Optimized selection of suitable sites for farmland consolidation projects using multi-objective genetic algorithms

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Abstract: In order to select suitable sites for farmland consolidation projects, correlation analysis and evolutionary algorithms were used to optimize the evaluation of ecological, social and economic factors, avoiding subjective selection and ignorance of spatial relationships among land attributes. Multi-objective Genetic Algorithms (MOGA) were applied to select the best sites from the perspective of spatial relationship and land attribute evaluation. With carefully defined restrictions and variables, multi-objective optimization is able to select several suitable sites for farmland consolidation projects. The results from a case study in Yangshan, Guangdong of China showed that the selected sites were on the central and southern Yangshan with expected flat terrain and abundant water resources. An empirical experiment also demonstrated that the proposed method is able to provide well selected sites for land consolidation projects.

Keywords: farmland consolidation, site selection, evaluation index system, multi-objective optimization, genetic algorithm, suitability

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1 Introduction

Land consolidation is a worldwide phenomenon, which may improve land productivity, the total factor productivity, and labour productivity[1,2]. According to Land Consolidation Planning of China (2011-2015), the purpose of land consolidation is to increase the quantity and quality of cultivated land, and to improve the ecological environment. In the spatial dimension, however, land consolidation is not to reallocate a single project but to centralize and connect more isolated construction projects together. From this point of view, agricultural land consolidation is useful to improve effectiveness of land cultivation, protect cultivated lands, ensure foodstuff security and to support sustainability of agriculture environment[2-4]. Generally, the site selection is the premise and guarantee of a farmland consolidation project. Therefore, the scientific and rational selection of the pilot area will help to maximize the benefit of a farmland consolidation operation.

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At present, the research on a farmland consolidation mainly focused on the evaluation of land consolidation[5], land remediation[6], ecological environment[7], landscape, social economy[8], and legal system, etc., nevertheless, little attention has been paid to the site selection. Site selection of land consolidation can be thought as an optimization issue[9]. Even though there are many methods (e.g., Equal Interval, Quartile, Natural Breaks and K-Means Cluster) that have been used in site selection, it is usually difficult to achieve the goal of farmland consolidation because, besides factors such as topography, geomorphology, climate, hydrology, soil, vegetation, land use, property ownership, and economic development level, isolated spatial evaluation units and fragments resulting from neglecting the spatial interdependence of the units[10] are a big challenge, especially in hilly region of Southern China where land fragmentation is present[11]. In addition, the site selection of current farmland consolidation projects is mainly dominated by local governments with little scientific consideration. Therefore, it is necessary to develop proper approaches to improve the site selection for a farmland consolidation.

The site selection of a land consolidation project is a process of multi-objective-based spatial location identification, therefore optimizing a particular solution to site selection with respect to a single objective could result in unacceptable results with respect to the other objectives[12].

This study was designed to define suitable sites for a farmland consolidation project using multi-objective genetic algorithms (MOGA) to evaluate constraints and requirements for a real farmland consolidation project conducted in northwest Guangdong Province of China.

2 Materials and methods

2.1 Study area

Yangshan County was selected for this study since it is one of the key areas of farmland remediation named by the Chinese government according to the National Land Remediation Plan (2011-2015). The study area is located in Yangshan County (Latitude 23°58′47″ to 24°55′52″N, Longitude 112°22′01″ to 113°01′06″E), northwest Guangdong Province (Figure 1). This county covers a total area of 341 837 square kilometers and has a population of 4.8 million. As of 2012, the gross domestic productivity (GDP) of Yangshan exceeded 74.4 billion Chinese Yuan (11.9 billion US Dollars). The area has a typical subtropical monsoonal climate, with the annual average temperature of around 20℃ and the annual average precipitation of 1 828 mm. The complex terrain in Yangshan is higher in the north and the south with monoclinic mountain leaning irregularly toward the hinterland, which forms a boat-shaped terrain. Of the whole county area, mountain occupies 90% while both basin and alluvial plain account for 10%. The geographical location and land use status of Yangshan County are shown in Figure 1.

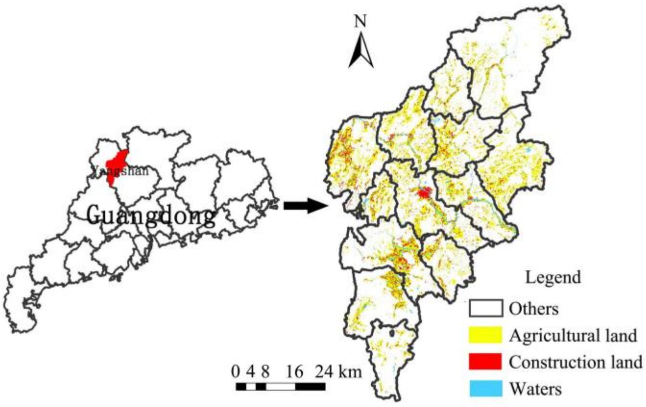

Figure 1 Geographical location and land use status of Yangshan County

2.2 Data

The data used in this study include: 2006-2020 Yangshan land use plan, current Yangshan land-use map, Yangshan soil map, Yangshan topographic map, the results database of agricultural land classification of Guangdong Province, the records of previous land consolidation projects from Land Bureau of Yangshan, and socio-economic data from the Statistical Yearbook of Qingyuan CIty (2008-2012)[13] .

2.3 Indicator System of multi-targets based suitability evaluation for farmland consolidation

The multi-targets based farmland consolidation should be satisfied with that: (1) the spatial unit is adjoined; (2) the selected location is a representative of the natural and economic conditions in the study region; and (3) the social, economic, and ecological sustainability is expected to be resulted in. As well, to establish a system of suitable indicators for location selection should take into account funding, environment impact, and ecological protection. In this study, both the specifications for planning and designing land consolidation projects (TD/T 1012-2000) and the specifications for inspecting land development and consolidation projects (TD/T 1013-2000) enacted by Chinese governments were referenced to guide the evaluation.

Furthermore, the quality of selected site lies on what kinds of factors are used and their weights. Generally, eco-environmental variables and the social and economic conditions are critical indicators. In order to maximize the independence among selected factors and simplify calculation, the Pearson's correlation coefficient method was used to refine factors in our work[11].

The traditional expert scoring method is subjective and may mislead decision-making[14]. Therefore, we proposed a three-layer system of index weights [15] based on AHP[16] and entropy law empowered to define index weights. In this system, the modified AHP method was used to determine the weights of the criterium layer against the target layer, and the entropy law method was used to determine the weights of the evaluation layer against the criterium layer.

An evaluation unit for land consolidation should be consistent in terms of land quality, land properties and land use. Therefore, mapping units were retrieved from the Chinese Second Land Use Survey. For each basic evaluation unit, the equation below (Equation (1)) was used to compute its weighted index derived from all selected indicators:

$$P_i = \sum_{i=1}^{n} W_i S_i \tag{1}$$

where, W_i is the weight of indicator (i); S_i is the parameter value of the indicator (i) dimensionless after standardization; P_i (i = 1, 2, ⋯; n) is the weighted index of the land unit i.

2.4 The model for suitability spatial evaluation

In order to meet the two requirements of the spatial suitability assessment that the types of land use are relatively similar and that the spatial attribute and the adjacent characteristics of selected sites are homogeneous, the following fitness functions were used:

$$f_i = F(g_i \cdot h_i) \tag{2}$$

$$g_i = \sum_{j=1}^{n} (W_{ij} Y_{ij}) \tag{3}$$

$$W_{ij} = C_{ij} / \sum_{j=1}^{n} C_{ij} \tag{4}$$

$$h_i = H(S_{p_{1i}, p_{2i}, \cdots, p_{ni}}) \tag{5}$$

where, i is the serial number of spatial unit (i=1, 2, …, n); n is the number of neighborhood units; f_i is the evaluation function of farmland rearrangement with the value of 0-1; g_i is the attribute evaluation function of the spatial units, which is the evaluation value of assessment unit i; W_{ij} is the weight value of indicator j in unit i; Y_{ij} is the index value of indicator j in unit i (by normalization, dimensionless); C_{ij} is the neighborhood spatial weights matrix; h_i is the evaluation function of candidate land space[17]; $S_{p_{1i}, p_{2i}, \cdots, p_{ni}}$ is the screening combination of unit i; and p_{ni} represents the n candidate land space unit.

2.5 Multi-objective genetic algorithm (MOGA)

Genetic algorithm (GA) has been widely used in many areas because of its advantages in solving complex issues associated with a large space, nonlinearity, and global optimization. GA is a kind of evolutionary algorithm in modeling the genetic operation of the nature to handle optimal problems[18], which has the characteristics of simple, robust and nonlinear reduction applying to parallel computation[12,17,19,20]. GA can search for the optimal solution under the definition of fitness function and select the fewer input factors under the premise of ensuring no loss of accuracy[12]. In terms of the multi-objective site selection of land consolidation, GA is one of the most suitable optimal technologies and therefore was used in this study following the steps as follows.

2.5.1 Initialization

At the initialization stage, the gene of GA can be constructed as binary string and the chromosome value at either 0 or 1. In the chromosome, value 1 stands for spatial units selected and 0 for the excluded. The whole spatial unit is coded with binary expressions. The size of the population of GA depends on the complexity of the problem. When the problem is more complex, the size of the initialized population should be larger[21,22], which was set as 128[25] in this study.

2.5.2 Optimization

According to the evolutionary mechanism of GA (i.e., the law of survival of the fittest among chromosomes), the iterative evolutionary computation was performed until better solutions are retained by gradually eliminating the worse solutions from the populations.

2.5.3 Fitness function

There are many factors involved in site selection (Table 1). As mentioned previously, the location selection must meet following requirements: a) adjacent evaluation units, i.e., highly homogeneous ecological environment characteristics, the shortest distance, contiguous area; b) the minimum cost of the distance between the evaluation unites and supportive infrastructure (power supply facilities, rural settlements, roads, etc.); and c) economic constraints, i.e., the target of economic feasibility is higher than the average of the region. Therefore, two fitness functions with i objectives were defined as follows:

Fitness function I:

$$f_1(x)=\sum\nolimits_{i=1}^{n}\min dis\ x(c)$$

$$s.t.: 20\le f_2(x)=\sum_{i=1}^{n} area\ x_i \le 80 \qquad (6)$$

$$area\ x_i \ge 80$$

The function 6 describes the land development and consolidation of space contiguous goals: $dis\,x(c)$ is Euclidean distance between evaluation unit c and q the site location, representing Euclidean distance sum between c and adjacent plots. According to the technical requirements of land remediation planning, its area ranged from 20 to 600 ha in the study area and the project area is relatively spatial concentrated; i is not more than seven.

The target of the second function is to minimize the cost in economic, social and environmental factors shown as follows:

Fitness function II:

$$\begin{aligned} f_2(x)=\sum_{i=1}^{m}\sum_{j=1}^{n}\{&Min[disx(c)\times road(p)]\times Croad \\ &+Min[dis_x(c)\times electric(p)]\times C_{relectric} \\ &+Min[dis_x(c)\times resident(p)]\times C_{relectric}\} \end{aligned} \qquad (7)$$

3 Results and discussion

3.1 The evaluation index system

On the basis of farmland classification, reserved resources survey and evaluation index system, and organized results of Yangshan hill slopes and gardens, the suitability evaluation index system for the location selection of multi-objective land consolidation project in Yangshan County was established[4,14,23]. And the indices resulted from both AHP and Entropy method were listed in Table 1.

3.1.1 Ecological environment (U_1)

Natural quality of agricultural land U_{11}, arable land irrigation U_{12}, terrain slope U_{13}, and cultivated land spatial connectivity U_{14} are included in the evaluation of ecological condition.

a. Natural quality of agricultural land U_{11}

According to the assessed index of natural soil quality in arable land, such indices as effective soil depth U_{111}, organic matter content of surface soil U_{112}, pH U_{113}, soil texture U_{114}, soil profile configuration U_{115} and under-groundwater level were assessed, and the index value and the weight of each factor were based on the outcome of agricultural land classification of Guangdong Province.

b. Farmland irrigation condition U_{12}

Distance from water U_{121} and precipitation U_{122} related to arable land irrigation facilities were selected for assessment.

c. Terrain slope U_{13}

Terrain slope, as a factor to measure soil erosion, landslide risk of the impacted area, has a great impact on the ecological environment. Slope U_{131} can be obtained through the topographic map of the study area. Small slope was selected as prior development, while slope>25° was prohibited from developing.

d. Cultivated land spatial connectivity U_{14}

Spatial connectivity is needed to achieve agricultural production scale and cost during agricultural land consolidation. Spatial contiguous area of cultivated land U_{141} was selected as the major measure in the study, and the total area of spatial contiguous arable land is the sum of contiguous area value of every evaluation unit processing by ArcGIS.

Table 1 Indices of land consolidation evaluation[4,14,23]

Target layer	Index layer	Factor layer	Weight	Factor grade	Factor score
U_1	U_{11}	U_{111}	0.085	>100 cm	100
				50-100 cm	90
				30-50 cm	70
				<30 cm	0
		U_{112}	0.06	0.9-1.0	90
				0.7-0.8	80
				0.64-0.7	70
		U_{113}	0.045	6.0-7.9, 7.9-8.5, 8.5-9.0	
		U_{114}	0.08	Loam soil	90
				Clay soil, Sandy loam soil	80
				Sand soil, Gravelly soil	70
		U_{115}	0.04	Homogeneous texture profile	100
				Sandwich textures profile	90
				Layer (cushion) texture profile profile	70
		U_{116}	0.02		
	U_{12}	U_{121}	0.055		
		U_{122}	0.045	>1000	100
				1000-500	90
				500-250	80
				<250	70
	U_{13}	U_{131}	0.1	<3	90
				3-6	80
				6-15	70
				>15	60
	U_{14}	U_{141}	0.055		
U_2	U_{21}	U_{211}	0.055		
		U_{212}	0.035		
		U_{213}	0.035		
		U_{214}	0.035		
	U_{22}	U_{221}	0.01	Match	100
				Not match	0
	U_{23}	U_{231}	0.01	No ownership controversy	100
				Ownership controversy	0
U_3	U_{31}	U_{311}	0.05		
		U_{312}	0.055		
	U_{32}	U_{321}	0.08		
		U_{322}	0.05		

Notes: U_1: Ecological environment, U_{11}: Natural quality of agricultural land (U_{111}: Effective soil depth, U_{112}: Organic matter content of surface soil, U_{113}: PH, U_{114}: Soil texture, U_{115}: Soil profile configuration, U_{116}: Under-groundwater level), U_{12}: Arable land irrigation (U_{121}: Distance from water, U_{122}: Precipitation), U_{13}: Terrain slope (U_{131}: Slope), U_{14}: Cultivated land spatial connectivity (U_{141}: Spatial contiguous area of cultivated land), U_2: Social development goal, U_{21}: Location of supporting infrastructure (U_{211}: Distance from the main road, U_{212}: Distance from rural residents, U_{213}: Road drainage density, U_{214}: Distance from the power supply facilities), U_{22}: Planning implementation (U_{221}: Condition of conforming to the requirements of the plan), U_{23}: Ownership (U_{231}: Ownership status), U_3: Economic feasibility condition of farmland consolidation, U_{31}: Level of agricultural output (U_{311}: Agricultural production value per square kilometers, U_{312}: Net income of farmers), U_{32}: Funding condition (U_{321}: Infrastructure investment per square kilometers, U_{322}: Farmland expropriation compensation).

3.1.2 Social development goal U_2

Social development goal U_2 contains location of supporting infrastructure U_{21}, planning implementation U_{22}, ownership U_{23} and so on. U_{21} includes distance from the main road U_{211}, distance from rural residents U_{212}, road drainage density U_{213} and distance from the power supply facilities U_{214}. The value of U_{211}, U_{212} and U_{214} can be obtained by ArcGIS buffer analysis. Road drainage density U_{213} is calculated in village as the basic unit, by the formula of road drainage density (U_{213}= (linear feature area + hydrolytic construction area + road drainage area)/ arable land area). The specific value in the formula can be acquired from present land-use map of Yangshan County. Road drainage density of each village we get equals to the specific value of the field. The higher the density value is, the more perfect the facilities are, and the smaller the engineering quantity would be, suggesting that it can be arranged on priority. U_{22} includes the condition of conforming to the requirements of the plan U_{221}. U_{23} includes the clearly defined ownership status U_{231}. We can get U_{22} and U_{23} through fieldwork combined with land use planning map and planning implementation assessment of Yangshan County. Location selection of farm land consolidation should keep meeting land use planning. Generally, the planned area except for agricultural areas and woodland cannot be developed. Besides, the arrangement should conform to the extent permitted by its allowances according to special planning for land development and complement farmland. Additionally, when the ownership status of the consolidation land is in dispute, the land consolidation is forbidden.

3.1.3 Economic feasibility condition of farmland consolidation U_3

Economic feasibility condition of farmland consolidation U_3 can be described by the level of agricultural output U_{31} and funding condition U_{32}. U_{31} can be indicated by the agricultural production value per square kilometers U_{311} representing regional agricultural production and living standard, and net income of farmers U_{312}. U_{32} is described as infrastructure investment per square kilometers U_{321} and farmland expropriation compensation U_{322}. Economic condition is mainly considered from agricultural production value and funding condition. The areas with high agricultural output and farmer income should be given priority of farmland consolidation to improve agricultural output and farmers' income and production. Specific data were mainly collected from Statistical Yearbook and government documents. In the quantization process of indicators, related regulations and standards can be referenced, for example, eco-environmental condition indicators can be normalized referring to *the Standard of Agricultural Land Classification*[24]. As to other quantitative indicators, we can normalize to original data directly. Every indicator is independent of one another. Indicators were processed independently and with independent weight in order to give priority to select perfect but with low output facilities. The severity should be determined by the weight when both offset.

3.2 Site suitability evaluation

Many factors have a substantial impact on the use of the land, and the ecology, economic, and social factors should be considered for the location selection of land consolidation projects. The value of land consolidation spatial unit was evaluated on basis of the proposed model (Equation (1)), and reclassified using Natural Intermittent Method in ArcGIS according to the suitability evaluation index system as listed in Table 1. The suitable candidate area for land consolidation is above 69 and the unsuitable area is under 50.

According to the criteria listed in Table 2, we generated the suitability map to show the candidate areas for site selection across the study region and results are illustrated in Figure 2. The appropriate areas for location selection fall in the regions of Grade 6 and Grade 5, which is mainly concentrated in central and south-central Yangshan County, including the most distributed towns of Yangcheng, Qigong, Libu, Lingbei, Xiaojiang, Qinglian, Dubu, and Taiping where there are better agricultural production conditions. Therefore, there is a potential to further improve land use efficiency and agricultural output. In view of the contiguous land consolidation, Yangshan County can be preliminary selected as the most suitable region for farmland consolidation.

Table 2 Classification of site suitability evaluation

Suitability	Preferential		More suitable		Suitable	
Indicator	>87	78-87	69-78	57-69	50 -57	<50
Grade	6	5	4	3	2	1

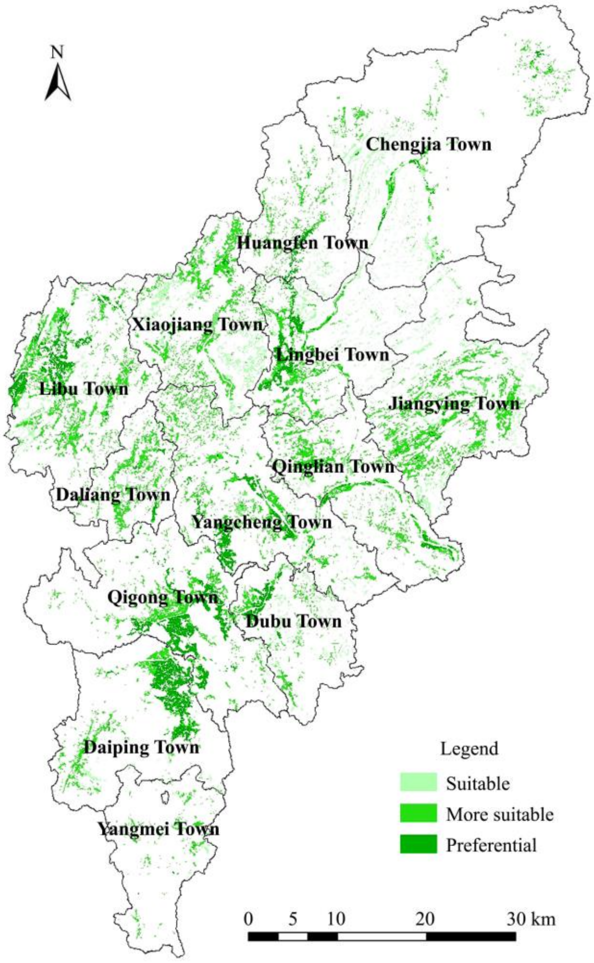

Figure 2 Site suitability classes of the farmland consolidation project

3.3 The experimental results

The steps of applying the MOGA on site selection of farmland consolidation in Yangshan County are as follows. The priority area and appropriate area obtained from the suitability evaluation were defined as the siting range. The center of each suitable polygon was identified and realigned the units according to the spatial evaluation value of farmland consolidation units (Equation (5)) and their geographical location relationships. Then, seven polygons were randomly extracted from the priority area as individual species. The priority area was divided into 4×12 grids based on the sample positions from which seven grids were randomly selected from 48 grids. Finally a new genetic individual of 8 polygons was extracted from each grid until 128[25] initial populations were generated. Then the fitness value was calculated for each initial population (an individual) according to fitness function I (Equation (6)) and fitness function II (Equation (7)) as the shortest distance to the adjacent traffic lines and being high quality contiguous land, etc., from which an average fitness value for the all initial populations was resulted. The initial individuals with the fitness value greater than the average value were eliminated, and the individuals whose fitness values are smaller than the average of all individuals were grouped to form a cross-chromosome with the minimum fitness value following a certain proportion rule. Next, a certain number of individuals are randomly selected to conduct gene mutation by which favorable genes were found and to retain for multiple iterations until the fittest individual occurred. In this study, the size of individual populations is 128[25]; the maximum number of iterations is 150; the mutation probability is 0.98; and the crossover probability is 0.01.

Based on the genetic algorithm mentioned above, the *farmland consolidation site choice* 1 (At point of "A" in Figure 3) and *farmland consolidation site choice* 2 (At point of "B" in Figure 3) of the selected location by multiple iterations are shown in Figure 3. For *farmland consolidation site choice* 1 as shown in Figures 4 and 5, its fitness value is about 8 after the 15th iterations. The selected site of *farmland consolidation site choice* 1 located in Qigong Town, which is in the central part of southern Yangshan with convenient transportation, plentiful water resources and high economic development level next to Yangcheng. This town has concentrated distribution plains with larger area, stronger land suitability and better spatial contiguous, which meets the reality of land use. In terms of *farmland consolidation site choice* 2 (shown in Figures 6 and 7), its fitness value is about 7 after the 17th iterations. The selected site, located in Libu Town, is a flat alluvial plain with good land quality, and strong land suitability. The result also accords with the reality of land use. Both of the two choices belong to regions requiring intensive use of land, so there is an urgent need to improve land use efficiency and output level by land consolidation. It is clear that the results are consistent with the reality.

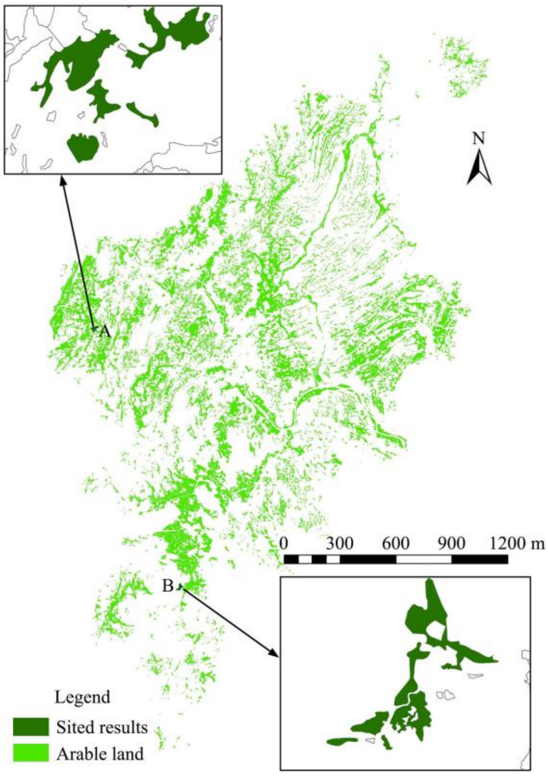

Figure 3 The result of location choices according to the Multi-objective Genetic Algorithms (A: farmland consolidation site choice 1 and B: farmland consolidation site choice 2)

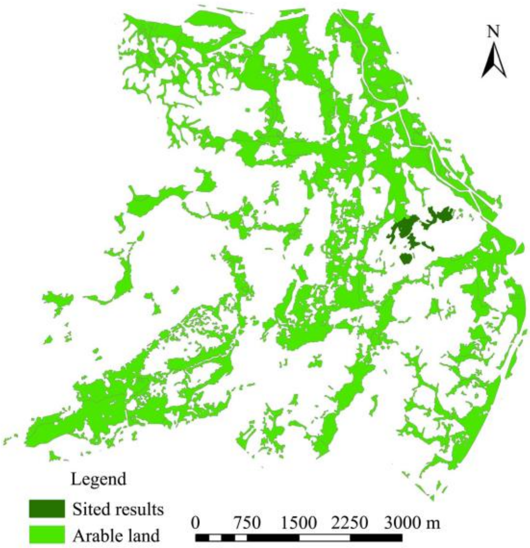

Figure 4 The result map of the location of *farmland consolidation site selection* 1

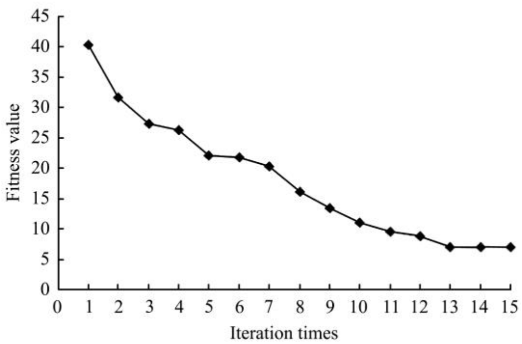

Figure 5 The test function graph of the location of *farmland consolidation site choice* 1

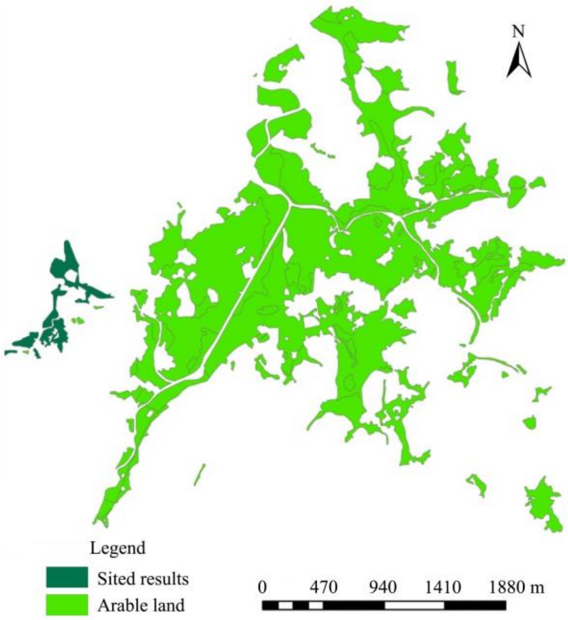

Figure 6 The result map of the location of *farmland consolidation site selection* 2

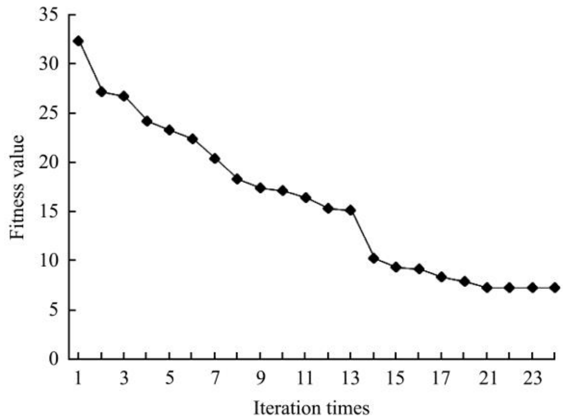

Figure 7 The test function graph of the location of *farmland consolidation site choice* 2

4 Conclusions

Many engineering problems involve simultaneous optimization of multiple objectives. The paper focuses on salient issues to improve the MOGA algorithm for location selection. The proposed approach has strong robustness, excellent performance in distributed computing, and is easy to be combined with other algorithms. By applying the multi-objective genetic algorithms, we established a system to evaluate the land suitability across a region for farmland consolidation projects in Yangshan. Simulation results also indicated that this method is more efficient for the site selection than a straightforward exhaustive search method because of its advantages in satisfying ecological, social and economic constraints across the consolidation region and avoiding the isolated plots or debris after the consolidation. It should be noted that to avoid some potential disadvantages of the method, the futrue step is to improve the current method from the following two aspects including excavating the optimizing ability with the swarm intelligence algorithm, and improving the computation ability by coupling with parallel algorithms.

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