STUDY ON THE MAIN FACTORS AFFECTING SOIL FERTILITY AND IMPROVEMENT PATHWAYS IN HENAN PROVINCE, CHINA

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(Received 15th Jun 2025; accepted 21st Aug 2025)

Abstract. This study is based on the strategic role of Henan Province as a major winter wheat production region in China, against the backdrop of global soil degradation leading to reduced crop yields, limited arable land in China, and a high proportion of low- and medium-yield farmland. Using data from 170 soil samples in Soil Series of China: Henan Volume as the core foundation, the study integrates climate and topographic variables to construct a factor system influencing wheat yield. This system includes soil physicochemical properties (e.g., available phosphorus, total potassium, soil organic matter), soil configuration (e.g., effective soil depth, soil configuration scores), climatic conditions (e.g., average monthly precipitation, sunshine duration), and topographic factors (e.g., elevation), aiming to identify the dominant yield-driving factors across different regions and propose targeted strategies for improvement. Data processing was conducted using SPSS Statistics 26 and Esri ArcGIS 10.8.1. Spatial interpolation methods such as ordinary kriging and radial basis functions were employed to construct a control grid with 10 km intervals (1,564 control points). Combined with the Geodetector model, the analysis focused on five cultivated zones in Henan Province: the piedmont plains of the Yanshan–Taihang Mountains, the Huang-Huai Plain, the hilly and mountainous areas of the Hubei-Henan-Anhui region, the western Henan mountainous and hilly region, and the low-lying plains of Hebei-Shandong-Henan. The results show significant regional differences in dominant factors. In the Yanshan–Taihang piedmont plains, climate (sunshine duration, accumulated temperature), topography (elevation), and soil physicochemical properties (available phosphorus, total potassium) jointly influenced yield, each with an explanatory power above 0.4. In the Huang-Huai Plain, average monthly precipitation and elevation emerged as core factors by regulating water availability. In the hilly and mountainous areas of the Hubei-Henan-Anhui region, soil configuration (e.g., restrictive layers) was the primary factor, followed by soil nutrients (e.g., available phosphorus). In the western Henan mountainous region, available phosphorus, accumulated temperature, and sunshine duration were key due to the need for matching nutrient supply with climatic conditions. In the low-lying plains of Hebei-Shandong-Henan, poor drainage and soil salinization directly constrained yields.
Keywords: *soil system, dominant factors, geodetector, region-specific improvement strategies*

Introduction

Soil fertility worldwide is currently facing numerous critical challenges. According to the Food and Agriculture Organization of the United Nations (FAO and ITPS, 2015; FAO, 2017), soil degradation driven by current agricultural practices has become a serious concern and is projected to cause a reduction of up to 25% in global food

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2306_1081910839

production by the end of this century. Since World War II, approximately one-third of the world's arable land has experienced degradation, with annual crop yields declining by as much as 1% (Oldfield et al., 2019). The drivers of soil erosion and degradation are diverse and complex. Agricultural intensification has exacerbated soil erosion, reduced soil organic matter content (Lal, 2020), and led to soil acidification and salinity shifts , while also disrupting soil microbial communities (Rillig et al., 2019). Excessive use of synthetic nitrogen fertilizers damages the balance of soil organic matter and microbial populations (Bünemann et al., 2018), and alters soil pH. When soil pH falls below 5.5, aluminum toxicity becomes a major concern, restricting plant uptake of essential nutrients.

In China, the contradiction between a large population base and limited arable land resources is particularly acute. The per capita availability of cultivated land is only 29% of the global average, and the proportion of low- and medium-yield farmland remains high (Amundson et al., 2015). This situation has become a major bottleneck restricting both balanced increases in food production and improvements in land productivity (Fageria et al., 2008). Against this backdrop, the scientific utilization of land and detailed assessment of soil fertility have emerged as effective approaches to mitigating the loss of arable land and addressing the looming food crisis. From the perspective of soil-limiting factors, the Chinese academic community generally defines low- and medium-yield farmland as land where poor soil environmental conditions or the presence of one or more limiting factors—such as poor soil structure or nutrient imbalance—hinder the full realization of soil productivity, ultimately resulting in low and unstable crop yields (Mohanty et al., 2007). Alternatively, such land can be understood as cultivated areas where suboptimal environmental conditions and insufficient application of integrated agricultural technologies lead to mismatches among various environmental factors required for healthy crop growth (Mango, et al., 2017; Kijima, et al., 2011).

In recent years, significant progress has been made in research related to soil fertility, with major focus areas including the selection of evaluation units, the establishment of assessment frameworks, and the choice of evaluation methods (Minasny et al., 2017; Padarian et al., 2020). Current assessments of soil fertility are gradually evolving toward greater quantification and standardization (Viscarra Rossel et al., 2018), enabling more accurate and objective evaluation results that better reflect the intrinsic characteristics of soil productivity (Poggio et al., 2021; Bonfante et al., 2015). As the concept of soil fertility continues to expand, there is growing consensus in the academic community that fertility is not determined by a single factor, but rather by the balance and synergy among multiple soil properties (Soussana et al., 2019; Vågen et al., 2013). However, a universally accepted definition of soil fertility is still lacking. The absence of a rigorously defined scientific concept and standardized quantitative indicators has hindered the scientific robustness and objectivity of many soil fertility evaluations.Studies exploring the relationship between soil fertility and soil configuration remain limited. Most existing research has focused on the distribution patterns of soil nutrients—particularly nitrogen and phosphorus—along soil profiles (Akhtar et al., 2018), while the spatial distribution of soil physical properties and their influence on fertility have received far less attention, highlighting the need for deeper investigation (Poeplau et al., 2015). Soil configuration, defined as the spatial arrangement and combination of diagnostic horizons within the soil profile, directly affects soil morphology and pedogenic processes. It is also closely linked to soil fertility and productive potential (Chávez et al., 2011; Hassan et al., 2021). Nevertheless, current indicators of soil quality primarily emphasize traditional physicochemical properties, with limited consideration of soil configuration. Recent

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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studies have demonstrated that soil configuration plays a crucial role in agricultural performance, strongly influencing soil tillage properties and fertilizer effectiveness (Toriyama et al., 2005; Wang et al., 2015). In addition, crop yields respond sensitively to variations in climate and topographic conditions (Cossani et al., 2018), further underscoring the importance of integrating multiple environmental factors into fertility assessments.

Henan Province is a major winter wheat production region in China, where soil fertility plays a critical role in agricultural development (Zheng et al., 2016). The efficient and sustainable utilization of soil resources is essential to advancing the wheat industry in the province. In recent years, significant progress has been made in the soil system classification of Henan, resulting in a comprehensive understanding of major soil types, representative soil taxa, and their basic physicochemical properties. These achievements provide a solid foundation for translating soil classification data into practical applications for local production and land management. This study builds upon the latest advances in China's soil taxonomic system and utilizes data from 170 soil samples documented in *Soil Series of China: Henan Volume* to construct a comprehensive factor system influencing wheat yield. Referring to the national standard *Classification for the Quality Grade of Agricultural Land in China* (GB/T 28407–2012), Henan Province is divided into five distinct agricultural zones. The spatial distribution characteristics of different influencing factors are analyzed accordingly. A Geographical Detector model is employed to perform region-specific analysis, aiming to identify the dominant soil fertility factors affecting crop yields in each zone and to propose targeted improvement strategies (Abe et al., 2009). This methodological framework is intended to provide a novel approach for achieving food security under limited arable land resources worldwide. It also aligns with the FAO's global "Soil Health Protection" initiative (Koch et al., 2013; Ladha et al., 2016), contributing to the realization of the United Nations Sustainable Development Goals (SDGs), particularly "Zero Hunger" and "Life on Land" (Ladha, 2025). Ultimately, the study offers practical and scalable solutions for global soil conservation, agricultural adaptation to climate change, and other pressing sustainability challenges.

Materials and methods

Materials

Soil data were derived from the latest edition of the *Soil Series of China: Henan Volume*, published in 2019. A total of 170 valid soil sample points were extracted, with sampling records dated between 2012 and 2013, and the data has been updated to 2024. These samples cover nearly all counties and districts within the cultivated regions of Henan Province, with a concentration in the northern and southern areas, as shown in *Fig. 1*. Wheat yield data for each county and district were obtained from the *Henan Statistical Yearbook* (2024), representing the 2023 production figures. Climate data were sourced from the China Meteorological Administration (CMA), comprising 18 valid meteorological stations, with records spanning from October 1, 2022, to Mayr 1, 2023. Topographic data were extracted from the Henan Province 2010 Digital Elevation Model (DEM), provided by the Geospatial Data Cloud (GDC), with a spatial resolution of 30 meters.

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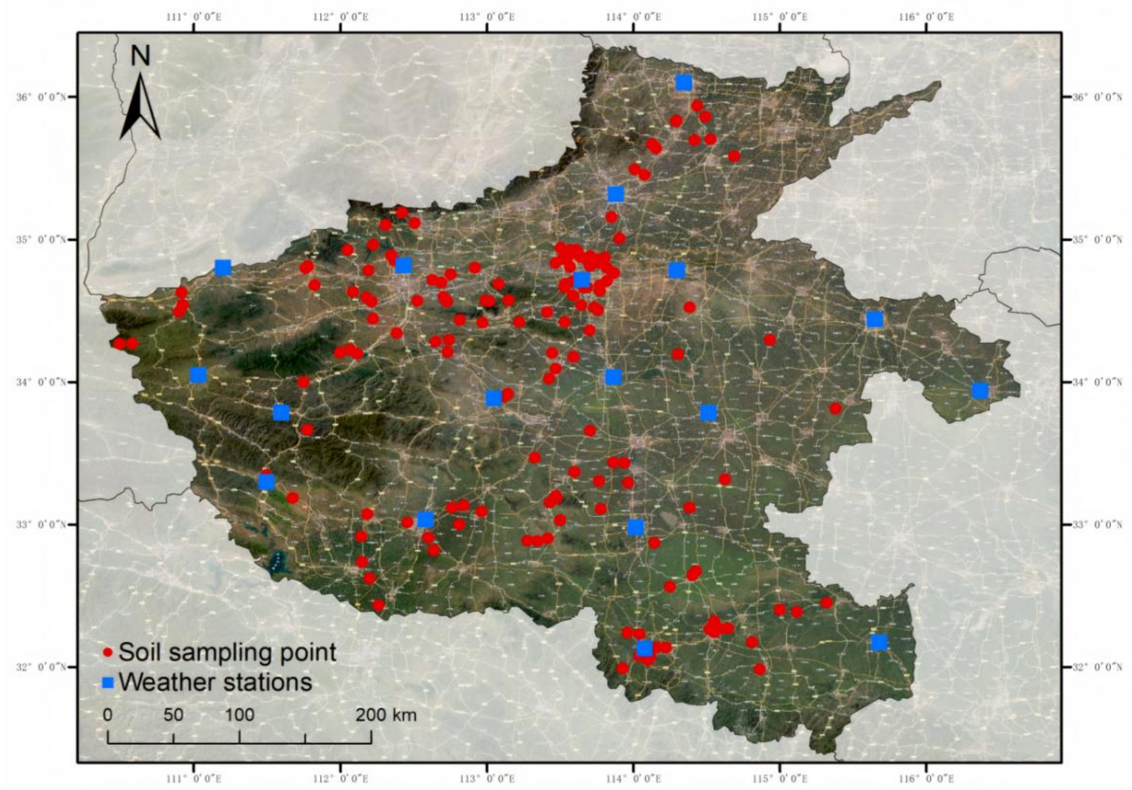

***Figure 1.** The map of distribution of soil samples*

Research methods and data processing

In this study, SPSS Statistics 26 and R 4.0.5 were used for data processing and modeling analysis, and the geographic data projection coordinate system was WGS 1984 UTM Zone 50N.

The above data were used to construct a system of wheat yield influencing factors, including four aspects, soil physicochemical properties, soil configuration, climatic conditions, and topographic conditions, which are shown in *Table 1*, and the values of soil physicochemical properties indexes of each point profile, except for moisture, were weighted according to the proportion of the thickness of the soil layer at each point; the soil moisture data were derived from remote sensing inversion. Climate factor data selected sunshine duration, average monthly rainfall and >10°C accumulated temperature as climate condition indicators. The data of terrain factor selects the altitude.

***Table 1.** The system of impact factors of wheat yield*

Categories	Type	Unit
Soil Physical and Chemical Properties	Effective phosphorus	$g{\cdot}kg^{-1}$
	Potassium	$mg{\cdot}kg^{-1}$
	Soil organic matter	$g{\cdot}kg^{-1}$
	Soil conductivity	$\mu s{\cdot}cm^{-1}$
	Soil pH	-
	Soil moisture	%
Soil configuration	Effective soil thickness	cm
	Soil configuration score	-

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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Climatic conditions	Average monthly rainfall Duration of sunshine Accumulated temperature	mm·month^{-1} hours·month^{-1} °C
Terrain conditions	Elevation	m

The soil configuration scores were assigned based on the classification and corresponding grading values of soil indicators for the Huang-Huai-Hai region, as defined in the *Classification for the Quality Grade of Agricultural Land in China* (GB/T 28407–2012), as shown in *Table 2*.

Table 2. *Soil profile configuration scores in the Huang-Huai-Hai Region*

Score	Soil Profile Configuration
100	Homogeneous loam; Loam/Clay/Loam
90	Loam/Clay/Clay; Loam/Sand/Loam; Sand/Clay/Clay
80	Clay/Sand/Clay; Homogeneous clay
70	Sand/Clay/Sand
60	Loam/Sand/Sand; Clay/Sand/Sand
40	Homogeneous sand

Drawing on the method proposed by Wang et al. (2017) for handling non-uniformly distributed point data, this study constructed spatial interpolation surfaces and control grid points across the entire Henan Province. Appropriate interpolation methods were applied to each variable, and factor values were subsequently extracted using the control grid. Specifically, soil available phosphorus and total potassium were interpolated using Ordinary Kriging (Kravchenko et al., 1999); soil pH was interpolated using the Radial Basis Function method (Zandi et al., 2011); soil electrical conductivity with Ordinary Kriging (Robinson et al., 2006); and soil organic matter with Splines (Robinson et al., 2006). Soil configuration and effective soil layer thickness were interpolated using Ordinary Cokriging (Gozdowski et al., 2015), while soil moisture data were directly extracted from remote sensing raster datasets (Bai et al., 2019). Variable values were re-extracted at 1,564 effective control points spaced at 10 km intervals using the established control grid (Wang et al., 2017).

In this study, different standard farming system zones were analyzed using the Geographic Detector to derive the dominant factors affecting wheat yield in different zones and the degree of influence, and to explore the factor influence paths in different zones.

The Geographical Detector is based on the second law of geography. Since it is much more difficult for two two-dimensional variables to agree in spatial distribution than the agreement of one-dimensional curves of two variables (Wang et al., 2017), the correlations revealed by geographic probes are more likely to be causal. The model equation is as follows:

$$P_{D,L} = 1 - \frac{1}{n\sigma_U^2}\sum_{i=1}^{k} n_i\sigma_i^2 \quad \text{(Eq.1)}$$

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where: $P_{D,L}$ is the degree of influence of the influence factor on the dependent variable, the value of the domain of [0,1], the higher the value means that the influence of the influence factor on the degree of influence of the wheat yield; σ^2 is the variance of the wheat yield in the study area; σ_i^2, n_i is the variance and the number of samples within the various strata; k is the number of types of the influence factor for the discretization process, i.e., the number of strata in the geodetic detector; n is the number of samples within the study area, i.e., the number of control samples of the various standard cropping system zones in the present study.

Geodetectors are better at handling discrete variables than continuous variables, and the data obtained in this study are all continuous variables. Therefore, this study set the number of classifications from 3 to 7 under different partitions and used five algorithms, QUANTILE, GEOMETRIC, NATURAL, SD, and EQUAL, to automatically classify the data in order to obtain the optimal classification results.

Determination method for soil profile texture configuration

Based on the layered soil texture data obtained from 170 soil profile samples, the original 12 soil texture classes were simplified and merged into three broader texture categories—sandy, loamy, and clayey—according to the similarity in their agronomic performance. Specifically, sand, loamy sand, and silt were grouped into the sandy category (s); loam, silt loam, and sandy loam into the loamy category (l); and sandy clay loam, clay loam, silty clay loam, sandy clay, silty clay, and clay into the clayey category (c). To further characterize the vertical structure of soil profiles, soil horizons were categorized based on their position within the profile and the simplified texture class. Layers with a thickness of less than 10 cm were excluded from the analysis. The remaining profile layers were classified into three depth intervals: topsoil (A) from 0 to 30 cm, subsoil (B) from 30 to 60 cm, and bottom soil (C) from 60 to 100 cm. Combining the three texture categories with the three depth levels resulted in nine characteristic texture layers: sandy topsoil (A-s), loamy topsoil (A-l), clayey topsoil (A-c); sandy subsoil (B-s), loamy subsoil (B-l), clayey subsoil (B-c); and sandy bottom soil (C-s), loamy bottom soil (C-l), and clayey bottom soil (C-c).

Using the thickness data of these nine characteristic texture layers for all 170 samples, the Fuzzy C-Means (FCM) clustering algorithm was employed to identify typical combinations of characteristic layers within the profiles. These combinations, defined as soil profile texture configurations, represent distinct structural patterns of soil texture along the vertical profile. The FCM model also provided a membership degree for each sample, indicating the extent to which a soil profile belongs to each configuration type.

Results

Determination and spatial distribution of soil profile texture configurations

Based on the thickness data of characteristic texture layers from 170 soil profile samples, the Fuzzy C-Means (FCM) clustering algorithm was applied to identify distinct combinations of texture layers—referred to as soil profile texture configurations (*Table 3*). For each configuration, the model generated the central thickness values of the characteristic texture layers, along with the membership degree of each sample to the identified configuration types. A total of nine configuration types were automatically derived for the 170 soil profiles across the study area. The presence or absence of specific

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characteristic texture layers in each configuration type clearly illustrates the structural features of the soil profiles. For example, the *loam–clay–loam* configuration represents a typical profile consisting of loamy topsoil, clayey subsoil, and loamy bottom soil, with central thickness values of approximately 34 cm, 33 cm, and 33 cm, respectively.

Table 3. *Soil profile texture patterns and their corresponding centroids of 170 profiles*

Type	A-s	A-l	A-c	B-s	B-l	B-c	C-s	C-l	C-c
Loam / Clay / Loam		34				33		33	
Loam / Loam / Clay		30							39
Loam / Clay / Clay		31				37			33
Clay / Clay / Clay			24			32			32
Sand / Sand / Clay	22			35					30
Sand / Sand / Sand	23			37			40		
Sand / Loam / Loam	21				40			37	
Loam / Loam / Sand		30			43		35		
Loam / Loam / Loam		31			44			34	

Based on the membership degrees of each sample to the nine soil profile texture configurations, ordinary kriging interpolation was applied to generate continuous surface maps of membership for each individual configuration type. These interpolated maps were then converted into raster grids with a spatial resolution of 120 m × 120 m. Each grid cell was assigned to a specific configuration type using a “hard classification” approach, based on the maximum membership degree (i.e., defuzzification). This process produced a clear spatial prediction map of soil profile texture configurations across the study area. Among the nine configuration types, the *loam–loam–loam* profile was the most widespread, forming large contiguous areas primarily in the central and western parts of the study region. The *loam–clay–clay* type ranked second in spatial extent and was mainly distributed in the southern portion of the region. The remaining configurations had relatively limited spatial distributions. Although the *sand–sand–sand* configuration was observed in the original 170 soil profiles, its spatial extent was too small to be retained in the maximum membership classification and was thus excluded from the final predictive mapping. As a result, this study focuses on the eight major soil profile texture configurations.

Wheat yield spatial pattern

The wheat yield data in Henan Province were graded using the natural breakpoint method, and the high-yielding wheat areas (yield ranging from 6,685.65 to 8,357.1 $kg \cdot ha^{-1}$) in Henan Province were mainly located in the Huanghuaihai area and the low-lying plains of Jiluyu and Henan, as well as in the Nanyang Basin. Wheat low-yielding areas (<5,014 $kg \cdot ha^{-1}$) are mainly located in western Henan, as shown in *Figure 2*. Referring to the "Agricultural Land Quality Grading Procedure" (GB/T28407-2012), Henan Province is divided into five standardized farming system level 2 zones: Yanshan-Taishan pre-mountain plains, Huanghuai plains, EYWH hilly mountainous area, western Yu mountainous area, and Jiluyu low-lying plains, as shown in *Figure 3*.

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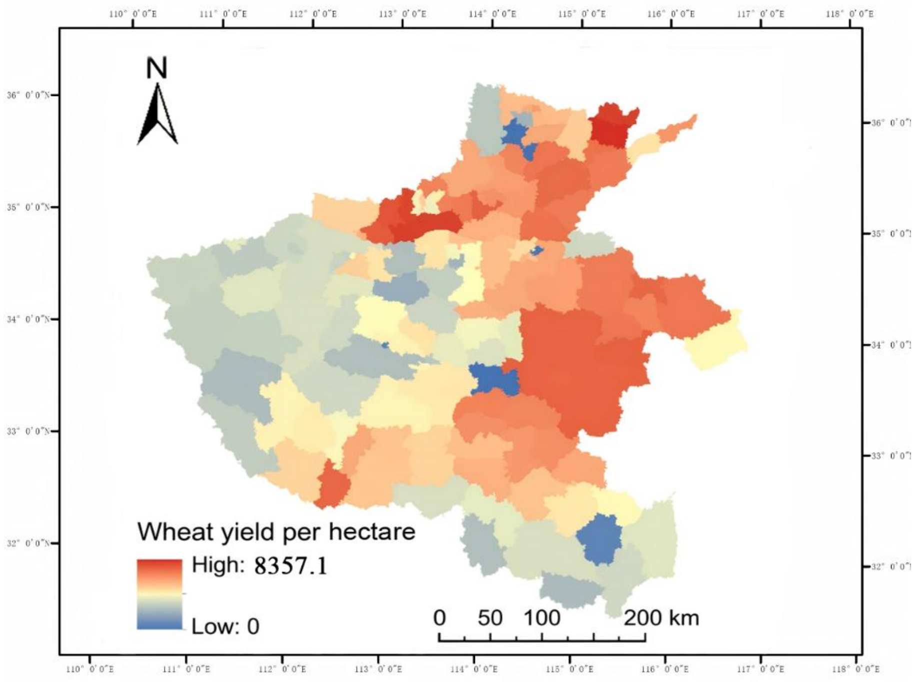

Figure 2. Spatial distribution of wheat yield in Henan Province

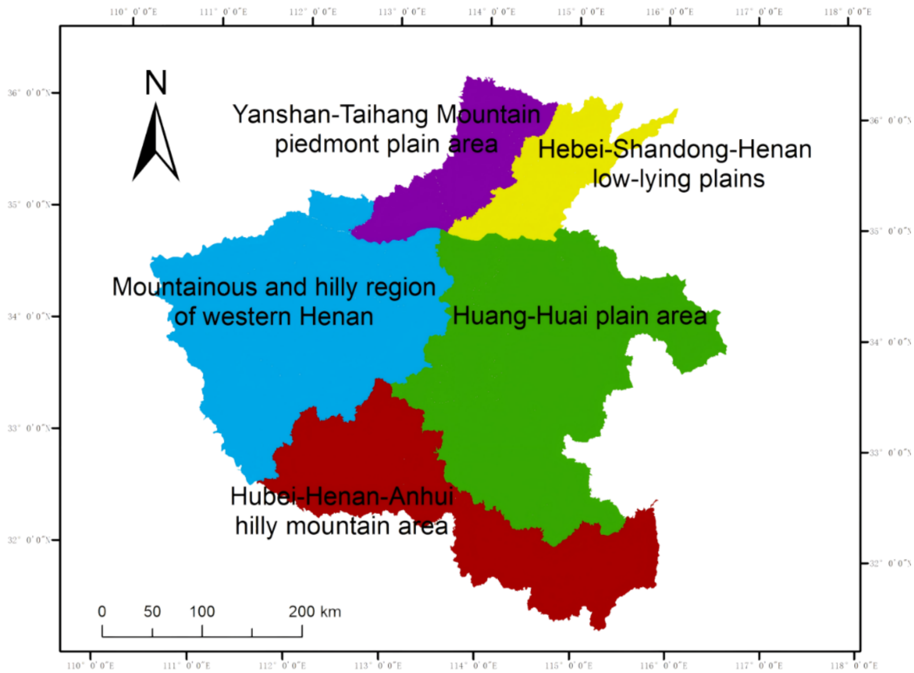

Figure 3. Standard tillage system zoning

Spatial patterns of influencing factors

In the Yanshan-Taishan pre-mountain plains area, Huanghuai plains area, EYWH hilly mountainous area, western Yushu mountainous area, and Jilu-Yu low-lying plains area, the whole potassium content ranged from 10.00 to 19.85 g·kg^{-1}, with spatial

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characteristics showing lower in the southwest and higher in the northeast; the conductivity value ranged from 89.59 to 427.93 μs·cm^{-1}, with spatial characteristics showing higher in the northwest; the organic matter content ranged from 3.23 to 19.37 g·kg^{-1}, with spatial characteristics showing that it was higher in the mountainous and hilly areas of western Henan; pH values ranged from 7.35 to 8.35, with spatial characteristics showing that it was lower in the south and higher in the north and west; quick-acting phosphorus content ranged from 4.27 to 8.12 mg·kg^{-1}, with spatial characteristics showing that it was high at the edges and low in the center; and the range of soil moisture ranged from 3.32 to 16.76 %, with spatial characteristics showing that it was higher in the south. characterized as higher in the south. The soil configuration score was 67.50-100, with spatial characteristics lower in the Huanghuai Plain and Nanyang Basin; the effective thickness of the soil layer was 74.85-97.83 cm, with spatial characteristics lower in the south and the hilly areas of western Henan.During the entire wheat growing season (from October 2023 to May 2024), The average monthly precipitation is 6.45~178.22mm, with the spatial characteristics of high in the southeast and low in the northwest; the sunshine duration is 107.55~257.23h, with the spatial characteristics of high in the northwest and low in the rest. The cumulative temperature ranges from 4730.10 to 5561.60°C, with spatial characteristics high in the southeast, followed by the central part, and lowest in the northwest and northeast. The altitude ranges from 54.80 to 2413.60m, and the spatial characteristics are high in the northwest. The specific spatial distribution of each factor is shown in *Figure 4*.

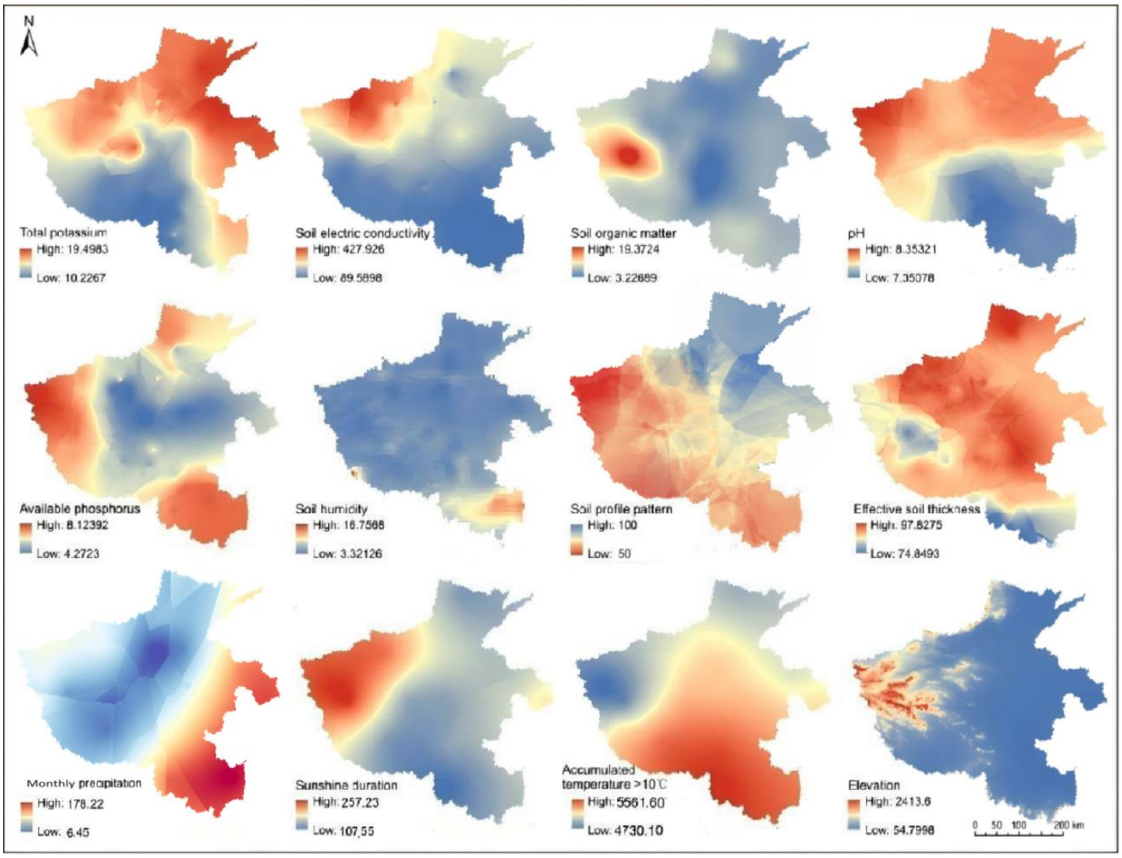

***Figure 4.** Spatial interpolation distribution of impact factors*

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DOI: http://dx.doi.org/10.15666/aeer/2306_1081910839

Geodetector analysis

Using the geographic detector approach and setting a threshold of 0.4 for the explanatory power of influencing factors, the dominant factors affecting wheat yield in different farming zones of Henan Province were identified. In the Yanshan-Taihang pre-mountain plain area, the main influencing factors were climate, topographic conditions, and soil physicochemical properties. In the Huanghuai Plain area, average monthly precipitation and elevation were the key determinants. In the hilly and mountainous region spanning Hubei, Henan, and Anhui (EYWH region), soil configuration emerged as the most significant factor, followed by soil physicochemical properties, with climate and topographic conditions having comparatively lesser influence. In the mountainous and hilly area of western Henan, the primary influencing factors were available phosphorus, cumulative temperature, and sunshine duration. Lastly, in the low-lying plains of Hebei, Shandong, and Henan (Jilu-Yu region), soil configuration was identified as the dominant factor. Detailed results for each region and variable are presented in *Table 4*.

Table 4. *Result of geographical detector*

Variable	Yanshan Taihang Mountain piedmont plain area		Huang-Huai Plain		Hubei, Henan and Anhui hilly areas		Mountainous and hilly area in western Henan		The low-lying plain area of Hebei-Shandong and Henan	
	q	p	q	p	q	p	q	p	q	p
Daylight hours	0.51	0.00	0.26	0.00	0.21	0.00	0.40	0.00	0.28	0.33
Soil conductivity	0.37	0.00	0.35	0.00	0.33	0.00	0.25	0.00	0.10	0.12
Soil pH	0.44	0.00	0.17	0.00	0.42	0.00	0.31	0.00	0.16	0.01
Soil organic matter	0.41	0.00	0.22	0.00	0.10	0.00	0.37	0.00	0.28	0.99
Average monthly precipitation	0.57	0.00	0.55	0.00	0.28	0.00	0.27	0.96	0.18	1.00
Soil configuration score	0.33	0.00	0.39	0.00	0.63	0.00	0.29	0.00	0.91	0.00
Total Potassium	0.51	0.00	0.12	0.00	0.46	0.00	0.31	0.00	0.18	0.12
Elevation	0.44	0.00	0.49	0.00	0.21	0.00	0.38	0.00	0.06	1.00
Effective soil thickness	0.45	0.00	0.10	0.00	0.37	0.00	0.26	0.00	0.12	0.98
Soil moisture	0.25	0.00	0.10	0.00	0.31	0.00	0.08	1.00	0.13	1.00
Effective phosphorus	0.54	0.00	0.07	0.00	0.50	0.00	0.48	0.00	0.07	0.36
Cumulative temperature	0.53	0.00	0.05	0.00	0.17	0.00	0.48	0.00	0.14	0.41

Discussion

Influence mechanism

The influence of dominant factors on wheat yield across different cultivation zones essentially reflects the interaction between natural conditions—such as soil, climate, and topography—and agricultural practices.

The Yanshan–Taihangshan pre-mountain plain area is situated in the transitional zone between mountainous and plain regions. Near the mountain slopes, soils are primarily composed of colluvial deposits, characterized by shallow profiles, coarse textures, poor physicochemical properties, and weak soil development—often classified as newly

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formed soils. These areas also feature steep slopes that are highly susceptible to soil erosion. In contrast, the areas farther from the slopes are mainly alluvial, with relatively thicker soil layers and silty textures. However, these soils are still poorly developed and nutrient-deficient, typically categorized as protosols, and are prone to flooding. As a result, in this region, factors such as climate, topography, soil physicochemical properties, and soil layer thickness emerge as dominant influences on yield. Specifically, wheat yield tends to increase with greater sunshine duration, accumulated temperature, precipitation, effective phosphorus, and total potassium content, as well as with thicker soil profiles; conversely, yield decreases with increasing elevation.

The Huanghuai Plain Zone, part of the Huang-Huai-Hai alluvial plain, is characterized by flat terrain and is the largest wheat-producing region in Henan Province, based on the 2015 land use and cover data. The area maintains stable soil fertility, with favorable and relatively homogeneous physicochemical properties. Due to long-term intensive cultivation, soil profiles across the region exhibit similar configurations, primarily consisting of anthropogenic soils with deep profiles, distinct stratification, and well-developed horizons. Consequently, the influence of soil-related factors on wheat yield is significantly reduced, while microclimatic and microtopographic factors play a more prominent role. Specifically, yield increases with higher monthly precipitation, but decreases with increasing elevation.

The hilly and mountainous region of Hubei-Henan-Anhui (EYWH), primarily involving the Nanyang Basin in Henan, is a low-lying area where water and nutrient minerals tend to accumulate. It is widely covered by fluvio-lacustrine sediments with fine textures. Soils in this region are mainly metamorphic or protosols, characterized by deep profiles and mineral compositions dominated by montmorillonite, illite, or mixed-layer clays, resulting in high expansion and contraction potential. When wet, these soils become sticky and plastic; when dry, they crack deeply and widely. The surface layer is rich in humus and other organic matter, and calcium carbonate nodules are prevalent within the soil body, sometimes forming hardened calcareous layers (e.g., caliche), which can impede root growth. As a result, unfavorable soil configurations—such as deep cracking and the presence of restrictive layers—become dominant limiting factors. However, wheat yield tends to increase with improvements in soil configuration, as reflected by higher soil configuration scores.

In the mountainous and hilly region of western Henan, which includes numerous mountain ranges, the Funiu Mountains serve as the primary landform, stretching over 800 li (approximately 400 km) from east to west, with elevations ranging from 1,000 to 2,000 meters. The area is characterized by relatively low temperatures and high humidity. Natural secondary forests dominate the vegetation, with dense understory shrubs and herbaceous plants, resulting in high vegetation coverage. As a result, soil erosion is relatively mild; however, strong leaching effects are present. The soils in this region exhibit clear vertical zonation: areas below 950 m are mainly dominated by leached soils, while areas between 950 m and 1,900 m contain a mix of leached and protosols, and above 1,900 m, protosols are predominant . In farmlands within this zone, leached soils generally exhibit favorable physicochemical properties and well-structured profiles, making soil fertility a key limiting factor for wheat yield. Additionally, the region's complex and diverse topography—especially variations in slope and aspect—leads to significant differences in temperature and sunshine duration. Consequently, effective phosphorus, cumulative temperature, and sunshine hours are the dominant yield-influencing factors, with yield increasing alongside higher levels of these indicators.

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DOI: http://dx.doi.org/10.15666/aeer/2306_1081910839

In the Jiluyu low-lying plain area, soils are deep due to repeated fluvial deposition. Because of hydraulic sorting, soil texture exhibits pronounced stratification, and the sediment composition is complex. Most soils in this area are weakly developed protosols. In the flat plains dominated by river and lake sedimentation, significant inputs of water and sediments from surrounding mountainous and hilly areas have formed thick sedimentary layers. The groundwater table in low-lying areas is generally high, and under natural conditions, poor internal and external drainage frequently leads to issues such as meadowization, gleying, and salinization. As such, soil configuration becomes the dominant factor influencing yield in this region, with yield increasing as soil configuration scores improve.

Suggestions

Upholding the strictest arable land protection system and thoroughly implementing the strategy of “storing grain in the land and in technology” are key tasks outlined in China’s 14th Five-Year Plan and its medium- to long-term economic development strategy. When food supply is relatively sufficient, measures such as crop rotation, fallow practices, and ecological restoration should be adopted to protect and rehabilitate farmland, giving overexploited arable land an opportunity to recover. Conversely, in times of food shortage, it is essential to rapidly adjust the cropping structure and restore grain production capacity to meet domestic demand. Therefore, the “grain storage in land” strategy must not overlook the importance of building healthy land productivity and allowing degraded farmland to rest and recover. By combining the protection and improvement of farmland resources, the overall grain production capacity can be both enhanced and safeguarded. This approach calls for the integration of four key aspects: land protection, land improvement, land conservation, and land utilization. From the perspective of farmers’ production practices, these mechanisms can be translated into concrete production constraints and directions for optimization.

Yanshan-Taihang Piedmont Plain Region: Enhancing Basic Soil Fertility through "Soil Nurturing". In this region, where natural constraints such as climate and topography are difficult to modify, enhancing soil fertility through targeted management is a practical and effective strategy to increase wheat yield. Priority should be given to policies focused on land protection and soil nurturing, aiming to steadily improve soil physicochemical properties. Farmers can mitigate the limitations of terrain and climate by improving key soil characteristics—such as increasing available phosphorus and total potassium levels—and by thickening the effective soil layer through measures like straw return and organic fertilizer application. This aligns with the findings of Li et al. (2023), who concluded that optimized soil configuration can alleviate topographic constraints by improving the soil’s capacity to retain water and nutrients. International research also supports this view. For example, In Mediterranean dryland trial, conservation tillage increased grain yield by 13% and protein content by 5% compared to conventional tillage. Preceding durum wheat with a legume crop (forage pea) instead of a cereal further boosted grain yield by up to 26% and protein yield by up to 31%. (Pagnani et al., 2019). Specific measures include: (1) Implement straw return combined with organic fertilizer application to improve soil organic matter and structure. Specifically, crushed wheat straw should be returned to the field together with well-composted farmyard manure. This approach aligns with the “grain storage in land” strategy, promoting sustainable use of straw resources while reducing dependence on chemical fertilizers (Liu et al., 2024). Long-term application of straw and organic manure can significantly increase wheat yield

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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by 12.8–18.4% and reduced nitrogen losses by 23.6–31.2% compared to conventional practices (Zhou et al., 2025). (2) Apply targeted nutrient supplementation based on soil test results: for phosphorus-deficient areas, apply diammonium phosphate (225-300 kg/ha); for potassium-deficient areas, apply potassium chloride (150-225 kg/ha). This prevents excessive or imbalanced fertilization, which could lead to soil acidification. European agricultural research has shown that precision fertilization based on soil testing can improve wheat nutrient use efficiency (Fabbri et al., 2025). (3) Promote terracing and green manure planting on sloped land to control soil erosion and improve soil health. This study demonstrated that implementing double no-till with rice straw retention in terraced sloping lands increased soil water content by 18.2–24.6%, while soil organic carbon and microbial biomass carbon rose significantly by 21.4% and 29.8%, respectively. This management practice enhanced lentil yield by 27.5% and reduced soil erosion by 31.3% (Layek et al., 2022).

Huang-Huai Plain Region: Prioritizing “Land Construction” to Enhance Water Use Efficiency. As a core wheat-producing region, the Huang–Huai Plain features relatively uniform soil conditions, but spatial variations in monthly precipitation and elevation significantly affect water availability. To mitigate the risks of rainfed agriculture, farmers need to proactively manage water through improved irrigation infrastructure—such as small-scale canal construction—and soil moisture conservation techniques like plastic film mulching. These approaches align with findings by Gao et al. (2025), who emphasized that in regions with stable soil conditions, effective water management is the key determinant of yield increases. International experiences further support this view. In the northwestern India's Punjab state, the use of precision irrigation and soil moisture monitoring has improved water use efficiency, resulting in corresponding yield gains (Kaur et al., 2025). Similarly, field trials in South Korea, the irrigation strategy based on soil available water content enables precise water supply during critical wheat growth stages by monitoring real-time moisture conditions in the root zone. Compared to rain-fed conditions, this approach significantly increased wheat yield by over 15% and improved irrigation water use efficiency by more than 20%. These findings highlight the dual benefits of the available water-based threshold strategy in enhancing both crop productivity and water conservation, offering a practical solution for small-scale farmers in arid and semi-arid regions (Kim et al., 2025). These cases highlight the universal significance of scientific water management in enhancing yield resilience under varying climatic conditions. Specific strategies for the Huang-Huai Plain include: (1) Irrigation system upgrades—promoting drip and sprinkler irrigation based on existing systems, with an initial investment of approximately ¥7,500-12,000/ha, which may be subsidized by government programs. (2) Soil moisture improvement—applying no-tillage with total green manure mulching and tillage with total green manure incorporation significantly increase soil water content in the 0–110 cm layer, promote maize root growth and photosynthetic capacity, and ultimately lead to a significant improvement in biomass and grain yield., maintaining stable yields even under drought conditions (Wang et al., 2025). (3) High-standard farmland construction—consolidating fragmented and low-yield plots, standardizing irrigation ditches and field roads, and preventing the non-agricultural conversion of fertile land. Large-scale farmland consolidation projects in EU countries have substantially improved infrastructure and increased average wheat yields (European Commission, 2018).

Hubei-Henan-Anhui Hilly Region & Hebei-Shandong-Henan Lowland Plains: Enhancing Productivity through “Land Modification” to Address Soil Structural

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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Constraints. In the hilly regions of Hubei, Henan, and Anhui, as well as the lowland plains across Hebei, Shandong, and northern Henan, wheat production is limited primarily by suboptimal soil configurations—such as plow pans, calcareous or saline layers, and poor water retention due to high clay content or cracking. Improving soil physical structure through both mechanical and agronomic means is critical for yield stabilization. This aligns with Tan et al. (2015), who reported that modifying vertical soil profiles can significantly enhance crop yield stability by overcoming natural structural barriers. A three-year experiment on the semi-arid Loess Plateau showed that 4.5 t/ha straw strip mulching increased 0–200 cm soil water storage by 15–25 mm, reduced evapotranspiration by 8 % and raised water-use efficiency by 0.12–0.15 kg/m³; kernels per spike and 1000-grain weight improved jointly, lifting winter wheat yield by 10–15 % on average while markedly decreasing year-to-year variability. (Huang et al., 2017). In Argentina's Pampa hills, deep plowing to 35-40 cm broke through calcareous layers, enabling root length density to increase by 50%, resulting in a 18-24% yield gain (Schneider et al., 2017). Based on these insights, recommended interventions include: (1) Subsurface constraint mitigation. In areas with calcareous or compacted layers, perform deep plowing to a depth of 30-40 cm, supplemented with sand (7,500-15,000 kg/ha) or gypsum (7,500-15,000 kg/ha) to improve soil structure and pH conditions. Long-term trials on sodic soils in India (Nayak et al., 2012) showed that deep tillage plus 7.5 t ha^{-1} phosphogypsum lowered exchangeable sodium percentage and bulk density, increased topsoil thickness from 8 to 18 cm, and raised wheat–rice system yields by 18–22%. (2) Topsoil reconstruction. In low-lying clay-rich zones, backfill with high-quality loam and apply straw mulch to improve tillage suitability. This technique has shown notable benefits in soil aeration and moisture retention. (3) Crop rotation and fallow systems. Introducing wheat-green manure rotations not only reduces continuous cropping stress but also increases soil organic matter (Yang et al., 2024). Canadian studies confirm that rotational systems help restore soil fertility and sustain yield growth in the long term (Soon and Clayton, 2002).

Western Henan Mountainous and Hilly Region: Optimizing Nutrient-Climate Coupling through "Land Utilization". In the mountainous and hilly areas of western Henan, wheat production is primarily constrained by low available phosphorus and significant variations in light and accumulated temperature. Farmers can address these limitations by applying phosphorus fertilizers (e.g., superphosphate) and optimizing planting density to match light conditions, along with selecting early-maturing varieties adapted to thermal constraints. This approach aligns with the findings of He et al. (2025), who emphasized that coordinating soil nutrient regulation with variety selection can significantly improve yields in mountainous regions. Similar practices have shown success in the highland areas of Ethiopia. For instance, a study in the central highlands demonstrated that split application of nitrogen fertilizer significantly boosts yield, nitrogen use efficiency, and grain protein content in durum wheat (Meseret et al., 2022). These findings offer valuable guidance for agriculture in western Henan, highlighting the importance of site-specific varietal and nutrient strategies. Specific recommended measures include: (1) Precision fertilization: Soil testing and formula-based fertilization (available through local agricultural service stations) should be adopted, applying nutrients according to the principle of "supplementing what is deficient". For example, in soils with available phosphorus below 5 mg/kg, superphosphate should be applied at 375-450 kg/ha to improve fertilizer use efficiency. On the Ethiopian highlands, such precision fertilization has improved phosphorus use efficiency by 5-18%, with corresponding yield

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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increases (Elias et al., 2019). (2) Variety-climate matching: In high-altitude zones with lower accumulated temperature, early-maturing cultivars should be selected. On sun-facing slopes with strong light conditions, cultivars with high light-use efficiency should be prioritized to maximize climatic resource utilization. Field trials in a warm, irrigated highland environment showed that wheat cultivars with high photosynthetic capacity raised radiation-use efficiency. When phosphorus nutrition was optimized, the additional gain translated into a 25% yield increase (Reynolds et al., 2000). (3) Ecological land protection: On steep, retired farmland, native tree species such as *Platycladus orientalis* should be planted to reduce soil erosion, while gentle slopes can be retained for cultivation. This strategy aims to harmonize ecological conservation with grain production. The establishment of shelterbelts has significantly altered soil carbon storage and physical structure, with specific metrics showing a substantial increase in soil inorganic carbon (SIC) by 18.6% to 41.2%, alongside a reduction in soil bulk density of 6.3% to 15.7%. These changes demonstrate that shelterbelts not only enhance the soil's carbon sequestration capacity but also improve porosity and aeration by reducing soil compaction, thereby effectively optimizing soil structure and contributing to a healthier foundation for ecosystem productivity (Zhu et al., 2023).

Conclusion

This study, based on 170 soil profile samples from the Soil Series of China: Henan Volume, established a comprehensive framework of wheat yield influencing factors by integrating soil, climate, and topographic variables. Using the geographical detector model, we analyzed five standard tillage zones across Henan Province and derived the following key conclusions:

(1) Dominant factors vary significantly across zones. In the Yanshan–Taihang Piedmont Plain region, wheat yield is primarily influenced by climate (sunshine duration and accumulated temperature), topography (elevation), and soil physicochemical properties (available phosphorus and total potassium), with all factors showing influence values exceeding 0.4. In the Huang–Huai Plain region, average monthly precipitation and elevation are dominant, as they regulate the spatial distribution of water resources. In the Hubei–Henan–Anhui hilly region, soil profile configuration (e.g., barrier layers, structural stability) is the primary limiting factor, followed by soil properties (e.g., available phosphorus), with weak influence from topography and climate. In the Western Henan mountainous region, yield is largely driven by available phosphorus, accumulated temperature, and sunshine, highlighting the importance of nutrient–climate coupling. In the Hebei–Shandong–Henan low-lying plains, soil configuration (e.g., drainage, salinity/alkalinity levels) is the sole dominant factor, directly constraining soil productivity.

(2) Improvement strategies must be region-specific. Based on the differences in dominant factors, tailored interventions should be adopted: the piedmont plain region should focus on "soil nurturing" to enhance soil physicochemical properties; the Huang–Huai Plain should pursue "land development" to optimize water resource management; the hilly and low-lying plain zones should emphasize "land modification" to overcome soil profile constraints; and the mountainous zone should adopt "land utilization" to maximize nutrient and climate synergies. The coordinated implementation of protection, construction, nurturing, and utilization can effectively tap into the wheat yield potential across the province.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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This research not only offers a scientific basis for the sustainable development of wheat production in Henan Province, China, but also provides valuable insights applicable to similar agricultural regions worldwide, with the following contributions:

(1) Value to agricultural practice in China. This study promotes the transformation of pedological data into production-oriented applications. This study leverages data from the *Soil Series of China: Henan Volume* to build a soil–climate–topography model linking multiple environmental factors with wheat yield. This transforms fundamental soil classification research into operational guidance, offering a practical pathway from “data to practice” for improving low- and medium-yield farmlands.

(2) Enhancing food security capacity. As Henan is a key winter wheat production base, the proposed region-specific strategies can be directly applied to agricultural production. precision-driven soil and land improvements are expected to potentially increase wheat yields in low- and medium-productivity areas, supporting China's national strategies of “storing grain in land and technology.”

(3) Methodological contribution to global agricultural research. By focusing on a region with complex terrain ("plain–hill–mountain" continuum), this study demonstrates the effectiveness of geographic detectors in analyzing multi-factor interactions. This approach offers a transferable research paradigm for similar global regions (e.g., South Asia’s Ganges Plain, South America’s La Plata Basin), especially through its framework of “tillage zone classification + dominant factor identification,” which helps resolve the ambiguity of factor influence at large spatial scales.

(4) Empirical contribution to understanding soil configuration and yield. Global studies on soil profile configuration have mostly focused on single soil types (e.g., black soils, red soils). By comparing configuration effects across five zones (e.g., barrier layers in hilly areas vs. salinization in low-lying plains), this study reveals how profile configurations operate under different geographic contexts, offering a novel perspective into soil management in tropical and subtropical monsoon regions.

(5) Contributing China’s experience to global food security governance. As a major agricultural nation, China’s approach to upgrading low- and medium-productivity land through "zone-specific precision strategies" holds direct relevance for developing countries facing arable land constraints (e.g., India, Bangladesh). For instance, techniques used in the Hebei–Shandong–Henan lowland region—such as deep plowing to break barrier layers and straw return to enhance structure—could be applied to reclaim saline-alkaline lands in the Ganges Delta, boosting global food productivity.

In summary, this study empirically reveals the interactive mechanisms of soil, climate, and topography in determining wheat yield. Theoretical insights and practical solutions derived here not only contribute to China's food security but also offer “evidence-based Chinese insights” for crop yield improvement and sustainable development in similar agricultural regions worldwide.

Author contributions. Conceptualization, L.Z. and W.W.; methodology, L.Z. and W.W.; validation, L.Z., W.W., J.Z. and Y.S.; formal analysis, J.Z. and Y.S.; writing—original draft preparation, J.Z. and Y.S.; writing—review and editing, L.Z. and W.W.; visualization, J.Z.; supervision, L.Z.; project administration, L.Z. and W.W.; funding acquisition, L.Z. and W.W. All authors have read and agreed to the published version of the manuscript.

Funding. This research was supported by the National Natural Science Foundation of China [Grant No. 41907001], the Guangzhou Science and Technology Program [Grant No. 2023A04J0932], the Third Batch of Huizhi Leader Creative Space Project in Chengde Hi-Tech Zone [Grant No. HZLC2024023], and by the Research Project of Hebei Minzu Normal University [Grant No. HX2024002].

Data availability statement. The data presented in this study are available on request from the corresponding author.

Acknowledgments. This work was supported by the National Natural Science Foundation of China.

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

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