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Land Use Allocation Based on Interval Multi-objective Linear Programming Model: A Case Study of Pi County in Sichuan Province

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Abstract: Adjusting and optimizing land use structure is one of the essential approaches to solve the conflict between land supply and demand. In this study, an uncertain interval multi-objective linear programming model was established and applied to analyzing the suitability of land use structure in Pi County of Sichuan Province. An adjustment scheme for optimizing land use structure was proposed on the basis of development planning drawn up by the local government. The results are summarized as follows: 1) the optimal adjustment scope for cropland area ranges from 27 976.75 ha to 31 029.08 ha, and the current area is less than the lower limit of the scope; 2) the optimal adjustment scope for garden land area ranges from 4 736.49 ha to 12 967.11 ha, and the current area is less than the lower limit; 3) the optimal adjustment scope for construction land ranges from 7 761.95 ha to 10 393.18 ha, and the current area is greater than the upper limit; 4) the optimal adjustment scope for industry and mining land ranges from 557.29 ha to 693.54 ha, and the current area exceeds the upper limit; and 5) the areas of forest land, grassland and other agricultural land are within the optimal adjustment scope. In order to maximize comprehensive benefit with the limited resources and the demand of sustainable development, the areas of cropland and garden land are supposed to be expanded properly, while the construction land should be controlled and reduced gradually, and the forest land and other agricultural land can be maintained at the current level in short period.

Keywords: land use structure optimization; land supply and demand balance; interval; multi-objective planning; uncertainty

1 Introduction

Land resources have great importance for supporting social and economic development. Due to the limited land resources in China, determining how to use land rationally and efficiently has been one of the key issues and has been paid increasing attention by researchers. Small amount of per capita land along with limited land resources has caused increasingly sharp contradiction between land supply and demand. What′s worse, the economic development has taken priority at the expense of land resources consumption, especially cropland. Adjusting and optimizing the existing land use structure and using land resources in a sustainable way are essential approaches to release the land stress on economy and society.

Land use structure refers to the area percentages for each kind of land use, i.e., cropland, garden land, forest land, grassland, construction land, industry and mining land, unused land and so on. The land resources allocation among the branches of national economy can be reflected by the land use structure (Wang, 1988; Wu, 1994). Optimizing land use structure means to adjust the land use quantity and spatial distribution rationally on the basis of the characteristics of land resources and the evaluation on land use suitability to achieve the maximum benefits of economy, society, and environment, and then to balance land ecosystem and maintain sustainable utilization of land resources (Li and Zhang, 2003).

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Mathematical methods, especially multi-objective model have been developed and applied in land use planning. Xiang and Kaiser (1992) used geographic information system (GIS) technique and multi-objective model to find reasons why endless conflicts about land use occur, and to suggest useful approaches to solve them. Verfura *et al*. (1998) proposed that land information system could be used for multi-objective planning in the places where natural resources stress is great. Chuvieco (1993) developed linear programming based on GIS to assemble and optimize spatial attributes, which has been applied to land use programming experiments in Spain. Yin and Liu (2001) studied the method of overall land use planning by a multi-objective planning model based on the land resources database. Hu *et al*. (1995) and Wu *et al*. (2009) introduced several methods for evaluation related to land use, and Hu *et al*. applied analytic hierarchy process based on expert knowledge and spatial analysis by GIS to analyze the land use suitability. Wu and Hua (1996) deduced and developed multi-objective mutant decision model and applied it for land use planning.

The methods for land use planning are mainly certain planning models at present, including linear programming method, system dynamics method, linear multi-objective planning method, analytic hierarchy process combined with GIS, *etc*. However, uncertain multi-objective programming model is rarely applied in the land use planning. In this study, an uncertain interval multi-objective linear programming model is improved and applied to optimizing and adjusting land use structure in Pi County of Sichuan Province of China in terms of comprehensive consideration of economy, society, ecosystem and techniques.

2 Current Situation of Land Use in Pi County

Pi County (30°43′–30°52′N, 103°42′–104°02′E) is located in the middle of Chengdu City of Sichuan Province (Fig. 1). There are 15 designated towns within it, and it occupies a total area of 43 750 ha with a population of approximately 495 000 in 2007. With rapid growth of economy, the county had achieved a GDP of 12.3×10^9 yuan (RMB) in 2007, and its per capita GDP had increased from 13 087 yuan in 2000 to 24 570 yuan in 2007.

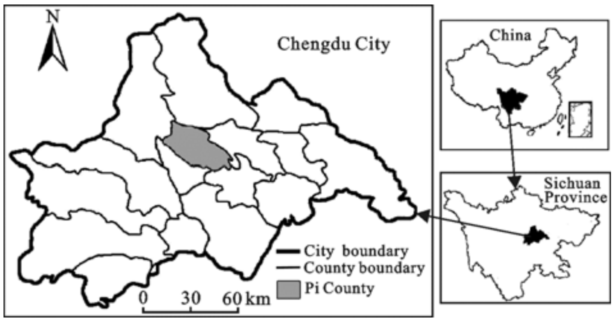

Fig. 1 Location sketch of Pi County

The current land use in Pi County can be classified into eight types: 1) cropland; 2) garden land; 3) forest land; 4) grassland; 5) other agricultural land (including land for livestock and poultry culture, agricultural facility, rural roads and so on); 6) construction land (including land for designated town, traffic, water conservancy facilities and rural residential area); 7) independent industry and mining land; and 8) unused land. The area of each kind of land use is shown in Table 1.

Table 1 Area of each kind of land use in Pi County in 2005

Land use type	Area (ha)	Percentage (%)
Cropland	27061.87	61.86
Garden land	2111.97	4.83
Forest land	66.77	0.15
Grassland	161.88	0.37
Other agricultural land	2310.73	5.28
Construction land	11200.35	25.60
Independent industry and mining land	739.32	1.69
Unused land	97.10	0.22

Source: Report on land use planning for Pi County in 2006

The land utilization ratio of Pi County was 99.8% in 2005 (Table 1), which was the highest in Sichuan Province and higher than the average value of the whole China. At the same time, there are some other issues in land use process, such as less per capita cultivated land, which is less than the average value of the whole Sichuan Province and even the whole China. Especially in Bitong Town and Xipu Town, the cultivated land per capita is even less than the warning line proposed by the United Nations Food and Agriculture Organization. The deficiency and immoderate utilization of land resources have resulted in a sharp contradiction among construction land, cropland and other land use types, which is an essential reason to choose Pi County as a study case.

3 Model Design Based on Interval Multi-objective Linear Programming

The methods which have been employed for uncertainty analysis in multi-objective programming are mainly stochastic planning and fuzzy planning (Liu and Zhao, 1998; Wang *et al*., 2004; Zadeh, 2005). Stochastic planning is focused on probability distribution of variable parameter, while fuzzy planning only deals with the uncertainty of the right items under model constraint but can not deal with the uncertainty of technical parameters (Sengupta *et al*., 2001; Singh *et al*., 2007; Sahoo *et al*., 2006). Besides, the additional difficulty for fuzzy planning is that the membership function also should be considered in the process (Kuwano, 1996; Guo *et al*., 1999; Chen, 2001).

In this study, the interval multi-objective linear programming model is improved and applied to optimizing land use structure of Pi County. The results derived from this model are more operable and feasible because actual uncertainties are basically considered in the process of modeling. At the same time, behavior scheme can be achieved and adjusted according to new information, individual preference, actual situation and relevant experience. Moreover, compared to common stochastic planning and fuzzy planning, the model used in this paper introduces interval to represent uncertain information for multi-objective planning. Interval has significant advantage on data acquisition and algorithm implementation because it is unnecessary to take the probability distribution and membership function into account (Wei and Ying, 1980; Chanas and Kuchta, 1996; Liu and Da, 1999).

3.1 Interval multi-objective linear programming model and its algorithm design

General form of the interval multi-objective linear programming model can be expressed as follows (Hu, 2004):

$$\min f_k^{\pm} = C_k^{\pm} X^{\pm},\ k = 1,\ 2,\ \dots,\ u \tag{1}$$

$$\max f_l^{\pm} = C_l^{\pm} X^{\pm},\ l = u+1,\ u+2,\ \dots,\ q \tag{2}$$

$$s.t. A_i^{\pm} X^{\pm} \le b_i^{\pm},\ i = 1,\ 2,\ \dots,\ m \tag{3}$$

$$A_i^{\pm} X^{\pm} \ge b_i^{\pm},\ i = m+1,\ m+2,\ \dots,\ n \tag{4}$$

$$X^{\pm} \ge 0$$

where $C_k^{\pm} \in R^{\pm 1\times t}$, $C_l^{\pm} \in R^{\pm 1\times t}$, $A_i^{\pm} \in R^{\pm u\times t}$, $b_i^{\pm} \in R^{\pm}$, $X^{\pm} \in R^{\pm u\times t}$, $R^{\pm}$ is the ensemble of interval, $f_k^{\pm}$, $f_l^{\pm}$ are objective functions, C_k, C_l, $A_i^{\pm}$, $b_i^{\pm}$, $b_j^{\pm}$ are known coefficients, $X^{\pm}$ is variable vector.

3.2 Determination on expected level of objectives

In order to avoid the impact of subjectivity of decision-makers on results, the original interval multi-objective programming model above is decomposed into single-objective sub-models as follows:

$$\min f^{\pm} = C^{\pm} X^{\pm} \tag{5}$$

$$s.t. A^{\pm} X^{\pm} \le b^{\pm} \tag{6}$$

$$X^{\pm} \ge 0$$

where $C^{\pm}$, $X^{\pm}$, $A^{\pm}$, $b^{\pm}$ are interval vectors.

For each interval single-objective programming model, supposing that the coefficients of the former k are positive while the other coefficients of n-k are negative, the sub-models corresponding to lower limit of objective-function are:

$$\min f^{-} = \sum_{j=1}^{k} c_j^{-} x_j^{-} + \sum_{j=k+1}^{n} c_j^{-} x_j^{+} \tag{7}$$

$$\begin{aligned} s.t. \sum_{j=1}^{k} \left| a_{ij} \right| + Sign(a_{ij}^{+}) x_j^{-} / b_i^{-} + \\ \sum_{j=k+1}^{n} \left| a_{ij} \right| - Sign(a_{ij}^{-}) x_j^{+} / b_i^{+} \le 1 \end{aligned} \tag{8}$$

$$x_j^{\pm} \ge 0,\quad j = 1,\ 2,\ \dots,\ n$$

where, $sign(\bullet)$ is sign function.

The sub-models to obtain objective upper limit, which are based on the solution of lower limit sub model ($x^{\pm}_{opt}$), are expressed as follows:

$$\min f^{+} = \sum_{j=1}^{k} c_j^{+} x_j^{+} + \sum_{j=k+1}^{n} c_j^{+} x_j^{-} \tag{9}$$

$$\begin{aligned} s.t. \sum_{j=1}^{k} \left| a_{ij} \right| - Sign(a_{ij}^{-}) x_j^{+} / b_i^{+} + \\ \sum_{j=k+1}^{n} \left| a_{ij} \right| + Sign(a_{ij}^{+}) x_j^{-} / b_i^{-} \le 1 \end{aligned} \tag{10}$$

$$x_j^{\pm} \ge 0,\quad j = 1,\ 2,\ \dots,\ n$$

$$x_j^{+} \ge x_{jopt}^{-},\quad j = 1,\ 2,\ \dots,\ k$$

$$x_j^{-} \le x_{jopt}^{+},\quad j = k+1,\ k+2,\ \dots,\ n$$

On the other hand, the models above can be converted to address the minimum value of objectives or can be solved in opposite process if maximum values of the objectives are required.

Thus, by solving the models above, the expected level $f^{\pm}=[f^{-}, f^{+}]$ and tolerance limit $f^{+}-f^{-}$ for each objective can be obtained.

3.3 Establishment of subsidiary models

Subsidiary models are established here to obtain final solution of $X^{\pm}$ and the corresponding values and objective-achievement level by taking all objective functions comprehensively. In order to measure achieved level of objective, a new parameter $\lambda^{\pm}$ is applied into the model. Subsidiary models are as follows:

$$\min \sum_{k=1}^{u} P_k \lambda_k^{\pm} + \sum_{l=u+1}^{q} P_l \lambda_l^{\pm} \tag{11}$$

$$s.t. f_k^{\pm}(X^{\pm}) \le f_k^{-} + \lambda_k^{\pm}(f_k^{+} - f_k^{-}),\ k=1, 2, \ldots, u \tag{12}$$

$$f_l^{\pm}(X^{\pm}) \ge f_l^{+} - \lambda_l^{+}(f_l^{+} - f_l^{-}),\ l=u+1,\ \ldots,\ q \tag{13}$$

$$A_i^{\pm} X^{\pm} \le b_i^{+} - \left| 1 - \sum_{k=1}^{u} (\lambda_k^{\pm}/u)(b_i^{+} - b_i^{-}) \right|,\ i=1, 2, \ldots, m \tag{14}$$

$$X^{\pm} \ge b_j^{-} + \left| 1 - \sum_{l=u+1}^{q} (\lambda_l^{\pm}/(q-u))(b_j^{+} - b_j^{-}) \right|,\ j=m+1, \ldots, n \tag{15}$$

$$0 \le \lambda_k^{\pm} \le 1,\ 0 \le \lambda_l^{\pm} \le 1,\ X^{\pm} \ge 0$$

where P_k, P_l are priority of objective functions.

Algorithm design of the whole model is shown in Fig. 2.

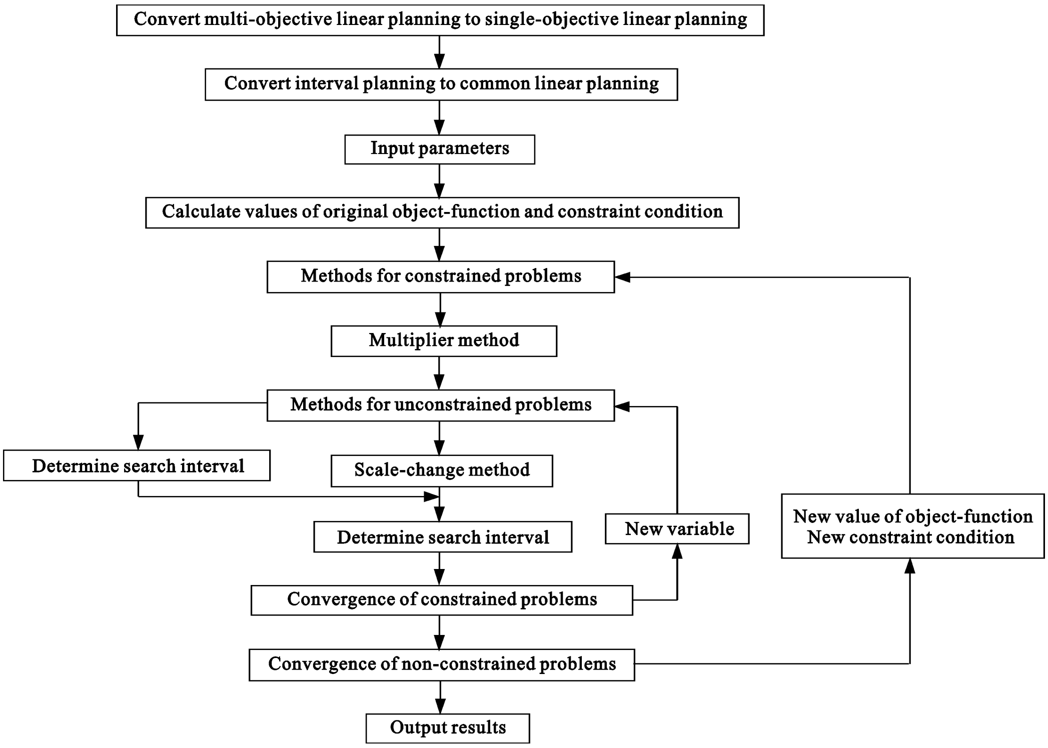

Fig. 2 Arithmetic flowchart of interval multi-objective linear programming model

4 Model Application for Land use

Generally speaking, rational land use planning can provide best benefit for urban development (Zhou and He, 2007). The optimal land use structure is determined based on the comprehensive consideration of natural resources, development of economy and society, peoples′ living requirement and environment protection. Land use benefit can be reflected from the aspects of economy, society and ecosystem.

The objectives for the set up model include economy, ecosystem and water consumption. Firstly, economic objective is given the highest priority according to the Tenth Five-year Plan of domestic economy and society development of Pi County, in which more products and services are required to be obtained from the limited land resources. Meanwhile, the restricting effects of land resources on economic development can be reduced. Secondly, ecological objective has a lower priority than economy. Benefits of economy and ecology should be combined together in order to make use of land resources in a sustainable way. Finally, land use structure adjustment is closely related to water resources and is restricted by water volume.

4.1 Economic objective function

The first objective-function of the model is maximum economic benefits with the highest priority, and it is expressed as follows:

$$\max f_1^{\pm} = \max C_1^{\pm} X^{\pm} \tag{16}$$

where $C_1^{\pm}$ is interval vector of the output per unit land area, $X^{\pm}$ is interval vector composed by the land area variables.

4.2 Ecological objective function

In order to reduce the impact on ecosystem and to obtain maximum economic benefits and sustainable development, the second objective-function should be ecological objective function, which can be expressed as follows:

$$\max f_2^{\pm} = \max C_2^{\pm} X^{\pm} \tag{17}$$

where $C_2^{\pm}$ is the effect of land use on ecosystem, which can be obtained usually from experts′ evaluation. Larger value of $C_2^{\pm}$ can bring more helpful land resources effect on ecosystem.

4.3 Water objective function

The third objective-function concerns consumed water volume. The average quantity of water consumption is used for water use planning. If actual water consumption is more than the excepted amount, the deviation of them is positive; otherwise, the deviation is negative. Water consumption function is developed to obtain the minimum sum of positive deviation and negative deviation, and it is expressed as follows:

$$\min f_3^{\pm} = d_1^{\pm} + d_2^{\pm} \tag{18}$$

where $d_1^{\pm}$ is positive deviation; $d_2^{\pm}$ is negative deviation.

4.4 Model constraint

4.4.1 Land area constraint

Conceptually, the sum of all land areas should be the total area in Pi County. However, due to the existence of unutilized land, the upper limit value for the land area is the total area of Pi County; the lower limit value is the total land area minus the unutilized land. Namely, the land area constraint $R_L^{\pm}$= [43652.9, 43750].

4.4.2 Population constraint

The population constraint can be expressed as:

$$P_C^{\pm}(x_6 + x_7) + P_R^{\pm}(\sum_{i=1}^{5} x_i) \le P_F^{\pm} \tag{19}$$

where $P_C^{\pm}$ is the interval of population density on construction land; $P_R^{\pm}$ is the interval of population density in rural areas; $P_F^{\pm}$ is the interval of predicted population; x_1 is cropland area; x_2 is garden land area; x_3 is forest land area; x_4 is grassland area; x_5 is other agricultural land area; x_6 is construction land area; x_7 is independent industry and mining land area.

And $P_C^{\pm}$=[9.8, 14.3], $P_R^{\pm}$=[4.2, 6.5], $P_F^{\pm}$=[380201, 446580].

4.4.3 Macroscopic planning constraint

Firstly, the total area of agriculture land should be greater than the current area of $A_R^{\pm}$. $A_R^{\pm}$=31631.347. It is expressed as below:

$$x_1 + x_2 + x_3 + x_4 + x_5 + x_6 + x_7 \ge A_R^{\pm} \tag{20}$$

Secondly, the land areas for construction, independent industry and mining should be controlled by macroscopic planning and be higher than the present area $A_C^{\pm}$. $A_C^{\pm}$=11200.35. It can be expressed as follows:

$$x_6 + x_7 \ge A_C^{\pm} \tag{21}$$

4.4.4 Constraint of agricultural product demand

The product of grain yield per unit area ($F^{\pm}$) and the cropland area (x_1) should be larger than the total agricultural product demand $D_F^{\pm}$, and $F^{\pm}$=[5500, 8500]; $D_F^{\pm}$=[18544500, 28873100].

$$F^{\pm} \times x_1 > D_F^{\pm} \tag{22}$$

4.4.5 Labor resources constraint

The total number of labor used for all kinds of land should be less than the total amount of labor.

Firstly, labor force used by per unit agricultural area is defined as $L_n^{\pm}$ and total amount of labor for agriculture is noted as $D_L^{\pm}$. Thus, it can be expressed as follows:

$$L_1^{\pm} \times x_1 + L_2^{\pm} \times x_2 + L_3^{\pm} \times x_3 + L_4^{\pm} \times x_4 + L_5^{\pm} \times x_5 \le D_L^{\pm} \tag{23}$$

And $L_1^{\pm}$=[2.5, 4.1], $L_2^{\pm}$=[1.3, 2.1], $L_3^{\pm}$=[1, 1.6], $L_4^{\pm}$=[0.8, 1.7], $L_5^{\pm}$=[0.4, 1].

where, L_1 is labor amount employed by cropland; L_2 is labor amount employed by garden land; L_3 is labor amount employed by forest land; L_4 is labor amount employed by grassland; L_5 is labor amount employed by other agricultural land.

Secondly, $D_U^{\pm}$ is labor amount used by non-agricultural sectors and it can be expressed as follows:

$$L_6^{\pm} \times x_6 + L_7^{\pm} \times x_7 \le D_U^{\pm} \tag{24}$$

where L_6 is labor amount employed by construction land; L_7 is labor amount employed by independent industry and mining land. And $L_6^{\pm} = [0.8926,\ 3.9270]$, $L_7^{\pm} = [11,\ 16]$, $D_U^{\pm} = [179211,\ 260497]$.

4.4.6 Objective constraint

In order to minimize the deviation of water consumption planning, the corresponding objective constraint can be estimated as follows:

$$W_A^{\pm} \times (x_1 + x_2 + x_3 + x_4 + x_5) + W_C^{\pm} \times (x_6 + x_7) - d_1 + d_2 = S_T^{\pm} \tag{25}$$

where $W_A^{\pm}$ is the interval of water volume consumed by per unit area of agricultural land; $W_C^{\pm}$ is the interval of water volume consumed by per unit area of construction land; $S_T^{\pm}$ is the interval for the average of total consumed water amount.

$W_A^{\pm} = [61.791,\ 190]$, $W_C^{\pm} = [131.86,\ 301.59]$,

$S_T^{\pm} = [4.5 \times 10^6,\ 1.98 \times 10^7]$

4.4.7 Mathematical model constraint

The constraint of mathematical model is expressed as follows:

$$x_i \ge 0,\ i = 1,\ \ldots,\ 7$$

5 Results and Discussion

5.1 Results

Taking Pi County of Sichuan Province as a study case, the expected values of each objective were obtained by interval single-objective programming models.

Table 2 Expected levels of each objective

Objective	Expected upper limit	Expected lower limit
Economic objective (yuan)	15.60×10^9	4.82×10^9
Ecological objective (yuan)	2.57×10^9	231×10^6
Water consumption (m^3)	5.87×10^6	0

Each objective has a different priority in multi-objective programming. Economic objective has been given the highest priority compared to ecological objective and water consumption according to the Tenth Five-year Plan of domestic economy and society development. Simulated areas are obtained by balancing all kinds of land use demands (Table 3). The values and achieved levels of each objective are shown in Table 4.

Table 3 Planning areas of each land use type

Land use type	Upper limit value (ha)	Lower limit value (ha)
Cropland	31029.08	27976.75
Garden land	12967.11	4736.49
Forest land	101.98	66.78
Grassland	325.68	161.88
Other agricultural land	8586.66	2195.64
Construction land	10393.18	7761.95
Individually industrial and mining land	693.54	557.29

Table 4 Values and achieved levels of each objective

Objective	Achieved upper limit	Achieved lower limit	Achieved lower level (λ^-)	Achieved upper level (λ^+)
Economic objective (yuan)	7.20×10^9	3.98×10^9	0	0.68
Ecological objective (yuan)	7.03×10^9	1.16×10^9	0.49	1.00
Water consumption (m^3)	17.40×10^6	3.18×10^6	0.47	1.00

5.2 Discussion

According to results from analyzing present data in Table 1 and modeling results in Table 3, the adjustment schemes are proposed as follows:

(1) The area of cropland has an optimal adjustment scope from 27 976.75 ha to 31 029.08 ha, while, the current area is 27 061.87 ha, less than the lower value of the optimal adjustment scope. Therefore, in terms of the current national cropland protection policy and the results of the model, the cropland area should be expanded properly.

(2) The optimal adjustment scope for garden land area ranges from 4 736.49 ha to 12 967.11 ha, while the current area is 2 111.97 ha, which is less than the lower limit. Thus, more land for planting fruit, tea and other relevant economic crops with high added value should be developed, and the industry chain should be formed to promote the process and sale of the relevant produc-

tions.

(3) The optimal adjustment scope for construction land ranges from 7 761.95 ha to 10 393.18 ha, while the current value is 11 200.35 ha, which is greater than the upper limit. Therefore, the area of construction land should be reduced by taking useful measures into effect.

(4) The optimal adjustment scope for industrial and mining land ranges from 557.29 ha to 693.54 ha, and the current value is 739.32 ha, which is larger than the upper limit. Thus, the land area for industry and mining should be controlled and reduced as well.

(5) The forest land, grassland are within the optimal adjustment scope and they can be sustained at the current level.

(6) Besides, in order to increase the economic benefit of land use, some of other agricultural lands should be diverted to other kinds of land uses, such as fruit, tea, *etc*.

6 Conclusions

Taking Pi County of Sichuan Province as a case, this study applies an interval multi-objective linear programming model to optimizing and adjusting land use structure in terms of comprehensive consideration of economy, society, ecosystem and techniques, and reaches the following conclusions.

(1) The expected maximum and minimum economic benefits produced by land use are 7.20×10^9 yuan and 3.98×10^9 yuan, respectively, in Pi County, Sichuan Province, with an average value of 5.59×10^9 yuan. According to the planning, ecosystem benefit ranges from 1.16×10^9 yuan to 7.03×10^9 yuan, with an average value of 4.10×10^9 yuan. Water consumption should be controlled within 3.18×10^6 to 17.4×10^6 m^3.

(2) The areas of cropland and garden land are less than the lower limit value of planning, therefore, these kinds of land should be expanded in order to maximize the benefit of economy, society and ecosystem. While the areas of construction land and industry and mining land are greater than the upper limit of the programming interval, which should be reduced to an appropriate extent. Moreover, the areas for forest land, grassland and other agricultural land are within the programming interval and can be maintained at the current extent.

(3) The Interval multi-objective linear programming model is improved and applied in this study to adjusting land use structure. The results show that the model is feasible to solve the problem for the uncertainty of land use planning.

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