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Urban land use optimization in mining area from the perspective of maximizing ecosystem services

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Abstract: Land use change and its ecological and environmental consequence in mining cities have been one of the most profound transformations taking place across the developing countries. Managers and researchers are working for the optimization of land use in mining cities to minimize ecological losses and improve the living environment. In this paper, an approach of optimizing the land use pattern from the perspective of maximizing ecosystem services was proposed based on the multi-objective optimization theory and Genetic Algorithm. The Liaoyuan City of the Jilin province in China was chosen as the case area. The results showed that there were 10 optimal scenarios of land use in study area to sustain higher comprehensive capacity of ecosystem services (including carbon storage, food and material productions, as well as soil conservation). And the tenth land use scenario with the highest carbon storage services was suggested as the prior land use optimization planning option. If planned as the tenth scenario, the mining patches and meadows in study area would be reduced significantly; the area of irrigated croplands, groves, woods, shrubs, shoals/wetlands and scenic sites would be increased; the built-up lands and transportation lands would also be increased slightly. It is hoped that this land use optimization approach would be used in the future land use planning in mining cities to improve the environment by supplying multiple ecosystem services with the demand of the economic and social development.

1. Introduction

The rapid urbanization has profoundly transformed the spatial pattern of urban land use in China. The expansion of human activities in the city makes the original natural ecological system into nature-society coupling system, then the system of material and energy flow is changed significantly [1-3]. Especially in the mining areas, the intensive mining activities have changed the surface feature, cleared the natural vegetation, and consequently induced the biodiversity losses as well as carbon pool disturbances, which will pose a major threat to urban sustainable development and human health [4, 5]. It is important for mining areas to improve urban ecosystem services by optimizing urban land use structure and land use pattern in the economic transitional stage.

A large body of researches have tried to find approaches of urban land use allocation, from the early attention to economic benefits to the ecological benefits; all reflect the strategic thinking of sustainable development [6, 7]. Numerous models and methods proposed, include linear programming model, multi-objective optimization model, grey linear programming model, spatial multinomial logistic model, stochastic simulation method, and genetic algorithm (GA) [8-11]. Among these



models and methods, GA-based multi-objective optimization model, advanced by Kalyanmoy Deb and others [12-13], is the most widely used measure in many fields, ranging from analyzing land use and land cover changes to evaluating the effects of landscape pattern on different kinds of ecosystem services. As a compromise between the timeframe and the optimality of the final solutions, GA is more suitable than the other models [14-15]. Central to this method is seeking the optimal solution for multi-objective urban land use allocation. Yet less attention has been paid to the process of urban land use allocation from the perspective of maximizing ecological benefits.

This study aims to exemplify the use and value of GA-based multi-objective optimization model in urban land use allocation with an emphasis on multiple ecosystem services and best carbon storage in mining area. The objectives of this study were: (1) to explore the multi-objective optimization model in indicating urban land use allocation for maximizing ecosystem services in a mining city; and (2) to select the optimization scenarios of urban land use allocation with the highest carbon storage.

2. Methodology

2.1. Study area and data sources

The study area is located in Liaoyuan City of Jilin Province (42.17°N to 43.13°N and from 124.51°E to 125.49°E, Figure 1), known for its mineral resources and listed as one of the pilot resource-depleted cities that need the economic transformation in China. The case area straddles the Longshan and Xi'an District, covering the area of 121 km². With the influence of human mining activities, the study area has witnessed a large scale of ground collapse and the consequent severe resource exhaustion and ecological damage.

The Landsat ETM+ and SPOT satellite images in 2014 were used to derive land use types with the help of land use survey data. We downloaded images with cloud cover assessment threshold of <5%, 30-m spatial resolution, from US Geological Survey Earth Resources Observation and Science Center. There were fifteen land use types: mining patches, cultivated lands, irrigated croplands, groves, woods, shrubs, meadows, rural residential areas, urban built-up areas, traffic lands, agricultural facilities and hydraulic, water bodies, floodplains, scenic sites, and bare lands.

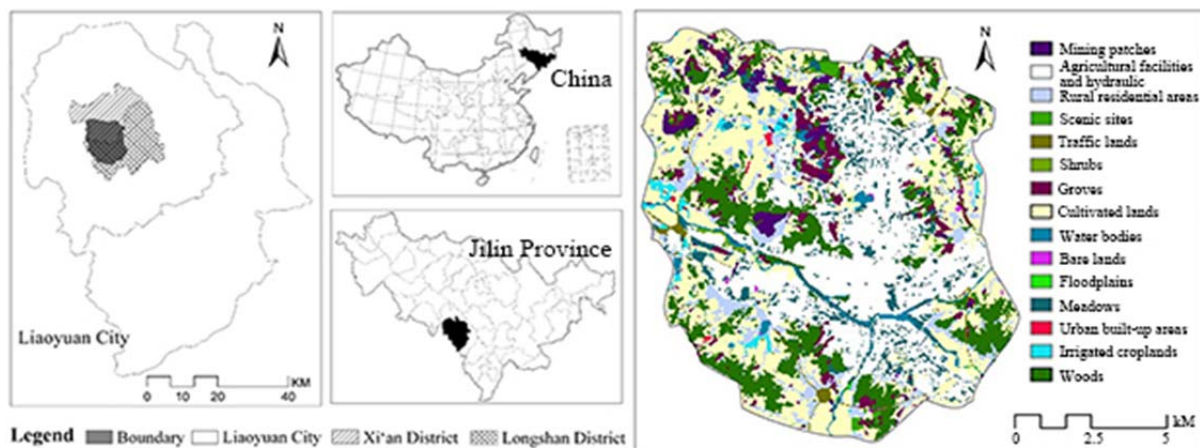


Figure 1. Location and LU/LC map of the study area.

2.2. Study methods

2.2.1. Ecosystem services per unit area of each land use type. Here, three kinds of ecosystem services are chosen based on the accessibility of data: the regulating service, providing service and supporting service. They are represented by the carbon sequestration and storage, food and raw material provision and soil conservation, respectively.

The data of carbon density for different land uses are gleaned from scientific literatures, including aboveground biomass, belowground biomass and soil carbon (Table 1). In this study, the growth status of vegetation is considered and NDVI value is used to characterize the growth status of vegetation. Based on this, the formula is modified as follows:

$$C_{total,t} = \sum_{k=1}^n [X_{kt}(C_{akt} + C_{bkt}) \times ndvi_{kt}] + X_t \times C_{st} \quad (1)$$

where, $C_{total,t}$ is the total amount of carbon stored in one type of land use t , C_{akt} and C_{bkt} is respectively the amount of carbon stored in aboveground biomass in each pixel k at the chosen resolution, $ndvi_{kt}$ is the normalized difference vegetation index in each pixel k of land use t , C_{st} is the soil carbon stored in each type of land use, and X_{kt} is the area of each pixel k of land use t , X_t is the total area of land use t .

Then the providing capacity of food and raw materials per unit area, as well as the supporting capacity of soil conservation, are collected and gathered from the research report about ecological risk and its prevention in Liaoyuan City (Table 1). The equation of food and material provision is given below:

$$P_{total,t} = P_t x_t = (P_{ft} + P_{mt}) x_t \quad (2)$$

where, $P_{total,t}$ is the total food and raw material supply of land use t , P_{ft} and P_{mt} represent the standardized value of food supply quantity and raw material supply quantity, respectively.

The equation of soil conservation is given as follows:

$$S_{total,t} = S_t x_t \quad (3)$$

where, S_{it} is the environmental support capacity of land use t , specifically is soil conservation capacity.

Table 1. Related parameters of various land use types ^a.

Number	Land use types	C_{akt}	C_{bkt}	C_{skt}	P_{fkt}	P_{mkt}	S_{kt}
1	Mining patches and bare lands	2.08	10.42	10.77	0	0	0.02
2	Cultivated land	3.40	14.28	15.00	7.69	0.09	0.17
3	Irrigated croplands	3.44	9.99	23.85	2.30	0.06	0.12
4	Groves	5.93	19.69	20.30	3.36	1.02	0.18
5	Woods	5.26	14.04	22.57	0.77	2.43	0.29
6	Shrubs	2.66	6.75	9.40	0.77	2.43	0.16
7	Meadows	2.04	9.40	9.99	2.30	0.05	0.08
8	Rural residential areas	3.48	13.95	14.58	0	0	0.05
9	Urban built-up areas	1.18	10.18	11.48	0	0	0.03
10	Traffic lands	0.37	7.28	8.23	0	0	0.04
11	Agricultural facilities and hydraulic structures	0.37	7.28	8.23	0	0	0.06
12	Water bodies	3.31	14.64	15.70	0.67	0	0.10
13	Floodplains	8.90	13.85	35.11	2.30	0.04	0.05
14	Scenic sites	3.44	13.85	14.47	0	0	0.06

^a the unit of C_{akt} , C_{bkt} , C_{skt} is mg/m^2 . P_{fkt} , P_{mkt} , S_{kt} is the standardized value.

2.2.2. Building the multi-objective optimization model of land use to sustain ecosystem services. The multi-objective optimization algorithm aims to identify solutions in the Pareto optimal set. In this study, the multi-objective optimization model is built with the support of MATLAB for the land use allocation to recover ecosystem services after land damages and ecological losses in Liaoyuan City; thus, the area of each land use type is set as the decision variables (the independent variable x), the capacities of carbon storage, food and raw material supplying and soil conservation are set to be the objective function (the dependent variable y), and constraints are set to meet the need of social and

economic development based on urban planning, and to the aim of increasing ecosystem services. The equations are given as follows:

- 1) The decision variable: x_i ($i = 1, 2, \dots, 15$),
where x_i is the area of each type of land use;
- 2) The objective function: $\max: f(x) = [f_1(x), f_2(x), f_3(x)]$,
where $f_1(x)$, $f_2(x)$ and $f_3(x)$ is respectively the variable of maximizing the carbon storage, food and raw materials supply and soil conservation capacity of land use allocation, and is calculated as:

$$f_1(x) = \max[\sum_{i=1}^{15} C_{total,t}],$$

$$f_2(x) = \max[\sum_{i=1}^{15} P_{total,t}],$$

$$f_3(x) = \max[\sum_{i=1}^{15} S_{total,t}];$$

- 3) Based on the land use status, the constraints are following as nine equations:
 $X = \sum_{i=1}^{15} x_i = 121.008$, where X is the total area of land use, equaling to 121.01 km²;
 $x_9 \geq 37.95$, where x_9 is the area of urban built-up lands that is more than 37.95 km²;
 $x_1 \leq 2.66$, where x_1 is the area of mining patches that is less than 2.66 km²;
 $x_8 \geq 9.78$, where x_8 is the area of rural residential areas that is more than 9.78 km²;
 $x_{10} \geq 1.63$, where x_{10} is the area of traffic lands that is more than 1.63 km²;
 $x_4 \geq 6.13$, where x_4 is the area of groves that is more than 6.13 km²;
 $29.35 \leq x_2 \leq 36.69$, where x_2 is the area of cultivated land that is more than 29.35 km² and less than 36.69 km²;
 $24.20 \leq (x_5 + x_6) \leq 36.30$, where x_5 and x_6 is the area of woodlands and shrubs that totally is more than 24.20 km² and less than 36.30 km²;
 $x_{15} = 0$, where x_{15} is the area of bare lands that equals to 0.

2.2.3. Solving land use optimization programs based on Genetic Algorithms (GA). GA is a stochastic search method for optimal solution of Darwin's biological evolution theory [9]. Here, GA is used to find the land use allocation solutions.

The study area is randomly assigned to 15 land use types as the initial allocation plan, and one "individual" in the "population" is formed. Multiple groups were repeated to form the "initial group". Next, all "individual" from the "group" (each type of land use types in accordance with the area code) is divided into three equal "subgroups" (respectively corresponding to the three sub-goals function of carbon storage, food and raw materials supply, and soil and water conservation). Then, each objective function value in its corresponding "subgroups" is calculated independently, and the individual with bigger objective function value is chosen to form a new "subgroup", and then all these newly generated "subgroups" are merged into a complete "group", and after that the crossover and mutation operations are conducted in this group to generate the next generation of complete groups. Such operations are repeated continuously, and the optimal solution of multi-objective land use were finally obtained.

3. Results and discussions

3.1. Synthesis of land use allocation scenarios based on the multi-objective model and Genetic Algorithms

Based on the above multi-objective land use optimization model, the GA calculation process stops when the generation was 582, resulting in 200 land use allocation scenarios. Figure 2 shows the final operation results. In the calculating process, the number of progeny generated by each individual is changing from 20 to 52, the average distance of all individuals in each generation of population is less than 2, the maximum distance of each individual in the last generation is 0.23, the speed of each run of the genetic algorithm is between 0 and 1. Then, 10 optimization scenarios with the maximum objective function value are selected from 200 optimization results (Table 2).

Table 2. Ten optimization scenarios by the multi-objective model and Genetic Algorithms ^a.

Land use types	The area of land use in optimal scenarios (km ²)										
	S0	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Mining patches	2.66	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Cultivated land	36.69	29.77	29.72	29.68	29.64	29.60	29.57	29.55	29.53	29.50	29.50
Irrigated croplands	1.33	2.65	2.66	2.67	2.68	2.69	2.70	2.70	2.71	2.71	2.71
Groves	6.13	7.73	7.74	7.74	7.75	7.76	7.76	7.77	7.77	7.78	7.78
Woods	19.17	22.82	22.81	23.01	23.01	23.02	23.01	23.00	23.01	23.00	23.00
Shrubs	0.29	1.50	1.48	1.42	1.41	1.40	1.38	1.38	1.37	1.36	1.36
Meadows	2.26	0.29	0.29	0.24	0.24	0.23	0.23	0.23	0.22	0.22	0.22
Rural residential areas	9.78	9.89	9.89	9.88	9.88	9.88	9.88	9.89	9.88	9.89	9.88
Urban built-up areas	37.95	37.99	37.99	37.98	37.98	37.99	37.98	37.98	37.99	37.97	37.99
Traffic lands	1.44	1.84	1.84	1.85	1.85	1.85	1.84	1.84	1.84	1.84	1.84
Agricultural facilities and hydraulic structures	0.18	0.30	0.30	0.36	0.37	0.37	0.38	0.37	0.37	0.38	0.37
Water bodies	2.25	2.07	2.07	2.08	2.08	2.08	2.09	2.09	2.08	2.09	2.08
Floodplains	0.07	3.11	3.16	3.09	3.10	3.13	3.15	3.16	3.19	3.21	3.22
Scenic sites	0.64	1.04	1.06	1.01	1.02	1.02	1.03	1.04	1.04	1.05	1.05
Bare lands	0	0	0	0	0	0	0	0	0	0	0

^a S0 represents the area of land use type before planning. S1-S10 represent the area of land use type after planning in each scenario. Unit, km².

As Table 2 shows, the area of cultivated land, mining patches, meadows, and water bodies decrease in the 10 optimization scenarios, while the area of other land uses increase, among which the woodland increases the most, and the variation ranges from 4.15 to 4.37 km², the cultivated land decreases the most, and the variation ranges from 6.92 to 7.19 km². The average area of woodland and cultivated land in the ten optimization scenarios are 22.97 and 29.61 km², respectively, and their average change values are 4.20 and -7.08 km², respectively. The area of mining patches is controlled from 0 to 0.02 km², and its average change value in the ten optimization scenarios is -2.65 km². The average area of urban built-up areas is 37.98 km², and its average change value in the ten optimization scenarios is 0.027 km². Specially, the average area of waterbodies and floodplains in the ten optimization scenarios are 2.08 and 3.15 km², and their average change values are -0.17 and 3.04 km², respectively.

3.2. Comparison of the carbon storages of ten land use optimal scenarios

The overall carbon storage capacity from S1 to S10 is shown in Figure 3. In the 10 optimization scenarios, the total carbon storage value ranges from 3.684×10^5 Mg (S2) to 3.696×10^5 Mg (S10), and is 3.690×10^5 Mg on average. Based on the previous restrictive constraint formulas, S10 has the highest capacity of carbon storage. Thus, S10 is suggested as the best optimization scenario for the future land use planning. If planned as S10 (Table 2), farmlands would be reduced to 7.188 km² significantly while woodland would be increased most to 4.169 km². In addition, the area of irrigated croplands, groves, shrubs, floodplains and scenic sites would be increased also; however the built-up areas and transportation lands would be increased slightly.

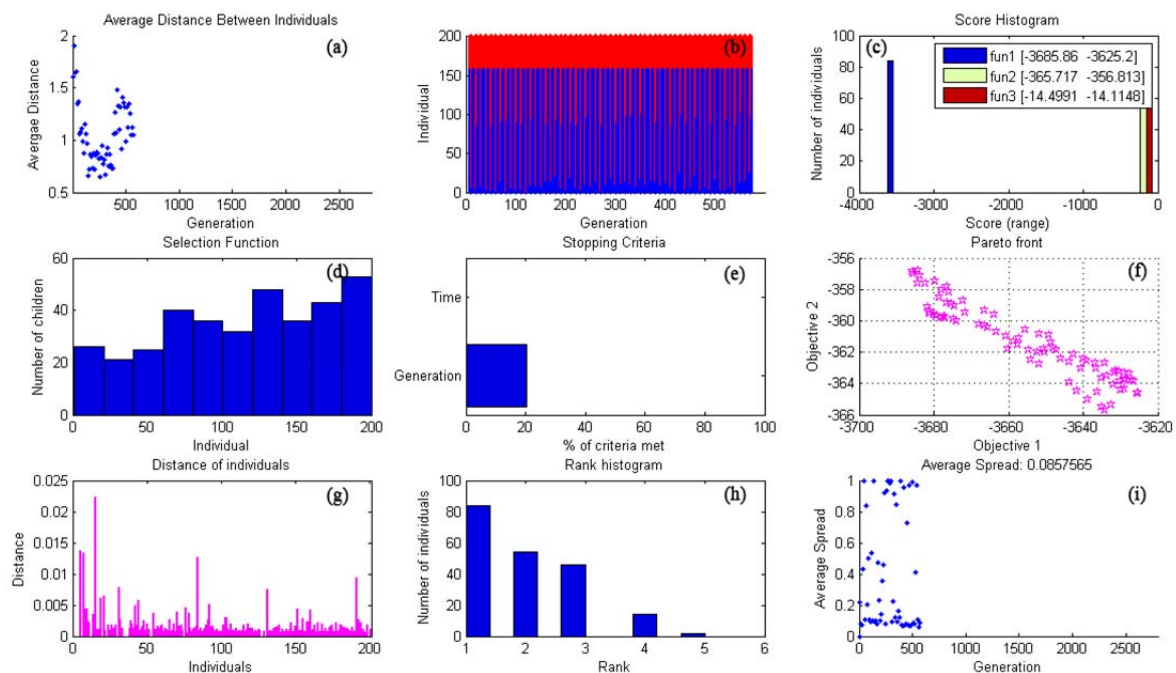


Figure 2. Genetic algorithm result.

a. average distance of all individuals in each generation; b. cross selection results of individuals in each generation; c. three objective function values at the end of the algorithm operation (negative value); d. the number of progeny generated by each individual; e. genetic algorithm stop condition; f. change of the first two objective function values during the algorithm operation; g. distance of each individual in the last generation; h. histogram distribution of individual fitness in final population; i. the average speed of the algorithm at each run.

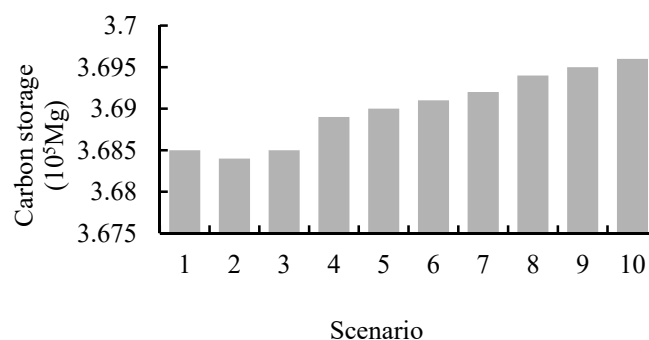


Figure 3. Carbon storage calculation of each optimization.

4. Conclusions and discussions

Mining activities have brought irreversible damages to urban ecosystems and environment. A lack of function-oriented land use allocation remains a barrier to the economic transformation development especially during the transition period of resource-depleted mining cities. Taking the mining city of Liaoyuan as a case study, the multi-objective optimization model and genetic algorithm are combined to optimize the land use structure. It is expected to provide a method framework for future land use allocation from the perspective of optimizing ecosystem services. This paper provided ten optimization scenarios given the goal of maximizing the ecosystem service capacity. The after-optimization land use scenario has both the maximum carbon storage amount that is 3.70×10^5 Mg, and have a higher capacity of production provision and soil conservation. The optimized land use

structure could be of value to land managers and policy makers, for it cannot only meet land use demands for economic and social development, but also would maintain the higher carbon storage amounts which can help to reduce the emission reduction pressure city faces.

Land use structure can obviously affect human activities and carbon emissions. Through land use rearrangement, we can increase carbon storage in Liaoyuan mining area. It is noted that carbon-rich land use types can also provide ecological benefits other than carbon storage, such as water conservation and flood control, erosion control, fuel, food, biodiversity and so on. That is to say, when planning and optimizing land use pattern, we need comprehensive considerations of land damage conditions, land reclamation, ecological restoration and human wellbeing before determining the final land use optimization program. But in this paper the spatial configuration of landscapes and the continuity of reclamation process have not been considered, which can be further studied in the future research.

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