

Article

Agricultural Land Suitability Assessment at the County Scale in Taiyuan, China

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Abstract: Conducting agricultural land suitability assessments (ALSA) scientifically is crucial for ensuring food security and fostering sustainable agricultural development. This study assessed the suitability of agricultural land in Taiyuan using a geographic information system (GIS) and the analytic hierarchy process (AHP), integrating factors such as topography, soil, water sources, and social conditions at a 1 km spatial resolution. The primary aim was to map the spatial distribution of agricultural land suitability and understand county-level variations. Given the irreversible impact of urban development on land use and the critical importance of ecological conservation, corresponding subtractions for urban and natural protected areas have been applied in this study during the assessment of agricultural land suitability. The findings revealed that Taiyuan's agricultural land suitability generally falls within an intermediate range, without areas classified as completely unsuitable (lowest rank) or suitable (highest rank). The agricultural land suitability does not reach the extreme conditions of being "unsuitable" (lowest rank) nor "suitable" (highest rank), reflecting an overall intermediate potential for agricultural production across the entirety of Taiyuan. The spatial distribution indicates higher suitability in the east and lower in the west, with 33.1% of Taiyuan's territorial area deemed relatively suitable, 61.3% moderately suitable, and only 5.6% generally suitable for agricultural production. Recommendations include focusing on high-economic-return crops in suitable areas, adopting drought-resistant varieties and enhancing agricultural infrastructure in moderately suitable areas, and prioritizing ecological conservation in generally suitable areas. Additionally, county-level strategies suggest differentiated agricultural models: agritourism and boutique agriculture in urban conflict areas like Qingxu and Wanbailin; cultivation of cold-resistant crops in ecologically fragile areas like Loufan; and sustainable agricultural practices like planting drought-resistant crops in water-scarce regions like Yangqu. This comprehensive assessment offers valuable insights for optimizing agricultural land allocation in Taiyuan, balancing economic development with ecological sustainability.

Keywords: agricultural land suitability assessment; geographic information system; analytic hierarchy process (AHP); sustainable development; food security



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1. Introduction

With the ongoing growth of the global population, land resources are becoming increasingly scarce, exacerbating the human–land contradiction [1,2]. Therefore, the scientific management and rational use of land resources have become pressing issues that need to be addressed globally [3–5]. Agricultural land suitability assessment is profoundly significant for ensuring food security, maintaining ecological balance, and promoting sustainable agricultural development. Moreover, it can offer scientific rationale and decision-making support to government agencies, agricultural enterprises, and farmers, thereby playing a crucial role in optimizing land use structure and allocation and achieving sustainable land resource utilization [6,7].

Extensive research has been conducted domestically and internationally on the suitability assessment of agricultural land. The evaluation methods mainly focus on the application of advanced technologies such as geographical information system (GIS), remote sensing, and multi-criteria decision making [8–11]. Additionally, big data and artificial intelligence (AI) are utilized in model training and prediction [12,13]. Agricultural land suitability assessments are now being integrated with precision agriculture, leveraging soil sensors and drones for accurate, real-time data [14].

In terms of evaluation factor selection, researchers in recent years have begun to focus more on comprehensive multi-factor assessments, considering climate, soil, topography, and water resources [15–18]. Furthermore, factors related to ecology and the environment, like soil health, biodiversity, and ecosystem services, are gradually being incorporated into the evaluation system to achieve coordinated development between agricultural production and the ecological environment [19,20]. In an interdisciplinary context, the suitability assessment of agricultural land has become increasingly integrated with the content of disciplines such as policy, planning, and land-use changes in recent years. Yet, the majority of research is commonly centered on a national or provincial scale, with county-level investigations being comparatively sparse [21].

Taiyuan is a city in northern China with a rich cultural heritage and a long history. Located in a mountainous area, it has a complex topography and scarce land resources [22]. Recent economic development and urban expansion have heightened the imbalance between the demand for and supply of agricultural land in Taiyuan [23]. Taiyuan City, as a primary agricultural area in Shanxi Province, ranks lower in grain crop yield within the province [24]. Compared to the capitals of the six central provinces, Taiyuan faces disadvantages such as the smallest agricultural volume and scale and the lowest proportion, making the dire situation of agricultural production in Taiyuan an urgent issue to address. Additionally, Taiyuan is a core area for economic development in both Shanxi and Northern China, where industrial pollution continuously damages the soil ecosystem [25]. Given the aforementioned reasons, conducting an assessment of the suitability of agricultural land in Taiyuan at the county level can help to optimize land use structure from a micro perspective and provide more precise guidance for agricultural production and land use decisions.

This study, utilizing a combination of multi-source data, aims to apply geographic information system (GIS) technology integrated with the analytic hierarchy process (AHP) for a comprehensive assessment of agricultural land suitability in Taiyuan. The study is structured to accomplish three key objectives: (1) to generate a spatial distribution map that accurately represents the varying degrees of agricultural land suitability across Taiyuan, which will serve as a visual tool to understand the spatial variability in land suitability; (2) to identify and analyze the key factors influencing agricultural land suitability in Taiyuan, which involves a detailed examination of both natural and anthropogenic elements that affect agricultural productivity; and (3) to provide targeted recommendations for optimizing agricultural production in different counties within Taiyuan. These suggestions will be grounded in findings from the suitability assessment and factor analysis, aimed at enhancing agricultural efficiency and sustainability.

2. Materials and Methods

2.1. Study Area and Data Sources and Preprocessing

2.1.1. Study Area

Taiyuan, located between 37°27' N and 38°25' N as well as 111°30' E and 113°09' E, is part of the Loess Plateau, one of the nine major agricultural zones. The terrains in the western, northern, and eastern regions are elevated, with the highest point reaching 1789.95 m. The central and southern regions are mainly composed of river valleys, with their lowest elevation at 760.39 m. The plain areas consist of continuous plots (Figure 1a). The Fen River, a tributary of the Yellow River, flows from north to south through the study area (Figure 1b), supplying irrigation water for the agricultural cultivation areas in the

central and southern parts. Overall, Taiyuan's topography rises in the north and descends in the south, taking on a dustpan-like shape.

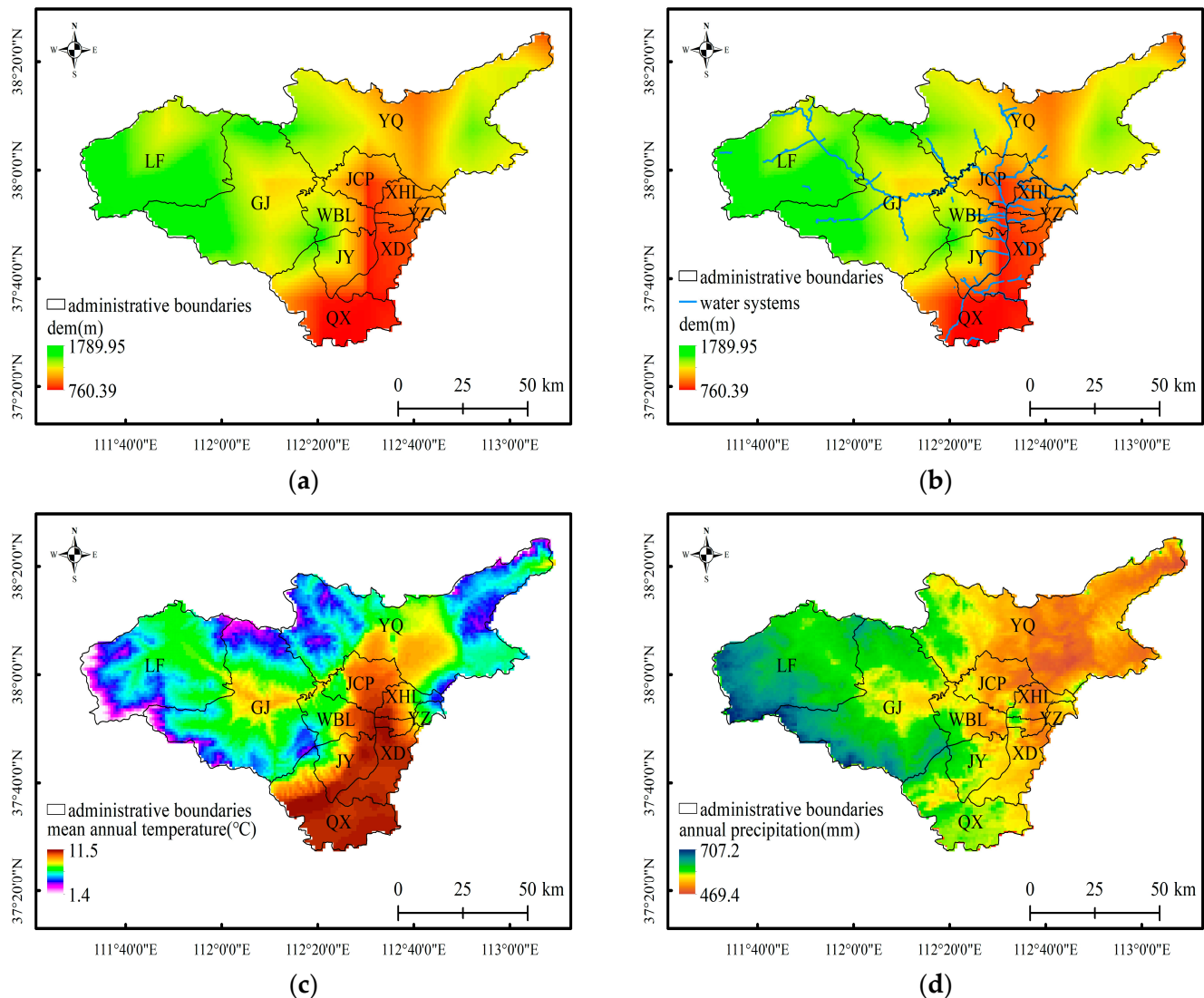


Figure 1. The basic information of Taiyuan. (a) Elevation; (b) water systems; (c) mean annual temperature; (d) annual precipitation. Note: GJ—Gujiao; JCP—Jiancaoping; JY—Jinyuan; LF—Loufan; QX—Qingxu; WBL—Wanbailin; XD—Xiaodian; XHL—Xinghualing; YQ—Yangqu; and YZ—Yingze.

Due to the topography and latitudinal and longitudinal variations, Taiyuan exhibits a temperate continental climate (Figure 1c). The city has an average annual temperature of 11.5 °C and receives 400–700 mm of precipitation yearly (Figure 1d). Taiyuan comprises six districts, three counties, and one county-level city. These include Jiancaoping, Jinyuan, Wanbailin, Xiaodian, Xinghualing, Yingze, Yangqu, Qingxu, Loufan, and Gujiao. As per the seventh national census of Taiyuan in 2021, the city had a population of approximately 5.3 million. Taiyuan has an annual crop planting area of 81.15 thousand hectares, with 64.03 thousand hectares for grains producing 257,644 tons—a 2.8% increase from 2021. The major crops in Taiyuan are wheat, maize, potatoes, oilseeds, edible fungi, fruits, and medicinal plants, vital to Shanxi Province's agriculture.

2.1.2. Data Sources and Preprocessing

The data in this study included the administrative boundaries of Taiyuan, digital elevation model (DEM), slope, monthly precipitation and average temperature, nature

reserves, 2020 land cover, roads, water systems, and the normalized difference vegetation Index (NDVI). Monthly precipitation data and monthly average temperature data were sourced from the National Science and Technology Infrastructure Platform—National Earth System Science Data Center [26]. The annual precipitation was the sum of the monthly precipitation, and the mean annual temperature was determined by averaging the monthly temperatures.

Data on Taiyuan's administrative boundaries [27], 2020 land cover [28], and water systems [29] were obtained from Resource and Environmental Science Data Registration and Publishing System. NDVI, DEM, nature reserves, and roads were obtained from the Resource and Environment Science and Data Center of the Chinese Academy of Sciences (<https://www.resdc.cn/data.aspx?DATAID=243>, accessed on 2 August 2003). Slope data were derived from a surface analysis of the DEM using ArcGIS 10.6. All raster data in this study used the WGS 1984 coordinate system with a 1 km × 1 km grid resolution.

Due to the irreversible impact of urban construction on the direction of land use and the significance of ecological conservation, urban construction and natural conservation areas were excluded from the Taiyuan agricultural land suitability assessment. Boundaries for natural conservation areas were sourced from the nature reserves dataset provided by the Resource and Environment Science and Data Center of the Chinese Academy of Sciences. Urban construction area boundaries were derived from the 2020 land cover data, which encompasses urban land, rural residential regions, and other constructed lands.

2.2. Methods

2.2.1. The Construction of the Index System

The factors that determine agricultural land suitability are varied and multifaceted. The evaluation index was selected based on the “Guidelines for Resource Environmental Carrying Capacity and Territorial Space Development Suitability Assessment of China (Trial)” (referred to as “Dual Assessment” guidelines) and the “Soil and Water Conservation Law of the People's Republic of China”, with consideration of Taiyuan's unique loess plateau topography. Considering data availability and drawing from existing studies [15,30], key natural parameters for agricultural land suitability assessment in this study included DEM, gradient, soil texture, soil erosion, distance to water sources, annual precipitation, and NDVI. Transportation factors, such as distance to roads, were also considered, as they significantly influence agricultural production.

For each selected assessment factor, levels were categorized to derive the single-factor assessment outcome for agricultural land suitability. Using the single-factor-level division, this study constructed a judgment matrix and determined weights for each factor through the analytic hierarchy process (AHP). Based on the single-factor assessment outcome and determined factor weights, the preliminary integrated assessment results of agricultural land suitability in Taiyuan were obtained. Finally, urban construction area and nature reserves data were employed for result correction, so the final integrated evaluation results of agricultural land suitability in Taiyuan were obtained. The assessment workflow of this study is illustrated in Figure 2.

2.2.2. Classification of Assessment Factor Levels

The classification of assessment factor levels is crucial for the reliability of agricultural land suitability assessment results. This research integrated the “Dual Assessment” guidelines with existing studies, considered the real conditions of Taiyuan, and accounted for attribute variations among different factors to categorize the assessment factors and assign them scores (Table 1).

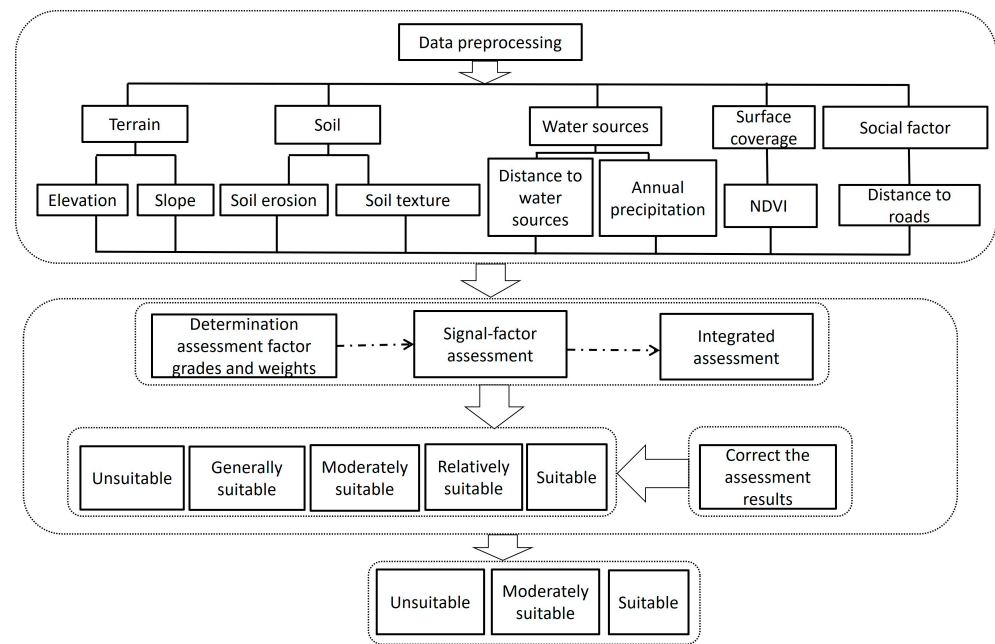


Figure 2. The workflow of agricultural land suitability assessment in Taiyuan.

Table 1. Classification of assessment factors and the corresponding score assignments.

Assessment Factors	Grading Criteria	Scores
DEM (m)	>900	5
	900–1100	4
	1100–1300	3
	1300–1500	2
	>1500	1
Slope (°)	0–2	5
	2–6	4
	6–15	3
	15–25	2
	>25	1
Soil erosion	slight	5
	light	4
	moderate	3
	strong	2
	very strong, severe	1
Soil texture (%)	<20	5
	20–40	4
	40–60	3
	60–80	2
	>80	1
Distance to water sources (km)	<1	5
	1–2	4
	2–3	3
	3–4	2
	>4	1
Annual precipitation (mm)	>1200	5
	800–1200	4
	400–800	3
	200–400	2
	<200	1

Table 1. Cont.

Assessment Factors	Grading Criteria	Scores
NDVI	<0.1	5
	0.1–0.3	4
	0.3–0.5	3
	0.5–0.7	2
	>0.7	1
Distance to roads (km)	<1	5
	1–2	4
	2–3	3
	3–4	2
	>4	1

1. DEM

Elevation significantly affects the accumulated environmental temperature and agricultural irrigation conditions. Insufficient temperature accumulation and water supply can hinder crop growth. Based on Taiyuan's geography and topography, elevations were categorized into five grades: below 900 m, 900–1100 m, 1100–1300 m, 1300–1500 m, and above 1500 m. The scores for each grade were 5, 4, 3, 2, and 1, respectively.

2. Slope

The slope indicates a region's terrain steepness and correlates with soil erosion and surface scouring. Generally, the smaller the slope, the gentler the terrain, and the more suitable it is for agricultural production. The "Soil and Water Conservation Law", banned crop cultivation on slopes steeper than 25°. In this study, based on slopes of 0~2°, 2~6°, 6~15°, 15~25°, and greater than 25°, Taiyuan City is divided into five grades: flatland, gentle slope, mild slope, moderately steep slope, and steep slope. The respective scores for each grade were 5, 4, 3, 2, and 1.

3. Soil erosion

In Taiyuan, hydraulic erosion is the primary cause of soil and water loss [31]. According to China's industry standard SL190-96 [32], "Soil Erosion Classification and Grading Standard", soil erosion is categorized into six levels: slight, light, moderate, strong, very strong, and severe. Very strong and severe erosion levels are unsuitable for agricultural activities. This present study combined these two levels into one, assigning it a score of 1. The scores assigned to the slight, light, moderate, and strong levels were 5, 4, 3, and 2, respectively.

4. Soil texture

Soil texture influences its water and nutrient retention, aeration, and root system development. This present study used soil silt content to characterize the suitability of soil texture for agricultural production. Based on the "Dual Assessment" guidelines and the "Third National Land Survey Technical Procedure" standards, this study categorized soil silt content into five groups: below 20%, 20–40%, 40–60%, 60–80%, and above 80%. Regions with soil silt content above 80% are unsuitable for agricultural production. The categories were scored as 5, 4, 3, 2, and 1, respectively.

5. Distance to water sources

Distance to rivers and channels indicates the potential for water access in agricultural production. Areas dense with river networks offer better irrigation conditions. The categorization of distance to water sources refers to the spatial distribution characteristics of the distance of farms from rural dwellings [33]. The distance was categorized into five levels: less than 1 km (near), 1–2 km (relatively near), 2–3 km (moderately near), 3–4 km (relatively far), and more than 4 km (far). The scores for each level were 5, 4, 3, 2, and 1, respectively.

6. Annual precipitation

Precipitation is a crucial moisture source for crop growth. Based on Taiyuan's actual precipitation and the "Dual Assessment" guidelines, this study classified annual precipitation into five grades: >1200 mm (very humid), 800–1200 mm (humid), 400–800 mm (semi-humid), 200–400 mm (semi-arid), and <200 mm (arid). Each grade was assigned a score from 5 to 1, respectively.

7. NDVI

Green vegetation plays vital ecological roles, such as conserving soil and water, replenishing water sources, and preventing wind erosion and sand movement. This study employed NDVI to quantify the surface coverage of green vegetation. A higher NDVI value indicates denser vegetation coverage, greater ecological importance, and reduced suitability for arbitrary agricultural activities. Based on Tang et al. [34], NDVI was segmented into five levels: >0.7, 0.5–0.7, 0.3–0.5, 0.1–0.3, and <0.1, corresponding to very high, high, moderately high, moderately low, and low vegetation cover, respectively. Scores of 1, 2, 3, 4, and 5 were assigned to these levels in that order.

8. Distance to roads

Generally, aside from agricultural cultivation bases requiring minimal external disturbances, convenient transportation significantly aids the growth of agricultural production activities. Therefore, areas near roads are preferable for agricultural activities. This study ranked distance to water sources at five levels: <1 km, 1–2 km, 2–3 km, 3–4 km, and ≥ 4 km, scoring them 5 to 1, respectively.

2.2.3. Determination of Assessment Factor Weights

This study employed the analytic hierarchy process (AHP), comparing factors two by two at each level, and the resulting judgment matrix was as follows:

$$C_{ij} = \begin{bmatrix} C_{11} & C_{12} \cdots & C_{1n} \\ C_{21} & C_{22} \cdots & C_{2n} \\ \vdots & \cdots & \vdots \\ C_{n1} & C_{n2} & C_{nn} \end{bmatrix} \quad (1)$$

where C_{ij} represents the importance ratio of C_i to C_j ($i, j = 1, 2, \dots, n$), and can be divided into five levels: equally important, slightly important, obviously important, strongly important, and extremely important. Herein, these levels assigned values of 1, 2, 3, 4, and 5, respectively, to construct a judgment matrix of agricultural production suitability in Taiyuan (Table 2).

Table 2. Assessment factor judgment matrix.

Assessment Factors	Elevation	Slope	Soil Erosion	Soil Texture	Distance to Water Sources	Annual Precipitation	NDVI	Distance to Roads
Elevation	1	1/3	1/2	1/2	1/5	1/3	2	1/2
Slope	3	1	3/2	4/3	3/5	1	6	3/2
Soil erosion	2	2/3	1	3/2	2/5	2/3	5	3/2
Soil texture	2	3/4	2/3	1	2/5	2/3	4	1
Distance to water sources	5	5/3	5/2	5/2	1	5/3	8	5/2
Annual precipitation	3	1	3/2	3/2	3/5	1	6	3/2
NDVI	1/2	1/6	1/5	1/4	1/8	1/6	1	1/4
Distance to roads	2	2/3	2/3	1	2/5	2/3	4	1

First, we normalized the column vector of the judgment matrix using $W_{ij} = C_{ij} / \sum_{i=1}^n C_{ij}$, obtaining the normalized column vector matrix W_{ij} ; Then, we added up the rows of the W_{ij}

to obtain the matrix W_i as $W_i = \sum_{j=1}^n W_{ij}$; Finally, we normalized W_i as $W_i = W_i / \sum_{i=1}^n W_i$, resulting in $W = (W_1, W_2, W_3, \dots)^T$, which gave the set of weight vectors. The approximation of the largest eigenroot was obtained by $\lambda = 1 / n \sum_{i=1}^n C W_i / W_i$. When the consistency check $CR = (CI/RI) < 0.1$, it is believed that the inconsistency level of matrix C_{ij} is within an acceptable range and the consistency test was successful.

The derived weight was $W = (0.054, 0.160, 0.124, 0.105, 0.264, 0.163, 0.027, 0.103)^T$, $CI = 0.005$; $RI = 1.410$; $CR = 0.004 < 0.1$, $CI = 0.005$; $RI = 1.410$; $CR = 0.004 < 0.1$, The consistency check was passed, with $\lambda_{max} = 8.034$.

2.2.4. Integrated Assessment Model

The integrated assessment score for suitability was derived from the weighted sum of each evaluation factor's grade scores using their respective weights. Based on the studies by Zhang [35] and Jiang et al. [17], the integrated assessment scores (5, 4, 3, 2, and 1) correspond to the suitability levels of suitable, relatively suitable, moderately suitable, generally suitable, and unsuitable, respectively. The integrated assessment model was as shown:

$$y = W_i F_i \quad (2)$$

where y indicates the integrated assessment score, W_i represents the weight value for each assessment factor, F_i is the score of each factor for suitability, and i stands for each assessment factor.

3. Results

3.1. Results of Single-Factor Assessment

1. DEM

Considering elevation, 12% of Taiyuan's land, mainly in the southern and southeastern regions, is suitable for agriculture. A total of 12% of Taiyuan's land, with a few narrow strips stretching from south to north in the central region, is relatively suitable for agriculture (Figure 3a). The central part of Taiyuan holds moderately and generally suitable areas, accounting for 22% and 32% of the land, with smaller sections in the northwest and northeast (Figure 3a). Finally, 21% of Taiyuan's land, primarily in the northwest, is unsuitable for agriculture (Figure 3a).

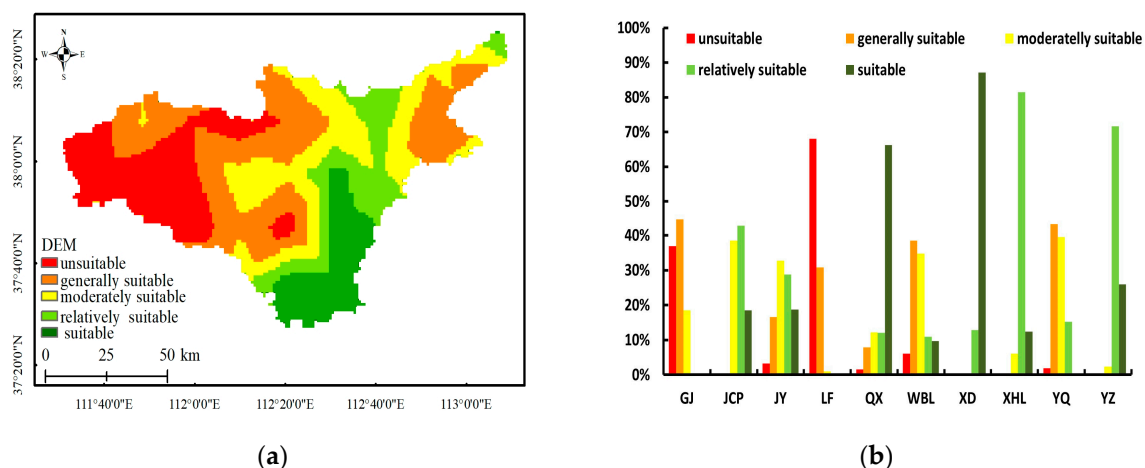


Figure 3. The result of single-factor assessment for elevation. (a) The spatial distribution pattern of agricultural land suitability for elevation. (b) Proportion of area with different suitability levels for elevation in each district/county. Note: GJ—Gujiao; JCP—Jiancaoping; JY—Jinyuan; LF—Loufan; QX—Qingxu; WBL—Wanbailin; XD—Xiaodian; XHL—Xinghualing; YQ—Yangqu; and YZ—Yingze.

At the county scale, areas unsuitable for agricultural production predominantly lie in the west and north of Gujiao (Figure 3b), cover most of Loufan, and are sparsely distributed

in Wanbailin and Jinyuan. Areas of general suitability are primarily located in most of Gujiao, northern Loufan, and eastern Yangqu. The areas that are generally suitable and unsuitable for farming cover the entirety of Loufan, suggesting that it is not ideal for agricultural cultivation. Areas of moderate suitability can be found in each administrative area other than Xiaodian. Areas of relative suitability are mainly distributed in Xinghualing and Yingze, but not in Gujiao. Qingxu and Xiaodian primarily contain areas suitable for agriculture, but Gujiao and Loufan contain few areas. Thus, the corresponding conclusion could be inferred that the overall agricultural production potential of Gujiao and Loufan is relatively low.

2. Slope

Considering the slope, areas suitable for agricultural production in Taiyuan are predominantly located in the southern and central regions (Figure 4a). Widespread areas are relatively suitable for agriculture, suggesting Taiyuan's abundant potential for arable land. The central region primarily contains areas that are moderately suitable for agriculture. Areas that are suitable, relatively suitable, and moderately suitable for agriculture cover 37%, 54%, and 9% of Taiyuan, respectively.

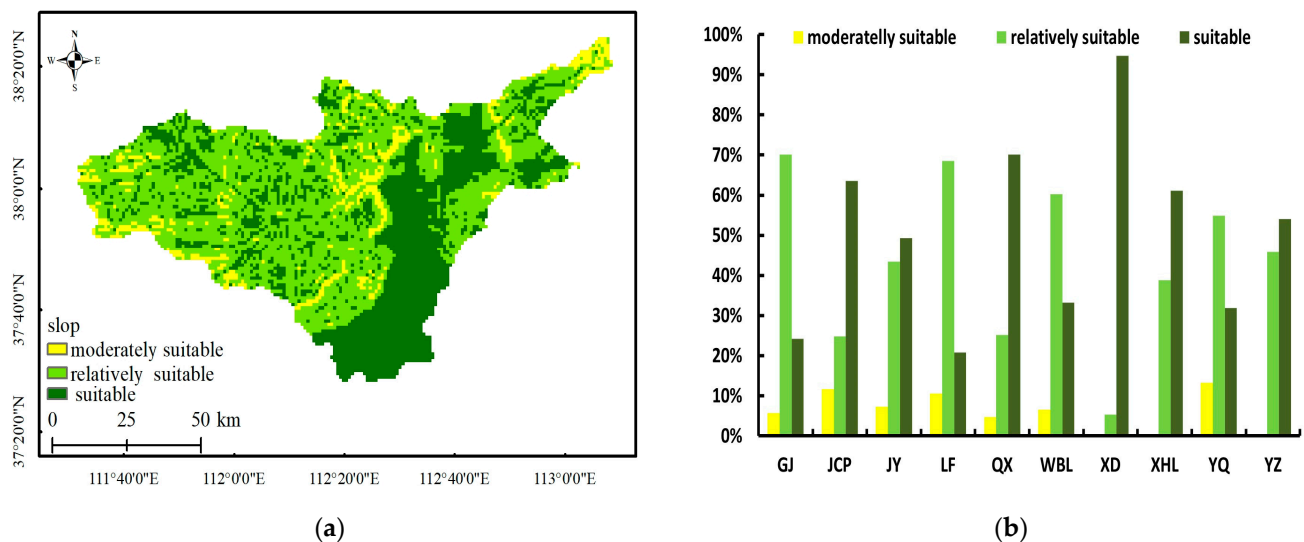


Figure 4. The result of single-factor assessment of slope. (a) The spatial distribution pattern of agricultural land suitability according to slope. (b) The spatial distribution pattern of agricultural land suitability according to slope. Note: GJ—Gujiao; JCP—Jiancaoping; JY—Jinyuan; LF—Loufan; QX—Qingxu; WBL—Wanbailin; XD—Xiaodian; XHL—Xinghualing; YQ—Yangqu; and YZ—Yingze.

At the county level, there are areas suitable for agricultural production within each administrative area, such as the southern and central parts of Qingxu, Xiaodian, Xinghualing, Gujia, Loufan, and Yangqu (Figure 4b). Areas relatively suitable for agriculture are primarily found in Gujiao, Loufan, and Yangqu. Areas moderately suitable for agriculture can be found in all administrative areas, except for Xiaodian, Xinghualing, and Yingze. Overall, Yangqu has the most widespread distribution of areas suitable for agriculture.

3. Soil erosion

In Taiyuan, the main areas with very strong soil erosion are in Loufan (northwest), comprising about 18.2% of Taiyuan's total area (Figure 5a). Pockets of strong soil erosion are found in both the western and eastern parts of Taiyuan. Areas with light or lesser degrees of soil erosion cover a broader area and are apt for agriculture. As soil erosion diminishes, agricultural land suitability improves, making up 3%, 6%, 27%, 12%, and 52% of Taiyuan's territory. In Jiancaoping, Jinyuan, Qingxu, and Xiaodian, the land is suitable for agriculture spans in 67%, 73%, 78%, and 89% of their respective areas (Figure 5b).

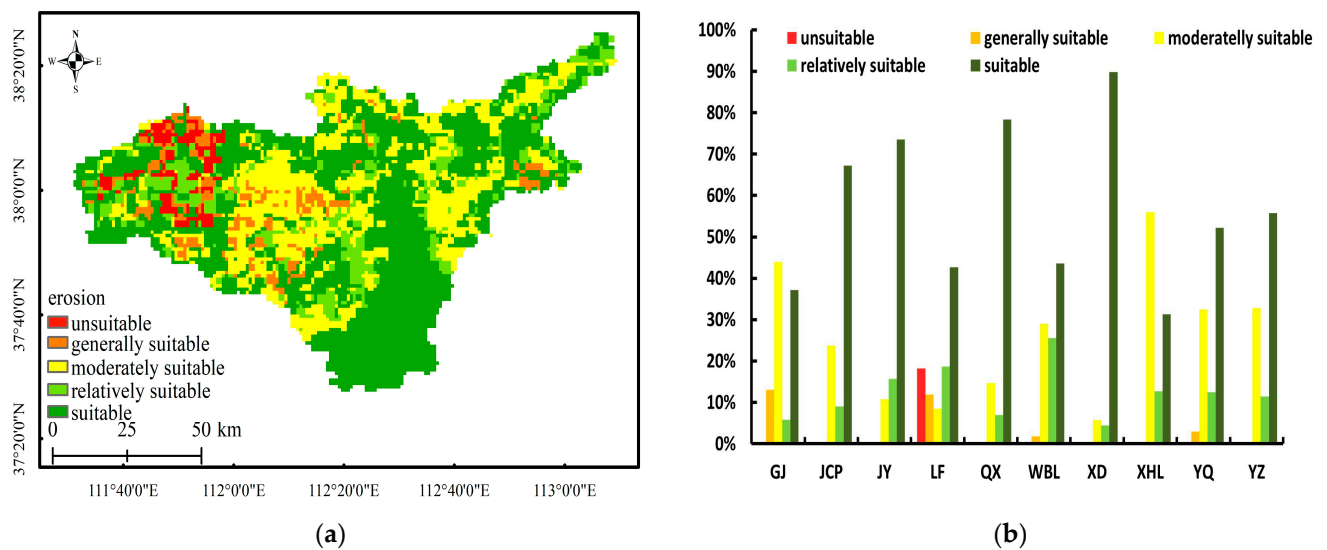


Figure 5. The result of single-factor assessment of soil erosion. (a) The spatial distribution pattern of agricultural land suitability according to soil erosion. (b) Proportion of areas with different suitability levels for soil erosion in each district/county. Note: GJ—Gujiao; JCP—Jiancaoping; JY—Jinyuan; LF—Loufan; QX—Qingxu; WBL—Wanbailin; XD—Xiaodian; XHL—Xinghualing; YQ—Yangqu; and YZ—Yingze.

4. Soil texture

From the perspective of soil texture, areas in Taiyuan with silt contents less than 20% occupy 99% of Taiyuan's land area, indicating that the soil in Taiyuan has high water retention, fertility, and permeability, making it suitable for agricultural production (Figure 6).

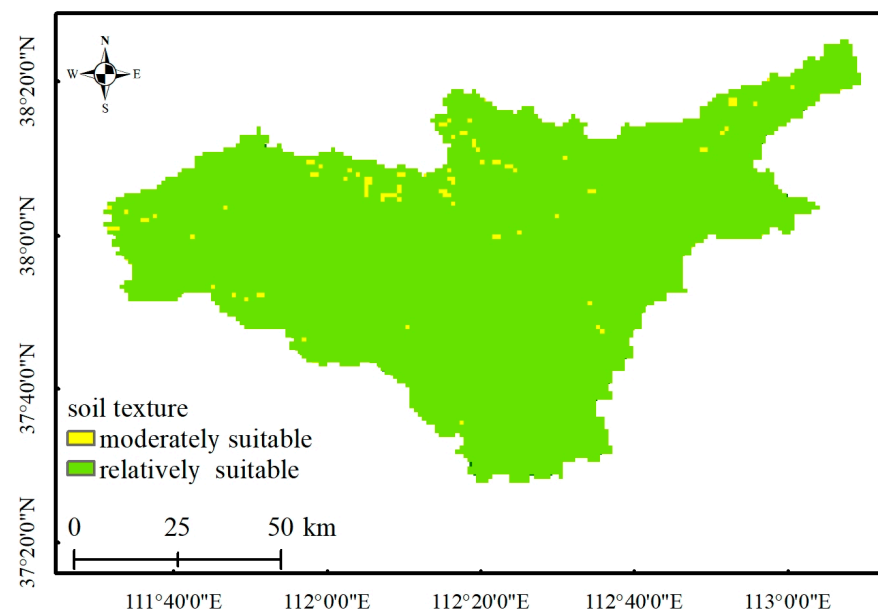


Figure 6. The results of single-factor assessment of soil texture.

5. Distance to water sources

Considering the distance to water sources, the regions in Taiyuan suitable for agriculture predominantly cluster around the primary river channels, representing just 17.26% of Taiyuan's total area. The northeastern, northern, and southwestern outskirts of Taiyuan primarily host areas unsuitable for agriculture, making up 50.64% of the city's land. Areas that

are relatively, moderately, and generally suitable, aligning generally with the distribution of suitable for agricultural production, account for 32.1% of the city's land (Figure 7a).

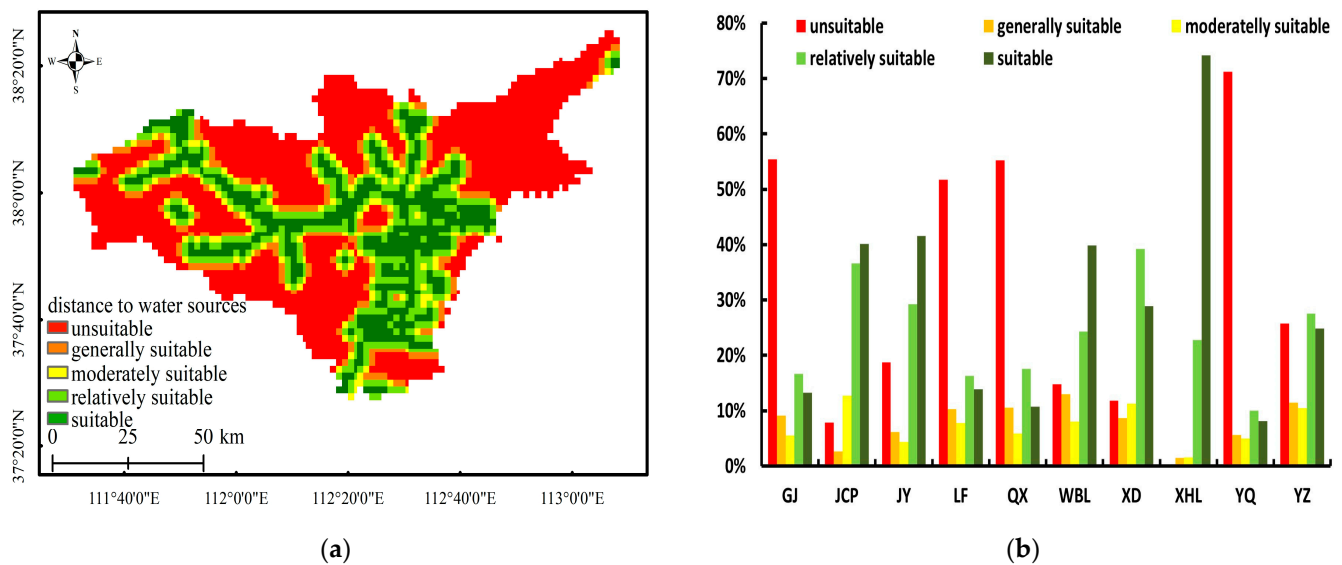


Figure 7. The result of single-factor assessment of distance to water sources. (a) The spatial distribution pattern of agricultural land suitability according to distance to water sources. (b) Proportion of area with different suitability levels for distance to water sources in each district/county. Note: GJ—Gujiao; JCP—Jiancaoping; JY—Jinyuan; LF—Loufan; QX—Qingxu; WBL—Wanbailin; XD—Xiaodian; XHL—Xinghualing; YQ—Yangqu; and YZ—Yingze.

At the county level, suitable agricultural areas are primarily found in Jinyua, Wanbailin, Xiaodian, Xinghualing, and Jiancaoping, comprising 40.13%, 39.83%, 28.91%, 74.18%, and 40.13% of their individual administrative regions. The regions unsuitable for agriculture are chiefly located in Yangqu (northeast), Loufan (northwest), and Gujiao (central Taiyuan). All administrative regions have five suitability grades, except for Xinghualing, which does not have unsuitability grades, as shown in Figure 7b.

6. Annual precipitation

Taiyuan experiences a warm, temperate, continental monsoon climate. Annual precipitation in Taiyuan varies between 400 and 800 mm, with a trend of increasing from the northeast to the southwest. Considering annual precipitation, Taiyuan's agricultural land is deemed moderately suitable. At the county level, western Loufan and Gujiao receive the most precipitation, whereas Jiancaoping, Xiaodian, Xinghualing, and Yingze receive less (Figure 8).

7. NDVI

From a vegetation coverage perspective, areas suitable for agricultural production in Taiyuan are mainly scattered in the central and northwestern regions, accounting for 0.75% of Taiyuan's land area. Regions relatively suitable for agriculture predominantly lie in the central and southern areas, covering 5.8% of the land area. Moderately suitable, generally suitable, and unsuitable areas are widely distributed, accounting for 7.4%, 27.5%, and 58.5% of Taiyuan's land area, respectively (Figure 9a). Areas in Gujiao and Yangqu, with dense vegetation coverage and vital ecological protection, are unsuitable for agriculture, representing 65.3% and 79.9% of their administrative regions, respectively. In Xiaodian and Yingze, areas suitable for agriculture constitute 4% and 6% of their administrative regions, respectively, as shown in Figure 9b.

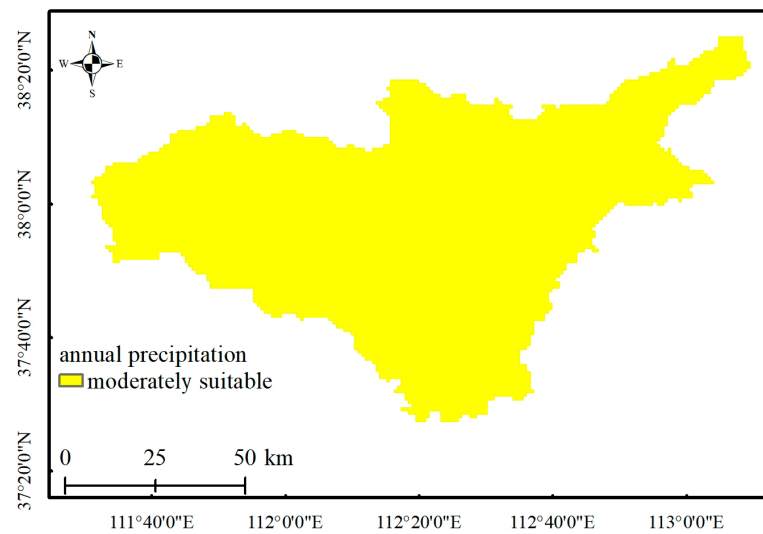


Figure 8. The result of single-factor assessment for annual precipitation.

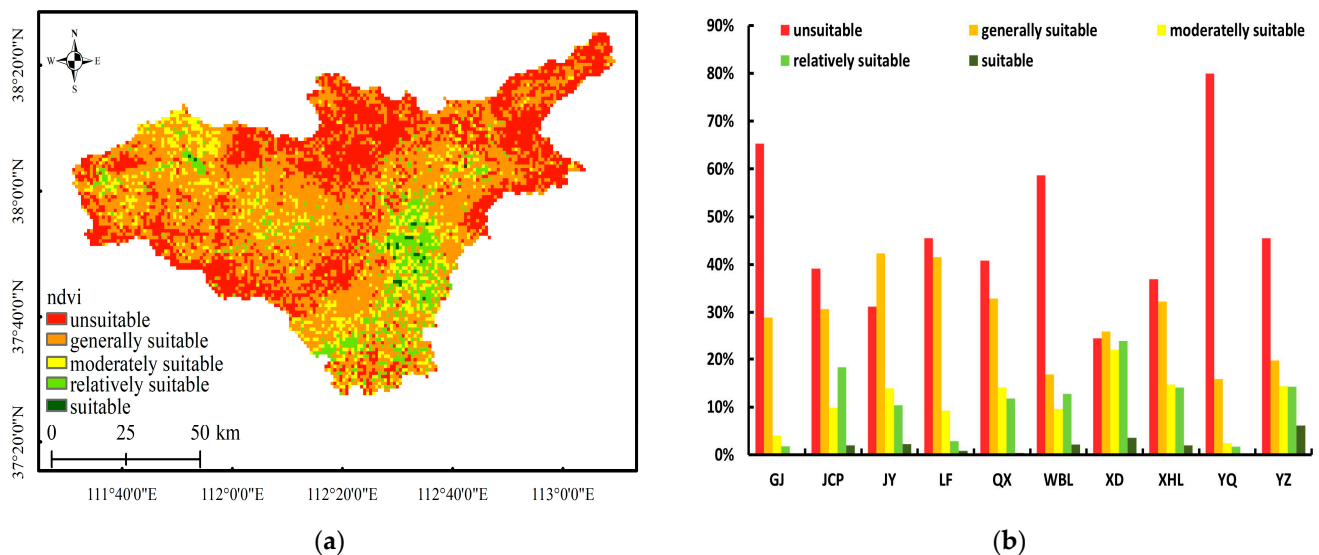


Figure 9. The result of single-factor assessment for NDVI. (a) The spatial distribution pattern of agricultural land suitability for NDVI. (b) Proportion of areas with different suitability levels for NDVI in each district/county. Note: GJ—Gujiao; JCP—Jiancaoping; JY—Jinyuan; LF—Loufan; QX—Qingxu; WBL—Wanbailin; XD—Xiaodian; XHL—Xinghualing; YQ—Yangqu; and YZ—Yingze.

8. Distance to roads

Road transportation convenience is pivotal to the ease of agricultural production. Areas in Taiyuan that are suitable for agriculture, based on road proximity, are primarily in the central, eastern, and southern regions, comprising 51.65% of the total land. Areas of relative, moderate, general suitability, and unsuitability are scattered, covering 25.83%, 6.44%, 6.91%, and 9.17% of Taiyuan's land, respectively (Figure 10a).

From the county-level perspective, regions in Taiyuan suitable for agricultural production are primarily located in the central and eastern areas, specifically in Jiancaoping, Jinyuan, Xiaodian, Xinghualing, and Yingze, accounting for 92%, 91%, 85%, 91%, and 81% of their respective administrative areas. Regions unsuitable for agriculture are primarily in Gujiao, Loufan, and the northeastern parts of Yangqu, making up 11%, 9%, and 16% of their respective administrative areas (Figure 10b).

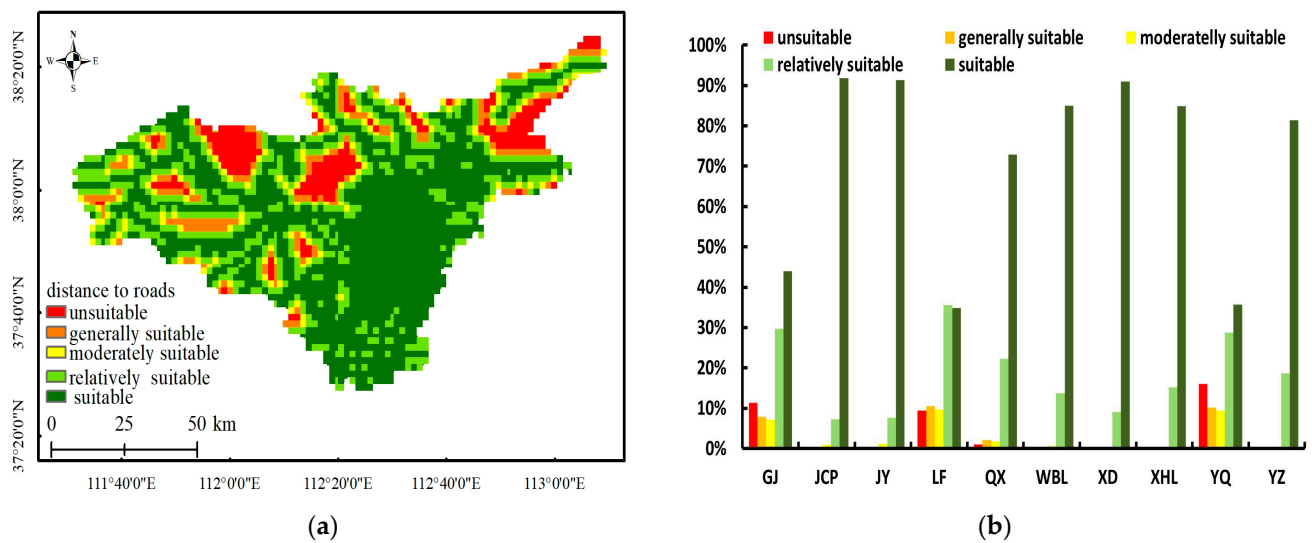


Figure 10. The result of single-factor assessment of distance to roads. (a) The spatial distribution pattern of agricultural land suitability according to distance to roads. (b) Proportion of areas with different suitability levels for distance to roads in each district/county. Note: GJ—Gujiao; JCP—Jiancaoping; JY—Jinyuan; LF—Loufan; QX—Qingxu; WBL—Wanbailin; XD—Xiaodian; XHL—Xinghualing; YQ—Yangqu; and YZ—Yingze.

3.2. Integrated Assessment Results

Based on the single-factor assessment results, this study used the geographically weighted regression method to determine the integrated suitability of agricultural land in Taiyuan. Not all single-factor assessments fit the five predefined categories (suitable, relatively suitable, moderately suitable, generally suitable, and unsuitable). Thus, the integrated assessment of Taiyuan's agricultural land yielded three levels: generally suitable, moderately suitable, and relatively suitable (Figure 11).

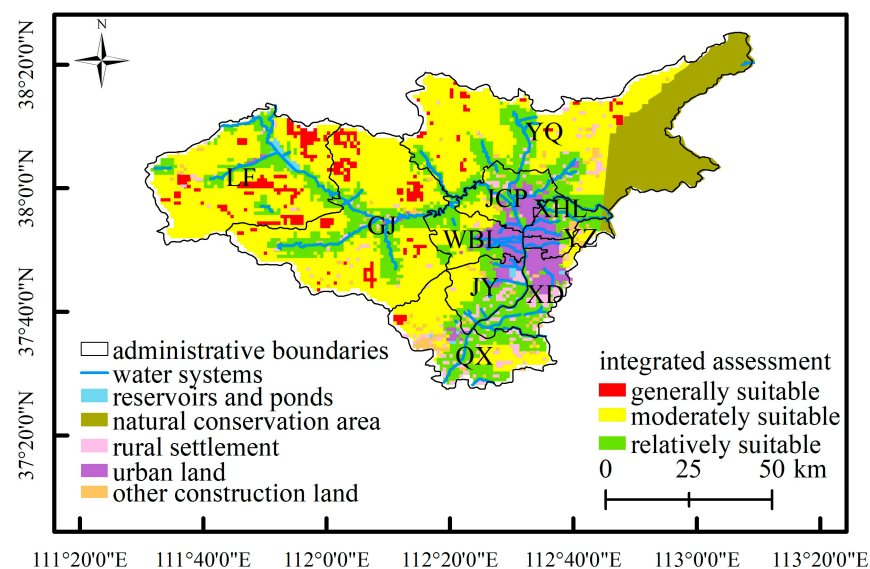


Figure 11. Integrated assessment results of agricultural land suitability in Taiyuan. Note: GJ—Gujiao; JCP—Jiancaoping; JY—Jinyuan; LF—Loufan; QX—Qingxu; WBL—Wanbailin; XD—Xiaodian; XHL—Xinghualing; YQ—Yangqu; and YZ—Yingze.

Areas in Taiyuan that are relatively suitable for agriculture comprise 33.1% of the total land (Table 3) and are mainly located in the central-eastern city zone (Figure 11), especially

in northern Gujiao, northeastern Loufan, and southwestern Yangqu. This pattern mirrors the distribution related to proximity to water sources (Figure 7). Areas moderately suited for agriculture make up 61.3% of Taiyuan's land (Table 3), and are predominantly found in the northern, northwestern, and western parts (Figure 11). Areas of general suitability intertwine with those that are moderately and relatively suitable. These areas are scattered across Gujiao, Loufan, Qingxu, and Yangqu, with a few adjacent land parcels (Figure 11).

Table 3. Area distribution of different suitability levels by district and county.

District/County	Generally Suitable		Moderately Suitable		Relatively Suitable		Total Area (km ²)
	Area (km ²)	Proportion (%)	Area (km ²)	Proportion (%)	Area (km ²)	Proportion (%)	
Gujiao	130	7.4	1198	68.1	433	24.6	1761
Jiancaoping	0	0.0	58	24.2	183	75.8	241
Jinyuan	0	0.0	100	37.7	165	62.3	266
Loufan	162	11.3	1004	70.0	269	18.8	1435
Qingxu	10	1.8	317	57.7	222	40.5	550
Wanbailin	0	0.0	121	47.3	135	52.7	255
Xiaodian	0	0.0	17	10.1	155	89.9	172
Xinghualing	0	0.0	3	2.7	98	97.3	100
Yangqu	47	3.3	977	69.3	385	27.4	1409
Yingze	0	0.0	23	54.1	19	45.9	42
Total area	348	5.6	3819	61.3	2064	33.1	6232

At the county scale, regions with moderate suitability for agricultural land are mainly distributed in Yangqu, Gujiao, and Loufan, comprising 69.3%, 68.1%, and 70% of their total areas, respectively (Table 3). The plots in these three regions have high continuity, which is ideal for large-scale cultivation. Regions with relative suitability for agricultural land are mainly located in Xinghualing, Xiaodian, and Jiancaoping, making up 97.3%, 89.9%, and 75.8% of their total areas, respectively (Table 3). In Xinghualing, Xiaodian, and Jiancaoping, developed transportation and water systems exist, and these areas have a lower altitude and slope compared to other counties. Favorable climatic conditions support vegetation growth, making these areas ideal for agricultural development in Taiyuan. However, their small administrative size and significant urban construction land proportion pose challenges for large-scale agricultural activities.

From the perspective of the county scale, areas moderately suitable for crop production are distributed mainly in Yangqu, Gujiao, and Loufan, accounting for 69.3%, 68.1%, and 70% of these administrative areas, respectively. These three county-level administrative regions have high plot connectivity levels in the mainland and are, thus, suitable for large-scale planting. The relatively suitable areas for agricultural production are distributed principally in Xinghualing, Xiaodian, and Jiancaoping, accounting for 97.3%, 89.9%, and 75.8% of their respective administrative areas; in these regions, transportation and water systems have been developed. These areas have lower elevations and slopes than other counties and districts and good hydrothermal conditions for vegetation growth. These places are, thus, the gold-standard locations suitable for developing crop production in Taiyuan; however, owing to their small administrative areas, urban construction areas occupy large proportions of their land space, and it is thus difficult to conduct large-scale agricultural production.

3.3. Cross-Validation of Assessment Results with Current Cultivated Data

This study further cross-validated the results of the agricultural land suitability assessment with the current data on cultivated land in Taiyuan. Initially, the current data on cultivated land, extracted from recent land use data (Figure 12b), was spatially overlaid with the distribution data of various suitability levels for agricultural land. This spatial overlay facilitated a detailed comparison of actual land use against assessed suitability. As

the final integrated assessment results of agricultural land suitability in Taiyuan yielded only three levels—generally suitable, moderately suitable, and relatively suitable—we analyzed the cross-validation results of the current cultivated land data with these three levels (Figure 12a).

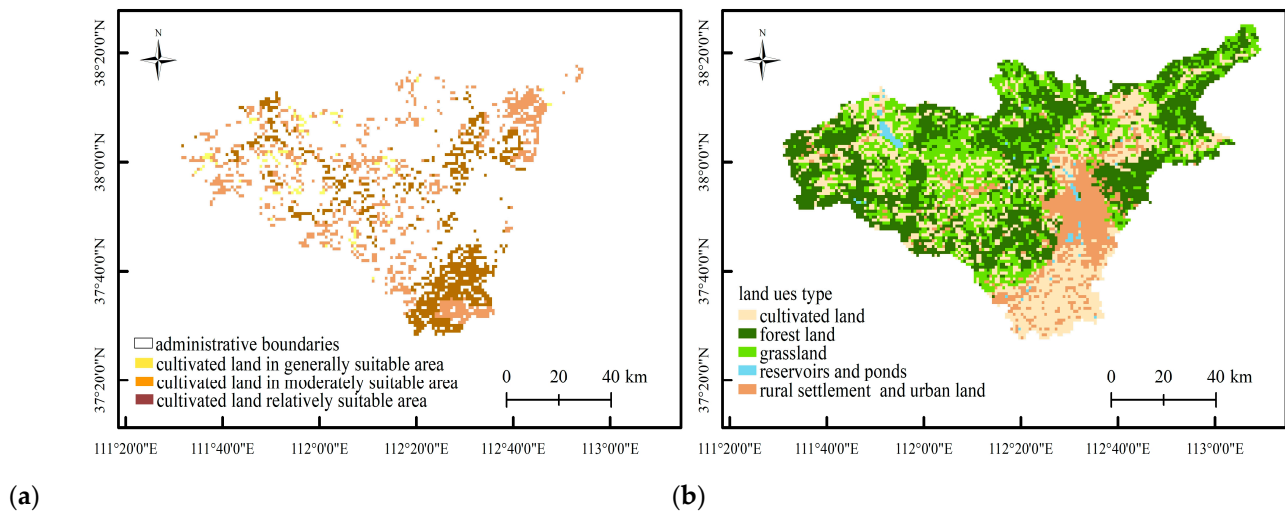


Figure 12. Cultivated land with various suitability levels and land use types. (a) Cultivated land with various suitability levels. (b) Land use type.

Based on the land use data from 2020, the total cultivated land area in Taiyuan is 1961 km². Within this, the area of cultivated land located in the relatively suitable regions is 882 km², accounting for 44.93% of the total cultivated land area of Taiyuan, and is predominantly concentrated in Xiaodian and Qingxu. Approximately 42.73% of the area in the relatively-suitable-grade regions is currently cultivated land. Theoretically, the relatively-suitable-grade areas are the more ideal regions for agricultural production in Taiyuan, but currently, only half of the area is used as cultivated land. The main reason for this may be the encroachment of urban construction land on agricultural land.

The cultivated land area distributed in the moderately-suitable-grade regions is 983 km², which accounts for 50.08% of the total cultivated land area of Taiyuan, scattered across all districts and counties beyond Xinghualing. Approximately 25.74% of the moderately suitable areas are currently used as cultivated land, and these lands represent potential zones for agricultural production in Taiyuan City. Given the ongoing increase in population and the rising demand for food, these potential areas might be converted into cultivable land in the future through enhancements in agricultural infrastructure, like farmlands. Therefore, the area of current cultivated land distributed in the moderately suitable regions exceeds half of the total cultivated land area in Taiyuan.

The area of cultivated land distributed in generally suitable grade areas is 98 km², accounting for 4.99% of the total cultivated land of Taiyuan, primarily located in Yangqu, Gujiao, and Loufan. In these areas, the high elevation and predominantly mountainous landscape, coupled with underdeveloped water systems, result in average annual temperatures lower than in other regions, theoretically hindering their suitability for agricultural activities. However, within the generally suitable areas, 28.14% is currently used as cultivated land, accounting for nearly one-third. An integrated analysis of the current cultivated land data revealed that 95.01% of it is situated in areas classified as moderately or relatively suitable for agricultural production, indicating a rational distribution of agricultural land in Taiyuan.

4. Discussion

Compared to previous studies conducted on a larger scale to assess agricultural land suitability [36], this study selected counties as assessment units at the city level,

which, to some extent, better meets the localized and detailed requirements of agricultural production planning and layout. Currently, the combination of geographic information technology and hierarchical analysis is one of the important methods for conducting suitability evaluation studies [2], and this study has also employed a comparable approach. To meticulously illustrate the spatial patterns of agricultural land suitability in Taiyuan, the spatial distributions of single-factor assessments were initially examined (Figures 3–10). Subsequently, a geographic weighted regression was performed on multiple assessment factors. Ultimately, the correction was made using data from natural conservation areas, simplifying the procedural steps and diminishing the complexity of the evaluation process relative to earlier studies [16].

Regarding the selection of assessment factors, this study took both natural and socio-economic factors into account, distinguishing it from certain previous studies. Kang et al., who approached their study from the perspective of agricultural production function, selected factors like grain yield per unit; proportion of output value in agriculture, forestry, animal husbandry, and fishery; economic density; fiscal contribution; and total fixed investment to construct an agricultural production suitability evaluation index system for Taiyuan [37]. Huang selected indicators such as cultivated land area, average agricultural output value per unit area, average livestock output value per unit area, and grassland area to construct an evaluation index system, and assessed the suitability of agricultural production in Taiyuan from both provincial and municipal perspectives [38]. In these previous studies, indicators were more heavily weighted towards socio-economic conditions, neglecting the impact of natural conditions on agricultural production. Moreover, in this study, grid data with a resolution of 1 km were employed to generate assessment factors, which, compared to previous research, took into account the differences both at the county scale and within the counties, leading to a more detailed assessment. To further investigate the credibility of the evaluation results, this study conducted a cross-validation with the current data on cultivated land [39]. The validation results revealed that 95.01% of the current cultivated land in Taiyuan is distributed in areas where agricultural production suitability was moderate or higher, indicating a relatively rational layout of agricultural land in Taiyuan.

Land ownership systems and agricultural production investment are both socio-economic phenomena [40]. Donkor et al. pointed out that the relationship between farmers and the land tenure system was influenced by various factors [41]. Socio-economic attributes, including residential status and racial disparities, can account for the land ownership decisions of farmers. Changes in land ownership systems can alter the subjective motivations of farmers, leading to shifts in agricultural production practices. Mao et al., focusing on cotton farmers in China, explored the relationship between property rights systems and the production behavior of different agricultural entities [42]. They concluded that land circulation inhibited farmers' green production practices, with this inhibitory effect being more significant among risk-averse farmers, local farmers, and minority farmers. Extending the duration of land-use rights could promote green production by farmers. Large-scale production farmers were more inclined towards green production. Thu et al. also confirmed that land ownership systems could alter the production behaviors of farmers [43].

The imperfection of present land ownership systems severely hinders the sustainable development of the agricultural economy [44]. Addressing the current issues, Trukhachev et al. explored potential paths for sustainable agricultural economic development from the perspective of land ownership relations [45]. Yang et al., in the context of specific practices in banana production, also confirmed the relationship between land tenure systems and sustainable agricultural production [46]. Previous research has indicated a positive correlation between the stability of land ownership and the adoption of sustainable agricultural practices by farmers, particularly among those who own their cultivated farmland. Akram et al. also believed that compared to tenants, landowners were more willing to implement strategies for soil improvement and increased agricultural productivity, thus promoting

sustainable development in the agricultural economy [47]. Zhang et al., regarding land tenure systems as an agricultural production factor, explored the causal effects between land tenure systems and agricultural production efficiency [48]. They demonstrated that the stability of land property rights may directly or indirectly affect agricultural production efficiency. There was diversity in terms of how it improved the agricultural production efficiency.

The ownership system is widely applied in poverty alleviation, such as poverty alleviation through land assetization. This poverty alleviation model is akin to asset income poverty alleviation in its logic: changing the status of land property rights, participating in the market as asset shareholders, and increasing the income avenues for the poor. Guo et al. have validated the practical significance of poverty alleviation through land assetization. They indicated that the root cause of rural poverty lied in land issues. The key to eradicating poverty lied in the assetization of land property rights, creating a mechanism for sharing linked benefits and fostering the sustained impact of land assetization in poverty alleviation [40]. The challenge of acquiring and spatially quantifying land property rights data means that this research does not account for the influence of systemic factors, particularly land property rights systems, on the evaluation results, potentially impacting their reliability.

Due to the difficulty of obtaining land ownership data and its challenge in spatial quantification, this study did not consider the impact of institutional factors, especially land ownership systems, on the assessment results, which may affect the credibility of the outcomes.

5. Conclusions and Policy Implications

In this study, Taiyuan's agricultural land suitability was assessed by integrating raster data factors with 1 km spatial resolution, such as topography, soil, water sources, and social conditions, using a geographic information system (GIS) and the analytic hierarchy process (AHP). The objectives were to delineate the spatial distribution of agricultural land suitability and discern county-level variations within Taiyuan. This study provides insights into enhancing agricultural land allocation and fostering sustainable development in Taiyuan. The primary findings and recommendations from our research include:

(1) In Taiyuan, the agricultural land suitability does not reach the extremes of being either "unsuitable" (lowest rank) or "suitable" (highest rank). This suggests that Taiyuan's overall agricultural production potential is intermediate. The spatial distribution pattern of agricultural land suitability is generally higher in the east and lower in the west, showing significant spatial heterogeneities. Generally, suitable areas only constitute 5.6% of Taiyuan's land. In contrast, moderately and relatively suitable areas cover 61.3% and 33.1%, respectively.

Relatively suitable areas are predominantly in Taiyuan's central and eastern regions, aligning with the distribution of population, roadways, and rivers. These areas have soils with low silt contents, indicating favorable water and environmental conditions for agriculture. However, within the relatively suitable areas, only 42.73% is currently used as cultivated land, accounting for less than half, which may be related to the demand for land resources due to rapid urban development. To some extent, this limits the development space for agriculture. Moving forward, these regions should focus on crops with high economic returns to meet diverse market demands.

Areas of moderate suitability are prevalent in the northern, western, and central regions, where topographical constraints primarily limit agricultural production. In addition, marginal areas in the north and west are also influenced by water availability and transportation. Within the moderately suitable areas, 25.74% is currently used as cultivated land. These areas should opt for drought-resistant crop varieties. Additionally, there should be a push for high-standard farmland construction and mechanization projects to boost agricultural infrastructure and land productivity.

Generally suitable areas exhibit the distribution characteristic of “broad dispersal and minor clustering”. These regions are primarily located in the western mountainous regions characterized by steep terrain, poor location conditions, and inadequate water supply. In regions generally suitable for agricultural production, nearly one-third of the land has been cultivated for farming. In the later stages, it is necessary to follow the principle of ecological priority and systematically retire farmland that is less productive and potentially harmful to the ecological environment.

(2) From the perspective of county-level industrial economics, differentiated agricultural production models and land-use adjustment strategies should be adopted for various county-level regions. For areas like Qingxu, Wanbailin, Xiaodian, Jinyuan, Xinghualing, Yingze, and Jiancaoping, which are suitable for agricultural production and located in the Fen River valley with the necessary heat and soil conditions for agriculture, the administrative regions are relatively small and the urban construction areas are large, highlighting the conflict between population and land. Therefore, it is feasible to develop agritourism or boutique agriculture in these areas suitable for agricultural production, creating high-value-added agricultural products to meet the demands of urban residents while exploiting the multifunctionality of agriculture.

Loufan, located in the middle and upper reaches of the Fen River, within the northwestern Loess Plateau, has loose soil and a fragile ecological environment. Surrounded by mountains in the southwest and undulating hills in the northeast, the terrain is higher in the southwest and lower in the northeast. Spring cold and frost events occur frequently. Therefore, on the basis of protecting water sources and ecological barriers, it is possible to cultivate cold-resistant and soil-consolidating crops, such as sorghum and wheat. Due to the steep terrain and human activities in the aforementioned areas, soil erosion is severe. Implementing fish-scale pit projects can facilitate planting within these pits, help to retain water and nutrients, and prevent soil erosion.

Yangqu faces water scarcity. The northeastern part of Yangqu is home to a significant natural conservation area, commonly known as the “natural oxygen bar”. Under the premise of prioritizing ecological protection, it is feasible to undertake the construction of biological corridors and appropriately plant drought-resistant crops like peach and sea buckthorn, which offer both economic and ecological benefits, thus promoting sustainable agricultural development in the county.

This study explored agricultural land suitability at the county scale. Due to diverse and complex factors affecting agricultural production and constraints on data availability, this research has certain limitations. (1) Impacts of extreme climate events and disaster incidents on agricultural production were not considered; (2) differences in crop types were not considered in the assessment results; and (3) the impact of institutional factors, especially land ownership systems, was neglected due to difficulties in obtaining relevant data. These aspects will be further explored in subsequent research.

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