Quantifying the demographic distribution characteristics of ecological space quality to achieve urban agglomeration sustainability

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Abstract

Human activities are changing the quality of ecological spaces continually, and creating increasing imbalances in ecosystem services. Hence it is necessary to identify the distribution equity in ecological spaces. In 2018, the Pearl River Delta urban agglomeration was used as a test case to analyze the distribution characteristics of ecological space quality (ESQ) among different demographic groups and explore socioeconomic factors’ determining forces. The imbalance in ESQ distribution was less than that in income. At the urban and rural scales, the difference in ESQ was not significant, but rural areas had both the best and worst ecological space. Further, the equality of urban ESQ was higher than that in rural areas. Higher-quality ecological spaces were concentrated both in low-income groups, in addition to the cities of Guangzhou and Shenzhen. In areas with higher income gaps, the ecological pressure was concentrated primarily on low-income counties, but more ecological health risks were detected among high-income counties. Limiting rural population density and increasing rural residents’ income can improve the ESQ significantly. The government should improve ecological protection consciousness and ecological compensation policies, particularly with respect to the supervision of, and compensation for, ecological spaces for low-income counties in rural areas to reduce the imbalance in ecosystem services and the burden on those counties.

1. Introduction

Ecological space is an area that provides ecosystem services. The term refers to external conditions that support human survival and provide food, water, oxygen, energy, and entertainment (Ouyang et al 2016, Song et al 2018). With increasing population densities and the continued urban expansion, humans are changing ecological spaces’ amount and quality by occupying or disturbing them (Wang et al 2018c, Xu et al 2019a), and affecting regional ecosystem services and residents’ living conditions thereby (Huang et al 2019, Luisetti et al 2019). Regional ecological space quality (ESQ) is related closely to human health. Residents’ contact with high quality ecological spaces helps reduce mortality and enhances the quality of life (Kondo et al 2018). The loss of ecological spaces and decline in their quality increases residents’ anxiety, reduces immunoresistance, and increases human morbidity and mortality (Gascon et al 2017, Li 2017, Macintyre et al 2018). For example, rising urban temperatures have increased the prevalence of diabetes, asthma, and other diseases (Chakraborty et al 2019). Further, ESQ determines residents’ living environment, thus is the key factor in evaluating the degree and pattern of regional ecosystem service distribution (Belmeziti et al 2018, Miao et al 2016).
In the urbanization process, because of population density, cultural differences, income levels, and world views, the distribution of ESQ among demographic groups has obvious effects (Chakraborty et al 2019, Chamberlain et al 2019). This unequal distribution of ESQ is the primary reason why imbalances exist between the supply and demand of ecosystem services, and is also the leading factor in urban ecological health risks (Schirpke et al 2019). Particularly in China, where urbanization is rapid, the inequality in ecological resource allocation is increasing gradually, and has resulted in potential risks to urban ecological security and human health (Yuan et al 2018, Chen et al 2020). For example, an imbalance in the supply and demand of ecosystem services in most urban agglomerations has resulted in serious ecological problems, including air pollution, flooding, and the creation of heat islands (Wang et al 2016, Zhang et al 2017, Kang et al 2018, Mi et al 2019).

To determine the goals of sustainable development, the reasonable distribution of ecological space is an important factor that should be considered (Li et al 2017). Currently, more attention has focused on ecological spaces’ spatial-temporal distribution, determining factors, and benefits (Tubiello et al 2015, Schulp et al 2019), as well as the balance between the supply and demand for ecosystem services (Wu et al 2019). Inadequate consideration of ESQ in previous studies has led to unrestricted urban land planning and ecological management, intensified the transfer, and increase in ecological problems, and affected social sustainability and stability (Martin 2016, Wu et al 2019).

The equality of ecological space distribution is an important issue in urban development and planning (Mears et al 2019). Current research on balanced ecological spaces focuses largely on accessibility (Fan et al 2017, Mears et al 2019). However, most studies regard different ecological spaces as homogeneous in their evaluations and ignore the distribution of quality in these spaces. Moreover, land planning has neglected ecological quality and encroached upon these areas blindly, and thus, has aggravated the imbalance between land supply and demand (Brindley et al 2019). For example, expanding green areas while neglecting their quality will result in constructed green spaces that offer poor ecological benefits per unit area. Although accessibility increases, the imbalance between supply and demand also increases instability in socioeconomic factors (Su et al 2016). Thus, ESQ’s relative distribution may be the key factor necessary in urban planning and human wellbeing to produce environmentally sustainable and socially resilient cities, particularly in China.

Urban agglomerations will become the trend in cities’ future development (Fang and Yu 2017). The integration of natural and socioeconomic resources has increased the rapid development of both the population and economy (Chen 2015b, Chen et al 2017), but has intensified the disturbance of ecological spaces as well (Ning et al 2018). The Pearl River Delta (PRD) urban agglomeration has a large area of ecological space, and with the implementation of ecological policy, its quality has tended to be stable; however, there remains a highly prominent imbalance between ecological supply and demand (Hu et al 2019, Chen et al 2020). This has become an important factor that restricts the urban agglomeration’s sustainable development. Therefore, by combining ESQ assessment models and socioeconomic data, our goal was to: (a) explore the ESQ’s distribution characteristics at the urban–rural scale; (b) explore the ESQ’s distribution characteristics among demographic groups, and (c) evaluate socioeconomic factors’ causal effects of on urban and rural ESQ quantitatively. Our study is a novel attempt to explore ESQ distributions among different demographic groups. These findings will serve as a theoretical basis for urban and rural ecological planning in urban agglomerations, as well as help improve countermeasures and suggest ways to optimize regional ecological spaces, and promote urban agglomerations’ sustainable development.

2. Material and methods

2.1. Study area

The PRD urban agglomeration is located in Guangdong Province, China, and includes nine cities: Guangzhou (GZ); Shenzhen (SZ); Foshan (FS); Dongguan (DG); Huizhou (HZ); Jiangmen (JM); Zhongshan (ZS); Zuhai (ZH), and Zhaqoing (ZQ). In 2018, the total land area was approximately $5.5 \times 10^5$ km$^2$, the permanent population was ~63 million, and the urbanization rate was 85.3% (Lin and Li 2019). The PRD has the highest urbanization rate in China and is one of the largest urban agglomerations in the world (Jiao et al 2019). However, the imbalances in economic, social, and urban development, the increase in social demand and lag in public supply, and the rapid expansion of cities and increases in environmental pressure have become the prominent issues that need to be addressed and resolved (Chen et al 2017, Dong and Xu 2019).

2.2. Data processing

2.2.1. Ecological space

Ecological space refers to a space accompanied by its natural attributes, and can be defined as an ecological resource that plays an important role in providing ecosystem services within a given region (Wang et al 2011). To facilitate evaluation and management, we defined ecological space as a land use space that provides ecosystem services for the long-term development of the environment, economy, and society, including natural, artificial, and semi-artificial land use types (Ngom et al 2016, Chen et al 2020). The ecological space data in 2018 were obtained from the Resource and Environment Data Cloud Platform.
ESQ is the ecosystem’s external state and an index for residents to perception the living environment’s quality and is also the principal manifestation of policy objectives. The ESQ determines the services of an ecological space, which affects residents’ usability and comfort directly (Chen et al. 2020). The ESQ is the key factor used to evaluate regional ecological benefits. In evaluating ESQ, it is helpful to discriminate the spatiotemporal characteristics of ecosystem functions and ecological security. The ESQ in this study represents the ecological space’s services and stability and can be regarded as the cumulative amount of ecological benefit. Based upon the Technical Criterion for Ecosystem Status Evaluation (HJ 192–2015) the Ministry of Environmental Protection of China issued and Chen et al. (2020), we selected indicators that represent the external characteristics of ecological spaces and public preferences to assess ESQ in 2018, which can enhance not only decision-makers’ understanding of ecological space, but also ecological space’s importance in urban planning and policy-making. These indices included organism abundance (OI), vegetation (VI), water density (WI), land fragility (LFI), air quality (API), outdoor recreation (ORI), and landscape connectivity (LCI).

OI was calculated as a biodiversity index, and the biodiversity of land use types was determined by referring to Chen et al. (2020).

\[ VI = \frac{\sum_{i=1}^{n} P_i}{n}, \]

where \( P_i \) is the mean of the normalized difference vegetation index (NDVI) with a monthly maximum of 5–9 months, using MOD13Q1 data (https://ladsweb.modaps.eosdis.nasa.gov) and resampled the resolution data to 30 m, and \( n \) is a regional image element.

WI was calculated as follows:

\[ WI = \frac{RL + W + WR}{3}, \]

where RL is the river length and W is the water area, which were derived from land use data, and WR is water resources, which was characterized by total annual rainfall. The rainfall data were based upon daily observation data from more than 2400 meteorological stations in China and were generated through sorting, computing, and ANUSPLIN interpolation spatial interpolation. The annual rainfall data were derived from the Resource and Environment Data Cloud Platform of Chinese Academy of Sciences (www.resdc.cn/), and are used widely in China. We used the ArcGIS mask to extract the study area and resampled the resolution data to 30 m.

The index weight of LFI was calculated based on soil erosion (Chen et al. 2020). Soil erosion measurements were derived from the Resource and Environment Science Data Center (www.resdc.cn/) and resampled the resolution data to 30 m.

API was characterized based on the air quality monitoring data of 53 monitoring stations in the PRD urban agglomeration. The data were obtained from the Environmental Data Center of the Ministry of Environmental Protection of China (http://datacenter.mep.gov.cn). The air quality monitoring data were interpolated using the Kriging method in ArcGIS and the resolution data were resampled to 30 m.

ORI was calculated using the ESTIMAP recreation method (Baró et al 2016). The model used for assessing ORI focused on everyday nature-based recreational activities. The score for each evaluation unit was determined by its degree of naturalness, nature protection, and water area.

LCI was calculated using the moving window method in Fragstats v4.2 (University of Massachusetts, MA, USA) and resampled the resolution data to 30 m.

The index weight was chosen by analytic hierarchy process. The calculation formula of ESQ was as follows:

\[ ESQ = 0.18 \times OI + 0.15 \times VI + 0.09 \times WI + 0.15 \times LFI + 0.14 \times API + 0.18 \times ORI + 0.11 \times LCI. \]  

2.2.3. Urban and rural classification

Currently, there are no obvious demarcation lines between urban and rural areas in the PRD. Built-up land in the land use data was divided into urban-town land, rural land, and other built-up lands, given that some small towns in the PRD cannot be regarded as urban. Referring to previous studies and focusing on socioeconomic data available, we defined township administrative units in which the continuous built-up land area was greater than 6 km² as urban (Peng et al. 2012, Yang et al. 2019). By comparison with reality, it covers largely most of the urban areas in the densely populated and economically developed areas of the study regions (figure S2).

2.2.4. Evaluating the equity in ESQ distributions

Resource allocation is a common problem in social economics in which Lorenz curves and concentration curves are used to represent the distribution...

<https://ladsweb.modaps.eosdis.nasa.gov>
characteristics of resources and income (Chakraborty et al 2019). The Lorenz curve reflects the cumulative percentage of the population’s income or ESQ from low to high. The greater the curvature of the Lorenz curve, the more unequal the distribution. The demographic distribution in this study represented distribution differences in ESQ among high- and low-income groups that we analyzed and computed through the concentration curve. It represents the city’s different quality of ecological space distribution equilibrium, i.e., whether residents have equal access to good ecological resources and related services. Quantitative analysis of the distribution of the equity of ESQ can effectively identify inefficient and imbalanced areas of ecological benefit, thus providing suggestions for the construction and management of ecological space. We conducted the analysis of the association between ESQ distribution and income data by combining satellite remote sensing with census data. The concentration curve reflects the cumulative percentage of ESQ from low-income groups to high-income groups. An upward curve indicates a higher ESQ i.e. more concentrated in low-income groups.

Reduction of ecological spaces’ area and quality affects regional ecosystem services, and thus increases ecological health risks (Kang et al 2018, Hu et al 2019). Different demographic groups exert different causal effects on ecological spaces because of different income levels, values, and cultural views, such that different groups face different ecological pressures and problems (Chakraborty et al 2019). The Gini and concentration indices were used to facilitate a cross-scale analysis to distinguish the typologies of urban and rural areas and conduct a qualitative analysis of ecological pressure and ecological risk (the ecological risk refers primarily to the probability of ecological problems residents face) (appendix text S1).

Each county and city’s population (total annual permanent resident population) and income (per capita disposable annual income) data for 2018 were obtained from the Statistical Yearbook, the bulletin of national economic and social development, and census data. Socioeconomic data were gathered at the county level. However, because of a lack of data for DG and ZS, these two cities were not incorporated in the analysis. SZ had only urban statistical data, and only urban distribution characteristics were counted. Because of the availability of socioeconomic data, income and ESQ were averaged and were assumed to be distributed evenly at the county level.

2.2.5. Determining forces

Urbanization processes are the principal factors that affect regional ESQ, socioeconomic factors play a leading role as well (Wu et al 2019, Xu et al 2019b). This study focused only on socioeconomic factors’ causal effects on ESQ. Based upon the data available and previous research (Kleemann et al 2017, Zhang et al 2018, Wang et al 2018a, Wu et al 2019), socioeconomic factors, including population density, industrial structure, residents’ disposable income and education level, and impermeable surfaces, were selected for the analysis. These factors can represent regional urbanization and socioeconomic levels. Each county and urban’s socioeconomic data for 2018 were obtained from the Statistical Yearbook, bulletin of national economic and social development, and census data, and were gathered at the county level. Impervious surface data were derived from land use data. All data were normalized to eliminate dimensions. Geographical weighted regression (GWR) can explain the differences in socioeconomic effects in the determining factors of ESQ better (Xu et al 2019b, Chen et al 2020). Assuming m predictors \((j \in (1, 2, \ldots, m))\) and n observations, the linear formation of the GWR model for observation \(i\) \((i \in (1, 2, \ldots, n))\) at location \((u_i, v_i)\) was calculated as:

\[
y_i = \sum_j \beta_j (u_i, v_i) x_{ij} + \varepsilon_i, \tag{4}
\]

in which \(y_i\) is the response variable, \(x_{ij}\) is the \(j\)th predictor variable, \(\beta_j (u_i, v_i)\) is the \(j\)th coefficient, and \(\varepsilon_i\) is the error term. In this study, data processing and model-fitting were developed using ArcGIS v. 10.6.

We collected the urban agglomeration’s socioeconomic data in 2018 systematically at the county level. There are 42 statistical units (urban) and 36 statistical units (rural) that can be used in the GWR model. Through the effective numbers were both less than the statistical unit, we found that the sample size was sufficient (table S1). In this study, although the \(R^2\) of the GWR methods were not very high, the model’s standard error was less than 3.93 in urban areas and 2.67 in rural areas. According to previous studies (Ren et al 2020), the GWR methods yield better model fits than do other regression models.

3. Results

3.1. Multiscale spatial distribution of ESQ

Statistical analysis of spatial distribution characteristics of ESQ based on the rural and urban scale. The spatial distribution range of ESQ in the PRD was quite variable (12.7–91.7), but the quality was concentrated from approximately 35–75 (the maximum value is 100), and accounted for 90.3% of ecological space. The spatial distribution in the low ESQ was concentrated largely in the central and southern parts of urban agglomerations, and the average ESQ among cities was similar (≈0.5). The low-value areas in city ESQ were concentrated in GZ and FS, while the high-value areas were concentrated primarily in SZ. The differences between urban and rural areas were also small, mainly from GZ (0.1) to DG (3.3). The differences were concentrated largely in the high and low value areas of ESQ (figure 1). Rural areas had both the...
best and worst ecological space in the PRD, and were
the primary areas of ecological protection and restora-
tion. The low-value areas in rural ESQ were concen-
trated in JM and HZ, and the high-value areas were
concentrated primarily in ZQ and the north of GZ,
and HZ. The urban areas of GZ and FS, and the rural
areas of JM and HZ were the main regions of ecolo-
gical restoration and construction, while ZQ and SZ
were the primary regions of ecological protection.

3.2. Typologies of ESQ inequality
ESQ and income distribution at the urban agglom-
eration scale were relatively equal (Gini index, <0.2).
The equality in the ESQ distribution was higher
than that in income (ESQ Gini index < income
Gini index) (figure S3(a)). On the urban–rural scale,
the equality of urban ESQ distribution was higher
than in rural areas in the PRD (figure 2), particu-
larly in HZ, where the distribution was the most
equal (Gini index = 0.01). In JM and ZQ, the rural
areas’ ESQ distribution equality was generally higher
than that in urban areas. This was primarily because
the area was largely mountainous, and the residents
had extensive ecological space and relatively scattered
communities.

The ESQ distribution equality among demo-
graphic groups was relatively equal at the urban
agglomeration scale (concentration coefficient,
0.005) (figure S3(b)). However, according to the con-
centration curves (figure 3), high-quality ecological
spaces were concentrated in high-income counties
at the urban scale, while their distribution was
concentrated in low-income counties in rural areas.

With respect to the cities’ urban and rural scales, the
distributions of ESQ among different demographic
groups were varied. The equality in the distribu-
tion of urban ESQ in different demographic groups
was higher than that in rural areas. In GZ and SZ,
high-quality urban ecological spaces were concen-
trated generally in high-income counties, while in
other cities, they were concentrated largely in low-
income counties. High-quality ecological spaces in
rural areas were all concentrated in low-income

To summarize these results for cross-city compar-
ison, figure 4 shows each city’s classification into one
of four typologies. In HZ, the city of JM and the rural
of GZ should be noticed, which had higher income
gaps, high-quality ecological spaces were distributed
primarily in low-income counties. Because of urb-
anization and the entry of the real estate market,
pressure on low-income counties’ ecological spaces
has increased gradually, and caused these counties
to destroy ecological spaces and develop the built-
up land. Moreover, the growing population has exer-
ted more pressure on the surrounding ecological
spaces. High-income counties generally had smal-
ler areas and lower ESQ. Although they invested in
ecological construction, the increase in the imbal-
ance between supply and demand overall increased
urban ecological health risks, and led to a series of
environmental problems that affected high-income
**Figure 2.** ESQ (blue) and income (red) Lorenz curves of urban (straight lines) and rural (dotted lines) areas in the PRD urban agglomeration. ESQ: ecological space quality.

**Figure 3.** ESQ (blue) and income (red) concentration curves of urban (straight lines) and rural (dotted lines) areas in the PRD urban agglomeration. ESQ: ecological space quality.
Figure 4. Classification of urban and rural areas based upon ESQ concentration and Gini indices. For the concentration index, the classification threshold at the x-intercept is zero. For the Gini index, the y-intercept is the mean Gini index of the cities. ESQ: ecological space quality, GZ: Guangzhou, SZ: Shenzhen, ZH: Zhuhai, FS: Foshan, JM: Jiangmen, ZQ: Zhaoqing, DG: Dongguan, ZS: Zhongshan, HZ: Huizhou.

Figure 5. The socioeconomic determining factors of ESQ in the urban and rural areas of the PRD urban agglomeration. ESQ: ecological space quality, GZ: Guangzhou, SZ: Shenzhen, ZH: Zhuhai, FS: Foshan, JM: Jiangmen, ZQ: Zhaoqing, DG: Dongguan, ZS: Zhongshan, HZ: Huizhou.

3.3. Socioeconomic determining factors of ESQ

The socioeconomic factors’ causal effects were nearly the same among the cities, but the urban and rural areas’ determining factors varied (figure 5). Socioeconomic factors’ effects on urban areas were greater than those on rural areas, which indicates that urban areas will be the key areas urbanization will affect. Population density was associated positively with ESQ in the urban areas, but negatively in the rural areas. The disposable income was the converse, and had a negative determining effect on ESQ in the urban, and a positive effect in the rural areas. Urban ESQ was determined primarily by population density and impervious surfaces. Increases in urban population were associated positively with ESQ, while increases in impervious surfaces were associated with it negatively, and all decreased in intensity from West to East (figure S4). In rural areas, population density and education determined ESQ largely. Increases
in rural population were associated negatively with ESQ, but increases in the education level and income were associated positively with ESQ. As in the rural areas, the intensity of population density decreased from West to East, same as the urban. Educational level's determining effect on the ESQ in rural areas decreased gradually from the inland to coastal areas (figure S5).

4. Discussion

Improving regional ESQ and enhancing ecosystem services are the primary goals of urban sustainable development (Schröter et al 2017, Langemeyer et al 2018). Particularly in highly urbanized agglomerations, the imbalance between the supply and demand of ecosystem services is extremely prominent (Bryan et al 2018, Yan et al 2018). Its essence is the balance of ecological space distribution, including area and quality (Yahdjian et al 2015). The government of China is striving currently to build ecological spaces, and is carrying out ecological construction and restoration to eliminate the gap between supply and demand as well (Chen 2015a). Since 2004, the PRD has implemented several ecological construction and restoration projects successively. As our results showed, the distribution of ecological spaces is now relatively uniform; however, ecological health risks and the imbalance between supply and demand of ecosystem services still increased (Dong and Xu 2019, Hu et al 2019). This study also indicated qualitatively that the cause of this imbalance is a lack of understanding of the balance of ESQ distribution among different demographic groups that has resulted in the blind implementation of ecological management strategies and irrational internal ecological planning and construction. This study indicated that the main problems at present are ecological pressure concentrated on low-income groups. Hence, efforts in ecological management should be focused now on low-income counties. To address these issues, the government should strengthen the evaluation and monitoring of ESQ distribution with high-resolution images or data; provide ecological compensation in rural areas and implement diversified ecological compensation through government, social capital, and individual capital cooperation; i.e. the government should encourage high-income groups in the urban to bear the cost of ecological construction and restoration and guide residents with high-quality ecological spaces in rural areas to participate in ecological construction and restoration. In urban planning, calculations of urban carrying capacity should be made a priority to guarantee the number of ecological facilities, and high-quality ecological space should be achieved based upon landscape evaluations. For example, the mangrove wetland ecosystem in SZ is affected seriously by urban expansion and environmental pollution. During the implementation of its ecological restoration project, real-time monitoring of aquatic environments was strengthened, and various methods, such as ecosystem service assessment and management, were used to implement hierarchical treatment and protection. In ecological management, nearby residents were encouraged to set up volunteer teams to participate in the protection and management activities, and the initiative was sent to the entire city to encourage donations that were used to implement of ecological compensation and project area management.

The findings of this study also revealed that the distributions of ESQ among different demographic groups at the urban and rural scale varied. Specifically, the urban high-quality ecological spaces in GZ and SZ were concentrated largely in high-income groups, unlike other cities. GZ is a city with a long history that has more places of interest and historical sites; hence, more high-quality ecological space was built and concentrated in high-income communities. SZ has focused on the protection of natural ecological spaces in urban development and construction. With urban development, the original residents and immigrants were concentrated in the city near workplaces, and formed a ‘village in the city’, while high-income residents chose to live in high-quality ecological communities. Because of urbanization, the economic and cultural centers in other cities and rural areas were concentrated largely in the interior, which exerted more pressure on ecological spaces, and thereby damaged and degraded ecological spaces, while the quality of suburban and rural ecological spaces was generally high. This was also reflected in the determining force of socioeconomic status. The analysis of causal factors revealed that demographic factors, particularly population density, were the common dominant factors associated with the ESQ. However, the determining effect of urban and rural scale was the converse. We found that population density had a positive effect on ESQ in the urban, but a negative effect in the rural areas, which was attributable to population growth. Accordingly, the PRD analyzed the ecological carrying capacity and carried out ecological construction and ecological restoration projects to improve ESQ to meet the residents’ needs, including the construction of ecological space and implementation of ecological restoration (Chen et al 2020). This has been concentrated primarily within the high-income urban areas, particularly in SZ and GZ. The government has invested much money to build and enhance ecological space, and such policies as returning cropland to forest, establishing nature reserves, and engaging in ecological restoration, are underway (Wang et al 2018b, Chen et al 2021). However, the lack of control in rural areas, and the increased population density has increased
the ecological pressure, and infringed upon and damaged the ecological space. This resulted in the reduction of the ESQ and high-quality ecological spaces became relatively concentrated in low-income groups in rural areas. However, increasing rural residents’ income could promote the improvement of ecological quality, and thus, an ecological compensation policy was necessary in rural areas. Further, education had a positive effect on ESQ in the rural areas that reduced gradually from the inland to coastal areas. The Northern region of the PRD is primarily a mountainous area with low urbanization, and hence, urbanization’s pressure on the ecological space is relatively low. Improvement in the residents’ educational level helps them implement scientific ecological management measures, and protect and restore ecological space further. The coastal area is largely highly urbanized, and urbanization’s pressure on the regional ecological space is higher. Further, the effect of improved educational level on the ESQ is weaker than in the inland area.

There were some limitations to the analysis that should be noted. Because of the lack of obvious boundaries in the urban–rural gradient classification, an urban area was also regarded as a rural area in some towns with small area distributions, which caused some data inaccuracy; however, the area of these samples was small and had little effect on the results. We should note that spatial inconsistencies existed between land use data and partial assessment data that will introduce uncertainties in ESQ assessment. As a result, our analysis may have missed some detailed information at small scales. However, because the region was investigated at the county level, the large resolution data (e.g. NDVI, which is 250 m) still have spatial gradients suitable for the ESQ analysis. Because of a lack of data in the ESQ evaluation process, assessment indicators were not comprehensive but generally reflected the actual situation in regional ecological spaces. Because of the limitations of the data and to avoid repetition with the ESQ assessment indicators, when determining forces were explored, there were fewer determining force indicators. In the future, as more data become available and are refined, we intend to discuss urbanization’s causal effects on ESQ in greater detail.

5. Conclusions

There were no considerable differences in ESQ at multiple scales of the urban agglomeration. The spatial distribution in the low ESQ was concentrated largely in the areas surrounding built-up land, and GZ and FS were the main cities where ecological restoration and construction efforts are underway. For areas with a large income gap and high-quality ecological space concentrated in low-income groups, ecological pressures were concentrated more on low-income groups, but ecological health risks were enhanced for high-income groups. Socioeconomic factors had obvious causal effects on ESQ, but there were also considerable differences between urban and rural areas. To solve the imbalance in the ESQ distribution, the government should strengthen the construction of urban ecological spaces, increase the supervision of the rural ecological space, and implement ecological compensation to reduce ecological pressures, concentrated primarily in HZ and rural areas in GZ. Collectively, the findings of this study provide a theoretical basis for sustainable urban development and the construction of a fair and harmonious society.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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