Multi-objective Spatial Optimization and Evaluation of Land Use in Xishuangbanna

Xinyue Liang¹, Jiarong Chen², Hanli Chen³, Anqi Li⁴, Hongzhou Wang²*

¹ School of Computer Science and Technology, Beijing Institute of Technology, 102488, China
² School of Mathematics and Statistics, Beijing Institute of Technology, 102488, China
³ School of Automation, Beijing Institute of Technology, 102488, China
⁴ Faculty of Geographical Science, Beijing Normal University, 100875, China

Abstract. Effective management of environmental resources and energy demands optimal land use, which is a crucial issue in environmental planning and assessment nowadays. This paper proposes a method for optimal land use in the Xishuangbanna Prefecture, with three objectives (maximum economic efficiency, ecological efficiency, and land compactness) and corresponding constraints according to the development needs and environmental resources characteristics. The multi-objective optimization algorithm (improved NSGA-II) is used to explore a set of solutions for land use optimization in which all objectives are optimal and weighed. Among them, representative solutions are selected (the no-preference solution and the solutions in which each of the three objectives prevails). After optimization, a comprehensive evaluation model is established to further assess representative solutions based on the analytic hierarchy process, which has good adaptability and flexibility for different decision orientations. The paper provides decision support for land use planning and assessment in the Xishuangbanna Prefecture and can be extended to other regions.

1. Introduction

Land use optimization is a method for managing environmental resources through quantitative design and spatial allocation of different land use types. It often involves a trade-off between multiple objectives. Mathematical planning methods, such as linear programming [1], have been introduced to improve reliability, and Pareto frontier-based optimization was developed to reduce subjectivity. Furthermore, heuristic algorithms have been proposed to improve efficiency, such as the multi-objective simulated annealing algorithm [2], the Pareto archived evolution strategy [3], the Non-dominated Sorting Genetic Algorithm (NSGA) [4] and its second generation (NSGA-II) [5]. In 2011, Cao [6] proposed an improved NSGA-II algorithm for land use optimization.

Despite these advances, existing land use planning models lack a way to evaluate and decide on solutions in the Pareto optimal solution set. After establishing a multi-objective optimization model, this paper proposes an evaluation model to provide a universal method for land use planning solutions, extending existing research.

2. NSGA-II Multi-objective Optimization Model

2.1. Improved NSGA-II

The genetic algorithm (GA) [6] is an iterative algorithm that starts with an initial population of solutions, evaluates each candidate's properties, and forms a new population based on their fitness. It generates population $Q_t$ from $P_t$ by crossover and mutation, then forms the next generation $P_{t+1}$ by selecting elite candidates from the combined population of $P_t$ and $Q_t$. The selection criteria are dominance and crowding distance, which are discussed in detail below.

The chromosomes in the GA model are encoded as land use types, each of which represents a scheme of the combination of different land use types. For two chromosomes $x_1$ and $x_2$ in the combined population of $P_t$ and $Q_t$, the sufficient condition for $x_1$ to dominate $x_2$ ($rank_{x_1} < rank_{x_2}$) is that for any $i (i = 1, 2, 3, ..., m)$, there is $f_i(x_1) \geq f_i(x_2)$ for a maximal optimization problem. Chromosomes with a smaller Pareto rank can be selected for the next iteration. If the total number of chromosomes in the selected ranks exceeds the expected number of offspring population $P_{t+1}$, we should compare and select the chromosomes in the last-selected rank based on crowding distance, for choosing chromosomes that are less crowded in the same rank is considered beneficial to increase the diversity in the next generation.

As shown in Figure 1, for land use optimization problems, we improve the NSGA-II algorithm in initialization, crossover, and patch variation operators [6]. The initialization operator yields individuals with 90% initial cells and 10% random cells. The crossover operator, randomly chooses locations and the shape of the crossover...
patches in the parent and then swaps the two patches for next steps. The patch variation operator generates mutation patches and selects a land use type as the mutation direction. It then randomly selects a 3×3 window and a shape in it on the parent to be mutated and checks if there is a cell with the same land use type around the window. If not, the operator returns to choose another window and another mutation direction.

Fig. 1. Flow chart of the improved NSGA-II algorithm

2.2. Land Use Multi-objective Optimization Model in Xishuangbanna

In our work, the MODIS sensor products (500-m MCD12Q1) of 2021 were used to explore the land use types of the study area (see Figure 2). We resample it to a 500m×500m raster image using MATLAB, obtaining a matrix with 359 rows and 432 columns. Land use types are simplified into 5 categories, including forest, grassland, wetland, farmland and building land which are coded as 1-5 respectively. A "0" code indicates the land outside the boundary. The decision variable of the algorithm is the different land use units in Xishuangbanna, denoted as $x_{ijk}$.

For each cell $(i,j)$ in the matrix, $x_{ijk} = 1$ if its land use type is $k$, otherwise $x_{ijk} = 0$.

Fig. 2. Current status of land use types in Xishuangbanna Prefecture

Then, we set the objective functions and the constraints. The Work Plan for the Territorial Spatial Planning of Xishuangbanna Prefecture (2020-2035) [7] aims to optimize urban, agricultural, and ecological spaces while designating areas for ecological protection, basic farmland, and historical and cultural preservation. To achieve this, economic and ecological trade-offs must be made. To address this, two objective functions have been created: total economic benefit (Eq. (1)) and total ecological benefit (Eq. (2)). The spatial layout's compactness is also crucial for resources utilization efficiency and traffic conditions, so it is taken as the third objective function (Eq. (3)-(4)). This paper aims to maximize economic efficiency, ecological efficiency, and compactness in Xishuangbanna.

$$\text{max } f_1 = \sum_{k=1}^{K} \sum_{i=1}^{M} \sum_{j=1}^{N} a_k x_{ijk}$$ (1)

$$\text{max } f_2 = \sum_{k=1}^{K} \sum_{i=1}^{M} \sum_{j=1}^{N} b_k x_{ijk}$$ (2)

$$\text{max } f_3 = \sum_{k=1}^{K} \sum_{i=1}^{M} \sum_{j=1}^{N} r_{ijk} x_{ijk}$$ (3)

$$r_{ijk} = \sum_{e=1}^{1} \sum_{d=1}^{1} x_{(i+e)(j+d)k} - x_{ijk}$$ (4)

Where: $M$ and $N$ represent the number of rows and columns in the matrix, $K$ represents the number of land use types, and Economic efficiency coefficient $a_k$ and ecological efficiency coefficient $b_k$ are set for each land use type. Constraints are also necessary to ensure that the planning result is feasible [8]. To minimize transformation costs and avoid negative impacts on development, the number of cells that change in the solution does not exceed 20% of the total (Eq. (5)), otherwise, all objective function values are multiplied by a penalty factor $\sigma = 0.6$.

$$\frac{\sum_{k=1}^{K} \sum_{i=1}^{M} \sum_{j=1}^{N} |x_{ijk} - x_{ijk}|}{2PQ} < 20\%$$ (5)

To decide economic efficiency coefficients, we obtain the output value of agriculture, forestry, pastoralism, fishery, and tourism income in Xishuangbanna in 2021 from Yunnan Statistical Yearbook 2022 [9], which will be used to calculate the output value for five land types. Economic efficiency coefficient is obtained by dividing the output value by the area of each land type which is determined by remote sensing data.

To decide ecological efficiency coefficients, we use ESV (Ecosystem Services Values), which is determined by Costanza [10] and Xie’s [11] equivalence factor table and adjusted by Wang [12] and others. The value coefficients are normalized to compare the different optimization objectives in the total objective function (Table 1).

Table 1. Ecological efficiency and economic efficiency coefficients

<table>
<thead>
<tr>
<th></th>
<th>Forest</th>
<th>Grassland</th>
<th>Farmland</th>
<th>Building land</th>
<th>Wetland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ecological efficiency</td>
<td>1</td>
<td>0.596</td>
<td>0.200</td>
<td>0</td>
<td>2.647</td>
</tr>
<tr>
<td>Economic efficiency</td>
<td>1</td>
<td>0.606</td>
<td>55.279</td>
<td>1941.04</td>
<td>778.84</td>
</tr>
</tbody>
</table>

3. Land Use Optimization Results and Evaluation

3.1. Optimization Results

Our improved NSGA-II algorithm uses a population size of 100, maximum evolutionary generation of 600. The literature [12] shows that although the stochastic
algorithm is stochastic, the overall pattern of one experiment is consistent with that of multiple experiments. The results are non-dominated solutions scattered on a Pareto frontier as shown in Figure 3, each corresponding to one land optimization scheme. Different strategies are used to select four specific solutions for examination, including no-preference, economic benefit, ecological benefit, and compactness preference. For example, the solution with the highest value in $f_1$ is selected as the economic benefit preference solution, and the ecological benefit and compactness preference solutions are obtained similarly. The three objective function values are then normalized and summed, and the solution with the median value is selected as the no-preference solution. The four optimized solutions are used to compare with the current land use situation in Xishuangbanna.

The four optimization strategies of land use in Xishuangbanna are shown in Figure 4 and Table 2. Overall, the difference between the optimization solutions is relatively small. There are large areas of forests and grasslands in the east and southeast, while building lands and wetlands radially along the central and western regions. For the economic benefit preference solution, its building land scale increases by 0.0112%, while the forest is greatly reduced by 0.0774%. Thus, the economic benefits were significantly improved, 3~7% higher than other solutions. For the ecological benefit preference solution, the wetland increases by 0.0168%, and the forest decreases by only 0.0011%. Due to the high ecological efficiency coefficient of wetlands, $f_2$ increased by 18.6552%. It is noteworthy that the compactness indicators of all four strategies decrease, suggesting that optimization may lead to fragmented distribution of land.

The four optimization strategies of land use are shown in Figure 4 and Table 2. Overall, the difference between the optimization solutions is relatively small. There are large areas of forests and grasslands in the east and southeast, while building lands and wetlands radially along the central and western regions. For the economic benefit preference solution, its building land scale increases by 0.0112%, while the forest is greatly reduced by 0.0774%. Thus, the economic benefits were significantly improved, 3~7% higher than other solutions. For the ecological benefit preference solution, the wetland increases by 0.0168%, and the forest decreases by only 0.0011%. Due to the high ecological efficiency coefficient of wetlands, $f_2$ increased by 18.6552%. It is noteworthy that the compactness indicators of all four strategies decrease, suggesting that optimization may lead to fragmented distribution of land.

### Table 2. Land use type changes corresponding to the four strategies

<table>
<thead>
<tr>
<th></th>
<th>$f_1$ preference</th>
<th>$f_2$ preference</th>
<th>$f_3$ preference</th>
<th>No-preference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td>-0.0774%</td>
<td>-0.0011%</td>
<td>-0.0157%</td>
<td>-0.0101%</td>
</tr>
<tr>
<td>Grassland</td>
<td>0.0079%</td>
<td>-0.0516%</td>
<td>0.0011%</td>
<td>-0.0049%</td>
</tr>
<tr>
<td>Wetland</td>
<td>0.0213%</td>
<td>0.0168%</td>
<td>0.0067%</td>
<td>0.0067%</td>
</tr>
<tr>
<td>Farmland</td>
<td>-0.0146%</td>
<td>-0.0079%</td>
<td>-0.0112%</td>
<td>-0.0123%</td>
</tr>
<tr>
<td>Building land</td>
<td>0.0112%</td>
<td>0.0034%</td>
<td>-0.0090%</td>
<td>-0.0090%</td>
</tr>
</tbody>
</table>

### 3.2. Optimization Result Evaluation by AHP

Analytic hierarchy process (AHP) is a simple, flexible, and practical multi-criteria decision-making method for quantitative analysis of qualitative problems characterized by the quantitative description of the importance between two elements.
To develop an evaluation model for different land use optimization schemes using AHP, a hierarchical structure is established by using the best land use optimization scheme as the target layer (A), the economic, ecological, and spatial compactness degree as the criterion layer (B), and the four land use optimization policies selected above as the measure layer (C). The Work Plan for the Territorial Spatial Planning of Xishuangbanna Prefecture (2020-2035) [7] mentions that spatial compactness calls on attention because of the need to delineate the boundaries between urban and ecological zones, and secondly economic benefits are constantly emphasized, so the weights of each criterion in the target layer are obtained. Then a judgment matrix is constructed, in which the weight of spatial compactness (B3) is the highest, followed by economic (B1), and ecological (B2). Thus, the contribution of the three indicators to land use planning is obtained: economy 0.2388, ecology 0.1368, and spatial compactness 0.6244.

Thus, the final ranking of the four optimization strategies obtained by AHP is: economic benefits preference > ecological benefits preference > compactness preference > no-preference.

4. Conclusion

This paper studies land use optimization in Xishuangbanna using the improved NSGA-II algorithm. A multi-objective optimization model is established based on natural resources conditions and policies, with three objectives: maximizing economic benefits, ecological benefits, and compactness. The final results of the four different preferences are selected from the Pareto frontier and scored by AHP.

The experimental results show that all four optimization strategies can effectively optimize the land use of Xishuangbanna in economic and ecological aspects, but may lead to fragmented distribution of land. The final ranking of the four optimization strategies obtained by AHP is: economic benefits preference > ecological benefits preference > compactness preference > no-preference. The model has good adaptability in the face of different requirements since NSGA-II and AHP has the advantages of simplicity and flexibility, which can be the future research direction.

References