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The Optimal Zoning of Non-Grain-Producing Cultivated Land Consolidation Potential: A Case Study of the Dujiangyan Irrigation District

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Abstract: Non-grain-producing cultivated land (NGPCL) greatly affects sustainable agricultural development and food security, and its consolidation is important. With the Dujiangyan irrigation district as an example, an empirical study of NGPCL consolidation zoning was performed following the idea of "connotation definition and classification—potential identification—consolidation zoning". On the basis of expert evaluation, NGPCL was classified into three levels according to the degree of damage to cultivated land by crop type. NGPCL was common in the study area, accounting for 53.8% of the total area. The spatial pattern of NGPCL was characterized as "continuous in the south and scattered in the north". The assessment of theoretical and realistic NGPCL consolidation potentials suggested that areas with medium consolidation potential exhibited a contiguous distribution in the southern part of the study area, whereas it was dispersed in other regions. The proportion of area suitable for consolidation exceeded 40%. Finally, through a multiobjective optimization algorithm, a potential zoning scheme for NGPCL consolidation was constructed. The final experimental results revealed that the areas with medium or high consolidation potential accounted for 97.54% of the total area. This study is useful for supporting the governance of NGPCL.

Keywords: non-grain production; cultivated land protection; consolidation potential; multi-objective optimization; food security

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1. Introduction

Food security is crucial for people's livelihoods, and the conservation of cultivated land is directly linked to sustainable food production. According to the latest report on the global food crisis by the United Nations World Food Program in May 2023, approximately 258 million people in 58 countries and regions are currently experiencing severe food insecurity [1]. In the context of rapid urbanization, limited space for grain output growth, farming conditions, and land use scale have become the main factors restricting agricultural development and threatening food security [2]. How can cultivated areas be improved to ensure food security and promote the sustainable development of agriculture? This is a serious challenge facing both developed and developing countries.

In international practice, legislation and rigorous law enforcement serve as fundamental safeguards for cultivated land, while achieving a balance of interests through

administrative intervention is an essential measure for planning and safeguarding basic farmland [3,4]. Countries such as the United States and the Netherlands delineate urban boundaries and agricultural protected areas through urban development control planning [5]. This approach is combined with land consolidation to adjust the land ownership pattern and scale to protect cultivated land [6]. In recent years, driven by social development and economic interests, there has been a significant increase in the large-scale substitution of grain cultivation with high-yield economic production methods (such as forestry, fruit production, pond excavation, and aquaculture), known as the establishment of non-grain-producing cultivated land (NGPCL). This trend is due primarily to the high costs, low income levels, and high risks associated with traditional grain cultivation [7]. Although NGPCL diversifies agricultural production types and exerts a positive impact on the economy overall, an increase in NGPCL ratios along with certain NGPCL types may lead to detrimental effects on cultivated land productivity, particularly topsoil layer destruction and aggravated agricultural pollution [8]. In contrast to the strict prohibition by various governments on non-agricultural activities and other irreversible damage to cultivated land [9], NGPCL has gained widespread adoption in many countries because of its substantial economic benefits and potential reversibility for food production purposes [10–12]. China is presently implementing its strictest protection system for cultivated lands in combination with a "land use control institution" approach. From 2014 to 2023, China's No. 1 Central Document consistently underscored the necessity of addressing NGPCL to ensure stable grain production levels while preserving sown areas [13,14]. The prevention of NGPCL formation has become an important issue related to food security and agricultural modernization in China and has received much attention.

Given the gravity of these issues, numerous scholars have researched NGPCL, such as its identification, classification, evaluation, and optimization. In terms of NGPCL identification, large-scale studies are typically based on surveys and statistical yearbooks. Various indicators, such as the ratio of the NGPCL planting area to the total sown crop or total cultivated land area, the ratio of grain income to total agricultural income, and the ratio of the number of grain farmers to large farming households, are typically utilized to analyze NGPCL trends [15–17]. Among these indicators, the ratio of the NGPCL planted area to the total cultivated area has been widely applied [15]. However, these measurement methods are generally applied at the level of large-scale administrative divisions of provinces and cities, ignoring the differences in NGPCL at the local and regional scales, as well as differences in NGPCL types [17,18]. Additionally, some researchers have used remote sensing data to identify planting types and temporal/spatial changes in local cultivated land spaces while analyzing the NGPCL spatial pattern [18–21] to quantify NGPCL trends.

According to existing research on NGPCL classification, some scholars have classified NGPCL into three categories that differ from food crop production in terms of crop planting type [22,23], farming structure [24,25], and production mode [20]. Other researchers have classified cultivated land as paddy field dry farming, economic fruit tree planting, economic tree planting, or pond digging for aquaculture [26]. Notably, in China's "National Technical Consolidations for the Verification of the Results of the Third National Land Survey", the attributes of the current status of cultivated land were noted as "can be restored" or "engineering restoration" [27]. This has become the mainstream practice for the classification of existing NGPCL.

However, simply analyzing the NGPCL governance path on the basis of the spatial pattern revealed by identification efforts can no longer meet the actual needs of management departments. Therefore, determining how to manage NGPCL and realize the sustainable development of rural areas is highly practical. At present, there are still some gaps in the consolidation research on NGPCL. Considering that the premise of NGPCL governance is to clarify its consolidation potential [28], an evaluation and optimization of NGPCL are performed in combination with the research concept of land consolidation potential [29,30]. In previous studies of land consolidation potential, the following three mainstream methods were used. First, the gap between the theoretical and actual

productivity of cultivated land was used to represent the potential of cultivated land consolidation [31,32]. Second, based on the technical methods of cultivated land quality grade assessment, the quality grade and area of cultivated land were calculated, and potential improvements were recommended [33]. However, the abovementioned methods of assessing the cultivated land consolidation potential are relatively mature. Moreover, in terms of calculation results, cultivated land productivity and cultivated land quality grades after regulation often reach the ideal state according to indicators [34]. The actual production conditions and social and economic conditions are not fully considered, which may result in inaccurate grades. Third, cultivated land suitability and multifunctional evaluation methods have been adopted to determine the area of cultivated land that can be regulated on the basis of the results of cultivated land function and suitability evaluations [35–37]. Most studies of cultivated land suitability are based on natural factors such as climate, terrain conditions, and soil conditions (the thickness of the effective soil layer, surface soil texture, soil organic matter content, soil pH value, etc.), and few researchers have considered the ecological environment or social and economic factors [38,39]. Other researchers have proposed optimization objectives related to economic benefits, ecological benefits, and land compactness with the help of multiobjective optimization algorithms (MOOAs) and explored optimal consolidation plans when all objectives are achieved [40]. However, such studies often use land type merging, contiguous analysis, and other means to estimate patterns regarding the regulation of cultivated land, but these methods are focused mostly on promoting the establishment of contiguous cultivated land in a single direction [41,42], and in-depth discussions of the quantity, quality, and consolidation cost of cultivated land resources are lacking. In another study, an intention survey was employed to analyze the promotional impact of introducing a public participation mechanism during the stage of land consolidation and planning preparation, aiming to ensure land protection and enhance land planning [42,43]. However, such research is still independent and has not been included in formal NGPCL evaluation systems [42]. Other research on cultivated land regulation strategies has resulted in the proposal of various measures to promote rehabilitation, such as strengthening the management of cultivated land use, improving the land transfer market, and increasing grain subsidies [44]. Most of these measures fall within the "one-size-fits-all" category, ignoring the differences in the management of cultivated land of various types in different spaces.

In conclusion, the primary objectives of NGPCL assessment are to expand the effective cultivated land area, increase the agricultural production efficiency, and ensure food security. Considering that there are still knowledge gaps in the existing research on the assessment and remediation of NGPCL in terms of definition, classification, and identification of such land, as well as the selection of remediation indicators, a new approach is needed; specifically, this approach must be applicable at the village and town scales, which were rarely considered in previous studies. In this study, the methods for potential NGPCL consolidation are assessed, aiming to establish a scientific foundation for understanding NPGCL issues and consolidation strategies while also offering guidance for other countries at similar stages of development worldwide. The specific objectives are as follows:

(1) Understanding NGPCL of various types;
(2) Identifying the status quo and spatial pattern of NGPCL;
(3) Assessing the NGPCL consolidation potential;
(4) Exploring the governance of NGPCL.

2. Materials and Methods

2.1. Study Area

Dujiangyan city is a county-level city in Chengdu, Sichuan Province, China, named after the world-famous Dujiangyan Water Conservancy Project. The irrigation system that extends from the Dujiangyan Water Conservancy Project covers an area of more than 7100 km^2, and this area has become the main grain-producing area of Sichuan, China. The research area is located at the source of the Dujiangyan Water Conservancy Project (latitude

30°44′–31°02′ N, longitude 103°0–103°47′ E) and covers an area of approximately 254 km^2 (the cultivated land area is approximately 179.92 km^2). The terrain in the area is flat, the slope is low, and the average altitude is approximately 600 m (Figure 1).

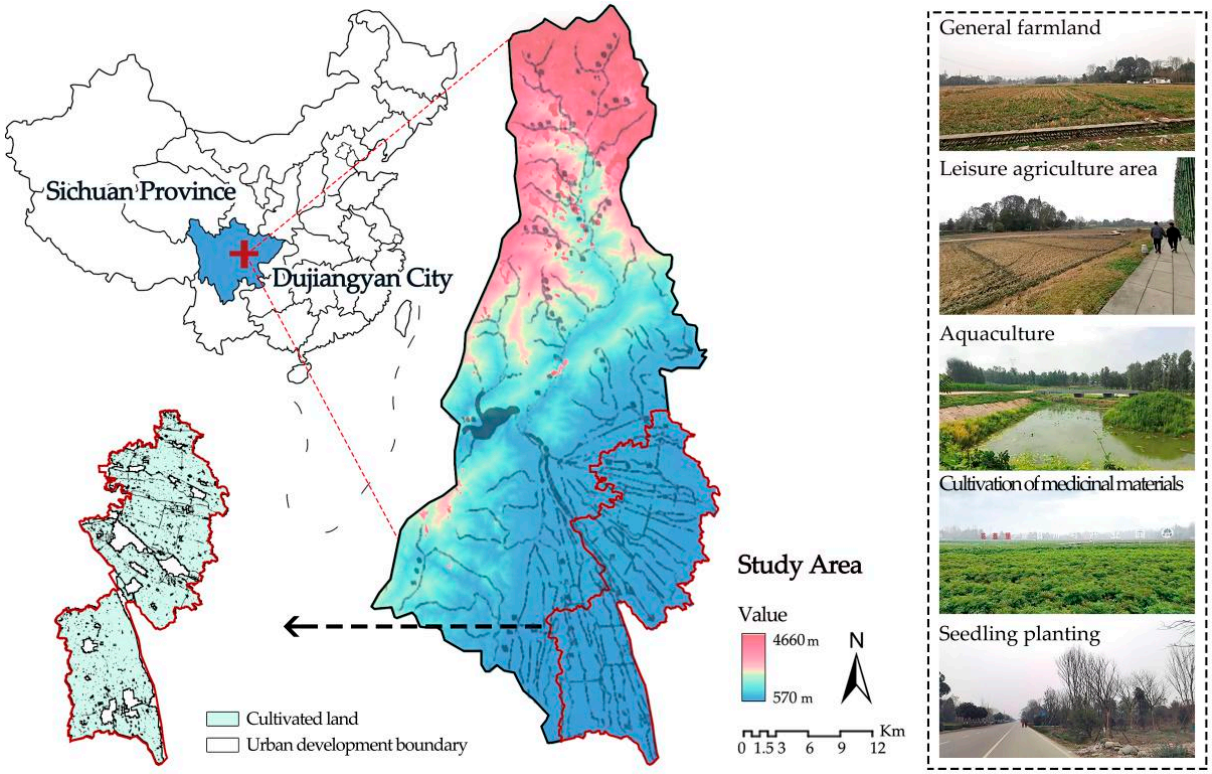


Figure 1. Overview of the study area.

In the cultivated land areas in the study region, the main crop types are rice, wheat, corn, soybean, and potato. However, with the advance of urbanization, the proportion of food crops in the gross regional product has fallen below 8%. The types of NGPCL in the study area are mainly seedling planting, fruit planting (*Actinidia chinensis* Planch., *Vitis vinifera* L., etc.), the cultivation of medicinal materials (*Ligusticum sinense* "Chuanxiong", etc.), and aquaculture (*Oncorhynchus mykiss*, etc.). The seedling planting area is wide and covers a large area, and it is connected to the adjacent Wenjiang District and Pidu District (the administrative region under the jurisdiction of Chengdu), forming an industrial cluster with a planting area of more than 700 km^2, which is the largest seedling planting area in Southwest China. Therefore, as a typical representation of NGPCL in Southwest China, this region is selected as the study area of NGPCL governance, which can provide a reference for other NGPCL governance cases in China and even worldwide.

2.2. Data Sources

The data sources used in this study included network open data, planning data, and survey data.

The network open data were as follows: (1) Remote sensing images were obtained from the geospatial Data Cloud Platform (http://www.gscloud.cn/ (accessed on 8 July 2021)). The Landsat 8 OLI-TIRS image (scene No. 129-039) obtained on 28 July 2020, when plant growth was observable and cloud cover was low, was selected as the interpretation data source and was mainly used for processing and analysis to determine the current land use type. (2) Digital elevation model (DEM) data from the geospatial Data Cloud Platform (http://www.gscloud.cn/ (accessed on 6 July 2021)) were used mainly for the calculation of topographic-related indicators. (3) Open street map (OSM) data from the Open Street Map website (https://www.openstreetmap.org/ (accessed on 25 November

2020)) were used. The following data were employed for location and road index analysis: (4) the normalized difference vegetation index (NDVI), with data obtained from the Chinese Academy of Sciences Resources and Environment Data Service Center (http://www.resdc.cn/Default.aspx (accessed on 8 October 2021)), was used, mainly to represent the regional vegetation coverage.

Planning data, such as the quality of cultivated land resources, water system maps, and related planning documents for Dujiangyan, were obtained from the Chengdu Land Consolidation and Ecological Rehabilitation Center and the Dujiangyan Irrigation District Management Committee and were mainly used for the index-based analysis of cultivated land and water areas.

The survey data included NGPCL classifications (for details, see Appendix A Questionnaire A1), realistic consolidation condition weights (for details, see Appendix A Table A1), social intentions (for details, see Appendix A **Questionnaire A2**), etc. The first two datasets were obtained in April 2024 through consultation with experts in relevant fields. Considering the importance of public participation in farmland protection, a survey of the willingness of farmland stakeholders to rectify NGPCL in 30 communities and 8 areas with tourist attractions within the study area from October 2021 to January 2024 was conducted (the selection of survey points was based on spatial balance and representativeness principles). The survey targets included government workers, farmers, and tourists, who are the main stakeholders of cultivated land. Three dimensions of the survey were used: perception of cultivated land status, planting intention, and satisfaction with agriculture (landscape). A total of 581 questionnaires were issued (107 for government workers, 316 for residents, and 158 for tourists), and 95.3% of the questionnaires were returned.

2.3. Research Framework

The framework of the NGPCL consolidation potential in the Dujiangyan irrigation district is shown in Figure 2. The specific decision-making path is as follows.

(1) To obtain a better understanding of NGPCL, remote sensing data, satellite images, and field investigation results were used. NGPCL was divided according to land attributes, the crop planting structure, and damage to cultivated land for various crop types. The NGPCL rate was subsequently calculated, the corresponding spatial pattern was analyzed, the NGPCL identification results were divided into farmland patches, and the theoretical NGPCL consolidation potential was obtained by dividing the proportion of the damage degree in farmland patches by area into 5 levels.

(2) To assess the constraints of realistic conditions on the consolidation potential of NGPCL, four realistic conditions, namely, farming conditions, environmental conditions, social will, and consolidation costs, were evaluated, and the analytical hierarchy process was comprehensively applied to calculate the weight of each evaluation factor and to complete the quantification and superposition of each index. Each index was then associated with a farmland patch and uniformly divided into 5 levels, which constituted the theoretical consolidation potential of NGPCL.

(3) To obtain realistic consolidation potential zoning model results, the theoretical and real consolidation potentials were matched; if the matching difference was ± 1, then the corresponding cultivated patch was extracted, and the original grade was retained. For the remaining cultivated land patches, MOOA was applied to construct a zoning model of NGPCL consolidation potential with the objectives of optimizing farming conditions, maximizing ecological benefits, maximizing social agricultural development intentions, minimizing the restoration cost, and minimizing plot change.

(4) Finally, considering the background of food, territorial, and space security, strategic suggestions for NGPCL governance were proposed.

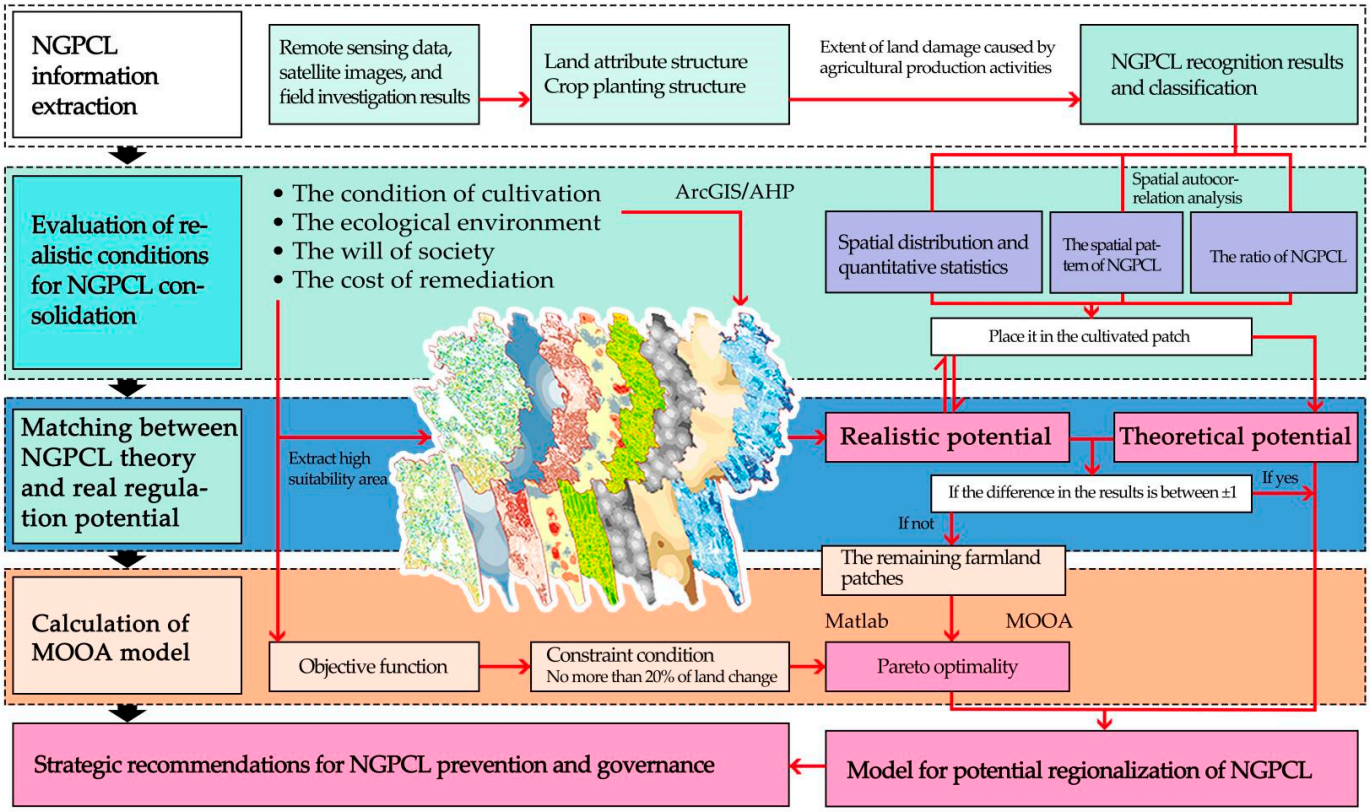


Figure 2. Diagram of the proposed method and processes.

2.4. Methodology and Research Process

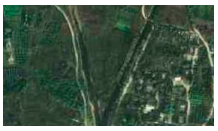
2.4.1. NGPCL Information Extraction

1. Classification and Extraction of NGPCL

The land use classification results for cultivated land, forestland, water area, construction land, and wasteland areas were obtained via the interactive interpretation of remote sensing images (the accuracy of land use interpretation reached 81.43%). According to the identification results, the main land use types in the study area are cultivated land and forestland [45]. The interpretation results were subsequently superimposed on the farmland boundaries in the study area to obtain the land use types within these boundaries.

For the identification of NGPCL, first, non-agricultural land and other cultivated land within the farmland boundaries were extracted according to the land use type combined with satellite map verification. Second, NGPCL was not analyzed on the basis of land attributes, as in previous studies, and the actual crop type in each land patch within the farmland boundaries was labeled through an artificial visual comparison of satellite images and field observations [46]. Additionally, 18 experts in the fields of urban and rural planning, land management, and landscape architecture were consulted. On the basis of the degree of damage to cultivated land caused by different types of crops, the classification of NGPCL was completed, and the degree of cultivated land damage was classified (Table 1).

Table 1. Classification of NGPCL.

Crop Type	Expert Rating	Land Use Type	Example of Satellite Imagery	Example Environments	Potential Grade	Description
Chinese herbal planting	0.47	Other gardens and cultivated land			Highest	The root system is short, and the damage to the soil layer is limited
Tobacco planting	1					
Tea planting	2.47					
Fruit planting	2.47	Orchard				
Herbaceous flower planting	2.53	Other gardens				
Turf planting	2.4					
Shrub planting	4.4	Bushland				
Fast-growing forest planting	4.87	Forestland			Medium	Coarse root system, easily resulting in soil degradation and acidification; soil ball transplantation reduces the thickness of the plowing layer
Seedling planting	4.87					
Pond culture	4.87	Breeding pond			Lowest	Extensive excavation or hardening of the soil surface
Livestock breeding	4.87	Facility agricultural land				
Non-agricultural, paved, occupied, or other cultivated land occupied						

2. Calculation of the NGPCL ratio

The following formula was used to calculate the ratio of the NGPCL area to the total cultivated land area [47]:

$$P = \frac{s_1 + s_2}{S} \times 100\% \quad (1)$$

where P is the NGPCL ratio, S is the total area of cultivated land, s_1 is the cultivated land used for production activities other than crop production, such as food and vegetable production, and s_2 is the cultivated land used for other purposes, such as non-and wasteland areas.

3. Spatial autocorrelation analysis

Spatial autocorrelation analysis has been widely used to reveal the distribution patterns of spatial elements [46]. Moran's index in spatial autocorrelation analysis is used to determine the general trend of the spatial correlation of the NGPCL regional unit attribute values that are similar in the study area. The formula is as follows:

$$M = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} Wij(x_i - \overline{x})(x_j - \overline{x})}{S^2\sum_{i=1}^{n}\sum_{j=1}^{n} Wij} \quad (2)$$

where n is the number of research objects; x_i and x_j represent the attribute values of spatial units i and j, respectively; W_{ij} is the spatial weight matrix; S^2 is the observed variance; and x is the average of the observed values. The value of M ranges from -1 to 1. When $M > 0$,

there is a positive spatial correlation. When the value is high, the degree of agglomeration is high. When $M < 0$, the spatial correlation is negative; if the negative correlation is small, the correlation is strong, and $M = 0$ indicates that the space is uncorrelated and has an independent random distribution.

2.4.2. Identification of the Consolidation Potential of NGPCL

The NGPCL consolidation potential can be defined as the threshold size of the consolidation of NGPCL in a specific area into cultivated land on the basis of policy and demand [48]. On the basis of the setting of the threshold size, theoretical and realistic consolidation potentials were considered.

1. Theoretical consolidation potential

The identification of the theoretical consolidation potential is related to the degree of damage to cultivated land caused by NGPCL production activities to reduce the difficulty of NGPCL restoration. The NGPCL classification of the degree of cultivated land damage also reflects the difficulty of restoring cultivated land; that is, when the degree of damage is low, the degree of restoration difficulty is low, and the theoretical consolidation potential is high. Moreover, considering that land consolidation was generally carried out in cultivated land patches [49], the NGPCL classification results are applied to cultivated land patches. The area proportion corresponding to the NGPCL grade for a single cultivated patch was used to determine the theoretical consolidation potential of NGPCL. The formula is as follows:

$$p_A = \frac{A_i}{A} \times 100\%,\ i = 1, 2, 3 \tag{3}$$

$$V_{\mathrm{i}} = \begin{cases} A_{\mathrm{i}} \ , \ \mathrm{p_A} \geq 50\% \\ \mathrm{mean}(pA),\ \mathrm{p_A} \leq 50\% \end{cases} \tag{4}$$

In Formula (3), p_A represents the ratio of the area of a single cultivated patch (A) to that of a single NGPCL type (A_i), where $_i$ represents "Value" in the NGPCL classification. In Formula (4), V_i represents the value of the level-i theoretical consolidation potential; if p_A exceeds 50%, then the original value of A_i is retained; if p_A is less than 50%, the average is taken according to the p_A of each A_i within the cultivated patch.

The theoretical NGPCL consolidation potential is divided into 5 levels, from small to large, representing the areas with the highest, high, medium, low, and lowest consolidation potentials.

2. The realistic consolidation conditions

In terms of practical consolidation potential, on the basis of relevant technical regulations and existing studies [48,50–54], four realistic conditions, namely, farming conditions, environmental conditions, social will, and consolidation costs, were considered. First, to eliminate the potential conflict between ecological protection and agricultural production, an assessment of farming conditions and the ecological environment was carried out, aiming to estimate the resources and environmental conditions needed to maximize the theoretical NGPCL consolidation potential [19,47]. Notably, the evaluation of farming conditions was based on two natural and artificial factors, and the impact of production-related factors on agriculture was analyzed, encompassing 5 categories and 15 indicators. The environmental evaluation was based on indicators from a territorial space evaluation [52] and involved assessments of 8 indicators in the 2 categories of ecological sensitivity and the importance of the ecological service function. In addition to these conditions, the consolidation of NGPCL is affected by social factors, such as social will and consolidation costs [48,50]. Among them, social will accounts for the cognitive promotion of agricultural development by the main stakeholders in the three categories of farmland use, namely, workers, farmers, and tourists; on the basis of the social willingness questionnaire, 8 indicators in 3 categories were constructed [44]. Additionally, accounting for the cost of cultivated

land restoration, such as time and monetary costs, a restoration cost evaluation scheme was constructed, spanning 3 categories and 6 indicators (see details in Appendix A Table A1).

The analytical hierarchy process was used to construct a realistic consolidation potential hierarchical model with the help of 13 experts. Then, yaahp V12.11 software released by meta-decision was subsequently introduced for group decision analysis, and the weights of various indicators showing improvement potential were determined; the overall consistency ratio was 0.0696 (CR < 0.1), indicating that the judgment matrix passed the consistency test. The grid calculator in ArcGIS 10.7 software released by Esri was subsequently used to achieve index superposition, and the classification of the consolidation potential was based on the theoretical consolidation potential grade above.

2.4.3. Construction of the Zoning Model of the NGPCL Consolidation Potential

Figure 3 shows the workflow and examples of NGPCL regulation potential zoning.

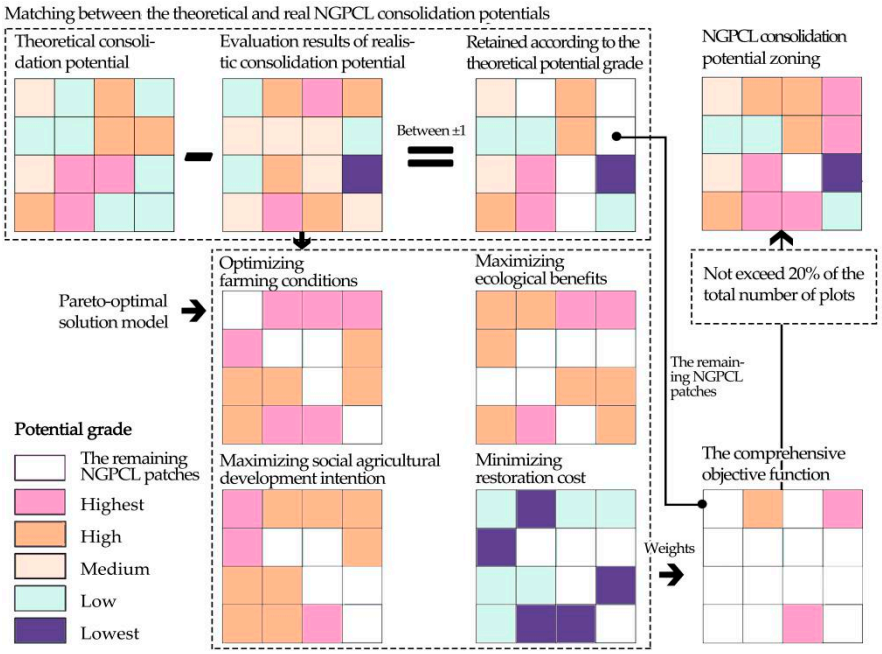


Figure 3. Example of NGPCL regulation potential zoning process.

1. Matching between the theoretical and realistic NGPCL consolidation potentials

To match the theoretical and realistic NGPCL consolidation potentials, the following formula was used:

$$|T - R_x| <= |1|, D = T \quad (5)$$

where D is the matching difference between the theoretical consolidation potential (T) and the four realistic consolidation potentials (R_x). If the matching difference between D and the four theoretical consolidation potentials was within ±1, then the cultivated land patch was extracted, and the original grade was retained according to the theoretical consolidation potential grade.

2. Construction of the MOOA

The MOOA was constructed with the remaining cultivated land patches as the assessment objects. In this study, the Pareto-optimal solution model was used to obtain the optimal solution of the objective function, with the goal of optimizing the states of resource optimization and efficiency.

First, the four objective functions related to optimizing farming conditions, maximizing ecological benefits, maximizing social agricultural development intention, and minimizing

restoration cost were combined into a comprehensive objective function with corresponding weights. The specific formula is as follows:

$$F(x) = w_1 f_{1(x)} + w_2 f_{2(x)} \ldots w_4 f_{4(x)} \quad (6)$$

where $F_{(x)}$ is the comprehensive objective function, $f_{1(x)} \ldots f_{4(x)}$ represent the four objective functions, and $w_1 \ldots w_4$ are the corresponding weight coefficients.

Second, to reduce the restoration cost, the planning results should generally reflect the status quo; otherwise, labor and money will be wasted, which will have a negative impact on development. Therefore, the number of plots with changes in the consolidation potential grade should not exceed 20% of the total number of plots as a constraint condition, and the formula is as follows:

$$\frac{\sum_i Z_i}{I} < 20\% \quad (7)$$

In the formula, the total number of plots in the region is I, and the number of plots with changes in the consolidation potential is $\sum_i Z_i$.

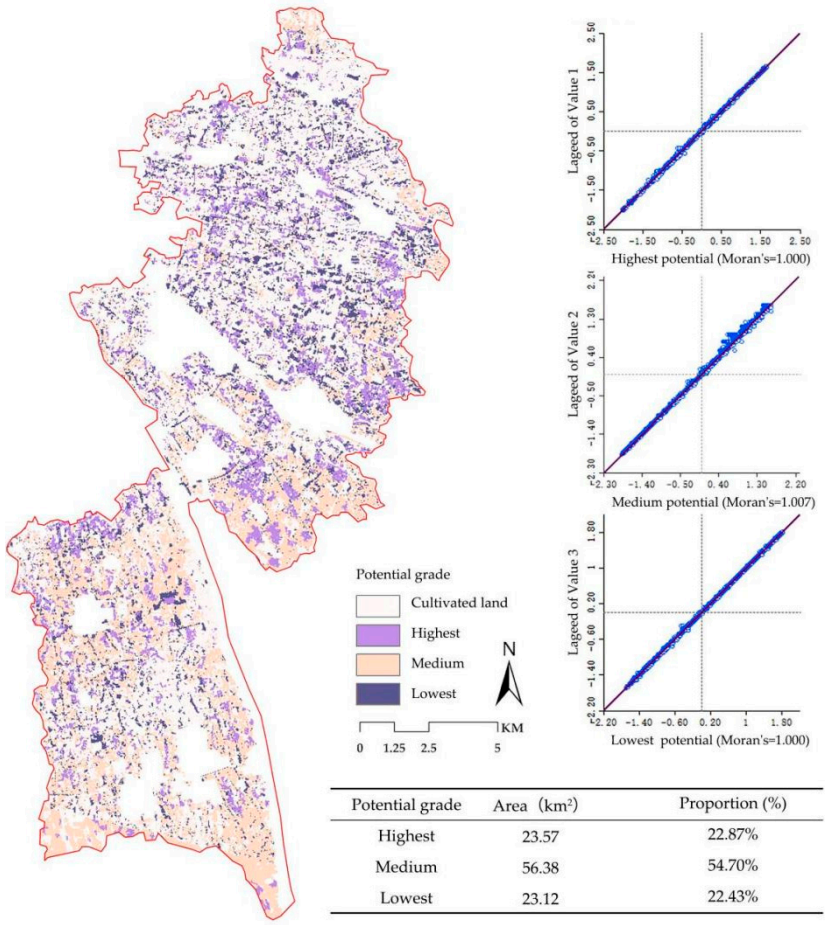
In terms of algorithms, on the basis of the MATLAB r2023b platform released by MathWorks in the United States, the export conversion tool in the YALMIP environment was used, and the CPLEX solver was applied to solve the NGPCL restoration potential decision model of the study area. The unbiased Pareto-optimal solution from the perspective of tradeoff was used to establish the zoning scheme for the NGPCL consolidation potential, and the classification of the consolidation potential was the same as that described above.

3. Results

3.1. Characteristics of NGPCL

According to the classification of NGPCL in Section 2.4.1, NGPCL identification was performed (Figure 4). A total area of 103.08 km^2 of NGPCL was extracted, accounting for 40.58% of the total study area. On the basis of Formula (1), the NGPCL ratio in the study area was calculated to be 53.8% (relative to the total area of cultivated land), confirming that most of the cultivated land in the study area is used for nonfood production. According to the classification of the degree of damage caused by NGPCL to cultivated land, the area of medium-potential land dominated by seedling planting was the largest, reaching 56.38 km^2 (54.7%). Moreover, spatial patches with the lowest potential were small and distributed throughout the whole region, covering 23.12 km^2 (22.43%) of the cultivated land space.

According to Formula (2), the Moran indices for the overall and cultivated land patches in the study area were positive, indicating a positive spatial correlation (p value < 0.05). Considering the large number of farmland patches and relatively dense distribution of these patches, the potential grades were determined to be linearly distributed. In the figure, the product of the horizontal and vertical coordinates is the local Moran index of the theoretical regulation potential at certain levels. The hierarchical classification of NGPCL in the study area indicated that the areas with the highest potential and lowest potential are distributed mainly in low–low aggregation areas, as illustrated in a scatter plot (the third quadrant); these areas are spatially scattered and located mainly in the middle and northern parts of the study area. Only the scatterplot of the medium-potential areas included a high–high aggregation area (the first quadrant); specifically, NGPCL shows a continuous concentrated distribution trend in the south, but it is still relatively scattered in the north.



Potential grade	Area (km²)	Proportion (%)
Highest	23.57	22.87%
Medium	56.38	54.70%
Lowest	23.12	22.43%

Figure 4. Statistics and spatial models of the NGPCL recognition results in the Dujiangyan irrigation district.

3.2. Evaluation of Realistic Conditions for NGPCL Consolidation

On the basis of the four current spatial evaluation factors, namely, the cultivation conditions, the environmental conditions, the will of society, and the cost of consolidation, a realistic condition evaluation of NGPCL consolidation was performed; the evaluation results were associated with farmland patches, and classification into 5 levels was performed (Figure 5a). In general, the agricultural development background of the study area is good, all stakeholders show a strong willingness to develop agriculture, and the restoration cost of NGPCL in the regional agricultural space is low. In addition, the proportion of areas with a median–medium or greater consolidation potential accounted for more than 92% of the total study area, and the NGPCL consolidation potential was high (Table 2). Additionally, the proportion of land classified in the lowest consolidation potential category was relatively small, and the distribution of these areas was relatively scattered.

Table 2. Potential grades of NGPCL consolidation based on realistic condition evaluation.

	Graded Area (km²)/Proportion (%)				
	Highest	**High**	**Medium**	**Low**	**Lowest**
The conditions of cultivation	5.77 (3.21%)	80.31 (44.63%)	88.77 (49.34%)	4.86 (2.70%)	1.03 (0.57%)
The environmental conditions	0.14 (0.08%)	41.75 (23.21%)	50.10 (27.85%)	85.07 (47.28%)	3.73 (2.07%)
The will of society	64.02 (35.58%)	55.49 (30.84%)	47.03 (26.14%)	13.01 (7.23%)	1.19 (0.66%)
The cost of consolidation	3.22 (1.79%)	34.84 (19.36%)	141.21 (78.48%)	-	-

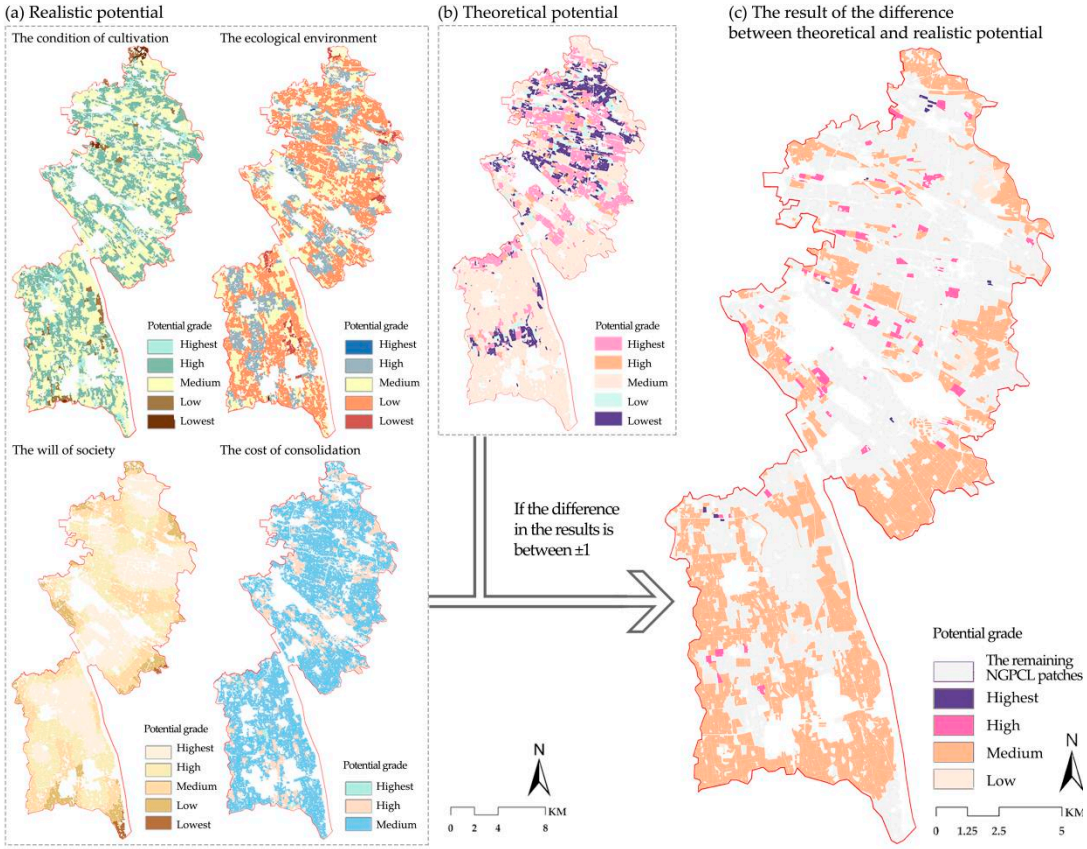


Figure 5. (**a**) Realistic potential; (**b**) theoretical potential; (**c**) theoretical and realistic consolidation potential matching results.

3.3. NGPCL Consolidation Potential Zoning Process

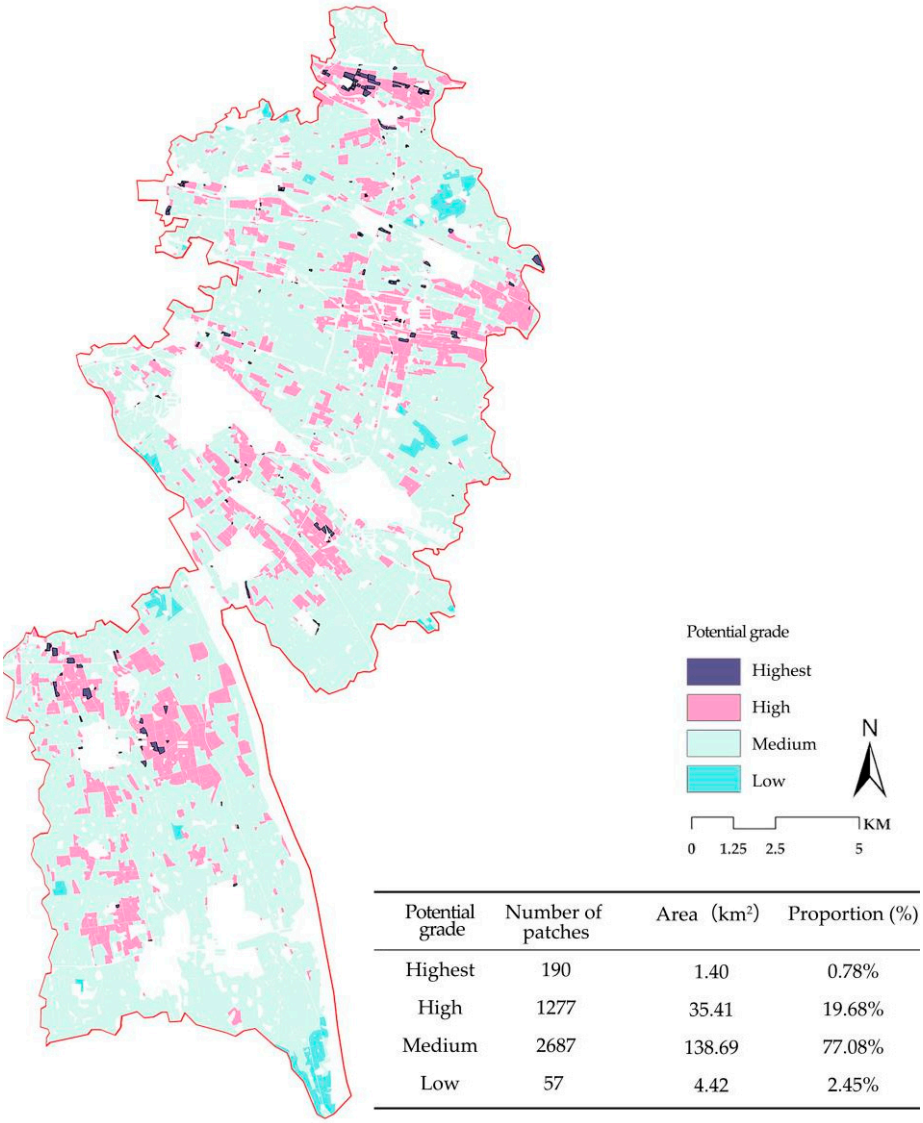
3.3.1. Matching of the Theoretical and Realistic Consolidation Potentials

The theoretical NGPCL consolidation potential in the study area was calculated according to Formulas (3) and (4) (Figure 5b). Overall, the areas with high potential for NGPCL consolidation are located mainly in the northern part of the study area, but their spatial distributions are relatively scattered. Although the potential for NGPCL consolidation in the southern region is medium, the spatial distribution is contiguous, which is conducive to transforming many areas into contiguous high-standard farmland zones in future NGPCL consolidation.

Formula (5) was used to determine the match between the theoretical and realistic consolidation potentials (Figure 5c). A total area of 80.60 km^2 (accounting for 44.80%) was extracted, with a total of 1432 cultivated land patches, mainly with medium consolidation potential. According to the matching results, the contiguous areas are mainly concentrated in the southern part of the study area, whereas the northern consolidation potential area is concentrated mainly at the boundary of the study area, with a sporadic distribution in the center.

3.3.2. NGPCL Consolidation Potential Zoning

For the remaining 2779 cultivated land patches, MOOA was used to calculate the Pareto-optimal solution without preference from a trade-off perspective, and, ultimately, a zoning plan for the potential of NGPCL consolidation in the study area was obtained (Figure 6). Areas with medium consolidation potential accounted for a relatively large proportion of the total area in terms of patch quantity, followed by areas with high consolidation potential; those two grades accounted for 96.76% of the total cultivated land area. The overall potential for NGPCL consolidation in the research area is good.



Potential grade	Number of patches	Area (km²)	Proportion (%)
Highest	190	1.40	0.78%
High	1277	35.41	19.68%
Medium	2687	138.69	77.08%
Low	57	4.42	2.45%

Figure 6. Zoning scheme of the regulatory potential of NGPCL in the study area.

4. Discussion

4.1. Understanding the NGPCL Phenomenon

4.1.1. NGPCL Phenomenon and Spatial Pattern

The world's overall annual grain output is on the rise, but this has been a distraction from the serious decline in grain production due to NGPCL transformation [55]. This study provides evidence from the Dujiangyan Irrigation Project to evaluate this trend. The experimental results show that the ratio of NGPCL in the region has exceeded 50%. The statistical branch of the local government noted that the total grain output of Dujiangyan in 2023 was only 63.7% of that in 2006 [56], exceeding the national average in China [57,58]. According to the data regarding cultivated land quality, the majority of cultivated land in the region is irrigated land or paddy fields (dry land accounts for less than 1% of all land). These two types of arable land are where rice, China's main food source, is produced. In these regions, areas with high consolidation potential account for the highest proportion of all classifications, reaching 34.9% and 27.8%, respectively, and areas with medium consolidation potential account for approximately 17%. These findings indicate that these NGPCL phenomena strongly affect food security.

Research on the spatial pattern of NGPCL indicates that NGPCL often exhibits spatial clustering effects because land operators rent surrounding farmland to expand production

and the business scale after economic benefits emerge [59]. In contrast to the results of previous studies, the experimental results of this study reveal that the spatial features of various types of land patches in NGPCL areas are discrete and that the spatial patterns are "contiguous in the south and scattered in the north". A search of the planning data provided by the Chengdu Land Consolidation and Ecological Rehabilitation Center revealed that the southern part of the study area is still dominated by seedling planting, so patches are relatively concentrated there. After multiple rounds of land consolidation, the spatial pattern of cultivated land in northern China has become diverse and fragmented via the processes of functional transformation, land concentration, and the dispersion of various types of land, thus increasing the difficulty of NGPCL consolidation.

4.1.2. Causes of NGPCL Formation and Related Governance Dilemmas

Previous studies have analyzed the reasons for the emergence of NGPCL from the perspectives of nature, policy systems, and economic factors [60–62]. In addition to the reasons already discussed, many inevitable NGPCL governance challenges exist in the region. First, the current policy in the research area states that cultivated land should be used for at least one season of food crop cultivation and that nonfood crop cultivation systems must be able to be converted to food production systems after one season. For the nursery industry, which has occupied a large area of cultivated land within the research area for several years or decades, this policy is not applicable. Second, owing to the cost–benefit gap, labor forces have migrated outward to seek higher returns, leading to a serious aging phenomenon in agricultural production [63]. One farmer said, "Now it's not that we don't want to grow food. We're getting older and don't have the energy, so it's easier to manage planting trees." Additionally, the experimental results revealed that the nursery industry in the study area has been developing for many years and that a fixed and contiguous industrial model has been formed. As one farmer said, "Now that the real estate industry is declining, the nursery stock market is also declining, and the trees cannot be sold... If we cut them down, we cannot bear to let them go, and we have to wait for them to be put there." Such long-term occupation cannot generate economic benefits, and planting seedlings removes topsoil and causes certain damage to the quality of cultivated land. However, farmers find it difficult to comply with the demand to directly abandon years of investment, restore farmland, and plant food. If farmers are forced to restore cultivated land in NGPCL areas, it will have a significant effect on the regional industrial chain and farmers' income [64,65]. These factors greatly limit the restoration of NGPCL.

4.2. Discussion on the Zoning of NGPCL Consolidation Potential

Previous studies rarely analyzed the governance path and consolidation potential of NGPCL [21,28]. This study extends beyond applying a single cultivated land self-index for evaluation, innovatively considering NGPCL theory and realistic consolidation potential as the main components of NGPCL consolidation. Additionally, environmental, economic, and social factors are considered in the determination of the consolidation potential. Moreover, public participation is included as an important part of realistic condition evaluation, and public participation evaluation is separated from environmental evaluation.

The proposed method relies on existing land consolidation approaches but not entirely on the MOOA in the optimization process. Instead, NGPCL theory is integrated with practical potential for transformation. This approach reflects not only the current situation of farmland damage and the corresponding difficulty of restoration under ideal conditions but also the achievable degree of theoretical potential transformation under the multiobjective constraints of cultivation conditions, the environment, social willingness, and consolidation costs. Moreover, in the selection of the objective function in the MOOA, unlike previous objectives such as maximizing economic benefits, ecological benefits, and land compactness [40], this study considers factors such as the spatial environment and social development, which represent the constraints of agricultural production stakeholders and costs of NGPCL consolidation. These methodological improvements align estimates of

the consolidation potential closely with the real cultivated land space, providing a refined approach for the future consolidation of NGPCL.

Compared with previous studies at the provincial and municipal levels, in this study, a hierarchical zoning scheme is proposed on the basis of cultivated land patches, which can be effectively used to analyze the spatial heterogeneity of the NGPCL consolidation potential at the meso- and microscales and guide NGPCL consolidation at the scale of specific cultivated land patches.

4.3. Policy Recommendations for Promoting NGPCL Governance

The NGPCL phenomenon in the research area is substantial, and there is an urgent need to protect farmland. Therefore, the following suggestions are proposed.

A classification system for NGPCL based on indicators such as land classification or damage should be constructed to achieve more accurate identification, classification, and control of NGPCL and to ensure the rational use of cultivated land. For example, crop types that damage the cultivation layer should be prohibited, NGPCL behaviors that do not damage the cultivation layer should be promoted through market mechanisms, and preventive measures to prevent further increases in NGPCL should be taken.

An NGPCL hierarchical, partitioned, and phased governance system should be established. For example, in areas with high potential for improvement, priority should be given to carrying out farmland improvement work, restoring food production, and establishing phased governance goals. For areas with low consolidation potential, the reasons for the low potential should be thoroughly analyzed, the recovery costs should be evaluated, and the governance of such areas should be completed in stages.

The interests of farmers should be safeguarded, and their willingness to plant should be strengthened. Increasing food subsidies and providing a better policy environment for grain cultivation can strengthen the willingness to plant. Owing to planting limitations and land abandonment associated with aging and population loss, land transfer should be carried out on the basis of the surrounding environment and the locations of land patches to form contiguous and easily managed planting spaces. Moreover, for those engaged in long-term NGPCL production activities that occupy farmland, a comprehensive survey of crop types and production times is recommended to ensure the interests of farmers in various seasons. However, certain production regulations should be established after the sale of land to create a spatiotemporally differentiated control approach.

4.4. Limitations and Prospects

At present, the understanding of NGPCL in academic circles is not unified, leading to different classification standards for NGPCL in different regions [22–26]. In this study, existing research results, field investigations and expert opinions were combined to classify the types of croplands experiencing NGPCL transformation according to the degree of damage. This classification method is direct. However, the NGPCL classification results of this study may not be applicable to other regions considering the differences in crop planting types globally and among regions, which may lead to limitations in the classification approach. Therefore, in future studies, crop type statistics at the local, regional, or national scale can be used to form a more applicable NGPCL classification system.

In this study, remote sensing data were applied for land use classification, and they were used as the basis for NGPCL classification. Remote sensing data have the advantages of regular updating and easy acquisition, but the recognition accuracy of objects in images is still affected by subjective factors [66]. The land use data provided by the government are relatively accurate, but they are less commonly released and more difficult to obtain than other types of remote sensing data. Therefore, choosing the best data for classifying NGPCL should be the focus of future research.

Moreover, the natural conditions of cultivated land are highly complex, and factors such as terrain, water systems, and land area characteristics all impact NGPCL patterns [39,60]. In this study, NGPCL in plain areas was explored, but the NGPCL situation under complex terrain conditions such as mountains and hills was not analyzed. Future research should include sites with diverse terrains, and the spatial distribution characteristics and aggregation of different NGPCLs should be explored considering differences in the natural environment.

5. Conclusions

Following the research idea of "connotation definition and classification—potential identification—consolidation zoning", an empirical study of NGPCL potential estimation and regional regulation was conducted with the Dujiangyan Irrigation District as an example. The results revealed that the phenomenon of NGPCL transformation in the study area is serious (the NGPCL rate is 53.8%), and the NGPCL recognition results displayed the trend of "contiguous in the south and scattered in the north". Notably, the spatial imbalance was obvious. The theoretical potential of land can directly reflect the difficulty of restoring the NGPCL status quo, and the realistic consolidation potential was considered with real-world constraints to obtain realistic zoning results. The matching of theoretical and realistic potentials revealed that areas with medium consolidation potential are common and continuously distributed, and they could be the focus of farmland consolidation in the future. The final zoning results of the NGPCL consolidation potential indicate that the study area has high NGPCL consolidation potential, and the area with medium or greater consolidation potential accounts for 97.54% (4154 cultivated land patches) of the total area; these results can be used to guide NGPCL consolidation in the future.

The decision method developed for NGPCL consolidation potential zoning proposed in this paper can be used to obtain quantitative solutions under multiple conditions given multiobjective trade-offs and can be applied to guide regional and national restoration efforts and land consolidation project planning.

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Institutional Review Board Statement: Ethical review and approval were waived for this study, due to all data will be anonymized, and respondents' confidentiality will be strictly maintained.

Informed Consent Statement: The questionnaire survey was conducted only after all participants were aware of the content and verbally agreed.

Data Availability Statement: The data are not publicly available due to privacy concerns.

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

Appendix A

Table A1. Realistic evaluation index system for NGPCL consolidation.

Target Layer	Criterion Layer	Index	Basis of Classification	Assigned Value	Weight
The conditions of cultivation	Topographic conditions	Slope	Slope < 3°	1	0.2015
			3° < Slope < 8°	2	
			8° < Slope < 15°	3	
			15° < Slope < 25°	4	
			Slope > 25°	5	
		Aspect	South	1	0.1314
			Southeast, Southwest	2	
			East, West	3	
			Northeast, Northwest	4	
			North	5	
	Soil conditions	Soil organic matter content	≥3.0%	1	0.0746
			3.0–2.0%	2	
			2.0–1.0%	3	
			0.6–1.0%	4	
			<0.6%	5	
		Soil pH value	6.0–6.5	1	0.0725
			5.0–6.0; 6.5–7.3	2	
			4.0–5.0; 7.3–8.3	3	
			<4.0, >8.3	5	
		Effective soil layer thickness	≥100 cm	1	0.055
			60–100 cm	2	
			30–60 cm	3	
			<30 cm	5	
		Surface soil texture	Loam	1	0.0451
			Clay	2	
			Sandy soil	3	
			Gravelly soil	5	
	Plot conditions	Plot area	Contiguous farmland area > 18 hm^2	1	0.0451
			Contiguous farmland area > 3 hm^2	2	
			Contiguous farmland area > 1 hm^2	3	
			Contiguous farmland area > 0.5 hm^2	4	
			Contiguous farmland area < 0.5 hm^2	5	
		Grade of cultivated land quality	The cultivated land quality grade is 8	1	0.0419
			The cultivated land quality grade is 9	3	
			The cultivated land quality grade is 10	5	
		Plot regularity	According to the calculation results, five levels are divided according to the natural break classification		0.0288
	Irrigation and drainage conditions	Distance from water			0.0266
		Irrigation conditions			0.0254
		Drainage conditions	The drainage system is relatively sound	1	0.0243
			The drainage system is generally sound	3	
			The drainage system is not sound	5	
	Location and traffic conditions	Distance from road	According to the calculation results, five levels are divided according to the natural break classification		0.0206
		Distance from settlements			0.02
		Tillage road density			0.0192

Table A1. *Cont.*

Target Layer	Criterion Layer	Index	Basis of Classification	Assigned Value	Weight
The ecological environment	Ecological sensitivity evaluation	Elevation	Elevation < 600 m	1	0.0189
			600 m < Elevation < 700 m	2	
			Elevation > 700 m	3	
		Slope	The same as the slope index above		0.0173
		Aspect	The same as the aspect index above		0.0128
		Spatial distribution of water resources	>200 m buffer for rivers, >100 m buffer for ponds	1	0.0123
			100–200 m buffer for rivers, 50–100 m buffer for ponds	2	
			50–100 m buffer for rivers, 20–50 m buffer for ponds	3	
			20–50 m buffer for rivers, 10–20 m buffer for ponds	4	
			0–20 m buffer for rivers, 0–10 m buffer for ponds	5	
		Land use type	Land for construction, wasteland	1	0.0114
			Farmland	3	
			Waters, woodland	5	
	Evaluation of the importance of ecological service functions	Security of water resources	No water, distance > 150 m	1	0.0101
			Dispersed small water bodies, distance $\leq$ 150 m	2	
			Relatively concentrated small water bodies, distance < 100 m	3	
			Medium area water bodies, distance < 50 m	4	
			Large area of water bodies, distance < 20 m	5	
		Vegetation coverage	20% < Coverage $\leq$ 35%	1	0.0088
			35% < Coverage $\leq$ 45%	2	
			45% < Coverage $\leq$ 60%	3	
			Coverage > 60%	5	
		Ecological disturbance of development and construction	The density of traffic, villages, and towns is very high, and the population is more than 5000	1	0.0085
			The density of transportation, villages, and towns is high, with 4000 < population $\leq$ 5000	2	
			The density of traffic, villages, and towns is in the middle, with 3000 < population $\leq$ 4000	3	
			The density of traffic and villages is low, with a population of greater than 2000 and $\leq$3000	4	
			The density of traffic, villages and towns is very low, 1000 < population $\leq$ 2000	5	

Table A1. *Cont.*

Target Layer	Criterion Layer	Index	Basis of Classification	Assigned Value	Weight
The will of society	Spatial cognition of government workers	Industrial spatial development perception	According to the calculation results, five levels are divided according to the natural break classification		0.0083
		Perception of agricultural development status			0.0074
	Agricultural industry cognition	Industry satisfaction			0.0067
		Satisfaction with permanent basic farmland demarcation			0.0066
		Satisfaction degree of cultivated land occupation			0.0057
		Planting intention intensity			0.0057
	Tourist value perception	Agricultural landscape identity			0.0049
		Current landscape satisfaction			0.0047
The costs of consolidation	The monetary costs of consolidation	Consolidation area	According to the area size of a single NGPCL, it is divided into 5 classes according to the natural break classification		0.0042
		Project rehabilitation measures' cost	Value 1 in NGPCL	1	0.0027
			Trees such as fruit trees in Value 1 of NGPCL	2	
			Value 2 in NGPCL	3	
			Value 3 in NGPCL	4	
			Other non-agricultural occupation	5	
		Soil fertility restoration costs	According to the soil pH, organic matter content, heavy metal content, and other indicators, according to the natural discontinuous classification of 5 levels		0.0027
	The time costs of consolidation	The time it takes to plow	According to the estimated end time of NGPCL production activities in the current quarter, there are 5 levels according to the natural break classification		0.0050
	The opportunity costs of consolidation	Contiguity of land	The boundary distance is $\leq$10 m, and the contiguous cultivated land area is $\geq$5 hm^2	1	0.0019
			Boundary distance $\leq$ 10 m, 5 hm^2 > contiguous cultivated land area > 2 hm^2	2	
			Boundary distance $\leq$ 10 m, 2 hm^2 > contiguous cultivated land area > 1 hm^2	3	
			Boundary distance $\leq$ 10 m, 1 hm^2 > contiguous cultivated land area > 0.5 hm^2	4	
			Boundary distance $\leq$ 10 m, 0.1 hm^2 > contiguous cultivated land area	5	
		Distance from existing cultivated land	According to the distance from the existing cultivated land, it is divided into 5 levels according to the natural break classification		0.0013

Questionnaire A1. Non-grain-producing cultivated land (NGPCL) classification survey.

Dear expert,

Greetings! The author is currently investigating non-grain production activities on cultivated land. To enhance the objectivity and scientific rigor of the definition and classification of NGPCL proposed in this research, we kindly request your expertise and academic insights in this field to provide ratings for various crop types that delineate NGPCL through this questionnaire. Please note that the questionnaire is intended solely for academic research purposes, and your participation would be appreciated.

(Kindly note that the focus of this study is specifically on discussing "NGPCL" in cultivated land areas and does not encompass the "non-agricultural" issues arising from construction and industrial land encroachment on cultivated areas.)

The details are as follows:

1. Which of the following production activities falls within the scope of NGPCL?

☐ Chinese herbal planting, ☐ Tobacco planting, ☐ Tea planting, ☐ Fruit planting, ☐ Herbaceous flower planting, ☐ Turf planting, ☐ Fast-growing forest planting, ☐ Seedling planting, ☐ Shrub planting, ☐ Livestock breeding, ☐ Pond culture

Other types of crops: _____

2. Please score the damage to cultivated land caused by the following crop type (the higher the score is, the higher the degree of damage):

Types of Crop Type	**Grade**				
Chinese herbal planting	1☐	2☐	3☐	4☐	5☐
Tobacco planting	1☐	2☐	3☐	4☐	5☐
Tea planting	1☐	2☐	3☐	4☐	5☐
Fruit planting	1☐	2☐	3☐	4☐	5☐
Herbaceous flower planting	1☐	2☐	3☐	4☐	5☐
Turf planting	1☐	2☐	3☐	4☐	5☐
Fast-growing forest planting	1☐	2☐	3☐	4☐	5☐
Seedling planting	1☐	2☐	3☐	4☐	5☐
Shrub planting	1☐	2☐	3☐	4☐	5☐
Livestock breeding	1☐	2☐	3☐	4☐	5☐
Pond culture	1☐	2☐	3☐	4☐	5☐

Questionnaire A2. Investigation of non-grain-producing cultivated land (NGPCL) in the Dujiangyan irrigation district.

Dear participant,

Greetings! We are currently conducting a survey on NGPCL in the Dujiangyan irrigation district. We sincerely appreciate your valuable input amidst your busy schedule. This questionnaire does not include any personal information. By completing the questionnaire, you consent to the use of the data for scientific research purposes. Your contribution to this study is greatly appreciated. The survey comprises multiple-choice and fill-in-the-blank questions, where providing your details is mandatory but providing answers is optional. Each item features 5 rating levels; kindly mark "√" next to the appropriate choice. A lower score indicates lower satisfaction with the content or suggests that it is in poor condition.

You are currently located at _____ company (skip to 1)/community (skip to 2)/scenic spot (skip to 3)

1. Questionnaires for government workers

1. What do you think of the current agricultural development in your region?
   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
2. What do you think of the development prospects of the agricultural industry in your region
   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
3. What do you think of the NGPCL phenomenon?_____
4. What problems do you think exist in the agricultural space in your region?_____

2. Questionnaires for farmers

1. What is your family's main source of income?
   A. Being a farmer B. Owning a business C.Being a worker D. Others_____
2. How satisfied are you with the agricultural industry in your region?
   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
3. How satisfied are you with the permanent basic farmland designation in your area?
   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
4. How satisfied are you with the farmland compensation in your area?
   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
5. If you want to participate in agricultural planting in the future, how strong is your willingness to plant?
   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
6. What problems and difficulties do you think exist in agricultural production in your region?
   _____

3. Questionnaire for tourists

1. What attracts you most to the region's natural landscape (multiple choices)
   A. Geological landform B. Woodland vegetation C. Pastoral landscape D. River wetland E. Biological landscape F. Others_____
1. How satisfied are you with the current landscape of the area?
   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
2. How do you like the agricultural landscape in the countryside?
   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
3. What do you think the agricultural landscape should look like?_____
4. What problems do you think exist in the regional agricultural landscape?_____

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