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Abstract: The urban composite ecosystem was broken down into three daughter systems of nature, economics, and society to prevent the uncertainty of results arising from the disagreement of assessment indices. In addition, the traditional method for emergy analysis was improved and integrated with the fuzzy clustering model in order to provide a new method for the proper evaluation of the health of urban ecosystems from the perspective of energy-material coupling. With this new method, the health of urban ecosystem in Changchun, China was evaluated. Results showed that by continuously adjusting the energy structure, the industry structure, and the development mode, the urban ecosystem of Changchun City gradually transitioned from the unhealthy to the healthy status. However, a membership value of only 0.77 indicated the weak health of the ecosystem where the environmental load rate gradually increased every year. Emergy analysis using the fuzzy clustering integration model demonstrated the whole health status of urban composite systems with a certain degree of operability and replicability.

Keywords: ecosystem; health evaluation; environmental load rate; evaluation system; China.

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1 Introduction

The research about ecosystem health started in North America in the 1980s (Li et al., 2008; Schaeffer and Cox, 1992; Karr et al., 1986; Costanza et al., 1992; Gautam et al., 2014). According to D.J. Rapport, a healthy ecosystem is that with no diseases and symptoms and able to support a sustainable development. Thus, these types of ecosystems remain active with time, are organised, independent, and able to recover after facing external stress (Rapport, 1989). Urban ecosystems, which combine nature, society, and economy, are strongly disturbed by human activities. The comprehensive evaluation of ecosystem sustainability can be used to determine the degree of health of the system, as well as identify potential hazards. Thus, proper procedures should be adopted for the management and protection of ecosystem health (Xiao et al., 2003; Zhang et al., 2005).

In 'International Ecosystem Health Meeting – The Management of Ecosystem Health' (1999), the lack of proper technologies for the evaluation of ecosystem health was listed as one of the key problems. Thus, health ecosystem evaluation has gradually become one new research area. Currently, the development of the proper index system and the design of a suitable model are the primary methods used to assess ecosystem health status. System dynamics uses feedback control theory and computer simulation. These tools are combined with ecological footprint theory and geographic information system to perform research on regional economy, environment, and industrial systems (Björklund et al., 2001; Azlina and Yaziz, 2020). Vega-Azamar et al. (2013) evaluated urban environmental sustainability of Montreal Island in Canada using emergy analysis. Usón et al. (2011) evaluated the sustainability of development of urban composite ecosystems using the ecological efficiency analysis model. Zeng et al. (2005) applied the fuzzy optimisation model to perform the time sequence evaluation of urban ecosystem health of Shanghai. Li et al. (2010) selected the grey system theory to determine the relationship between the change of precipitation in the arid ecosystem and water utilisation by plants.

Emergy analysis was proposed by H.T. Odum in 1980s (Odum, 1988). Emergy refers to the contained or needed energy of a given energy category for the production of a certain energy category. Odum further explained emergy in economic systems. Herein, the possessed emergy is the total quantity of energy (Jansson et al., 1995). Using the concept of emergy module as well as the transformation unit – the emergy transformation rate – emergy analysis can be used to determine the transformation of energy and materials in economic systems. Using quantitative analysis, the evaluation of the utilisation of natural resources in ecosystems was conducted. Also, the sustainability of the development was estimated, thus providing scientific reference for the formulation of economic policies. Emergy transformation rate, which can be used for emergy analysis in macro regions, was roughly estimated by Odum and later accepted by many researchers. Brown and Ulgiati (1999) indicated that the quotient between the systemic emergy yield rate (EYR), which evaluates the systemic yield efficiency, environmental pressure, and environmental load rate (ELR), can be used to calculate the sustainable performance of the system. In 1997, Dhifallah applied this theory to estimate the emergy of agricultural ecosystems in Tunisia in 1991. In order to understand the value of water resources in different environments, Björklund calculated the energy level structure. Johanna, Ulrika, and Torbjörn also calculated the emergy input of various resources during wastewater treatment processes to confirm the economic value and feasibility of the system (Björklund et al., 2001).

Recently, fuzzy mathematical methods were used to evaluate ecosystem health. The corresponding theoretical foundation included the transformation from qualitative evaluation to quantitative evaluation using fuzzy membership functions. A whole evaluation was obtained for the object confined by different factors. Because of strong systematisation, fuzzy problems were solved. However, quantification was difficult and in consequence, it was not suitable for the solution of uncertain problems (Shear, 1996; Xu et al., 2005; Lyons et al., 2000). The basic idea was as follows. First, the fuzzy comprehensive evaluation indexes were constructed. Later, the weight vector was constructed process method. Then, the appropriate membership function was determined in order to further establish the evaluation matrix. Finally, the appropriate composition factors were adopted. In addition, the resulting vector was explained, demonstrating the health grade of the ecosystem.

Although emergy analysis can be used as a standard and conversion unit to measure natural resources in the urban ecosystem, the accuracy of its calculation is poor, and fuzzy mathematics is not able to solve this problem. At present, emergy analysis with the fuzzy mathematics coupling method has not been used to analyse the sustainability of urban ecosystems. Therefore, in the present research, these two methods were combined to create a model that can be used to evaluate the sustainability of urban ecosystems.

2 Material and methods

2.1 The profile of the studied area

Changchun City is located 43°05′–45°15′N and 124°18′–127°05′E in the middle latitude of the northern hemisphere and belongs to the North temperate zone. Changchun is located in the northeast of China, the geographical centre of the northeast, bordering Songyuan, Siping, Jilin and Harbin respectively, and is the central city of the Northeast Asian economic circle with a total population of 7.538 million. Land area of which administrative boundary is 20.59353 thousand square kilometres, among which 18,246 km^2 correspond to farmland. Changchun displays a humid hill-land zone in the eastern area and a semi-arid plain zone in the western area. Thus, it presents a temperate continental humid climate. In this region, the Dahei Mountains run from northeast to southeast. Changchun is irrigated by the Songhua River, Yinma River, and the middle and lower reaches of the Yitong River. Also, Changchun City reported a gross regional product of 663.803 billion Yuan. This amount increased by 3.6% in 2020. Also, the first industry reported profits for 55.382 billion Yuan with a decrease of 2.4%. In addition, the second industry reported profits for 275.812 billion Yuan with an increase of 8%. In the case of the third industry (334.609 billion Yuan) the increase was of 0.3%.

2.2 Raw data sources

The annual data of natural environment and economic social development in Changchun City were used in this work. Including energy, resources and environment, industry, agriculture, fixed asset investment and population. The *Statistical Yearbook of China*

(2001–2011) and the *Statistical Yearbook of Changchun City* (2001–2011) were the sources of information.

2.3 The study method

2.3.1 The improved emergy analysis method

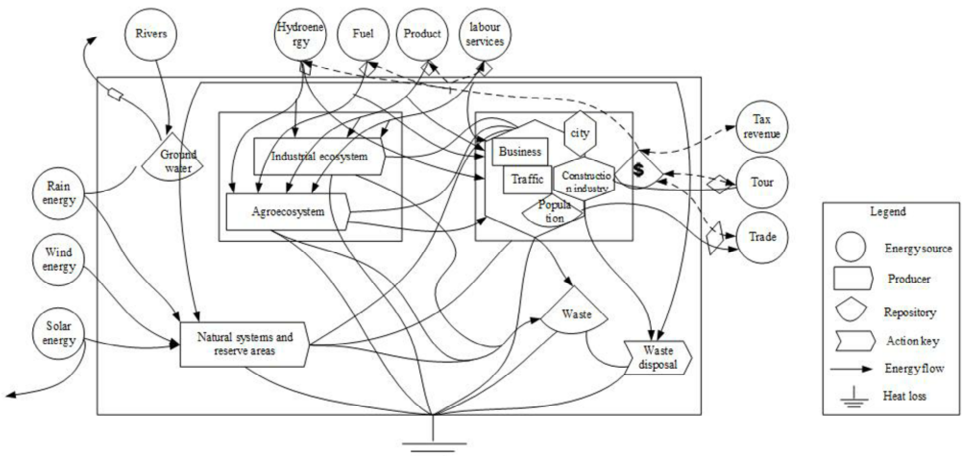
The emergy index system was established considering the findings of Odum (1988) and Ma and Wang (1984). The urban ecosystem was divided into three categories including nature, economy, and society. Also, six secondary indexes were setup in parallel, including the emergy flow index, the emergy source index, and the comprehensive index. The tertiary index, which provided city characteristics, was setup below these six secondary indexes. In addition, the sustainable development index was included according to the Odum theory to evaluate the development of the composite ecological economic system of Changchun was evaluated. The results of every index are shown in Table 1.

Table 1 Emergy evaluation of ecosystem in Changchun City

Index		*Calculating formula*
Emergy flow index	Renewable emergy (R, *sej*)	
	Nonrenewable emergy (N, *sej*)	
	Input emergy (I, *sej*)	
	Output emergy (O, *sej*)	
	Total used emergy (U, *sej*)	$U = R + N + I$
Emergy source index	Emergy self-support ratio (ESR, %)	$ESR = (R + N)/U$
	Renewable emergy ratio (RER, %)	$RER = R/U$
Social system evaluation	Emergy per person (EPP, $sej \cdot cap^{-1}$)	$EPP = U/P$
	Emergy per area (EPA, $sej \cdot m^{-2}$)	$EPA = U/area$
	Population carrying capacity (PCC_{up})	$PCC_{up} = 8PCC_{down}$
	Population carrying capacity (PCC_{down})	$PCC_{down} = (R/U)P$
Economic system	Emergy yield ratio (EYR)	$EYR = U/I$
	Emergy and dollar ration (F, $sej \cdot \$^{-1}$)	$f = U/GDP$
	Emergy exchange ration (EER)	$EER = (I + N)/R$
Natural system evaluation	Emergy waste ratio (EWR)	$EWR = W/U$
	Emergy loading ratio (ELR)	$ELR = (I + N)/R$
	Emergy waste (W, *sej*)	
Composite index	Emergy sustainable index (ESI)	$ESI = EYR/ELR$
	Emergy index for sustainable development ($EISD$)	$EISD – EYR \times EER/ELR$

The emergy flow diagram of Changchun urban composite ecosystem was built using the emergy analysis of the ecological, economic, and social subsystems of Changchun urban composite ecosystem (Figure 1). The urban complex ecosystem of Changchun includes the natural ecosystem subsystem, agricultural ecosystem subsystem, industrial ecosystem subsystem, transportation, tourism, trade, and other socio-economic subsystems.

Figure 1 Emergy flow diagram of Changchun urban ecosystem



Herein, the relevant emergy flow in Changchun from 2000 to 2010 was calculated using the emergy analysis, index system, and emergy flow diagram of Changchun urban composite ecosystem.

This method uses the law of conservation of energy to express the total amount of energy invested in a product, service or process. In order to accurately measure material flow, energy flow, the emergy analysis converts different types of substances, energy, and services present in the urban metabolic system into the same standard energy.

2.3.2 Fuzzy evaluation index system

Urban ecosystem was the composite open system comprised by the three subsystems nature, economy, and society. According to the system theory, open systems always exchange materials, energy, and information with the external environment. However, traditional evaluations of ecosystem health have been based on five aspects including activity, resilience, development power, organisation structure, and the maintenance of the ecosystem service function (Rapport, 1998; Rapport et al., 1998). Nevertheless, this kind of evaluation does not consider the energy exchange between the system and the external environment. This situation leads to the possible deviation between the final result and the real health status of the composite ecosystem. Thus, when designing fuzzy evaluation indexes, the wholeness, adaptability, and efficiency of the ecosystem should be considered (Kong et al., 2002).

In the present work, we considered the characteristics of different subsystems of the urban composite ecosystem and combined the emergy evaluation index with the health index of the traditional ecosystem. Thus, the index system was established considering these five aspects.

Fuzzy mathematics is a mathematical method that can be used to accurately analyse real phenomena. When a general set is considered, an element can only belong to one or zero sets. However, in a fuzzy set, the elements may belong to different sets at the same time. The concept of urban ecosystem health displays a fuzzy nature. Because 'healthy' and 'unhealthy' do not have clear boundaries, it is difficult to answer whether or not an urban ecosystem belongs to the set of health. Therefore, urban ecosystems have both 'healthy' and 'unhealthy' components to some extent and in consequence, in the assessment of urban ecosystem health, a fuzzy set should be considered. When the fuzzy comprehensive evaluation is performed, the process is divided into five steps: identification and selection of indicators, fuzzy evaluation, and establishment of the relative membership matrix, weight determination, and analysis of the results.

2.3.3 Membership function calculation

Let r_{kj} be the relative membership degree of the k^{th} index to the j^{th} standard:

1 For positive indicators (benefit indicators, the greater the index value, the higher the health level), r_{kj} was calculated as follows:

$$r_{i,j+1} = \frac{x_i - l_{i,j}}{l_{i,j+1} - l_{i,j}}, \tag{1}$$

2 For negative indicators (cost indicators, the smaller the value, the higher the health level), we used the formula:

$$r_{i,j+1} = \frac{x_i - l_{i,j}}{l_{i,j+1} + l_{i,j}}, \tag{2}$$

2.3.4 Confirmation of the index weight

Weight corresponded to the contribution of different evaluation indexes to the evaluation result. In this case, w_j indicated the relative importance of the index 21 with respect to other indexes. When $0 \le wj \le 1$, $\sum_{i=1}^{m} w_j = 1$, the index weight vector was $w = \{w_1, w_2, \ldots, w_m\}$. The index weight was confirmed using the information entropy method.

The mean square deviation method was used to calculate the weight of evaluation elements. The steps are shown below:

1 Standard range method is used to process data, and the formula is:

$$\text{Positive index: } X_{ij} = \frac{x_{ij} - x_{j\min}}{x_{j\max} - x_{j\min}} X_{ij} \in [0, 1]; \tag{3}$$

$$\text{Negative index: } X_{ij} = \frac{x_{j\max} - x_{ij}}{x_{j\max} - x_{j\min}} X_{ij} \in [0, 1] \tag{4}$$

where X_{ij}, $x_{j\max}$, $x_{j\min}$ correspond to the original value, maximum value, minimum value.

2 The mean square deviation of the index $J - \sigma_j$ was calculated using:

$$б_j = \sqrt{\sum_{i=1}^{n} \frac{\left(X_{ij} - \bar{X}_j\right)\left(X_{ij} - \bar{X}_j\right)^2}{n-1}} \tag{5}$$

where X_j is the mean value of random variables, which was calculated using:

$$\bar{X}_j = \frac{1}{n}\sum_{i=1}^{n} X_{ij} \tag{6}$$

where n is a particular year (n = 1, 2, 3, 4, 5).

3 The weight coefficient w of each index was determined using:

$$w_j = б_j \Big/ \sum_{j=1}^{m} б_j , \tag{7}$$

where m corresponds to the number of indicators.

2.3.5 Evaluation of the sustainability of urban ecosystems

The sustainability of the ecosystem is a relative concept that contains a certain degree of fuzziness. For this reason, it is difficult to determine this parameter. In the present work, the membership matrix was created using the acquired data and considering the classification standards. Later, the fuzzy set was obtained by multiplying the weights of different factors by the membership matrix. Thus, a comprehensive judgement set was obtained, illustrating the membership extents of different evaluation factors to different standards and demonstrating the fuzziness of the health grade. Also, the illness and the health standard values of urban ecosystems were setup. The health level was determined by comparing the health status of different subsystems with the standard values.

In the event N elements in the k^{th} subsystem were present, a total of M kinds of health status were involved. Thus, the matrix M represented those M kinds of different health grades.

$$M_{(x_{ij})} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{ij} & \cdots & x_{im} \\ x_{21} & x_{22} & \cdots & x_{2j} & \cdots & x_{2m} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{il} & x_{i2} & \cdots & x_{ij} & \cdots & x_{in} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nj} & \cdots & x_{nm} \end{bmatrix}$$

where X_{ij} is the j^{th} state value of the i^{th} index of urban ecosystem, (i = 1, 2, …, n, j = 1, 2, …, m).

Vector $O_1 = (y_1', y_2', \ldots, y_j', \ldots, y_n')$ and $O_2 = (y_1'', y_{n2}'', \ldots, y_j'', \ldots, y_n'')$ represent the healthy target value and the relative illness value, respectively. After standardisation, the matrix M was transformed to the matrix N.

$$N\left(x_{ij}'\right) = \begin{bmatrix} x_{11}' & x_{12}' & \cdots & x_{ij}' & \cdots & x_{im}' \\ x_{21}' & x_{22}' & \cdots & x_{2j}' & \cdots & x_{2m}' \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{il}' & x_{i2}' & \cdots & x_{ij}' & \cdots & x_{in}' \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{n1}' & x_{n2}' & \cdots & x_{nj}' & \cdots & x_{nm}' \end{bmatrix}$$

The relative illness value and the healthy target value corresponded to vector $O_1' = (0, 0, \ldots, 0, \ldots, 0)$ and $O_2' = (1, 1, \ldots, 1, \ldots, 1)$.

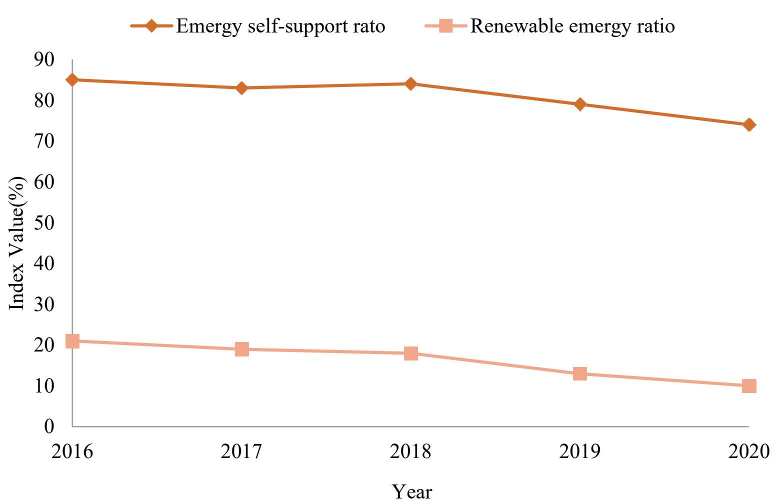
3 Results and discussion

3.1 Analysis on energy and energy flow of Changchun City

3.1.1 Emergy source in ecosystems of Changchun City

Emergy self-sufficiency rate (ESR) can be used to evaluate the ability of a given region to support a natural ecosystem. Renewable resource emergy rate (RER) is a measure of the potential of a region to support a natural ecosystem. According to the data, no significant changes were observed in the amount of renewable resources that could be used by urban ecosystems of the Changchun City in 2016–2020. Thus, the total amount of renewable resources was stable. However, the input of non-renewable resource and external resource continuously increased. Thus, the utilisation ratio of renewable resource decreased. These data was correlated with the quantity of energy recently expended in Changchun City. The main energy consumption of Changchun City was supplemented by coal, which in 2018 reached 20.095 million tons of standard coal. This corresponded to a ratio of coal consumption of 60%. However, more than 80% of the coal was provided by other places rather than Changchun City. On the other hand, the consumption of local renewable and non-renewable resources also decreased, thus maintaining the stability of the total quantity of renewable resources.

Figure 2 Indices emergy source of eco-economic system in Changchun City from 2016 to 2020 (see online version for colours)

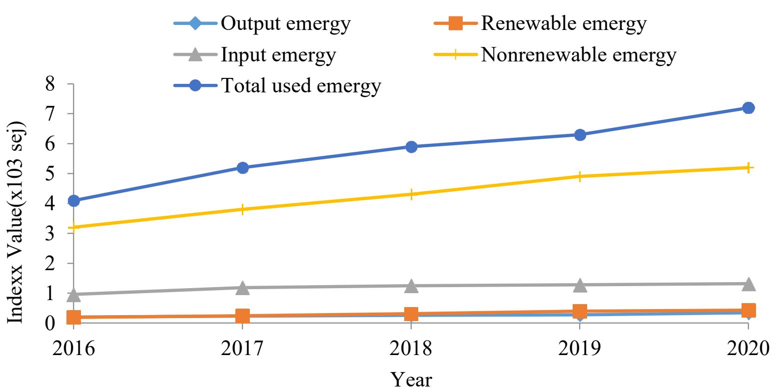


As Figure 2 shows, ESR of Changchun City decreased in 2016–2020 from 85% to 74%. In addition, RER decreased from 21% to 10%. The ratio of the input emergy and the innate emergy increased from 11% to 24%. The rate of emergy self-sufficiency in urban ecosystem was maintained around 0.23. Thus, a slightly decreasing trend was observed with a small change in amplitude. Emergy self-sufficiency rate is the ratio between the total input emergy of local renewable and nonrenewable resources and the input emergy of other places. The higher this value, the higher the self-sufficiency ability of the system. The emergy self-sufficiency rate of Changchun City was relatively low. This indicates that the system continuously relied on the input of external resources during the process of rapid development.

3.1.2 Analysis of emergy flow in ecosystems of the Changchun City

In the composite ecosystem of the whole city, significant changes in non-renewable resources (*N*) were observed in 2016–2020 (Figure 3). This occurred because the value of the total industrial output showed a rapid increasing rate of 8.5% on an annual basis. On the other hand, this city was trying to improve the unreasonable energy structure and established the first urban garbage power plant and biomass fuel power plant in Northeastern China. Power generation by urban garbage and biomass was able to improve the energy structure.

Figure 3 Emergy fiow of eco-economic system in Changchun City from 2016 to 2020 (see online version for colours)

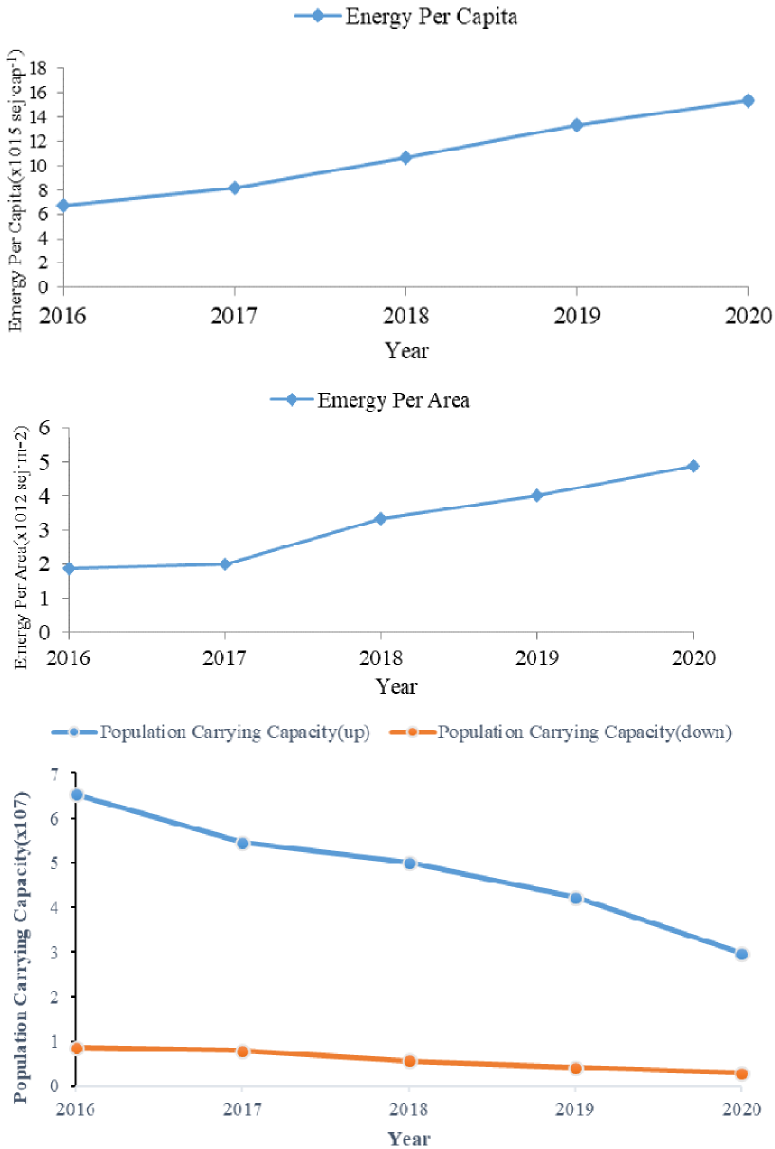


3.2 Emergy analysis of ecosystem in Changchun City

3.2.1 Emergy analysis of social subsystem of ecosystem in Changchun City

Per capita emergy corresponds to the per capita amount of emergy used in one district. This index is used to estimate the standard of living. The emergy density is the ratio between the total amount of emergy used in one district to the total area of the district. This parameter evaluates the strength and level of development of the measured district. For example, EPP of Changchun City increased from 6.70 × 10^{15} $sej{\cdot}cap^{-1}$ to 15.35 × 10^{15} $sej{\cdot}cap^{-1}$. EPA increased from 1.86 × 10^{12} $sej{\cdot}m^{-2}$ to 4.87 × 10^{12} $sej{\cdot}m^{-2}$. The upper limit of PCC decreased from 65.3 million to 29.7 million people. The lower limit of PCC decreased from 8.60 million to 3.50 million people (Figure 4). These data indicated that the standard and quality of living in Changchun significantly increased during the studied period. Besides, the degree of emergy also levelled up. However, the carrying capacity was not significantly modified mainly because the population changed slightly during this period and the natural ecosystem was not dramatically destroyed.

Figure 4 Subsystem evaluation of urban ecosystem in Changchun from 2016 to 2020 (see online version for colours)

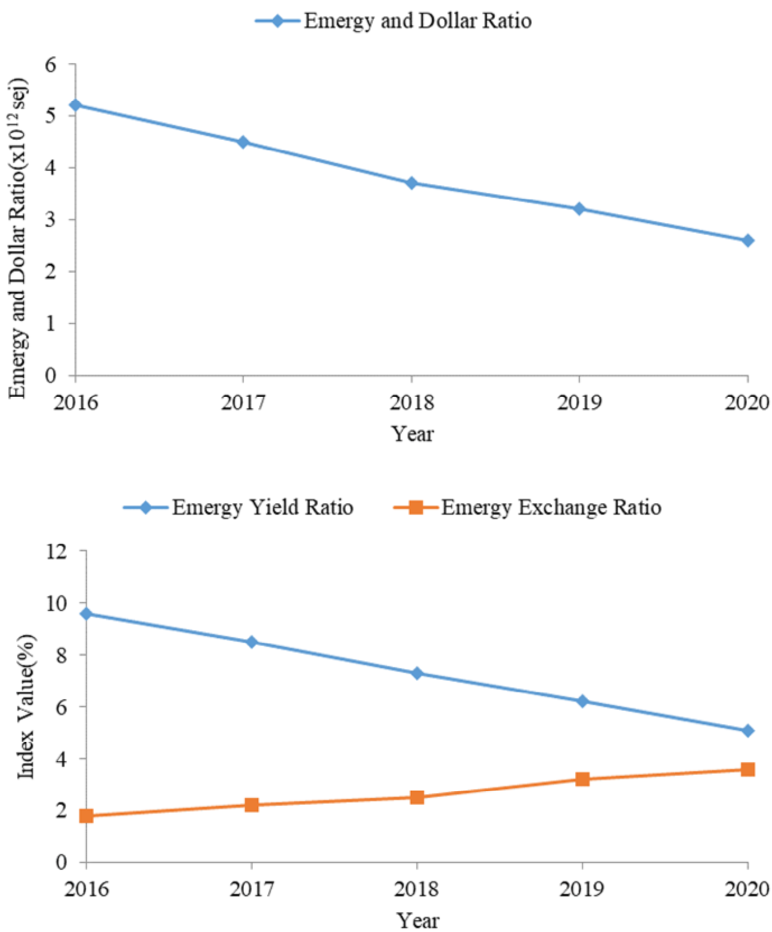


3.2.2 Emergy analysis of economic subsystem in Changchun City

The emergy yield rate indicates the ability of a system to provide the basic energy for the economic process to develop. EER is the ratio between the imported goods and services and the exported goods and demonstrates the degree of development of the system. The larger the rate of emergy exchange, the higher the degree of development. The ratio of emergy and currency corresponds to the emergy quantity, which is equivalent to unit currency. The smaller the ratio, the higher the developing of the economy in the district.

According to Figure 5, the emergy yield rate and the emergy currency rate in Changchun City indicated a decreasing trend in 2016–2020. In addition, the emergy exchange rate showed an overall increasing trend. The decreasing trend of EYR demonstrated the gradual decreasing efficiency of energy production in the whole urban composite ecosystem in Changchun City. In addition, the energy strength decreased and the technology efficiency gradually increased due to the continuous change of energy structure and industry structure.

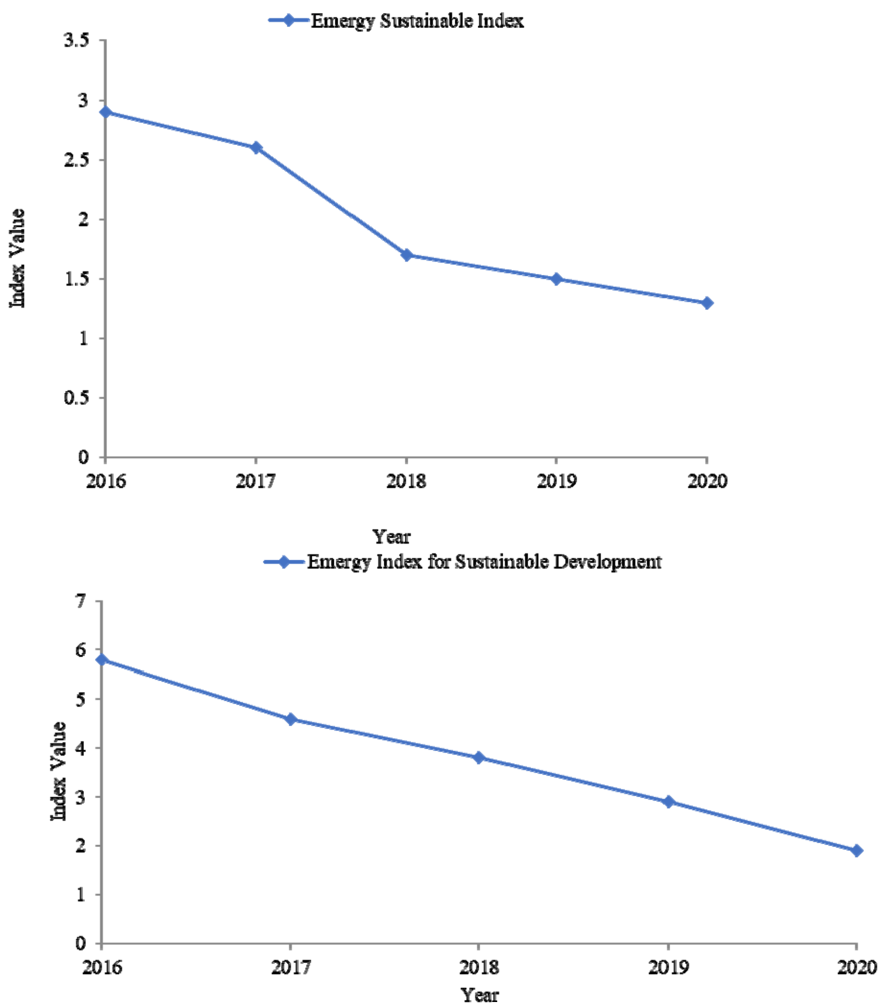
Figure 5 Economic subsystem evaluation of urban ecosystem in Changchun from 2016 to 2020 (see online version for colours)



3.2.3 *Emergy analysis of natural subsystem of ecosystem in Changchun City*

The waste emergy ratio measures the renewable ability of urban metabolic systems. Environmental load rate indicates the environmental load of urban metabolic systems. The environmental load rate of Changchun City in 2016–2020 was always in a state of high loading. The economic structure of Changchun City mainly included the raw material processing, digging, and light industry. Due to recent rapid expanding of the scale of raw material processing industry, a large amount of external resources, were required. With the continuous increase in economy as well as the utilised total amount and the strength of the systemic emergy, the systemic environmental load rate of Changchun City continuously increased placing a large pressure on the environment.

Figure 6 Sustainable development of urban ecosystems in Changchun from 2016 to 2020 (see online version for colours)



3.3 *Fuzzy clustering evaluation of ecosystem sustainability in Changchun City*

3.3.1 *Comprehensive index of ecosystem in Changchun*

The improved emergy-based index of sustainable development (EISD) demonstrated the changes of systemic socioeconomic efficiency. The higher the EISD value, the higher the socioeconomic efficiency under environmental pressure. ESI and EISD of Changchun City in the recent five years indicated an initial decreasing and then increasing trend

(Figure 6). Thus, the rate of energy recovery increased and the sustainability of the economic sub-ecosystem continuously increased due to the continuous adjustment of industrial structure in Changchun City.

3.3.2 Emergy analysis: fuzzy clustering integrated evaluation system

Traditional methods to analyse emergy are not able to accurately determine the health of ecosystem because they display two deficiencies:

1 Yhe environmental load rate corresponds to the ratio between systemic energy and the nonrenewable resource during resource consumption. Thus, it only considers one part of the influence of the systemic environment. The systemic environmental pressure accounts for the consumption of systemic resources (resource and energy) and the influence of emissions on the whole systemic process. ELR only demonstrated the former aspect of environmental influence of the system but did not explained the latter aspect of the systemic environmental influence.

2 The basic function of the economic ecosystem corresponded to energy flow, the cycling of materials, the currency circulation, and the exchange of information within the system. Emergy analysis evaluates systemic sustainability from the perspective of energy flow and does not consider energy flow, material flow, and current flow. Because of this, the integration of emergy analysis and the sustainability evaluation index of the ecosystem can be used to determine the sustainability of urban composite ecosystems. The evaluation items are shown in Table 2.

Table 2 Evaluation items of urban ecosystem sustainability

System	*1st level indicator*	*2nd level indicator*	*Health standard*	*Morbidity standard*	*Weight*
Natural subsystem	Organisation	Per capita surface water resources (m^3)	1,750	813	0.135
		Forest coverage (%)	>50	<20	0.013
		Greening coverage rate of built-up area (%)	>50	<20	0.013
		Per capita public green space area (m^2)	>11	<1.90	0.105
	Resilience	Proportion of investment in environmental pollution control in GDP (%)	>3.5	<0.8	0.20
		Comprehensive prevention and control index of urban air pollution	0.45	>0.90	0.075
		Urban domestic sewage treatment rate (%)	>80	<10	0.15
		Comprehensive utilisation rate of industrial solid waste (%)	100	<51.5	0.077
		Standard rate of industrial wastewater discharge (%)	100	<48.7	0.068

Table 2 Evaluation items of urban ecosystem sustainability (continued)

System	*1st level indicator*	*2nd level indicator*	*Health standard*	*Morbidity standard*	*Weight*
Economic subsystem	Vigour	Natural population growth rate (%)	5	>13	0.033
		Per capita GDP (Yuan)	40,000	<4,100	0.070
		Per capita disposable income (Yuan)	2	<0.4	0.052
	Development ability	Land output rate (%)	>3,000	<1,000	0.076
		Proportion of fixed asset in GDP (%)	>40	<14.2	0.060
		Proportion of infrastructure investment in GDP (%)	>12	<1.75	0.090
		Proportion of R&D expenses in GDP (%)	>4	<0.2	0.143
		Energy consumption per 10,000 Yuan GDP (tSCE)	<0.50	>1.52	0.064
		Water consumption per 10,000 Yuan GDP(t)	<250	>1,129	0.103
Social subsystem	Organisation	Unemployment rate of urban population	<1.2	>3.5	0.179
		Per capita net income of farmers (Yuan)	>6,000	<2,363	0.117
	Maintenance of ecosystem services	Teachers per 10,000	>480	<338	0.032
		Number of doctors per 10,000 people	>50	<7	0.122
		Per capita housing area of urban residents (m^2)	>25	<10	0.086
Emergy composite index	Sustainable development	Emergy sustainable index	<1	<10	0.205
		Emergy index for sustainable development	>0.9	<0.57	0.210

3.3.3 Comprehensive evaluation of ecosystem sustainability in Changchun City

In the present work, the health level of urban composite ecosystems of Changchun City (2016–2020) was evaluated using the integrated evaluation method (Table 3 and Figure 7).

According to data in Figure 7, the ecological health of Changchun City improved in the last five years. However, the urban ecosystem of Changchun City in 2016 displayed an unhealthy state. The year of 2017 corresponded to the transition period from the unhealthy to the relatively healthy status. In addition, between 2018–2020, a weak health was observed with a membership value of only 0.77. This indicated a clear gap towards the healthy state. In this case, the economic development favoured the sustainability of the ecosystem. However, the rapid economic development disguised other enharmonic factors to some extent. The health index of natural subsystems showed an increasing trend. An exception was observed in 2016 and 2018 where the index was smaller than that in the previous year. The health index of the economic subsystem gradually increased. It was also found that the health index of the social subsystem gradually increased, except those in 2016 and 2018 that showed a slight decrease as compared to those in previous years. These results indicated that the health levels of different subsystems showed a gradual increasing trend with respect to time.

Figure 7 Variable trend of urban complex ecosystem and subsystem of Changchun City (see online version for colours)

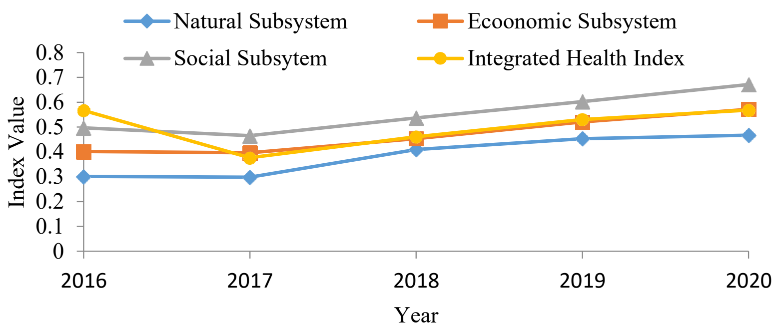


Table 3 Evaluation of ecosystem health in Changchun City

Year	*Health index*			*Integrated health index*
	Natural subsystem	*Economic subsystem*	*Social subsystem*	
2016	0.301	0.402	0.497	0.567
2107	0.298	0.396	0.465	0.376
2018	0.410	0.453	0.537	0.461
2019	0.453	0.520	0.602	0.531
2020	0.467	0.572	0.671	0.568

4 Conclusions and discussion

4.1 Conclusions

1. In the present work, a new method for the evaluation of health in urban composite ecosystems was proposed. The health of urban composite ecosystems in Changchun City, China was determined according to the related theory of open system and considering the input and the output of material-energy-information. This process eliminated the deficiencies shown by traditional methods where emergy was usually calculated only considering the input and the output of materials.
2. In the present research, the emergy evaluation system and urban ecosystem sustainability evaluation index system were built and the index weights were determined. The fuzzy mathematics method was used to evaluate the ecosystem sustainability of Changchun City in 2016–2020. During this period, the urban ecosystem of Changchun City experienced a process from unhealthy state to transitional state and then to weak health state. Data indicated that the natural

subsystem and the social subsystem displayed a good development. In addition, the assessment results provided information on the development of ecosystem health.

4.2 Discussion

Different elements in urban systems cannot be seen as individual parts as they are correlated and mutually influenced. For this reason, they form an indivisible entity that should not be separated. Thus, the evaluation process must consider their mutual relationship. Specifically, the evaluation of the level of health of the complete urban composite ecosystem and the relative level of health of each subsystem requires the identification of the stress symptoms and the stress factors. These data will serve to perform a better planning and construction of urban environments.

The method presented herein is simple and practical. It also reduces the uncertainty caused by the determination of health standards during the study of ecosystem sustainability. Standardised methods and index weighting should be the core of the comprehensive evaluation. However, since at present no classical weighting methods are available, subjective and objective weighting methods are still used. During the evaluation process, the subjective determination of indicators is based on the basic knowledge on urban ecology. However, no significant research has been performed on structure, function, and processes. For this reason, the present investigation does not consider the correlation between the elements. With the further development of urban ecology, the relationship between the elements of urban ecosystem can be more accurately studied. Therefore, the standardisation method and empowerment should be further studied in the future.

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