Chin. Geogra. Sci. 2011 21(4) 496–510
doi: 10.1007/s11769-011-0490-0
www.springerlink.com/content/1002-0063

Research Progress on Evaluation Frameworks of Regional Ecological Sustainability

PENG Jian[1, 2], WANG Yanglin[1], WU Jiansheng[1, 2], SHEN Hong[1, 2], PAN Yajing[1, 2]

(*1. Laboratory for Earth Surface Processes, Ministry of Education, College of Urban and Environmental Sciences, Peking University, Beijing 100871, China*; *2. Key Laboratory for Environmental and Urban Sciences, Shenzhen Graduate School, Peking University, Shenzhen 518055, China*)

Abstract: As natural ecosystems provide the material basis and fundamental support for regional sustainable development, the sustainability of natural ecosystems is an important prerequisite and a viable approach for the achievement of regional sustainable development. It is also the final criteria to assess whether sustainable development paradigm is successful. Along with the increasing impacts of human activities on natural ecosystems, the evaluation of regional ecological sustainability has become one of the key issues for research on macro ecology and sustainable development. Based on different unit of indicators, this study firstly groups the evaluation frameworks of regional ecological sustainability into three major types: comprehensive index evaluation with dimensionless unit, monetary valuation, and biophysical quantity measurement. We then discuss and compare these types in terms of basic principles, scope of applications, advantages and shortcomings. Finally, drawn on the discussion about characteristics of ecological sustainability, we outline the current trend and future directions of regional ecological sustainability evaluation, for instance, transition from sustainable development evaluation to sustainability science, integration of goal-oriented and problem-solving approaches, combination of spatial pattern analysis and ecological sustainability evaluation, and enhancement of ecological sustainability evaluation at landscape scale.

Keywords: evaluation framework; regional ecological sustainability; research progress; research prospects; comprehensive index evaluation; monetary valuation; biophysical quantity measurement

Citation: Peng Jian, Wang Yanglin, Wu Jiansheng, Shen Hong, Pan Yajing, 2011 Research progress on evaluation frameworks of regional ecological sustainability. *Chinese Geographical Science*, 21(4): 496–510. doi: 10.1007/s11769-011-0490-0

1 Introduction

Natural ecosystems are the fundamental support for the life systems on earth, and can not be replaced by any man-made capital. The sustainable development of natural ecosystems aims to maintain the regional ecological sustainability, that is to say, to sustain the comprehensive functions of regional ecosystems under the disturbance of natural processes and human activities. Ecological sustainability is an important prerequisite and a basic principle for regional sustainable development (Parris and Kates, 2003), and the concerns have been raised by researchers from both environmental policy and sustainable development (Parsons, 1995).

The concept of sustainable development originated from the protection of natural resources and ecological environment. It focuses on the coordination of environment and development, nature and society, human needs and ecological integrity (Kates *et al.*, 2001; Clark and Dickson, 2003). The verification of sustainability should include not only ecological dimensions but also human ones (Forman, 1990). Taking a general review on studies of global sustainable development, all emphases are put on the ecological or environmental restrictions for human survival (Kidd, 2005), no matter the environmental focus during the 1970s to the early 1990s, or the

Received date: 2010-01-05; accepted date: 2010-05-25
Foundation item: Under the auspices of National Natural Science Foundation of China (No. 40635028, 40801066), State Key Laboratory of Earth Surface Processes and Resource Ecology of China (No. 2008-KF-04)
Corresponding author: WU Jiansheng. E-mail: wujs@szpku.edu.cn

environmental/social focus in the middle 1990s, or the integrated approach in the 2000s. Although there are many debates on the definition of sustainable development, it is no doubt that the success of sustainable development paradigm is ultimately determined by ecological sustainability (Linehan and Gross, 1998). Some scholars proposed that the sustainable development included three fundamental principles: ecological sustainability, economic efficiency and human equity (Parris and Kates, 2003; Sutton, 2003), while ecological sustainability is the prerequisite for inter-generational equity (Langhelle, 2000). Because environmental degradation is inefficient and unfair for the next generation, ecological sustainability can be an alternative of efficiency and equity (Sutton, 2003). In this meaning, sustainable development is just the theoretical form of ecological sustainability, while ecological sustainability is the basic approach to achieve real sustainability (Franke, 1996).

Currently, one of the key study areas of ecological sustainability evaluation is to build a quantitative evaluation framework (Fu *et al.*, 2001). According to the number of indicators or structure types, many scholars tend to classify the sustainable development evaluation frameworks into single indicator models, integrated accounting system models, multi-indicators models, or systematic indicators models. This kind of classification reflects only the external differences among evaluation frameworks, and fails to reveal the flaws of each evaluation model in epistemological and methodological aspects. Therefore, it will not help improve and optimize evaluation models. In contrast, the classification based on the unit of indicators could reflect the differences in methodology, and could compare advantages and disadvantages of different evaluation models, which is more meaningful for sustainable development practices. Accordingly, existing evaluation frameworks of regional ecological sustainability can be divided into three categories: comprehensive index evaluation with dimensionless unit, money-oriented evaluation, and biophysical quantity measurement (Hardi and Barg, 1997). These frameworks vary in perspective of measurement methods, and have different theoretical or methodological advantages and disadvantages. However, to date, few studies have been conducted to compare these various evaluation frameworks. This study aims to compare the basic principles, scope of applications, advantages and shortcomings of these three kinds of evaluation frameworks, and to point out further research directions.

2 Research Progress of Comprehensive Index Evaluation Frameworks with Dimensionless Unit

Comprehensive index evaluation frameworks with dimensionless unit consider ecological sustainability as a multi-level decision making process involving various fields. These models try to analyze the essential features of ecological sustainability from the theoretical level, and integrate ecological sustainability into a unified system constructed by a multi-level indicators system. Compared with money-oriented evaluation frameworks and biophysical quantity measurement frameworks, it is easier for the comprehensive index evaluation frameworks to collect research data, and it is much simple as well as operable. One of the key issues for comprehensive index evaluation frameworks is to ascertain the weight of indicators (Cai and Shang, 2009), because different indicators vary greatly in size, dimension, and implication to ecological sustainability. As a kind of value orientation, there are usually two approaches to determine the weight of indicators, i.e. subjective weighting method and objective weighting method. Although the objective weighting method is more objective to determine indicators′ weight, it is hard to reflect the relative difference of indicators, as the weight is greatly affected by the specific values of indicators. The subjective method, based on such expert experiences as Delphi method, can grasp the various importance among indicators. As a result, the subjective method is more reasonable and widely used in comprehensive index evaluation frameworks, although it is of less objectivity.

The threshold of evaluation indicators is another key and difficult issue in the comprehensive index evaluation frameworks with dimensionless unit. At present, thresholds used frequently include national, industrial and local standard values, the relevant planning or target values, the background standard values, analog standard values, or the experts′ values, but all the above values are lack of clear ecological implications. Therefore, comprehensive index evaluation frameworks are not good at responding to the status of regional ecological sustainability accurately. This is the most significant shortcoming compared with the biophysical quantity measurement frameworks. Additionally, since more and more indicators are included in the indicators system, and there are more information overlaps among correlating indicators, data pertinence. Therefore, redundancy among indicators has become one of the major difficulties. The rational solution to this problem is to enhance indicators′ independence using principal component analysis method.

At present, the comprehensive index evaluation framework with dimensionless unit of ecological sustainability has not been used widely, in contrast to the fact that comprehensive index evaluation frameworks have been widely applied to sustainable development evaluation. This is mainly resulted from difficulties of the decomposition of system targets. It is widely accepted that regional sustainable development systems could be divided into three sustainable sub-systems of economic, ecological and social systems. But researcheres and scholars have not reached a consensus about the decomposition of the ecological sustainability, although some scholars suggest that diversity, recycling, stability and productivity are the four basic properties of ecosystem sustainability (Dalsgaard *et al*., 1995). The existing evaluation indicators of regional ecological sustainability mostly adopt the environmental, resource, economic and social decomposition programs. Similar to the evaluation indicators system of sustainable development, it is difficult to reflect the difference of the targets between ecological sustainability and sustainable development. Other researchers just established comprehensive evaluation indicators system without decomposition of ecological sustainability targets, which resulted in the lack of theoretical basis and ambiguous instruction.

Proposed by Global Leaders of Tomorrow Environment Task Force (GLTETF) of the World Economic Forum, Yale Center for Environmental Law and Policy (YCELP) and Center for International Earth Science Network of Columbia University (CIESIN), Environmental Sustainability Index (ESI) is a successful example of comprehensive evaluation of ecological sustainability (Sutton, 2003). ESI is an integrated index containing 20 key indicators and 67 variables. It can reflect the state and the pressure of environmental systems, human vulnerability to environmental changes, the capacity of social and institutional responses to environmental challenges, and the responsiveness for the needs of global cooperation (YCELP, 2002). ESI could be used to carry out the systematic and quantitative comparison of environmental sustainability among different countries. But due to lack of data about certain issues with high priority, ESI has some defects in practice. For example, non-ideal data sources will result in incomplete coverage of countries. The lack of time series data will hinder the validation of correctness seriously, and restrict it as a good tool to identify environment factors (Zhang *et al.*, 2002).

As we know, the essence of ecological sustainability evaluation is to filter, define and measure the impact of human activities and the ability of the life-support systems of Earth to absorb these impacts, which can be divided into three independent aspects, i.e. the maximum sustainable use, the maximum sustainable absorption, and human environmental impact (the product of population, affluence and technology) (Daily and Ehrlich, 1992; Smith, 1995). As the technology can increase or decrease the impact of population and affluence on the natural environment, Smith (1995) put forward a similar model of human environmental impact assessment, in which the technology is replaced by the culture, institutions and technology effect (CITE). It can be concluded that ESI is a practice of the CITE concept to a large extent (Sutton, 2003).

3 Research Progress of Monetary Valuation Frameworks

Monetary valuation is a new idea for the ecological sustainability assessment. This kind of evaluation framework presumes that if welfare of the society does not decrease over time, the development is sustainable. At present, monetary valuation models include valuation of ecosystem services, genuine saving ratio, integrated system of environment and economic accounts, and other methods. As these models assume that man-made capital and natural capital can be substitutes for each other, that is, the loss of environmental degradation can be made up by the profits of man-made capital. Therefore, money-oriented evaluation framework is considered as a method for the weak sustainability evaluation (Rennings and Wiggering, 1997). However, this compensatory investment is difficult to achieve in ecology, and the degradation of ecosystems is irreversible usually. Thus, monetary valuation methodologies, especially the methods of genuine saving ratio and integrated system of environment and economic accounts which add natural capital to man-made capital, may mask the true physical storage of materials and energy flows in ecosystems, if compared to the comprehensive index evaluation models and biophysical quantity measurement methods. As the ecological sustainability focuses on the sustainability of ecosystem structure and function, while monetary valuation models pay more attentions to valuation than ecosystem storage assessment, these models are regarded as evaluation methods of sustainable development in general instead of an effective evaluation approach for ecological sustainability (Xu and Zhang, 2000).

In addition, monetary valuation frameworks are also criticized due to the following theoretical or technical flaws: 1) relying widely on valuation assumptions without market transactions, the valued price can hardly reflect the scarcity of natural resources; 2) due to great difference among valuation standards in different regions or periods, and unable to determine the discount rate when dealing with future fairness, it is difficult to compare the sustainability in various areas and in different periods; 3) the frameworks can not provide objectives and approaches to achieve ecological sustainability. Despite of above defects, monetary valuation models focus on the ecological basis of human development, which has corrected the misleading of traditional economic indicators to a large extent. Taking the currency as the unit of evaluation indicators, monetary valuation models after all provide a possible approach to ecological sustainability evaluation.

3.1 Ecosystem services valuation

The application of ecosystem services valuation in the evaluation of regional ecological sustainability is based on the following theoretical premises: the ecosystem is the final supporting system directly or indirectly for all the life in the earth, and human civilization will collapse without the basic supporting services from ecosystems; furthermore, the reduction of ecosystem services′ value means the decline of supporting capability for sustainable development. Therefore, in essence, the method of ecosystem services valuation can not respond directly to the sustainability issues of regional ecosystems, which is its supreme methodological shortcoming. And in the process of measurement, due to the incompleteness of evaluation content, existing methods of ecosystem services valuation can only measure the minimum value (Fu *et al.*, 2009; Feng *et al.*, 2010; Xie *et al.*, 2010). Because of ambiguous definitions and inconsistent classifications of ecosystem services with poor understanding of ecosystem complexity and inadequate recognition of ecosystem services′ exclusiveness and complementary, double counting has been recognized as another common problem in ecosystem services valuation (Costanza, 2008; Bennett *et al.*, 2009; Raudsepp-Hearne *et al.*, 2010; Fu *et al.*, 2011). As a result, it is difficult to give an accurate and absolute value of ecosystem services. Furthermore, as we know, social objectives determine the basis of ecosystem services valuation (Costanza, 2003), but social goals are quite different at various regions or periods, which leads to the non-uniform valuation standards and will undoubtedly increase the difficulty to compare the valuation results between different regions or periods. As one kind of monetary valuation models, the method of ecosystem services valuation also needs a wide range of valuation assumptions for potential value of ecosystem services, which is of great uncertainty.

However, the defects discussed above can not write off the importance of ecosystem services valuation for ecological sustainability evaluation. Through two promotions by Costanza *et al.* (1997) and the program of Millennium Ecosystem Assessment (MA, 2005), ecosystem services valuation is of global acceptance now. Many scholars have carried out a direct assessment of ecological sustainability based on the valuation results. For example, Pearce and Atkinson (1993) defined the weak sustainability without reduction of natural capital; using the ratio of national ecosystem services′ value to nighttime light emission monitored through satellite images, Sutton (2003) proposed an empirical ecological sustainability index. Shi *et al.* (2005) pointed out that the ecological capital based on ecosystem services are the ecological capacity or ecological load of regional sustainable development, and the ratio of regional ecological capital to GDP could characterize the coordination between economic growth and ecological protection in the process of regional development.

3.2 Genuine saving ratio

Genuine saving ratio was raised in 1995 by the World Bank. In this method, net savings are equal to the total savings minus the external debt and the depreciation of products and assets. Genuine savings refer to net savings minus resource depletion and environmental pollution, and it comes to genuine saving ratio when genuine savings are divided by GDP (World Bank, 1995). Generally speaking, the genuine savings can directly quantify the capacity for sustainable development in a certain country or region. When genuine saving ratio continues to be positive, it indicates wealth growing and sustainable development; otherwise, if genuine saving ratio comes to be negative, it eventually leads to the decline of wealth and unsustainability of regional development.

The method of genuine saving ratio breaks national wealth into four parts, namely natural capital, man-made capital, human capital and social capital, which is more comprehensive and reasonable in theory. Furthermore, through the valuation of natural capital, the method enables the measurement of environmental cost in the process of economic development. It is much operable with the application of national/regional balance account, which resulted in the wide use of the method at various spatial scales, such as the global, national and regional scales (Li *et al.*, 2004).

However, the method of genuine saving ratio still has many shortcomings which are mainly reflected in the following two aspects. On one hand, due to the change of natural resource prices over time, it is difficult to estimate the value of natural capital accurately. On the other hand, there are certain distortions in the characterization of sustainability in the areas with great loss of health due to resource depletion and environmental pollution, where the genuine saving ratio may remain to be positive (Li *et al.*, 2004).

3.3 Integrated system of environment and economic accounts

Aiming to make up the defect of neglecting natural resource scarcity and environmental quality decline in the system of national accounts promulgated in 1968, United Nations has developed the Integrated System of Environment and Economic Accounts (SEEA) in 1993. This system includes four parts, i.e. the balance account of man-made and natural capital, the matrix of the environmental externalities of economic activities and the cost of reducing the externalities, the definition of protective expenditures, and the valuation of natural resources and environment (United Nations Statistics Division, 2000). Economic benefits have been regarded as the result of human usage of natural environmental services in this system. On the basis of keeping the integrality of the existing national economic accounts system, the integrated system uses satellite accounts to revise traditional economic accounts with adding a new account of environment-related flows and stock, and correlating physical resources accounts with monetary environment accounts, as well as the liabilities of assets. Thus, the integrated system can adjust the traditional indicators of incomes and produces according to the environmental loss, and integrate economic growth with environmental change to a uniform accounting system, which can be used to comprehensively reflect the sustainability of development.

Because the property rights of natural resources are not strictly prescribed, the method of SEEA avoids many technical difficulties due to the lag in economic study of natural resources valuation and property rights. As the system can be used to monitor the process of environmental objectives in sustainable development strategic plan, and to measure environmental impact of specific development policies, it is an effective tool combining environmental problem with economic policies, and has been implemented in many countries (Costanza *et al.*, 2001; Zhang *et al.*, 2002).

However, there are still many issues that have to be resolved during the implementation of SEEA. First of all, the method of environmental costs valuation is yet to be improved; secondly, the net domestic product (NDP) indicators are adjusted according to environmental costs, while the gross domestic product (GDP) indicators remain unchanged. Thus, GDP is still not a good reflection of the depletion and degradation of natural resources; and lastly, it is overlooked that there is great inconsistency in the spatial and temporal scales among ecological and economic systems (Holub *et al.*, 1999).

4 Research Progress of Biophysical Quantity Measurement Frameworks

When used for regional ecological sustainability evaluation, the biophysical quantity measurement frameworks assume that the human well-being will decline with unsustainable development if human's usage exceeds regeneration ability of natural resources (Haberl *et al.*, 2004b). Because of its ability to measure the threshold of key ecological functions, biophysical quantity is often considered as an important evaluation factor for strong sustainability (Rennings and Wiggering, 1997). It mainly includes such comprehensive evaluation models as ecological footprint, emergy analysis, material flow analysis and human appropriation of net primary production, which are operable and widely used.

In these frameworks, the evaluation unit is biophysical quantity and does not require subjective determination of indicator weight, and evaluation results do not depend on human preferences, economic policies, technological or other factors. Therefore, the results of biophysical quantity evaluation can reflect objectively the relationship between supply and demand of natural resources and ecosystem services so as to avoid the influence of price change, at the same time they can be used for direct comparison of sustainability status in different regions and periods. Due to its objectiveness, the frameworks of biophysical quantity measurement are superior to the monetary evaluation frameworks, and have developed rapidly in recent years.

However, because regional trade and associated flows of biophysical quantities often result in the non-closed characteristics of the study area, there are errors between evaluation results and the fact. The trade is the main points and difficulties of all kinds of biophysical quantity evaluation methods. Compared with regional scale, biophysical quantity evaluation is more meaningful at the global or national scales. Furthermore, one method of biophysical quantity evaluation can only assess one aspect of ecological sustainability of coupled human and nature system, and cannot respond to other aspects of ecological sustainability, therefore the single biophysical quantity evaluation model is also not suitable for the comprehensive evaluation of regional ecological sustainability. Integrated indicators derived from two or more kinds of biophysical quantity evaluation models are in great need.

4.1 Ecological footprint

Ecological footprint (EF) was firstly raised by Rees (1992) with crucial methodological revision by Wackernagel and Rees (1996). This framework emphasizes the importance of the earth surface on the ecological processes and associated ecological sustainability. Generally speaking, through converting the socio-economic metabolism into related bio-productive land, EF method can quantify human occupation on natural ecosystems and thus judge the sustainability status of regional development through comparing human occupation with the ecological carrying capacity provided by natural ecosystems. The method of ecological footprint highlights the increase of human consumption and associated consequences, the key land resources in sustainable development, the spatial distribution of available resources, the impacts of trade on sustainable development, and the regional re-allocation of natural resources under environmental pressure, all of which are the key topics closely related with sustainable development (Wackernagel and Rees, 1996). Accordingly, EF method has received a universal acceptance with wide application of ecological sustainability evaluation at different spatial scales, such as global, national and regional scales.

The method of EF measures two key issues related with the survival of human beings under the limit of the Earth′s support, i.e. the absorption and conversion of pollution as well as waste, and the consumption of renewable resources. It provides an account system to calculate the impacts of human consumption on the natural environment. The EF method has the following methodological advantages when used to evaluate the ecological sustainability: firstly, EF indicators have clear ecological implications and practical guidance for the sustainable development; secondly, evaluation results are comparable among various regions or periods; and lastly, the method is simple and operable with accessible data requirements. Therefore, the method of ecological footprint is thought to be a successful approach to closely combining human beings with their supporting systems (Deutsch *et al.*, 2000), and thus has become one of the most popular biophysical quantity measurement methods used to evaluate regional ecological sustainability.

There are still some methodological shortcomings of the EF method, which have brought lots of academic debates (Peng *et al.*, 2006c). Firstly, the method assumes the transferability among all kinds of bio-productive land and their products, which is a kind of weak sustainability assessment complying with the Hartwick principles. Secondly, the EF method can not reflect the differences of land quality, especially the change of land bio-productivity in study periods due to technical innovation. It needs further discussions for the rationality of parameters in the long time series ecological footprint analysis. Thirdly, the relativity of the global mean productivity may lead to the non-absoluteness of evaluation results, which thus makes it uneasy for the public to perceive the implications of ecological deficit and ecological surplus. Fourthly, the EF method pays more attentions to the direct consumption without considering the indirect consumption of natural resources, which leads to the minimum assessment of human consumption. And lastly, the method assumes that all kinds of bio-productive land are mutually exclusive in space, while in fact there are various kinds of land use compatibility, such as the combination of agriculture and forestry in the same piece of land. Notwithstanding these theoretical shortcomings, the ecological footprint method can effectively assess the ecological sustainability of regional development (Wackernagel, 2009), at least in terms of the supply and demand of biologically productive land at global scale.

4.2 Emergy analysis

Emergy analysis is raised by H T Odum in the late 1980s based on energy analysis. Emergy evaluates the work previously done to make a product or service. Transforming different kinds of energy that is difficult to be compared directly into unified solar emergy with the index of conversion rate of solar emergy, this method can link the tangible resource supply and intangible ecosystem services from natural ecosystems with material production and human consumption. Thus, for the first time the value of natural capital is added into environmental-economic systems to measure the environmental externalities and associated contribution to the economic process. The method of emergy analysis is regarded as a new approach to evaluate the sustainability of coupled human and nature system, and can overcome the following defects that exist in the traditional methods of energy or economic analysis: the difficulty to measure the importance of natural resources to human society as well as the externalities of environment, the non-additivity among different kinds of energy, and the instability of price affected by market.

The method of emergy analysis specifically adopts the emergy sustainability index and related indicators to assess the ecological efficiency as well as sustainability of regional development. At present, various case studies have been conducted to evaluate ecological sustainability at different spatial scales based on emergy analysis. As the concept of emergy highlights the importance of environment sub-system in complex system of sustainable development, and can quantify the material flow and energy flow among the environment and economic sub-system, it is seen to be able to provide more detailed information for the analysis on the process of sustainable development (Geber and Bjorklund, 2001; Fu *et al.*, 2004). However, the method of emergy analysis still has some methodological shortcomings and need to be improved (Peng *et al.*, 2006a). Firstly, results of emergy analysis are not precise because the same conversion rate of solar emergy was used for each kind of resources or products, whether their production processes is the same or not. Secondly, what emergy analysis measures is the consumption of solar energy in the production process of materials. In essence, it is an evaluation framework according to theory of cost axiology, and can not measure human demands or willingness to pay for the ecosystem services, while there are great quantitative differences between these two values. Thirdly, it is also difficult to accurately define the thresholds of ecological sustainability in emergy analysis, and only the change of sustainability can be quantified through the horizontal comparison among different spatial units or the vertical comparison of the same spatial unit during different periods.

4.3 Material flow analysis

Material flow analysis (MFA) comes from early European studies on social metabolism and industrial metabolism. Through analyzing the exploitation, production, transformation, consumption, recycling, abandoning and other processes of natural resources, MFA can reveal the flow characteristics and conversion efficiency of materials in a specific area, and thus identify the direct source of environmental stress. With the application of such comprehensive indicators as total material requirement, material use ratio, material productivity, and environmental efficiency, MFA can quantify material exchange between economic subsystem and natural subsystem, and thus measure the extent of social metabolism objectively and evaluate environmental pressure resulting from economic activities, all of which provide a suitable tool for tracking the biophysical flows relating to regional socio-economic system at any spatial scale (Haberl *et al.*, 2004a).

Till now, MFA has been conducted in many countries, such as Germany, United States, Austria, Brazil, Venezuela, Japan, and European Union. There are also various case studies on regional or industrial MFA. Although there is rapid development on MFA study in recent years, MFA still requires improvement on the following aspects (Peng *et al.*, 2006b): firstly, it can not directly define the ecological sustainability threshold, which is the biggest challenge of this framework; secondly, MFA assumes that natural resources can be replaced by each other, and the weight of different materials can be added directly, therefore MFA belongs to the assumption of weak sustainability evaluation; but each unit of different materials often have rather different economic contribution and environmental impacts; thirdly, hidden flow coefficient, the key index of material flow analysis, is vital to the accuracy of results. However, the global mean value of hidden flow coefficient for each kind of materials is often used in MFA case studies whether it is conducted at global, national, or regional scales. Without measuring the actual value of hidden flow coefficient, existing studies are not able to accurately measure the quantity of material flow; fourthly, there are few studies to analyze various material flows within the economic system. Most studies only evaluated the ecological sustainability of the whole system, but cannot measure the impact of material flows in subsystems on the sustainability status of the whole system. As a result, MFA can hardly propose an operable approach for regional ecological sustainability; fifthly, although huge data are used in MFA studies, a considerable number of materials cannot be included in the accounting system due to lacking of data, which resulted in a preliminary estimation of material flow rather than an accurate accounting; and lastly, because of the inaccessibility of research data needed in material flow accounting at the meso-scale and small-scale, particularly the poor availability of import and export data, MFA can hardly be conducted at regional scale.

4.4 Human appropriation of net primary production

Human appropriation of net primary production (HANPP) is defined as the difference between the net primary productivity of potential natural vegetation and the net primary productivity of the actual vegetation remaining after harvest (Haberl, 1997; Haberl *et al.*, 2002; O′Neill *et al.*, 2007). Using joule, the amount of dry matter or carbon as the unit of measurement, the method of HANPP is mainly used to measure the proportion of net primary productivity which still remains in the nature under a certain land use/ land cover patterns and land use practices. The HANPP framework assumes that the proportion of the net primary productivity occupied by human beings is able to be used to measure the degree of human domination on natural ecosystems, and a higher HANPP would endanger natural biodiversity (Haberl *et al.*, 2004b; 2007).

With the application of land use/ land cover data, the method of HANPP highlights the importance of earth surface to ecological processes, and combines land use with socio-economic metabolism. Through measuring the change of material and energy flows due to human domination, HANPP tries to answer the upper ecological limit of human sustainable development (Haberl *et al.*, 2004b). Moreover, because this limitation is insurmountable at the global or local level, this indicator has been seen as the core ecological parameters of sustainable development (Haberl, 1997; Erb *et al.*, 2009). Currently, HANPP research is still in the stage of theoretical improvement and methodology design, which mainly focuses on the following issues (Peng *et al.*, 2007): 1) the improvement of calculation models of the actual and potential NPP in order to enhance the result accuracy; 2) the comparison of merits and shortcomings between HANPP and other methods of biophysical quantity measurement; 3) the analysis of the relationships among HANPP, bioenergy development and land use change (Kohlheb and Krausman, 2009); and 4) the empirical assessment of HANPP with the focus on processes, trajectories and implications in all scales (Erb *et al.*, 2009), since previous researches were only carried out at global or national scale.

Although HANPP is thought to be able to combine the methodology of industrial ecology with bio-geophysical analysis and thus has a good prospects (Haberl *et al.*, 2004b), HANPP still have some technical problems to be solved, which limits its wide application (Peng *et al.*, 2007). First of all, due to data absence, the existing studies can only assess human appropriation of net primary production in the terrestrial ecosystems of earth above the ground (Schwarzlmüller, 2009), and there is still no effective approach to calculating the NPP in marine or aquatic ecosystems as well as the underground part of terrestrial ecosystems. Secondly, because of the difficulty in acquiring data covering the whole study area, the existing HANPP evaluation at global or national scale mainly relies on the extrapolation of the location-scale measurements. The uncertainty of key parameters often leads to the great variation of the evaluation results. Lastly, although 100% of the HANPP means the ultimate destruction of the Earth, the ecological implications of other proportion of HANPP are still not clear. The great shortcoming for the method of HANPP is unable to define the sustainability thresholds, which is the very reason for few application of HANPP in ecological sustainability evaluation over the past 20 years.

5 Research Prospects and Promises

The evaluation framework of sustainable development generally includes three aspects, i.e. social, economic and ecological evaluation. Among them, the socio-economic evaluation focuses on assessing the status of development; and ecological evaluation, namely, the ecological sustainability evaluation refers to the sustainability assessment of development, and has always been the hot and key topics in sustainable development studies. Furthermore, due to the complexity of ecosystem processes, there are three great challenges for the evaluation of ecological sustainability. First of all, it is not easy to define the ecological sustainability thresholds of indicators, while it is necessary for a successful evaluation framework. Because of the presence of ecological resilience, natural ecosystems can adapt and respond to external disturbance by themselves, and thus keep the status of sustainability within a certain extent. Although it is acknowledged that ecological sustainability thresholds are correlated with ecosystem structure, ecological processes, and the extent of external disturbance, it is hard to clarify the thresholds in all existing evaluation frameworks. Secondly, few ecological sustainability evaluations have been conducted to measure the time lag effect of ecological sustainability. As we know, it is not synchronous for the change of different ecosystem components correlated in various ecosystem processes, under the same impact of external disturbance. Thus, there is time lag between the emergence of external disturbance and the change of ecological sustainability status, with the more complex ecosystem structure for the longer time lag. However, we can hardly monitor the time lag of ecological sustainability, although long-term landscape change studies have been recognized to be necessary to understand the mechanism of time lag (Metzger, 2008). Lastly, it is in great need of the integration of ecological sustainability and cultural sustainability. Along with the change of evaluation focus on ecological sustainability from ecosystem structure to ecosystem functions, and to ecosystem processes, it is acknowledged that a given ecosystem processes result from a certain cultural traditions. Both the ecological and cultural dimensions are advocated in landscape sustainability studies and practices (Musacchio, 2009a). Therefore, it is important for the maintaining of ecological sustainability to protect and keep traditional culture, since a strong emphasis on the cultural dimension will contribute to achieving sustainability (Wu, 2010).

Among the three types of evaluation frameworks of regional ecological sustainability, the biophysical quantity evaluation framework is the most popular because of its relative objectivity in the assessment compared with the frameworks of monetary valuation and comprehensive index evaluation. Although the biophysical quantity methods are effective in evaluating the ecological sustainability in a specific view, such as in the view of bio-productive land, material or energy flow, and net primary production, the evaluation results are not related with other aspects of sustainability issues. Therefore, single biophysical quantity method is not suitable to the comprehensive assessment of regional ecological sustainability. Ecological sustainability refers to an integrated complex system, and only the comprehensive index evaluation framework is able to integrate all kinds of information related with ecological sustainability issues into a comprehensive indicator. Meanwhile, all the three kinds of evaluation frameworks assumed the substitution between natural and man-made capital, which can not meet the requirements for strong sustainability evaluation of natural ecosystems. Therefore, it can be concluded that regional ecological sustainability evaluation is still at the initial stage, and further studies are in great need. Apart from the methodological improvement for the specific evaluation frameworks, further directions are classified as the following issues to make great methodological development of regional ecological sustainability evaluation.

5.1 Transition from ecological sustainability evaluation to sustainability science

Along with the development of interdisciplinary studies among biology, ecology, geology, biogeochemistry, economics, sociology, anthropology, geography and other related disciplines, sustainability science is taking shape in recent years. Regarding sustainability as a mutual feedback between human society and natural ecosystems, sustainability science goes beyond the traditional simplistic understanding of sustainable development which thinks that sustainable development can be achieved through overlaying environmental protection goals with the political objectives of economic growth and social welfare (Kates *et al.*, 2001).

Therefore, along with the thorough understanding of sustainability concept, the focus of regional ecological sustainability evaluation will be transferred from the comprehensive evaluation aiming at ecological or economic targets to the integrated evaluation based on combined ecological and economic processes. This integrated evaluation should be able to characterize the change of natural ecosystems, and associated human or natural driving forces and responses. As a cross discipline covering nature and society, it is convinced that landscape ecology can make significant contribution to the transition from ecological sustainability evaluation to sustainability science in theory and practice (Wu, 2006). And correlating socioeconomic activities with ecosystem processes and services, land use and land cover change has been regarded as a critical component of sustainability science, which is a possible approach to ecological sustainability evaluation in the view of sustainability science.

5.2 Integration of goal-oriented and problem-solving approaches

Goal-oriented and problem-solving approaches represent two distinct kinds of targets decomposition in the process of evaluation. Widely used in the evaluation of various topics, both approaches have their own advantages and disadvantages. In details, under the premise of proposing the overall goals, goal-oriented approach will establish the sub-goals and then adopt the top-down model in the evaluation. Thus, the overall goal is always focused and followed, which results in the coherence between the evaluation results and targets. Through the extensive investigations on the evaluation objects, problem-solving methods aim to propose the main problems correlated with the evaluation targets and associated influencing factors and solutions. Thus, problem-solving methods can respond to the overall goals in the end from bottom to up, with the pertinence characteristics of the evaluation results. Among three types of evaluation frameworks of regional ecological sustainability discussed above, the comprehensive index evaluation frameworks belongs to the goal-oriented approach, because this evaluation framework is oriented to measure the whole sustainability of coupled human and nature system. On the contrary, frameworks of monetary valuation and biophysical quantity measurement can be classified as problem-solving approaches, as they focus on one specific ecological aspect of regional sustainability issues.

To date, along with the occurrence of more and more emergent ecological or environmental conflicts, problem-solving approaches are encouraged and recognized to make valuable contribution towards achieving landscape sustainability (Fu and Lu, 2006; Opdam, 2007; Metzger, 2008; McAlpine *et al.*, 2010). However, in comparison, object-oriented evaluation can select more comprehensive indicators, but it can not effectively characterize the critical issues due to lack of pertinence; problem-solving assessment highlights the impact of key issues on the evaluation targets, but fails to measure the system goals comprehensively. Therefore, the integration of top-down and bottom-up approaches are advocated (Verburg and Overmars, 2009). It is thought to be a great help to the realization of the comprehensive evaluation with generality and pertinence to integrate goal-oriented and problem-solving approaches, namely, to decompose overall goals into sub-goals, and to select key issues to evaluate sub-goals. Furthermore, based on the comprehensive decomposition of the overall goal of ecological sustainability, a comprehensive index system could be built with the application of various biophysical quantity indicators or monetary indicators. The decomposition model of pressure-state-response proposed by Peng (2007) is a good example, which is a new direction in the further studies of ecological sustainability evaluation.

5.3 Combination of spatial pattern analysis and ecological sustainability evaluation

According to landscape ecology, the spatial patterns contain information on the mechanisms that they emerge from. Since spatial patterns and ecological functions are interrelated, a certain landscape function can only be realized in a certain landscape patterns, and the sustainability of regional ecosystem services is affected by landscape spatial patterns. Thus, along with the development of indicators for integrating landscape patterns and ecological processes (Chen *et al.*, 2009; 2010), it is argued by a lot of scholars that landscape pattern indicator is an important factor in regional ecological sustainability evaluation, and sustainability assessment should take spatial dimensions into account (Franke, 1996; Xiao *et al.*, 1997; Backhaus *et al.*, 2002; Blaschke, 2006).

In fact, according to the understanding of mutual feedback between human society and natural ecosystems in sustainability science, three levels can be distinguished in the evaluation of regional ecological sustainability: firstly, it is a kind of single factor analysis of the mutual feedback between human activities and the change of such ecological factors as regional climate, soil, hydrology, and vegetation; secondly, based on the construction of integrated indicators or indicator system, it is the comprehensive index evaluation of regional ecological sustainability with the integration of various kinds of mutual feedback analysis in the first level; and thirdly, it is to evaluate ecological sustainability in the view of spatial patterns, with a focus on the interaction mechanism between spatial patterns, ecological processes, and socio-economic activities. However, the existing sustainability indicators are usually derived from the parameters that are not sensitive to spatial dimensions (Backhaus *et al.*, 2002). All the existing regional ecological sustainability evaluation, regardless of using the method of comprehensive index evaluation, monetary valuation, or biophysical quantity measurement, belong to the category of landscape function studies without considering the impact of spatial patterns on the function of ecological sustainability, even though the indicators of landscape patterns have been proven to be good indicators for ecological sustainability evaluation (Peterseil *et al.*, 2004). Therefore, it is in great need to combine spatial pattern analysis with ecological sustainability evaluation through measuring the correlation between landscape patterns and the coupled social and natural processes.

5.4 Enhancement of ecological sustainability evaluation at landscape scale

As it is achieved in a certain space with temporal dynamics, ecological sustainability has a clear feature of scale dependence. The sustainability status is changing due to the change of spatial or temporal scales (Forman, 1990). Among various spatial scales, there are three scales of great ecological implications, i.e. ecosystem, landscape and global scale. Generally speaking, although the study at global scale can enhance public awareness to ecological sustainability, it will lose local features which are vital to policy making. Thus, the global scale is not an operational spatial approach. As the sustainability at ecosystem scale is difficult to keep stable during human generations, which is not consistent with the essence of sustainable development, the ecosystem is also not a suitable spatial scale for ecological sustainability studies. On the contrary, landscape has obvious boundaries, common ecological processes, as well as the relative stability during human generations; therefore it is the most appropriate spatial scale and practical tool for ecological sustainability study with sensitive responding to environmental change (Forman, 1990; Xiao *et al.*, 1997; Blaschke, 2006), although it has not yet reached worldwide recognition (Naveh, 2007). The basis of a sustainable future is the continuation of landscape ecological processes dominated by human activities (Brunckhorst *et al.*, 2006). The ecological sustainability assessment at landscape scales is regarded as an important step to understand and characterize ecological sustainability comprehensively (Peterseil *et al.*, 2004). Aiming at integrating socio-economic activities and ecological processes at landscape scale, landscape sustainability assessment can help to enhance the opportunities for supporting human beings and their environment (Lee *et al.*, 1992). Therefore, it can be concluded that ecological sustainability evaluation at landscape scale should be the core of ecological sustainability evaluation.

Although landscape scale is of great importance to achieve ecological sustainability, and sustainable development at landscape scale has also be seen as one of the ten research topics in future landscape ecology (Wu and Hobbs, 2002), few ecological sustainability studies have been carried out at landscape scale (Leitao and Ahern, 2002). It remains stagnant for the understanding of landscape in the view of sustainability (Peterseil *et al.*, 2004), while a precise definition is in urgent need (Aronson, 2011). And it is still a major challenge for landscape ecologists to define landscape sustainability and design sustainable landscapes (Lovell and Johnston, 2009; Pearson and McAlpine, 2010; Musacchio, 2009b; 2011), although it is acknowledged that it is necessary to maintain and restore multiple functions and services of landscapes in a changing world to achieve landscape sustainability (Fu *et al.*, 2008; Termorshuizen and Opdam, 2009). Meanwhile, as a multidisciplinary and transdisciplinary science, landscape ecology has not made notable contribution to landscape sustainability problems (Potschin and Haines-Young, 2006), although it is thought to be an essential part of sustainability science (Wu, 2006; 2010; Naveh, 2007; Musacchio, 2009b; 2011; Aronson, 2011), offering a way to find solutions (Wu, 2006; 2007; Naveh, 2007; Fu *et al.*, 2008; Pearson and McAlpine, 2010). And it is claimed that there is limited impact of landscape ecology on sustainable landscape management and planning (Naveh, 2007). Therefore, there is an urgent need to develop a comprehensive and operable concept of landscapes sustainability with the combination of spatial pattern analysis and ecological sustainability evaluation.

References

Aronson J, 2011. Sustainability science demands that we define our terms across diverse disciplines. *Landscape Ecology*, 26(4): 457–460. doi: 10.1007/s10980-011-9586-2

Backhaus R, Bock M, Weiers S, 2002. The spatial dimension of landscape sustainability. *Environment, Development and Sustainability*, 4(3): 237–251. doi: 10.1023/A:1021138602157

Bennett E M, Peterson G D, Gordon L J, 2009. Understanding relationships among multiple ecosystem services. *Ecology Letters*, 12(12): 1–11. doi: 10.1111/j.1461-0248.2009.01387.x

Blaschke T, 2006. The role of the spatial dimension within the framework of sustainable landscapes and natural capital. *Landscape and Urban Planning*, 75(3–4): 198–226. doi: 10.1016/j.landurbplan.2005.02.013

Brunckhorst D, Coop P, Reeve I, 2006. 'Eco-civic' optimization: A nested framework for planning and managing landscapes. *Landscape and Urban Planning*, 75(3–4): 265–281. doi: 10.1016/j.landurbplan.2005.04.001

Cai C M, Shang J C, 2009. Comprehensive evaluation on urban sustainable development of Harbin City in Northeast China. *Chinese Geographical Science*, 19(2): 144–150. doi: 10.1007/s11769-009-0144-7

Chen L D, Tian H Y, Fu B J *et al.*, 2009. Development of a new index for integrating landscape patterns with ecological processes at watershed scale. *Chinese Geographical Science*, 19(1): 37–45. doi: 10.1007/s11769-009-0037-9

Chen L D, Wang J P, Wei W *et al.*, 2010. Effects of landscape restoration on soil water storage and water use in the Loess Plateau Region, China. *Forest Ecology and Management*, 259(7): 1291–1298. doi:10.1016/j.foreco.2009.10.025

Clark W C, Dickson N M, 2003. Sustainability science: The emerging research program. *Proceedings of the National Academy of Sciences of the United States of America*, 100(14): 8059–8061. doi: 10.1073/pnas.1231333100

Costanza R, 2003. Social goals and the valuation of natural capital. *Environmental Monitoring and Assessment*, 86(1–2): 19–28. doi: 10.1023/A:1024045221992

Costanza R, 2008. Ecosystem services: Multiple classification systems are needed. *Biological Conservation*, 141(2): 350–352. doi: 10.1016/j.biocon.2007.12.020

Costanza R, d'Arge R, de Groot R *et al.*, 1997. The value of the world's ecosystem services and natural capital. *Nature*, 387 (6630): 253–260. doi: 10.1016/S0921-8009(98)00020-2

Costanza R, Farber S, Castaneda B *et al.*, 2001. Green national accounting: Goals and methods. In: Cleveland C J *et al*. (eds.). *The Economics of Nature and the Nature of Economics*. Cheltenham: Edward Elgar, 262–281.

Daily G C, Ehrlich P R, 1992. Population, sustainability, and earth's carrying capacity: A framework for estimating population sizes and lifestyles that could be sustained without undermining future generations. *BioScience*, 42(10): 761–771.

Dalsgaard J P T, Lightfoot C, Christensen V, 1995. Towards quantification of ecological sustainability in farming systems analysis. *Ecological Engineering*, 4(3): 181–189. doi: 10.1016/0925-8574(94)00057-C

Deutsch L, Jansson A, Troell M *et al.*, 2000. The 'ecological footprint': Communicating human dependence on nature's work. *Ecological Economics*, 32(3): 351–355. doi: 10.1016/S0921-8009(99)00152-4

Erb K, Krausmann F, Gaube V *et al.*, 2009. Analyzing the global human appropriation of net primary production-process, trajectories, implications: An introduction. *Ecological Economics*, 69(2): 250–259. doi:10.1016/j.ecolecon.2009.07.001

Feng X M, Fu B J, Yang X J *et al.*, 2010. Remote sensing of ecosystem services: An opportunity for spatially explicit assessment. *Chinese Geographical Science*, 20(6): 522–535. doi: 10.1007/s11769-010-0428-y

Forman R T T, 1990. Ecologically sustainable landscapes: The role of spatial configuration. In: Zonneveld I S *et al.* (eds.). *Changing Landscapes*: *An Ecological Perspectives*. New York: Springer-Verlag, 261–278.

Franke T T, 1996. Making future landscapes: Defining a path to qualified sustainability. *Landscape and Urban Planning*, 35(4): 241–246. doi: 10.1016/S0169-2046(96)00319-2

Fu Bojie, Liu Shiliang, Ma Keming, 2001. The contents and methods of integrated ecosystem assessment (IEA). *Acta Ecologica Sinica*, 21(11): 1885–1892. (in Chinese)

Fu B J, Lu Y H, 2006. The progress and perspectives of landscape ecology in China. *Progress in Physical Geography*, 30(2): 232–244. doi: 10.1191/0309133306pp479ra

Fu B J, Lu Y H, Chen L D, 2008. Expanding the bridging capability of landscape ecology. *Landscape Ecology*, 23(4): 375–376. doi: 10.1007/s10980-008-9214-y

Fu B J, Su C H, Wei Y P *et al.*, 2011. Double counting in ecosystem services valuation: Causes and countermeasures. *Ecological Research*, 26(1): 1–14. doi: 10.1007/s11284-010-0766-3

Fu Bojie, Zhou Guoyi, Bai Yongfei *et al.*, 2009. The main terrestrial ecosystem services and ecological security in China. *Advances in Earth Science*, 24(6): 571–576. (in Chinese)

Fu Xiao, Wu Gang, Liu Yang, 2004. Analytical theories of exergy and emergy for ecological research. *Acta Ecologica Sinica*, 24(11): 2621–2626. (in Chinese)

Geber U, Bjorklund J, 2001. The relationship between ecosystem services and purchased input in Swedish waste water treatment systems, a case study. *Ecological Engineering*, 18(1): 39–59. doi:10.1016/S0925-8574(01)00064-7

Haberl H, 1997. Human appropriation of net primary production as an environmental indicator: Implications for sustainable development. *A Journal of the Human Environment* (*AMBIO*), 26(3): 143– 146.

Haberl H, Erb K H, Krausmann F *et al.*, 2007. Quantifying and mapping the human appropriation of net primary production in earth′s terrestrial ecosystems. *Proceedings of the National Academy of Sciences of the United States of America*, 104(31): 12942–12947. doi: 10.1073/pnas.0704243104

Haberl H, Fischer-Kowalski M, Krausmann F *et al.*, 2004a. Progress towards sustainability? What the conceptual framework of material and energy flow accounting (MEFA) can offer. *Land Use Policy*, 21(3): 199–213. doi:10.1016/j.landusepol.2003.10.013

Haberl H, Krausmann F, Erb K H *et al.*, 2002. Human appropriation of net primary production. *Science*, 296(5575): 1968–1969. doi: 10.1126/science.296.5575.1968

Haberl H, Wackernagel M, Krausmann F *et al.*, 2004b. Ecological footprints and human appropriation of net primary production: A comparison. *Land Use Policy*, 21(3): 279–288. doi:10.1016/j.landusepol.2003.10.008

Hardi P, Barg S, 1997. *Measuring Sustainable Development*: *Review of Current Practice*. Toronto: International Institute for Sustainable Development.

Holub H W, Tappeiner G, Tappeiner U, 1999. Some remarks on the ′system of integrated environmental and economic accounting′ of the United Nations. *Ecological Economics*, 29(3): 329–336. doi: 10.1016/S0921-8009(98)00087-1

Kates R W, Clark W C, Corell R *et al.*, 2001. Sustainability science. *Science*, 292(5517): 641–642. doi: 10.1126/science.1059386

Kidd S, 2005. The environmental dimension of sustainable regional development in the English Regions: Reflections upon the experience of North West England. *European Environment*, 15(5): 266–281. doi: 10.1002/eet.391

Kohlheb N, Krausman F, 2009. Land use change, biomass production and HANPP: The case of Hungary 1961–2005. *Ecological Economics*, 69(2): 292–300. doi:10.1016/j.ecolecon.2009.07.010

Langhelle O, 2000. Why ecological modernization and sustainable development should not be conflated. *Journal of Environmental Policy & Planning*, 2(4): 303–322. doi: 10.1080/714038563

Lee R G, Flamm R, Turner M G *et al.*, 1992. Integrating sustainable development and environmental vitality: A landscape ecology approach. In: Naiman R J (ed). *Watershed Management: Balancing Sustainability and Environmental Change*. New York: Springer-Verlag, 499–521.

Leitao A B, Ahern J, 2002. Applying landscape ecological concepts and metrics in sustainable landscape planning. *Landscape and Urban Planning*, 59(2): 65–93. doi:10.1016/S0169-2046(02)00005-1

Li Ming, Wang Qing, Wu Daqian *et al.*, 2004. Valuation of sustainable development in Zhaoyuan City based on the method of genuine saving. *Journal of Shandong University* (*Engineering Science*), 34(5): 109–115. (in Chinese)

Linehan J R, Gross M, 1998. Back to the future, back to basis: The social ecology of landscapes and the future of landscape planning. *Landscape and Urban Planning*, 42(2–4): 207–223. doi:10.1016/S0169-2046(98)00088-7

Lovell S T, Johnston D M, 2009. Creating multifunctional landscapes: How can the field of ecology inform the design of the landscape? *Frontiers in Ecology and the Environment*, 7(4): 212–220. doi: 10.1890/070178

MA (Millennium Ecosystem Assessment), 2005. *Ecosystems and Human Well-being*: *Scenarios*. Washington, D.C.: Island Press.

Metzger J P, 2008. Landscape ecology: Perspectives based on the 2007 IALE world congress. *Landscape Ecology*, 23(5): 501–504. doi: 10.1007/s10980-008-9217-8

McAlpine C A, Seabrook L M, Rhodes J R *et al.*, 2010. Can a problem-solving approach strengthen landscape ecology′s contribution to sustainable landscape planning? *Landscape Ecology*, 25(8): 1155–1168. doi: 10.1007/s10980-010-9514-x

Musacchio L R, 2009a. The ecology and culture of landscape sustainability: Emerging knowledge and innovation in landscape research and practice. *Landscape Ecology*, 24(8): 989–992. doi: 10.1007/s10980-009-9393-1

Musacchio L R, 2009b. The scientific basis for the design of landscape sustainability: A conceptual framework for translational landscape research and practice of designed landscapes and the six Es of landscape sustainability. *Landscape Ecology*, 24(8): 993–1013. doi: 10.1007/s10980-009-9396-y

Musacchio L R, 2011. The grand challenge to operationalize landscape sustainability and the design-in-science paradigm. *Landscape Ecology*, 26(1): 1–5. doi: 10.1007/s10980-010-9562-2

Naveh Z, 2007. Landscape ecology and sustainability. *Landscape Ecology*, 22(10): 1437–1440. doi: 10.1007/s10980-007-9171-x

O′Neill D W, Tyedmers P H, Beazley K F, 2007. Human appropriation of net primary production (HANPP) in Nova Scotia, Canada. *Regional Environmental Change*, 7(1): 1–14. doi: 10.1007/s10113-006-0021-1

Opdam P, 2007. Deconstructing and reassembling the landscape system. *Landscape Ecology*, 22(10): 1445–1446. doi: 10.1007/s10980-007-9169-4

Parris T M, Kates R W, 2003. Characterizing a sustainability transition: Goals, targets, trends, and driving forces. *Proceedings of the National Academy of Sciences of the United States of America*, 100(14): 8068–8073. doi: 10.1073/pnas.1231336100

Parsons R, 1995. Conflict between ecological sustainability and environmental aesthetics: Conundrum, canard or curiosity. *Landscape and Urban Planning*, 32(3): 227–244. doi: 10.1016/0169-2046(95)07004-E

Pearce D W, Atkinson G, 1993. Capital theory and the measure of sustainable development: An indicator of weak sustainability. *Ecological Economics*, 8(2): 103–108. doi: 10.1016/0921-8009(93)90039-9

Pearson D M, McAlpine C A, 2010. Landscape ecology: An integrated science for sustainability in a changing world. *Landscape Ecology*, 25(8): 1151–1154. doi: 10.1007/s10980-010-9512-z

Peng Jian, 2007. *Regional Ecological Sustainability Evaluation Based on Landscape Pattern*. Beijing: Peking University. (in Chinese)

Peng Jian, Liu Song, Lu Jing, 2006a. Retrospect and prospect of research on emergy analysis in the ecological assessment of regional sustainable development. *China Population*, *Resources and Environment*, 16(5): 47–51. (in Chinese)

Peng Jian, Wang Yanglin, Wu Jiansheng *et al.*, 2006b. Progress and prospect of material flow analysis in the ecological assessment of regional sustainable development. *Resources Science*, 28(6): 189–195. (in Chinese)

Peng Jian, Wang Yanglin, Wu Jiansheng, 2007. Human appropriation of net primary production: An approach for ecological assessment of regional sustainable development. *Journal of Natural Resources*, 22(1): 153–158. (in Chinese)

Peng Jian, Wu Jiansheng, Jiang Yiyi *et al.*, 2006c. Shortcomings of applying ecological footprints to the ecological assessment of regional sustainable development. *Acta Ecologica Sinica*, 26(8): 2716–2722. (in Chinese)

Peterseil J, Wrbka T, Plutzar C *et al.*, 2004. Evaluating the ecological sustainability of Austrian agricultural landscapes: The SINUS approach. *Land Use Policy*, 21(3): 307–320. doi:10.1016/j.landusepol.2003.10.01

Potschin M B, Haines-Young R H, 2006. Landscape and sustainability. *Landscape and Urban Planning*, 75(3–4): 155–161. doi: 10.1016/j.landurbplan.2005.03.006

Raudsepp-Hearne C, Peterson G D, Bennett E M, 2010. Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. *Proceedings of the National Academy of Sciences of the United States of America*, 107(11): 5242–5247. doi: 10.1073/pnas.0907284107

Rees W E, 1992. Ecological footprints and appropriated carrying capacity: What urban economics leaves out? *Environment and Urbanization*, 4(2): 121–130.

Rennings K, Wiggering H, 1997. Steps towards indicators of sustainable development: Linking economic and ecological concepts. *Ecological Economics*, 20(1): 25–36. doi: 10.1016/S0921-8009(96)00108-5

Schwarzlmüller E, 2009. Human appropriation of aboveground net primary production in Spain, 1955–2003: An empirical analysis of the industrialization of land use. *Ecological Economics*, 69(2): 282–291. doi:10.1016/j.ecolecon.2009.07.016

Shi Peijun, Zhang Shuying, Pan Yaozhong *et al.*, 2005. Ecosystem capital and regional sustainable development. *Journal of Beijing Normal University* (*Social Science*), (2): 131–137. (in Chinese)

Smith C L, 1995. Assessing the limits to growth. *BioScience,* 45(7): 478–483.

Sutton P C, 2003. An empirical environmental sustainability index derived solely from nighttime satellite imagery and ecosystem service valuation. *Population and Environment*, 24(4): 293–311. doi: 10.1023/A:1022412304827

Termorshuizen J W, Opdam P, 2009. Landscape services as a bridge between landscape ecology and sustainable development. *Landscape Ecology*, 24(8): 1037–1052. doi: 10.1007/s10980-008-9314-8

United Nations Statistics Division, 2000. *Integrated Environmental and Economic Accounting*: *An Operational Manual*. New York: United Nations.

Verburg P H, Overmars K P, 2009. Combining top-down and bottom-up dynamics in land use modeling: Exploring the future of abandoned farmlands in Europe with the Dyna-CLUE model. *Landscape Ecology*, 24(9): 1167–1181. doi: 10.1007/s10980-009-9355-7

Wackernagel M, 2009. Methodological advancements in footprint analysis. *Ecological Economics*, 68(7): 1925–1927. doi: 10.1016/j.ecolecon.2009.03.012

Wackernagel M, Rees W E, 1996. *Our Ecological Footprint*: *Reducing Human Impact on the Earth*. Gabriola Island: New Society Publishers.

World Bank, 1995. *Monitoring Environmental Progress*: *A Report on Working Progress*. Washington: World Bank Press.

Wu J, 2006. Landscape ecology, cross-disciplinarity, and sustainability science. *Landscape Ecology*, 21(1): 1–4. doi: 10.1007/s10980-006-7195-2

Wu J, 2007. Past, present and future of landscape ecology. *Landscape Ecology*, 22(10): 1433–1435. doi10.1007/s10980-007-9172-9

Wu J, 2010. Landscape of culture and culture of landscape: Does landscape ecology need culture? *Landscape Ecology*, 25(8): 1147–1150. doi: 10.1007/s10980-010-9524-8

Wu J, Hobbs R, 2002. Key issues and research priorities in landscape ecology: An idiosyncratic synthesis. *Landscape Ecology*, 17(4): 355–365. doi: 10.1023/A:1020561630963

Xiao Duning, Bu Rencang, Li Xiuzhen, 1997. Spatial ecology and landscape heterogeneity. *Acta Ecologica Sinica*, 17(5): 453–461. (in Chinese)

Xie G D, Li W H, Xiao Y *et al.*, 2010. Forest ecosystem services and their values in Beijing. *Chinese Geographical Science*, 20(1): 51–58. doi: 10.1007/s11769-010-0051-y

Xu Zhongmin, Zhang Zhiqiang, 2000. Classification and assessment on indicators of measuring sustainable development. *Journal of Northwest Normal University* (*Natural Science*), 36(4): 82–87. (in Chinese)

YCELP (Yale Center for Environmental Law and Policy), 2002. *Environmental Sustainability Index*: *An Initiative of the Global Leaders of Tomorrow Environment Task Force, World Economic Forum*. New Haven: Yale Center for Environmental Law and Policy.

Zhang Zhiqiang, Chen Guodong, Xu Zhongmin, 2002. Review of indicators and methodologies for measuring sustainable development and their applications. *Journal of Glaciology and Geocryology*, 24(4): 344–360. (in Chinese)