

Review of evaluation on ecological carrying capacity: The progress and trend of methodology

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Abstract. The ecological carrying capacity (ECC) has been regarded as an important reference to indicate the level of regional sustainable development since the very beginning of twenty-first century. By a brief review of the main progress in ECC evaluation methodologies in recent five years, this paper systematically discusses the features and differences of these methods and expounds the current states and future development trend of ECC methodology. The result shows that further exploration in terms of the dynamic, comprehensive and intelligent assessment technologies needs to be provided in order to form a unified and scientific ECC methodology system and to produce a reliable basis for environmental-economic decision-makings.

1. Introduction

In recent years, the rapid economic expansion has not only weakened the sustainability of natural resource consumption, but also caused serious environmental degradations in many countries and regions. Therefore, it is urgent to scientifically assess the potential and pressure of carrying capacity supported by natural resources and environment. This is precisely where the ecological carrying capacity (ECC) comes in, which reflects the maximum population with a certain living standard and the intensity of social and economic activities that are sustained by the ecosystem in a specific country or a region [1].

Along with the evolution of ECC's concept, a variety of methods and models have been conducted on ECC from multiple dimensions such as water resource carrying capacity, land carrying capacity, resources carrying capacity, environmental carrying capacity and comprehensive carrying capacity. These evaluation methods, from simple assessment index system to complex system dynamics modelling, from static measurement to dynamic analysis and from the earlier ecological footprint with strenuous computational process to the artificial intelligence methods suitable for dealing with massive data, have been witnessed great progresses [2].

What are the main differences among these methods? Can the current assessment methodology be competent for the ECC evaluation task? Which direction will they go in the future? In order to answer these questions, this paper systematically reviews the progress of the methodology for evaluating ECC



in the last five years, and proposes opinions on its development trends based on the synthetic comparison between different models.

2. The evolution of ECC's evaluation methodology

We surveyed the literature in recent five years from online databases of ScienceDirect and CNKI (China national knowledge internet) using by three searching keywords including 'ecological', 'carrying capacity' and 'evaluation (or assessment)'. On this basis, the ECC evaluation methodology is divided into six sub-categories, such as evaluation index system (EIS), ecological footprint (EF), system dynamics (SD) method, decision-making optimization (DMO) model, safety coefficient (SC) method and artificial intelligence (AI) method.

2.1. The evaluation index system method

The integrity and representativeness of index system can, to a large extent, determine the valid of an EIS method. The index system of water resource carrying capacity is, for example, generally composed of natural endowment, self-purification capacity of water environment, level of productivity and human living standards. While atmospheric environment, pollution control and social economy are common indexes for measuring atmospheric carrying capacity. In addition to index design, weight setting of indicators matter heavily as well. Compared with subjective weighting method (e.g. analytic hierarchy process), objective weighting technique can overcome the subjective deviations in weight setting. The latter consists of multiple techniques such as sequential global common factor analysis [3], entropy weight method [4] and principal component analysis [5], etc.

With the development of evaluation technology and the increasing requirements of data processing, many novel assessment models have been introduced into EIS framework, thus forming a variety of hybrid models. These newly introduced methods, usually combined with EIS, include PSR(pressure-state-response)[6] that is systematic, causality and sustainability oriented, or its variant D-PSR-C(driving force-pressure-state-response-control) or GRA-TOPSIS models. The recently arisen GIS (Geographic Information System)-supported techniques [7], or the integrated methods such as GIS plus DSS (Decision-making Support System) [8], GIS plus fuzzy set [9] and GIS plus remote sensing [10], can be more competent for spatial information analysis and processing.

2.2. The ecological footprint method

Ecological footprint refers to the area of biological productivity that maintains the survival of a person, region or country, which links to the waste that can be discharged by human beings. EF analysis is usually applied to measure water ecological carrying capacity [11] or bearing capacity of atmospheric environment [12], and can not only reduce the valuation bias caused by data scarcity when combined with DEA [13], but also effectively identify the potential effects of emissions pollution on the entire process and the environment when LCA is incorporated into the assessment framework [14].

The traditional EF methods focus on static, other than dynamic, evaluation on the levels of resources and environmental carrying capacity. In order to implement the upgrading and optimization based on ecological development, more and more attention have been paid on to dynamic analysis, especially from the per capita perspective, in this research domain [15].

2.3. The system dynamics method

As well known, ecological carrying capacity research features by multiple factors, complex feedback relations, and a large number of data overlapping and changing over time. In light of the systematicness and complexity of ECC evaluation, the introduction of system dynamics method can be an effective alternative for analysing the causal relationships of all elements within a system. For instance, reference [16] determined the optimal economic development based on modes of water environmental carrying capacity and system dynamics prediction. By considering various important socio-economic and environmental factors and their correlations, reference [17] simulated the development trends for water resource carrying capacity in Luanhe River Basin, northern China.

Similarly, the hybrid models combining SD with many other methods also appear in the evaluation of ECC. Representative studies include the combination of SD and AHP (Analytic Hierarchy Process) to assess regional water ecological carrying capacity [18], and the dynamic hybrid modelling based on SD and AB (agent-based) technique for capturing the spatial and attributive information of ecological system in a natural and computationally efficient way [19].

2.4. The decision-making optimization model

The DMO models are mainly for exploring the optimal path of economic and social development with specific constraints on resources and environmental carrying capacity. In view of the fuzziness and uncertainty of environmental evolution, for example, a multi-objective programming (MOP) model consisting of a fuzzy linear programming (FLP) and an uncertain linear programming (ILP) were framed to help the decision-maker to determine the pattern of industrial structure [20]. By integrating stochastic programming and interval linear programming, an inexact stochastic multiple objectives programming (ISMOP) was proposed to optimize the industrial structure in Huai River Basin within Shandong, China [21].

In consideration of the natural spatial heterogeneities of water environment carrying capacity, more and more spatial optimization models for ECC have been designed. In a recent literature, for instance, an object-oriented spatial programming in which the ecological red line is regarded as a constraint and specific point location information was obtained from the input-output table was conceived [22].

2.5. The safety coefficient method

The SC method, also known as the loading rate evaluation method, usually reveals the safety degree of the ecological carrying capacity in certain region by comparing local ECC with the maximum carrying potential or the environmental capacity [23]. Both maximum carrying potential and environmental capacity reflect the maximum allowable discharge of pollutants permitted by specific regional environment without exceeding local environmental target.

However, there are many uncertainties in the calculation of environmental capacity, such as technical methods, data support and reliability of measurements, leaving huge difficulties for SC methods to be widely applied in the short term. While being as the ultimate manifestation of environmental carrying, environmental quality provides an effective and scientific reference to be followed in environmental management. Consequently, reference [24] applied a model of environmental carrying capacity evaluation based on environmental quality standards to determine the levels of environmental loading in Beijing-Tianjin-Hebei regions.

2.6. The artificial intelligence method

Recently, the increasing complexity of environmental-economic problems and the massive and heterogeneous characteristics of data have proposed urgent requirements of the application of intelligent methods with excellent data processing abilities. Some traditional intelligent methods, including but not limited to, machine learning, Bayesian Network model and deep learning have been utilized in dealing with important environmental problems.

With the rapid development of big data and cloud computing technologies, two recent papers evaluated the environmental quality [25] or environmental carrying capacity [26] using by the most advanced machine learning technique or cloud model respectively. Unfortunately, the existing literature in this field is extreme scarce, meanwhile some technical difficulties such as the natural transformation between uncertain languages and quantitative values in cloud model or the identification of deep convolutional network characteristics need to be further explored.

3. The comparison and development trend of ECC evaluation methodology

3.1. The comparison among ECC methods

In general, each assessment technique has both advantages and disadvantages based on our literature research.

For example, the EIS method can reveal the comprehensive state of resources and environment with a simple and repeatable operation process thereby has been widely used. While EIS is mainly regarded as a means of identification rather than regulation due to its undesirable ability in prediction. By contrast, the SD model can overcome this dilemma by decomposing complicated system into separate sub-systems. However, some difficulties such as the reasonable simplification for complicated systems and the determination of parameter variations are still a stumbling block to the prosperity of SD methods.

Different from the direct calculations of ECC by EIS or SD methods, the SC technique focuses on obtaining relative safety degree of ECC by comparing current loading state with environmental standards or environmental capacity. Nevertheless, all of the above methods can provide only information on ECC, and failed to unify the economy and the environment into one theoretical framework to guide the government decision-making. Comparatively, the DMO model is able to present the basis for guiding the economic decision-making according to the evaluated ECC values.

In addition, compared to the extraneous calculation process of most of the previously mentioned methods including EF and SD that may seem even powerless in the absence of data, the AI methods based on big data and cloud computing are more competent for processing massive data in the environmental field.

Table 1 further clearly depicts the comparison of the above ECC evaluation methods.

Table 1. Comparison of the above ECC evaluation methods.

	Strengths	Weaknesses
EIS	Simple and repeatable calculation process	Poor prediction ability
EF	Simultaneous Evaluation of regional ECC from both supply and demand sides	Complicated computing process and strict requirements on data
SD	Excellent ability in dealing with complex, nonlinear and feedback problems	Poor optimization ability
DMO	Good performance and robust computation results from dynamic, uncertain and multi-objectives complex problems	Inability to deal with massive data
SC	Intuitive and easy to understand results	Considerable uncertainties in terms of technical methods, data support and the reliability of the results
AI	Excellent performance of mining massive and heterogeneous environmental and economic data	Insufficient research and technical obstacles to be tackled

3.2. The expected evolution trends of ECC methods

There exist firm grounds to believe that, according to current literature survey, the future research on ECC will show the following three trends: First is dynamics. The traditional static quantitative studies will be replaced by more dynamic assessments, in order to full accurately reveal the true states of regional ECC. Second is comprehensiveness. More and more hybrid models will be widely adopted in ECC evaluations, so as to give full play to the advantages of different assessment techniques. Third is

intelligence. New intelligent evaluation models aiming for massive environmental and economic data will be proposed to adapt the complexity, uncertainty and multi-source heterogeneity of current environment-economy decision-makings.

4. Conclusions

It is shown that, based on our results from the investigation on nearly five years literature in ecological carrying capacity, distinctive features of each ECC method and obvious gap in their application, operation and applicability are pervasive. Moreover, the uniform, standard, systematic and scientific methodology has not been formed due to the restriction to single environmental element research on regional levels.

Accurate and reliable evaluation of regional ECC is a prerequisite for the implementation of environmental regulation and economic structure upgrading. It can be expected that, in view of the increasing complexity of environmental problems and the increasingly massive and heterogeneous data, the hybrid and dynamic assessment models and the artificial intelligence methods based on big data and cloud computing will play more and more important roles in the study of ECC.

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