RESEARCH ARTICLE

Spatial-temporal pattern and urban-rural gradient of comprehensive ecological security in urban agglomeration in South China from 2000 to 2020

Xiaojun Wang[1,2] · Guangxu Liu[3] · Churan Zhang[4] · Yiling Liao[5]

Abstract

The ecological security (ES) of urban agglomeration and surrounding environmental system is related to the sustainable development of cities, which is a hot spot that we must pay attention to. In this study, four subsystems composed of natural base, landscape structure, ecosystem stability, and anthropogenic interference were used to evaluate the comprehensive ecological security (CES) of Guangdong-Hong Kong-Macao Greater Bay Area (GHMGBA) in 2000, 2010 and 2020. The results show that CES of the region was generally well. The central urban region of GHMGBA was unsafety with an area proportion of about 24.5%, the periphery was safety with an area proportion of about 43.5%, and the others are transitional zone. From 2000 to 2020, the CES change first slightly decreases and then relatively stable, and the transfer of different safety levels mainly occurs in the transitional zone. In 2010-2020 the transfer of different levels of CES is more frequent than in 2000-2010, indicating that the spatial-temporal pattern of CES fluctuated sharply during 2010-2020. The urban-rural gradient showed that with the increase of distance, CES fluctuations increase, but decreases at about 20-40km, 60-80km and 120-140km away from the city center, which may be sub-urban regions. The overall CES change range gradually decreases with increasing distance from urban centers. This study helps to understand the temporal and spatial distribution of ecological environment and urban-rural gradient in typical urban regions, and provides a reference for the collaborative planning of urban agglomeration.

Keywords Ecological security · Landscape structure · Ecosystem stability · Anthropogenic interference · Guangdong-Hong Kong-Macao Greater Bay Area (GHMGBA)

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Introduction

Ecological security (ES) is a landscape structure that maintains the balance between environment and development (Gong et al. 2009). It is the state of "environmental health" and the capacity of an ecosystem, and the overall sensitivity of an ecosystem to various external influences (Zhang et al. 2017; Feng et al. 2018). ES has become a research hotspot in different environmental contexts and at different spatial-temporal scales, such as ecologically fragile areas (Fan et al. 2021), arid zones (Li et al. 2019), urban agglomerations (Chu et al. 2017; Zhang et al. 2020a), county scales (Fu et al. 2020; Jin et al. 2021), watershed scale (Yu et al. 2014; Gao et al. 2020), and national and global scale (Cheng et al. 2021; Huang et al. 2020a). Coastal and riverside areas are naturally more likely to form urban areas, while there is also competition for land resources (Jin et al. 2018; Zhang et al. 2022a), and urban area is a concentrated region where

the intersection of natural environment and human society. Therefore, strengthening the study of ES in typical regions is necessary to maintain ecological health as well as to ensure sustainable socioeconomic development. And remote sensing provides excellent technical support for ecological health surveys (Abbaszadeh Tehrani et al. 2022).

China is experiencing significant urbanization. The provincial capital cities of China, such as Hangzhou, Wuhan and Jinan, have attracted attention to their ES (Cen et al. 2015; Gao et al. 2017; Huang et al. 2020b). There were generally increasing trend of intensive land use system and landscape ecological security in Hangzhou from 1992 to 2012 based the pressure-state-response model (Cen et al. 2015). Not only the pressure-state-response model was used to assess contemporary ES, cellular automata have also been used to simulate and predict urban ES in Wuhan, and economic development and urban construction have been found to be important causes of ES changes (Gao et al. 2017). Based on the circuit theory, ecosystem services as ecological sources and biodiversity construction resistance surface were used to assess the ES of Jinan, and this method obtained a spatial pattern of ES at the grid scale (Huang et al. 2020b). More studies have focused on urban agglomerations in China. The Beijing-Tianjin-Hebei urban agglomeration is a representative urban agglomeration in North China, where the ES risk was high and the ES was generally unsafety from 2005-2018, with the northern outperforming the southern and spatial differentiation increasing, considering ecosystem service supply as an effective reference for ES assessment (Chu et al. 2017; Peng et al. 2021; Zhang et al. 2017). The Yangtze River Delta Urban Agglomeration has the highest GDP and the largest population in China. Rapid changes in anthropogenic land use threaten ecological security, and therefore are applied to construct ES patterns, indicating that the level of urbanization was inversely proportional to the level of ES (Zhang et al. 2020a; Zhang et al. 2022b). In addition, technique for order of preference by similarity to an ideal solution method and gray correlation method showed that urbanization, ecological pathology, economic development, population pressure, land pressure and water pressure drive the change of ES pattern in the region (Huang et al. 2021). The results of these case studies show that the application of methods with different focuses to ES assessment in different regions has obtained abundant reference material. Unifying one method does not necessarily lead to great results. On the contrary, it is needed to enrich the research in this field with multiple methods. The existing evaluation mainly considers one or more aspects of ecological security, and cannot fully present comprehensive ecological security. The latter needs to consider comprehensive factors such as natural environment, landscape structure, ecological restoration, and socio-economic conditions.

The Guangdong-Hong Kong-Macao Greater Bay Area (GHMGBA) is a highly urbanized region and one of the major urban agglomerations in South China. ES assessment has been carried out in several cities of GHMGBA, such as Guangzhou, Foshan, and Pearl River Delta (Zhang et al. 2006; Gong et al. 2009; Li et al. 2020a; Jiao et al. 2021). More and more studies have been conducted with GHMGBA as a whole and analyzing the gradient characteristics. This study aims to assess the spatial-temporal characteristics of ES in GHMGBA from 2000-2018. Two new perspectives, an assessment methodology based on four subsystems, and an analysis of the spatial-temporal characteristics from an urban-rural gradient. Strengthening the study on ES in this region could help to reconcile the relationship between economy and environment, which is conducive to the sustainable development of urban agglomerations, and also provide a reference for related studies.

Materials and methods

Study area

The GHMGBA (21°33′-24°24′N, 111°21′-115°25′E) is located in the coastal area of South China, with high topography in the north and low topography in the south, generally flat and open, and the plain accounts for 66.7% of the total area of the region (Fig. 1). This area has a subtropical monsoon climate (Wang et al. 2021a), with well hydrothermal conditions, annual precipitation of more than 1500 mm, average annual temperature of 20-25°C, and subtropical evergreen broad-leaved forests as the main vegetation type. The GHMGBA has 11 cities, including nine cities in Guangdong Province (Guangzhou, Foshan, Dongguan, Shenzhen, Huizhou, Zhongshan, Zhuhai, Zhaoqing, and Jiangmen), Hong Kong, and Macao (Fig. 1), and it aims to become one of the four major global Bay Areas. The GHMGBA has economic development rapidly in recent decades, with strong land use change (Yang et al. 2021), rapid expansion of urban space (Zhang et al. 2020b), large differences in comprehensive carrying capacity among cities (Weng et al. 2020), as well as the disturbance of the ecosystem by human activities has deepened significantly (Wang et al. 2022).

Research framework and data

The implementation of GHMGBA comprehensive ecological security assessment involves four steps (Fig. 2): (1) understanding the natural environment and socio-economic conditions of GHMGBA; (2) Establish an evaluation dataset based on the comprehensive ecological security index; (3) Analyze the characteristics of the ecological security
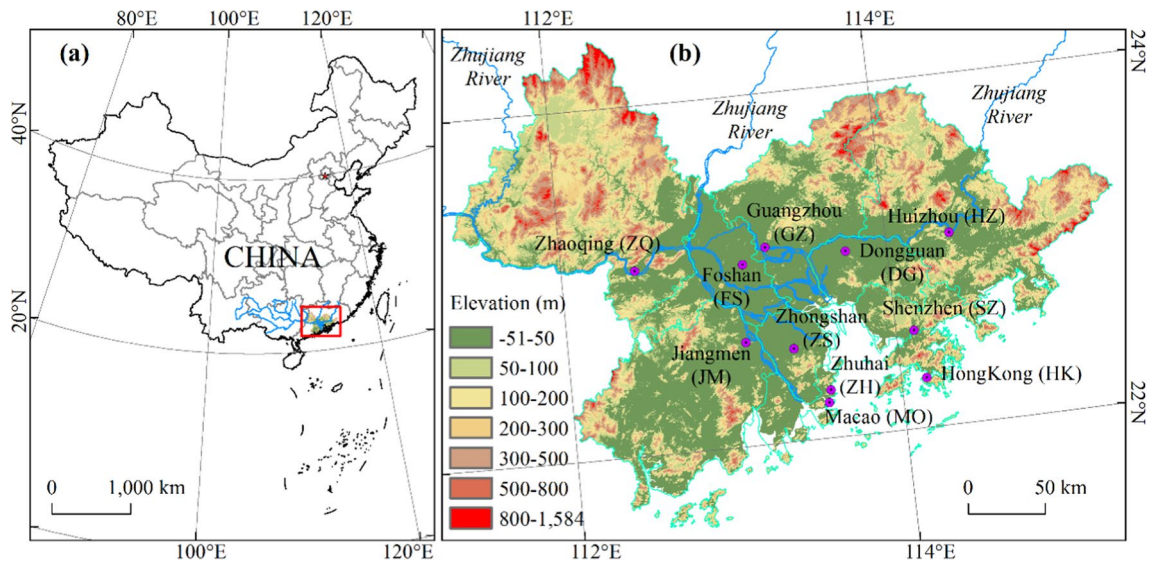
Fig. 1 Location and elevation of the Guangdong-Hong Kong-Macao Greater Bay Area (GHMGBA). (**a**) Location of GHMGBA in South China; (**b**) Distribution of 11 cities in GHMGBA
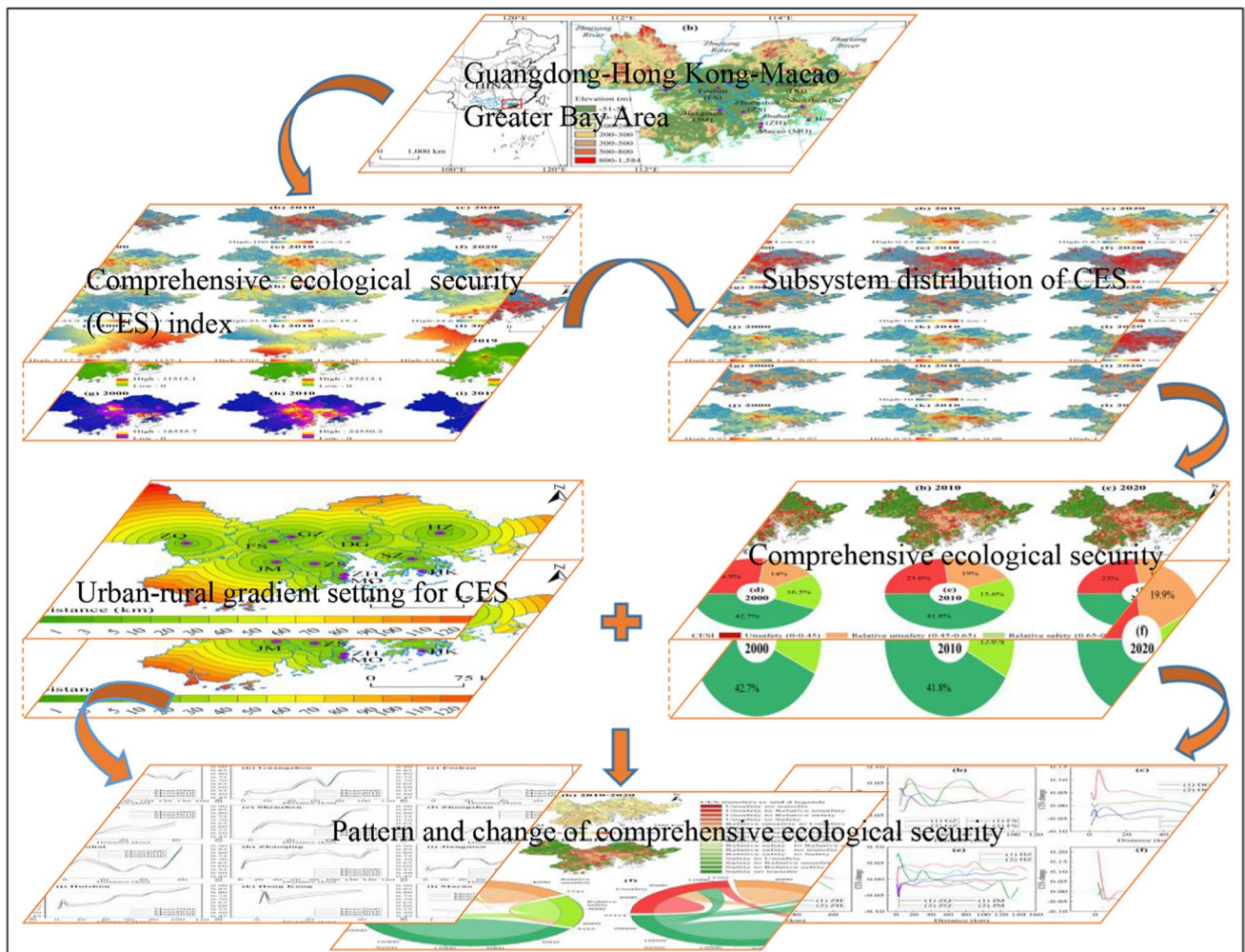

Fig. 2 Research framework

subsystem; (4) Analyze the comprehensive ecological pattern and changes based on spatial and urban-rural gradients.

There are five types of data are provided. The climate data, include the annual mean temperature and annual precipitation for 2000, 2010 and 2020, comes from China Meteorological Data Service Centre (http://data.cma.cn). Based on ArcGIS 10.2 platform, Kriging interpolation method is used to spatialize climate data (1×1 km). The land use/land cover (LULC) and normalized difference vegetation index (NDVI) (1×1 km) for 2000, 2010 and 2020 are from Resource and Environmental Science Data Center (RESDC, http://www.resdc.cn/), Chinese Academy of Sciences. In addition, the spatial distribution data (1×1 km) of population and gross domestic product (GDP) in 2000, 2010 and 2019 are also from the RESDC. ArcGIS 10.2 and Origin 2021 are used for data processing and drawing.

Evaluation model of comprehensive ecological security

The CES model includes four aspects: regional natural base, landscape structure, ecosystem stability and anthropogenic interference, which is calculated as follows (Kang et al. 2007):

$$CESI = \frac{NNBI + NLSI + NSBI + (1 - NAII)}{4} \quad (1)$$

Where, $CESI$ is the comprehensive ecological security index; $NNBI$ is the normalized regional natural base index; $NLSI$ is the normalized landscape structure index; $NESI$ is the normalized ecosystem stability index; $NAII$ is the normalized anthropogenic interference index. The natural base index reflect the natural environmental conditions of the study area, which is the basis of landscape ecology. The landscape structure index reflects the fragmentation degree of the landscape and the aggregation degree of individual distribution of different patch numbers. The ecosystem stability index describes the resistance and resilience of an ecosystem when it is disturbed by the outside world. Anthropogenic interference indicate the degree of external interference in the area. They are extremely important for comprehensive ecological security evaluation.

Natural base index (NBI)

Biological, vegetation, and climatic are important factors to measure the impact of natural base on ecosystems. In this study, these factors were weighted and superimposed as the NBI of the study area, calculated as follows:

$$NBI = \lambda_b NI_b + \lambda_v NI_v + \lambda_c NI_c \quad (2)$$

Where, NI_b is the normalized biological abundance; NI_v is the normalized vegetation cover index; NI_c is the normalized climate index; λ_b, λ_v and λ_c are weight of the three indexes, which are set as 0.4, 0.3 and 0.3, respectively, based on the regional overview and relevant references (Guo et al. 2017; MEPPRC 2015). Biological abundance is an excellent indicator for evaluating the natural environment, reflecting the climate and environmental conditions to a certain extent, and is a relatively comprehensive indicator, so it has a larger weight. Vegetation cover can be more sensitive to environmental changes and easy to monitor through remote sensing technology. Climate is an indicator of obvious changes in the external environment, and the statistical data are relatively reliable.

(1) Biological abundance index, which refers to the difference in the number of biological species per unit area between different ecosystem types, and can indirectly reflect the degree of biological abundance (Fig. 3a-c). The calculation formula is as follows (Guo et al. 2017):

$$I_b = A_{bio} \times (0.35 \times FL + 0.21$$
$$\times GL + 0.28 \times WB + 0.11 \quad (3)$$
$$\times CL + 0.04 \times BL + 0.01 \times UL)/TAA_{bio} = 100/A_{max}$$

Where, A_{bio} is the normalized index of biological abundance; FL, GL, WB, CL, BL and UL are forest land, grassland, water body, cultivated land, build-up land and unused land, respectively; TA is the area; A_{max} is the maximum value of biological abundance index before normalization. These formulas are calculated based on China and cover more biological abundance in different environmental backgrounds. This is a wider area and also includes the GHMGBA, so they are basically applicable to the study area.

(B) Vegetation cover index, which can reflect the degree of vegetation sparseness, and NDVI was used to illustrate the vegetation cover status in this study (Fig. 3d-f).

(C) The climate index, which can reflect the climate state of the earth surface, and defined by the superposition of annual mean temperature (weight 0.4) and annual precipitation (weight 0.6) (Fig. 3g-l). Among them, the statistical data of the GHMGBA shows that precipitation has greater spatial variability, so the weight is greater.

Landscape structure index (LSI)

Fragmentation reflects the degree of fragmentation of patches, and separation reflects the degree of separation between patches. They constructed LSI to reflect the degree of habitat security. The calculation formula is as follows:
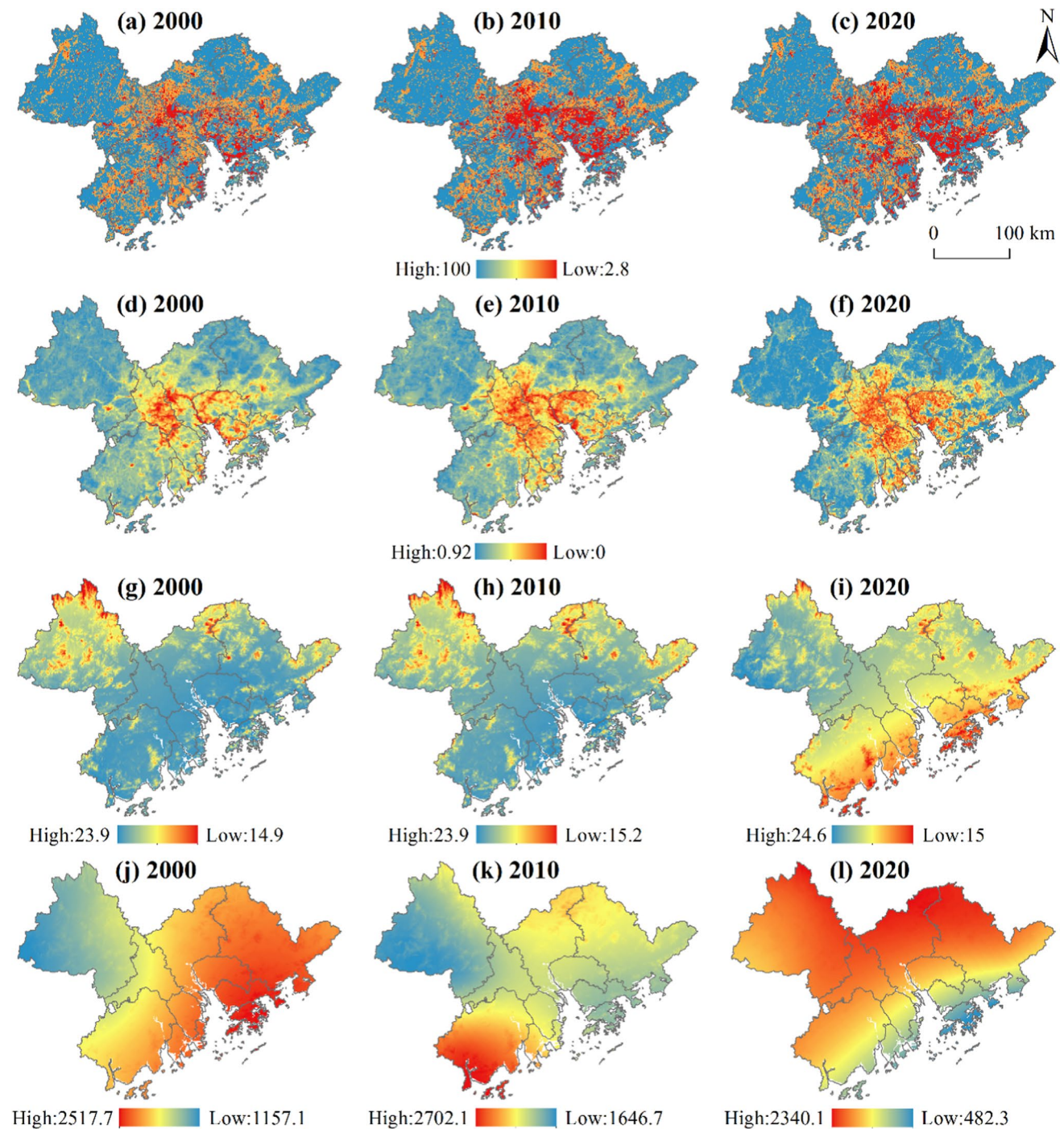
Fig. 3 Factors distribution of natural base index from 2000 to 2020. (**a**)-(**c**) Biological abundance; (**d**)-(**f**) NDVI; (**g**)-(**i**) Temperature; (**j**)-(**l**) Precipitation

$$LSI = 1 - \left(\lambda_{CI} \times CI_k + \lambda_{SI} \times SI_k \right) A_i / A$$
$$SI = \frac{1/2\sqrt{NP_i/TA}}{PA_i/TA} \qquad (4)$$
$$CI = \frac{NP_i}{MPA_i} = \frac{NP_i^2}{PA_i}$$

Where, LSI is landscape structure index; CI is landscape fragmentation; SI is landscape separation, λ_{CI} and λ_{SI} are the weights of fragmentation and separation, respectively; A_i denotes the area of class i landscape and A is the total area of the region; NP is the number of patches; PA is the area of patches; MPA is the average area of patches; TA is the total area of patches. In this study Fragstats 4.2 was used to calculate these indicators (Table 1).

Ecosystem stability index (ESI)

The ecosystem stability includes both resistance stability and resilience stability. Reduced ecosystem stability indicates that the ecosystem is vulnerable. This study assigns values to different land use types to represent ecosystem stability based on previous studies in China and the South China (Chen and Wang 2020; Lin et al. 2020; Guo 2016), which shows that unused and difficult-to-use lands are the most vulnerable and built-up lands are the most stable (Table 1). The reason is that, in general, ecosystems in the primary successional stage, with a simple food chain structure and a low biodiversity index, are more fragile; while ecosystems in areas subject to anthropogenic improvement, with negative entropy input through management, tend to be more stable than other habitat types (Xu et al. 2001).

Anthropogenic interference index (AII)

The anthropogenic interference index is used to characterize the level of anthropogenic influence on the ecosystem. There are three factors in this study, land use disturbance (Table 1) (Wang et al. 2021b, 2022) (weight 0.4), population (weight 0.3) and GDP (weight 0.3) (Fig. 4), whose normalized results are superimposed to define the AII of CES. Where the population and GDP data are less spatially effective and therefore less weighted.

Urban-rural gradient

In order to analyze the spatial characteristics of CES pattern and CES change, buffer zones were constructed along the urban-rural gradient from the urban center (Fig. 5). As the topographic relief of GHMGBA is relatively gentle on the whole, it is acceptable to use equidistant concentric circles as the buffer zones (Dai et al. 2018; Guo et al. 2022). First, the 11 urban centers (administrative center) are input as a whole to create a buffer for the whole region; then, the sub-buffers within each of the 11 cities are clipped; third, the value of CES and CES change corresponding to different distances in the buffer zones are counted respectively, and plotted in statistical charts. Considering that GHMGBA is a whole and each city is a sub-region of the same level, and the traffic and population flows between cities are very frequent, so it is acceptable to set the same buffer zone distance for each city and also convenient to compare the differences between cities.

Results

Subsystem characteristics of comprehensive ecological security

The four subsystems of CES were concentrated in the middle and diffused to the periphery in a point axis manner. Among them, the average value of natural base index was 0.2 to 0.86, the landscape structure index was 0.44 to 0.99, and the ecosystem stability index was 1 to 10, and they take the middle as the low value center. The mean value of anthropogenic interference index was 0.007 to 0.96, and it take the middle as the high value center (Fig. 6).

From 2000 to 2020, the low value area of the natural base index gradually expanded from Guangzhou to the southern

Table 1 Classification of landscape structure, ecosystem stability and land use disturbance based on land use/land cover

	Land use type	LSI			ESI	Disturbance
		2000	2010	2020		
CL	Paddy field, dry land	0.467	0.436	0.418	4	0.76
FL	Forest land	0.978	0.975	0.973	9	0.28
	Shrub land	0.992	0.992	0.992	8	0.46
	Sparse woodland	0.908	0.911	0.91	7	0.53
	Other woodland	0.935	0.872	0.891	6	0.63
GL	high coverage grassland	0.955	0.959	0.957	7	0.42
	medium coverage grassland	0.999	0.999	0.999	6	0.57
	low coverage grassland	1	1	1	5	0.71
WB	River and canal	0.979	0.979	0.977	3	0.5
	Lake and reservoir	0.915	0.919	0.92	2	0.29
	Shoal and beach land	0.998	0.998	0.998	2	0.23
	Sea	1	1	1	2	0.1
BL	City and town, rural residential area land	0.786	0.718	0.665	10	0.96
UL	Unused or difficult to use land	1	1	1	1	0.25

Note: CL, FL, GL, WB, BL and UL represent cultivated land, forest land, grassland, water body, build-up land and unused land, respectively.
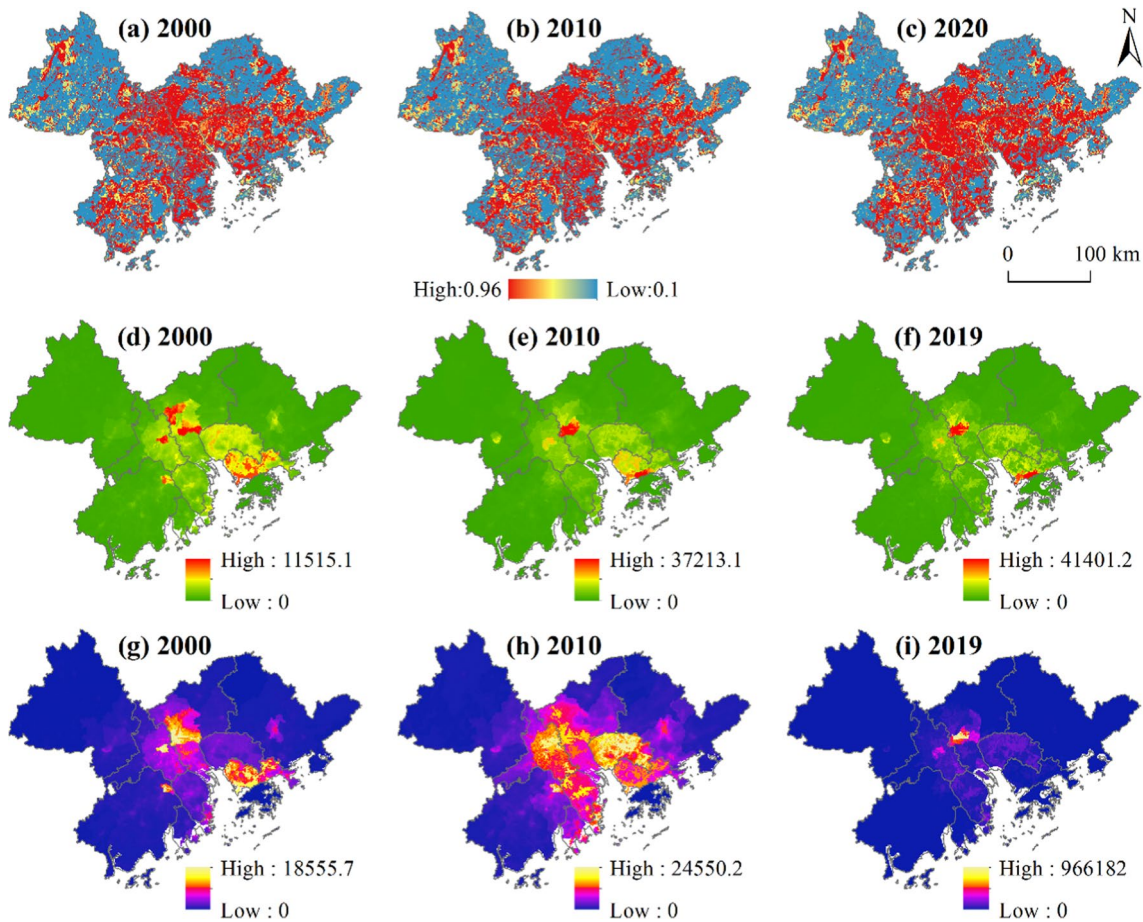
Fig. 4 Factors distribution of anthropogenic interference index. (**a**)-(**c**) Land use based HDI (from 2000 to 2020); (**d**)-(**f**) Population (person/km^2) (from 2000 to 2015); (**g**)-(**i**) GDP (10000 yuan/km^2) (from 2000 to 2015)
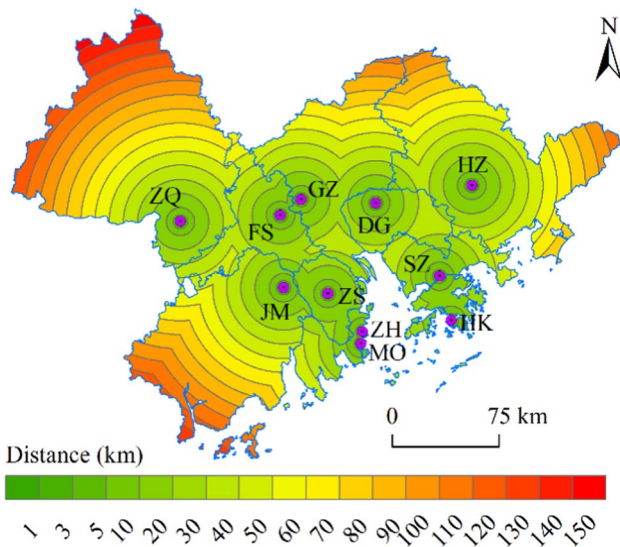

Fig. 5 City centered buffer zones setting

cities, indicating that the natural base condition gradually deteriorated; the landscape structure index had a large low value area, indicating that the landscape structure was poor overall; the low value area of the ecosystem stability index decreased, indicating that the ecosystem stability increased; the high value area of the anthropogenic disturbance index expanded significantly, indicating that the disturbance of human activities to ecosystem had increased significantly.

Comprehensive ecological security

Comprehensive ecological security pattern

The CES evaluation results of the study area were obtained by superimposing the regional natural base index, landscape structure index, ecosystem stability index and anthropogenic interference index. The values of the CES index in the GHMGBA in 2000, 2010 and 2020 were 0.228-0.919 (mean 0.687), 0.223-0.924 (mean
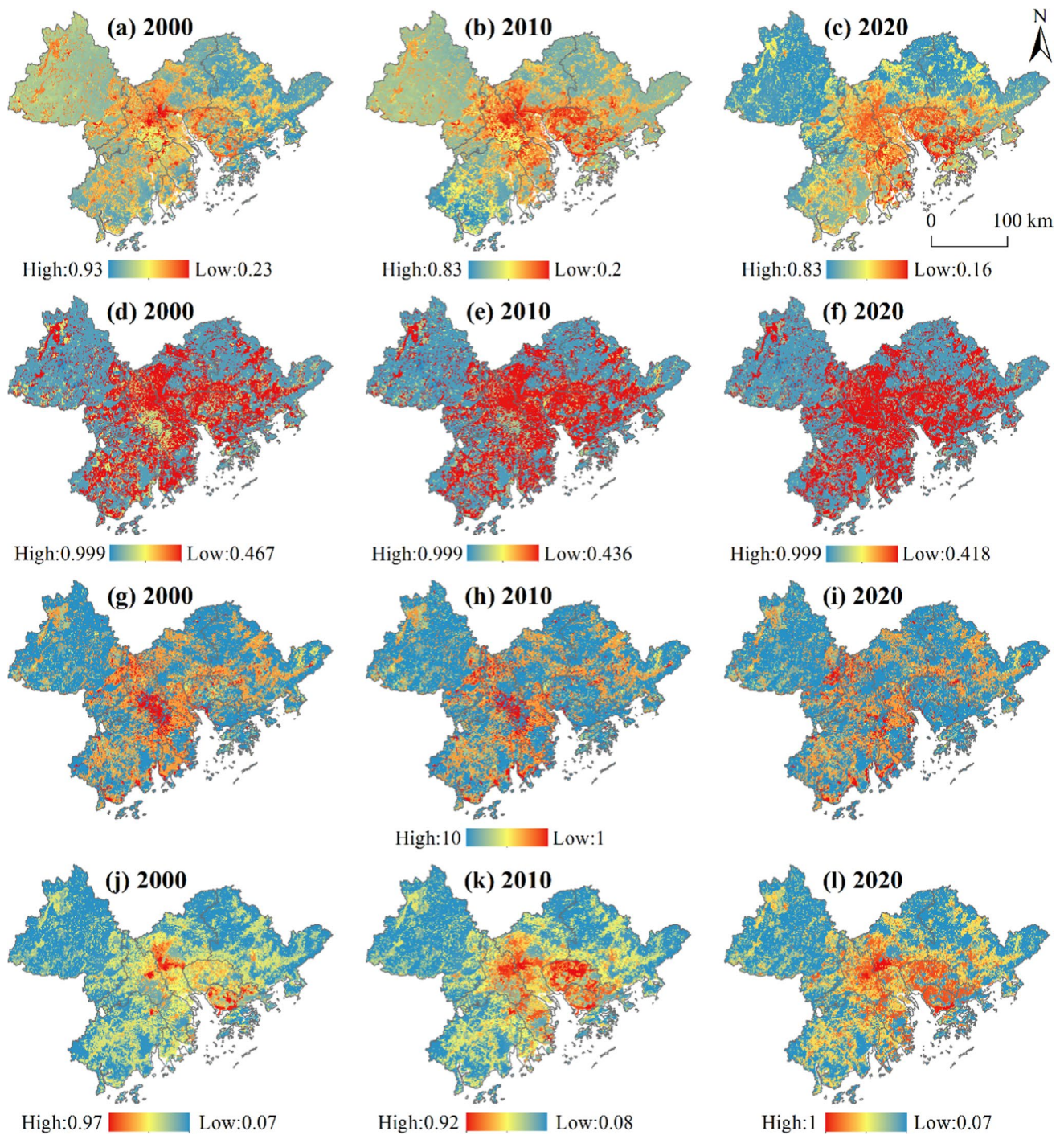
Fig. 6 Subsystem distribution of CES from 2000 to 2020. (**a**)-(**c**) Natural base index; (**d**)-(**f**) Landscape structure index; (**g**)-(**i**) Ecosystem stability index; (**j**)-(**l**) Anthropogenic interference index

0.679) and 0.294-0.918 (mean 0.701), respectively, indicating that the ES of the study area was generally well. Referring to the Jenks Natural Breaks method, the CES were classified into four levels (Fig. 7a-c).

The safety region were distributed periphery of the GHMGBA, concentrated in Zhaoqing, northern Guangzhou, eastern and northern Huizhou, Hong Kong, Shenzhen, and Jiangmen, area proportions from 41.8% to 46% (mean 43.5%) (Fig. 7). The unsafety region were concentrated in the central regions of Guangzhou, Foshan, Zhongshan, and Dongguan, area proportions from 23% to 26.9% (mean 24.5%). The relative unsafety and
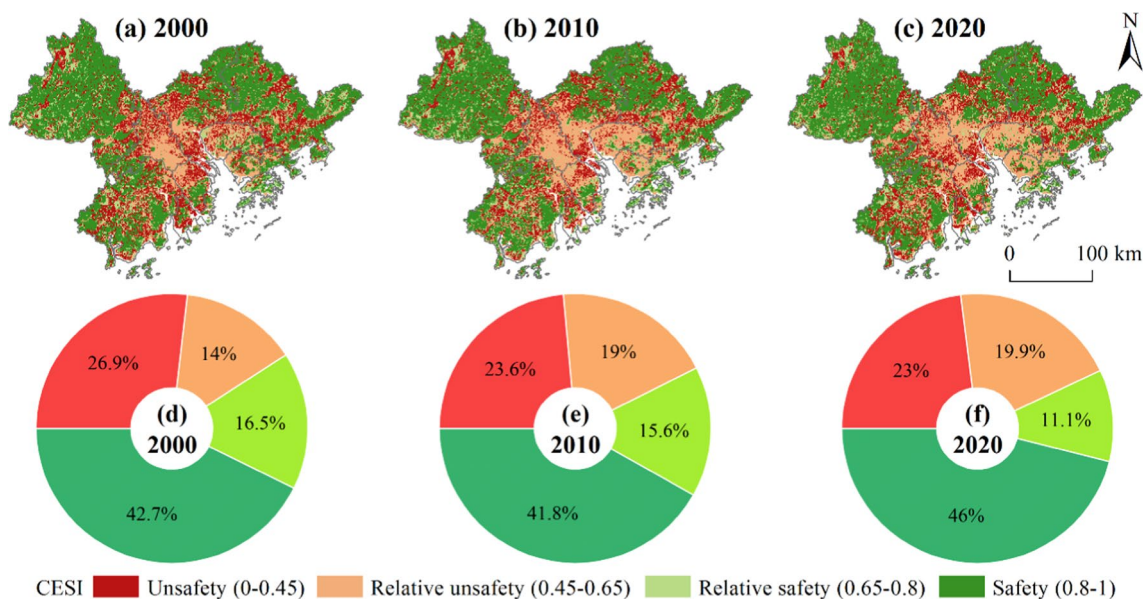
Fig. 7 CES distribution aggregation characteristics from 2000 to 2020. (**a**)-(**c**) CES distribution (**d**)-(**f**) Area proportion statistics

relative safety region were distributed in the transition zone, area proportions from 14% to 19.9% (mean 17.6%) and from 11.1% to 16.5% (mean 14.4%), respectively. The GHMGBA is mainly surrounded by forest land, with high stability index and weak human disturbance, and the regional natural base index and landscape structure index are high, so the CES index is high and the ecosystem is stable. The central of the GHMGBA is mainly construction land, which increased rapidly during the study period. Although the ecosystem stability is high, there is strong anthropogenic interference, poor regional natural base and fragmented landscape structure, so the CES index is low and the ecosystem is unstable.

Urban-rural gradient of comprehensive ecological security

The urban-rural gradient of CES distribution showed a fluctuating increasing trend of CES in 2000, 2010 and 2020 with increasing distance from the city center, indicating that the further away from the city, the safer the ecosystem (Fig. 8). For the GHMGBA as a whole and the nine cities in Guangdong (Guangzhou, Foshan, Dongguan, Shenzhen, Zhongshan, Zhuhai, Zhaoqing, Jiangmen, and Huizhou), the CES decreased slightly at about 20-40 km, 60-80 km, and 120-140 km from the city center, respectively, which may be due to the suburban region leading to a lower CES (Fig. 8a-j).

The overall CES of GHMGBA was relative unsafety (CES < 0.65), relative safety (0.65 < CES < 0.8) and safety (CES >0.8) at 0-40km, 40-140km and greater than 140km,

respectively (Fig. 8a). At 40-50km, Guangzhou, Foshan, Dongguan, Shenzhen, Zhuhai, Jiangmen and Huizhou, elevated from relative unsafety to relative safety (Fig. 8b-e, g, i-j). Zhongshan has been in a relative unsafety state (Fig. 8f). Zhaoqing was relative safety and safety about greater than 5 km, with the highest CES of GHMGBA (Fig. 8h). CES in Hong Kong was relative safety and safety (Fig. 8k). The area of Macao is small, and CES also showed a fluctuation upward trend from the city center to the outside (Fig. 8l).

Comprehensive ecological security change

Comprehensive ecological security pattern change

From 2000 to 2020, the spatial distribution of CES in the study area changed little on the whole, and there were differences in the area proportions at different levels. The proportion of unsafety and relative safety regions decreased by 3.9% and 5.4% respectively, and the proportion of relative unsafety and safety regions increased by 5.9% and 3.3% respectively (Fig. 7).

In addition, the change characteristics of CES in the two transition periods of 2000-2010 and 2020-2020 were obtained by subtracting 2000 from CES in 2010 and subtracting 2010 from CES in 2020. The spatial characteristics of CES changes also showed smaller changes in CES for the two transitional periods (Fig. 9a, b). In 2000-2010, CES changes from -0.37 to 0.52 (mean -0.009), with an overall decrease, and slightly significant in Dongguan, Foshan and
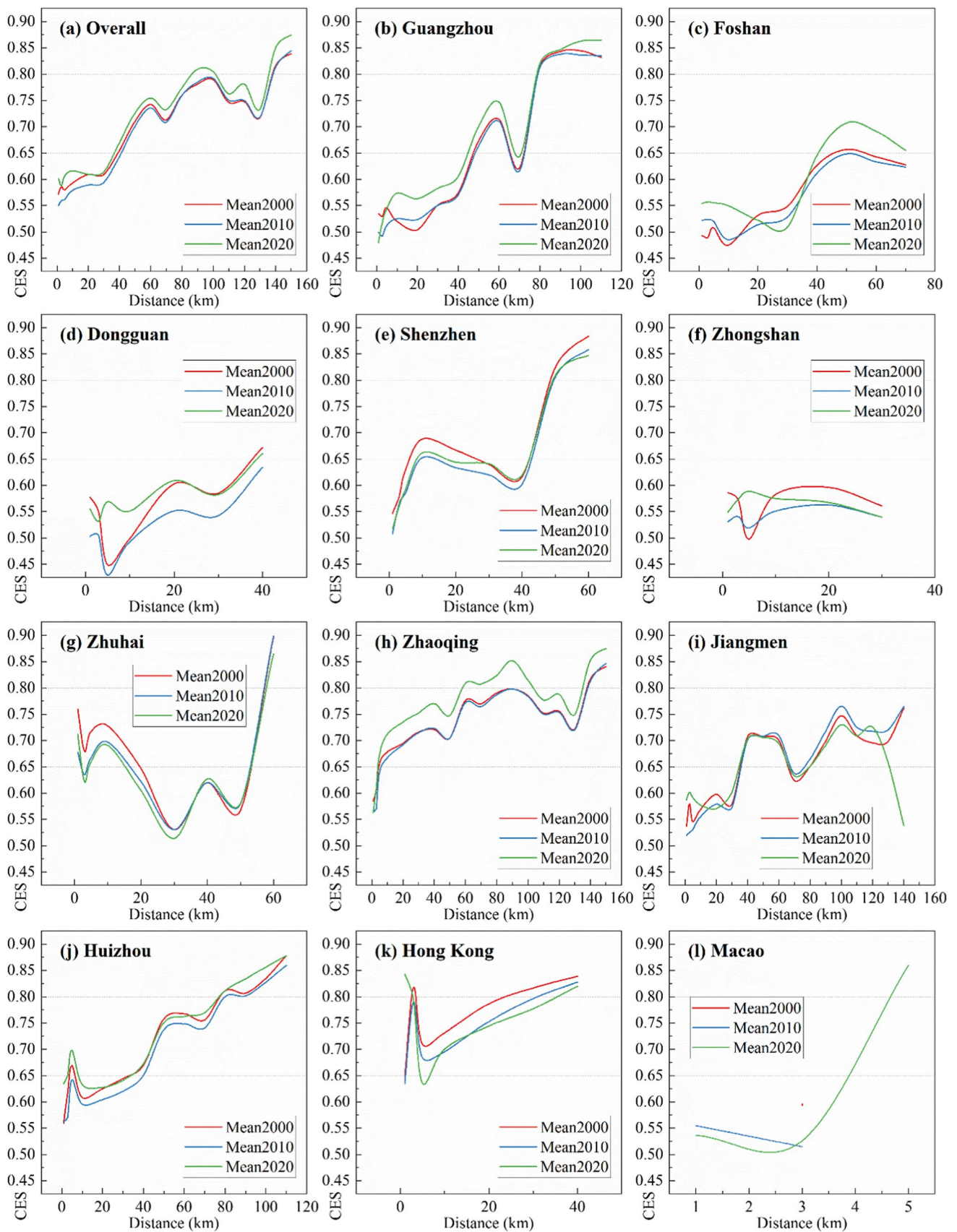
Fig. 8 Urban-rural gradient of CES pattern. (**a**) Overall results of GHMGBA; (**b**)-(**l**) results in different cities
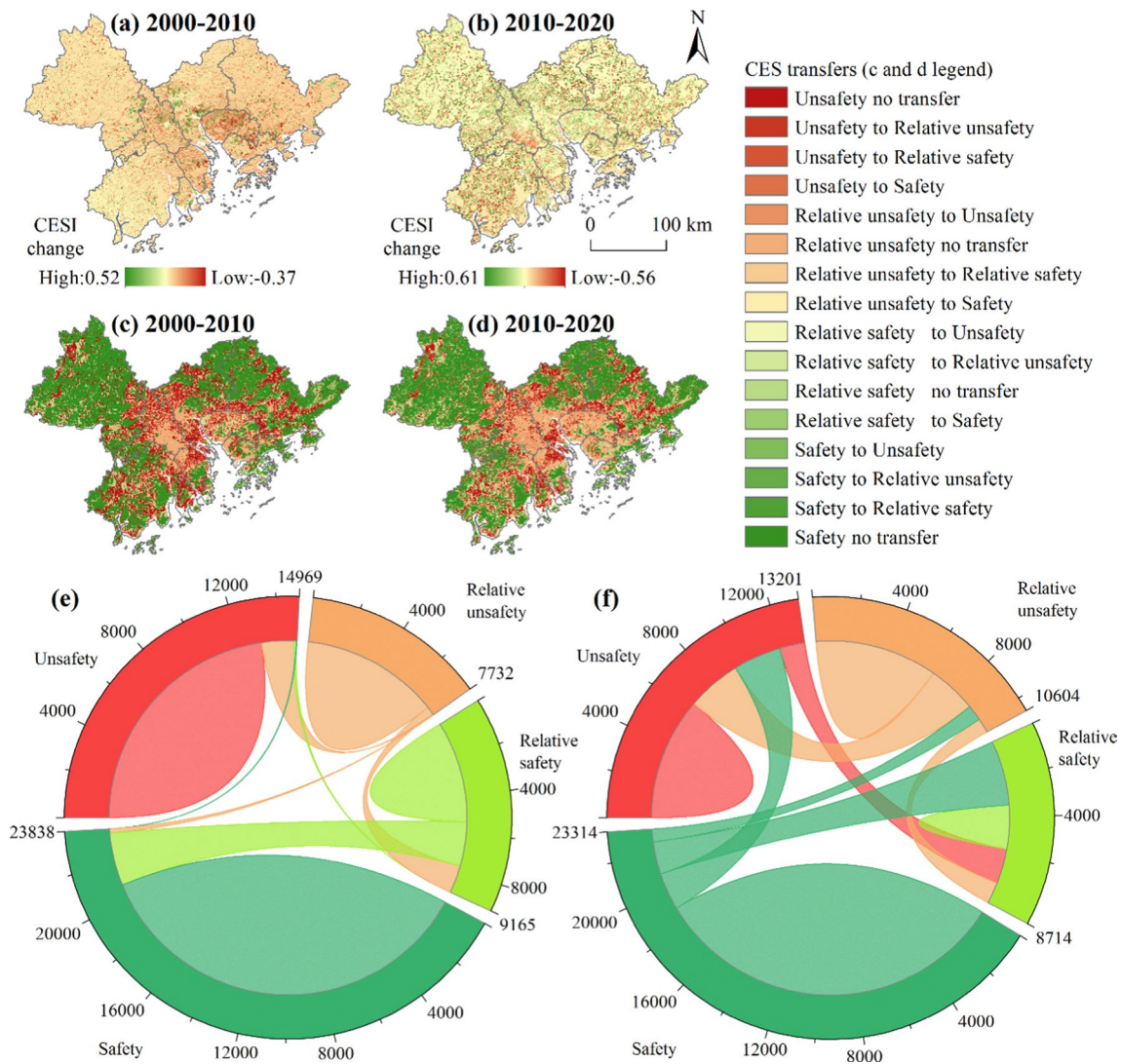
Fig. 9 CES changes and transfers from 2000 to 2020. (**a**)-(**b**) CES changes from 2000 to 2010 and from 2010 to 2020; (**c**)-(**d**) CES transfers from 2000 to 2010 and from 2010 to 2020; (**e**)-(**f**) CES transfers chord diagram from 2000 to 2010 and from 2010 to 2020

Zhongshan (Fig. 9a). In 2010-2020, CES changes from -0.56 to 0.61 (mean 0.022), with increased spatial heterogeneity, and both increasing and decreasing CES regions were distributed in GHMGBA (Fig. 9b).

The transfer characteristics of different levels of CES showed that each levels was dominated by non-transfer (Fig. 9c-f). For the spatial distribution, the transfer between different levels mainly occurs in the transition zone, with the central of GHMGBA mainly transferred between unsafety and other three levels, and the periphery mainly transferred between safety and other three levels (Fig. 9c, d). For the transfer region, in 2000-2010, unsafety, relative unsafety, relative safety and safety were transferred sequentially (Fig. 9e); and in 2010-2020, the transfer between each levels and the other three classes was very frequent (Fig. 9f),

indicating that the spatial-temporal pattern of CES fluctuated sharply during this period.

Urban-rural gradient of comprehensive ecological security change

The urban-rural gradient of CES changes showed that most of the changes were from -0.05 to 0.05, with many of the changes in 2000-2010 being below 0 and those in 2010-2020 being mostly above 0 and fluctuating slightly significantly (Fig. 10). Overall, with increasing distance, the characteristics of CES changes in 2000-2010 tended to be constant from decreasing, and fluctuated between 0.01 and 0.05 in 2010-2020 (Fig. 10a). The change of CES in Guangzhou and Foshan had more obvious fluctuations in 20-40 km and
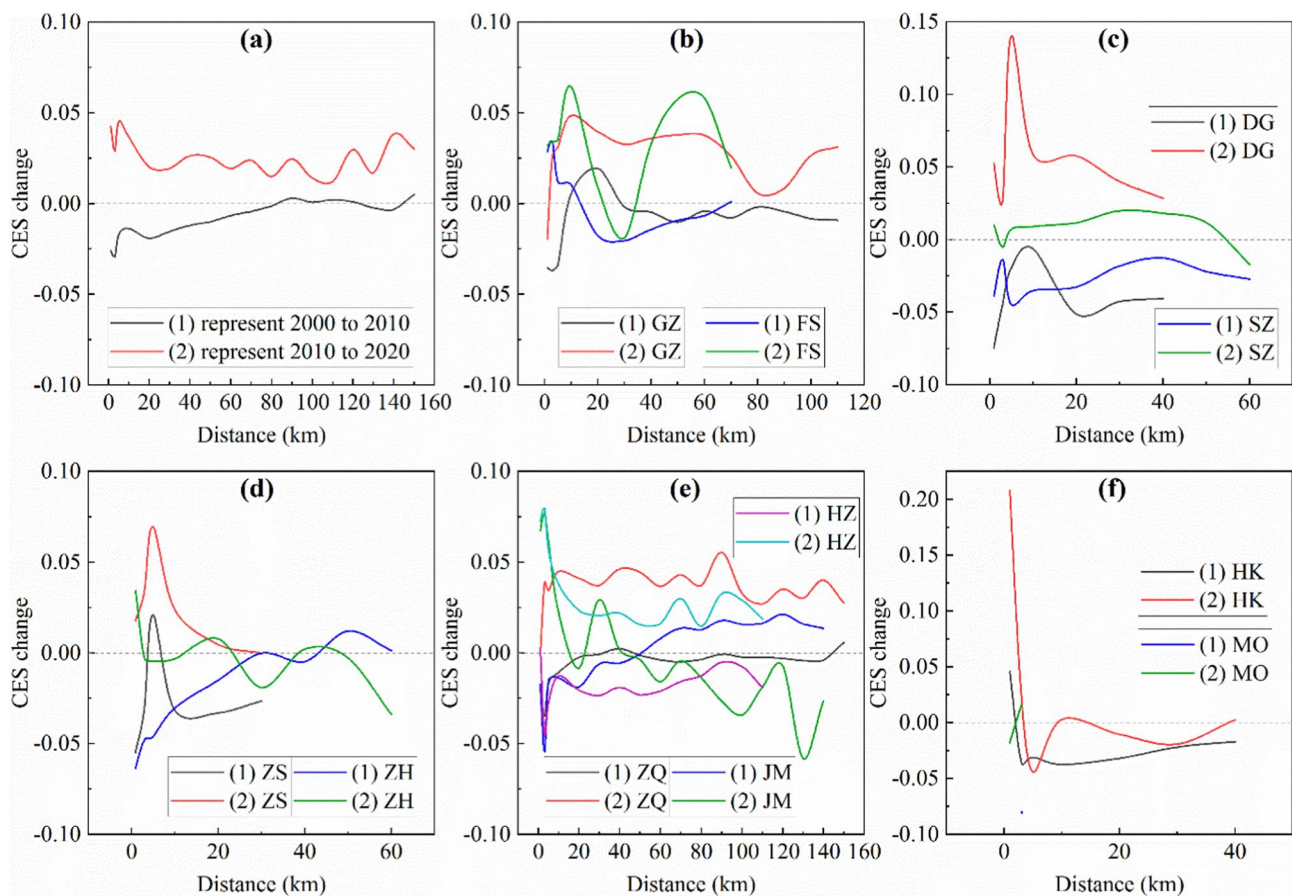
Fig. 10 Urban-rural gradient of CES change. (**a**) Overall results of GHMGBA; (**b**)-(**f**) results in different cities. In the legend, (1) and (2) represent from 2000 to 2010 and from 2010 to 2020 respectively

60-100 km (Fig. 10b). The CES changes in Dongguan and Shenzhen were clearly bounded by 0 (constant) around 2010, which was consistent with the overall trend, and Dongguan had significant changes within 0-10km (Fig. 10c). As the distance increases, the CES change in Zhongshan and Zhuhai gradually tends to 0 (Fig. 10d). Huizhou, Zhaoqing and Jiangmen are at the periphery of GHMGBA, and the three cities had insignificant changes of CES after greater than 10 km, excepted for Jiangmen, where CES gradually got worse with increasing distance from 2010-2020 (Fig. 10e). Hong Kong had the most significant decreasing trend at 0-10 km (Fig. 10f).

Discussion

Ecological security assessment methods

There are many methods used to evaluate ES. The minimum cumulative resistance model (Peng et al. 2018; Dong et al. 2019; Liu et al. 2020; Dai et al. 2021; Zhou et al. 2021), the pressure-state-response model (Du et al. 2013; Gao et al.

2017; Ou et al. 2017; Wang et al. 2019; Huang et al. 2021) and their improved methods (Peng et al. 2021) are well generalized and have been widely used. In addition, fuzzy mathematics (Jiang 2011), projection pursuit (Gao et al. 2012), ecological (renewable/emergy) footprint (Li et al. 2014; Bi et al. 2020; Zhang and Ma 2021), entropy matter-element model (Wu et al. 2019), circuit theory (Huang et al. 2020b), DEMATEL-ANP (Ghosh et al. 2021), and InVEST models (Moarrab et al. 2021) have also been applied to ES assessment in different regions.

These methods have assessed regional ecological security from different perspectives, providing a rich choice of methods and comparisons for relevant studies in different regions. However, they are still inadequate in evaluating the impact of regional landscape units or spatial structure of cover types on ES (Kang et al. 2007). Whether an ecosystem is safety or not is related to its constituents and external disturbances. Therefore, the evaluation of ecosystem security can be considered from multiple perspectives such as natural background, ecosystem and external disturbance, and the CES model in this study is considering these aspects. In particular, the model was better applied in a typical urban

agglomeration of a typical developing country. This helps to enrich the application cases of this model.

Differences and similarities of ecological security in the different studies

In this study, the ES of the GHMGBA was comprehensively evaluated using the natural base and landscape pattern indices, and the results showed that the ecosystem of the central developed cities was unsafety and the surrounding less developed areas was safety. However, Han et al. (2016) evaluated the land ES pattern of the Pearl River Delta urban agglomeration from four aspects: land use resource utilization, economic development level, environmental condition, and coordinated social development, which is basically opposite to the results of this study. The reason for this may be the difference in evaluation perspectives. Han et al. (2016) mainly used socio-economic indicators and most of the indicators reflected positive correlation with land ES in terms of high and low values, so that Shenzhen and Guangzhou had the highest land security. More relevant studies have well correspondence. Zhang et al. (2006) analyzed the general characteristics of ES in the developed city of Foshan in the GHMGBA in terms of ecological carrying capacity and ecological risk, Gong et al. (2009) assessed and predicted the ES of Guangzhou City using cellular automata model in four aspects (ecosystem service, vegetation cover, transportation, urban built-up area), Jiao et al. (2021) constructed an early warning pattern of ES in the Pearl River Delta using landscape disturbance and vulnerability, Gao et al. (2010, 2012) constructed and calculated a landscape vulnerability index and a landscape security adjacency index based on the projection pursuit method to assess the landscape ES, Hu et al. (2018), Wen et al. (2020), Li et al. (2020a) and Li et al. (2020b) assessed the urban ES of the Pearl River Delta using the pressure-state-response model, and Wu et al. (2020), Wang et al. (2021c) and Zhou et al. (2020) assessed the ES based on the minimum cumulative resistance model from ecosystem services. The results obtained by these methods are basically consistent with the ES pattern of this study, indicating that the basic results between different methods could be compared with each other, and also shows that the results of this study are reasonable. Compared with the indicator method and pressure-state-response model, which evaluate from the urban perspective, this study makes the spatial pattern more refined based on raster data; compared with the minimum cumulative resistance model, which is also based on the raster scale, the comprehensive evaluation perspective of this study is relatively comprehensive entire.

Policy implications and deficiency

Environmental problems caused by economic and social development have prompted the government and society to pay attention to ES. For example, Guangzhou, Dongguan, Zhuhai, Huizhou and Zhaoqing within GHMGBA have successfully established a national forest city, Shenzhen has successfully established a national green and low-carbon city, Zhongshan has established a national demonstration city for ecological civilization construction, Foshan has implemented the construction of 55 ecological parks, and Jiangmen actively carried out the "100 day remediation action of environmental law enforcement" (Hu et al. 2018). Based on the results of our ES, there are some suggestions that can be provided. (1) Conduct an ES survey and delineate key protection areas. Firstly, we should conduct an ES survey and analyze in detail the distribution of different ES levels in the region and the specific problems faced. On this basis, then divide the key protection areas, such as the unsafety areas caused by human activities. (2) Construction of ecological corridors to link isolated ecological parks. In this study, some isolated ecological safety zones are distributed in the ecologically unsafety and relatively unsafety areas in and around the city. Ecological corridors are used to link these isolated ecological circles and prevent them from disappearing. (3) Rational planning of land space to avoid disorderly expansion of urban land. In this study, ecological unsafety and relative unsafety areas are mainly distributed in and around cities, which suggests that we need to rational use land resources in urban and rural planning, make full use of the original ecosystem, and avoid disorderly development leading to irreversible destruction of the ecosystem.

There are also shortcomings in the indicators and model used in this study. The interannual fluctuations of climate elements such as temperature and precipitation in the natural base index are relatively obvious, which may affect the results. Subsequent studies may consider using multi-year averages to reduce the adverse effects of interannual fluctuations if longer time scales can be involved. In addition, considering the importance of ecosystem structure, internal function, stability and external disturbance to maintain ecological security, the four subsystems of the CES evaluation are equally weighted, and there is no spatial difference, but there may be differences in practice, which need to be further quantified in subsequent studies.

Conclusion

In this study, comprehensively evaluated the ES of Guangdong-Hong Kong-Macao Greater Bay Area (GHMGBA) in 2000, 2010 and 2020 from four aspects: natural base, landscape structure, ecosystem stability, and anthropogenic interference. The four subsystems of CES were concentrated in the middle and diffused to the periphery in a point axis manner.

The mean values of the CES index in the GHMGBA in 2000, 2010 and 2020 were 0.687, 0.679 and 0.701,

respectively, indicating that the ES of the study area was generally well. The safety and unsafety region were distributed periphery and central regions in GHMGBA. Area proportions of unsafety, relative unsafety, relative safety and safety were 24.5%, 17.6%, 14.4% and 43.5%, respectively. The urban-rural gradient of CES distribution showed a fluctuating increasing trend of CES in 2000, 2010 and 2020 and decreased slightly at about 20-40 km, 60-80 km, and 120-140 km with increasing distance from the city center.

The spatial characteristics of CES changes showed smaller changes in CES for the transitional periods of 2000-2010 and 2010-2020. The transfer characteristics of different levels of CES showed that each levels was dominated by non-transfer. For the transfer region, unsafety, relative unsafety, relative safety and safety were transferred sequentially in 2000-2010; and the transfer between each levels and the other three classes was very frequent in 2010-2020. The urban-rural gradient of CES changes showed that the changes gradually decreases with increasing distance from urban centers.

The CES model in this study considers four aspects of the ecosystem and external environment, which is an important complement to the ES assessment methods. The CES results of GHMGBA can be compared with the relevant results of other methods, indicating the reasonableness of the results of this study. This study helps to understand the temporal and spatial distribution of ecological environment and urban-rural gradient in typical urban regions, and provides a reference for the collaborative planning of urban agglomeration.

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Data availability All data supporting the findings of this study are included within the article. Data will be made available from authors on reasonable request.

Declarations

Ethics in publishing Not applicable.

Consent for publication Not applicable.

Consent to participate Not applicable.

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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