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Planning regional ecosystem sustainability under multiple uncertainties—An interval stochastic credibility-constrained programming approach

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ABSTRACT

Inherent uncertainties in regional ecosystems can affect the modeling processes and the relevant results for managing and planning the real-world problems. In this study, an interval stochastic credibility-constrained programming (ISCP) method is developed for tacking multiple uncertainties expressed as intervals, fuzzy sets and probability distributions. The ISCP method is applied to planning regional ecosystem sustainability in the City of Dongying (China), in which ecosystem services valuation approach is directly incorporated within the optimization processes. Results associated with credibility levels of resources availability and the effects of sensitive ecological factors on the ecosystem services and ecological benefit are analyzed. Results show that a tighter limitation of ecological resources availability could cause lower economic development, particularly for oil field and oil refinery industries. Tradeoffs among social, economic and natural subsystems are also examined under different credibility levels, which are provided for generating optimal strategies in supporting of balancing the city's economic and ecological sustainable development. Results of sensitivity analysis reveal that runoff coefficient is one of the most sensitive ecological factors in the process of calculating the ecological benefit. The findings can provide scientific bases for the integration of economic and ecological activities as well as the development of regional ecosystem-sustainability strategies.

1. Introduction

In many regions and countries (e.g., China), with rapid socio-economic development and speedy population growth, the adverse effects of human activities on the natural ecosystem have become serious. The importance of ecosystem sustainability is broadly accepted as maintaining natural resources, and the sustainability is increasingly used as a guide for future regional economic and ecological development (Odum and Barrett, 2005). Ecosystems are becoming increasingly interconnected with other development of related issues and also with various factors such as social, economic, environmental, legal and political. Effective planning of ecosystems is important for facilitating socio-economic development and eco-environmental sustainability. However, such a planning effort is complicated with uncertainties that exist in ecosystems. For example, dynamic interactions exist between pollutant loadings and receiving lands (or watersheds), associated with a variety of uncertainties. 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). Therefore, it is of significance to develop effective modeling tools to formulate the long-term sustainable development of regional ecosystems.

Previously, a wide range of systems analysis methods were proposed for regional ecosystem management and planning in response to such complexities and uncertainties (Komatsu et al., 2007; Seppelt et al., 2009; Erol and Randhir, 2013; Marzin et al., 2014; Boluwade and Madramootoo, 2015; Ahmadi and Moridi, 2015; Rahmani and Zarghami, 2015; Slapnik et al., 2015; Song et al., 2015; Tan et al., 2015;

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Xia et al., 2015; Gobeyn et al., 2016). For example, Dowd (2007) proposed a new sequential data assimilation approach based on Markov Chain Monte Carlo (MCMC) to estimate the time evolving probability distribution of the ecosystem state; results indicated that MCMC is effective for characterizing the ecosystem state, which illustrated how non-Gaussian information originates, and how it could be used to characterize ecosystem properties. Kaya and Kahraman (2011) formulated an integrated fuzzy multiple criteria model for the selection of the best forestation district in metropolitan region, in which the weights of the selection criteria were determined by fuzzy pairwise comparison matrices of analytic hierarchy process. Feng et al. (2014) employed a fuzzy analytic hierarchy process approach to assess the coastal reclamation suitability of Lianyungang, China; for the Danjiangkou reservoir area, results showed that 31.59% of the coastline is unsuitable and 38.79% of the coastline is forbidden, which could be used for coastline protection projects. Chatterjee et al. (2015) used fuzzy analytic network process to assess the relative importance of different factors related to preservation and restoration of ecological balance in Keoladeo National Park, India; the findings showed that the water supply, optimizing the land use structure and strengthening wetland protection laws should be further enhanced by decision makers.

Generally, stochastic programming (SP) is effective for problems where an analysis of policy scenarios is desired and coefficients are random with known probability distributions; however, it is often difficult to build a probability distribution due to the lack of data or the high cost for acquiring the data (Qin et al., 2007). Fuzzy programming (FP) is effective in dealing with decision problems under fuzzy goal and constraints and handling ambiguous coefficients in the objective function and constraints; nevertheless, they have difficulties in facilitating the analysis of various policy scenarios that are associated with different levels of economic penalties when the pre-regulated targets (Li et al., 2010). Most of the previous studies rely on individual fuzzy or stochastic methods to deal with the uncertainties. In fact, regional ecosystem sustainability issues are surrounded with multiple uncertainties because many uncertain factors (e.g., land use pattern, ecological threshold, geographical condition, pollutant emission criterion, policy variation) are involved. For example, land reclamation intensity and natural sources availability are affected by ecological threshold, nutrient cycle and soil erosion are influenced by geographical condition, and pollutants emission permit and vegetation covering depend on economic and ecological policy. These factors, as well as their interactions, lead to uncertainties in input parameters which can be showed to complexities in the relevant decision-making process. In ecosystems management and planning problems, uncertainties expressed as intervals, probabilistic and possibilistic distributions can be effectively communicated. If merely individual fuzzy or stochastic methods are employed under such complexities, robustness of the optimization results may be significantly influenced due to the problems of over-simplification or over-specification for uncertainties (Li et al., 2009). Therefore, more robust approach for effectively reflecting multiple uncertainties to support regional ecosystem sustainability is desired.

The objective of this study is to develop an interval stochastic credibility-constrained programming (ISCP) method for planning regional ecosystem sustainability under multiple uncertainties. ISCP can deal with uncertainties expressed as interval, fuzzy sets and probability distributions. The developed approach will be applied to the City of Dongying in support of regional ecosystem sustainability. A number of scenarios that are associated with credibility levels of resources availability and the effects of sensitive ecological factors on the ecosystem services and ecological benefit will be analyzed, which can help the local decision makers in gaining insight into the tradeoff among social, economic and natural subsystems.

2. Methodology

2.1. Fuzzy credibility-constrained programming

Credibility constrained programming (CCP) is effective for tackle independent uncertainties in the constraint's left-and right-hand sides and thus optimize the satisfaction of the system performance (Zhang and Huang, 2011). In CCP, credibility constraints are addressed through fuzzy sets in constraint to express relationship between satisfaction degree and system-failure risk. In general, a fuzzy credibility-constrained programming (FCP) model can be formulated as follows:

$$Max f = \sum_{j=1}^{n} c_j x_j \tag{1a}$$

subject to:

$$Cr\left\{\sum_{j=1}^{n} a_{ij} x_j \leq \tilde{b}_i\right\} \geq \lambda_i \tag{1b}$$

$$x_j \geq 0, i = 1, 2, \ldots, n, \tag{1c}$$

where x = $(x_1, x_2, \ldots, x_i)$ is a vector of non-fuzzy decision variables, c_j are cost coefficients, a_{ij} are technical coefficients. And $\tilde{b}_i$ are right-hand side coefficients, some of which can be expressed fuzzy numbers. Let ξ be a fuzzy variable with membership function μ, and let μ and r be real numbers. The possibility of a fuzzy event, characterized by $\xi \leq r$, is defined by $Pos\left\{\xi \leq r\right\} = \sup_{u \leq r} \mu(u)$, while the necessity of a fuzzy event, characterized by $\xi \leq r$, is defined by $Nec\left\{\xi \leq r\right\} = \sup_{u > r} \mu(u)$(Trumbo and McComa, 2003). The credibility measure (Cr) is an average of the possibility measure and the necessity measure (Pishvaee et al., 2012); then, Cr is the credibility measure which is firstly proposed and was widely used in many research areas (Zhang and Huang, 2011). Let ξ be a fuzzy variable with membership function μ, and let r be real numbers. The credibility measure can be defined as follows (Pishvaee et al., 2012):

$$Cr\left\{\xi \leq r\right\} = \frac{1}{2}\left(\sup_{x \leq r} \mu(x) + 1 - \sup_{x > r} \mu(x)\right) \tag{2}$$