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Evaluating the influence of human disturbance on the ecosystem service scarcity value: an insightful exploration in Guangxi region

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Investigating how human disturbance affects the ecosystem service scarcity value (ESSV) is crucial for maintaining ecosystem stability and achieving sustainable development goals (SDGs). This study separately assessed ESSV and human disturbance in Guangxi from 1990 to 2020, revealing their spatiotemporal distribution differences over time. The environmental Kuznets curve (EKC) is used to analyze the interrelationship between the two, with the purpose of filling the gap in current research. The main results are as follows: (1) From 1990 to 2020, ESSV in Guangxi increased significantly and reached its highest value in 2020. Under the four scenarios, ESSV increased significantly in Scenarios 2 and 4. Spatially, high ESSV was mainly distributed in some cities in central, southern, western and northeastern Guangxi. (2) The index of human disturbance in Guangxi continued to increase during the study period, with a high level of human disturbance in the central urban area and a low level of human disturbance in the peripheral areas, which were distributed in a radial pattern. (3) According to the EKC, the relationship between ESSV and human disturbance in Guangxi followed an inverted N-shaped curve. In addition, after 2010, the coupling and coordination level was dominated by "slightly balanced development", and the area of "ESSV significantly lagged" gradually increased. This study provides a new perspective for understanding ESSV and its relationship with human disturbances, and provides an important reference for the sustainable management of ecosystems and the formulation of ecological conservation policies.

Keywords Ecosystem service scarcity value (ESSV), Human disturbance, Environmental Kuznets curve, Coupling coordination degree (CCD)

Ecosystem services (ESs) encompass a wide range of benefits that humans derive directly or indirectly from the natural environment; these benefits include essential products and services necessary for human survival and are facilitated through the ecological structures, functions, and processes of ecosystems[1,2]. Ecosystem service value (ESV), as a core indicator for measuring ESs, has been widely discussed globally[3]. Costanza et al.[1] first used equivalence to assess the value of global ESs. However, due to ongoing societal development and increasing demands for production and living standards, ESs are becoming scarce[4]. Balancing the supply and demand of ESs while considering current well-being and equity across various scales is a crucial challenge[5,6]. Bryan et al. proposed the concept of the scarcity value of ESs, which reveals the imbalance between the supply of ESs and increasing human demand during social development, thus causing changes in ESV[7,8]. ESSV is a further extension of ES valuation that incorporates changes in supply and demand factors through an economic lens[9]. By increasing the scarcity coefficients of supply and demand, it is possible to capture the impact of land use changes on ESV during human disturbances. Moreover, the 2030 Agenda for Sustainable Development emphasizes the need to address economic, social, and environmental issues comprehensively to achieve the SDGs[10]. In this context, ES is increasingly recognized as a key enabler of the SDG process[11]. Theories of ecosystem service supply and demand assessment are not limited to biodiversity theory[4], landscape ecology theory and ecological economic theory[12], but also extend to stakeholder theory[13] and ecological deficit taxation theory[14]. As a result, methods for quantifying ESSV have gradually diversified, with remote sensing, socioeconomic, meteorological

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and questionnaire data being widely used[15]. Some scholars have evaluated ESSV[16–18]. Kang et al. analyzed the evolving trend of ESV in Chengdu over the past 20 years, by changing the scarcity coefficient under different scenarios[8]. Li et al. analyzed the impact of various factors on ESSV using a certain climate zone in China as an example[19]. Lin et al. introduced a novel model to explore the response of ESSV to land use change[20]. Wang et al. analyzed the spatial and temporal patterns and changes in the supply and demand of ecosystem services in China and explored their interactions in the context of economic development and urbanization drivers[21]. Fang et al. used a geographical detector model to analyze the impacts of climate change and human activities on ecosystem services in different regions of China[22]. Li et al. simulated four ecological restoration scenarios in a typical watershed of the Qinghai-Tibetan Plateau, and quantified and compared the cost-effectiveness of ESVs under these scenarios[23]. Therefore, conducting quantitative analyses of urban development, particularly assessments of the impact of human disturbance on ESs, is highly important for importance in guiding sustainable urban planning.

Ecosystems provide resources and services essential to human society[24], including food production, freshwater and forest resource management, climate and air quality regulation, and pest and disease control, encompassing all facets of human production and life[25]. At present, ESSV has been quantified by various methods[26–28], but the influence of human disturbance on ESSV has rarely been studied, and the influence of market demand factors has been ignored. Yuan et al. argued that urban sprawl diminishes ecosystems and their capacity to offer various benefits to humans, and they suggested that economic development heavily relies on the extent of urban built-up land, thereby increasing ESSV[29]. Zhang et al. suggested that the degree of scarcity of ESs as consumer goods depends on their own supply and the amount of social demand[30]. If market demand for a particular ES function continues to rise, but supply falls short of demand, the scarcity of that type of ES function will increase rapidly[31]. The degree of demand for each type of ES is different, which leads to different values of scarcity for each type of ES, and this difference depends on the public or private attributes of the service[32]. Moreover, since the Industrial Revolution, human disturbance to the ecological environment has exploded on an unprecedented scale, and human disturbance has severely affected the ability of the environment to provide ESs[33]. Among human activities, land-use change may have profound impacts on ecosystems[34]. A large amount of land has been used to build residential, commercial, and industrial sites, leading to the depletion and destruction of land resources[35]. Over-exploitation of land can lead to severe ecological issues, including desertification, ecosystem degradation, and more extreme weather events[36], further intensifying the scarcity of ESs. Some studies have shown that with increasing urbanization level, regional ESSV increases significantly, public goods and services grow faster than private products do, and demand is the main driver of increased scarcity[19,37]. With the advancement of the social economy, human disturbance and ESs have attracted increasing attention from scholars. The relationships between human activities and ecosystems have been explored through the construction of spatial analysis models, and interconnection analysis. Ai et al. reported that human disturbances negatively affect ecosystem services to varying degrees[38], and Chen et al. reported a strong negative correlation between ecosystem services and human disturbances in the Xiangxi region[39], as did Han, Xiao[40,41]. Although the relationship between human disturbance and ESs has been widely explored in the past, the effects of changes in supply and demand on the results have not been considered when discussing the effects of human disturbance on ESs. Therefore, this study confirms the relationship through the environmental Kuznets curve and constructs a coupled coordination model based on human disturbance and ESSV to explore the coupling effects and the level of coordinated development between human disturbance and ESSV at spatial and temporal scales.

The Guangxi Zhuang Autonomous Region is located in the western part of South China. In recent decades, along with the overall development of China's economy, Guangxi's economy has also steadily improved with the pace of the country's development[42]. However, with the rapid development of urbanization and industrialization and the continuation of human disturbances, its ecological environment is facing unprecedented pressure[43]. According to relevant information, during the past thirty years, the average annual temperature in Guangxi has increased by 0.7 °C; the average annual precipitation has increased by 372.16 mm[44]; large amounts of arable land, forestland, and grassland have been transformed into construction land; soil erosion is severe; and rocky desertification is widely distributed[45]. Therefore, in this study, Guangxi, which is located in Southwest China, was used as the study area, the ESSV and human disturbance evaluation index system were established separately, and differences in the spatial and temporal distributions were analyzed. In addition, we utilize the environmental Kuznets curve to verify the relationship between ESSV and human disturbance and design an integrated coupled system covering ESSV and human disturbance. This study focuses on the following questions:1) What are the spatial and temporal trends of ESSV in Guangxi over the past 30 years? 2) How did human disturbance evolve spatially and temporally in Guangxi during this period? 3) What is the relationship between ESSV and human disturbance across different regions, and how does the coupling coordination state vary over time? 4) How can Guangxi achieve sustainable economic and ecosystem development amid rapid urbanization? This study examines the interplay between ESSV and human disturbance, providing not only a scientific basis and decision-making support for the formulation of effective ecological management policies and the promotion of regional sustainable development in Guangxi but also valuable experiences and strategies for the coordinated development of humans and the environment in similar regions across China and even globally.

Materials and methods

Study area

Guangxi (20°54′-26°24′ N, 104°28′-112°04′ E) (Fig. 1) is located in the western part of southern China[46]. It comprises 14 prefecture-level cities and 60 counties (including 12 autonomous counties), with a population of 50.12 million and a total area of 237,600 km^2[47]. Guangxi is bordered by the Gulf of Tonkin to the south, the Nanling Mountains to the north, and the Yunnan-Guizhou Plateau to the west, serving as a transition zone from this plateau to the southeastern coastal hills[48,49]. The terrain is elevated in the northwest and slopes downward

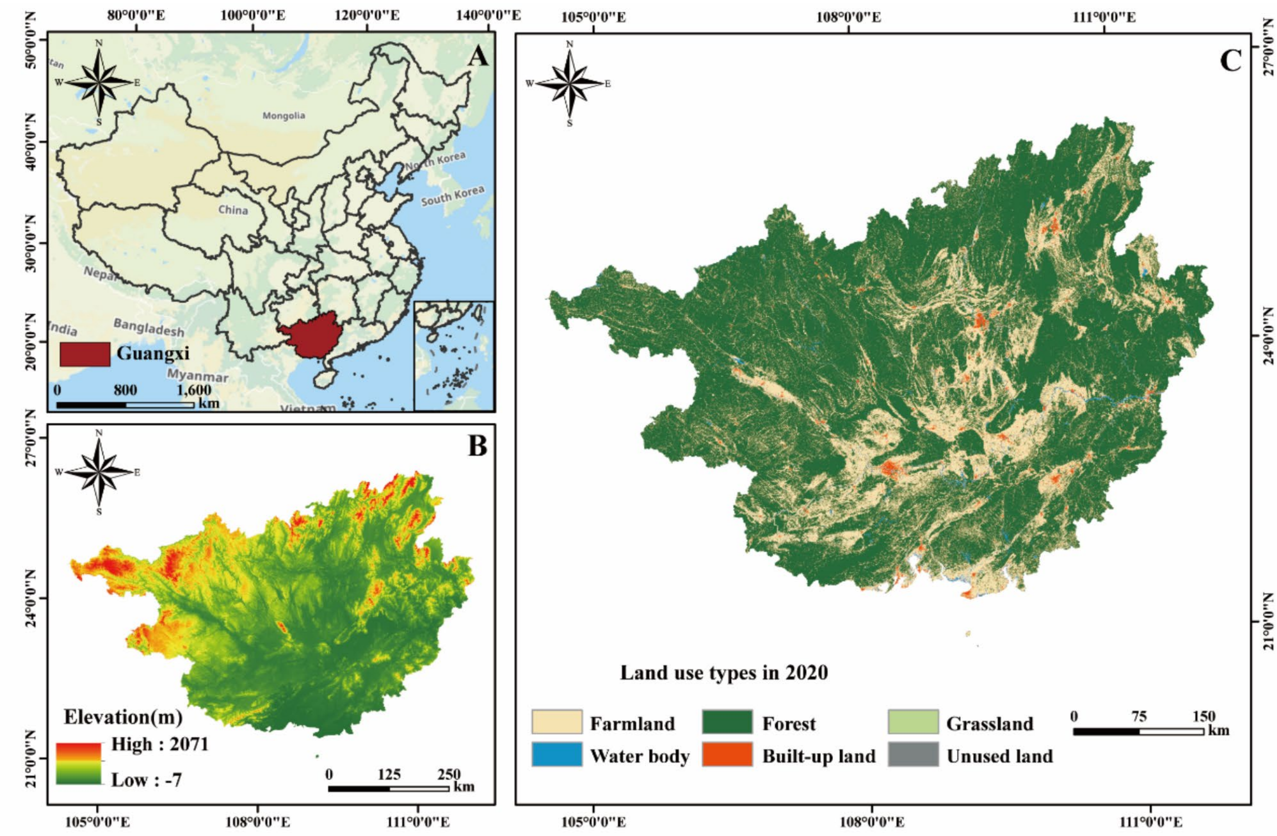

Fig. 1. (**A**) Map of study area. (**B**) The DEM of the study. (**C**) The Land use and land cover in 2020.

toward the southeast, featuring a variety of basin sizes[50]. The mountainous areas are mostly isolated, with complex hills and extensive rocky desertification, characterized by distinctive karst landforms[51]. Guangxi is located in a low latitude area and has a subtropical monsoon climate, rain and heat in the same period, rainfall is abundant[52]. By the end of 2020, Guangxi's gross domestic product (GDP) of 2.22 trillion yuan and a per capita GDP of 44,309 yuan[53]. It is uniquely positioned as the only region in China with both land and sea connections to Association of Southeast Asian Nations (ASEAN) countries, providing key access to the sea in Southwest China and serving as a significant new free trade zone with important national strategic value[54]. Examining the impact of human disturbance on the ESSV in Guangxi offers a valuable case study for understanding these effects in regions that are both ecologically fragile and socioeconomically distinctive.

Data sources

In this study, multi-source data are used to assess ESSV and human disturbance in Guangxi from 1990 to 2020, and the relationship between them is analyzed. The data used to evaluate ESSV include land use and socio-economic data (gridded population density, gridded gross domestic product, Engel coefficient, grain output, consumer price index, average grain price). The land use/cover change (LUCC) datasets for the years 1990, 1995, 2000, 2005, 2010, 2015 and 2020 was obtained from the Chinese Academy of Sciences Resource Environmental Data Center (RESDC) (http://www.resdc.cn), featuring a spatial resolution of 30 m. The LUCC types were reclassified into six categories: farmland, forest, grassland, water body, built-up land and unused land. We acquired population density (PD), gross domestic product density (GDPD) and for the study area at a resolution of 1 km from the Chinese Academy of Sciences Resource Environmental Data Center (RESDC) (http://www.resdc.cn). The night light (NL) data were obtained from the National Oceanic and Atmospheric Administration (http://ncc.nesdis.noaa.gov/) at a resolution of 1 km × 1 km. The digital elevation model (DEM) were derived from the geospatial data cloud (http://www.gscloud.cn/) with a raw resolution of 30 m × 30 m. Socio-economic data and statistics for the calculation of ESSV were sourced from China Statistical Yearbook (1990–2023) and Guangxi Statistical Yearbook (1990–2023). The framework of this study is shown in Fig. 2.

Methods

Valuation of ESSV

(1) Valuation of ESV

This study employs the unit area equivalent factor method to determine ESV. Combining the average yield per unit area of major grain crops and the average price of major grain crops in Guangxi from 1990 to 2020 [55], the formula used is as follows:

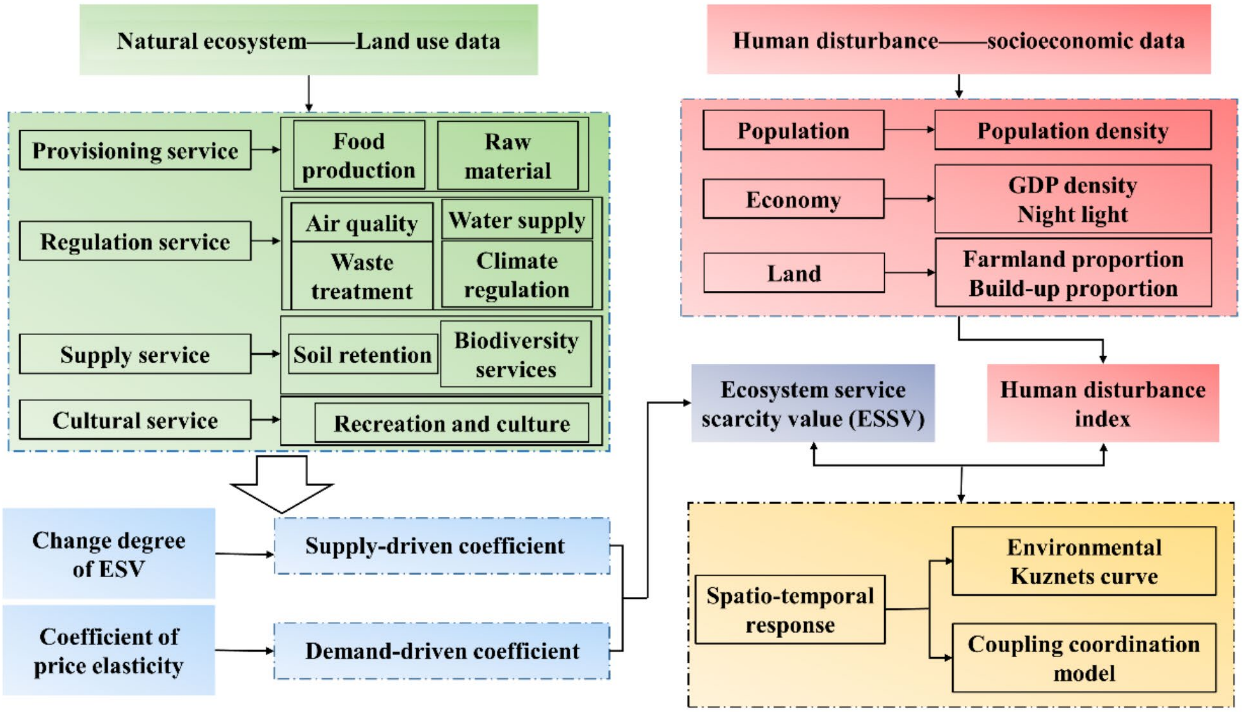

Fig. 2. Framework of this study.

Change scenarios	Variations in scarcity value			
	Demand(P_{jt}^{Dem})		Supply(ΔP_{jt}^{Sup})	
	Private products	Public products	Private products	Public products
Naive	0.000	0.000	0.000	0.000
Demand elasticity (scenario 2)	0.250	0.000	0.000	0.250
Supply elasticity (scenario 3)	0.000	0.500	0.250	0.000
Demand and supply elasticity (scenario 4)	0.250	0.500	0.250	0.250

Table 1. Variations in scarcity value across the four scenarios.

$$E_a = 1/7 \times P \times Q$$

$$ESV = \alpha_{i,t} \times VC_{ij}$$

Where E_a represents the unit value of ESs in Guangxi; *P* represents the average price of major food crops in 2020; *Q* represents the average grain yield per unit area of major grain crops from 1990 to 2020; $\alpha_{i,t}$ is the area of land use type *i* at time *t*; VC_{ij} is the per-unit value (US$/hm^2) of land use type *i* under an ES type *j*.

(2) Coefficients adjustment for ESSV

Price elasticity significantly influences changes in scarcity value. Therefore, it was utilized to evaluate the extent of change in the scarcity value of ESs[56]. Depending on their attributes, ESs are categorized into private or public products[57,58]. Public products feature elastic demand and inelastic supply, whereas private products display the reverse characteristics[37]. The price elasticities and associated changes in scarcity value for different ESs are derived from Bryan et al.[7], as detailed in Table 1. The ES naïve value refers to the ecosystem's physical supply value without taking into account how interactions between supply and demand impact on scarcity, with a view to providing theoretical support for ecological conservation. Scenarios 2, 3 and 4 respectively reflect the impact of demand, supply and the combination of supply and demand on the ESSV by increasing supply price elasticity, demand price elasticity and simultaneously increasing supply and demand price elasticity[58]. Scenarios 2, 3 and 4 provide guidance for coordinating the balance between regional development and environmental protection by studying the impact of supply and demand on the value of ecosystem services[59]. Comparisons among the four scenarios are based on scenario 1, with the 1990 data standardized to 1, serving as the reference for all calculations. The formula used is as follows:

$$ESSV_{it} = \alpha_{i,t} \times VC_{ij} \times \left(1 + \Delta p_{jt}^{Sup} + \Delta p_{jt}^{Dem}\right)$$

Where $ESSV_{it}$ represents ESSV of land use type *i* at time *t*; Δp_{jt}^{Sup} is the relative change in scarcity value affected by supply under an ES type *j* at time *t*; Δp_{jt}^{Dem} is the relative change in scarcity value affected by demand under an ES type *j* at time *t*.

$$\Delta p_{jt}^{Sup} = \Delta Q_{jt}^{Sup} \times \Delta P_{jt}^{Sup}$$

$$\Delta Q_{jt}^{Sup} = -\left(\sum ESV_{jt1} - \sum ESV_{jt0}\right) / \sum ESV_{jt0}$$

$$\Delta p_{jt}^{Dem} = \Delta Q_{jt}^{Dem} \times \Delta P_{jt}^{Dem}$$

$$\Delta Q_{jt}^{Dem} = \left(WTP_{jt1} - WTP_{jt0}\right) / WTP_{jt0}$$

$$WTP_{jt} = POP_t \times GDP_t \times \epsilon_{jt}$$

Where ΔQ_{jt}^{Sup} and ΔQ_{jt}^{Dem} represents the proportional change supply and demand of ES *j* at time *t*, respectively; ΔP_{jt}^{Sup} and ΔP_{jt}^{Dem} represents to the relative changes in ESSV due to a 100% decrease in supply or demand, respectively; ESV_{jt} are the ESV under an ES type *j* at time *t*; WTP_{jt} represents the wishes of people to pay for the ES *j* at time *t*; POP_t represents the total population in Guangxi at time *t*; GDP_t represents the real per capita GDP at time t, adjusted for inflation to 2020 values; ε_{jt} represents the income elasticity of demand for ES *j* at time *t*.

Quantifying human disturbances

Humans generate material goods and obtain services through socio-economic activities, and in the process cause different types of land to be disturbed by human activities in different ways and with different intensities[60]. This study uses the farmland proportion (FP), built-up land proportion (BLP), population density (PD), gross domestic product density (GDPD), and night light (NL) data to quantify human disturbance. After standardizing the four indicators, the human disturbance index is calculated using the following formula:

$$u = \sum_s \sum_t w_s m_{st}$$

Where u is human disturbance index; w_s is the weight of the indicator *s*; m_{st} represents the standardized value of indicator *s* at time *t*.

Environmental Kuznets curve

This study uses the EKC to explore the relationship between ESSV and human disturbance. The EKC represents a dynamic relationship between the environment and economy, emphasizing long-term change processes[61]. The EKC is assessed by the nature of the impact of income (human disturbance) and its square on environmental degradation (ESSV)[62]. The shape of the curve is verified by the square of the significant and positive coefficient and elasticity of human disturbance simultaneously with the significant and negative coefficient and elasticity of human disturbance[63]. Based on EKC's proven research[64], its formula is as follows:

$$Y_k = \beta_0 + \beta_1 X_k + \beta_2 X_k^2 + \beta_3 X_k^3 + \epsilon$$

Evaluating the EKC may confirm the validity of these conditions:

1. $\beta_1 = \beta_2 = \beta_3 = 0$. No relationship between X_k and Y_k.
2. $\beta_1 \neq 0$, $\beta_2 = \beta_3 = 0$. Linear relationship between X_k and Y_k.
3. $\beta_1 < 0$, $\beta_2 > 0$, $\beta_3 = 0$. U-shaped relationship.
4. $\beta_1 > 0$, $\beta_2 < 0$,$\beta_3 = 0$. Inverted U-shaped relationship.
5. $\beta_1 < 0$, $\beta_2 > 0$, $\beta_3 < 0$. Opposed to the N-shaped curve.
6. $\beta_1 > 0$, $\beta_2 < 0$, $\beta_3 > 0$. Cubic polynomial or N-shaped curve.

Where Y_k represents the logarithm of ESSV. X_k represents the logarithm of human disturbance. β_0 is the cross section effect. β_1, β_2 andβ_3 are the explanatory variable coefficients. $\epsilon \sim (0, \sigma^2)$.

The coupling coordination model

Coupling describes the interactions of mutual dependence, influence, and constraint among multiple systems or within a single system[65]. The phenomenon of "coupling" exists in all areas of society and is of universal significance[66]. The higher the value of the CCD, it indicates that there is a good and high-level mutual promotion relationship between subsystems, and the whole system structure tends to be more stable[67]. To assess the degree of coordinated development between ESSV and human disturbance, the following formula is employed to construct the CCD model:

$$C = \left\{ \frac{f(\alpha) \times f(\beta)}{\left[\frac{f(\alpha)+f(\beta)}{2} \right]^2} \right\}^{\frac{1}{2}}$$

$$T = af(\alpha) + bf(\beta)$$

$$D = \sqrt{C \times T}$$

where D represents the CCD value, which ranges from 0 to 1. $f(\alpha)$ represents the ESSV in scenario 4, while $f(\beta)$ represents the human disturbance index. C is the degree of coupling between the ESSV and human disturbance index, while T is the degree of coordination between the ESSV and human disturbance index, with assigned values of a and b representing the contributions of each subsystem. Given the equal importance of ESSV and human disturbance, both and b are set to 0.5.

Based on previous studies and the actual situation in Guangxi, we established the classification criteria and types of CCD (Fig. 3).

Results

Spatial and temporal changes in the ESV

In general, the spatial distribution of the ESV from 1990 to 2020 exhibited obvious aggregation characteristics, and the trend of spatial and temporal changes was relatively stable (Fig. 4). In terms of time, the ESV in Guangxi generally fluctuated, and the area of each grade of ESV changed (Table 2). From 1990 to 1995, the ESV slightly increased by 1.49%, reaching its peak during the study period. In addition, 2000–2020 was a declining phase, with the ESV decreasing by 5.88%, and the ESV reached the lowest level in the study interval in 2020. From a spatial perspective, the ESV in Guangxi from 1990 to 2020 exhibited a divergent spatial characteristic of "low in the middle and high around", in which the highest value area was distributed in the vicinity of the central water body. From 1990 to 2020, the areas of the "extremely low" value and the "medium" value decreased by 1.59% and 2.56%, respectively. The areas of the "low" value, the "high" value, and the "extremely high" value increased by 3.77%, 0.33%, and 0.05%, respectively.

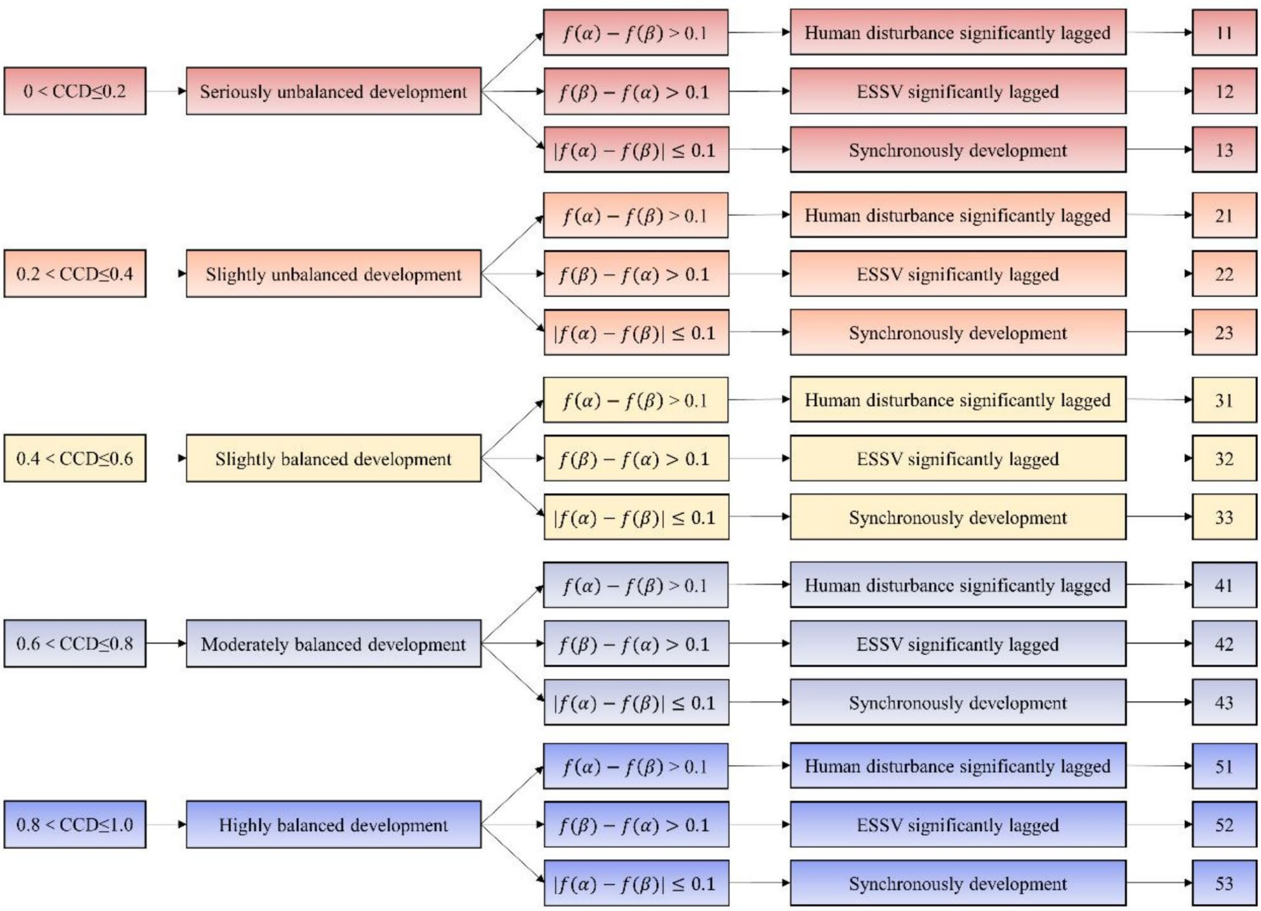

Fig. 3. The coupling coordination characteristics of ESSV and human disturbance.

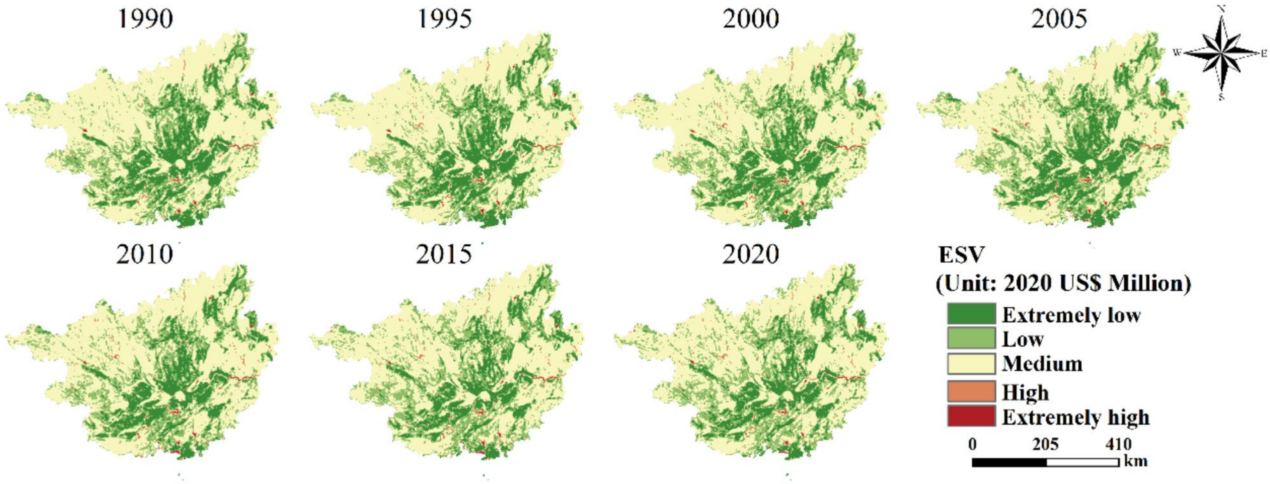

Fig. 4. Spatial-temporal distribution of the ESV.

Year	1990	1995	2000	2005	2010	2015	2020
ESV	0.067	0.068	0.068	0.065	0.066	0.064	0.064
Extremely low	16.61%	16.62%	16.06%	18.13%	16.30%	16.30%	15.02%
Low	23.71%	23.71%	23.56%	25.13%	24.06%	24.06%	27.48%
Medium	58.78%	58.78%	59.17%	55.53%	58.21%	58.21%	56.22%
High	0.70%	0.70%	0.98%	0.97%	1.12%	1.12%	1.03%
Extremely high	0.19%	0.19%	0.22%	0.23%	0.31%	0.31%	0.24%

Table 2. The average ESV and area proportion of each class. *The ESV's units are US$ million.

Scenario	1990	1995	2000	2005	2010	2015	2020
Scenario 1	0.067	0.068	0.068	0.065	0.066	0.064	0.064
Scenario 2	0.067	0.069	0.073	0.086	0.131	0.180	0.201
Scenario 3	0.067	0.069	0.072	0.082	0.117	0.152	0.169
Scenario 4	0.067	0.071	0.078	0.101	0.180	0.223	0.307

Table 3. The average ESSV under four scenarios (unit: US$ million).

Spatiotemporal characteristics of ESSV

The ESSVs from 1990 to 2020 under the four scenarios are presented in Table 3; Fig. 5. The average ESSV order for the seven periods is the largest in Scenario 4, followed by Scenarios 2, 3, and 1. Scenarios 2, 3, and 4 have values that are 70.61%, 53.91%, and 117.12% higher than that of Scenario 1, respectively, and Scenarios 2 and 4 have significantly higher ESSVs than Scenarios 1 and 3. At the same time, the ESSVs of the four scenarios show the following trend between 1990 and 2020: except for Scenario 1, the ESSVs of Scenarios 2, 3, and 4 show a gradual increasing trend, reaching the highest value in 2020. The ESSV of Scenario 1 shows a fluctuating trend, with little overall change. ESSV increases significantly when demand is considered, indicating that human demand on ecosystems strongly influences ESSV, whereas changes in the value of supply do not significantly affect changes in ESSV.

Considering that Scenario 4 is the best case for generating the price elasticity of ESs when supply and demand change simultaneously, this study focuses on Scenario 4 to study the ESSV in the subsequent analysis (Fig. 6). In terms of time, from 1990 to 2020, ESSV in Guangxi showed an overall growth trend, and ESSV increased by 3.58 times. Among them, the growth rate of ESSV from 2005 to 2010 was the highest, increasing by 78.21%. Spatially, ESSV changed significantly in 1990, 1995, 2000, 2005, 2010, 2015, and 2020. The regions with high ESSVs are located primarily in the central, southern, northeastern and southwestern parts of Guangxi, whereas the regions with low ESSVs are located predominantly in the northern, northwestern, and southeastern parts of Guangxi. Before 2010, the types of "medium" ESSV areas were prevalent, covering 65% of Guangxi and mainly surrounding the forest and grassland regions. After 2010, the percentage of regions with "medium" ESSV rapidly decreased, dropping to 0.1% in 2020. In contrast, the "high" and "extremely high" ESSV regions increased rapidly, and the proportion will increase to 96.44% by 2020. From 1990 to 2010, it was distributed mainly within built-up

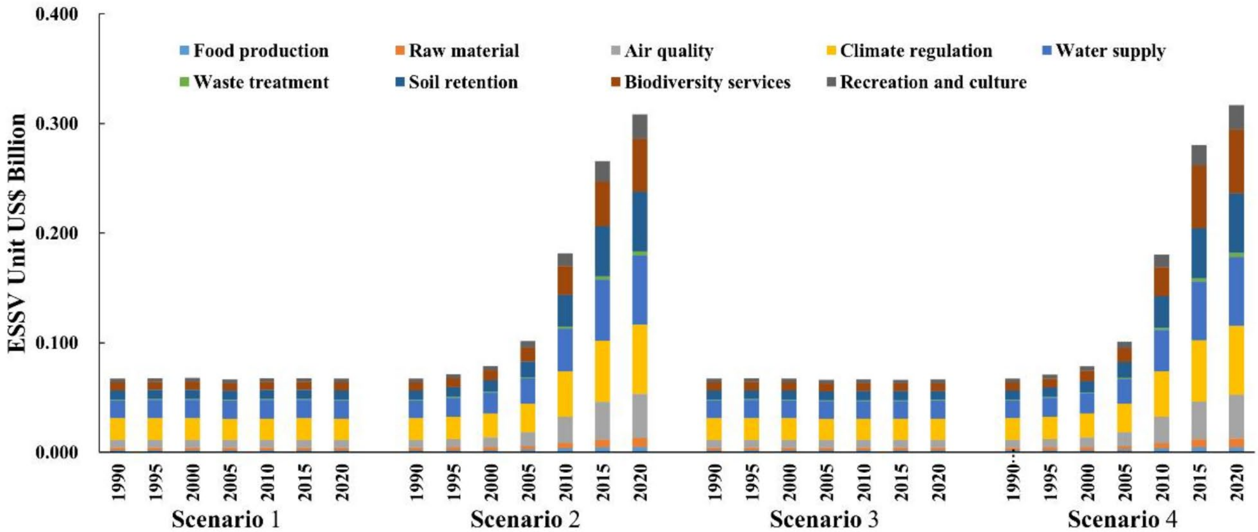

Fig. 5. The overall ESSV of each ES under four scenarios.

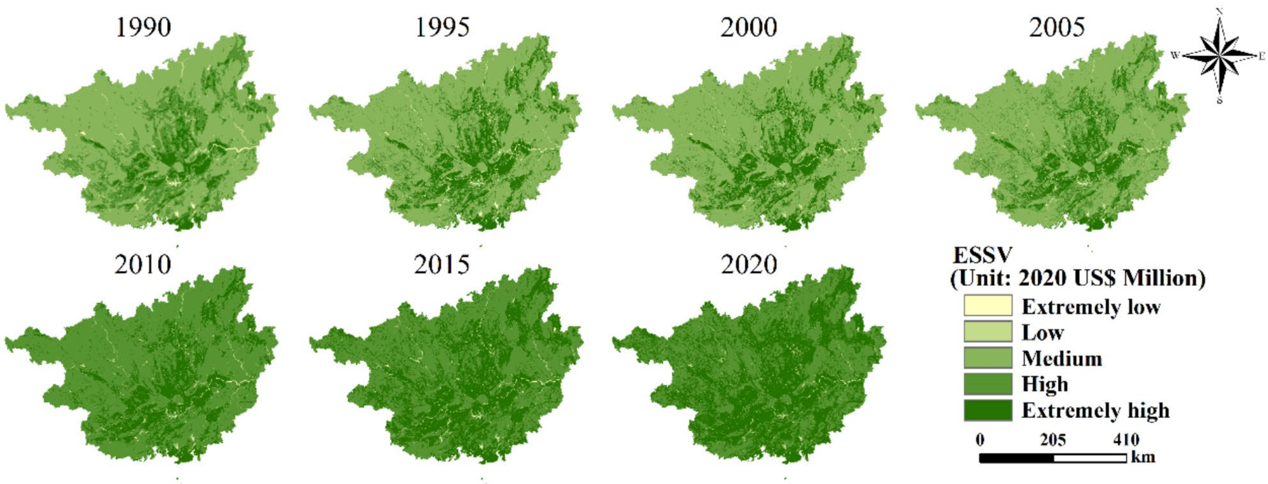

Fig. 6. Spatial-temporal distribution of the ESSV under scenario 4.

land and farmland; however, by 2020, its range has expanded to include not only built-up land and farmland but also parts of forest and grassland, indicating a significant increase in demand-driven scarcity since 2010.

Changes in human disturbances

The entropy weight method calculates that the weights GDPD and PD are the largest (0.2519 and 0.2245, respectively), followed by those of BLP, NL, and FP (0.1924, 0.1856, and 0.1456, respectively). The human disturbance index can be divided into five levels according to the actual situation in Guangxi. Figures 7 and 8 present the spatial and temporal changes in human disturbances in Guangxi from 1990 to 2020. In terms of temporal change, the human disturbance index of Guangxi shows a trend of continuous increase, which is in line with the developmental characteristics of the process of human disturbance in China. From 1990 to 2010, the growth of the human disturbance index in Guangxi was slow; after 2010, following the complete initiation of the China-ASEAN Free Trade Area, Guangxi emerged as a key area for China's open cooperation with ASEAN, and its level of human disturbance significantly increased. In terms of spatial change, central cities experience greater levels of human disturbance, which diminishes in the outlying regions. Nanning, Liuzhou, Guilin, and Beihai are the most severely disturbed areas in Guangxi. The northwestern part of Guangxi has experienced a low level of human disturbance, with minimal changes over the past 30 years. Notably, the process of human disturbance has changed significantly since 2010. Prior to this, the main proportions of human disturbance levels were "extremely low" and "low", accounting for 70.41–79.70%. Between 2010 and 2020, the rate of human disturbance intensified notably, with the areas classified as "high" and "extremely high" growing by 11.32%. This increase was predominantly observed in urban and suburban regions.

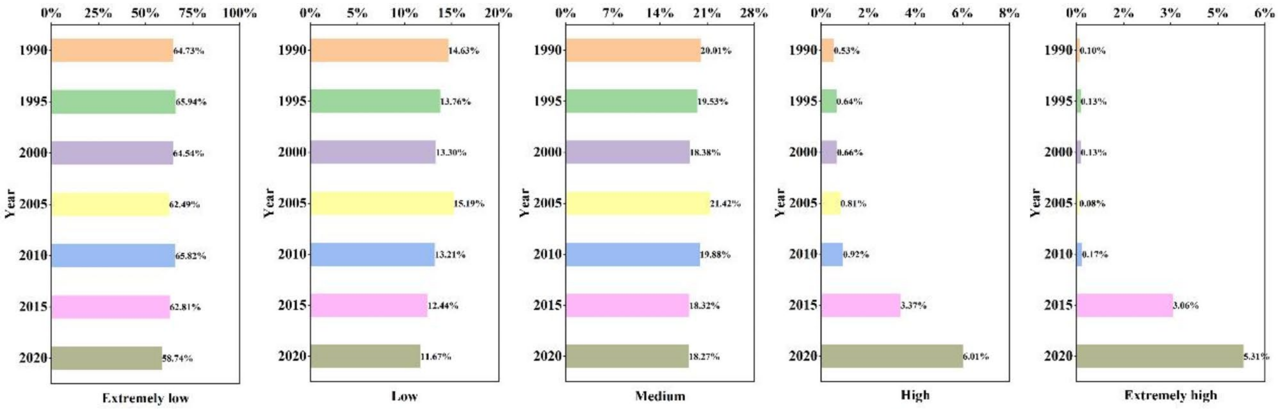

Fig. 7. The proportion change of areas with different degree of human disturbance.

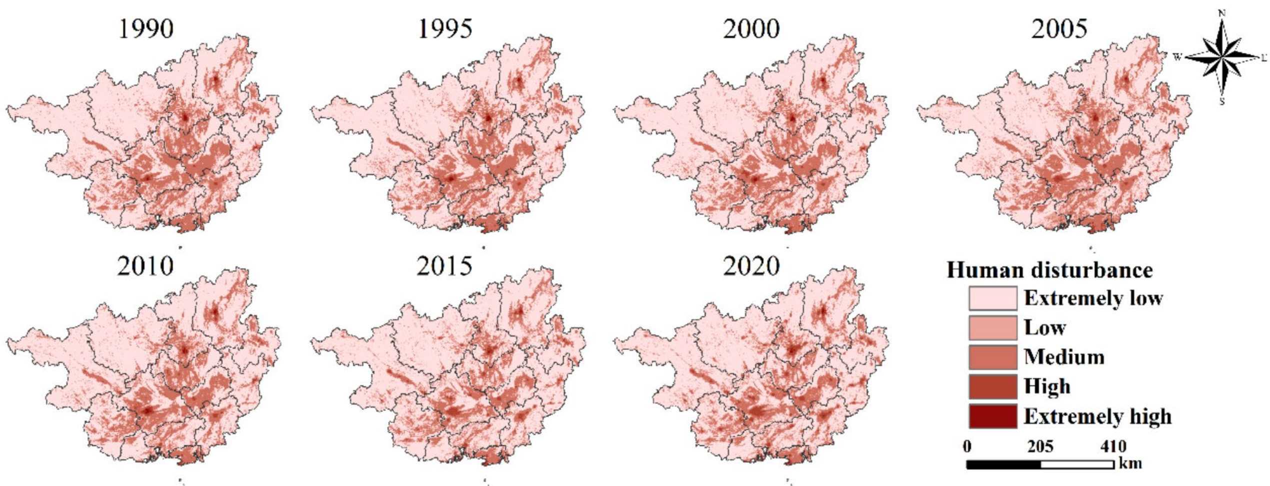

Fig. 8. Spatial-temporal distribution of human disturbance.

Correlation analysis between ESSV and human disturbance

According to the analysis in Fig. 9, the relationship between ESSV and human disturbance in Guangxi during the period of 1990–2020 generally shows a complex curve pattern rather than a simple inverted "N" shape. Specifically, in most years, the relationship conforms to the characteristics of the environmental Kuznets curve (EKC), but its shape may have some variability and complexity. In the early stage of economic development, with increasing human disturbance, ESSV showed a downward trend. This stage is the initial stage of industrialization and urbanization, the ecosystem has a certain resistance, and human disturbance has not had a large negative impact on the ecosystem, resulting in a reduction in ESSV. However, with further economic growth, ESSV is on the rise, reflecting a serious negative impact of high-intensity disturbances on the ecosystem. Finally, when human disturbance continues to intensify to a relatively high level, it is accompanied by positive effects, such as technological progress and the implementation of environmental governance measures, resulting in a decline in ESSV within a certain range. The first of the two key inflection points identified in the study centered on the human disturbance index between 0.15 and 0.30, and the second was between 0.60 and 0.75. These inflection points reveal the characteristics of changes in the value of ecosystem services under different disturbance intensities. The first inflection point (0.15–0.30), an interval that represents the early stage of economic development, when industrialization and urbanization have just begun, puts relatively little pressure on the ecosystem, but the ESSV gradually increases with increasing disturbance. The second turning point (0.60–0.75), reflects the urban areas with relatively mature economic development, high population density and industrial activities, causing greater pressure on the ecosystem, and the gradual improvement of the industrial governance system, resulting in a decline in ESSV after reaching a certain peak.

Quantification of the CCD between ESSV and human disturbances

To investigate the effects of human disturbance on the ESSV and their mutual interactions, we use the CCD model to quantitatively assess the degree and pattern of their coupled coordination across both time and space. Specifically, higher CCD values imply stronger coupling between ESSV and human disturbance subsystems;

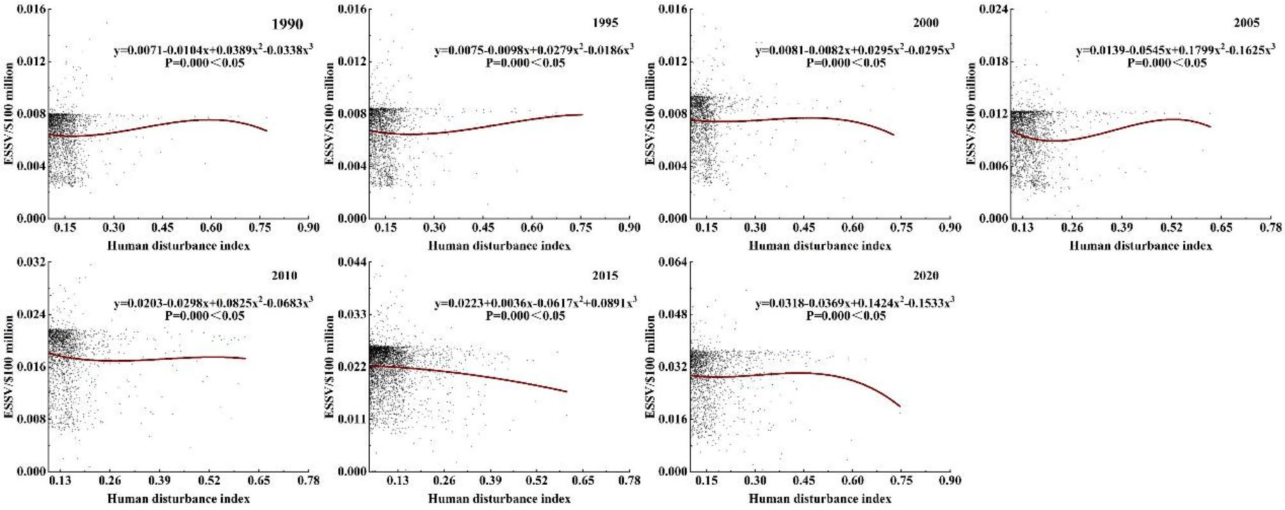

Fig. 9. The ESSV and human disturbance fit curves.

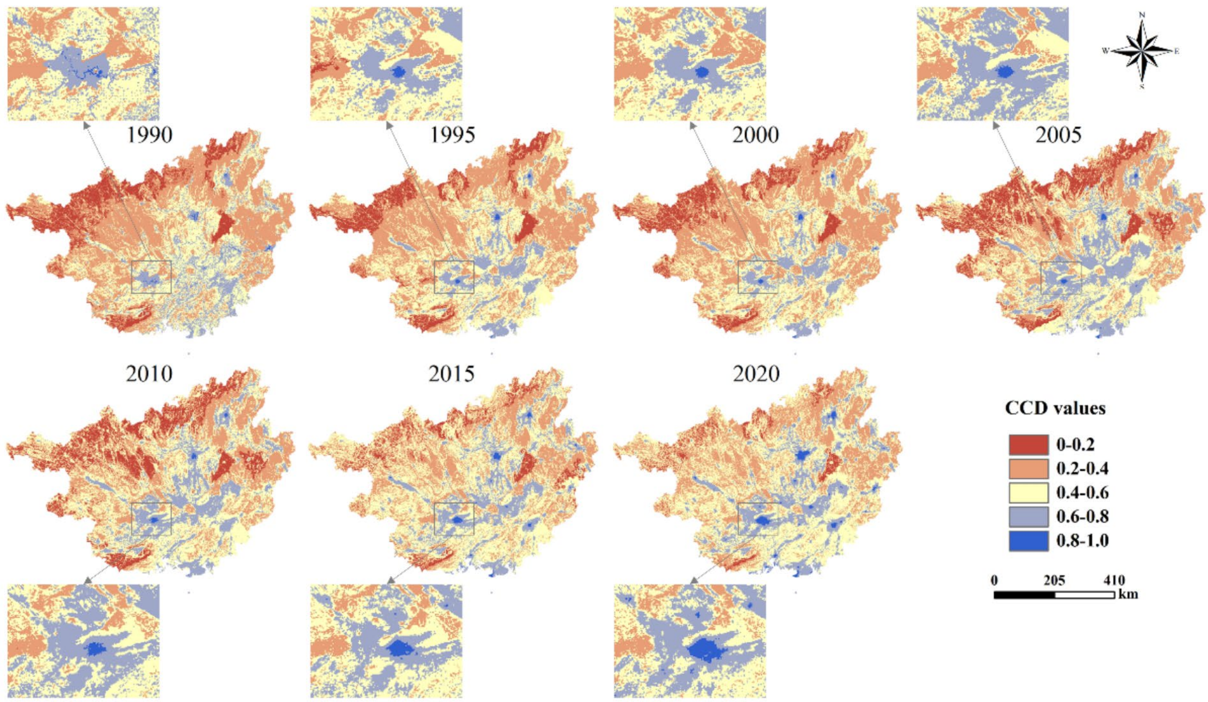

Fig. 10. Spatial-temporal distribution of the CCD.

conversely, lower CCD values indicate a less desirable state of coordination. Figure 10 reveals that from 1990 to 2020, the CCD values between ESSV and human disturbance in Guangxi has generally trended upwards. This period has the following main characteristics: Firstly, "slightly unbalanced development" and "seriously unbalanced development" dominated before 2010, and "slightly balanced development" dominated after 2010. Secondly, the proportion of "seriously unbalanced development" increased first and then decreased, reaching a peak of 14.0% in 2005. Finally, the proportion of "moderately balanced development" and "highly balanced development" regions increased. Spatially, the CCD pattern in Guangxi remained relatively stable from 1990 to 2020. The regions with a higher coordination degree are mainly concentrated in Nanning, Liuzhou, Guilin, Beihai and other cities with better economic development and earlier development of human disturbance.

The coupling coordination characteristics of ESSV and human disturbance in Guangxi changed from 1990 to 2020. Areas with "human disturbance significantly lagged" accounted for over 98.5% of the region, and displayed a decline from 1990 to 2020, with the most significant decline of 0.91% occurring between 2015 and 2020. The proportion of areas with "ESSV significantly lagged" increased by 0.26% from 1990 to 2020, with the largest rise of 0.25% also from 2015 to 2020. Furthermore, areas exhibiting "synchronous development" saw an increase in proportion, rising by 0.77% overall, with the largest growth of 0.66% occurring between 2015 and 2020. Areas with ESSV significantly lagged are located in urban areas with good economic development such as Nanning, Guilin, Liuzhou, and Beihai.

Discussion

Spatial–temporal changes in ESSV in Guangxi

Disregarding the scarcity induced by changes in supply and demand (Scenario 1), ESSV decreases from 0.067 (2020 US$ million) in 1990 to 0.064 (2020 US$ million) in 2020, primarily due to reduced forest and grassland areas and increased built-up and unused land[68]. In Scenario 2, which solely accounts for demand elasticity, GDP per capita and income elasticity are utilized to evaluate changes in demand. From 1990 to 2020, Guangxi's population grew by 14.76 million, while its per capita GDP increased to 41.50 times the 1990 level. The surge in demand continuously increased the ESSV. In Scenario 3, which focuses solely on supply elasticity, ESSV in Guangxi in 2020 increased by 1.52 times compared with 1990 baseline.

In Scenario 4, which considers simultaneous changes in supply and demand, ESSV increases 3.58 times, from 0.067 (2020 US$ million) to 0.307 (2020 US$ million). From 1990 to 2020, the scarcity values of all types of ES tended to increase (Fig. 5). Among them, biodiversity services (690.38%), recreation and culture (5706.83%) and soil retention (553.49%) showed the most significant growth, whereas food production grew the slowest (113.17%). ESSV is influenced by various elements, including the type of products, price elasticity relative to income, and the wishes of the people to pay on demand[69]. In addition, in 2010, the establishment of China-ASEAN ushered in major opportunities for Guangxi's financial cooperation. While the regional GDP and total import and export trade increased rapidly, ESSV also experienced explosive growth. Moreover, we find that the growth rate of ESSV for public products considerably exceeds that for private products. Specifically, the ESSV proportion for private products decreased from 60.94 to 44.76%. In terms of supply, the provision of ESs in Guangxi remained relatively stable from 1990 to 2020. Thus, we deduce that as population and economic development progress, the impact of demand on ESSV is greater than that of supply, indicating an imbalance in the supply-demand relationship. Notably, the wishes of the people to pay for ESs shifted from private products to public products over this period.

Guangxi's geography features high elevations in the north and lower elevations in the south[70], with mountains in the northwest and basins in the central and southern regions[71]. Consequently, the northern part is dominated by forest and grassland, whereas the central and southern areas are dominated by cultivated land, influencing the spatial distribution of ESSV. Through existing research, we understand that the low appreciation of the scarcity value of private products is due to the existence of many alternative products[72]. Therefore, during the study period, with the increase in demand and the restriction of supply, the ESSV of the public type is greater than that of the private type in Guangxi. In Guangxi, forests and grasslands provide a relatively high proportion of public services. However, during the study period, the expansion of built-up land in Guangxi led to a decrease in the proportion of forest and grassland, which directly led to an increase in ESSV in the central, southern, northeastern and southwestern parts of Guangxi. The strong demand has caused the high-value area of ESSV to shift from the central part of the basin to the surrounding forest and grassland areas. Additionally, variations in regional economic development and ecological demand also impact ESSV's distribution[73]. Cities in Guangxi, primarily in the northeastern, central, and southern areas, have greater economic development and population density, resulting in a greater distribution of ESSV[74]. The low-ESSV areas are located mainly in the border areas of China and Vietnam; the junction of Guangxi with Guizhou, Guangdong, Hunan and Yunnan; and the fringe areas of urban agglomerations[75], which have limited development resources and relatively intact ecosystems. The high-ESSV areas experienced earlier economic development and affected most of the economic system of Guangxi. In the early stage of economic development, industrial pollution was more serious, ecosystems were damaged, and human demand for ecosystems gradually increased.

Coordinated and coupled relationships between ESSV and human disturbance

During the study period, the intensity of human disturbance tended to increase. The level of human disturbance was greater in northeastern and southwestern Guangxi than in northwestern and southeastern Guangxi, with the highest intensity in the central part of Guangxi. The weights of GDPD and PD are the largest, indicating that economic development and population growth are the main drivers of human disturbance. With economic growth, the process of industrialization and urbanization in Guangxi has accelerated, resulting in increased human demand for natural resources and ESs and increased human disturbance[76]. In terms of spatial distribution, ESSV and human disturbance in Guangxi exhibited a synergistic relationship. A suitable living environment and high economic development lead to a high level of human disturbance in central Guangxi[77]. Northwestern Guangxi is dominated by forests, with a low population density and low level of economic development, and the built-up area has become a key factor influencing human disturbance[78]. From 1990 to 2020, the urban area of Guangxi expanded, and the population density and income level gradually increased. During this period, human interference contributed to the increase in total ESSV by increasing consumer demand. The results revealed that the process of human disturbance changed significantly after 2010, which may be related to the policies and planning of Guangxi. Urban expansion planning and transportation infrastructure construction will increase the level of human disturbance[79]. With Guangxi becoming the forefront of opening up and cooperating with ASEAN[80], its socioeconomic structure has changed, shifting from an agriculture-led economy to an industrial and service-led economy[81], which may have led to a shift in the pattern of human disturbance. The EKC confirms that there is an inverse N-type relationship between ESSV and human disturbance. In the first stage, ESSV decreases with increasing human disturbance, primarily due to advancing industrialization and urbanization, the establishment of industrial systems, and the elimination of outdated production methods[82]. In the second stage, ESSV increases with the intensification of human disturbance, which is due to the increase in energy consumption with the further development of industrialization. This period often involves overexploitation of natural resources, underdeveloped science and technology, and the expansion of urbanization, leading to significant disturbance pressure[83]. In the third stage, when human disturbance reaches a certain level, ESSV decreases again with increasing human disturbance. At this stage, industrialization and urbanization continue to advance, the industry gradually transforms into intensive and intelligent[84], the improvement in the resource utilization efficiency of technological progress reduces the negative impact on the ecosystem, society begins to take measures to protect and restore the ecosystem[85], and ESSV declines. The two turning points in the study reflect the impacts of different stages of economic development on ESs. Spatially, when the human disturbance index reaches 0.15–0.3, these areas are concentrated in the early stages of economic development, where industrialization and urbanization have just begun, and the pressure on the ecosystem is relatively low[26]. When human disturbance reaches 0.6–0.75, these areas become more mature urban areas with more mature economic development, and face higher population densities and industrial activities, leading to increased pressure on ecosystems[86]. However, with the implementation of urban planning and environmental management measures, the ESSV in these highly disturbed areas will decrease, reflecting the necessity of ecological management and optimization[87]. Further spatial analyses revealed that central cities such as Nanning, Liuzhou, Guilin and Beihai have high levels of human disturbance, and the indicators of population, GDP and farmland disturbance all show increasing trends. Owing to the frequent economic activities and dense population, the ESSV in these areas tends to show large fluctuations in the high disturbance index (0.6–0.75) interval. At the early stage of economic development, when the human disturbance index was in the range of 0.15–0.3, it was mainly concentrated in the peripheral and less developed regions of Guangxi. Industrialization and urbanization in these regions have just begun, with relatively little impact on the ecosystem[88] and relatively smooth changes in ESSV. However, with the gradual integration of these regions into the larger economic system, their disturbance indices may gradually rise into higher disturbance intervals. The northwestern region of Guangxi has experienced a low level of human disturbance and has not changed much over the last 30 years. These regions are rich in natural resources, but the degree of exploitation is low, so the pressure on the ecosystem is relatively low[89]. Despite the slower pace of economic development in these regions, their lower disturbance indices ensure a lower ESSV, which is conducive to maintaining the ecological balance in the region. Since 2010, urban and suburban expansion has led to the growth of high and very high class areas, especially in the human disturbance index range of 0.6–0.75. Urban expansion and the construction of transportation infrastructure are the main drivers of this change[90]. Ecosystem services in high-disturbance areas may be seriously affected by excessive land use, pollution, and resource exploitation, leading to an increase in ESSV[91]. However, these cities also have stronger economic power and policy support to take ecological restoration and environmental management measures more quickly, and thus may achieve a reduction in ESSV to some extent. For these high-disturbance areas, more attention needs to be given to ecological and environmental management and optimization, and effective urban planning and environmental management measures need to be taken to safeguard economic development while reducing negative impacts on the ecosystem.

Human disturbance has intensified the scarcity of ecosystem services in Guangxi, exerting significant pressure on the ecological environment. In this era of rapid global development, it is very important for regional development to reasonably coordinate the coupling of human disturbance and the ecological environment and realize optimization. If the ESSV and human disturbance are increasingly coordinated, the CCD value will increase[92]. As human disturbance increases, minimizing the level of ESSV becomes critical. Therefore, the "ESSV significantly lagged" type represents the optimal coordination state, and the CCD value must exceed 0.4 to achieve a balance between ESSV and human disturbance. With the passage of time, the degree of coupling coordination between human disturbance and ESSV did not change significantly within the region, showing an increasing trend. Regions where "human disturbance significantly lagged" accounted for the majority but showed a decline, while regions where "ESSV significantly lagged" saw an increase. In general, before 2010, the study area was dominated by unbalanced development, reflecting that social development had a destructive effect on ESs, which may have been due to the degradation of ecosystems caused by overdevelopment and environmental protection[93]. After 2010, "slightly balanced development" was the main trend, and the relationship between human disturbance and ESs became more harmonious, which was a relatively optimistic trend and may have been due to the measures taken to protect and sustainably use the ecosystem. In our study, we found that the "highly balanced development" area is concentrated mainly in Nanning, Liuzhou, Guilin, Beihai and other economically developed cities, possibly because these cities have more resources to invest in environmental protection technology and infrastructure, promoting positive interactions between the protection of ESs and economic development. Therefore, future development in Guangxi can appropriately increase human disturbance and regional economic growth to improve and protect ecosystems more effectively. Although previous researchers have combined ESSV with urbanization[19,94], ecological security[95], and sustainable energy sources[17], this paper is the first to analyze the relationship between ESSV and human disturbances and find an inverted "N" curve. In terms of the ESSV calculation, this paper is consistent with previous studies[30] in that it uses price elasticity to quantify the impact of ESs on supply and demand.

Sustainability of ES management

Research on the impacts of ESSV and human disturbance can provide valuable insights for enhancing ecosystem protection and health in Guangxi. It also helps reduce ESSV while improving local ecosystem health, all within the context of maintaining high-quality economic development. From 1990 to 2020, except for Scenario 1, ESSV shows a significant upward trend. The main reason is that the growth of population and GDP has driven greater demand, and the other part is due to a slight reduction in the supply of ESs[52]. During rapid urbanization, maintaining a sustainable supply of ESs is vital. It is essential to manage urban development carefully to prevent the overexploitation of land resources, especially forests and grasslands[96]. When we consider the ESs, it is important to consider the thresholds at which they can sustain[97]. Additionally, the balance among ESs should be considered to prevent the loss of some services due to excessive protection of other services[98]. High-ESSV areas are concentrated mainly in the more developed areas of central Guangxi. The greater the degree of social benefits in urban areas, the more people will be attracted to migrate to cities[99]. Therefore, the government should encourage the policy of beneficiaries paying their high ESSV share. Moreover, the government should actively establish an environmental taxation system to clarify the supply of scarce ecosystem services[100], encourage more sustainable consumption, and better adjust supply and demand.

Different regions in Guangxi face different ecological pressures[78]. In general, the central, southern, northeastern and southwestern regions face greater ecological pressure, whereas the northern and southeastern regions have relatively stable ecological environments. For regions with stable ecological environments, urban construction can focus on the sustainable use of resources to ensure a balance between economic development and the ecological environment. In unstable regions, it is advisable to establish a thorough environmental monitoring system to monitor ecosystem changes in real time and prevent ongoing ecological degradation[101]. Furthermore, fostering innovation in green technology and sustainable business practices is essential for achieving balanced growth between the environment and the economy. These regions should change the excessive dependence on natural resources in their development mode, accelerate industrial transformation, and highlight the advantages of high-tech industries[102]. The overexploitation of farmland is also a cause of regional environmental instability. For these regions, the government should encourage high-standard farmland construction and land restoration to achieve increased food production while protecting the ecological environment[103]. Moreover, the government should incorporate public power into the environmental governance system and raise public awareness of environmental protection through various means[104], such as organizing environmental protection seminars and implementing an environmental protection point system. Finally, the promotion of cooperation among regional governments is essential for the solution of ecological and environmental problems, the sharing of successful experiences, and the sustainable conservation and management of ecosystems. Additionally, the government should assess the effects of various policies on the provision of ESs when devising regulations to guarantee the scientific integrity and stability of environmental policies.

Conclusion

This study explores the change of the ESSV in Guangxi, and uses environmental Kuznets curve to verify the relationship between ESSV and human disturbance. During the period of 1990–2020, ESSV in Guangxi increased significantly and reached the highest value in 2020, and the demand had a great influence on ESSV, while the supply had little influence on ESSV. Spatial and temporal distribution differences of ESSV appeared in Guangxi, and some cities in the north, west and southeast generally showed higher ESSV distribution. From 1990 to 2020, the region with the highest ESSV experienced a substantial increase. The environmental Kuznets curve confirms that there is basically an inverted N-shaped curve relationship between ESSV and human disturbance in Guangxi, and there are two inflection points. The first inflection point exists at the early stage of human disturbance, when the pressure on the ecosystem is small, but the ESSV increases with the increase of disturbance; the second inflection point exists at the more mature stage of economic development, when the population density and industrial activities are high, and the ESSV reaches the peak and then decreases again. We confirmed the relationship between ESSV and human disturbance in Guangxi with the inverted N-shaped curve through the environmental Kuznets curve, and found that the coupling and coordination level of the two showed an upward trend, the "human disturbance significantly lagged" region accounted for most of the area but showed a downward trend, and the "ESSV significantly lagged" region were gradually increasing. Generally speaking, after 2005, the study area was dominated by "slightly balanced development", with an increase in "moderately balanced development" and "highly balanced development" areas.

This study provides a reference for calculating ESSV and expands our understanding of its dynamics, offering important insights into the impact of human disturbance on ESSV. It also offers a theoretical foundation and practical guidance for future sustainable development strategies. With economic and social development, human demand for ecosystem services is gradually increasing, while the supply of ecosystem services is limited, the Government should rationally plan land use to effectively protect the sustainability of ecosystem service provision; and actively establish an environmental taxation system to encourage more sustainable consumption. At the same time, public power should be incorporated into the environmental governance system. Human disturbance has negative effects on multiple ecosystems, and intensive urban land use and preservation of land use types with higher ecological potential can promote more compact human disturbance. This paper takes Guangxi as a research area, which is located in the border region of China. The study of economic development and environmental coordination provides a reference for the management of similar regions in the world. However, there are still some shortcomings that need to be considered in future studies. Such as the elasticity coefficient of supply and demand of ESs is the result of previous studies, and the relevant information is less. Future research should delve deeper into the factors that influence the relationship between these elements.

Data availability

Some data for this study are not published due to [non-publication of data], but may be obtained from the corresponding authors upon reasonable request.Publicly available data: Data name—Data type—Data sourc-es—Land use/cover change (LUCC)—Raster—Chinese Academy of Sciences Resource Environmental Data Center https://www.resdc.cn/; Population density(PD)—Raster—Chinese Academy of Sciences Resource Env ironmental Data Center https://www.resdc.cn/; GDP density(GDPD)—Raster—Chinese Academy of Sciences Resource Environmental Data Center https://www.resdc.cn/; Night light(NL)—Raster—National Oceanic and

Atmospheric Administration http://ncc.nesdis.noaa.gov/; Digital elevation model (DEM)—Raster—Geospatial data cloud http://www.gscloud.cn/; Other dataObtaining other data could contact corresponding author with E-mail: songcs@ccps.gov.cn.

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Declarations

Competing interests
The authors declare no competing interests.

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