An integrated approach for assessing the urban ecosystem health of megacities in China

Chen Zeng a,b,*, Xiangzheng Deng b, Shan Xu c, Yiting Wang a, Jiaxing Cui c

a Department of Land Management, Huazhong Agricultural University, 430070 Wuhan, China
b Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, 100101 Beijing, China
c School of Resource and Environmental Science, Wuhan University, 430079 Wuhan, China

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ABSTRACT

In 2014, China adjusted its “city categorization standard.” The newly defined megalopolises and metropolises are under unprecedented pressure from various eco-environmental problems, making them suitable representatives for exploring the state of urban ecosystem health. In this study, we establish a two-layer indicator system to assess the urban ecosystem health and choose 33 indicators grouped into social, economic, transportation, facility, land, and management subsystems, with the aim of correlating human activities with the structure, vigor, resilience, and health of the urban ecosystem. We integrate subjective and objective methods to determine weights at different levels through the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), the analytic hierarchy process, and information entropy. In particular, we develop a spatial TOPSIS technique by introducing a Euclidean-distance-based weight to rank the health of the cities’ ecosystem in terms of the spatial effects among these cities. The results reveal that megalopolises such as Beijing, Shanghai, and Guangzhou have superior social and economic subsystems, whereas other megacities have advantages in transportation, facility, land, and management subsystems. From 2005 to 2010, the gaps among these cities in terms of urban ecosystem health significantly reduced regardless of the weight determination method. Not all indicators involved can help realize a better urban ecosystem. Nevertheless, they provide a reference point for making specific regulations to control human activity and improve eco-environmental management.

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1. Introduction

In 2014, China adjusted its “city categorization standard,” where the term “megapolises” was appended and the original four-tiered category was changed to a five-level system (State Council, 2014). This new categorization was designed to adapt to the rapid urbanization and industrialization in megacities in China. Environmental degradation due to mass migration, traffic, and industrial advancement is rampant in these large cities (Fang, 2014). In the face of eco-environmental problems caused by urbanization, ecological perspectives and ad hoc solutions have emerged and matured, and the assessment of urban ecosystem health has become a powerful tool (Chen & Wang, 2014; Liu, Zhan, & Deng, 2005).

In definition, urban ecosystem health has evolved from the concept of natural ecosystem health, which has been integrated with urban characteristics. In fact, in urban ecosystems, people live in high densities and structures and infrastructure cover much of the land surface (Pickett et al., 2011). Urban ecosystems are also characterized by high material and energy consumptions, high pollution, and low natural resources, making them vulnerable and instable (Jiang & Chen, 2011; Liu et al., 2011). Thus, urban ecosystem health describes a state in which an urban ecosystem maintains its integrity and health to continue supplying eco-services to humans maintaining a healthy state (Xu & Xie, 2012). Similar concepts have also been proposed such as “urban ecological health,” “urban ecological security,” and “urban ecological carrying capacity” (Su, Fath, & Yang, 2010); the distinct feature of “urban ecosystem health” lies in its focus on the reasonable structure and integral, efficient function of the ecosystem from the perspective of ecology, but it also emphasizes that the urban ecosystem can maintain its eco-services and prevent damage to human health and socioeconomic health. This integrated subject combines the characteristics of ecosystems and services for humans. With this concept, holistic operations and the development potential of urban ecosystems can be assessed and thus be applied extensively in urban management to evaluate the status quo of the urban ecosystem, identify the limiting factors, identify key problems, optimize the scheme, and guide ecological regulation (Su, Yang, & Chen, 2012a).

In the past years, an increasing number of studies have been conducted on urban ecosystem health or related assessments, which can
be generally categorized into three groups. The first group tends to
design the assessment via “pressure-state-response” or “pressure-
resilience” frameworks (Dizardroglu, Yigiticlanlar, & Dawes, 2010; 
Zhang, Ma, Zhan, & Chen, 2012). Attempts have been made to define
the pressure and response from human activities; to describe the
characteristics of the pattern, process, and service of ecosystems;
and to distinguish the external performance and internal metabolic
processes (Andersson et al., 2014; Ahern, 2013; Su, Fath, Yang,
Chen, & Liu, 2013). In this process, both physical indicators (soil
contamination, water pollution, and land-use/land cover) and socio-
economic indicators (population, economy, and management) are
measured and categorized (Zhang, Yang, & Yu, 2006; Su et al.,
2010). In the second group, land-use and land-cover change is
embedded in the urban ecosystem health assessment. Essentially,
land offers various services, such as food provision, energy, habitat,
accessibility, species diversity, and recreation, and hence occupies
an irreplaceable position in sustaining urban development (Chambers,
Simmons, & Wackernagel, 2014; Wackernagel et al.,
2004). In this sense, researchers have combined land-use structure
with its service and function to diagnose the urban ecosystem health
through empirical models and investigations (Yu et al., 2013). In the
context of rapid urbanization as well as widespread urban sprawl
and urban shrinkage, there is growing concern about maintaining
the land ecosystem health to realize a balanced urban ecosystem
(Großmann, Bontje, Haase, & Mykhnenko, 2013; Wu, Ye, Qi, &
Zhang, 2013). The third group considers the urban ecosystem as an
integration of the natural and artificial environment whose health
is largely reflected in its supply of eco-services to humans as well
as its ability to maintain their health (Xu & Xie, 2012). In this
group, more holistic frameworks including the vigor, structure, func-
tion, and resilience of the urban ecosystem are proposed, which also
highlight their spatiotemporal and multi-scale features (Su et al.,
2012b). In fact, these proposed approaches have already been ap-
p lied to typical cities such as Beijing, Shanghai, and Guangzhou
as well as urban clusters such as the Pearl River Delta and Yangzi
River Delta in China to diagnose the comprehensive health status
and to determine the limiting factors of the urban ecosystem (Li
et al., 2014; Su et al., 2013; Zhao & Chai, 2015).

In most cases, the common method for assessing urban ecosystem
health incorporates an index system and weight determination for a
final value that reflects the health status of each city. Previous research
has attempted to combine the advancements made in natural
ecosystem health assessment with the distinct features of urban areas.
Measures of vigor, structure, resilience, service function, population
health, and management have been integrated, whereas the link
between these components and socioeconomic activities is still weak.
The categorization of urban ecosystem health into subsystems directly
associated with population, economy, facility, transportation, land, and
management has still not been formulated. Weight determination has
been largely flexible, where the two mainstream subjective and
objective methods help determine contribution of each factor in
empirical studies. The assessment of urban ecosystem health requires
both methods when indicators are in a complex form, which can reduce
information redundancy and subjective bias. In addition, past attempts
of weight determination in city-related studies have neglected the
spatial effects in most cases despite urban development being a typical
spatiotemporal process.

In this study, we aimed to assess urban ecosystem health by
establishing a two-level indicator system associating ecosystem health with socioeconomic development. The information entropy,
Spatial Technique for Order Preference by Similarity to Ideal Solution (S-TOPSIS), and analytic hierarchy process (AHP) methods are
used to determine the weights in the process. These approaches
were applied to the newly categorized 13 megalopolises and
metropolises to evaluate their status quo and facilitate future
urban management.

2. Materials and methodology

2.1. Materials

Based on the new “city categorization standard” measured by
the number of permanent residents, Beijing, Tianjin, Shanghai, Guangzhou,
Chongqing, and Shenzhen have been categorized as the megalopolises
and Chengdu, Wuhan, Nanjing, Foshan, Dongwan, Xian, Shenyang,
Hangzhou, Harbin, and Hong Kong as the metropolises. For data
consistency and availability, we chose the 13 cities presented in Fig. 1
and Table 1 for the assessment of urban ecosystem health. Among
these 13 cities, Beijing and Hangzhou occupy the largest administrative
area; Chongqing has the largest population with >33 million in 2013; and
Beijing showed the highest gross domestic product (GDP) of
317.98 billion USD in 2013.

In the context of rapid urbanization, Beijing and Tianjin, as the
capital city and a rapidly developing zone, have improved their natural
resource utilization efficiency and contributed to the country’s economy
without compromising its own socioeconomic development (Wang &
Yang, 2015; Yu, Li, Jia, & Li, 2015). Nanjing, Shangai, and Hangzhou,
as typical cities in the Yangtze River Delta, have strictly controlled
the emission of pollutants to compensate for the eco-environmental
damage due to rapid industrialization and urbanization in recent years
(Li et al., 2014; Zhang & Gangopadhyay, 2015). Guangzhou and Foshan
are two representative cities in the Pearl River Delta that have seen
significant economic development and globalization, along with “low-
carbon and green development” (Li, Liang, Cockrell, Gibbins, & Reinier,
2012; Yang & Li, 2013). The remaining cities are located in the middle,
western, or northern regions of China, which slightly lag behind the
southeastern cities in terms of development. However, with the
national strategy of promoting the comprehensive development in
these areas, these cities have witnessed rapid development, with a
focus on building a resource-saving and environment-friendly society
(Zhang & Bao, 2015). Overall, all of these cities are pioneers of urban
and regional development but with various eco-environmental
problems, and the respective governments have taken several measures
to make improvements.

2.2. Methodology

2.2.1. Indicator system

Establishing an indicator system is one of the most important steps
of urban ecosystem health assessment. In general, indicators are
selected based on the principle of data acquisition, regionality, scientific,
representative, objectivity, and early warning (Ting & Qi, 2012). The
prerequisites for developing an indicator framework urban ecosystem
health assessment are categorized into two aspects. First, indicators
are organized in an integrated manner to strengthen the link between
natural ecosystems and human ecosystems. Factors representing
urban features are selected as comprehensively and systematically as
possible. Second, indicators must generally be easy to understand
and measure, as well as to regulate. The ultimate goal of urban ecological
assessment is the provision of guidelines for urban management. Highly
complex indicators can devalue the achievements in the assessment,
whereas pragmatic indicators provide comprehensive results for
further improvements to a city (Su et al., 2010).

Based on an extensive literature review, the urban ecosystem is
decomposed into six components, and a two-tier indicator system is
established in Table 2: (a) The social subsystem describes the growth
and living conditions of the population. X1 (population density), X2
(proportion of nonagricultural population), X3 (unemployment rate),
and X4 (natural population growth rate) are selected to indicate the
social structure. (b) The economic subsystem refers to a city’s vitality
and economic level. X5 (per-capita GDP), X6 (proportion of the added
value of the tertiary industry), X7 (proportion of the industrial added
value), X8 (average industrial output), X9 (worker average wage), and
X10 (investment in fixed assets per square kilometer) are selected to represent the economic structure and efficiency. (c) The transportation subsystem refers to the development of transportation to reflect the corresponding eco-environmental pressure as well as its service function. X11 (number of operating buses per square meter of road), X12 (urban per-capita road area), X13 (number of operating taxis per square meter of road), X14 (per-capita freight volume), and X15 (per-capita passenger volume) are selected. (d) The facility subsystem describes the consumption and service function of the urban ecosystem. X16 (water consumption per capita), X17 (electricity consumption per capita), X18 (gas consumption per capita), X19 (liquefied petroleum gas consumption per capita), X20 (per-capita green area), X21 (built-up area green coverage rate), and X22 (proportion of built-up area) are selected to reflect human utilization of natural resources. (e) The land subsystem represents the land-use structure to indicate the ecological services provided by the natural ecosystem. X23 (cropland percentage), X24 (forest cover percentage), X25 (grassland percentage), X26 (water area percentage), and X27 (unutilized land percentage) are selected to reflect the ecosystem resilience in terms of the structure of the landscape. (f) The management subsystem indicates the ability of human management to sustain long-term development. X28 (industrial wastewater treatment rate), X29 (industrial sulfur dioxide removal efficiency), X30 (industrial soot removal efficiency), X31 (comprehensive utilization rate of industrial solid waste), X32 (urban sewage treatment rate), and X33 (life garbage treatment rate) are selected to indicate systematic regulation.

2.2.2. Calculation of health state for subsystems

The urban ecosystem health assessment incorporates four steps, namely, standardization of the original data, weight determination, calculation of the subsystem score, and final urban ecosystem health assessment. First, the indicators are made dimensionless to realize the

### Table 1

| Megacity     | Geographical position | Area (km²) | Population (million) | GDP (billion USD) | Megalopolis/Metropolis |
|--------------|-----------------------|------------|----------------------|-------------------|-------------------------|
| Beijing      | North                 | 16,411     | 13.16                | 317.98            | Megalopolis             |
| Shanghai     | East                  | 6340       | 14.32                | 352.24            | Megalopolis             |
| Tianjin      | North                 | 11,760     | 10.04                | 234.32            | Megalopolis             |
| Chongqing    | Southwest             | 3303       | 33.58                | 251.44            | Megalopolis             |
| Guangzhou    | South                 | 7434       | 8.32                 | 147.59            | Metropolis              |
| Wuhan        | Middle                | 8494       | 11.88                | 148.53            | Metropolis              |
| Chengdu      | Southwest             | 12,132     | 6.43                 | 130.64            | Metropolis              |
| Nanjing      | East                  | 3798       | 3.82                 | 114.31            | Metropolis              |
| Foshan       | South                 | 10,108     | 8.07                 | 79.64             | Metropolis              |
| Xi’an        | Northwest             | 12,980     | 7.27                 | 116.73            | Metropolis              |
| Shenyang     | Northeast             | 16,596     | 7.07                 | 136.05            | Metropolis              |
| Hangzhou     | East                  | 53,068     | 9.95                 | 81.81             | Metropolis              |

Note: The exchange rate from RMB to USD is 6.1327 (retrieved on 6 April 2015).
| Ecological health | Socioeconomic system | Indicator | Reference sources |
|------------------|----------------------|-----------|-------------------|
| Structure and Population health | Social system | Population density (x1) | Colin (1997); Zhong and Peng (2003); Zeng et al. (2005); Ting & Qi (2012) |
| | | Population density of nonagricultural population (x2) | |
| | | Unemployment rate (x3) | |
| | | Natural population growth rate (x4) | |
| Structure and Vigor | Economy system | Per-capita GDP (x5) | Takano & Nakamura (1998), Guo et al. (2002), Zhong & Peng (2003) |
| | | Proportion of the added value of the tertiary industry (x6) | |
| | | Proportion of the added value of the secondary industry (x7) | |
| | | Average Industrial output (x8) | |
| | | Worker average wage (x9) | |
| | | Investment in fixed assets per square kilometer (x10) | |
| Function and Service | Transportation system | Number of operating buses per square meter of road (x11) | Ting & Qi (2012), Li & Li (2014), Zhang et al. (2008), Shi & Yang (2014) |
| | | Urban per-capita road area (x12) | |
| | | Number of operating taxis per square meter of road (x13) | |
| | | Per-capita freight volume (x14) | |
| | | Per-capita passenger volume (x15) | |
| Function and Service | Facility system | Water consumption per capita (x16) | |
| | | Electricity consumption per capita (x17) | Ting & Qi (2012), Li & Li (2014), Zhang et al. (2008), Shi & Yang (2014) |
| | | Gas consumption per capita (x18) | |
| | | Liquefied petroleum gas consumption per capita (x19) | |
| | | Per-capita green area (x20) | |
| | | Built-up area green coverage rate (x21) | |
| | | Proportion of built-up area (x22) | |
| Structure and Resilience | Land system | Cropland percentage (x23) | Douglas, I. (2012), Zeng et al. (2005), Cheng et al. (2011), Su & Fath (2012) |
| | | Forest cover percentage (x24) | |
| | | Grassland percentage (x25) | |
| | | Water area percentage (x26) | |
| | | Unutilized land percentage (x27) | |
| Function and Maintenance | Management system | Industrial wastewater treatment rate (x28) | Guo et al. (2002), Ting & Qi (2012), Costanza (2012), Li & Li (2014) |
| | | Industrial sulfur dioxide removal efficiency (x29) | |
| | | Industrial soot removal efficiency (x30) | |
| | | Comprehensive utilization rate of industrial solid waste (x31) | |
| | | Urban sewage treatment rate (x32) | |
| | | Life garbage treatment rate (x33) | |

Note: Indicators in gray imply its negative attributes.
comparability for both positive and negative indicators. Hence, maximum–minimum normalization arithmetic is used to convert the original data into the standard dataset within the range of 0–1. Weight determination is a key issue where strengths and weaknesses are found for either objective or subjective methods to obtain the weights of the indicators. At the bottom level of our indicator system, a total of 30 indicators are found in six subsystems, and information redundancy is inevitable. The entropy method can eliminate anthropogenic interference with the weight calculation of each indicator (Li & Li, 2014). As a result, we choose the entropy method to determine the weight of the indicators at the second level except for the land subsystem. The weights of the indicators in the land subsystem were determined in terms of the eco-services calculated by Costanza et al. (1997) and adjusted by Cheng et al. (2011) because land, an important form of resilience for natural ecosystems, is directly linked to urban ecosystem service. Standard values for comparison are needed for the six subsystems; thus, we add the weighted indicators in the subsystem, as specified in Eq. (1):

$$S_k = \sum_{i=1}^{n} w_i \times y_{ij}$$  \hspace{1cm} (1)

where $S_k$ is the summed score for the $k$th subsystem ($k = 1, \ldots, 6$), $w_i$ is the weight of the $i$th indicator, and $y_{ij}$ the standardized value of the corresponding indicator.

### 2.2.3. Weight given by spatial TOPSIS and final urban ecosystem health state

To obtain the weights of the six subsystems, we develop an S-TOPSIS combined with AHP to revise the final outcome. TOPSIS, developed by Hwang and Yoon (1981), is widely used for multiple attribute decision making. In TOPSIS, the chosen decision should be nearest to the positive-ideal solution and farthest from the negative-ideal solution (Chen & Tsoa, 2008). Many previous studies involve the TOPSIS theory and its applications, with the two mainstreams of quality assessment and site selection. Urban ecosystem health assessment is also a multiple-attribute decision-making issue. Basically, the prerequisite for TOPSIS is obtaining performance data for $n$ alternatives over $k$ criteria (Olson, 2004). Our study includes 13 megacities to formulate the “alternatives” and six normalized values for subsystems to represent the criteria, which conform to the conditions in TOPSIS. The study also takes the geography weight into account because urban development is a spatial process in itself and the neighboring cities still produce a remarkable effect. TOPSIS can accommodate this variable as the distance can be extended to include spatial relation in addition to any discrepancy in the attributes. Deng, Yeh, and Willis (2000) addressed the interdependence of the financial ratios in the intercompany comparison before and modified TOPSIS. In urban studies, city development is a typical spatiotemporal process where spatial effects cannot be neglected. One of the steps in TOPSIS is developing a distance over each criterion to both the ideal ($D^+$) and nadir ($D^-$). This step helps reflect the spatial influences because the Euclidean distance between the city and the ideal or the nadir can be embedded. Specifically, the weights for the subsystems by spatial TOPSIS are calculated in Eqs. (2)–(7):

The best solution state: $A^+ = (S_1^+, S_2^+, \ldots, S_k^+)$

The worst solution state: $A^- = (S_1^-, S_2^-, \ldots, S_k^-)$

The Euclidean distance between the jth city and the city in the ideal and the worst solution for the $k$th subsystem for the jth city is given as follows:

$$D^+_{jk} = \sqrt{(x_j - x_{jk}^+)^2 + (y_j - y_{jk}^+)^2}$$  \hspace{1cm} (2)

$$D^-_{jk} = \sqrt{(x_j - x_{jk}^-)^2 + (y_j - y_{jk}^-)^2}$$  \hspace{1cm} (3)

$$w_{jk} = \frac{D^+_{jk}}{\sum_{j=1}^{m} D^+_{jk}}$$

$\sum_{j=1}^{m} D^-_{jk}$  \hspace{1cm} (4)

where $D^+_{jk}$ is the distance to the ideal solution, $D^-_{jk}$ is the distance to the worst solution for the jth city, and $DIST_{jk}$ is the sum of distances from the jth city to all other cities:

$$C_{ij} = \frac{D^+_{ij}}{D^+_{ij} + D^-_{ij}}$$  \hspace{1cm} (5)

where $D^+_{ij}$ is the spatially weighted distance of the city to the best solution state, $D^-_{ij}$ is the spatially weighted distance of the city to the worst solution state, and $C_{ij}$ is the final outcome of the ith city as determined by S-TOPSIS.

However, the division of the urban ecological health system into these six components is subjective to some degree, which requires expertise to guarantee the accuracy of the outcome. Thus, we also use AHP to calculate the final value of urban ecosystem health for the 13 cities and obtain the value of each city as $C_{ij}$. Finally, the average of $C_{ij}$ from spatial TOPSIS and $C_{ij}$ from AHP generates the final scores representing the urban ecosystem health of the 13 megacities.

### 3. Results

#### 3.1. Statistics of the Indicators

Table 3 presents the maximum and minimum values of all variables in the urban ecosystem health assessment for the 13 cities in 2005 and 2010. For variables such as population density ($\times 1$), investment in fixed assets per square kilometer ($\times 10$), and proportion of built-up land area ($\times 22$), Shanghai had the highest values and Harbin the least in both 2005 and 2010. Foshan showed 100% nonagricultural population ($\times 2$) whereas Chongqing had the lowest proportion. Chongqing also showed a minimum unemployment rate ($\times 3$), per-capita GDP ($\times 5$), and water consumption per capita ($\times 16$) in 2005 and 2010. With respect to industrial development, Beijing had the highest proportion of the added value of the tertiary industry ($\times 6$) but the lowest of the secondary industry ($\times 7$), whereas the values in Foshan were the opposite. Nanjing had the lowest number of operating busses per square meter of road ($\times 11$) and the highest number of operating taxis per square meter of road ($\times 13$). Guangzhou had the highest per-capita freight volume ($\times 14$) but the lowest per-capita passenger volume ($\times 15$). In terms of electricity consumption per capita ($\times 17$), gas consumption per capita ($\times 18$), liquefied petroleum gas consumption per capita ($\times 19$), and per capita green area ($\times 20$), Foshan, Nanjing, Chengdu, and Guangzhou showed the maximum values, respectively, in both 2005 and 2010. With respect to land use, Hangzhou had the smallest proportion of cropland ($\times 23$) and the largest proportion of forestland ($\times 24$). Shanghai had the least percentage of forestland ($\times 24$), grassland ($\times 25$), and unutilized land ($\times 27$). However, Harbin had the lowest rates of industrial wastewater treatment ($\times 28$), industrial sulfur dioxide removal efficiency ($\times 29$), urban sewage treatment ($\times 32$), and
life garbage treatment (×33). Tianjin and Nanjing had the highest values of industrial wastewater treatment rate (×28) and industrial sulfur dioxide removal efficiency (×29) for both years.

The variance ratio reflects the gaps among these cities, which is calculated by dividing the variance by the mean value of each variable. The greatest gaps were observed in the unemployment rate (×3), industrial wastewater treatment rate (×28), and industrial soot removal efficiency (×30) for both years.

The variance ratio of the industrial soot removal efficiency (×30) increased from 502 in 2005 to 9823 in 2010. Conversely, gas consumption per capita (×18) differed the least from 2005 to 2010. Chongqing and Harbin were found to have the lowest value in 2005, whereas Harbin had the lowest value in 2010. Based on the AHP results, Nanjing ranked first in 2005 and Guangzhou rose from second place in 2005 to first in 2010. Chongqing and Harbin were found to have the lowest value in both 2005 and 2010. When the values from both methods were integrated, Nanjing still ranked first in 2005 and Guangzhou rose from second place in 2005 to first in 2010. Chongqing and Harbin were found to have the lowest value in both 2005 and 2010. When the values from both methods were integrated, Nanjing still ranked first in 2005 with a value of 0.55 and 0.50, followed by Guangzhou in second place in 2010. Both of which were followed by Hangzhou. Chongqing had the lowest value in 2005, whereas Harbin had the lowest value in 2010. Based on the AHP results, Nanjing ranked first in 2005 and Guangzhou rose from second place in 2005 to first in 2010. Chongqing and Harbin were found to have the lowest value in both 2005 and 2010. When the values from both methods were integrated, Nanjing still ranked first in 2005 with a value of 0.55 and 0.50, followed by Guangzhou in second place. The gaps among all the cities were markedly reduced, although the high-valued cities showed a decline in urban ecosystem health.

3.2 Urban ecological health

Fig. 2 presents the values of the six subsystems for the 13 cities, which differed slightly from 2005 to 2010. Most subsystems were superior in Beijing, Shanghai, and Tianjin, except for the land subsystem, which showed a small decline. The social subsystem in Wuhan and Nanjing improved from 0.56 to 0.87 and from 0.67 to 0.91, respectively; although Wuhan showed positive development, it showed a decline in the management subsystem. Xi’an, Shenyang, and Hangzhou showed distinct advancements in the social subsystem; however, slight changes were noted in the transportation, facility, and land subsystems. In general, the values of the facility and land subsystems were comparatively low, whereas the social subsystem was superior in Beijing and Shanghai, indicating high pressure from energy and resource utilization, as well as a high standard of population health. The transportation subsystem in Tianjin, Chongqing, Wuhan, Chengdu, Shenyang, and Harbin, produced a benign effect on the urban ecosystem health, whereas the vigor of the economic subsystem lagged behind in Chongqing, Xi’an, and Harbin. Conversely, the economic vigor was prominent in Guangzhou, as was its self-regulation capability in the management subsystem. Noticeably, the value of the management subsystem is the lowest, indicating the need to improve the regulation efficiency.

3.3 Overall ranking of the megacities

Fig. 3 presents the urban ecosystem health values for 2005 and 2010 calculated from S-TOPSIS, AHP, and the integrated method. With weight determination by S-TOPSIS, Nanjing was found to have the highest value in 2005 and Beijing in 2010, both of which were followed by Guangzhou. Chongqing had the lowest value in 2005, whereas Harbin had the lowest value in 2010. Based on the AHP results, Nanjing ranked first in 2005 and Guangzhou rose from second place in 2005 to first in 2010. Chongqing and Harbin were found to have the lowest value in both 2005 and 2010. When the values from both methods were integrated, Nanjing still ranked first in 2005 with a value of 0.55 and 0.50, followed by Guangzhou in second place. The gaps among all the cities were markedly reduced, although the high-valued cities showed a decline in urban ecosystem health.

4 Discussion

In addition to the rapid urbanization in recent years, the urban ecosystem is under great pressure from various eco-environmental problems (Deng, Huang, Rozelle, Zhang, & Li, 2015). Megacities serve not only as drivers of socioeconomic progress but urban ecosystem problems as well, reflecting the characteristics and effects of such problems (Su et al., 2012a). The newly categorized megalopolises and metropolises are ideal for assessing the urban ecosystem health, for comparing the negative impacts of anthropogenic activities, and for...
Fig. 2. Radar maps of the urban sub-ecosystem health values for the 13 cities in 2005 and 2010.
proposing recommendations for improvement (Chen, Chen, & Fath, 2014). Here, we use these 13 megalopolises and metropolises to illustrate our assessment of urban ecosystem health, which offers two main contributions.

The first contribution of the study is the established extended indicator system for urban ecosystem assessment. The indicator system is chosen depending on the complexity of the link between socioeconomic activities and the ecological environment (Li & Li, 2014). The health of the population, vigor, service function, resilience, and eco-management are represented by the social, economic, transportation, facility, land, and management subsystems for further insight into the pattern, process, and service of the urban ecosystem (Su et al., 2013). As a result, we divide the urban ecosystem into six socioeconomic subsystems to formulate the basic framework for the assessment. The use of various indicators to represent the health of each subsystem has certain limitations due to data representativeness and accessibility, scientific value, and objectivity. In total, we choose 33 indicators with each subsystem comprising four to seven indicators. Except for the land subsystem, all other indicators are retrieved from the City Statistical Yearbook, which guarantees consistency. The land-use data are interpreted from the remotely sensed images from the Chinese Academy of Sciences with a 1-km grid for increased accuracy and time (Liu, Liu, Zhuang, Zhang, & Deng, 2003; Liu et al., 2010). In fact, the urban ecosystem health assessment, in itself, is an integrated process that necessitates the incorporation of various data sources and indicator types in the future. Undoubtedly, the indicator system is not ideal, but it can be easily applied to other cities in China or even across the world.

The second contribution of our approach is the use of S-TOPSIS in determining the weights of the six subsystems. Generally, TOPSIS is used to determine the merit of schemes and the ranking of candidate schemes by measuring the distances between each scheme and the best or worst solutions (Chen, 2000). However, distance is not only a parameter measured by attribute but also a geographical term, especially when addressing urban-related problems (Dickinson, 2013). When...
the 13 metropolises or megalopolises are considered candidates for ranking, the distances among them directly influence their socioeconomic development and eco-environmental management because of the spatial effects of urban development. Therefore, we consider a spatially adjusted distance embedded in TOPSIS, which is calculated based on the Euclidean distance from the candidate city to the city in the “ideal” or the “wretched” situation. S-TOPSIS takes the spatial interaction of cities into account to determine the weights with greater accuracy. Traditional AHP is also used to demonstrate the effects of subjective results of each subsystem on the urban ecosystem health. The final integrated value that represents the urban ecosystem health state is obtained by incorporating values from both subjective and objective methods in line with the actual situation. We use the information entropy method to determine the weights of 28 indicators for the five subsystems because of the information efficiency; we also use the estimated ecosystem value of each land-use type to determine the weights in the land subsystem at this level. S-TOPSIS can also be applied to other multiple-attribute decision-making problems, particularly in urban studies, in the case of interdependence or spatial effects. In general, weight determination methods are considered flexible although the ways of adjusting or improving upon these methods require extensive study.

By assessing the urban ecosystem health in 13 megalopolises and metropolises in 2005 and 2010, we reveal that the strengths and weaknesses of all the cities show regional characteristics. With respect to social and economic subsystems, metropolises such as Beijing, Shanghai, and Guangzhou are superior to cities in western and northern regions of China such as Chongqing, Chengdu, and Xian. On the contrary, these cities place low-power levels on the urban ecosystem with respect to transportation. Both Guangzhou and Nanjing had the highest values in the facility and management subsystems. For the land subsystem, Foshan showed the most favorable land ecological service, followed by Wuhan, which is largely attributed to their physical environments. Nanjing and Beijing were ranked the top two in terms of the integrated value in 2005 and 2010, respectively. Not all indicators involved can help realize a better urban ecosystem, but they still provide a reference point for making specific regulations to control human activity and improve eco-environment management.

5. Conclusion

In this study, we apply an integrated approach to assess the urban ecosystem health in 13 newly defined megalopolises and metropolises in China in 2005 and 2010, respectively. The major contributions and conclusions can be summarized as follows.

First, we categorize urban ecosystem health system into six subsystems and establish a two-layer indicator system for the assessment. In total, we choose 33 indicators grouped into social, economic, transportation, facility, land, and management subsystems, with the aim of associating human activities with the health, vigor, and resilience of the urban ecosystem.

Second, we integrate the subjective and objective methods to determine the weights at different levels using S-TOPSIS, AHP, and information entropy. In particular, we develop an S-TOPSIS technique by introducing a Euclidean-distance-based weight to rank the cities based on the six subsystems and the varying spatial effects.

The results reveal that, in general, megalopolises such as Beijing, Shanghai, and Guangzhou have superior social and economic subsystems, whereas other megacities show advanced transportation, facility, land, and management subsystems. The gaps among these cities in terms of urban ecosystem health significantly reduced from 2005 to 2010 regardless of the method of weight determination. In the future, each subsystem can be improved upon for the ultimate goal of better urban ecosystem health for these megalopolises and metropolises.

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References

Ahern, J. (2013). Urban landscape sustainability and resilience: The promise and challenges of integrating ecology with urban planning and design. Landscape Ecology, 28(6), 1202–1212.

Andersson, E., Barthel, S., Borgström, S., Colding, J., Elmqvist, T., Folke, C., & Gren, A. (2014). Reconnecting cities to the biosphere: Stewardship of green infrastructure and urban ecosystem services. Ambio, 43(4), 445–453.

Chambers, N., Simmons, C., & Wackernagel, M. (2014). Sharing nature’s interest: Ecological footprints as an indicator of sustainability. Routledge.

Chen, C. T. (2000). Extensions of the TOPSIS for group decision-making under fuzzy environment. Fuzzy Sets and Systems, 114(1), 1–9.

Chen, T. Y., & Tsao, C. Y. (2008). The interval-valued fuzzy TOPSIS method and experimental analysis. Fuzzy Sets and Systems, 159(11), 1410–1428.

Chen, B., & Wang, R. (2014). Integrated ecological indicators for sustainable urban ecosystem evaluation and management. Ecological Indicators, 47, 1–4.

Chen, S., Chen, B., & Fath, B. D. (2014). Urban ecosystem modeling and global change: Potential for rational urban management and emissions mitigation. Environmental Pollution, 190, 139–149.

Cheng, L., Li, F., & Deng, H. F. (2011). Dynamic of land use and its ecosystem services in China’s megacities. Acta Ecologica Sinica, 31(20), 6194–6203.

Costanza, R., d’Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O’Neill, R. V., Paruelo, J., & Raskin, R. G. (1997). Sutton, P., van den Belt, M. The value of the world’s ecosystem services and natural capital. Nature, 387(6630), 253–260.

Deng, H., Yeh, C. H., & Willis, R. J. (2000). Inter-company comparison using modified TOPSIS with objective weights. Computers & Operations Research, 27(10), 963–973.

Deng, X., Huang, J., Rozelle, S., Zhang, J., & Li, Z. (2015). Impact of urbanization on cultivated land changes in China. Land Use Policy, 45, 1–7.

Dickson, R. E. (2013). City, region and regionalism: A geographical contribution to human ecology. Routledge.

Dzidzorgu, D., Yigitcanlar, T., & Dawes, L. A. (2010, August). Assessing the sustainability of urban ecosystems: An innovative approach. Proceedings of the 44th IBPS Conference. Vol. 1, pp. 545–559.

Fang, C. L. (2014). A review of Chinese urban development policy, emerging patterns and future adjustments. Geographical Research, 33(4), 674–685 (In Chinese).

Grafmann, K., Bonjte, M., Haase, A., & Mykhnenko, V. (2013). Shrinking cities: Notes for the further research agenda. Cities, 35, 221–225.

Hwang, C. L., & Yoon, K. (1981). Lecture notes in economics and mathematical systems. Multiple Objective Decision Making. Methods and Applications: A State-of-the-Art Survey (pp. 164).

Jiang, M. M., & Chen, B. (2011). Integrated urban ecosystem evaluation and modeling based on embodied cosmic energy. Ecological Modelling, 224, 2149–2165.

Li, Y., & Li, D. (2014). Assessment and forecast of Beijing and Shanghai’s urban ecosystem health. Science of the Total Environment, 467, 154–161.

Li, J., Liang, X., Cockerill, T., Gibbins, J., & Reiner, D. (2012). Opportunities and barriers for implementing CO2 capture ready designs: A case study of stakeholder perceptions in Guangdong, China. Energy Policy, 45, 243–251.

Li, Q., Song, J., Wang, E., Hu, H., Zhang, J., & Wang, Y. (2014). Economic growth and pollutant emissions in China: A spatial econometric analysis. Stochastic Environmental Research and Risk Assessment, 28(2), 429–442.

Liu, J., Liu, M., Zhou, D., Zhang, Z., & Deng, X. (2003). Study on spatial pattern of land-use change in China during 1995–2000. Science in China Series D: Earth Sciences, 46(4), 373–384.

Liu, J., Zhan, J., & Deng, X. (2005). Spatio-temporal patterns and driving forces of urban land expansion in China during the economic reform era. Ambio, 34(6), 450–455.

Liu, J., Zhang, Z., Xu, X., Kuang, W., Zhong, W., Zhou, W., & Jang, N. (2010). Spatial patterns and driving forces of land use change in China during the early 21st century. Journal of Geographical Sciences, 20(4), 483–494.

Liu, G. Y., Yang, Z. F., Chen, B., & Zhang, Y. (2011). Ecological network determination of sectoral linkages, utility relations and structural characteristics on urban ecological-economic system. Ecological Modelling, 222(15), 2825–2834.

Olson, D. L. (2004). Comparison of weights in TOPSIS models. Mathematical and Computer Modelling, 40(7), 721–727.

Pickett, S. T. A., Cadenasso, M. L., Grove, J. M., Boone, C. G., Grafmann, P. M., Irwin, E., & Warren, P. (2011). Urban ecological systems: Scientific foundations and a decade of progress. Journal of Environmental Management, 92(3), 331–362.

State Council (2014). Notice of the State Council on adjusting the standards for categorizing city sizes.

Su, M., Fath, B. D., & Yang, Z. (2010). Urban ecosystem health assessment: A method and application. Procedia Environmental Sciences, 13, 1134–1142.
Su, M., Yang, Z., Chen, B., Liu, G., Zhang, Y., Zhang, L., & Zhao, Y. (2012b). Urban ecosystem health assessment and its application in management: A multi-scale perspective. *Entropy, 15*(1), 1–9.

Su, M., Fath, B. D., Yang, Z., Chen, B., & Liu, G. (2013). Ecosystem health pattern analysis of urban clusters based on energy synthesis: Results and implication for management. *Energy Policy, 59*, 600–613.

Ting, Z., & Qi, Y. (2012). The urban land ecosystem health evaluation in Chengdu City. *Earth Science Research, 1*(2), 297.

Wackernagel, M., Monfreda, C., Schulz, N. B., Erb, K. H., Haberl, H., & Krausmann, F. (2004). Calculating national and global ecological footprint time series: Resolving conceptual challenges. *Land Use Policy, 21*(3), 271–278.

Wang, Z., & Yang, L. (2015). Delinking indicators on regional industry development and carbon emissions: Beijing–Tianjin–Hebei economic band case. *Ecological Indicators, 48*, 41–48.

Wu, K. Y., Ye, X. Y., Qi, Z. F., & Zhang, H. (2013). Impacts of land use/land cover change and socioeconomic development on regional ecosystem services: The case of fast-growing Hangzhou metropolitan area, China. *Cities, 31*, 276–284.

Xu, L., & Xie, X. (2012). Theoretic research on the relevant concepts of urban ecosystem carrying capacity. *Procedia Environmental Sciences, 13*, 863–872.

Yu, G., Yu, Q., Hu, L., Zhang, S., Fu, T., Zhou, X., ... Jia, H. (2013). Ecosystem health assessment based on analysis of a land use database. *Applied Geography, 44*, 154–164.

Yu, C., Li, H., Jia, X., & Li, Q. (2015). Improving resource utilization efficiency in China’s mineral resource-based cities: A case study of Chengde, Hebei province. *Resources, Conservation and Recycling, 94*, 1–10.

Zhang, W., & Bao, S. (2015). Created unequal: China’s regional pay inequality and its relationship with mega-trend urbanization. *Applied Geography, 59*, 600–613.

Zhang, J., & Gangopadhyay, P. (2015). Dynamics of environmental quality and economic development: The regional experience from Yangtze River Delta of China. *Applied Economics, 1–11* (ahead-of-print).

Zhang, Y., Yang, Z., & Yu, X. (2006). Measurement and evaluation of interactions in complex urban ecosystem. *Ecological Modelling, 196*(1), 77–89.

Zhang, X. C., Ma, C., Zhan, S. F., & Chen, W. P. (2012). Evaluation and simulation for ecological risk based on energy analysis and pressure-state-response model in a coastal city, China. *Procedia Environmental Sciences, 13*, 221–231.

Zhao, S., & Chai, L. (2015). A new assessment approach for urban ecosystem health basing on maximum information entropy method. *Stochastic Environmental Research and Risk Assessment, 1–13.*