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Theoretic Research on the Relevant Concepts of Urban Ecosystem Carrying Capacity

Linyu Xu[a*], Xiaodong Xie[a]

[a]*State Key Joint Laboratory of Environmental Simulation and Pollution Control. School of Environment, Beijing Normal University, 19 Xinjiekouwai Street, Haidian District, Beijing and 100875, China*

Abstract

Based on a review of related research literature and our own preliminary research, urban ecosystem carrying capacity and its relevant concepts (including urban ecosystem health, urban ecological security, and urban ecological risk) were identified starting from several aspects, such as the source, development, definition, function, evaluation methods, and limits. These aspects were systematically redefined by the urban ecological complex carrying capacity (UECCC) model, centering on the key concept of urban ecosystem carrying capacity. From this research, we found that urban ecosystem carrying capacity can be used to characterize urban ecosystem health, urban ecological security, and urban ecological risk (to some extent), such that these concepts can be connected together.

Keywords: Urban Ecosystem; Carrying capacity; Ecosystem health; Ecological security; Ecological risk

1. Introduction

In recent years, the acceleration of urbanization and increasing development of economies have brought about many complex problems in urban ecosystem, such as air pollution, water pollution, ecological degradation, and a scarcity of various resources [1]. To solve these problems and establish ecological cities, many scholars have concentrated on how to assess, plan, and manage urban ecosystems. Several important concepts are inevitably involved in such research, including carrying capacity, ecological security, ecosystem health, and ecological risk. However, the current state of research on these

* Corresponding author. Tel.:+ 86-10-5880-0618.
E-mail address: xly@bnu.edu.cn .

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important concepts is in disarray, and there is no acknowledged definition or unified understanding of these concepts. Most previous studies only involve one or a few concepts, e.g., primary studies on urban ecosystem health assessment by Guo et al. [2]. However, there are a few systematic studies of these important concepts. Some scholars like Xiao et al. [3] have analyzed the intrinsic relationships among ecological security, ecosystem health, and ecological risk, but a concept that is more closely related to these concepts, urban ecosystem carrying capacity, has not been taken into account.

In these concepts, the concept of 'carrying capacity' originates from ecology and stresses the internal interaction between organisms and their surrounding environments. Carrying capacity usually refers to the biological carrying capacity of a population level that can be supported for an organism, given the quantity of food, habitat, water, and other life infrastructure present. Therefore, the concept of 'carrying capacity' is an important basic theory in ecology. Along with phenomena such as land degeneration, environmental contamination, and population expansion, carrying capacity has been increasingly cited in the field of urban ecology and has become one of the main theories of the discipline.

In this paper, based on a review of related research literature and our preliminary research on urban ecosystem carrying capacity, the relevant concepts of urban ecosystem carrying capacity (including urban ecosystem health, urban ecological security, and urban ecological risk) are systematically redefined, and the relationships among them are identified, centering on the key concept of urban ecosystem carrying capacity.

2. Comparative analysis of the relevant concepts

To systematically investigate the relevant concepts of urban ecosystem carrying capacity, the links and difference between them must be identified, starting from their source, development, definition, function, evaluation methods, and limits.

2.1. Urban ecosystem carrying capacity

As mentioned above, since the first use of the concept of 'carrying capacity' in urban ecology, the notion of urban ecosystem carrying capacity has been involved in research on the theory of sustainable development, ecosystem health, ecosystem services, and the pressure-state-response (PSR) model. The concept, connotation, and meaning of carrying capacity have been being developed and perfected along with the development of ecology and society [4]. Particularly, after the complex urban ecosystem theory was proposed, the meaning of urban ecosystem carrying capacity developed into a more holistic and systematic concept [5].

However, at present, some domestic researchers only focus on the capacities of individual components [6], resulting in incomplete research into carrying capacity and the neglect of urban ecosystem balance. In practice, an urban population and its activities jointly form the core component of the urban system, interlinked with the urban eco-environment [7]. The development of an urban ecosystem is built upon the interactions between environmental carrying capacity (ECC), resource carrying capacity (RCC), and social-economic development capacity (SEDC). It is well established that precisely describing the system characteristics and variables can be prohibitively difficult [8]. Although significant progress has been made in evaluating carrying capacity, most current methods are non-quantitative and lack analytical rigor [9]. The modeling of ecological footprints [10] is currently the most representative quantitative method to evaluate carrying capacity, but it still lacks flexibility and adaptability in forecasting procedures [11].

The concept of compound carrying capacity (CCC) was introduced in our previous research [7] and studied as an index of the interactions between ECC, RCC, and SEDC. Because an urban ecosystem is different from a traditional natural ecosystem and its carrying object is humans (who have the ability to

change the structure of urban artificial sub-ecosystems to meet their own needs), this former study focuses on the ability of urban ecosystems to support humans and their activities. In contrast to traditional definitions and connotations of carrying capacity, urban ecosystem compound carrying capacity (UECCC) is defined as the potential ability to maintain urban ecosystem health, which includes the ability to develop under normal conditions (the intrinsic carrying capacity), and the ability of resilience under stress conditions (the acquired carrying capacity).

Most researchers agree that changes in technology affect the carrying capacity of a system. Evidently, new technologies affect how resources are consumed, and thus, if carrying capacity depends on the availability of a resource, the value of the carrying capacity changes [12]. For these reasons, the limit of UECCC based on fixed resource limits or a single, unchanging carrying capacity is unrealistic. Therefore, the UECCC is not a constant value but rather a dynamic value varying across stages along with the development of cities.

As discussed above, UECCC comprises both the sustainable ability of the natural ecosystem and the development ability of the social-economic system. The sustainable capacity determines the upper limit of the UECCC based on the maximum supply of resources and the maximum sustainable ability of the environment. The development ability determines the lower limit of the UECCC according to the minimum development ability of the social-economic system or the smallest size of the urban population. Thus, when the UECCC value is within these limits, the ecosystem will function well.

As for the function of the concept of urban ecosystem carrying capacity, it is clear that its function is to evaluate whether the urban environment is able to attain a development target and to describe how the urban ecosystem maintains its health.

2.2. Urban ecosystem health

The concept of ‘health’ was initially developed in the field of medical science, and it indicates that a person is physically, mentally, and socially in a good condition. Along with the rapid development of ecology, the concept of health has been gradually introduced into ecosystems. Leopold (1941) was the first to propose the concept of ecosystem health. Since then, many scholars [13, 14, 15, 16] have joined the discussion on the definition of ecosystem health and the selection of ecosystem health assessment indicators. In 1999, Rapport [17] defined ecosystem health as “to define the state, condition and performance of an ecosystem under the standards of meeting the appropriate objectives”. The connotation of ecosystem health should include two aspects: 1) the ability to meet reasonable requirements of human society and 2) the ability to self-maintain and update the ecosystem itself. Over the past decade, the concept of ecosystem health has been studied more deeply and entered the urban ecology literature.

Compared to the natural ecosystem, the urban ecosystem displays distinct characteristics. For instance, an urban ecosystem is strongly affected by human activities and, thus, has evolved into artificial ecosystem composed of both social and natural components. Therefore, urban ecosystem health can be defined as an objective state in which the supply of eco-services to human beings maintains its integrity and health and in which humans living in the cities, as well as the entire society, both maintain their health. Urban ecosystem health emphasizes the reasonable structure and integral, efficient function of the ecosystem from the perspective of ecology but additionally stresses that the urban ecosystem can maintain its eco-services and prevents damage to human health and socio-economic health [2].

Currently, the most common evaluation method for urban ecosystem health is to select appropriate quantitative indicators and establish an index system to evaluate the health condition of the urban ecosystem. At present, many scholars derive their assessment index system based on the theory proposed by Costanza [18], i.e., they evaluate urban ecosystem health through the aspects of vitality, organizational structure, resilience, maintenance of ecosystem services, and effects on human health. According to their

evaluation results, cities can be classified into different healthy levels: morbid, unhealthy, critical state, healthy, and very healthy. However, some problems still exist with method, such as the uncertainty and imperfection of evaluation standards. Hence, more research on evaluation methods for urban ecosystem health is needed.

It is clear that the function of the concept of urban ecosystem health is to evaluate whether the urban ecosystem is in a good condition and able to maintain its eco-services to maintain human health and socio-economic health. Additionally, urban ecosystem health can be described by degrees such that governments can take action to maintain urban ecosystem health, e.g., by adjusting urban development strategies and urban planning.

2.3. Urban ecological security

The concepts of 'security' usually refers to a state in which a country or region maintains social and political stability, without wars, and individuals or systems avoid suffering from inroads and destruction. In recent years, some scholars have advocated extending the meaning of security and transferring it from the political and military fields to the study of ecosystem [19]. Such researchers, like Shi et al. [20], propose that the meaning of ecological security includes two main parts: 1) that the structure and function of a natural ecosystem maintains its normal state and 2) the level of satisfaction with natural ecosystems supplying eco-services and supporting human activities. Currently, along with increasingly serious urban ecological problems, the concept of ecological security has been used in urban ecology, and urban ecological security has become a hot topic of research in ecological security.

Considering the peculiarities of urban ecosystems, the concept of urban ecological security is a subjective evaluation of the situation of an urban ecosystem from the human perspective. Therefore, urban ecological security can be defined as a state of an urban ecosystem in which the urban ecosystem can support sustainable development of a human society and economy and in which the natural environmental conditions meet human expectations.

Because different stages of urban development have different levels of socio-economic development, varying levels of stress are placed on natural ecosystems from human activities and thus determine different levels of urban ecological security. In addition, different spatial scales have different natural conditions, and thus, different natural conditions also determine different levels of urban ecological security. Therefore, urban ecological security has dynamic characteristics on both spatial and temporal scales [20].

Usually, urban ecological security is evaluated by selecting indicators and assigning weights based on the PSR model and then establishing an index system to calculate a status value. To establish a complete urban ecological security index system, indicators can be selected from the aspects of resource security, environmental security, biological security, and ecological disasters [21]. Further, the process used to calculate a status value for urban ecological security can be attributed to four methods, i.e., the mathematical model, ecological model method, the landscape model method, and the digital terrain model [22]. However, each of these methods includes shortcomings, so complex evaluation models have been developed by combining a variety of methods. Finally, to determine the level of urban ecological security, a security threshold must be established based on analysis of relevant information and expert advice.

Considering the concept of urban ecological security, it is clear that its function is to evaluate whether an urban ecosystem is able to satisfy human needs to maintain both health and urban development, as well as to describe the degree of security such that governments can adjust urban development strategies and urban planning to maintain urban ecological security.

2.4. Urban ecological risk

'Risk' is an age-old concept that means the possibility that something unpleasant or dangerous might happen or that someone or something is likely to be a danger or problem in the future. Most scholars, such as Hu and Lu [23, 24], maintain that risk is a concept composed of the possibility of unfortunate incidents and the damage caused by these incidents. Risk can be described by the product of the possibility of unfortunate incidents and the damage caused by these incidents. Since the 1980s, the concept of risk has been used in environmental assessment, and after ~30 years' research on risk assessment, ecological risk has receiver increasing attention. In short, ecological risk is a risk that an ecosystem and its components suffer. Ecological risk refers to adverse effects that uncertain accidents or disasters may have on the ecological system and its components in a certain area, including damage to ecosystem structure and function, thereby endangering ecosystem health and security [25, 26, 27].

Therefore, urban ecological risk encompasses the possibility of adverse effects on urban ecosystems and their components (including humans), as well as the loss of ecological benefits caused by human activities and natural factors in the urban development process. The loss refers to damage to the structure and function of an urban ecosystem, which thereby endangers urban ecological security and ecosystem health.

Currently, different countries have different ecological risk assessment methods. Indeed, there are numerous types of ecological risk assessment methods, but there is no a standard assessment framework. However, there are some similarities between these methods; each ecological risk assessment method includes hazards identification, exposure assessment, effect evaluation, and risk characterization. Because urban ecosystem is more complex than natural ecosystem and due to an emphasis on temporal and spatial characteristics, urban ecological risk assessment required the development of novel assessment models, such as the HPDP [28] and PETER [29] models.

It is clear that the function of urban ecological risk is to evaluate the possibility of an urban ecosystem being damaged and the seriousness of the damage, thereby permitting action to reduce the possibility of accidents and losses, ensuring that the city is running smoothly.

2.5. Relationships between the relevant concepts of urban ecosystem carrying capacity

According to an analysis of the four concepts described above from various aspects, such as the source, development, definition, function, evaluation methods, and limits (see Table 1), it is clear that there are several relationships among the concepts, which are as follows:

In terms of the source, we found that except for the urban ecosystem carrying capacity, the other concepts are all from completely different fields. Compared to the urban ecosystem carrying capacity, the other concepts do not have an acknowledged definition or a unified understanding, and further research into them is required.

In terms of the definition, we found that urban ecosystem carrying capacity is a type of potential ability of an urban ecosystem, urban ecosystem health is an objective state of an urban ecosystem, urban ecological security is a state of an urban ecosystem based on subjective evaluation from the perspective of humans, and urban ecological risk is the possibility and seriousness of damage to an urban ecosystem. These four concepts all include the urban ecosystem as a basic point. However, the urban ecosystem carrying capacity describes the intrinsic characteristics of the urban ecosystem, while the other concepts describe the external characteristics that an urban ecosystem expresses under outside pressure or influence.

In addition, it is generally recognized that urban ecological security and urban ecological risk are mutually inverse functions. They are both subjective evaluations from the inverse perspective.

In terms of the function, urban ecosystem carrying capacity and its relevant concepts are all meant to evaluate whether an urban ecosystem is able to attain a development target, and it must consider the inner and outer pressure put on an urban ecosystem (UEPIO) so that it can perform the assessment. However,

its relevant concepts do not need to consider the UEPIO because they consider outside pressure or influence in their definitions.

In terms of common evaluation methods, it is clear that the four methods all must establish an index system. Additionally, different evaluation methods for related concepts can learn from each other.

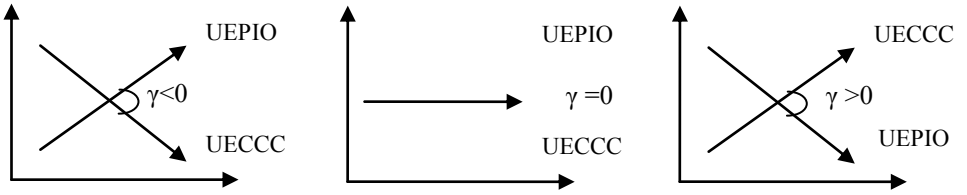
In terms of limits, urban ecosystem carrying capacity is a dynamic value varying across stages (along with the development of cities) and has upper and lower limits. Although the relevant concepts also have different levels, the level classification is relatively definite for a certain urban ecosystem. Additionally, a healthy ecosystem is secure, but a secure ecosystem may not be healthy. This means that the limits of urban ecological security are lower than those of urban ecosystem health. In a way, the sustainable security of an urban ecosystem is based on urban ecosystem health.

Table 1. Similarity analysis of urban ecosystem carrying capacity and human immunity.

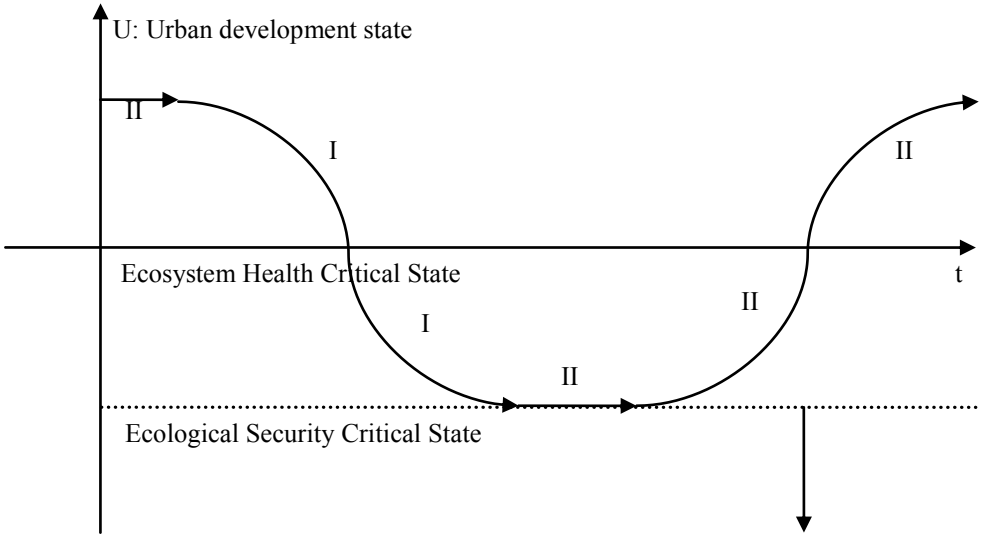
	Urban ecosystem carrying capacity	**Urban ecosystem health**	**Urban ecological security**	**Urban ecological risk**
Souce	Ecology	Medical science	Political and military fields	Social science and natural hazard fields
Definition	Urban ecosystem carrying capacity is defined as the potential ability to maintain urban ecosystem health, which includes the intrinsic carrying capacity and the acquired carrying capacity.	Urban ecosystem health is an objective state in which an urban ecosystem maintains its integrity and health to keep supplying eco-services to human, while the entire society maintains health.	Urban ecological security is a state in which an urban ecosystem can support sustainable development of human societies and economies, as well as human expectations for the natural environmental conditions in which they live.	Urban ecological risk means the possibility of adverse effects on an urban ecosystem and its components (including humans), as well as the loss of ecological benefits caused by human activities and natural factors in the urban development process.
Function	To evaluate whether the urban environment is able to attain the development target and to describe how the urban ecosystem maintains its health.	To evaluate whether the urban ecosystem is in a good condition and is able to maintain its eco-services and keep human health and socio-economic health from damage, as well as to describe its degree.	To evaluate whether the urban ecosystem is able to satisfy humans' needs to stay healthy and maintain urban development, as well as to describe its degree.	To evaluate the possibility and the seriousness that urban ecosystems are damaged.
Common evaluation method	Ecological footprint or UECCC model [7].	Establish an index system from aspects such as vitality, organizational structure, resilience, maintenance of ecosystem services, and effects on human health [18].	The index system method based on the pressure-state-response (PSR) model.	Include hazards identification, exposure assessment, effect evaluation, and risk characterization, e.g., the HPDP [28] and PETER [29] models.
Limits	The upper limit and the lower limit.	Five different healthy levels: morbid, unhealthy, critical state, healthy, and very healthy.	The security threshold based on analysis of relevant information and expert advice.	Different risk levels, such as high risk region, middle risk region, and low risk region.

3. Systematic research on the relevant concepts

As mentioned above, the UECCC (i.e., the potential ability to maintain urban ecosystem health) is not a constant value but rather a dynamic value varying across stages along with the development of cities. This dynamism of the UECCC can be illustrated by the demand of humans for eco-services (a stress on the urban ecosystem). Therefore, the intersection angle between the UECCC and the UEPIO at a certain stage can be used to illustrate the state of urban development. There are three developmental states according to the value of the slope, which can be positive, negative, or zero (see Fig. 1).



γ = the intersection angle between the UECCC and the UEPIO.



I: γ < 0; II: γ > 0; III: γ = 0.

Figure 1. Illustration of the relationships of the relevant concepts with the UECCC.

Accordingly, when the slope is positive, the UECCC will assume the advantage niche stepwise and facilitate rapid urban development. When the slope is zero, the UECCC reaches equilibrium with the UEPIO, and the urban system will develop steadily. When the slope is negative, the UEPIO will exhaust the advantage niche and terminate urban development. It should be noted that the curve of the urban

development state in Fig. 1 illustrates the urban development state along with the urban development, which is determined by comparison of the UECCC and the UEPIO.

Based on the analyses of urban ecosystem health and urban ecological security, the urban development state determines the health or security level of an urban ecosystem. Thus, when the urban development state decreases to lower than the urban ecosystem health critical state, the urban ecosystem supplying eco-services to humans is not able to maintain its integrity and health, and humans living in such cities are not able to maintain their health. When the urban development state continues to decline to less than the urban ecological security critical state, the urban ecosystem is not able to support sustainable development of a human society and economy, and natural environmental conditions are not within human expectations. At such a point, urban ecological risk (i.e., the integration of the possibility of the urban development state declining to lower than the urban ecological security critical state and the size of their consequences) will occur. The intrinsic relationships between urban ecosystem carrying capacity and its relevant concepts can be seen in Fig 1.

Therefore, urban ecosystem carrying capacity should be a key focus of research on urban ecosystem. Urban ecosystem carrying capacity can be used to characterize urban ecosystem health, urban ecological security, and urban ecological risk (to some extent) in an effort to achieve the ultimate goal: the sustainable development of cities.

4. Conclusions

In this paper, the relationships between urban ecosystem carrying capacity and its relevant concepts were identified, starting from their source, development, definition, function, evaluation methods, and limits. These concepts were then systematically redefined by the UECCC model. Our main conclusions are as follows:

a) Urban ecosystem carrying capacity describes the intrinsic characteristics of an urban ecosystem and the other concepts describes the external characteristics that an urban ecosystem expresses under outside pressure or influence;
b) Urban ecosystem health is an objective state of an urban ecosystem, and urban ecological security is a state of an urban ecosystem based on subjective evaluation from a human perspective. A healthy ecosystem is secure, but a secure ecosystem may not be healthy;
c) Urban ecological security and urban ecological risk are mutually inverse functions, and both are subjective evaluations from inverse perspectives;
d) Urban ecosystem carrying capacity is a dynamic value varying across stages along with the development of cities and has an upper and lower limit. Although the relevant concepts also have different levels, their level classification is relatively definite for a particular urban ecosystem;
e) The curve of the urban development state in Fig. 1 illustrates the urban development state along with urban development, which is determined by comparison of the UECCC and the UEPIO. Conversely, the urban development state determines the health or security or risk level of an urban ecosystem. Therefore, urban ecosystem carrying capacity can be used to characterize urban ecosystem health, urban ecological security, and urban ecological risk (to some extent).

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