the study area.

3.4. Geodetector Analysis

From the factor detection analysis (Table 4), it can be seen that the spatial variation in soil AK of each influencing factor was significantly affected, but the degree of influence was different. The descending order of the q value of soil AK of each influencing factor was pH value (0.160), soil parent material (0.107), mean annual temperature (0.101), soil

type (0.094), precipitation (0.084), slope (0.056), altitude (0.037), topsoil depth (0.035), and cropping system (0.032). Among them, soil pH was the dominant factor, and the soil parent material and mean annual temperature also had strong explanatory power, with q values larger than 0.1. Comparing the explanatory power of structural factors and random factors, we see that the q value of structural factors such as terrain factors, climate factors, and soil factors was also much larger than the q value of random factors such as cropping systems and topsoil depth. This shows that structural factors are the main driving force affecting the spatial variability of AK in cultivated soil in Shiyan, which is consistent with previous analysis.

Table 4. Q value of influencing factors.

Impact Factor	Terrain		Climate		Soil Factors			Human Factor	
	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9
Q	0.0372 ***	0.0556 ***	0.1007 ***	0.0837 ***	0.1065 ***	0.0949 ***	0.1599 ***	0.0321 **	0.0348 ***

Note: *** and ** represent significance at the 1% and 5% levels, respectively.

Nine factors were detected with interaction detectors (Table 5). The results show that, among the 36 pairs of interaction factors, there was non-linear enhancement for 27 pairs and double factor enhancement for 9 pairs (without an independent or weakening situation). The interaction of various environmental factors was greater than that of individual factors. It can be seen that the synergy of environmental factors enhances the interpretation of the spatial variability of soil AK, but the intensity of interaction between different factors is different. Among them, the interactive factors with greater explanatory power were soil pH ∩ slope (0.2366), soil pH ∩ cropping system (0.2291), soil parent material ∩ cropping system (0.2200), soil parent material ∩ temperature (0.2145), soil pH ∩ slope temperature (0.2124), soil parent material ∩ precipitation (0.2083), and soil parent material ∩ slope (0.2016), which all represent non-linear enhancement; and pH ∩ soil parent material (0.2318) and soil pH ∩ soil type (0.2099), which show double factor enhancement. Table 5 shows that the explanatory power of the interaction between soil pH, soil parent material, mean annual temperature, and other factors still dominates.

Table 5. Q values of dominant interactions between two covariates.

$X_i \cap X_j$	q (X_i)	q (X_j)	q ($X_i \cap X_j$)	q (X_i) + q (X_j)	Interaction Type	$X_i \cap X_j$	q (X_i)	q (X_j)	q ($X_i \cap X_j$)	q (X_i) + q (X_j)	Interaction Type
$X_1 \cap X_2$	0.0372	0.0556	0.1146	0.0928	non-linear	$X_3 \cap X_7$	0.1007	0.0556	0.2124	0.1563	non-linear
$X_1 \cap X_3$	0.0372	0.1007	0.1366	0.1379	two-factor	$X_3 \cap X_8$	0.1007	0.0556	0.1597	0.1563	non-linear
$X_1 \cap X_4$	0.0372	0.0837	0.1215	0.1209	non-linear	$X_3 \cap X_9$	0.1007	0.0556	0.1516	0.1563	two-facor
$X_1 \cap X_5$	0.0372	0.1065	0.1518	0.1437	non-linear	$X_4 \cap X_5$	0.0837	0.1065	0.2083	0.1902	non-linear
$X_1 \cap X_6$	0.0372	0.0944	0.1354	0.1316	non-linear	$X_4 \cap X_6$	0.0837	0.0944	0.1795	0.1781	non-linear
$X_1 \cap X_7$	0.0372	0.1599	0.1895	0.1971	two-factor	$X_4 \cap X_7$	0.0837	0.1599	0.1874	0.2436	two-factor
$X_1 \cap X_8$	0.0372	0.0321	0.1084	0.0693	non-linear	$X_4 \cap X_8$	0.0837	0.0321	0.1568	0.1158	non-linear
$X_2 \cap X_9$	0.0372	0.0348	0.1049	0.0720	non-linear	$X_4 \cap X_9$	0.0837	0.0348	0.1364	0.1185	non-linear
$X_2 \cap X_3$	0.0556	0.1007	0.1633	0.1563	non-linear	$X_5 \cap X_6$	0.1065	0.0944	0.1809	0.2009	two-factor
$X_2 \cap X_4$	0.0556	0.0837	0.1588	0.1393	non-linear	$X_5 \cap X_7$	0.1065	0.1599	0.2318	0.2664	two-factor
$X_2 \cap X_5$	0.0556	0.1065	0.2016	0.1621	non-linear	$X_5 \cap X_8$	0.1065	0.0321	0.2200	0.1386	non-linear
$X_2 \cap X_6$	0.0556	0.0944	0.1792	0.1500	non-linear	$X_5 \cap X_9$	0.1065	0.0348	0.1767	0.1413	non-linear
$X_2 \cap X_7$	0.0556	0.1599	0.2366	0.2155	non-linear	$X_6 \cap X_7$	0.0944	0.1599	0.2099	0.2543	two-factor
$X_2 \cap X_8$	0.0556	0.0321	0.1261	0.0877	non-linear	$X_6 \cap X_8$	0.0944	0.0321	0.1773	0.1265	non-linear
$X_5 \cap X_9$	0.0556	0.0348	0.1115	0.0904	non-linear	$X_6 \cap X_9$	0.0944	0.0348	0.1571	0.1292	non-linear
$X_3 \cap X_4$	0.1007	0.0837	0.1595	0.1844	two-factor	$X_7 \cap X_8$	0.1599	0.0321	0.2291	0.1920	non-linear
$X_3 \cap X_5$	0.1007	0.1065	0.2145	0.2072	non-linear	$X_7 \cap X_9$	0.1599	0.0348	0.1970	0.1947	non-linear
$X_3 \cap X_6$	0.1007	0.0944	0.1857	0.1951	two-factor	$X_8 \cap X_9$	0.0321	0.0348	0.1095	0.0669	non-linear

The results show that soil pH plays a dominant role in the spatial differentiation of soil AK in the study area. In this paper, the ordinary Kriging method was used to interpolate and plot soil pH and soil AK. According to the grading standards of China's second soil

survey, the soil pH in the study area was divided into zones, and a spatial distribution map of soil AK under different pH zones was obtained (Figure 3).

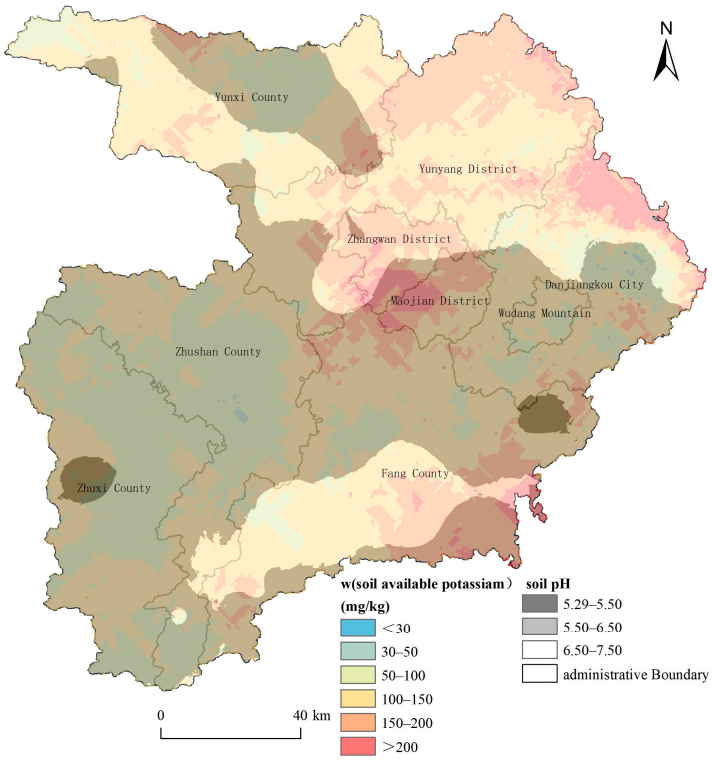


Figure 3. Spatial distribution map of soil AK under the background of soil pH zoning.

4. Discussion

To further explore the effects of various environmental variables on the differentiation of AK in cultivated soil in the study area, a correlation analysis was conducted between soil AK and environmental variables (Table 6). We found that soil AK was negatively correlated with altitude, field slope, annual precipitation, and plow layer thickness and positively correlated with annual average temperature and soil pH.

Table 6. Correlation analysis of soil AK and environmental variables.

Environmental Variable	Altitude	Slope	Precipitation	Temperature	Topsoil Depth	Soil pH
Pearson correlation coefficient	−0.138 **	−0.146 **	−0.268 **	0.287 **	−0.080 *	0.324 **
p-value	0.000	0.000	0.000	0.000	0.035	0.000

Note: ** At the 0.01 level (two-tailed), the correlation is significant. * At the 0.05 level (double tailed), the correlation is significant.

4.1. Influence of Terrain Factors on Spatial Variation in AK

4.1.1. Altitude

Terrain factors are closely related to water transport and material transport in soil. At different elevations, the local climate is different, which directly affects the redistribution of soil parent materials, thus causing variation in the distribution of soil AK [30]. According to the spatial distribution of the sampling points, the samples were divided into seven elevation groups with a group spacing of 100 m, and the average values of soil w (available potassium) in different elevation groups were calculated (Table 7). The analysis of variance showed that there was a significant difference in the content of soil AK among different elevation zones in the study area ($F = 5.295$, $p < 0.05$). The average range of soil AK content

in the seven altitude groups was 94.02–139.25 mg/kg, which shows a trend of increasing with altitude, and the variation coefficient of different altitude ranges from 46.42% to 56.19%, with a small difference. This may be because, the higher the altitude, the higher the weathering degree of the rock, the steeper the terrain, the more serious the erosion of the soil, the stronger the leaching effect, the more easily the soil AK is lost, the poorer the water and fertility conservation, the fewer available nutrients remain in the soil, the more soil elements are washed away with the rain, and the more readily AK accumulates with surface materials in low-lying areas. This is similar to previous research results [31], while Chen et al. [32] took three towns in Qinba Mountain, China, as the research area and found that the content of soil AK was significantly positively correlated with altitude, contrary to the research results in this paper. The differing results may have been affected by the research scale, and the specific reasons need to be further analyzed.

Table 7. Statistical characteristics of soil AK at different elevations.

Altitude	Sample Number	Range	Average Value	Standard Deviation	Coefficient of Variation (%)
≤200	73	25–299	139.25	66.94	48.07
200–300	182	17–350	133.06	74.76	56.19
300–400	121	26–321	117.53	66.11	56.25
400–500	98	27.58–302.00	106.67	49.52	46.42
500–600	104	20.79–327.00	108.43	56.82	52.40
600–700	53	31.46–255.00	94.02	47.26	50.27
>700	70	39.00–303.00	115.31	56.75	49.22

4.1.2. Slope

The terrain of the study area is complex, and the slope changes significantly, which leads to more intense soil potassium migration and soil erosion [33]. Table 8 shows that the maximum content of soil AK appeared in the slope range of <2°, and was far greater than the content of soil AK in other slope ranges. The content of soil AK in the slope range of 2–6° and 15–25° was relatively close. On the whole, it showed a gradual decrease with the increase in slope. This supports the research results of Jin et al. [34]. The analysis of variance showed that there was a very significant difference in the content of AK in the soil of different slopes in the study area ($F = 5.605$, $p < 0.05$). Due to the heavy rainfall in the study area, the soil erosion intensity in the area with a large slope was strong, the amount of surface soil loss was greater, the nutrient diversion loss was more serious, and the content of AK was low, so the distribution of the content of AK in the soil was low on steep slopes and high on gentle slopes. Among them, the content of AK in 2–6° soil was obviously low, which may be greatly affected by the background environment. In the process of farmland utilization, appropriate measures should be taken to fertilize the soil.

Table 8. Statistical characteristics of soil AK at different slopes.

Slope	Sample Number	Range	Average Value	Standard Deviation	Coefficient of Variation (%)
≤2°	7	119–340.00	182.57	78.21	42.84
2–6°	66	33–274.00	108.87	52.85	48.54
6–15°	357	20.79–350.00	127.39	69.95	54.91
15–25°	261	17.00–350.00	108.26	55.75	51.50
>25°	10	50.65–252.00	118.77	62.87	52.93

4.2. Effect of Climate Factors on Spatial Variability of AK

4.2.1. Mean Annual Temperature

The distribution, transformation, and effective utilization of soil potassium are closely related to climate factors [35]. According to the distribution of sampling points, the samples were divided into five temperature groups at intervals of 0.5 °C, and the relationship between the average value of soil AK content in different temperature groups and the

temperature was calculated. The variance showed that the difference was extremely significant ($F = 18.252$, $p < 0.05$). The average content of soil AK in the five elevation groups was 88.72–143.19 mg/kg (Table 9). With the increase in mean annual temperature, the content of soil AK showed a gradual increasing trend, which is roughly similar to the research results of Wu et al. [35]. Jin et al. [36] showed that the soil potassium supply capacity increases with an increase in temperature. The climate conditions in the study area are complex, and the average temperature decreases by 0.55 °C every 100 m above sea level. The high temperature and high humidity in the lower-altitude area are conducive to the release of slow-acting potassium in the soil, which increases the content of AK in the soil. In addition, paddy fields are mainly distributed at lower altitudes, with the water-drought cycle as the main influencing factor. Under alternating dry and wet conditions, due to the increase in crystallinity of amorphous aluminum silicate or iron aluminum oxide and the decrease in hydration, the potassium fixation in soil as AK will decrease [37], which will also lead to a higher content of AK in the soil at higher temperatures.

Table 9. Statistical characteristics of soil AK at different mean annual temperatures.

Range	Sample Number	Range	Average Value	Standard Deviation	Coefficient of Variation (%)
≤15.00	110	27.58–221.34	88.72	39.51	44.53%
15.00–15.50	159	20.79–327.00	105.09	51.37	48.88%
15.50–16.00	135	32.00–281.00	112.76	50.80	45.05%
16.00–16.50	138	36.00–350.00	143.19	71.61	50.01%
>16.50	159	17.00–340.00	137.96	78.91	57.20%

4.2.2. Annual Precipitation

The soil AK content varied according to the different rainfall levels in the study area (Table 10). When the precipitation for the year was ≤750 mm, the content of soil AK was the highest, and the difference between the content of soil AK in the range of ≤750 mm and 750–850 mm was small. When the precipitation was 950–1050 mm, the content of soil AK was the lowest. On the whole, it showed a gradual decrease with an increase in rainfall. When the annual precipitation was 850–950 mm, the coefficient of variation was the largest. The results of variance showed that there was a very significant difference in the content of soil AK in areas with different rainfall levels in the study area ($F = 27.729$, $p < 0.05$). The study area is a mountainous area where there are many concentrated rainstorms. The initial scouring characteristics of rainstorms are obvious. The leaching of potassium from agricultural soil is strong, and the leaching amount is greater in areas with more rainstorms, resulting in a low level of soil AK in areas with high annual precipitation. The research conclusion of this paper is consistent with the conclusion about the relationship between the spatial variation in soil AK and the annual precipitation in Danzhou, an agricultural area of Hainan, as explored by He et al. [38]. However, our findings are contrary to the conclusions of Wu et al. [35], who took Jiangjun, a village in the middle reaches of the Jinghe River, as their research area and found that the higher the annual precipitation, the higher the content of AK in the soil; this may be due to differences in research scale.

Table 10. Statistical characteristics of soil AK with different annual precipitation levels.

Range	Sample Number	Range	Average Value	Standard Deviation	Coefficient of Variation (%)
≤750	25	62.00–321.00	165.24	52.27	31.63
750–850	129	32.00–350.00	161.13	76.05	47.20
850–950	205	17.00–340.00	114.59	65.77	57.40
950–1050	218	20.79–281.00	97.16	45.01	46.33
>1050	124	36.48–303.00	111.28	54.73	49.18

4.3. Effect of Soil Factors on Spatial Variability of AK

4.3.1. Soil Parent Material

The soil parent material is one of the important factors affecting the content of soil AK [39]. The content of AK in cultivated land formed by different soil parent materials in the study area varied ($F = 11.806$, $p < 0.05$), as shown in Table 11. The coefficient of variation in soil AK developed by the eight parent materials was 33.13–60.34% (moderate). Various kinds of rock weathering materials are the main soil parent materials in the study area. The rock weathering materials are rich in potassium, which makes the potassium content in the soil formed by its development high. The soil AK content was also high, at more than 100 mg/kg. According to the classification criteria in the second soil survey, they were all above the moderate level, especially weathered red sandstone, at the rich level, and weathered carbonate close to the rich level. The argillaceous rock-developed soil had the widest distribution area of all rock weathering materials. The developed soil was sandy and easy to wash with water. The soil nutrient loss was serious, and the content of AK in the soil was low. The composition of the alluvial (sedimentary) deposits of the river and lake is complex, with more sand and less mud, and the texture is lighter. The soil is mainly distributed in the plain area on both sides of the river and so is strongly affected by water leaching, and the soil AK content was low. Quaternary old alluvial deposits were mainly distributed in the second-order land of 200–500 m low mountains and hills. The soil layer was deep and the nutrient content low. The difference between soil AK content and river and lake alluvial deposits was not significant. Chen et al. [32] reached similar conclusions in their research on the central mountainous areas of Qinba, China.

Table 11. Statistical characteristics of soil AK in different soil parent materials.

Parent Material Type	Sample Number	Range	Average Value	Standard Deviation	Coefficient of Variation (%)
Purple rock weathering	9	28–201	105.63	53.855	50.98
Carbonate weathering	53	43–299	146.30	70.641	48.29
Quartzite weathering	43	39–213	118.16	46.370	39.24
Argillaceous weathering	400	17–350	107.31	59.698	55.63
Crystalline rock weathering	16	34–321	134.54	81.185	60.34
Red sandstone weathering	60	36–350	177.74	77.456	43.58
River and lake flushing (sinking) deposits	40	32–199	117.33	38.877	33.13
Quaternary old alluvium	80	21–302	114.60	59.431	51.86

4.3.2. Soil Type

Relevant research shows that there are significant differences between different soil types, mainly due to the different types of bedrock and soil parent materials that form various soil types [38]. There are various soil types in the study area, and the difference in AK content in each soil type reached a significant level ($F = 9.352$, $p < 0.05$). Table 12 shows that the content of AK in purple soil, yellow cinnamon soil, brown soil, and lime soil was at a rich level, the fluvo-aquic soil was close to the rich level, and the content of AK in yellow brown soil and paddy soil was low and moderate, respectively. Among them, the content of AK in brown soil varied greatly, and the coefficient of variation was 70.82%. The variation degree of AK content in moisture soil was the smallest, with a coefficient of variation of only 17.69%. It may be that moister soil is concentrated on the floodplain and is greatly affected by water availability. The texture is sandy and the structure is loose. The AK is easily redistributed by water, and the content is moderate. Purple soil mainly develops in calcareous or neutral purple sandstone, with a loose parent material, easy disintegration, and rich mineral nutrients. The yellow cinnamon soil mainly develops from Quaternary old alluvium, which is deeply affected by tillage. The mature soil layer is thick, the texture is heavy, the tillage management is fine, and the soil fertility is strong. The distribution area of brown soil is small, mainly developed by carbonate weathering and argillaceous rock

weathering, and the texture is sticky; lime soil develops in carbonate rock weathering. Due to weak weathering, the utilization time is not long, and the AK level is relatively high. The yellow-brown soil is zonal soil in the study area, which is mostly acidic and neutral. The soil texture is mainly medium, light, or heavy, with a deep soil layer and rich nutrient content. Paddy soil is mostly distributed in valleys such as intermountain basins and the Hanjiang River and its tributaries. After long-term water cultivation and maturation, it accumulates rich soil nutrients, and the soil texture is heavy, and the absorption performance is good. Among all soil types, yellow-brown soil and paddy soil are the most widely distributed. After long-term tillage, the soil AK content should be rich. However, the content of AK in yellow brown soil and paddy soil was the lowest in this study, which may be due to good tillage conditions, the high multiple cropping index, the large consumption of agricultural production, and an insufficient supply of potassium fertilizer. Wang et al. [12] conducted research on cultivated land in the southwestern mountainous areas of Sichuan and found that the AK content in yellow brown soil was higher, while the AK content in tidal soil and paddy soil was lower, which differed significantly from the results of this study. Perhaps due to significant differences in soil formation environments in different regions, the AK content of the same soil type varies greatly in different areas, and the specific reasons need to be further analyzed in the future.

Table 12. Descriptive statistical characteristics of soil AK in different soil types.

Soil Types	Sample Number	Range	Average Value	Standard Deviation	Coefficient of Variation (%)
Tide soil	5	102–164	144.28	25.527	17.69
Yellow cinnamon soil	28	50–281	154.86	61.144	39.48
Yellow-brown soil	280	17–350	109.90	61.197	55.68
Limestone	31	43–299	150.42	68.583	45.59
Paddy soil	319	28–350	113.79	60.324	53.01
Purple soil	34	36–345	175.91	76.964	43.75
Brown soil	4	56–303	153.50	108.709	70.82

4.3.3. Soil pH

The soil pH in the study area was 4.49–8.44. According to the classification standard of soil pH in the second soil census, the content of AK in soil was grouped. It was found that there was a significant difference in soil AK between different pH groups ($F = 25.813$, $p < 0.05$) and a trend of increasing with an increase in pH (Table 13). The availability of potassium in soil is mainly affected by adsorption and fixation, on which pH has a strong influence. Under the condition of low soil pH, the K^+ saturation of soil colloid will decrease due to the decrease in actual CEC of soil and the competition between H_3O^+ and Al^{3+} with K^+. With a decrease in K^+ saturation, the effectiveness of K^+ also decreases [30]. With an increase in pH, the constant potential surface colloid produces new charges, which leads to an increase in K^+ adsorption capacity. At the same time, K^+ is more likely to replace Ca^{2+} in acidic to neutral environments, so that the amount of potassium migration decreases and the fixed amount increases [31]. Among them, the 4.5–5.5 group was larger than the 5.5–6.5 group of soil AK content. Abnormally, the coefficient of variation was 59.35%, larger than the coefficient of variation in other groups, presumably due to the cropping system, fertilization, and other human factors. In conclusion, the soil pH value can be appropriately increased in production to meet the needs of potassium fertilizer for the normal growth of crops.

Table 13. Descriptive statistical characteristics of soil AK in different soil pH.

Soil pH	Sample Number	Range	Average Value	Standard Deviation	Coefficient of Variation (%)
≤4.5	1	83.38	83.38	0.00	0.00%
4.5–5.5	85	20.79–350.00	109.18	64.80	59.35%
5.5–6.5	326	17.00–302.00	99.04	49.80	50.28%
6.5–7.5	174	32.00–350.00	133.94	67.54	50.43%
7.5–8.5	115	32.00–345.00	160.26	70.85	44.21%

4.4. Effects of Human Activities on Spatial Variability of AK

4.4.1. Cropping System

Due to the wide area and complex terrain of Shiyan, there are significant differences in the local climate, so the cropping system is complex (Table 14). There were significant differences in the content of AK in soil under different cropping systems ($F = 5.190$, $p < 0.05$). Table 14 shows that the content of AK in the maize-rice rotation system was the highest (152.91 mg/kg), at the rich level according to the classification standard in China's second soil census. Vegetable planting (142.84 mg/kg) was close to the rich level. The potato-corn intercropping system had the lowest content (94.38 mg/kg), followed by fruit tea planting (98.03 mg/kg), at the low level. The other cropping systems were between 100 and 150 mg/kg, which is moderate. The coefficient of variation in soil AK content under various systems ranged from 40.92% to 62.01%, showing moderate variation. Among them, the content of AK was the highest under the maize-rice rotation system, which may be due to the low altitude of the cultivated land; soil nutrients were enriched in the higher-altitude area. In addition, due to the better farming conditions, more fertilization also increased the AK content in the soil. The high content of AK in vegetable planting soil may be due to the good economic benefits of vegetable planting, farmers' emphasis on fertilizer input, and fine management of vegetable fields. Maize and potato are potassium-loving plants. According to field investigations, the yield per hectare of maize is 6000–7500 kg, and the yield per hectare of potatoes is 22,500–30,000 kg. The nutrient demand intensity of crop growth is high, and the crop takes more soil nutrients from the cultivated land, resulting in a low AK content in the soil. Tea trees and most fruit trees are potassium-loving plants, and their consumption of potassium is large. In addition, the planting area is slopy. Due to erosion caused by rainwater, soil nutrients are lost, resulting in a low soil AK content in tea fruit planting areas.

Table 14. Descriptive statistical characteristics of soil AK in different cropping systems.

Cropping System	Sample Number	Range	Average Value	Standard Deviation	Coefficient of Variation (%)
Tea fruit	79	17.00–288.00	98.03	56.70	57.83%
Vegetable	15	34.00–340.00	142.84	84.94	59.47%
Rice monoculture	55	28.92–201.00	100.81	44.60	44.24%
Rice-rape rotation	28	36.44–350.00	110.08	68.26	62.01%
Wheat-rice rotation	24	42.00–208.00	126.92	51.93	40.92%
Maize-wheat rotation	106	38.00–350.00	127.46	69.99	54.91%
Corn monoculture	87	37.00–302.00	132.84	61.01	45.92%
Maize-rice rotation	43	30.00–316.00	152.91	76.37	49.95%
Maize-potato intercropping	71	20.00–256.41	94.38	49.64	52.60%
Canola-corn rotation	193	25.00–321.00	121.67	65.03	53.45%

4.4.2. Plow Layers

The thickness of the plow layers directly affects the total amount of soil moisture infiltration, surface runoff, water evaporation, soil erosion, soil gas exchange, etc., and has an important impact on the AK content in the vertical direction of the soil. The thickness

of the plow layers in the study area ranged from 15 to 30 cm and can be divided into five groups at equal distances, with significant differences ($F = 7.825$, $p < 0.05$). Table 15 shows that the soil AK content was the highest when the cultivated layer thickness was 15–18 cm, lowest when the cultivated layer thickness was 21–24 cm, and relatively high when the plow layer thickness was 27–30 cm. Overall, the AK content first decreased and then increased with an increase in thickness. The correlation analysis (Table 6) shows that the thickness of the plow layer has a significant negative correlation with the AK content in the soil. Shi explored the spatial distribution of soil AK in typical tea gardens in Jiangsu and Zhejiang provinces of China [40], while Chen studied the spatial distribution of soil AK in the plow layers in the central Qingling and Daba mountainous areas, of China [32]. Both researchers obtained the same results: namely, there is a negative correlation between soil AK content and plow layers. This may be due to the fact that, compared with other nutrients, AK is more easily vertically diffused and fiercely contested by crop roots in deep soil layers. In addition, an increase in the thickness of plow layers causes damage to the plow bottom layer, leading to an increase in soil groundwater, which slows down the conversion of potassium availability and exacerbates the leaching and infiltration of AK [41,42]. This results in a negative correlation between soil AK content and plow layers. The soil AK content was highest when the plow layer thickness was 15–18 cm, indicating that this is beneficial for the accumulation of AK in the soil. Therefore, it is recommended that the thickness of the plow layer should be no thicker for agricultural production in this area; deep plowing should be avoided.

Table 15. Descriptive statistical characteristics of soil AK in different topsoil depths.

Topsoil Depth	Sample Number	Range	Average Value	Standard Deviation	Coefficient of Variation (%)
15–18	13	93–279	167.923	71.555	42.61
18–21	320	20–350	126.918	64.718	50.99
21–24	171	17–262	98.536	51.785	52.55
24–27	129	26–340	118.638	64.977	54.70
27–30	68	28–350	124.059	74.88	60.36

4.5. The Impact of Interaction Factors on AK Spatial Variation

In the natural environment, soil is a complex, coupled system, and the spatial distribution of AK in its internal soil is influenced by multiple factors. The purpose of the interaction detector is to test whether the interaction between each factor will increase, decrease, or be independent of the dependent variable, with the purpose of better explaining the driving mechanism. Based on the results of the effect of the interaction of influencing factors on the spatial differentiation of soil AK in the study area, we can see that the interaction of each environmental factor is greater than that of their individual effects, showing non-linear or dual factor enhancement between each environmental factor. Wang et al. [43]. applied a geodetector model to reveal the intrinsic relationship between the spatial influencing factors of soil total nitrogen in different climatic regions of Shaanxi Province, China, and found that the interactive influence of each factor was improved compared to the influence of a single factor, indicating mutual or non-linear enhancement effects. Lin et al. [44]. used a geodetector to analyze the spatial heterogeneity of pH in cultivated land in Anhui Province, China, and found that the interaction between various factors mainly exhibited non-linear enhancement and dual factor enhancement, similar to the results of this study. In future fine management of AK in cultivated land in the study area, not only the influence of dominant factors but also the interaction effect of various factors on the spatial variation in AK in cultivated land should be taken into account, thus providing a theoretical basis for soil and farmland quality improvement as well as promoting agricultural production.

5. Conclusions

The average content of AK in the plow layer of Shiyan was at a moderate level and showed moderate variation and a strong spatial autocorrelation. The spatial variation was mainly caused by structural factors. The spatial differentiation characteristics of the soil AK content are obvious: the overall spatial distribution pattern is high in the northeast and low in the southwest. The results of factor detection showed that soil pH played a dominant role in the spatial variation in soil AK in the study area. The soil parent material and mean annual temperature also had strong explanatory power, while other factors had a relatively weak explanatory power. The results of interaction detection showed that there was a non-linear enhancement or double factor enhancement between each environmental factor, and soil pH ∩ slope ranked first in terms of explanatory power. The interaction of soil pH, soil parent material, and mean annual temperature with other factors still dominated the explanatory power. In the process of the fine management of soil AK in the study area, when considering the influence of dominant factors, the influence of the interaction of various factors on the spatial variation in soil AK should also be considered.

Author Contributions: Z.W. conducted most of the experiments and wrote the manuscript. Y.Z. and L.X. revised the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Key R&D and Promotion Project of Henan Province (Soft Science Research) (232400411098), Doctoral Program of Nanyang Normal University (2022ZX042), National Social Sciences Cultivation Project of Nanyang Normal University in 2022 (2022PY018), Key Project of the Open Project of Nanyang Branch of Henan Academy of Social Sciences in 2022 (YJY202205), Key project of 2022 bidding project of Rural Revitalization Research Institute of Nanyang Normal University (2022sczx04), Key Project of the Open Project of Nanyang Branch of Henan Academy of Social Sciences in 2023 (YJY202301), 2024 Nanyang Normal University STP Project (2024STP011; 2023STP009).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to research privacy.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ismail, C. Potassium for better crop production and quality. *Plant Soil.* **2010**, *335*, 1–2.
2. Feng, X.J.; Simpson, M.J. Temperature and substrate controls on microbial phospholipid fatty acid composition during incubation of grassland soils contrasting in organic matter quality. *Soil Biol. Biochem.* **2009**, *41*, 804–812. [CrossRef]
3. Dent, D. *Soil as World Heritage*; Springer: Berlin/Heidelberg, Germany, 2014.
4. Du, H.; Wang, K.L.; Peng, W.X.; Zeng, F.P.; Song, T.Q.; Zhang, H.; Lu, S.Y. Spatial heterogeneity of soil mineral oxide components in depression between karst hills, Southwest China. *Chin. Geogr. Sci.* **2014**, *24*, 163–179. [CrossRef]
5. Wan, S.M.; Hou, J.Q.; Zhao, J.S.; Clarke, N.; Kempenaar, C.; Chen, X.L. Predicting soil organic matter, available nitrogen, available phosphorus and available potassium in a black soil using a nearby hyperspectral sensor system. *Sensors* **2024**, *24*, 2784. [CrossRef]
6. Sardans, J.; Pe·uelas, J. Potassium: Aneglected nutrient in global change. *Glob. Ecol. Biogeogr.* **2015**, *24*, 261–275. [CrossRef]
7. Zhang, S.L.; Zhang, X.Y.; Liu, X.B.; Liu, W.; Liu, Z.H. Spatial distribution of soil nutrient at depth in black soil of Northeast China:a case study of soil AK. *Nutr. Cycl. Agroecosystems* **2013**, *95*, 319–331. [CrossRef]
8. Cao, J.; Chen, Y.P.; Jiang, Y.; Mu, J.H.; Wang, H. Spatial and Temporal variation of soil available potassium and Its Influencing Factors in Shaanxi Province. *J. Soil Water Conserv.* **2021**, *35*, 296–302+311.
9. Ren, Q.W.; Wang, X.; Li, L.D.; You, H.D.; Bi, J. Vertical variation of soil physical and chemical properties at different altitudes in xiaowutai mountain. *J. Soil. Water Conserv.* **2019**, *33*, 241–247.
10. Wilkinson, S.R.; Stuedemann, J.A.; Belesky, D.P. Soil potassium distribution in grazed K-31 tall fescue pastures as affected by fertilization and endophytic fungus infection level. *Agron. J.* **1989**, *81*, 508–512. [CrossRef]
11. Mallarino, A.P.; Borges, R. Phosphorus and potassium distribution in soil following long-term deep-band fertilization in different tillage systems. *Soil Sci. Soc. Am. J.* **2006**, *70*, 702–707. [CrossRef]
12. Wang, Y.H.; Wang, C.Q.; Li, Q.Q.; Li, B.; Yu, L.Z.; Chen, Y.L.; Zhou, Y.G. Geostatistics and GIS analysis of soil available potassium in Mountainous Southwestern Sichuan. *Southwest China J. Agric. Sci.* **2016**, *29*, 651–657.

13. Zhang, Z.; Li, J.; Mamat, Z.; Ye, Q. Spatial heterogeneity of soil nutrients and salinization risk assessment of a small-scale farmland in Ebinur Basin in northwest China. *Acta Ecol. Sin.* **2017**, *37*, 819–828.
14. Dos Santos, R.O.; Franco, L.B.; Silva, S.A.; Sodré, G.A.; Menezes, A.A. Spatial variability of soil fertility and its relation with cocoa yield. *Revista Brasileira de Engenharia Agrícola e Ambiental* **2017**, *21*, 88–93. [CrossRef]
15. Wang, W.J.; Li, Z.W.; Wang, C.; Zheng, D.C.; Du, H.L. Prediction of available potassium content in cinmamon soil using hyperspectral imaging technology. *Spectrosc. Spectr. Anal.* **2019**, *39*, 1579–1585.
16. Han, Y.; Jing, Y.F.; Guo, X.; Li, Z.L.; Lin, W.L.; Chen, L.; Yi, D. Study on the factors influencing the spatial variability of soil potassium in cultivated land in Poyang Lake Plain based on boosted regression tree. *J. Plant Nutr. Fertil.* **2020**, *26*, 622–634.
17. Blanchet, G.; Libohova, Z.; Joost, S.; Rossier, N.; Schneider, A.; Jeangros, B.; Sinaj, J. Spatial variability of potassium in agricultural soils of the canton of Fribourg, Switzerland. *Geoderma* **2017**, *290*, 107–121. [CrossRef]
18. Wang, J.F.; Xu, C.D. Geodetector: Principle and prospective. *Acta Geogr. Sin.* **2017**, *72*, 116–134.
19. Wang, J.F.; Hu, Y. Environmental health risk detection with GeoDetector. *Environ. Model. Softw.* **2012**, *33*, 114–115. [CrossRef]
20. Huang, S.; Xiao, L.; Zhang, Y.; Wang, L.; Tang, L. Interactive effects of natural and anthropogenic factors on heterogenetic accumulations of heavy metals in surface soils through geodetector analysis. *Sci. Total Environ.* **2021**, *789*, 147937. [CrossRef]
21. Zhang, X.; Ruan, Y.; Xuan, W.; Bao, H.; Du, Z. Risk assessment and spatial regulation on urban ground collapse based on geo-detector: A case study of Hangzhou urban area. *Nat. Hazards* **2023**, *118*, 525–543. [CrossRef]
22. Wang, S.J.; Wang, J.Y.; Wang, Y. Effect of land prices on the spatial differentiation of housing prices: Evidence from cross-county analyses in China. *J. Geogr. Sci.* **2018**, *28*, 725–740. [CrossRef]
23. Notice of the Ministry of Agriculture on Issuing the Technical Specifications for Soil Testing and Formula Fertilization (Revised Edition in 2011). Available online: http://www.moa.gov.cn/ztzl/ctpfsf/gzdt/201109/t20110922_2293389.htm (accessed on 23 August 2024).
24. Taghizadeh-Toosi, A.; Olesen, J.E.; Kristensen, K.; Elsgaard, L.; Østergaard, H.S.; Lagdsmand, M.; Greve, M.H.; Christensen, B.T. Changes in carbon stocks of Danish agricultural mineral soils between 1986 and 2009. *Eur. J. Soil Sci.* **2014**, *65*, 730–740. [CrossRef]
25. Antwi, M.; Duker, A.A.; Fosu, M.; Abaidoo, R.C. Geospatial approach to study the spatial distribution of major soil nutrients in the Northern region of Ghana. *Cogent Geosci.* **2016**, *2*, 1201906. [CrossRef]
26. Lu, Z.Z.; Liu, G.M.; Yang, J.S.; Zhang, M.M. Spatial variability and distribution pattern of soil nutrients in Bohai coastala area. *Acta Pedol. Sin.* **2014**, *51*, 944–952.
27. Zhang, Z.Q.; Jiao, J.Y.; Chen, T.D.; Chen, Y.L.; Lin, H.; Xu, Q.; Cheng, Y.Z.; Zhao, W.T. Soil nutrient evaluation of alluvial fan in the middle and lower reaches of Lhasa River Basin. *J. Plant Nutr. Fertil.* **2022**, *28*, 2082–2096.
28. Cambardclla, C.A.; Moorman, T.B.; Novak, J.M.; Parkin, T.B.; Konopka, A.E. Field-scale variability of soil properties in central Iowa soils. *Soil. Sci. Soc. Am. J.* **1994**, *58*, 1501–1511. [CrossRef]
29. Webster, R. Quantitative spatial analysis of soil in the field. *Adv. Soil Sci.* **1985**, *3*, 1–70.
30. Kuchenbuch, R.; Claassen, N.; Jungk, A. Potassium availability in relation to soil moisture. *Plant Soil* **1986**, *95*, 233–243. [CrossRef]
31. Deng, O.P.; Zhou, X.; Huang, P.P.; Deng, L.J. Correlations between spatial variability of soil nutrients and topographic factors in the Purple Hilly Region of Sichuan. *Resour. Sci.* **2013**, *35*, 2434–2443.
32. Chen, Y.; Qi, Y.B.; Wang, Y.Y.; Zhang, L.L.; Liu, J.J. Spatial variability and factors affecting soil available potassium in the central Qinling-Daba Mountain area. *Res. Environ. Sci.* **2017**, *30*, 257–266.
33. Yang, W.D.; Wang, Z.Q.; Su, G.P.; Ding, G.W. Quantitative determination of red-soil erosion by an Eu tracer method. *Soil Tillage Res.* **2008**, *101*, 52–56. [CrossRef]
34. Jin, M.Q.; Peng, Y.Y.; Wang, P.; Feng, L.; Chen, L.Y.; Du, X.Y.; Li, Q.Q.; Wang, C.Q. Spatial Variability Characteristic and Its Influencing Factors of Tobacco Planting Soil Available N, P and K in Yanyuan County of Sichuan, China. *Soils* **2016**, *48*, 984–991.
35. Wu, L.J.; Yu, J.; Shi, J.S.; Wang, C.M.; Bi, Z.W.; Gao, J. Study on the evolution law of potassium with long time scale climate change in Jiangjun loess of the middle reaches of the jinghe river. *J. Shanghai Jiaotong Univ. Agric. Sci.* **2006**, *34*, 69–73.
36. Jin, J.Y.; Gao, G.L.; Wang, Z.L.; Zhang, N.F. Temperature effects on quantity and intensity (Q/I) relationship of potassium in selected soils. *Acta Pedol. Sin.* **1992**, *29*, 137–141.
37. Xu, X.Y.; Ma, Y.J.; Zhang, R.P. Research progress in transformation of soil potassium in relation to pottash application. *Chin. J. Soil. Sci.* **2003**, *34*, 489–492.
38. He, P.; Yang, L.P.; Xu, X.P.; Zhao, S.C.; Chen, F.; Li, S.T.; Tu, S.H.; Jin, J.Y.; Johnston, A.M. Temporal and spatial variation of soil available potassium in China (1990–2012). *Field Crops Res.* **2015**, *173*, 49–56. [CrossRef]
39. Zhang, L.E.; Shung, W.Y.; Yun, A.P.; Niu, L.A.; Hu, K.L. Spatio-temporal variability and the influencing factors of soil available potassium in 30 years in quzhou county, Hebei province. *Sci. Agric. Sin.* **2014**, *47*, 923–933.
40. Shi, L.B.; Fang, B.; Dong, L.K. Spatial distribution characteristics of available potassium in typical tea gardens in Jiangsu Province and Zhejiang Province. *Mt. Res.* **2017**, *35*, 160–169.
41. Deng, X.H.; Yang, L.L.; Zhou, M.L.; Tian, M.C.; Tian, F.; Feng, X.H.; Wu, Q.M. Distribution of available potassium contents of tobacco-growing soil and its influencing factors in karst region of Xiangxi. *Mt. Res.* **2013**, *31*, 519–526.
42. Thomas, G.W. Forms of aluminium in cation exchangers. *Trans. Int. Congr. Soil Sci.* **1960**, *2*, 364–369.

43. Wang, Q.; Chang, Q.R.; Huang, Y.; Shi, B.T.; Luo, L.L. Driving Factors and Interaction of STN Spatial Variation in Shaanxi Province Based on Geo-D. *Trans. Chin. Soc. Agric. Mach.* **2021**, *52*, 161–169.
44. Lin, Y.S.; Ma, K.; Zhou, H.; Llu, W.B.; Fang, F.M.; Zhi, J.J. Spatial variation and driving factors of soil pH in cultivated land of Anhui Province based on geomorphic unit. *Acta Sci. Circumstantiae* **2023**, *43*, 318–330.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.