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Estimating ecological sustainability in the Guangdong-Hong Kong-Macao Greater Bay Area, China: Retrospective analysis and prospective trajectories

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Abstract

In the 21st century, great changes have taken place in global land use and climate, which affect the ecological sustainable development of urban agglomerations. A systematic and scientific ecological sustainability assessment framework is crucially important for large urban agglomerations to achieve sustainable development. However, the parameters used in previous assessment methods have normally ignored spatial heterogeneity, and scenario analyses have mostly been based on the historical change trend of sustainability indexes and the strategy optimization of future land use of the whole region, which may lead to deviations in the evaluation and analysis accuracies against the background of rapid urban development and intensified global climate change. By incorporating remote sensing technology, this study proposes an improved emergy ecological footprint (EEF) method and a novel ecological sustainability index to comprehensively analyze the spatio-temporal variability of ecological security states (ESS) from 1994 to 2018 in the Guangdong-Hong Kong-Macao Greater Bay Area (GBA) and to predict its sustainable growth potential based on scenario analysis. Results showed that the pixel-based emergy revealed significant changes over time under climate change impacts with intense land use activities during the study period. The composition and spatial pattern of per capita emergy carrying capacity (ecc) and per capita emergy ecological footprint (eef) at pixel level also significantly changed in nine cities in the GBA. Besides, the annual change rate of primary industrial products has a significant positive linear correlation with that of the GBA's eef (P<0.001, R=0.42). Consequently, the ESS of the GBA gradually worsened from slight insecurity in the 1990s to moderate insecurity in 2018. If current trends in socio-economic activities continue, the ESS of the GBA will reach a high insecurity level. Our scenarios show that energy structure optimization, biological resource conservation, and industrial structure adjustment can limit the decrease in Flux and the increase of emergy ecological footprint intensity and altogether contribute to sub-security of the GBA in 2050.

Keywords: Ecological sustainability; Emergy ecological footprint; Remote sensing

application; Guangdong-Hong Kong-Macao Greater Bay Area

Nomenclature

ESD	ecological sustainability development	GED	global emergy density
EEF	emergy ecological footprint method	NED	national emergy density
GBA	Guangdong-Hong Kong-Macao Greater Bay Area	EMR	emergy currency ratio
ecc	emergy carrying capacity per capita	PPI	producer price index
ecc_1	emergy carrying capacity of natural renewable resources per capita	IFA	investment in fixed assets
ecc_2	emergy carrying capacity of socio-economic account per capita	HI	output value of high-tech industry
eef	emergy ecological footprint per capita	LS	labor services
eef_1	emergy ecological footprint of biological resources	Flux	emergy ecological deficit or surplus per capita
eef_2	emergy ecological footprint of primary industrial products	EFI	emergy ecological footprint intensity
eef_3	emergy ecological footprint of energy resources	ESS	ecological security state
eef_4	emergy ecological footprint of ecological services		

1. Introduction

The 11,700-year-long Holocene epoch with a relatively stable ecological system is the only state we know for certain that can support contemporary human societies (Steffen et al., 2015). However, there is increasing evidence that human activities are affecting ecological functioning to a degree that threatens the resilience of the ecological system — its ability to persist in a healthy state in the face of increasing human pressures and shocks — in some areas, especially in cities where more than half of the world's population now lives (Li et al., 2019a). Over the last three decades most urban areas across the globe have experienced dramatic changes in their structure and function, driven by anthropogenic transformations (e.g., urban intensification) as well as climate change effects. These have triggered a series of critical ecological-environmental challenges (Liu and Yang, 2020; Pan et al., 2019; Yu et al., 2019), such as urban heat island (Cao et al., 2016; Chen et al., 2021), water pollution (Hubacek et al., 2009) and increasing disaster risk (Su et al., 2017). Thus, there is an urgent need for a new paradigm that integrates the continued development of human societies and the maintenance of the ecological system in a resilient and sustainable state for urban areas.

Ecological sustainability development (ESD), developed from the sustainability concept, can contribute to such a paradigm by providing a science-based analysis of harmonizing nature and social development according to the principles and methods of ecology, or by incorporating humans and their social economic activities into the research framework of ecology (Mavrommati and Richardson, 2012), which is more in line with development in urban areas (Rauscher and Momtaz, 2014). Until now, a variety of methods for the assessment of ecological sustainability have been put forward. The ecological footprint (EF) methodology, proposed by Rees (1992) and developed by Wackenagel et al. (1999), has been promoted as an environmental accounting tool that tracks human demand on and the natural supply of the regenerative capacity of the planet. It has been widely used (Moore et al., 2013; Wackernagel, 2006; Xun and Hu, 2019) for ecological sustainability assessment owing to its advantages of demonstrating the impact of human activities on nature as the area needed to support consumption (Wang et al., 2018; Yang et al., 2018), a clear account system, standardized process of assessment, ease of use and results interpretation (Liu and Yang, 2020) compared to other ESD methods，such as material flow and energy flow analysis (Haberl et al., 2007, Lambrechet et al., 2017), life cycle assessment (Antón et al., 2007; Duan et al., 2017), emergy accounting (Odum, 1996; Viglia et al., 2018; Hu et al., 2019) and system dynamics analysis (Bautista et al., 2019). However, EF also has its inherent flaws. For instance, it ignores the discrepancies of ecological advantages among different regions as well as the socioeconomic impact on bio-productivity (Li et al., 2019b; Peng et al., 2018). It also underestimates the ecological surplus because some potential resources are not taken into consideration (Liu et al., 2008; Mikulčića et al., 2016).

To address the above-mentioned issues, Zhao et al. (2005) proposed a modified method by integrating the EF methodology with the emergy theory, namely the emergy ecological footprint (EEF). Emergy refers to the amount of solar equivalent energy that is used directly or indirectly in making a service or product (Odum, 1996). The EEF method is constructed by translating various types of energy flow into solar emergy through emergy transformity, and then converting them to the corresponding bio-productive land area (Chen and Chen, 2006; Li et al., 2019b; Siche et al., 2006). Thus, this hybrid method can better quantitatively analyze the relationship between the resources, environment, and economic activities (Liu and Yang, 2020; Zhao et al., 2005), and make up for the incomplete evaluations in the traditional EF method (He et al., 2016; Peng et al., 2018). The EEF has been extensively used to provide a scientific reference for the eco-economic system to achieve sustainable development at different spatial scales, such as national scales (Li et al., 2019b; Pereira and Ortega, 2012; Venetoulis and Talberth, 2008), provincial scales (Chen and Chen, 2006; Yang et al., 2018), city scales (Liu and Yang, 2020; Nakajima and Ortega, 2015; Pan et al., 2019) and other scales (Cuadra and Björklund, 2007; Zhao et al., 2013). However, the parameters used to calculate the emergy variable are normally combined for the whole study area using average data from statistical yearbooks without accounting for the spatial heterogeneity in time and space. These unified parametric methods most likely result in significant deviations in evaluation accuracies against the background of rapid urban development and intensified global climate change.

Furthermore, the factorial decomposition of past trends can help researchers explore the drivers of the changes in an objective variable. Meanwhile, based on the historical trends of all drivers and current policies, we can program the future trajectory of the objective variable (Zhao et al., 2007). However, previous studies have been conducted on scenario analyses using the grey model (Yang et al., 2016), neural network and other extrapolation methods mostly based on the historical change trend of sustainability indexes and strategy optimization of future land use of the whole region, but did not include the influence of climate change. Therefore, it is necessary to combine factorial decomposition based on high spatio-temporal resolution historical data with scenario analysis to form an exact analytic framework and coping strategy for highly urbanized regions, such as the Guangdong-Hong Kong-Macao Greater Bay Area (GBA), when the region or global climatic condition is predicted to change in the future. Unfortunately, such a research concept has been rarely adopted in previous related studies.

To fill the above-mentioned research gaps, we improved the traditional EEF method by adding remote sensing data to investigate the temporal and spatial variations in the ecological sustainability of the GBA, one of the four largest Bay areas (urban agglomerations) in the world (Xie et al., 2021), focusing not only on land-use change drivers but also on the effect of climate change factors. Subsequently, we developed a modified index integrating two ecological sustainability indicators — the emergy ecological deficit or surplus per capita (Flux) and emergy ecological footprint intensity (EFI) — to evaluate the ecological security states (ESS) of the GBA and each city during the study period. In addition, we conducted a combined factorial decomposition and scenario analysis to explore the potential of ESD in the GBA associated with climate change and anthropogenic activities in the future. The aims of this novel perspective were to (1) facilitate understanding the trajectories of ecological sustainability and the underlying drivers, and (2) identify the desirable pathways for decision-makers to improve sustainability of the GBA. Our modelling approach could represent a baseline for further applications in other urban agglomerations with similar characteristics. The technical routing map is illustrated in Fig. S1, and detailed methods are introduced in methodologies.

The rest of this paper is organized as follows. Section 2 describes the sources of data and research methodology; section 3 analyzes the results while section 4 discusses the policy insights and displays the conclusion based on the results.

2. Methods and Methodology

2.1 Study area

The GBA, which includes nine cities (Guangzhou, Shenzhen, Zhuhai, Foshan, Huizhou, Dongguan, Zhongshan, Jiangmen, and Zhaoqing) and two special administrative regions of Hong Kong and Macao, is located in a subtropical climate zone (Fig. 1a) with an average annual precipitation of 1500 mm and an average annual temperature of 22.3°C. It has a large marine area of 17,000 km^2 and long coastline of 1997 km. Its ecosystem has a strong response to climate change (Zheng and Xu, 2019); the average temperature has increased significantly with a rate of $0.22°C•(10a)^{-1}$ in inland areas (Wu et al., 2019) and $0.25\ °C•(10a)^{-1}$ in oceanic areas (Xing et al., 2018) during the past 58 years. In the past four decades of rapid economic development and urbanization, its construction land has expanded 0.70 times while the ecological space has been shrinking (Fig. 1b and c). Sensitive ecosystem response and dwindling ecological space are accelerating the deterioration of the ecological environment, which would in turn restrict the sustainable development of the GBA.

Fig. 1. Schematic diagram of the climate zone where the GBA is located and its ecological spatial change. Plot (a) is the spatial distribution of temperature zones in China, while plots (b) and (c) are the spatial distribution of land use in 1994 and 2018, respectively.

2.2 Methodology

2.2.1 The improved EEF methodology frame

The EEF methodology proposed by Zhao et al. (2005) consists of two main components: (1) the emergy carrying capacity per capita (ecc) provided by natural environmental services, and (2) the emergy ecological footprint per capita (eef)

produced by anthropogenic activities. The calculation formulas for ecc and eef are found in Supplemental *Method S1* and *Method S2*.

Here we provided an improved EEF methodology frame, with the added remote-sensing data, to improve on the parameterization limitations in previous EEF studies. The parameterization differences between traditional EEF methodology and the improved EEF methodology are shown in Table 1.

Insert Table 1 here.

2.2.2 A novel classification method for the ecological security states (ESS) evaluation

The Flux (emergy ecological deficit or surplus per capita, equation [1]) and EFI (emergy ecological footprint intensity, equation [2]) are two common indicators that quantitatively reflect regional ecological security states (Pan et al., 2019). For Flux, when $\mathrm{Flux} < 0$, an ecological deficit arises, indicating that the consumption of resources exceeds the regional ecological carrying capacity. Conversely, when $\mathrm{Flux} > 0$, an ecological surplus arises, indicating that regional ecological carrying capacity can meet the consumption of resources (Peng et al., 2018). $\mathrm{Flux} = 0$ indicates a balance between human consumption and environmental support. For EFI, when $\mathrm{EFI} < 1$, human consumption is lower than environmental carrying capacity, which indicates that the study area is in a state of ecological security. When $\mathrm{EFI} > 1$, the pressure sustained by the ecosystem is larger than the ecological capacity, which indicates this region cannot achieve ecological security. The larger the EFI, the worse the ecological security. When $\mathrm{EFI} = 1$, the pressure caused by anthropogenic activity is in equilibrium with the environmental carrying capacity, which reflects the ecological balance of the region.

$$\mathrm{Flux} = ecc - eef \tag{1}$$

$$\mathrm{EFI} = eef/ecc \tag{2}$$

However, in most cases, evaluation results for ecological security states obtained by one index alone are very likely inconsistent with that of another (Pan et al., 2019), which has plagued policy-makers. Here, by comprehensively considering the numerical distribution and the interrelation between these two parameters (Fig. S2), we proposed a novel classification standard for the ecological security states (ESS) based on both

Flux and EFI. The novel classification criteria are shown in Table 2.

Insert Table 2 here.

2.2.3 Scenario designs for forecasting ESS of the GBA in 2050

To explore the potential for ecological sustainability capacities' improvement of the GBA in 2050 by the application of certain measures, i.e., improvement of energy efficiency, regulation of biological resource consumption and industrial upgrading, under the conditions of global warming exacerbation and constructed land expansion, we defined four scenarios. Scenario 4 was the strongest when the above three measures were carried out simultaneously, while scenario 1 was the mildest.

Scenario 1: Median business-as-usual (BAU): (1) the per capita constructed land will expand to 126 m^2 according to *Method S3* in Supplemental Material; (2) the global average temperature will increase by 1.4°C and the sea surface temperature will increase by 0.95°C in 2050 according to the RCP8.5 scenario in the IPCC (*Method S4*); (3) energy consumption will improve by 39.6% according to the results for China in "2050 world and China energy outlook" that was predicted by the RCP8.5 scenario in the IPCC (*Method S5*); (4) the socioeconomic account, including investment in fixed assets, output value of high-tech industry and labor services, is a linear extrapolation according to historical trending, while the per capita consumption of biological resources is predicted by the bilinear model; (5) other parameters will be the same as those in 2018.

Scenario 2: Strict energy efficiency control scenario: (1) energy consumption will be reduced by 24F% as predicted by scenario RCP2.6 in the IPCC (*Method S5*); (2) correspondingly, the global average temperature will increase by 0.9°C and the sea surface temperature will increase by 0.64°C according to the RCP2.6 scenario in IPCC (*Method S4*); (3) the other parameters will be the same as those in Scenario 1.

Scenario 3: Scenario of strict controls on both energy efficiency and consumption of biological resources: (1) assuming that everyone's consumption of biological resources will not enhance with the increase of their income, staying at the level of 2018; (2) moreover, food (consumption of biological resources) waste will be reduced by 35% according to "State of Food and agriculture (SOFA) 2019" issued by FAO; (3) other settings will be the same as in Scenario 2.

Scenario 4: Scenario of strict controls on both energy efficiency and consumption of biological resources, and optimization of the industrial structure: (1) due to the largest share (up to 85%) of cement industry in eef_2, only the cement industry was considered for industrial structure optimization in our study. The output of cement in the GBA in 2050 is expected to decrease by 68.8% according to the study by Gao (2019). Other settings will be the same as in Scenario 3.

3. Results and Analysis

3.1 Evaluation of the ecc in the GBA between 1994 and 2018

As shown in Fig. 2, the ecc of the GBA exhibited a significant downward trend during the study period. The ecc in 1994, consisting of 59% ecc_1 and 41% ecc_2, decreased from 2.37 ha/cap to 1.33 ha/cap in 2018. However, total emergy slowly rose from 1.28E+22 sej in 1994 to 1.29E+22 sej in 2009, and then rapidly increased to 1.34E+22 sej in 2018 (Fig. S3). It can be concluded that in the past 25 years, even the total emergy in the GBA has been increasing; the decrease in trend of ecc can be largely attributed to the expanding population (Fig. S4).

Fig. 2. Proportion of emergy carrying capacity per capita (ecc) components: emergy carrying capacity of natural renewable resources per capita (ecc_1), emergy carrying capacity of social economic accounts per capita (ecc_2), and changes in ecc.

With the development of the economy, society and technology, ecc_2 and its proportion to ecc have been gradually increasing since 2007 (Fig. S5b and Fig. 2). This indirectly showed that the growth of carrying capacity brought about by economic and social development has exceeded the rate of population growth. Fig. S5b also showed that the carrying capacity contributed by the high-tech industry increased from 11% in 1994 to 39% in 2018, while investments in fixed assets and labor services decreased by 4% and 16%, respectively, during the same period.

In addition, the proportion of ecc_1 to ecc during 1994 and 2018 was slightly greater than that of ecc_2 (Fig. 2), which reflected the ecc's primary reliance on ecc_1 and that the GBA has unique natural ecological advantages. Over the past 25 years, although the annual average amount of the emergy of renewable resources has remained basically stable, tidal energy and ocean wave were the two largest energy inputs (Fig. S5a). It is evident that the ocean plays an extremely important role in supporting the development of the GBA. However, in the past 25 years, there has been an obvious trade-off relationship between the emerges from ocean wave energy and tidal energy, with the emergy of ocean wave increasing from 5.10E+21 sej in 1994 to 6.12E+21 sej in 2018 and the emergy of tidal energy decreasing from 4.33E+21 in 1994 to 4.15E+21 in 2018 (Fig. S5a) due to ocean warming (Reguero et al., 2019).

In addition, from the perspective of pixel level, the spatio-temporal pattern of the emergy of the renewable resources in the GBA was subject to great changes (Fig. 3a). In 2018, more grid-based emergy of renewable resources in land field decreased and the corresponding emergy of high frequency shifted to a lower level when compared to that in 1994 (Fig. 3b). Furthermore, during the study period, the corresponding emergy of high frequency in land field presented changing characteristics among different cities (Fig. 3c-m). Based on the frequency variation curves, the corresponding emergy of high frequency in eastern cities of the GBA in 2018 was lower and more concentrated than that in 1994 (e.g., Guangzhou, Fig. 4c; Dongguan, Fig. 3d; Huizhou, Fig. 3e; Shenzhen, Fig. 3g; and Hong Kong, Fig. 3i), while the corresponding emergy of high frequency showed no obvious difference (e.g., Foshan, Fig. 3g; Zhongshan, Fig. 3l; Zhaoqing, Fig. 3f; and Zhuhai, Fig. 3k) or was even higher (e.g., Jiangmen, Fig. 3j) in western cities of the GBA. This may be mainly related to the intensity of land development in different cities during the past 25 years. Numerous studies have shown that land development intensity in the east bank of the Pearl River Delta is much higher than that of the west bank since the Reform and Opening-up (Li et al., 2020). All the results indicate that the temporal-spatial variation of ecc in the GBA was co-influenced by climate change and land use change.

Fig. 3. Spatial variation of emergy of renewable resources in the GBA (a) and the frequency

variation of the corresponding emergy of renewable resources in 1994 and 2018 for the GBA (b) and each city (c-m).

3.2 Evaluation of the eef in the GBA between 1994 and 2018

The eef of the GBA in 2018 is shown in Table S3 and Fig. S6b. eef_1, eef_2, eef_3 and eef_4 were 3.51 ha/cap, 1.78 ha/cap, 7.92 ha/cap, and 0.38 ha/cap, respectively (Table S4). The eef_3 sectors revealed the highest eef followed by the eef_1 and eef_2 sectors, while the eef_4 sectors showed the lowest (Fig. 4).

Fig. 4. Changes of per capita emergy ecological footprint (eef) components in the GBA. eef_1, eef of biological resources; eef_2, eef of primary industrial products; eef_3, eef of energy resources; eef_4, eef of ecological services.

However, the percentage of these four sectors accounting for eef has changed dramatically between 1994 and 2018 (Fig. S6). In 1994, at the beginning of China's Reform and Opening up, eef_1, eef_2 and eef_3 were three dominant sectors for eef in the GBA, accounting for 28%, 24% and 39%, respectively. However, eef_2 has been subsequently declining, notably by less than 20% since 1998, and a significant decrease occurred in 2008 and 2009 (Fig. 4). This is probably due to the fact that the traditional growth model relied on primary industrial products that were gradually replaced by a brand new development model dependent on technology-intensive industries since China's Eleventh Five-Year Plan period (Zhang and Zeng, 2017). The eef_1 gradually increased to 3.51 ha/cap in 2018, which was 25% more than that in the 1990s. As depicted in Table S3 and Fig. S7, such an increase in eef_1 hints at the underlying changes in GBA's per capita disposable income. Interestingly, although the eef_3 was always the dominant contributor of eef in the GBA and growth throughout the study period, it significantly reduced the growth rate and even halted growth at the end of each decade (Fig. S8 and Table S3). This trend may have much to do with the government's management model in China, which set energy conservation goals associated with carbon emissions reduction at the beginning of the decade and assessed the achievement at the end of the decade.

Fig. 5. Spatial distribution of the percentage of per capita emergy ecological footprint (eef) components in1994 (a) and 2018 (b).

For the nine cities in the GBA, we found that great changes have taken place in the eef as well as in the four components of eef (Fig. 5, Fig. S9). The change in eef_2 has a significant positive correlation with the change rate of eef (R=0.83, P<0.001) (Fig. 6), followed by eef_3 (R=0.49, P<0.001). This indicates that the variations of eef_2 and eef_3 contributed most to the *eef* trend. When cities changed their development model from a per capita biological resource consumption (eef_1 shares the highest proportion in the eef) to primary industrial products (eef_2) orientation, such as Huizhou and Zhaoqing, or from a per capita biological resource consumption (eef_1) to energy resource consumption (eef_3) orientation, as in Shenzhen, Zhongshan, Dongguan and Zhuhai, the eef resulted in a rapid growth trend (Fig.5, Fig. S9).

Fig. 6. Correlation between the change rate of per capita emergy ecological footprint (eef) and its components.

3.3 Ecological security state (ESS) of the GBA from 1994 to 2018

Flux decreased from -4.66 ha/cap in 1994 to -11.91 ha/cap in 2008, while EFI increased from 2.51 ha/cap in 1994 to 8.12 ha/cap in 2018 (Fig. S10). Furthermore, we proposed a novel ESS classification criterion based on Flux and EFI to quantify the temporal variation trends of ESS for the GBA and nine cities from 1994 to 2018 (Fig. 7).

Fig. 7. Ecological security state (ESS) level of each city in the GBA.

Overall, the GBA was in a state of slight insecurity (Level 3) before 2010, but it has been classified as moderate insecurity (Level 4) ever since. This indicates that

GBA's resource consumption and pollutant discharge have exceeded the supply and purification capacity of the ecosystem, and that the situation has become very serious, putting more pressure on the ecosystem. However, not all cities are in such unsustainable states. According to Fig. 7, Zhuhai's ESS remained at the status of security (Level 1) from 1994 to 2018. On the contrary, the ecological sustainability of Foshan was the worst among the 11 cities. Its ESS reached the highest level - extreme insecurity state (Level 6) since 1995. This was closely related to Foshan's high energy consumption and high pollution leading industries, e.g., ceramic industry (Shen and Wei, 2012). From 1994 to 2018, significant changes took place in the ESS of Huizhou, Dongguan and Guangzhou. Huizhou's ESS gradually changed from a security state to a moderate insecurity state, especially after 2010 when Huizhou began to enter a high-speed urbanization and industrialization development model becoming a new growth pole for economic growth in the Pearl River Delta as pointed out in the "Outline of the Reform and Development Plan for the Pearl River Delta Region (2008-2020)" (Liu and Ye, 2013). In the early 1990s, Dongguan was mainly in a state of moderate insecurity, then its ESS level continued to rise, reaching an extreme insecurity state during 2005 and 2015. Although its ESS has dropped in recent years, it is still at high insecurity status. Guangzhou has also been rising from a slight insecurity status since the early 1990s to high insecurity in recent years. The other cities' ESS levels have stayed between the sub-security status and slight insecurity status. Based on the above, although the government has issued a series of eco-environmental policies in recent years, ecological sustainability still faces great challenges due to the relatively extensive production mode and non-intensive land development mode in this region.

3.4 Prospective trajectories of ecological sustainability in the GBA from 2018 to 2050

The GBA is one of the most dynamic economic zones in China and even the world, playing an important strategic role in national development planning (Wu et al., 2020). Therefore, how to enhance the sustainable growth capacity of the GBA and ensure harmonious development of the economy, society and environment is an urgent challenge this region must face, as well as a concern to politicians and scientists worldwide.

Our scenario results showed that the GBA has the potential to strengthen its sustainable development capacity and thus reduce the level of insecurity in 2050. Under the median business-as-usual (BAU) scenario (scenario 1), along with construction land expanding and global warming, the Flux and EFI in the GBA will decrease to -15.5 and 9.35, respectively, by 2050, about 26.5% and 8.4% lower than reported in 2018 (Fig. 8). This implies that according to this development mode, the level of ESS in the GBA may deteriorate to an extreme insecurity status (Fig. S11).

Under scenario 2, the Flux of the GBA will be -11.40 by 2050, about 6.9% and 26.4% higher than that in 2018 and in scenario 1, respectively. Meanwhile, the EFI will decrease to 7.16 by 2050, about 29.9% and 23.4% lower than that in 2018 and in scenario 1, respectively (Fig. 8). The warning level of ESS in the GBA may rapidly decrease two levels to a moderate insecurity status (Fig. S11). These results show that it is necessary for ecological security to reduce energy intensity.

Under scenario 3, the Flux of the GBA will increase to -6.10 while the EFI will decrease to 4.30 by 2050 through further regulation of biological resources. Accordingly, the ESS in this region improved from moderate insecurity in 2018 to slight insecurity in 2050. This indicates that the consumption of biological resources is another important factor for generating the ecological footprint.

Scenario 4 optimized the industrial structure and reduced cement output on the basis of scenario 3. The Flux of the GBA will increase to -4.98 by 2050, about 59.3% and 18.4% higher than that in 2018 and in scenario 3, respectively. On the other hand, the EFI will decrease to 3.69 by 2050, about 63.9% and 14.2% lower than that in 2018 and in scenario 3, respectively (Fig. 8). As a result, the level of ESS will reach the sub-security status by combining improved energy efficiency, regulation of biological resource consumption and industrial upgrading under the conditions of global warming exacerbation and constructed land expansion (Fig. S11).

Although primary industrial products revealed a strong positive correlation with the GBA's eef (Fig. 5), future growth in this region will lead to a large-scale occurrence of capital construction. A decline in share of primary industrial products dominated by the cement industry will be limited by 2050. Therefore, improved sustainable development brought about by an adjustment of the industrial structure is weaker than that generated by the adjustment of the energy structure and the optimization of biological resources.

Fig. 8. The four prediction scenarios of the emergy ecological deficit or surplus per capita (Flux) (a) and emergy ecological footprint intensity (EFI) (b).

4. Discussion and Conclusion

With the accelerated urbanization and industrialization process of recent decades, urban agglomerations have been growing and becoming the focus of scientists and policy-makers (Bi et al., 2020; He et al., 2019; Kourtit et al., 2020). Meanwhile, the continued deterioration of the environment and massive depletion of natural resources induced by rapid urbanization and climate change have been recognized as a principal threat to ecological sustainable development (Eustachio et al., 2019; Liu et al., 2019; Sandifer et al., 2015). Establishing a systematic and scientific ecological sustainability assessment framework and ecological governance system are of paramount importance for the sustainable development of large urban agglomerations, such as the GBA, which is the world's fourth largest bay area. However, the previous EEF method does not seem to work well with the ecological sustainability assessment in these large urban agglomerations due to their conspicuous spatial and temporal heterogeneity. In this study an improved EEF method, which combined remote sensing data, was established to comprehensively evaluate temporal and spatial variations in the ecological sustainability of the GBA from 1994 to 2018.

Our results show that although the sum of renewable resources of the emergy amount of the GBA did not reveal evident changes in trends from 1994 to 2018, its composition and spatial pattern at pixel level significantly changed, mainly due to the combined effect of climate change and land use change related to social and economic anthropogenic activities. The GBA's ecc_1, which is associated with oceans, is the most important contributor to the *ecc* of the GBA, with an average share reaching 75%. Also, climate change would have a strong impact on the emergy of renewable resources of oceans by affecting tidal range and wave height (Fig. S5a). It follows that with increasing global warming, the ocean's activity will be further intensified (Reguero et al., 2019). However, another study (Bi et al., 2020) using the EF method, which does not consider the significant contribution of wave energy and tidal energy, found that the GBA developed from a weakly unsustainable development state in 2000 to a strongly unsustainable development state in 2015, which is more serious than the results given by our study. In addition, Bi et al. (2020) found that all cities are in an unsustainable development state, with Hong Kong having the lowest sustainable development capacity. However, we found that the cities with coastlines, such as Hong Kong, Zhuhai, Jiangmen and Macao, have been in a state of sustainable or sub-sustainable development, while Foshan has been facing the greatest environmental pressure. It indicated that ignoring the role of the ocean, as well as the impact of global climate change on ocean energy, would lead to substantial deviations to the sustainability evaluation of coastal cities or regions. Moreover, we further found that using the traditional EEF method provided by Liu and Yang (2020), which does not consider the spatio-temporal variations of pixel scale, overestimates the GBA's ecc by 15% compared with our results (Fig. S12). Therefore, a combination of remote sensing data and traditional economic and social statistics data can improve the accuracy of regional ecological sustainability assessment to provide a more scientific basis for decision-makers.

Furthermore, the eef in the GBA has increased by 75% in the past 25 years, which is similar to the results of many studies conducted on other urban agglomerations (Liu and Yang, 2020). However, this study further found that the annual change rate of primary industrial products has a significant positive linear correlation with that of the GBA's eef, followed by that of energy demand, and used these correlations to explain the temporal and spatial variations of eef for the nine cities.

This study provides for the first time, to our knowledge, meaningful and practical scenario predictions to explore the potential for ecological sustainability capacities improvement of the GBA in 2050 by applying certain measures, i.e., improvement of energy efficiency, regulation of biological resource consumption and industrial upgrading, under the conditions of global warming exacerbation and constructed land expansion. The uncertainty underlying these scenarios is considerable and is based on uncertainties in the consciousness change in biological resource consumption and other industrial structures besides cement industries. Despite the uncertainties, the scenarios illustrate the enormous potential for an improvement in the sustainability of the GBA. The uncertainties change the magnitude of potential, but the underlying possibility for sustainability improvement remain.

Our scenario analyses have shown that if the GBA maintains its current production and lifestyle, climate change and the expansion of construction land will change the ecological security status of the GBA deteriorating to extreme security status. By improving energy efficiency, regulating biological resource consumption and upgrading industrial structure the EFI can be reduced by about 63.9% (Fig. 9). It means that in order to improve the GBA's sustainability, policy-makers should primarily consider implementing strategies to reduce biological resource consumption. The government can advocate resource-saving consumption patterns and encourage green consumption to improve people's consumption structure of biological resources through media publicizing, including TV, social media platforms, pamphlets, billboards, and so on. In addition, policy-makers should consider implementing strategies to improve energy efficiency. For example, a lower energy consumption quota should be assigned to low energy efficiency city sectors (Su et al., 2020), forcing them to carry out equipment transformation. We also suggest encouraging profit-driven enterprises to adopt a cleaner production mode by allowing consumption forces to determine production and increasing the market share of clean energy products. The realization of these measures is very feasible thanks to the strong willingness and enforcement of government in the GBA to achieve the "carbon neutrality" goal by 2060.

In general, the improved EEF method used in this study can have a significant positive impact on the regional assessment and planning of sustainable development of urban agglomerations. However, some shortcomings should not be ignored. The ecc calculated herein is slightly larger than the actual one, since some renewable resources stemming from the same source (e.g., solar energy) have probably been repeated consideration. In addition, given the difficulty of obtaining ocean spatial data and the small impact of ocean emergy spatial distribution on the internal planning of urban agglomerations, we did not carry out spatial research in the oceanic region. Therefore, further study should be undertaken to establish more comprehensive and scientific methods based on pixel level for a better use in other similar regions of the world, especially in coastal urban agglomerations.

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References

Antón, A., Castells, F., Montero, J.I., 2007. Land use indicators in life cycle assessment. Case study: The environmental impact of Mediterranean greenhouses. J. Clean. Prod. 15, 432-438. https://doi.org/10.1016/j.jclepro.2005.10.001.

Bautista, S., Espinoza, A., Narvaez, P., Camargo, M., Morel, L., 2019. A system dynamics approach for sustainability assessment of biodiesel production in Colombia. Baseline simulation. J. Clean. Prod. 213, 1-20. https://doi.org/10.1016/j.jclepro.2018.12.111.

Bi, M. L., Xie, G. D., Yao, C. Y., 2020. Ecological security assessment based on the renewable ecological footprint in the Guangdong-Hong Kong-Macao Greater Bay Area, China. Ecol. Indicat. 116(18), 106432.

Cao, C., Lee, X., Liu, S., Schultz, N., Xiao, W., Zhang, M., Zhao, L., 2016. Urban heat islands in China enhanced by haze pollution. Nat. Commun. 7, 12509.

Chen, B., Chen, G.Q., 2006. Ecological footprint accounting based on emergy—A case study of the Chinese society. Ecol. Model. 198, 101-114. https://doi.org/10.1016/j.ecolmodel.2006.04.022.

Chen, S., Yu, Z., Liu, M., Da, L., Faiz, M., 2021. Trends of the contributions of biophysical (climate) and socioeconomic elements to regional heat islands. Sci. Rep. 11, 12696.

Cuadra, M., Björklund, J., 2007. Assessment of economic and ecological carrying capacity of agricultural crops in Nicaragua. Ecol. Indicat. 7(1), 133-149.

Duan, N., Liu, X.D., Dai, J., Lin, C., Xia, X.H., Gao, R.Y., Wang, Y., Chen, S.Q., Yang, J., Qi, J., 2017. Evaluating the environmental impacts of an urban wetland park based on emergy accounting and life cycle assessment: A case study in Beijing. Ecol. Model. 222, 351-359. https://doi.org/10.1016/j.ecolmodel.2010.08.028.

Eustachio, J.H.P.P., Caldana, A.C.F., Liboni, L.B., Martinelli, D.P., 2019. Systemic indicator of sustainable development: Proposal and application of a framework. J. Clean. Prod. 241, 118383. https://doi.org/10.1016/J.JCLEPRO.2019.118383.

Haberl, H., Weisz, H., Bartley, D.M., Brugère, C., Soto, D., Gerber, P., Harvey, B., 2007. The potential use of the Materials and Energy Flow Analysis (MEFA) framework to evaluate the environmental costs of agricultural production systems and possible applications to aquaculture.

He, J., Wan, Y., Feng, L., Ai, J., Wang, Y., 2016. An integrated data envelopment analysis and emergy-based ecological footprint methodology in evaluating sustainable development, a case study of Jiangsu Province, China. Ecol. Indicat. 70, 23-34. https://doi.org/10.1016/j.ecolind.2016.05.042.

He, Q., Zeng, C., Xie, P., Tan, S., Wu, J., 2019. Comparison of urban growth patterns and changes between three urban agglomerations in China and three metropolises in the USA from 1995 to 2015. Sustain. Cities Soc. 50, 101649.

Hu S.B., He L.J., Wang J.Y., 2001. Compilation of heat flow data in the continental area of China (3rd edition). Chinese Journal of Geophysics.

Hu, W., Hu, Y., Hu, Z., Huang, Y., Zhao, Y., Ren, M., 2019. Emergy-based sustainability evaluation of China's marine eco-economic system during 2006–2015. Ocean Coast Manag. 179, 104811. https://doi.org/10.1016/j.ocecoaman.2019.05.013.

Hubacek, K., Guan, D., Barrett, J., Wiedmann, T., 2009. Environmental implications of urbanization and lifestyle change in China: ecological and water footprints. J. Clean. Prod. 17(14), 1241-1248.

Jiang, G.Z., Gao, P., Rao, S., Zhang, L.Y., Tang, X.Y., Huang, F., Zhao, P., Pang, Z., He, L.J., Hu, S.B., Wang, J.Y., 2016. Compilation of heat flow data in the continental area of China (4th edition). Chinese Journal of Geophysics, 59(8), 2892-2910.

Kourtit, K., Nijkamp, P., Suzuki, S., 2020. Are global cities sustainability champions? A double delinking analysis of environmental performance of urban agglomerations. Sci. Total Environ. 709, 134963.

Lambrecht, H., Hottenroth, H., Schröer, T., Schulenburg, F., 2017. Optimization-aided material and energy flow analysis for a low carbon industry. J. Clean. Prod. 167, 1148-1154. https://doi.org/10.1016/j.jclepro.2017.08.053.

Li, D., Liao, W., Rigden, A.J., Liu, X., Shevliakova, E., 2019a. Urban heat island:

aerodynamics or imperviousness?. Sci. Adv. 5(4), eaau4299.

Li, J., Chen, Y., Xu, C., Li, Z., 2019b. Evaluation and analysis of ecological security in arid areas of Central Asia based on the emergy ecological footprint (EEF) model. J. Clean. Prod. 235, 664-677. https://doi.org/10.1016/j.jclepro.2019.07.005.

Li, X.Y., Chen M.Q., Wang J.L., 2020. Dynamic development monitoring of urban construction land in Pearl River Delta with DMSP/OLS images. Remote Sensening Information 35(06), 138-144.

Liu, C., Yang, M., 2020. An empirical analysis of dynamic changes in ecological sustainability and its relationship with urbanization in a coastal city: The case of Xiamen in China. J. Clean. Prod. 256, 120482. https://doi.org/10.1016/j.jclepro.2020.120482.

Liu, Q. P., Lin, Z. S., Feng, N. H., Liu, Y. M., 2008. A modified model of ecological footprint accounting and its application to cropland in Jiangsu, China. Pedosphere 18 (2), 154-162. https://doi.org/10.1016/S1002-0160(08)60003-X.

Liu, W., Zhan, J., Zhao, F., Yan, H., Zhang, F., Wei, X., 2019. Impacts of urbanization-induced land-use changes on ecosystem services: A case study of the Pearl River Delta Metropolitan Region, China. Ecol. Indicat. 98(MAR.), 228-238.

Liu, Y,G., Ye, L.Q., 2013. Path Creation with Politics of Scale in the Regional Development: A Case Study of Huizhou City. Sci. Geogr. Sin. 33(09), 1029-1036. (in Chinese)

Mavrommati, G., Richardson, G., 2012. Experts' evaluation of concepts of ecologically sustainable development applied to coastal ecosystems. Ocean Coast Manag. 69(DEC.), 27-34.

Mikulčić, H., Cabezas, H., Vujanović, M., Duić, N., 2016. Environmental assessment of different cement manufacturing processes based on emergy and ecological footprint analysis. J. Clean. Prod. 130, 213-221. https://doi.org/10.1016/j.jclepro.2016.01.087.

Moore, J., Kissinger, M., Rees, W.E., 2013. An urban metabolism and ecological footprint assessment of Metro Vancouver. J. Environ. Manag. 124, 51-61.

https://doi.org/10.1016/j.jenvman.2013.03.009.

Nakajima, E. S., Ortega, E., 2015. Exploring the sustainable horticulture productions systems using the emergy assessment to restore the regional sustainability. J. Clean. Prod. 96, 531-538.

Odum, H.T., 1996. Environmental Accounting: Emergy and Environmental Decision Making. John Wiley & Sons, New York, p. 370.

Pan, H., Zhuang, M., Geng, Y., Wu, F., Dong, H., 2019. Emergy-based ecological footprint analysis for a mega-city: The dynamic changes of Shanghai. J. Clean. Prod. 210, 552-562. https://doi.org/10.1016/j.jclepro.2018.11.064.

Peng, W., Wang, X., Li, X., He, C., 2018. Sustainability evaluation based on the emergy ecological footprint method: A case study of Qingdao, China, from 2004 to 2014. Ecol. Indicat. 85, 1249-1261. https://doi.org/10.1016/j.ecolind.2017.12.020.

Pereira, L., Ortega, E., 2012. A modified footprint method: the case study of Brazil. Ecol. Indicat. 16, 113-127.

Rauscher R.C., Momtaz, S., 2014. Planning for Sustainable Communities. In: Brooklyn's Bushwick - Urban Renewal in New York, USA. Springer, Cham. https://doi.org/10.1007/978-3-319-05762-0_3.

Rees, W.E., 1992. Ecological Footprints and Appropriated Carrying Capacity: What Urban Economics Leaves Out. Environ. Urbanization 4, 121-130.

Reguero, B.G., Losada, I.J., Méndez, F.J., 2019. A recent increase in global wave power as a consequence of oceanic warming. Nat. Commun. 10, 205.

Sandifer, P.A., Sutton-Grier, A.E., Ward, B.P., 2015. Exploring connections among nature, biodiversity, ecosystem services, and human health and well-being: opportunities to enhance health and biodiversity conservation. Ecosyst. Serv. 12, 1–15.

Shen, J., Wei, C., 2012. Relocation Mechanisms of the ceramics industry impacted by the environmental regulations in Foshan city. Acta. Geogr. Sin. 67, 467-478.

Siche, J.R., Pereira, L., Agostinho, F., Ortega, E., 2010. Convergence of ecological footprint and emergy analysis as a sustainability indicator of countries: Peru as case study. Commun. Nonlinear. Sci. 15, 3182–3192. https://doi.org/10.1016/j.cnsns.2009.10.027.

Steffen, W., Richardson, K., Rockstrom, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., Vries, W.D., Wit, C.A.D., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sörlin, S., 2015. Planetary boundaries: guiding human development on a changing planet. Science 348(6240), 1217.

Su, M.R., Zheng, Y., Hao, Y., Chen, Q.H., Chen, S.H., Chen, Z.Y., Xie, H., 2017. The influence of landscape pattern on the risk of urban water-logging and flood disaster. Ecol. Indicat. 92(SEP.), 133-140.

Su, Y., Zheng, B., Ciais, P., Wu, J., Lafortezza, R., 2020. Retrospect driving forces and forecasting reduction potentials of energy-related industrial carbon emissions from China's manufacturing at city level. Environ. Res. Lett. 15, 074020.

Viglia, S., Civitillo, D.F., Cacciapuoti, G., Ulgiati, S., 2018. Indicators of environmental loading and sustainability of urban systems. An emergy-based environmental footprint. Ecol. Indicat. 94, 82-99. https://doi.org/10.1016/j.ecolind.2017.03.060.

Wackernagel, M., 2006. Ecological footprint accounting—comparing earth's biological capacity with an economy's resource demand. Springer Netherlands.

Wackernagel, M., Onisto, L., Bello, P., Linares, A.C., Guerrero, M.G.S., 1999. National natural capital accounting with the ecological footprint concept. Ecol. Econ. 29(3), 375-390.

Wang J.Y., Huang S.P., 1990. Compilation of heat flow data in the continental area of China (2nd edition). Ssmology and Geology (04), 364.

Wang, P., Deng, X., Zhou, H., Qi, W., 2018. Responses of urban ecosystem health to precipitation extreme: a case study in Beijing and Tianjin. J. Clean. Prod. 177, 124-133. https://doi.org/10.1016/j.jclepro.2017.12.125.

Wu, H.Y., Zhai, Z.H., Zhang, Y., 2019. Analysis of climate change in Guangdong-Hong Kong-Macao Greater Bay Area. Torrential Rain and Disasters 38(04), 303-310.

Wu, M. , Wu, J. , Zang, C., 2020. A comprehensive evaluation of the eco-carrying capacity and green economy in the Guangdong-Hong Kong-Macao Greater Bay Area, China. J. Clean. Prod. 281(1), 124945.

Xie, H., Zhang, Y., Chen, Y., Peng, Q., Zhu, J., 2021. A case study of development and utilization of urban underground space in Shenzhen and the Guangdong-Hong Kong-Macao Greater Bay Area. Tunn. Undergr. Sp. Tech. 107, 103651.

Xing, C.Y., Zhu, J.J., Wu, S.A., 2018. Climate change characteristics of thermal condition in the South China Sea. Marine Forecasts 35(06), 13-23.

Xun, F., Hu, Y., 2019. Evaluation of ecological sustainability based on a revised three-dimensional ecological footprint model in Shandong Province, China. Sci. Total Environ. 649, 582-591. https://doi.org/10.1016/j.scitotenv.2018.08.116.

Yang, Q., Liu, G., Hao, Y., Coscieme, L., Zhang, J., Jiang, N., Casazza, M., Giannetti, B.F., 2018. Quantitative analysis of the dynamic changes of ecological security in the provinces of China through emergy-ecological footprint hybrid indicators. J. Clean. Prod. 184, 678-695. https://doi.org/10.1016/j.jclepro.2018.02.271.

Yang, Q., Peng, C., Zhou, F., Geng, Y., Jing, H., Ren, W., Xue, B., 2016. an emergy-ecological footprint model based evaluation of ecological security at the old industrial area in northeast China: a case study of Liaoning province. J. Appl. Ecol. 5, 1594-1602.

Yi, F., Feng, W., Cao, H., 2018. Wave analysis based on ERA-Interim reanalysis data in the South China Sea. Marine Forecasts 35, 44-51.

Yu, L., Wu, X., Zheng, X., Zheng, T., Xin, J., Walther, M., 2019. An index system constructed for ecological stress assessment of the coastal zone: a case study of Shandong, China. J. Environ. Manag. 232(FEB.15), 499–504.

Zhang, X., Zeng, H., 2017. Dynamic of three dimensional ecological footprint in the Pearl River Delta and its driving factors. J Acta Scientiae Circumstantiae 37, 771-778.

Zhao, S., Li, Z., Li, W., 2005. A modified method of ecological footprint calculation and its application. Ecol. Model. 185, 65-75. https://doi.org/10.1016/j.ecolmodel.2004.11.016.

Zhao, S., Song, K., Gui, F., Cai, H., Jin, W., Wu, C., 2013. The emergy ecological footprint for small fish farm in China. Ecol. Indicat. 29, 62-67. https://doi.org/10.1016/j.ecolind.2012.12.009.

Zhao, W., Liu, J. S., Kong, F. E., 2007. Scenario prediction of regional ecological footprint:a case of Jilin province. Resources Science. 29(1), 165-171.

Zheng, H.Z., Xu, L.Y., 2019. With regard to tacking climate change, international experience of flexible planning strategy in Guangdong-Hong Kong-Macao Greater Bay Area and its enlightenment. World Environment 01, 44-48.

TABLE LEGENDS

Table 1. Comparison of data sources of traditional EEF methodology and improved EEF methodology.

Index	**Sub-index**	**Data**	**Data sources**	
			EEF methodology	**Improved EEF methodology**
ecc	ecc_1	**Solar radiation**	Literatures or statistical yearbooks	Chinese meteorological forcing dataset, which provided by the national science and technology resource sharing service platform.
		Precipitation	Literatures or statistical yearbooks	
		Wind speed	Statistical yearbooks	
		Albedo	Literatures	MODIS albedo product (MCD43C3)
		Evapotranspiration rate	Literatures	MODIS evapotranspiration product (MYD16A2)
		Heat flow	Literatures	Literatures
		Wave height	Ocean data statistics website or literatures	Ocean data statistics website or literatures
		Tidal	Ocean Data Statistics website	The global sea level observation system (GLOSS)
	ecc_2	**Output value of high-tech industry**	Guangdong Statistical Yearbook, the statistical yearbooks of cities	
		Investment in fixed assets		
		Labor services		
eef	eef_1	**Consumption of agricultural products**	Guangdong Statistical Yearbook, Guangdong Rural Statistical Yearbook, the statistical yearbooks of cities, the Food and Agriculture Organization (FAO) Database on production and trade.	
	eef_2	**Primary industrial production**		
	eef_3	**Energy consumption**		
	eef_4	**Air and water pollutant emissions**		

Table 2. The novel ecological security state (ESS) classification based on Flux and EFI values.

Level	ESS	Range of EFI and Flux
1	Security	$0 < \text{EFI} \leq 1$ or $\text{Flux} > 0$
2	Sub-security	$1 < \text{EFI} \leq 5$ and $-5 \leq \text{Flux} < 0$
3	Slight insecurity	$1 < \text{EFI} \leq 5$ and $-10 \leq \text{Flux} < -5$
		$5 < \text{EFI} \leq 10$ and $-10 \leq \text{Flux} < 0$
4	Moderate insecurity	$1 < \text{EFI} \leq 10$ and $-12 \leq \text{Flux} < -10$
		$10 < \text{EFI} \leq 15$ and $-12 \leq \text{Flux} < 0$
5	High insecurity	$1 < \text{EFI} \leq 15$ and $-15 \leq \text{Flux} < -12$
		$15 < \text{EFI} \leq 20$ and $-15 \leq \text{Flux} < 0$
6	Extreme insecurity	$\text{EFI} \geq 20$ or $\text{Flux} < -15$

Flux, emergy ecological deficit or surplus per capita; EFI, emergy ecological footprint intensity.