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A Hybrid Inexact Optimization Model for Land-use Allocation of China

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Abstract: Land scarcity has become the prominent obstacle on the way to sustainable development for China. Under the constraints of land shortage, how to allocate the finite land resources to the multiple land users in China considering various political, environmental, ecological and economic conditions have become research topics with great significance. In this study, an interval fuzzy national-scale land-use model (IFNLM) was developed for optimizing land systems of China. IFNLM is based on an integration of existing interval linear programming (ILP), and fuzzy flexible programming (FFP) techniques. IFNLM allows uncertainties expressed as discrete interval values and fuzzy sets to be incorporated within a general optimization framework. It can also facilitate national-scale land-use planning under various environmental, ecological, social conditions within a multi-period and multi-option context. Then, IFNLM was applied to a real case study of land-use planning in China. The satisfaction degree of environmental constraints is between 0.69 and 0.97, the system benefit will between 198.25×10^{12} USD and 229.67×10^{12} USD. The results indicated that the hybrid model can help generate desired policies for land-use allocation with a maximized economic benefit and minimized environmental violation risk. Optimized land-use allocation patterns can be generated from the proposed IFNLM.
Keywords: land-use planning; uncertain model; interval linear programming (ILP); fuzzy flexible programming (FFP); environmental protection; interval fuzzy national-scale land-use model (IFNLM)

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1 Introduction

Land use change is both the result and a cause of diverse interactions between society and the environment (Verburg *et al*., 2010). Land-use problems associated with land-use change, socio-economic development and environmental protection have been growing concerns faced by many regional and/or national authorities. For example, land scarcity and degeneration can not only pose a variety of impacts on eco-environment, but also hinder sustainable regional development. Therefore, problems involving the efficient allocation of land have challenged land resource managers (Maqsood *et al*., 2005).

In China, land-use allocation is an essential task for preserving valuable land resources and facilitating sustainable socioeconomic development. Previously, a wide range of mathematical techniques were developed to examine economic, environmental and ecological impacts of various land-use actions, and thus aid decision makers in formulating effective land-use allocation policies (Collins and Barry, 1986; Mendoza, 1987; McDonald, 2001; Ligmann-Zielinska *et al*., 2008; Mitsova *et al*., 2011). For example, McDonald (2001) used a cost-benefit analysis method for the assessment of local land-use allocation decisions based on a se-

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quence of microeconomic models (e.g., Cobb-Douglas Production Function). Ligmann-Zielinska *et al.* (2008) examined the applicability of spatial optimization as a generative modeling technique for multiobjective sustainable land-use allocation in a town of the state of Washington, where spatial optimization was used to generate a number of compromise spatial alternatives that are feasible and different from each other. Mitsova *et al.* (2011) use the cellular automata (CA)—Markov chain model to simulate land cover change and integrate protection of environmentally sensitive areas into urban growth projections at a regional scale.

However, uncertainties may exist in many system components and their interactions, and affect the related decision processes, which have placed land-use allocation problems beyond the conventional mathematical programming methods (Messina and Bosetti, 2003; Saak, 2004). Uncertainties may be derived from random feature of various natural processes as well as errors in estimated modeling parameters (Li *et al.*, 2009a; 2009b). Uncertainties can also arise due to human-induced imprecision or fuzziness, such as lack of available data and biased judgment (or preferences) in assigning priority factors (weighting levels) to multiple management objectives (Li *et al.*, 2011; Huang *et al.*, 2001). For example, randomness may arise due to uncertain nature of input parameters (e.g., land-resource availabilities, land demands, land-use patterns, as well as environmental and ecological requirements) (Huang, 1998; Lu *et al.*, 2014), and imprecision or fuzziness is associated with land quality standards and environmental goals (Huang *et al.*, 2002; Liu *et al.*, 2003). The volume and concentration of wastewater generated by industrial land use may vary with unit and scale of each industry as well as categories and amounts of its products (Huang, 1996; Zhou *et al.*, 2013); the efficiency for mitigating pollutant emission may also vary with conditions at wastewater treatment plants (e.g., reagent ratio, temperature, pH level, and inlet pollutant concentrations). When the related cost coefficients and wastewater flows are not available as deterministic values, cost for wastewater treatment can also be uncertain. These uncertainties can be further amplified by not only interactions among various uncertain and dynamic impact factors, but also their associations with economic implications of satisfied or violated environmental requirements. Such complexities and uncertainties have to be considered when planning land development and pollution control. Systems analysis techniques could be used for generating a desired compromise between environmental and economic objectives. Unfortunately, in China, there is a lack of sustainable development plan for facilitating efficient and equitable land use management. Therefore, it is deemed necessary to employ effective optimization methods for tackling these complexities.

Over the past decades, many efforts were made for dealing with the uncertainties in resource management and allocation through fuzzy flexible programming (FFP) approaches (Chang *et al.*, 2001; Bashir *et al.*, 2009; Lv *et al.*, 2010; Lu *et al.*, 2013). FFP is effective in dealing with decision problems under fuzzy goal and constraints and handling ambiguous coefficients in the objective function and constraints; however, when many uncertain parameters are expressed as discrete interval numbers, interactions among these uncertainties may lead to serious complexities, particularly for large-scale problems (Huang *et al.*, 1993). Another attractive approach for resources management under uncertainty was interval linear programming (ILP) (Huang *et al.*, 1992). ILP can effectively reflect interval uncertainties. Based on an implicit distribution assumption, the ILP will not require exact information for its model parameters since interval numbers are acceptable for the uncertain inputs. According to the above review, the FFP is effective in reflecting fuzzy goals and constraints, but not so much for discrete uncertainties. In comparison, the ILP can deal with the interval uncertainties, but has difficulties when goals and constraints are expressed as fuzzy sets. One potential approach for better reflecting uncertainties in the land system is to incorporate the ILP within the FFP framework.

Therefore, this study aims to develop an interval fuzzy national-scale land-use model (IFNLM) method for planning China′s land-use systems under multiple uncertainties. The objectives of this paper include: 1) development of an IFNLM method, with uncertainties expressed as discrete intervals and fuzzy sets being addressed; 2) application of IFNLM to a real-world case for planning national land-use allocation, where interval solutions in association will be obtained and interpreted; 3) provision of a comparison of results for system benefits under different ecological and environmental requirements, such that desired alternatives for national land-use management can be identified, and 4) analysis of interactions among land-use allocation, economic cost and benefit, ecological balance, and environmental protection. The results will be helpful for supporting adjustment of the interrelationship between the conflicting economic objective and environmental requirement.

2 Materials and Methods

2.1 Study area

The study area of this paper is part of China, not including Hong Kong, Macao and Taiwan. China is located in the east of Asia, consisting of 34 provinces, autonomous regions, municipalities, and special administrative region directly under the central government. Around 34% of the China′s entire territory is made up of mountain area. China is the most important developing country in the world. In the past 10 years, China′s economic growth rate was approximately 9%.

With the proposed regional policy that ′first eastern development′, ′western development′, and ′revitalization of Northeast old industrial base′, four regions in China have basically shaped (Fig. 1). Eastern China is an important engine of economic growth in China. With the urbanization and industrialization process accelerating, a large number of land areas convert to construction land which makes the contradiction between land supply and demand be sharpened. Northeastern China, as an old industrial base, also has a high level of urbanization level and a stable economic development speed. And this region does not lack of land resources (the per capita arable land areas in this region are 1.61 ha). Though the conversion to construction land use is not very frequent, most of this conversion has occupied the arable land, leading to the decrease of arable land area. In order to protect the arable land, land reclamation and development of unused land in the region should be paid full attention. Central China is an important region which will be developed for another urbanization and industrialization base in the future. Therefore, large areas of land will convert to construction land. Although Western China has plenty of land resources, it lacks of effective development and utilization. This is due to the abominable natural conditions. On the one hand, investment in geological exploration is inadequate; on the other hand, the contradiction between protection and development in this region is another thorny problem.

In short, these land problems have seriously hindered the economic development and environmental protection of China. Consequently, in planning China′s land-use system, systematic analysis of the related resources, environmental and socio-economic objectives/restriction based on projected applicable conditions should be undertaken.

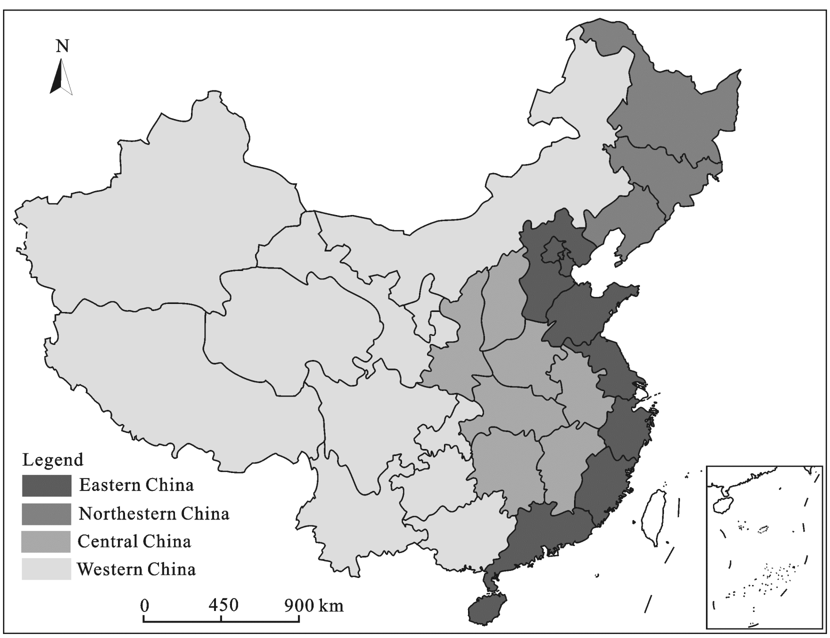

Fig. 1 Regionalization of study area

2.2 Interval fuzzy national-scale land-use model (IFNLM)

The land use system in China is considered as an uncertain system, in this study, three time periods (2011–2015; 2016–2020; 2021–2025) are considered. The land manager is responsible for allocating land resource in the four regions of China. The decision variables in the land-use allocation system represent the areas of different types of land over the time horizon. The objective is to achieve the maximum benefit from the land-use system. The constraints include all of the relationships between the decision variables and environmental/ecological/social restrictions. The IFNLM for this planning problem can be structured as follows: Objective function:

$$\text{Max } f(x)^{\pm} = \sum_{i=1}^{4}\sum_{t=1}^{3}\left(\text{BP}_{i,j=1,t}^{\pm}\times x_{i,j=1,t}^{\pm}\right)+ \sum_{i=1}^{4}\sum_{t=1}^{3}\left(\text{BP}_{i,j=2,t}^{\pm}\times x_{i,j=2,t}^{\pm}\right)+ \sum_{i=1}^{4}\sum_{t=1}^{3}\left(\text{BP}_{i,j=3,t}^{\pm}\times x_{i,j=3,t}^{\pm}\right)- \sum_{i=1}^{4}\sum_{t=1}^{3}\left[(\text{WC}_{i,j=1,t}^{\pm}+\text{SC}_{i,j=1,t}^{\pm})\times x_{i,j=1,t}^{\pm}\right]- \sum_{i=1}^{4}\sum_{t=1}^{3}\left[(\text{WC}_{i,j=2,t}^{\pm}+\text{SC}_{i,j=2,t}^{\pm})\times x_{i,j=2,t}^{\pm}\right]- \sum_{i=1}^{4}\sum_{t=1}^{3}\left[(\text{WC}_{i,j=3,t}^{\pm}+\text{SC}_{i,j=3,t}^{\pm})\times x_{i,j=3,t}^{\pm}\right]- \sum_{i=1}^{4}\sum_{t=1}^{3}\left(\text{GC}_{i,j=4,t}^{\pm}\times x_{i,j=4,t}^{\pm}\right)- \sum_{i=1}^{4}\sum_{t=1}^{3}\left(\text{PC}_{i,j=5,t}^{\pm}\times x_{i,j=5,t}^{\pm}\right) \quad (1)$$

where ± means interval values; $f(x)$ is objective function which means net system benefit over the planning horizon (USD); $x_{i,j,t}$ means variables, where i means names of region, and i = 1 for Eastern China; i = 2 for Northeastern China; i = 3 for Central China, and i = 4 for Western China; j mean types of land use. According to the Land Use Classification Standard promulgated by Chinese Administration of Quality Supervision, Inspection and Quarantine (2007) and some foreign classification standard (Liu *et al.*, 2007), we combined cultivated land, garden land, forest and grassland into agricultural land; commercial land, industrial and warehouse land, residential land and public land are combined into residential and industrial land; special use land and other land are combined into unused land, where j = 1 for agricultural land; j = 2 for residential and industrial land; j = 3 for transportation land; j = 4 for water body, and j = 5 for unused land; t mean the time periods: t = 1 for 2011–2015; t = 2 for 2016–2020; t = 3 for 2021–2025. $\text{BP}_{i,j,t}$ is unit benefit of land-use type j in region i in period t (USD/ha); $\text{WC}_{i,j,t}$ is unit wastewater-tackling cost of land-use type j in region i in period t (USD/ha); $\text{SC}_{i,j,t}$ is unit solid-waste-tackling cost of land-use type j in region i in period t (USD/ha); $\text{GC}_{i,j=4,t}$ is unit maintenance costs of water body in region i in period t (USD/ha); $\text{PC}_{i,j=5,t}$ means unit maintenance costs of unused land in region i in period t (USD/ha).

Constraints:

$$\sum_{i=1}^{4}\sum_{t=1}^{3}\left[(\text{WC}_{i,j=1,t}^{\pm}+\text{SC}_{i,j=1,t}^{\pm})\times x_{i,j=1,t}^{\pm}\right]+ \sum_{i=1}^{4}\sum_{t=1}^{3}\left[(\text{WC}_{i,j=2,t}^{\pm}+\text{SC}_{i,j=2,t}^{\pm})\times x_{i,j=2,t}^{\pm}\right]+ \sum_{i=1}^{4}\sum_{t=1}^{3}\left[(\text{WC}_{i,j=3,t}^{\pm}+\text{SC}_{i,j=3,t}^{\pm})\times x_{i,j=3,t}^{\pm}\right]+ \sum_{i=1}^{4}\sum_{t=1}^{3}\left(\text{GC}_{i,j=4,t}^{\pm}\times x_{i,j=4,t}^{\pm}\right)+ \sum_{i=1}^{4}\sum_{t=1}^{3}\left(\text{PC}_{i,j=5,t}^{\pm}\times x_{i,j=5,t}^{\pm}\right)\le \text{MGI}_{i,t}^{\pm} \quad (2)$$

where MGI_t is maximum government investment in period t (USD).

$$\sum_{i=1}^{4}\sum_{j=1}^{5}\sum_{t=1}^{3} x_{i,j,t}^{\pm} = \text{TLA}_{i,j,t}^{\pm} \quad (3)$$

where TLA_t is total land area in period t, including agricultural land, residential and industrial land, transportation land, water body, and unused land (ha).

$$\sum_{i=1}^{4}\sum_{t=1}^{3} x_{i,j=2,t}^{\pm}/\text{P}_{i,t}^{\pm} \ge \text{MIGL}^{\pm} \quad (4)$$

where $\text{P}_{i,t}$ is total population until period t (person); MIGL means minimum area of residential and industrial land per capita in period t (ha/person).

$$\sum_{i=1}^{4}\sum_{t=1}^{3} x_{i,j=3,t}^{\pm} / \mathrm{P}_{i,t}^{\pm} \geq \mathrm{MIPL}^{\pm} \tag{5}$$

where MIPL is minimum area of transportation land per capita in period t (ha/person).

$$\sum_{i=1}^{4}\sum_{t=1}^{3} x_{i,j=1,t}^{\pm} \geq \mathrm{MIRL}^{\pm} \tag{6}$$

where MIRL is minimum area of agricultural land in period t (ha).

$$\sum_{i=1}^{4}\sum_{t=1}^{3} x_{i,j=4,t}^{\pm} \geq \mathrm{MIAL}^{\pm} \tag{7}$$

where MIAL is the minimum area of water body in period t (ha).

$$\sum_{i=1}^{4}\sum_{t=1}^{3} x_{i,j=2,t}^{\pm} \geq \mathrm{MIIL}^{\pm} \tag{8}$$

where MIIL is minimum area of residential and industrial land in period t (ha).

$$\sum_{i=1}^{4}\sum_{t=1}^{3} x_{i,j=3,t}^{\pm} \geq \mathrm{MICL}^{\pm} \tag{9}$$

where MICL is minimum area of transportation land in period t (ha).

$$\sum_{i=1}^{4}\sum_{j=1}^{5}\sum_{t=1}^{3}\left(\mathrm{UWP}_{i,j,t}^{\pm} \times x_{i,j,t}^{\pm}\right) \leq \mathrm{MAW}_{i,t}^{\pm} \tag{10}$$

where $\mathrm{UWP}_{i,j,t}$ means unit water consumption of land-use type j in region i at period t (kg/ha); $\mathrm{MAW}_{i,j,t}$ represents water supply capacity in period t (kg).

$$\sum_{i=1}^{4}\sum_{j=1}^{5}\sum_{t=1}^{3}\left(\mathrm{UEP}_{i,j,t}^{\pm} \times x_{i,j,t}^{\pm}\right) \leq \mathrm{MAE}_{i,t}^{\pm} \tag{11}$$

where $\mathrm{UEP}_{i,j,t}$ is unit quantity of electricity consumption of land-use type j in region i in period t (kilowatt-hour/ha); $\mathrm{MAE}_{i,j,t}$ is electricity supply capacity in period t (kilowatt-hour).

$$\sum_{i=1}^{4}\sum_{t=1}^{3}\mathrm{RWP}_{i,j=1,t}^{\pm} \times x_{i,j=1,t}^{\pm} + \sum_{i=1}^{4}\sum_{t=1}^{3}\mathrm{IWP}_{i,j=2,t}^{\pm} \times x_{i,j=2,t}^{\pm} + \sum_{i=1}^{4}\sum_{t=1}^{3}\mathrm{CWP}_{i,j=3,t}^{\pm} \times x_{i,j=3,t}^{\pm} \leq \mathrm{MAWC}_{i,t}^{\pm} \tag{12}$$

where $\mathrm{RWP}_{i,j=1,t}$ is the wastewater discharging factor of agricultural land in region i in period t (kg/ha); $\mathrm{IWP}_{i,j=2,t}$ is wastewater discharging factor of residential and industrial land in region i in period t (kg/ha); $\mathrm{CWP}_{i,j=3,t}$ means wastewater discharging factor of transportation land in region i in period t (kg/ha); MAWC_t represents wastewater treatment plant capacity in period t (kg).

$$\sum_{i=1}^{4}\sum_{t=1}^{3}\mathrm{RSP}_{i,j=1,t}^{\pm} \times x_{i,j=1,t}^{\pm} + \sum_{i=1}^{4}\sum_{t=1}^{3}\mathrm{ISP}_{i,j=2,t}^{\pm} \times x_{i,j=2,t}^{\pm} + \sum_{i=1}^{4}\sum_{t=1}^{3}\mathrm{CSP}_{i,j=3,t}^{\pm} \times x_{i,j=3,t}^{\pm} \leq \mathrm{MASC}_{i,t}^{\pm} \tag{13}$$

where $\mathrm{RSP}_{i,j=1,t}$ means solid-waste discharging factor of agricultural land in region i in period t (kg/ha); $\mathrm{ISP}_{i,j=2,t}$ is solid-waste discharging factor of residenti al and industrial land in region i in period t (kg/ha); $\mathrm{CSP}_{i,j=3,t}$ means solid-waste discharging factor of transportation land in region i in period t (kg/ha); MASC_t means the solid-waste treatment plant capacity (except landfill) in period t (kg).

$$x_{i,j,t}^{\pm} \geq 0 \tag{14}$$

In the IFNLM, the decision variables are land-use types, and the objective is to maximize the net system benefit through allocating the land resources to different users. The constraints help define the interrelationships among the decision variables and the land-resources management conditions. In detail, constraints in Equation (2) present the maximum government investment in each time period; constraints Equation (3) mean that the sum of land area is defined at first; constraints in equations (4) and (5) indicate the minimum residential and industrial land and transportation land area per capita during the study period; constraints in equations (6)–(9) indicate the minimum land area during the study period; constraints in Equation (10) present the maximum water consumption during the study period; constraints in Equation (11) present the maximum quantity of electricity consumption during the study period; constraints in equations (12) and (13) give the environmental constraints; constraints in Equation (14) are the non-negative constraints. According to solution algorithm provided by Huang *et al*. (1993), this IFNLM model can be transformed into two deterministic sub-models, which correspond to the upper and lower bounds for the desired objective function value. Figure 2 illustrates the general framework of the IFNLM.

2.3 Model parameters

The parameters of the IFNLM model including three types: interval beneficial parameters for each land use; interval cost parameters for each land use; interval technical, economic and environmental parameters. We can get these parameters through three ways: forecasting model method, land suitability assessment and land evaluation. Some of these parameters could be got through land evaluation by the method of index forecasting model. First, we can get the initial data from the statistic yearbook of China from 1990 to 2010 (National Bureau of Statistics of the People's Republic of China, 1991–2011); then we use index forecasting model to forecast the data between 2011 and 2025. By this method, we can get the parameters as follows: interval benefit from different land-use types; interval cost from different land-use types. Table 1 and Table 2 present the data of these parameters.

Other parameters (include the minimum area of every type of land, MIGL, MIPL, MIRL, MIAL, MIIL, and MICL) could be got based on AQSIQ (Chinese Administration of Quality Supervision, Inspection and Quarantine) and land-use suitability assessment by means of GIS technology. Other parameters (environmental capacity) including wastewater treatment plant capacity (MAWC) and solid-waste treatment plant capacity (MASC) can be got through environment bulletin of China (http://jcs.mep.gov.cn/hjzl/zkgb/). Table 3 presents the data of these parameters.

3 Results and Analyses

3.1 Optimized allocation results

3.1.1 Optimized allocation for agricultural land

Based on data of the parameters and the algorithm provided by Huang *et al*. (1993), we can calculate IFNLM in the Microsoft Excel or Matlab. We can get the optimized interval areas of every type of land uses and

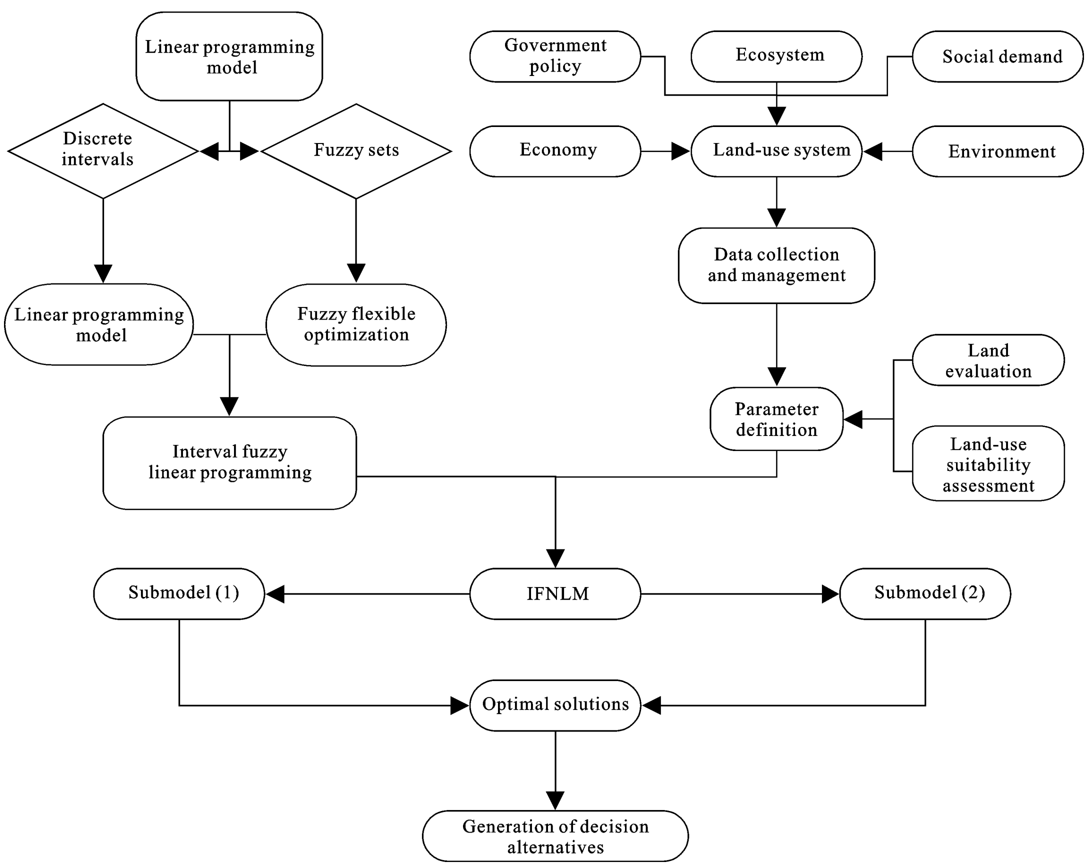

Fig. 2 Framework for interval fuzzy national-scale land-use model (IFNLM)

Table 1 Interval benefit for different unit land-use types

Benefit (10^6 USD/ha)	Period		
	$t = 1$	$t = 2$	$t = 3$
$BP_{i=1,j=2}$	[8.6, 8.9]	[10.0, 11.8]	[11.0, 13.9]
$BP_{i=2,j=2}$	[8.4, 8.6]	[10.1, 11.6]	[11.4, 13.6]
$BP_{i=3,j=2}$	[7.9, 8.4]	[9.2, 10.4]	[10.4, 13.4]
$BP_{i=1,j=3}$	[5.1, 5.4]	[6.5, 6.8]	[8.3, 8.4]
$BP_{i=2,j=3}$	[4.8, 5.6]	[5.7, 6.2]	[7.5, 7.6]
$BP_{i=3,j=3}$	[3.7, 3.8]	[4.5, 4.6]	[5.1, 5.2]

Notes: $BP_{i,j}$ is unit benefit of land-use type j in region i. i = 1 for Eastern China; i = 2 for Northeastern China; i = 3 for Central China, and i = 4 for Western China. j = 1 for agricultural land; j = 2 for residential and industrial land; j = 3 for transportation land; j = 4 for water body, and j = 5 for unused land. t mean the time periods: t = 1 for 2011–2015; t = 2 for 2016–2020; t = 3 for 2021–2025

Table 2 Interval costs for different land-use types

Cost	Period		
	$t = 1$	$t = 2$	$t = 3$
$WC_{i=1,j=2}$ (USD/ha)	[613.8, 678.4]	[766.2, 816.3]	[874.6, 902.4]
$WC_{i=2,j=2}$ (USD/ha)	[587.5, 673.3]	[729.6, 784.3]	[830.6, 942.0]
$WC_{i=3,j=2}$ (USD/ha)	[449.8, 489.7]	[562.6, 618.3]	[716.3, 752.2]
$SC_{i=1,j=2}$ (10^3 USD/ha)	[5.2, 6.2]	[7.3, 7.9]	[8.6, 9.4]
$SC_{i=2,j=2}$ (10^3 USD/ha)	[4.8, 5.3]	[6.7, 7.0]	[8.4, 9.0]
$SC_{i=3,j=2}$ (10^3 USD/ha)	[4.4, 4.6]	[5.7, 6.0]	[7.2, 8.0]
$WC_{i=1,j=3}$ (USD/ha)	[779.4, 842.7]	[862.9, 941.3]	[942.0, 1068.3]
$WC_{i=2,j=3}$ (USD/ha)	[763.3, 854.1]	[838.0, 859.6]	[930.3, 998.4]
$WC_{i=3,j=3}$ (USD/ha)	[716.4, 778.7]	[782.3, 856.2]	[909.8, 984.3]
$SC_{i=1,j=3}$ (10^3 USD/ha)	[7.1, 7.5]	[8.8, 9.6]	[9.6, 10.3]
$SC_{i=2,j=3}$ (10^3 USD/ha)	[6.7, 6.9]	[8.6, 9.0]	[10.0, 10.3]
$SC_{i=3,j=3}$ (10^3 USD/ha)	[6.2, 6.5]	[7.6, 8.1]	[9.3, 11.3]
$GC_{i=1,j=4}$ (10^3 USD/ha)	[4.0, 4.3]	[5.1, 5.4]	[6.2, 6.9]
$GC_{i=2,j=4}$ (10^3 USD/ha)	[3.7, 4.0]	[4.7, 5.0]	[5.9, 6.5]
$GC_{i=3,j=4}$ (10^3 USD/ha)	[3.4, 4.0]	[4.5, 4.9]	[5.6, 6.0]
$PC_{i=1,j=5}$ (10^3 USD/ha)	[8.5, 9.0]	[9.8, 12.5]	[10.8, 14.7]
$PC_{i=2,j=5}$ (10^3 USD/ha)	[7.9,8.3]	[9.1, 9.6]	[10.3, 13.7]
$PC_{i=3,j=5}$ (10^3 USD/ha)	[7.6,8.1]	[7.0, 8.8]	[10.1, 13.7]

Notes: $WC_{i,j}$ is unit wastewater-tackling cost of land-use type j in region i; $SC_{i,j}$ is unit solid-waste-tackling cost of land-use type j in region i; $GC_{i,j}$ is unit maintenance costs of land-use type j in region i; $PC_{i,j}$ means unit maintenance costs of land-use type j in region i

system benefits. Moreover, the optimized interval constraints satisfaction degree ($\lambda^{\pm}$) also can be calculated by the model. The optimized allocation for the agricultural land of the four regions during three periods is presented in Fig. 3. During 2011–2015, the area of agricultural land sector in the Western China would be the largest (i.e. [4272.4, 4446.8] × 10^3 ha), while the

Table 3 Interval economic, environmental and technical data

Data	Period		
	$t = 1$	$t = 2$	$t = 3$
MGI_t (10^6 USD)	[456.4, 892.5]	[1032.6, 1372.5]	[1638.3, 2347.6]
TLA_t (10^6 ha)	960	960	960
Pt (10^9 person)	1.34	1.34	1.34
MIRL (10^3 ha)	[2.3, 2.7]	[2.7, 3.4]	[3.4, 4.1]
MIGL (ha/person)	[13, 15]	[16, 18]	[20, 22]
MIPL (ha/person)	[23, 25]	[26, 28]	[31, 33]
MIAL (10^3 ha)	[1.10, 1.20]	[1.05, 1.15]	[0.90, 1.00]
$MAWC_t$ (10^6 kg)	127.6	127.9	128.1
LSP_t (10^6 kg)	[0.7, 1.2]	[0.8, 1.6]	[0.9, 2.0]
$MASC_t$ (10^9 kg)	1.239	1.241	1.272

Notes: MGI_t is maximum government investment in period t; TLA_t is total land area in period t; P_t is total population until period t; MIRL is minimum area of agricultural land; MIGL is minimum area of residential and industrial land per capita; MIPL is minimum area of transportation land per capita; MIAL is minimum area of water body; $MAWC_t$ is wastewater treatment plant capacity in period t; LSP_t is solid-waste treatment plant capacity by landfill in period t; $MASC_t$ means solid-waste treatment plant capacity (except landfill) in period t

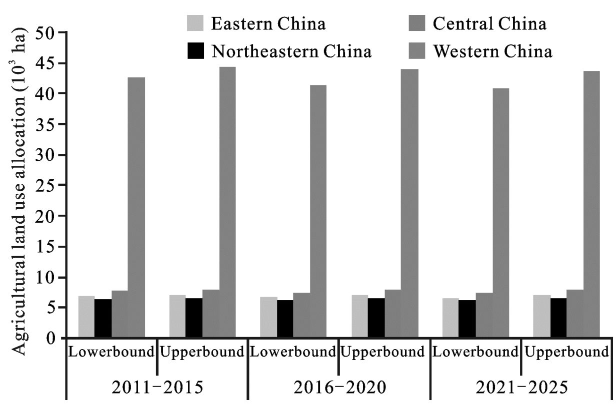

Fig. 3 Optimized allocation for agricultural land in China from 2011 to 2025

Central China would be in the next place (i.e. [763.6, 794.8] × 10^3 ha), the Eastern China would be in the third place (i.e. [678.4, 706.1] × 10^3 ha), the Northeastern China would be in the last place (i.e. [629.5, 655.2] × 10^3 ha). Similarly, between 2016–2020, the areas of agricultural land of the Western China, Central China, Eastern China and Northeastern China would be [4141.6, 4403.2] × 10^3 ha, [740.2, 787.0] × 10^3 ha, [657.6, 699.2] × 10^3 ha, and [610.2, 648.8] × 10^3 ha, respectively. During 2021–2025, the lands in the four regions would become [4098.1, 4368.3] × 10^3 ha, [732.4, 780.8] × 10^3 ha, [650.7, 693.6] × 10^3 ha, and [603.8, 643.6] × 10^3 ha, respectively. The results indicate that the area of agricultural land in the four regions would decrease slightly with the time. In fact, it directly results from the economic development. Although the Central government emphasizes the importance of agricultural land protection and slows down the speed of GDP growth in 'Twelfth Five-year Plan' (2011–2015), the local governments will not give up economic benefit easily regardless of the sustainability for industries. The development of urbanization and industrialization will not bring about the desired result of farmland protection. Conversely, the metropolis also includes the surrounding rich farmland, which resulted in the contradictions between economic development and food security. At the same time, many challenges to sustainable development are becoming serious and spread with the expansion of cities.

3.1.2 Optimized allocation for residential and industrial land

The optimized allocation for the residential and industrial land of the four regions during three periods is presented in Fig. 4. During 2011–2015, the areas of residential and industrial land in the Western China would be the largest (i.e. [114.9, 120.8] × 10^3 ha), while the Eastern China would be in the next place (i.e. [104.4, 109.7] × 10^3 ha), the Central China would be in the third place (i.e. [87.9, 92.4] × 10^3 ha), the Northeastern China would be in the last place (i.e. [39.3, 41.3] × 10^3 ha). Similarly, during 2016–2020, the areas of residential and industrial land of the Western China, the Eastern China, the Central China and Northeastern China would be [117.3, 125.6] × 10^3 ha, [106.5, 114.1] × 10^3 ha, [89.7, 96.0] × 10^3 ha, and [40.1, 42.9] × 10^3 ha, respectively. During 2021–2025, the lands in the four regions would become [118.6, 126.8] × 10^3 ha, [107.7, 115.1] × 10^3 ha, [90.7, 97.0] × 10^3 ha, and [40.5, 43.3] × 10^3 ha, respectively. The results indicate that the areas of residential and industrial land in the four regions would increase with the time. Different land policy should be taken to guide the expansion of urban industrial land in different regions. It is desirable to appropriately increase the construction land in the Western China. However, there are some significant differences between Southwestern China and Northwestern China. The development of the former plays a great role in stabilization of minority areas and border areas. In contrast, the latter emphasizes construction of ecology and environment. Northeastern China need promote the transformation of resource-exhausted cities, and use the inventory of land efficiently. Most important of all, enough urban land should be allocated to new industries in order to ensure economic growth. The Central China should stress coordination between supply and demand of construction land from the industrial policy. It is necessary to control excessive growth of the high energy consumption and pollution industries through land policy. Eastern China should pay attention to intensive use of urban land, and promote the upgrading of industrial structure. Besides, the optimization of spatial structure is especially crucial for sustainable development.

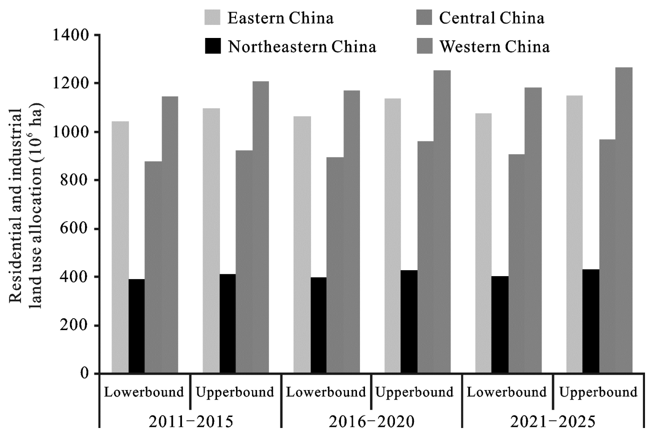

Fig. 4 Optimized allocation for residential and industrial land in China from 2011 to 2025

3.1.3 Optimized allocation for transportation land

The optimized allocation for the transportation land of the four regions during three periods is presented in Fig. 5. During 2011–2015, area of transportation land in the Western China would be the largest (i.e. [21.6, 22.9] × 10^3 ha), while the Central China would be in the next place (i.e. [13.2, 14.0] × 10^6 ha), the Eastern China would be in the third place (i.e. [12.6, 13.3] × 10^3 ha), the Northeastern China would be in the last place (i.e. [6.0, 6.3] × 10^3 ha). Similarly, between 2016–2020, the areas of transportation land in the Western China, Central China, Eastern China and Northeastern China would be [22.5, 23.8] × 10^3 ha, [13.8, 14.6] × 10^3 ha, [13.1, 13.9] × 10^3 ha, and [6.2, 6.6] × 10^3 ha, respectively. During 2021–2025, the lands in the four regions would become [22.7, 24.0] × 10^3 ha, [13.9, 14.7] × 10^3 ha, [13.2, 14.0] × 10^3 ha, and [6.3, 6.7] × 10^3 ha, respectively. The results indicate that the area of transportation land in the four regions would increase with the time. China is in the process of industrialization and urbanization, which is be characterized by large-scale population

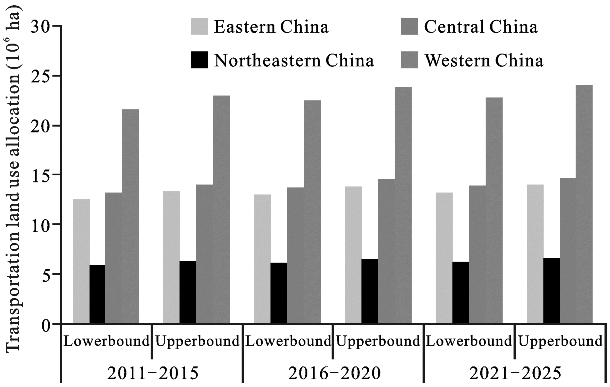

Fig. 5 Optimized allocation for transportation land in China from 2011 to 2025

migration. Transport infrastructure becomes to play stronger role in guiding population distribution, industry distribution and the evolution of the urban system. Therefore, the construction of transport infrastructure and its spatial optimization is sensible obviously. Consequently, the increase of transport infrastructure is inevitable.

3.1.4 Optimized allocation for unused land

The optimized allocation for the unused land of the four regions during three periods is presented in Fig. 6. During 2011–2015, the land areas of unused land in the Western China would be the largest (i.e. [2099.3, 2250.8] × 10^3 ha), while the Central China would be in the next place (i.e. [133.6, 143.2] × 10^3 ha), the Eastern China would be in the third place (i.e. [110.3, 118.3] × 10^6 ha), the Northeastern China would be in the last place (i.e. [92.0, 98.7] × 10^3 ha). Similarly, during 2016–2020, the land areas of unused land sector of the Western China, Central China, Eastern China and Northeastern China would be [2077.7, 2185.9] × 10^3 ha, [132.2, 139.1] × 10^3 ha, [109.2, 114.9] × 10^3 ha, and [91.1, 95.8] × 10^3 ha, respectively. During 2021–2025, the lands in the four regions would become [1890.7, 2120.3] × 10^3 ha, [120.3, 135.0] × 10^3 ha, [99.4, 111.4] × 10^3 ha, and [82.9, 93.0] × 10^3 ha, respectively. The results indicate that the area of unused land in the four regions would decrease with the time. Unused land does not only have an important ecological function, but also the production function and carrier of human activity. With the increase of new construction land, more and more unused land is being developed to meet the need of rapid economic development. In addition, due to the dynamic balance of arable land, one of the most important measures is to convert the

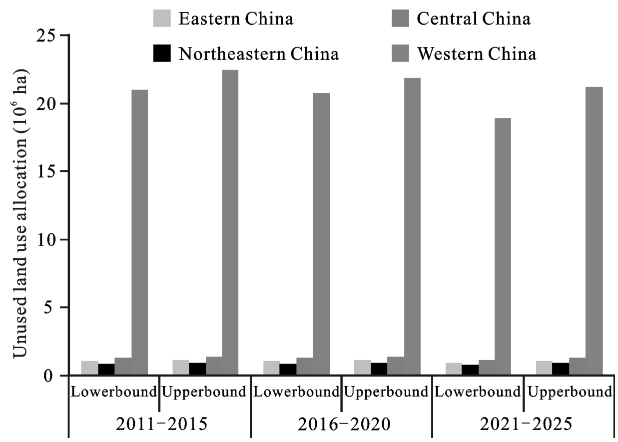

Fig. 6 Optimized allocation for unused land in China from 2011 to 2025

unused land into arable land. In fact, as the function of unused land works, the amount of it will gradually decrease.

3.1.5 Optimized allocation for water body

Analysis of the modeling solutions for water body is provided below, while this for unused land can be similarly interpreted. The optimized allocation for the water body of the four regions during three periods is presented in Fig. 7. During 2011–2015, the area of water body in the Eastern China would be the largest (i.e. [19.0, 19.3] × 10^3 ha), while the Central China would be in the next place (i.e. [18.6, 19.0] × 10^3 ha), the Western China would be in the third place (i.e. [18.4, 18.7] × 10^3 ha), the Northeastern China would be in the last place (i.e. [9.4, 9.6] × 10^3 ha). Similarly, between 2016-2020, the land areas of water sector of the Eastern China, Central China, Western China and Northeastern China would be [19.6, 20.7] × 10^3 ha, [19.2, 20.3] × 10^3 ha, [18.9, 20.0] × 10^3 ha, and [9.7, 10.2] × 10^3 ha, respectively. During 2021–2025, the lands in the four regions would become [20.9, 21.9] × 10^3 ha, [20.5, 21.4] × 10^3 ha, [20.2, 21.1] × 10^3 ha, and [10.3, 10.8] × 10^3 ha, respectively. The results indicate that the area of water body in the four regions would increase with the time. Water conservancy construction is directly related to national food security, flood control, water supply and ecological security. During the 'Twelfth Five-year Plan' (2011–2015), water conservancy construction will be considered as high priority over other infrastructure construction nationwide. Then, water conservancy construction will be improved increasingly, and rural development will be fostered further.

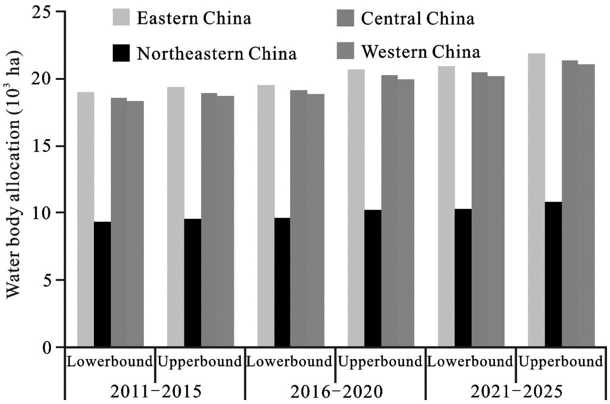

Fig. 7 Optimized allocation for water body in China from 2011 to 2025

3.1.6 Optimized system benefit

The results based on Figs. 3 to 7 also indicate that the expected $\lambda^{\pm}$ values is [0.69, 0.97]. The $\lambda^{\pm}$ level represents the possibility of satisfying all objective and constraints under the given system conditions. It corresponds to the decision makers′ preference regarding economic and environmental tradeoffs. In detail, λ^{+} corresponds to a high system benefit (f^{+}= 229.67 × 10^{12} USD) and optimistic strategies for land-use allocation, representing the maximum degree of overall satisfaction under loose environmental and ecological constraints. In comparison, λ^{-} corresponds to a low system benefit (f^{-}=198.25 × 10^{12} USD) and conservative strategies for land-use allocation, representing the maximum degree of overall satisfaction under strict environmental and ecological constraints.

The obtained results indicate that uncertainties that exist in the system parameters can be effectively reflected as intervals and membership functions in the IFNLM, with reasonable solutions generated. Thus, the hybrid model can help generate desired policies for land-use allocation with a maximized economic benefit and minimized environmental and ecological violation risk.

3.2 Comparing IFNLM with linear programming model

Substituting all parameters by deterministic average values, the study problem can then be converted into a traditional linear programming model. First, objective function solution of the IFNLM is [198.25, 229.67] × 10^{12} USD, and solution of linear programming model is 213.96 × 10^{12} USD. Second, variables solutions of IFNLM are showed in sections 3.1.1 to 3.1.5 and solutions of linear programming model (2011–2015) are showed in Fig. 8. Compare the two models′ results we can find that: 1) linear programming can only provide deterministic values but can not reflect the interval uncertainties in the land-use systems. In practice, if we know the optimized interval land-use patterns and system benefit, we could make more sound decisions. For example, the higher benefit correspond to disadvantageous system conditions (e.g., higher environmental risk), while those with a lower benefit correspond to less demanding conditions. We can set suitable land-use patterns to fit the develop objective according to the development preference; 2) No relaxation on capacity constraints is allowed in the interval programming model, while IFNLM with fuzzy constraints and objective which can support in-depth analysis of the tradeoff between system cost and system-failure risk. It may potentially result in over-stringent constraints and thus decreased system benefit.

4 Conclusions

An IFNLM has been proposed for land management in China under uncertainty. It is based on the interval fuzzy linear programming (IFLP) model which incorporates techniques of interval linear programming and fuzzy flexible programming within a general optimization framework. The IFNLM has advantages in uncertainty reflection, model coupling, risk assessment, and multi-scenario analysis in comparison to the other land management methods. It can deal with uncertainties expressed as discrete intervals, fuzzy sets and their combinations.

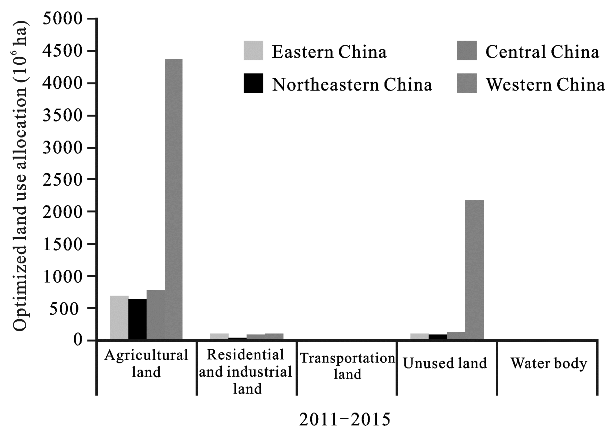

Fig. 8 Optimized allocation results of land use by using linear programming model from 2011 to 2015

The model was applied to the land-use allocation of China. The results indicate that potentially useful information can be obtained through this model. Generally, lower satisfaction degree (λ) levels would result in lower system benefits, lower constraint-violation levels, higher system reliability, and lower system risk, and vice versa. The modeling results help to generate a number of decision alternatives under various economic, environmental, social and ecological conditions, allowing more in-depth analyses of tradeoffs between eco-environmental constraints and socio-economic objectives as well as those between system optimality and reliability. The general approach is applicable to a wide range of land management problems where uncertainty exists for input parameters and considerable care is needed to balance off environmental and economic objectives. In general, although this proposed model is for the first time introduced to the land management field, the results suggest that it is also applicable to other resource management problems.

One potential extension of this research is about the reflection of various environmental and socioeconomic concerns related to the land resources management. Generally, techniques that can help extend the developed model to other problems that involve policies with multi-region and multi-period concerns would include: 1) inexact multistage multi-objective quadratic programming, which can be used for multi-criterion decision analysis under multiple objectives and may result in an infinite number of feasible alternatives; 2) consideration of more constraints in the modeling formulation such as technical requirements, management strategies, capital limitations, and environmental regulations; 3) post-modeling analysis techniques (e.g., multi-criteria decision analysis, analytical hierarchy process technique, dual programming, parametric programming, and multivariate analysis) for supporting fine adjustments of the generated solutions and systematic analyses of tradeoffs among multiple criteria. Another potential extension of this research is to integrate GIS model into the IFNLM. GIS has been widely applied to land-use allocation problems. In fact, with the aid of powerful function of data management and various spatial analyses, GIS can effectively improve reliability, advancement and consistency of source data. Therefore, it is necessary to develop a model which integrates GIS and IFNLM for further study. These extensions would support in-depth examination of implicit and qualitative information related to various system conditions and criteria that is deemed crucial by the decision makers.

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