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Integrated Quantity, Quality and Ecology of County-Level Arable Land Improvement Potential Comprehensive Zoning: The Example of Tongxu County, China

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Abstract

The scientific evaluation of arable land remediation potential can be used to formulate remediation policies based on local conditions. This study took arable land resources in Tongxu County, China as the research object and administrative villages as the evaluation unit, constructed an evaluation index system by integrating three aspects—quantity, quality and ecology. Based on the evaluation of arable land remediation potential, the K-means++ spatial clustering algorithm combined with elbow method is used to divide the remediation partition and give the remediation strategy. The results showed that: 1) the evaluation index system of arable land improvement potential, which integrated "quantity-quality-ecology", was more systematic in analyzing the potential of arable land improvement than the previous single target evaluation index, and explored its internal linkage. 2) There are some spatial differences in the quantitative, qualitative and ecological potentials in Tongxu County, with the quantitative potential being higher in Changzhi Township, the intersection of Lizhuang Township and the southern part of Yuhuangmiao Township, the qualitative potential being more evenly distributed, and the ecological potential being higher around Chengguan Township. 3) Through K-means++ clustering algorithm combined with elbow method, Tongxu County was divided into five subzones: quality improvement zone, intensive improvement zone, quantity improvement zone, comprehensive improvement zone and health improvement zone, among which the highest percentage of quality improvement zone and the lowest percentage of comprehensive improvement zone were 49.2% and 1.5% respectively, and differentiated remediation strategies were provided by research for each sub-district to promote high quality of arable land.

Keywords

Arable Land Remediation, Potential Evaluation, Remediation Zoning, K-Means++

1. Introduction

Land resources are the basic resources for human survival and development. As the best part of land resources, the development of urbanization and industrialization has led to the decrease of arable land, especially the encroachment of high quality arable land resources and the pollution of arable land by heavy metals, resulting in the unsustainable utilization of arable land resources (Irwin & Bockstael, 2007; Sklenicka, Janovska, Salek, Vlasak, & Molnarova, 2014; Teshome, Graaff, Ritsema, & Kassie, 2016). The improvement of arable land is an important step to realize the transformation of land use from rough to intensive and economical (Tan, Heerink, & Qu, 2004).

Arable land remediation potential is the ability to achieve an optimal state, in terms of the reorganization and reoptimization of the utilization mode, intensity, distribution and human-land relationship of arable land resources within a certain area, integrating the needs of social and economic development (Song & OuYang, 2012). The scientific evaluation and comprehensive zoning of arable land remediation potential can provide a basis and reference for determining key areas of arable land remediation and formulating remediation plans. It can effectively solve the problems of the declining quality, increasing fragmentation, decreasing production capacity and deteriorating ecological environment of arable land (Sun et al., 2020). Therefore, how to conduct scientific assessments of arable land remediation potential, involving whole-area coverage, and how to rationalize the layout of an arable land remediation zoning strategy are important issues that need to be studied (Zhang, Tian, & Bi, 2020).

Previous research on arable land remediation has mainly focused on improving the quantity and quality of arable land (Jia, 2012). It calculated the total amount of replenishable cropland through the coefficient of new cropland (Yan, Hou, Zhu, Wang, & Cheng, 2004), and it assessed the quality of the improvement potential based on Agricultural land class-based upgraded (Gao et al., 2016; Tang, Pan, Liu, & Ren, 2014) or restrictive factor improvements (Zhao, Liu, Zhang, & Wang, 2019; Zhao, Xu, Zhang, Zhou, & Chang, 2020). At present, some scholars begin to express the ecological potential of arable land remediation using the change values of ecosystems services, environmental enhancement, landscape improvement, ecological risk and other aspects (Huang, 2020; Pei, Wei, Wang, Qin, & Hou, 2014; Xie, Zhang, Zhang, Chen, & Li, 2015). Howerer, in general most studies have a single objective of cropland remediation. With the continuous development of green development and ecological civilization construction (Tang, Pan, Hao, & Liu, 2015), it is difficult to meet the requirements of single target arable land remediation. And it has become a new requirement to promote the "trinity" protection of arable land in terms of quantity, quality, and ecology. So it is of great significance to systematically analyze the potential of arable land remediation to solve the problems of spatial development and utilization, restore the spatial function of the land, and improve the spatial quality of the land (Yan et al., 2004).

In terms of remediation partitioning methods, most scholars have used cluster analysis (Yan, 2014), spatial autocorrelation (Fan, 2019), weighted summation modeling (Zheng, Jiang, & Zhang, 2018), and topographic features (An & Tian, 2018) to study remediation zoning. The k-means cluster analysis algorithm has also been widely applied to land remediation, arable land productivity and ecological functions because of its advantages of easy implementation, suitability for high-dimensional data and good reflection of the spatial aggregation characteristics of arable land. However, because the results are largely influenced by the number of clusters, and the initial cluster center selection, sometimes the most ideal results cannot be achieved. The K-means++ cluster analysis method is able to better determine the initial cluster center, and the elbow method can determine the optimal effect when the number of clusters has been determined.

Based on this, this study took Tongxu County of Henan Province—a typical grain-producing area in China—as the research object and, from the perspective of a comprehensive analysis of quantity, quality and ecology, built an evaluation index system based on quantity, quality and ecology to evaluate the potential. And k-means++ cluster analysis combined with the elbow method was employed to partition the potential of arable land remediation on the basis of its potential evaluation. These aimed to provide a reference for the preparation and implementation of land remediation planning in the new era.

2. Materials and Methods

2.1. Study Area

Tongxu County is located in the central eastern part of Henan Province, Chian, in the middle and lower reaches of the Yellow River, and belongs to the East Henan Plain, the terrain of which is inclined from the northwest to the southeast (**Figure 1**). The relative difference in ground elevation is about 10 m, the slope being small. The county's soil area is 64249.47 ha, with sandy and silty soils being predominant, accounting for 99.45% of the soil area. The annual rainfall is 682 mm, and the average annual temperature is 14.6˚C. The main crops are winter wheat and summer corn. With economic development, industrial land has encroached on the arable land and the environment has deteriorated. The total arable land decreased by 1805.21 ha between 2009 and 2019, while the fragmentation of arable land patches is continuing to increase, year after year. As an agricultural region with a low degree of intensification, Tongxu County is strongly typical, lending itself to the study of its arable land remediation evaluation and zoning strategy.

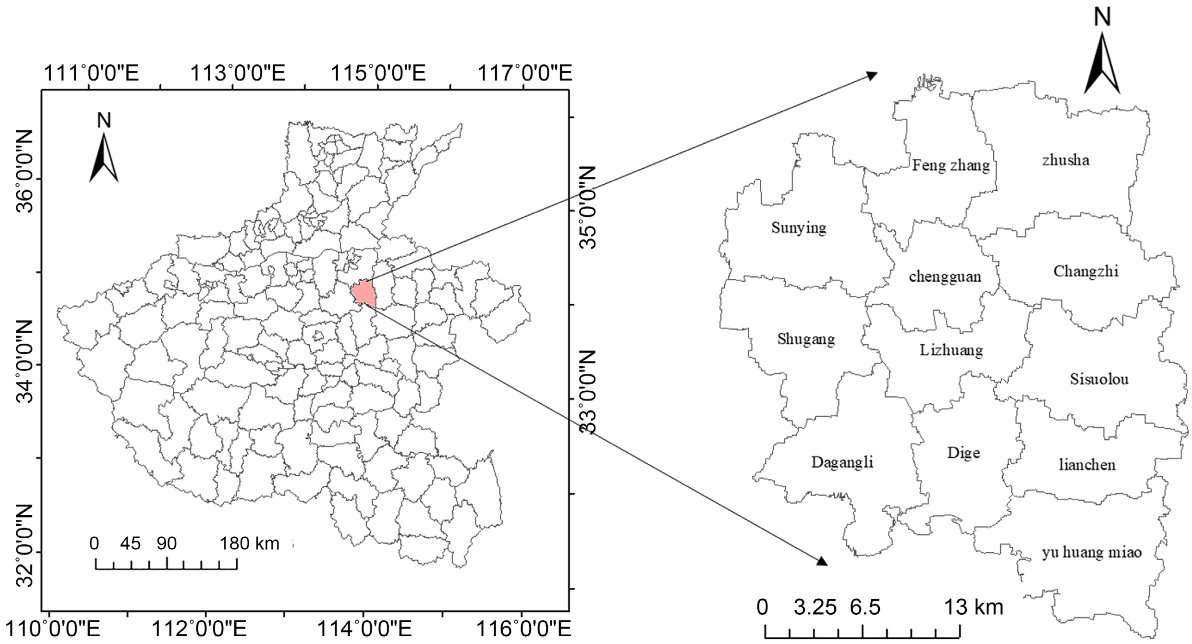

Figure 1. Location map of Tongxu County.

2.2. Methodological and Data Resources

Land-use data were accessed from the database of the Third National Land Survey of Tongxu County. They included arable land, field cans, ditches, ponds and water, rural roads and other land, administrative district boundary-attribute data, and village survey area boundary-attribute data (see Classification of Current Land Use Situation GBT 21010-2017 and Land Survey Database Standard).

The arable land quality data were from the 2015 county-level agricultural land classification unit database, and included the natural grade index, utilization grade index and land-use coefficient (see Agricultural Land Quality Classification Database Standards). Socioeconomic data were obtained from the 2016-2017 yearbook of Tongxu County.

Taking into account the accessibility of the data and the comprehensiveness of the potential measurements, this study took the administrative village as the evaluation unit for the calculations, with 319 evaluation units being obtained. Firstly, the evaluation index system was constructed in terms of quantity, quality and ecology. And then the potential evaluation was carried out by calculating each index and the comprehensive potential value of each evaluation unit. Finally, the remediation partition was calculated using a combination of the K-means++ clustering method and the elbow method. Based on the potential characteristics of the partition, a remediation strategy was provided. When calculating the comprehensive potential value of each evaluation unit, the entropy weight method was used to calculate the weight, and then the weighted summation method was used to obtain the final remediation potential for each evaluation unit. Finally, the natural breakpoint method in ArcMap was used to classify the remediation potential of the arable land (Figure 2).

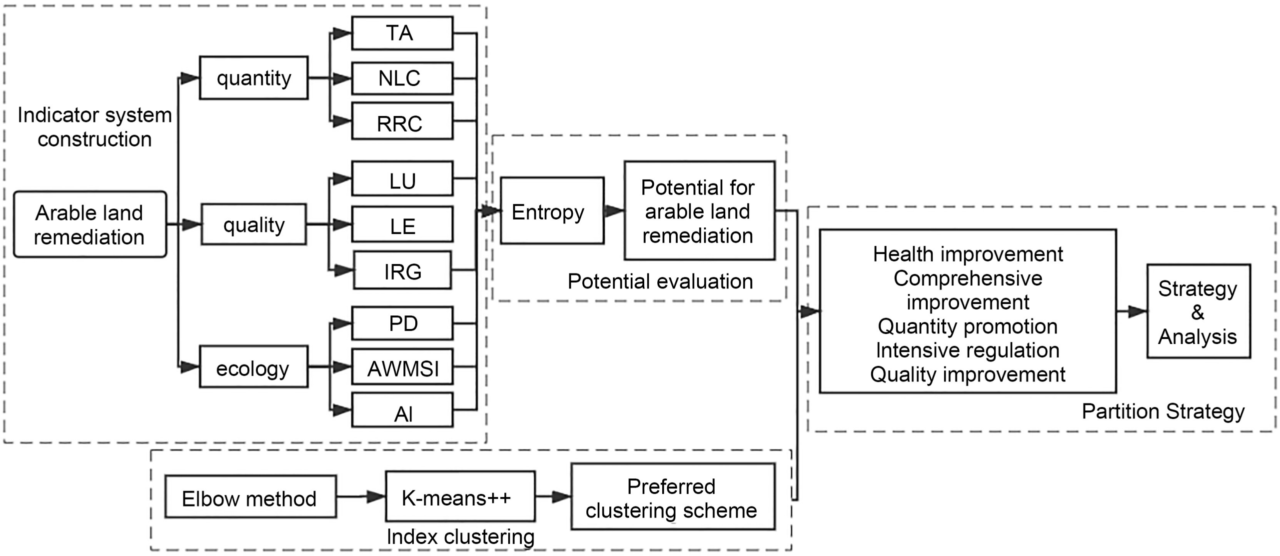

Figure 2. Research ideas.

2.3. Construction of Evaluation Index System

Following the principles of comprehensiveness, dominance, regional differences, science and operability, this paper constructs an integrated "quantity-quality-ecology" index system for evaluating the potential of arable land remediation to achieve the multiple goals of increasing arable land area, improving arable land productivity and optimizing landscape ecological patterns.

The quantitative potential is expressed in increasing the effective arable land area by reducing the proportion of other types of land and related agricultural facilities land in the arable land (Liu, 2019). The total area to be remediated indicates the total coverage that can be used to increase the area of arable land, the non-cultivated land coefficient expresses the distribution of arable land, and non-cultivated land, and the reserve resource coefficient indicates the proportion that can be converted into arable land after remediation. The area of arable land to be remediated, the non-cultivated land coefficient, and the reserve resource coefficient are selected in this paper to effectively reflect the potential to increase the effective area after remediation.

The quality potential of arable land improvement lies in improving the natural state or existing utilization level of arable land through arable land improvement engineering measures in order to improve the production capacity of arable land. The land use improvement index indicates the closeness of the available indicated actual output level to the maximum local actual output level. The land economic improvement index indicates the progressive degree of capital input efficiency to the maximum local input efficiency. And the irrigation guarantee rate reflects the guarantee of arable land capacity facilities. These three indicators were selected to characterize the potential of each administrative village in improving the productivity of arable land and increasing food production.

At present, the meaning of ecological potential is rich. Considering that, Tongxu County is located in the central flatlands with little topographic changes and a high proportion of arable land, but the fragmentation of arable land is deepening. By introducing the landscape ecology pattern index into the analysis of arable land potential, we can consider the form of spatial layout of arable land panels and optimize spatial allocation (Li, Hai, & Liu, 2018), which is consistent with the goal of arable land remediation. The ecological potential in this paper refers to the analysis of the state of regional landscape ecological pattern from the perspective of landscape pattern, which can optimize the potential of land use structure through remediation, and also reflects the urgency of remediation. In terms of index selection, drawing on existing research results (Li, Li, Lv, & Liu, 2017), we chose the patch density to characterize the characteristics of arable land elements, the area-weighted shape index to characterize the shape of plots, and the aggregation index to characterize the degree of aggregation of arable land.

A summary of the evaluation index system for arable land remediation is shown in **Table 1**.

2.4. Arable Land Potential Evaluation Methods

2.4.1. Arable Land Potential Evaluation Methods

The entropy weighting method determines the weights based on the magnitude of the variability of the indicators (Liu et al., 2022). The premise is that, if the information entropy of an indicator is small, the greater the degree of variability the indicator deserves, the greater the role it can play in the comprehensive evaluation, and the greater its weight. In this paper, the potential value of each administrative village under each indicator is standardized and input, and the weight of the indicator under the comprehensive evaluation index system is calculated. The specific steps are given below.

Calculate the weight of the *i*th evaluation unit under the *j*th indicator:

$$p_{ij} = \frac{r_{ij}}{\sum_{i=1}^{n} r_{ij}} \tag{1}$$

In the Equation, r_{ij} denotes the standardized value of the *j*th evaluation index of the *j*th administrative village.

Calculate the information entropy of the *j*th indicator:

$$e_j = -k \sum_{i=1}^{n} p_{ij} \ln\left(p_{ij}\right) \tag{2}$$

In the Equation, $k = \frac{1}{\ln(n)} > 0$, $e_j \geq 0$.

Determine the weights of each indicator:

$$w_{ij} = \frac{1 - e_j}{\sum_{j=1}^{m} \left(1 - e_j\right)} \tag{3}$$

Table 1. Evaluation index system of cultivated land remediation potential.

Guideline layer	Indicator layer	Calculation method	Description	Indicator attributes
Quantity	Total area to be remediated	TAR	This study refers to arable land, land for related supporting facilities, serving agricultural production (fields and canals, ditches, ponds and water, rural roads, etc.), and other agricultural land and vacant land of small size distributed among arable land, etc.	+
	Non-cultivated land coefficient	$NLC = D_c + D_d + D_p + D_r + D_a$	D_c, D_d, D_p, D_r, D_a are the proportions of dry ditch, ditch, pond water surface, rural road and field can in agricultural land, respectively	+
	Reserve resource coefficient	$RRC = \frac{R}{A}$	R is the reserve resource of arable land in the village, A is the area of arable land in the village	+
Quality	Land use improvement index	$LU = 1 - \frac{Y_i}{Y_{\max}}$	Y_i is the unit yield of the designated crop in the village under normal input, and $Y_{\max}$ is the highest unit yield of the designated crop in the province	+
	Land use improvement index	$LE = 1 - \frac{m_i}{M_{\max}}$	m_i is the output-cost index of the designated crop in the village, and $M_{\max}$ is the maximum output-cost index of the designated crop in the province	+
	Irrigation guarantee rate	$IGR = \frac{DH + DR + DK}{3}$	DH is the density of rivers in the evaluation unit, DR is the density of reservoirs in the evaluation unit, DK is the density of ponds in the evaluation unit	+
Ecology	Patch density	$PD = \frac{N}{A}$	N is the number of cultivated patches in the village, A is the total area of cultivated patches in the village	+
	Area-weighted mean shape index	$AWMSI = \sum_{i}^{n} \left(\frac{0.25P_i}{\sqrt{a_i}} \right) \left(\frac{a_i}{A} \right)$	The perimeter of each patch is divided by the square root of the area, multiplied by the ratio of the patch area to the total area of cultivated land, which are then added together	-
	Aggregation index	$AI = \left[\frac{g_i}{\max \to g_{ii}} \right]$	g_{ii} is the number of similar adjacent patches of the corresponding landscape type, AI is based on the same type of area, calculated by the length of the common boundary between pixels	-

2.4.2. Weighted Summation Calculation of Comprehensive Potential

The potential of each administrative village is the weighted sum of the potential value of each indicator and the weight of the corresponding indicator (Yu, Luo, Wang, & Zheng, 2020):

$$F_i = \sum_{i=1}^{m} w_j * r_{ij} \tag{4}$$

In the formula, F_i is the potential value of the ith administrative village.

2.5. Cultivated Land Potential Partitioning Method

K-means clustering belongs to unsupervised learning method. Based on the size of the spacing between samples, the mean value of the divided class cluster points is taken as the centroid (center of mass) of the class cluster. The centroid of each class cluster and class cluster division are automatically calculated and updated through continuous iteration of the data set until the cycle stops when the center of the cluster converges, dividing the sample set into K classes (Xie, Liu, & Wei, 2021). K-means++ randomly selects a point as the initial cluster centroid on the basis of K-means randomly selects all initial cluster centroids, calculates the probability of becoming the next cluster center according to the distance between the remaining samples and the nearest cluster center, and the roulette wheel method selects the next cluster center. It iterates until the next cluster center is selected all clustering centroids, reducing the large differences in results due to different initial clustering centers.

In this paper, we use K-means++ to determine the remediation partition of 319 administrative villages in Tongxu County. Each administrative village is recorded as a sample point, and the number, quality and ecological normalized potential values of administrative villages are the three characteristic dimension values of the sample. The data set $X = \{x_n \mid n = 1, 2, \cdots, 319\}$, $x_i = \{x_{i1}, x_{i2}, x_{i3}\}$ the input data set is updated iteratively, and the clustering result $M = \{M_1, M_2, \cdots, M_k\}$ is the comprehensive partition result of arable land remediation, and the naming of each partition is obtained from the analysis.

The clustering algorithm needs to set the number of clusters artificially, and different values have an important impact on the results of remediation partitioning. Most of the current research is based on the judgment of clustering results, elbow method using different k values corresponding to the magnitude of change in the Sum of the Squared Errors (*SSE*) to find the optimal number of clusters. When the number of set clusters gradually increases, the error sum of squares decreases and changes significantly. And when the number of clusters reaches a certain value, the change begins to level off, the error sum of squares change folding line graph is the value corresponding to the inflection point can be determined as the optimal number of categories. In this paper, the number of clusters k is determined by combining the elbow method with the error sum of squares formula as follows:

$$SSE = \sum_{i=1}^{k} \sum_{p \in M_i} \left\| p - q_i \right\|^2 \quad (5)$$

3. Results

3.1. Evaluation of Arable *Land Remediation Potential*

In ArcGIS, the natural breakpoint method was used to divide the potential indicators of arable land remediation in Tongxu County into five levels, from low to high. The evaluation results of the potential for arable land remediation in Tongxu County are shown in **Figure 3** and **Figure 4**.

In terms of quantitative potential, its potential value was higher (0.313 - 0.494) in the area with a more concentrated distribution, mainly around the intersections of Chengguan Town, Changzhi Town, Liwang Township and south of Yuhuangmiao Township, with a total of seven administrative villages. This was

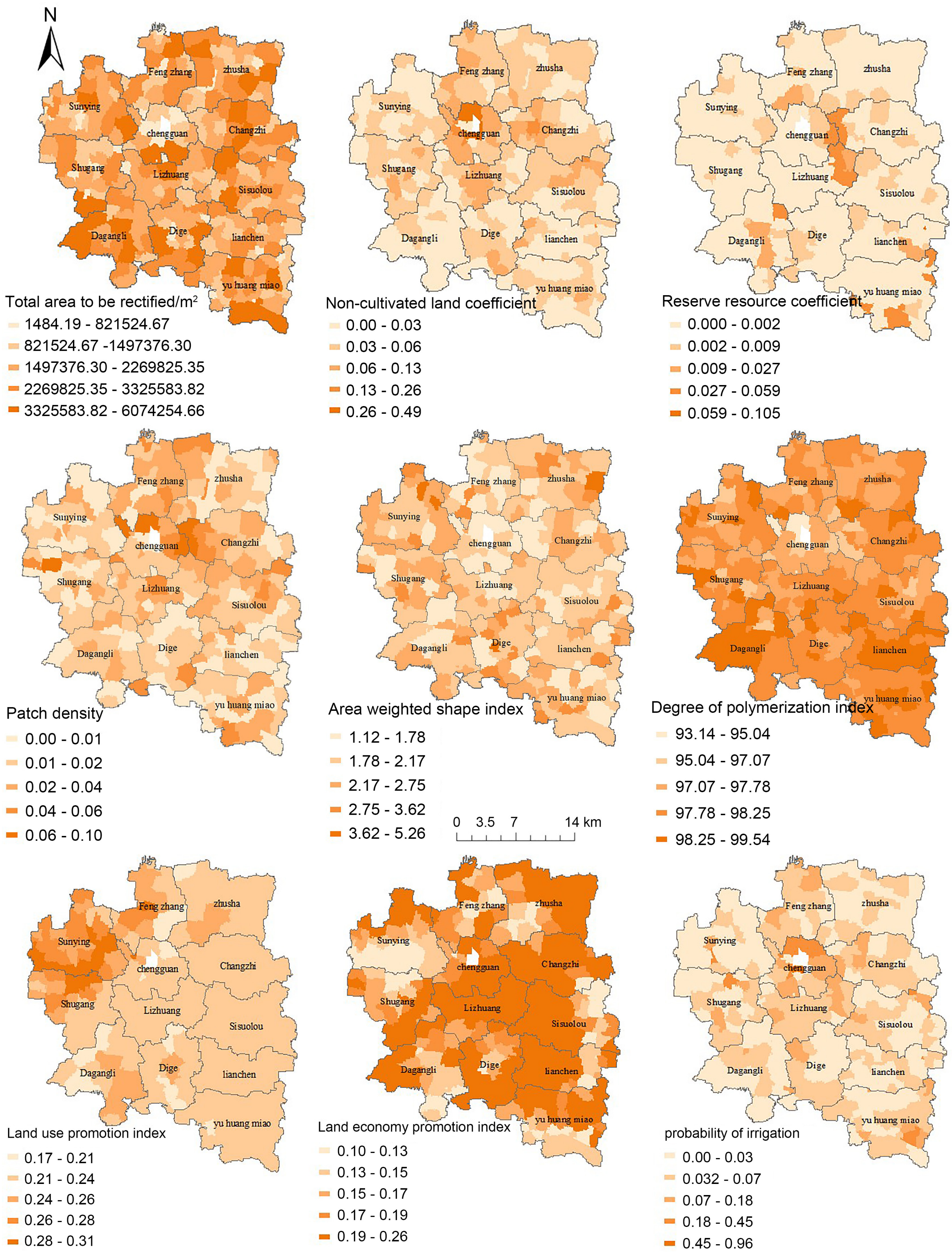

Figure 3. Spatial distributions of each index.

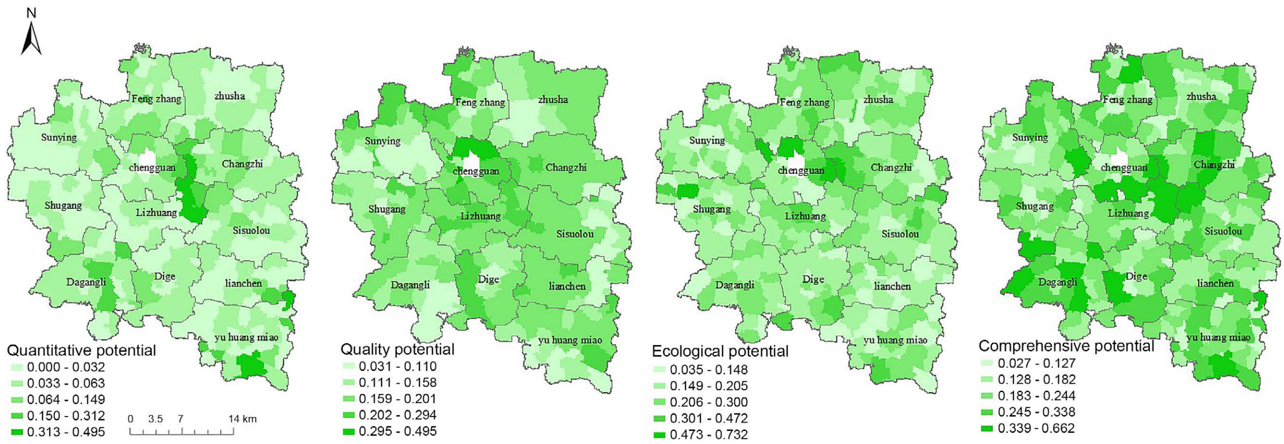

Figure 4. Quantity, quality, ecology and potential for comprehensive improvement in Tongxu County.

followed by a potential value of 0.150 - 0.312, and a total of 11 administrative villages, accounting for 5.7% of the total number of villages in the county. The coefficient of non-arable land in Tongxu County was higher in proportion to the townships around Chengguanzheng, where ditches and rural roads account for a larger proportion. The overall reserve resource coefficient was low, mainly due to vacant land and inland mudflats, where development potential is limited.

In terms of quality potential, the potential value was mainly concentrated where values were 0.16 - 0.20, with a total of 147 administrative villages, of which 47 administrative villages with higher potential value, accounting for 15%. In the northwestern Tongxu County, the land-use coefficient around Sunying Township was low, with a large enhancement index, while the land economic coefficient was high, and its enhancement potential was not large.

In terms of ecological potential, the potential values were mostly distributed in the 0.149 - 0.205 range, with the administrative villages with higher potential values totaling 24, accounting for 7.6% of the county. The ecological potential of Tongxu County as a whole was based on the greater fragmentation of arable land around Chengguan Town in the central part, with its higher patch density values and lower area-weighted shape index and aggregation. Contrary to this, the degree of intensification around Tongxu County was higher, with lower patch density and higher aggregation.

In terms of integrated potential, its intersection with the Chengguan, Changzhi and Liwang Townships, and with the Dagangli and Jinggang Townships gave higher potential values. 23 administrative villages have integrated potential values of 0.339 - 0.662, and 51 administrative villages have integrated potential values of 0.245 - 0.338, accounting for 23.5% of Tongxu County. Although the comprehensive potential value can reflect the urgency of arable land remediation, the direction of remediation was not clear, and choosing the same remediation method is not conducive to the best use of arable-land capacity.

3.2. Cultivated Land Remediation Potential Zoning

Figure 5 shows the change in the error sum of the squares using the elbow method.

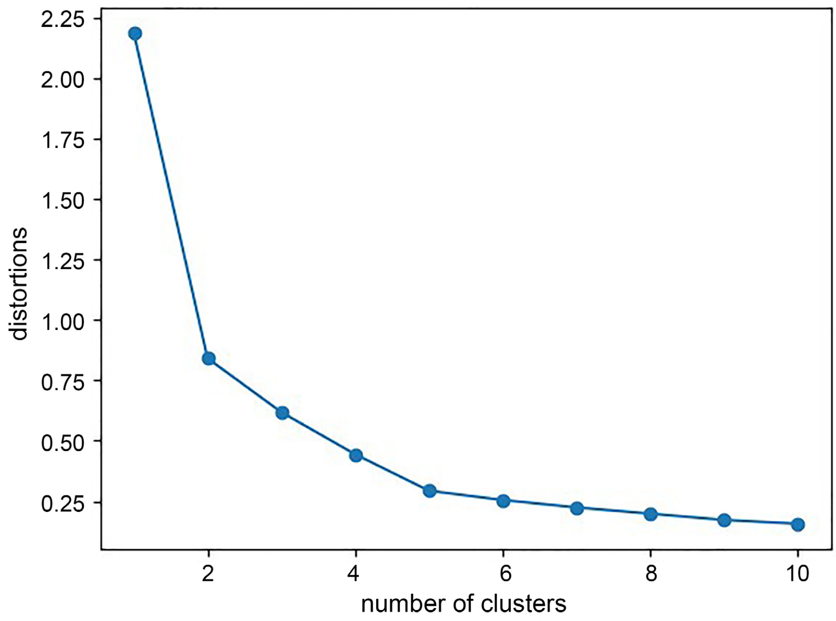

Figure 5. Elbow method change curve.

As the number of clusters increases from 1 to 10, the error sum of the squares gradually decreases. The change of slope is more obvious when the number of clusters is 2 and 5. Considering the poor effect of partitioning when the number of clusters is 2, 5 is the optimal solution.

The potential was partitioned using the k-means++ method and displayed in ArcGIS, and the distribution is shown in Figure 6, with its potential characteristics in the different dimensions of quantity, quality and ecology being shown in Table 2. The comprehensive potential value of arable land remediation in Tongxu County was divided into five levels, from high to low; the high and low potential values of each partition are given in Table 3. According to the zoning results obtained by the clustering algorithm, and the potential values and comprehensive potential highs and lows of each zoning in different dimensions in Table 3 and Table 2, the five zoning areas were named as health improvement zone, comprehensive improvement zone, quantity improvement zone, intensive improvement zone, and quality improvement zone.

The health improvement zone had a total area of about 11886.72 ha, accounting for 21%, and its overall comprehensive improvement potential ranked last in the improvement subzone of Tongxu County. This zone had advantages in promoting agricultural scale, mechanization and industrialization. It should focus on promoting the concentration and contiguity of its arable land, vigorously building high-standard basic farmland, realizing a high and stable yield of arable crops, and accelerating the realization of agricultural modernization in the region.

A comprehensive remediation area, mainly located in Chengguan Town and the intersection with Changzhi Town. It had a total area of about 859.28 ha, accounting for 1.5%, and ranking second in the comprehensive remediation potential

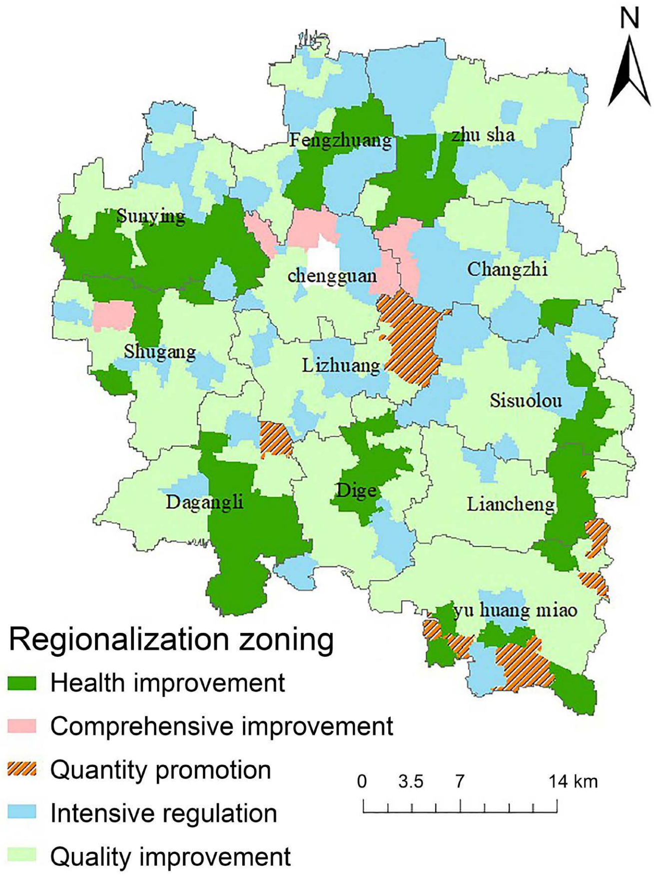

Figure 6. Cultivated land remediation potential zoning in Tongxu County.

Table 2. Category characteristics of remediation areas in Tongxu County.

Partition category	Quantitative potential	Quality potential	Ecological potential
Quality improvement area	low	middle	low
Intensive regulation area	low	middle	high
Quantity promotion area	high	middle	low
Comprehensive improvement area	middle	high	high
Health improvement area	low	low	low

Table 3. Area of cultivated land involved in each potential level in each remediation area in Tongxu County (unit: hectare).

Regionalization zoning	Grade I	Grade II	Grade III	Grade IV	Grade V	Total
Quality improvement area	3144.11	7045.28	8425.46	6565.55	2600.65	27781.05
Intensive regulation area	246.13	122.13	491.02	0	0	859.28
Quantity promotion area	1684.58	272.34	0	0	0	1956.93
Comprehensive improvement area	950.45	5313.68	4381.2	2926.76	467.2	14039.29
Health improvement area	1175.84	1673.84	2983.97	4449.22	1603.84	11886.72
Total	7201.12	14427.29	16281.65	13941.53	4671.68	56523.27

in the zoning. Chengguan Town is the administrative land of Tongxu County, which comprises mainly construction land. Therefore, the fragmentation of surrounding arable land is high, the scale rate and production stability are low, and the development capacity of arable land is poor. The remediation should make full use of the available resources to alleviate the degree of fragmentation of the arable land and to improve the scale rate of the arable land as the core. It should focus on the economical and intensive use of the arable land, adjust the structure of the agricultural industry, promote land transfer and moderate-scale operations, improve the utilization rate of the arable land resources, and also focus on the balance between industrial land and agricultural land use.

The quantity enhancement area was mainly distributed in the Li Zhuang and Yuhuangmiao Townships, with a total area of about 1956.93 ha, accounting for 3.5% of the total area of Tongxu County. This is not a high percentage, but the comprehensive potential value of this area ranked first in the subdistrict, with high potential values in all three dimensions, the quantity potential was especially obvious. The area is dominated by agriculture-related facilities, so the configuration is less reasonable, the coefficient of arable land is low, the distribution of patches is more scattered, the reserve resources are relatively large, and the possibility of converting non-arable land resources into arable land resources is greater. Remediation should focus on adjusting the land-use situation, and reasonably supplementing of arable land.

The comprehensive potential for the intensive remediation of a total area of about 14039.29 ha, ccounting for 24.8%, it ranked third among the subdistricts, with a relatively high potential for remediation in all aspects. The degree of intensification of arable land use in this area is not enough, while at the same time, there is still room to improve the capacity of the arable land, the degree of fine fragmentation, the quality of the arable land as the core. There should be a focus on the development and utilization of protective arable land reserve resources, and improvements in the rate of the scale of arable land and the agricultural ecological environment, a consolidation of the agricultural foundation, promotion of large-scale operations, enhancement of the efficiency and competitive advantage of arable land utilization, development of efficient and modern agricultural practices, and a focus on agricultural development.

The total area of quality improvement was about 27781.05 ha, accounting for 49.2% of the total area of Tongxu County. It involved almost all the townships, reflecting the overall characteristics of Tongxu County, whose comprehensive potential was not high. In the upgrade, attention should be paid to improving soil conditions, implementing crop rotation with fallow intervals, applying new technologies to improve the production capacity of the arable land, and carrying out arable land protections and corrective actions to alleviate agricultural surface-source pollution, soil erosion and other problems. There should also be a promotion of the sustainable use of arable land resources, and an improvement in the quality of arable land, in order to achieve high and stable arable yields, while focusing on the construction of high-standard basic farmland.

4. Conclusions

In this study, the potential for arable land remediation in Tongxu County was examined, and proposed a trinity of "quantity-quality-ecology" evaluation index system, which enriched and expanded the connotation of arable land remediation to a certain extent. In addition, the combination of K-means++ and elbow method was used to divide Tongxu County into five arable land remediation potential divisions. It avoided the subjectivity of partitioning and highlights the characteristics of each partition. Finally, a preliminary analysis of the zoning results and characteristics was made, and each zoning area can be reasonably remediated according to the potential characteristics to promote high-quality development of arable land.

Subsequent studies can include consideration of the realism and feasibility of remediation and the urgency of the people's will to remediate, enhance the continuity of zoning, and further improve the achievability of the arable land remediation zoning.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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