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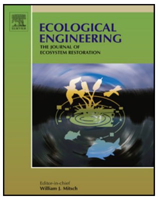

An interval robust stochastic programming method for planning carbon sink trading to support regional ecosystem sustainability—A case study of Zhangjiakou, China

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ABSTRACT

In this study, an interval two-stage robust optimization method (ITRM) is developed for planning carbon-emission trading between ecosystem and industrial systems under uncertainty. The developed ITRM incorporates interval-parameter programming (IPP) and two-stage stochastic programming (TSP) within a robust optimization (RO) framework to deal with uncertainties presented as both probabilities and intervals and to reflect economic penalties as corrective measures or recourse against any infeasibilities arising due to a particular realization of an uncertain event. Compared with the traditional TSP, ITRM can effectively reflect the risk generated by stochastic programming process and enhance the robustness of the model, such that it is suitable for risk-aversive planners under high-variability conditions. The ITRM is applied to a case of carbon sink trading of Zhangjiakou and carbon dioxide (CO_2) emission planning under uncertainty. The results obtained reveal that carbon trading mechanism can greatly optimize the allocation of resources and reduce the cost of emission abatement. The results also reveal that the contribution of forest ecosystems to carbon sinks and ecosystem services than others. Moreover, the system benefit would decrease as the robustness level is raised. Results indicate that when the robustness level is relatively low, the decision makers would pay more attention to the economic benefit of the system and neglect the stability of the system.

1. Introduction

Ecosystem is an important carrier of the development of human society and economy, which can not only provide human species abundant natural resources, but also create a good environment for the survival and development of human beings. The complex interactions between social and ecological systems have fundamentally changed in China during the past several decades (Zhou et al., 2015). With the rapid development of our society and economy, human activities have caused dramatic damage to the normal operation of the ecosystem, which in turn directly restrict the survival and development of human beings. The impact of human activities and natural factors on the global ecosystem is continually increasing, such as industrial development, increasing urbanization, population growth, and human-activity expansion, exacerbates the degeneration of ecosystem services (Zang and Zou, 2017). Therefore, it is urgent how to effectively take the path of sustainable development and coordinate the relationship between human and nature. The ecosystem service approach stresses the functions of the ecosystems and the benefits people derive from them and it has become a focus of interest for scientists, policy makers, and stakeholders over the last decade (Troy and Wilson, 2006; Khan and Valeo, 2016). Previously, a wide range of mathematical techniques were proposed for ecological model with a sustainable development manner. Hein et al. (2006) established an enhanced framework for the valuation of ecosystem services, which was used to support the development and implementation of the ecosystem management plan. Wang et al. (2010) developed an ecosystem service value evaluation framework for selecting

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relevant valuation methods to evaluate different types of coastal ecosystem service losses associated with land reclamation projects. Rao et al. (2014) presented a practical framework based on eco-compensation mechanism for developing the marine ecological damage compensation standard, which considered spatial variation in ecological services and included many different types of ocean uses that were common in coastal waters around the world.

Among these approaches, one effective ecological compensation method is to put carbon sink into the market considering the trading, which could have important significance to improve the ecological compensation. One of the main functions of the ecosystem service is that it could absorb CO_2 from the atmosphere and store it in the carbon pools, biomass and soil, whilst wood-based energy production can be used to substitute fossil energy and consequently reduce greenhouse gas emissions (Marika et al., 2015; Huang et al., 2016; Behera et al., 2017). As the largest terrestrial ecosystem carbon pool, forest ecosystems have stored 50–60% of carbon in terrestrial ecosystems (Swain et al., 2016; Tsai et al., 2017). Mechanism of carbon sink trading in response to climate change refers to the process and activity of ecosystem to absorb carbon dioxide in the atmosphere and fix it in vegetation or soil, so as to reduce the concentration of carbon dioxide in the atmosphere, which is the lowest cost method to reduce the global warming. Excessive levels of carbon can be moderated by the natural carbon absorbing properties of soil and plant life. For example, Goodale et al. (2002) analyzed the forest-sector carbon budgets of Canada, the United States of America, Europe, Russia and China and found that northern forests and woodland constituted a total sink consisting of living biomass, forest products, dead wood, the forest floor and soil organic matter. Dong et al. (2003) used a regression model to represent the relationship between forest biomass and the normalized-difference vegetation index of different countries, where results indicate that the implementation of carbon sink trading mechanism is feasible for China.

Since 2007, China's carbon emissions from energy consumption have topped the world and have been growing at a speed of 10% each year (Wang et al., 2014; Li et al., 2015). As one of the world's largest greenhouse gas (GHG) emitters, China has launched a number of national programs to reduce the GHG emission. For example, in 2015 Paris Climate Conference (PCC), a new policy "Paris agreement" was proposed to strengthen global response to climate change threats and China committed to reduce its carbon intensity by 60–65% from 2015 to 2020. Meanwhile, the national carbon emissions trading system will be established in 2017. In China's pilot Emission Trading Scheme (ETS), ecological carbon sink is one of the complementary mechanisms. It means that ecological carbon sink carbon can be traded in the Emission Trading Scheme (ETS), which is why the government invests in large-scale afforestation projects (Zhou and Lan, 2016).

Due to the nature of the ecosystem and the blindness and subjectivity of human cognition, there is a lot of uncertain information in the process of ecological planning, which makes it become a complex and uncertain system, including the fields of economy, management, ecology, society and environment. In this system, some factors are uncertain; meanwhile, these factors can interact among themselves, which make the uncertainty more prominent. Besides, the process of carbon sinks is a complex economic process, which includes emission rights market, technology market, capital market and information market from the market point of view. The large scale of the transaction, a large number of uncertain factors and the related departments and professional fields are the embodiment of the complexity of carbon trading. Moreover, in the practical carbon-trading system, a variety of uncertainties exist, such as carbon dioxide accounting, enterprise production process, carbon sink sequestration measurement, ecological and economic parameters and even measuring instrument error. The amount of carbon dioxide emitted by the enterprise is affected by the production capacity of the enterprise. However, the ability of an enterprise to produce is a random process, which may vary with different needs and costs, leading to GHG greenhouse gas emissions fluctuating within a range. For example, carbon emission inventory from the factory generation sector may vary with the productivity and demand, which can be represented as a random variable. A great number of research efforts were undertaken for planning carbon emission mitigation under uncertainty in industrial systems. Li et al. (2011a,b) discussed carbon emission trading scheme with an integrated energy system by creating an interval-fuzzy two-stage stochastic programming, which could effectively tackle uncertainties described in terms of probability density functions, fuzzy membership functions and discrete intervals.

The main objective of this study is to advance an interval two-stage robust optimization method (ITRM) for planning carbon sink trading of Zhangjiakou to support regional ecosystem sustainability in which carbon sinks function of different ecosystems and carbon trading mechanism are introduced into the modeling formulation. The impact of carbon sinks on carbon emissions trading under different robust values will be analyzed. A case study in Zhangjiakou Region will then be provided for demonstrating the applicability of the developed method. The results will help decision makers: (a) gain deep insights into the tradeoffs between economic objective, ecological benefit and carbon emission trading scheme; (b) make reasonable planning for the current land based on carbon sink; (c) managing carbon emission with effective trading scheme between ecosystem and industrial system.

2. Methodology

In Two-stage stochastic programming (TSP), decision variables can be divided into two subsets. The first-stage decision is to be made before uncertain information is revealed, whereas the second-stage decision is used to minimize 'penalties' that may appear due to any infeasibility (Chen et al., 2012). A general TSP model can be formulated as follows (Li et al., 2007):

$$Maxf = C_{T_1}X - \sum_{h=1}^{s} p_h D_{T_2} Y \tag{1a}$$

$$\text{subjectto} \tag{1b}$$

$$A_i X + A_i{}' Y \le w_{ih}, i \in M, M = 1, 2, \ldots, m_2, h = 1, 2, \ldots, s, \forall h \tag{1c}$$

$$x_j \ge 0, x_j \in X, j = 1, 2, \ldots, n_1 \tag{1d}$$

$$y_{jh} \ge 0, y_{jh} \in Y, j = 1, 2, \ldots, n_2; h = 1, 2, \ldots, s \tag{1e}$$

where x_j is the decision variable in the first-stage and y_j is the second-stage. Random variables y_j take discrete values w_h with probability levels p_h, where $h = 1, 2\ldots$ s and $\Sigma p_h = 1$. Obviously, model (1) can effectively deal with uncertainties in the right-hand sides presented as random variables when the coefficients in the objective function and left-hand sides of constraints are deterministic (Li et al., 2008).

Robust optimization (RO) can tackle the decision makers' favored risk aversion or service-level function and yield a series of solutions that are progressively less sensitive to realizations of the data in a scenario set (Leung et al., 2007). It is also a hybrid of stochastic and goal programs, which can balance the tradeoff between the variability of those random values and the expected recourse costs (Mulvey and Vanderbei, 1995). The formula is as follows:

$$Maxf = C_{T_1}X - \sum_{h=1}^{s} p_h D_{T_2} Y - \rho \sum_{h=1}^{s} p_h \left| D_{T_2} Y - p_h \sum_{h}^{s} D_{T_2} Y \right| \tag{2a}$$