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Identifying the Interactive Coercive Relationships Between Urbanization and Eco-Environmental Quality in the Yangtze and Yellow River Basins, China

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Abstract: Urbanization, as an important engine of modernization, plays an important role in promoting regional economy and improving living standards. Nevertheless, unchecked urban expansion over recent decades has strained natural resources and the environment, leading to crises, especially in densely populated urban areas that act as ecological barriers within river basins. The investigation of the interactive coercive relationship between the urbanization level (UL) and eco-environmental quality (EEQ) can facilitate the identification of sustainable pathways towards regional sustainability. Therefore, this study employed a set of multidisciplinary approaches, integrating simple linear regression, bivariate spatial autocorrelation, and coupling coordination degree (CCD) models, alongside multi-source remote sensing data to analyze the interactive coercive relationship between UL and EEQ in the Yangtze and Yellow River basins (YYRBs) in China. Key findings included a 6.97% improvement in EEQ in the Yellow River basin (YLRB) from 2001 to 2020, with higher values in the southeastern and southwestern regions and lower values in the central region, while the Yangtze River basin (YTRB) saw only a 1.28% increase, characterized by a lower EEQ in the west and higher levels in the middle and east, although the Yangtze River Delta showed a decline and significant variation among tributaries. UL rose steadily in both basins, especially in the middle reaches of the YLRB. Spatial autocorrelation analysis revealed a positive correlation between UL and EEQ in the YLRB, whereas a negative correlation was found in the YTRB. The CCD between UL and EEQ in the YYRBs improved, particularly in the middle and lower reaches, indicating the need for integrated urban development strategies that consider regional ecological capacities. These findings provided a scientific basis for ecological protection and sustainable urban development at a large river basin scale.

Keywords: urbanization; eco-environmental quality; bivariate spatial autocorrelation; coupling coordination model; the Yangtze and Yellow River basins

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1. Introduction

The adoption of the 2030 Agenda for Sustainable Development marks the official establishment of the global Sustainable Development Goals (SDGs). SDG 11 is "Sustainable Cities and Communities". Following this, the Second Session of the United Nations Habitat Assembly convened, focusing on sustainable urban futures and addressing concerns from governments and stakeholders about urbanization issues [1]. Urbanization is an inevitable consequence of accelerated socio-economic growth. Most countries have implemented strategies to facilitate this process, with developed nations showing a trend of rapidly concentrating production factors in urban areas while effectively adapting to population migration and economic change [2]. In contrast, developing countries often experience rapid population aggregation alongside stagnant industrialization, leading to "pseudo-urbanization" [3,4]. Since 2010, China has entered a phase of higher regional economic integration, which is particularly evident in river basin economies. While rapid urbanization has brought some economic and social benefits, it has also led to significant challenges [5,6]. Extensive construction projects have resulted in excessive consumption and the degradation of land resources, while urban pollutants have surged, exacerbating the urban heat island effect [7,8]. Additionally, there has been the overuse of water resources and increased water pollution, negatively impacting ecological carrying capacity and regional environments [9]. These factors hinder the advancement of high-standard urbanization. Despite some recent progress, the overall trajectory toward the achievement of established objectives has been unfavorable. This indicates that improving eco-environmental quality (EEQ) is crucial for China to meet its SDG 11 by 2030.

The term "ecological environment" refers to the collective biotic and abiotic elements that constitute a specific environment. The concept is fundamentally linked to human health, safety, and overall well-being [10]. Assessing EEQ involves evaluation through various qualitative and quantitative indicators [11]. The concept of "human habitat environment science", introduced in the 1950s, established a new research field focused on the assessment of human habitat quality [12]. This research has evolved alongside the environmental implications of economic and social development, aiming to facilitate practical applications [13]. Initially, evaluations relied on single indicators, but they have progressed to incorporate comprehensive approaches, shifting from qualitative assessments to quantitative visual analyses. Modern evaluations utilize remote sensing data and principal component analysis for objective weighting, enhancing the precision and breadth of the data used [14]. This evolution has led to the maturation and standardization of evaluation systems, providing timely insights into regional eco-environment conditions and trends [15]. It also aids in identifying current issues and developing effective strategies for ecological protection. The effective monitoring and evaluation of eco-environments are crucial for ensuring the necessary environmental oversight [16]. The ecological environmental index has emerged as a primary research method, defining indicator systems, methodologies, and assessment technologies across various sub-fields [17]. The China high-resolution EEQ dataset exhibits a high degree of consistency with the eco-environmental index provided by the Ministry of Ecology and Environment, which can address the research gap in the field of monitoring EEQ.

Urbanization is a complex process with significant environmental impacts, especially in regions experiencing rapid economic growth and population increases [6]. To mitigate the negative consequences of urbanization and promote sustainable human development, it is crucial to analyze the development trends and coercive interactions between UL and the eco-environment [18]. As urbanization accelerates, large populations move to urban areas, exacerbating human–land conflicts and creating urgent ecological challenges [19]. Since the 1980s, research has increasingly focused on the interplay between UL and the eco-environment [20]. Scholars have suggested that urbanization facilitates the spread of invasive plant species, which can lead to a decline in native species, particularly rare ones [21]. This process can contribute to biological homogenization, where urban areas become more similar in their ecological characteristics [22]. To counteract these trends, the development of targeted protection and management strategies for specific urban habitats and their remaining natural areas is essential. Additionally, the relationship between economic development and resource–environment dynamics, as illustrated by decoupling theory, has garnered significant attention. This theory reflects the coupling coordination degree

(CCD) between economic growth and environmental sustainability [23]. Most current research focuses on the interrelationship between urban development and the eco-environment in major urban agglomerations, highlighting the need for the development of comprehensive strategies to address these challenges.

However, despite the growing body of literature examining the interrelationship between urban development and the eco-environment in major urban agglomerations, there remains a critical gap in understanding the interactive coercive relationships between urbanization level (UL) and EEQ at the large river basin scale, such as in the case of the Yangtze and Yellow River basins (YYRBs) in China [24,25]. Existing studies often focus on urbanization dynamics or EEQ in isolation, neglecting the complex interactions and feedback mechanisms between them [26,27]. Urbanization and eco-environmental change are interdependent yet distinct sub-systems that together form a coupled system characterized by dynamic interactions and mutual influences. This study constructed a CCD model to quantify the relationship between UL and EEQ in the YYRBs, aiming to elucidate their coordinated development status and dynamic changes. Additionally, spatial autocorrelation analysis was employed to explore the interrelationship between UL and EEQ. This method examined the spatial distribution of both UL and EEQ, identified inter-regional correlations and highlighted geospatial heterogeneity. In this way, it provided a more comprehensive perspective on the interactions between UL and EEQ across different regions.

The YYRBs, comprising two of China’s most densely populated and economically dynamic regions, are a prime case for examining the challenges and opportunities associated with urbanization and its interactions with EEQ. The YYRBs have undergone rapid urbanization over the past few decades, driven by industrialization, urban migration, and infrastructure development [28,29]. This urban expansion has brought about significant changes in land use, resource consumption, pollution levels, and ecosystem services, creating both opportunities and challenges in terms of sustainable development. This study aimed to address the aforementioned gap by examining the interactive coercive relationship between UL and EEQ of the YYRBs at the prefecture-level city scale. Therefore, we employed a multidisciplinary approach in conjunction with a simple linear regression model to elucidate the dynamic trends in EEQ over an extended time series. Furthermore, the bivariate spatial autocorrelation model and the CCD model were introduced to reveal their interactive coercive relationship. Undertaking these activities, we expected to achieve the following objectives, aiming to (1) analyze the spatiotemporal patterns of EEQ in the YYRBs, (2) measure the spatiotemporal patterns of UL in the YYRBs, and (3) identify the spatiotemporal variations in the CCD of UL and EEQ across the YYRBs. The findings in this study would contribute to informing policy-making and decision-making processes in the context of sustainable development in big basins globally.

2. Materials and Methods

2.1. Study Area

The Yangtze River and the Yellow River are regarded as the mother rivers of China (see Figure 1). They have nourished the time-honored Chinese civilization and nurtured the industrious and courageous Chinese people. The Yangtze River is China’s longest river and the world’s third longest river, spanning from 90°33′E to 122°25′E and from 24°30′N to 35°45′N. The Yangtze River basin (YTRB) accounts for 20% of China’s land area, carrying 1/3 of the population. The area is characterized by a high degree of topographic complexity and diversity, as well as a considerable range of climatic types. The diverse climate has led to the formation of a multitude of ecosystem types, which in turn have made the YTRB an important habitat for rare and endangered wildlife in China. The Yellow River basin (YLRB) is situated between 32°10′N and 41°50′N and between 95°53′E and 119°05′E. It plays an instrumental role in the national economic development pattern, encompassing 27.3% of the country’s area, serving as a domicile for 23.3% of the country’s population, and contributing 21.8% of the total economic output. The terrain is low in the east and high in the west, with varied regional topographies and diverse climates, making the area a significant ecological barrier and economic zone in China. The accelerated urbanization in the YYRBs has intensified the deterioration of the eco-environment. The urbanization process has an obvious coercive effect on the EEQ, while the EEQ also has an obvious constraint effect on the urbanization process. This two-way interaction and coercive relationship is particularly prominent in the YYRBs. This requires that we attach great importance to the protection and restoration of the eco-environment while promoting urbanization in order to achieve the sustainable development of the two big basins.

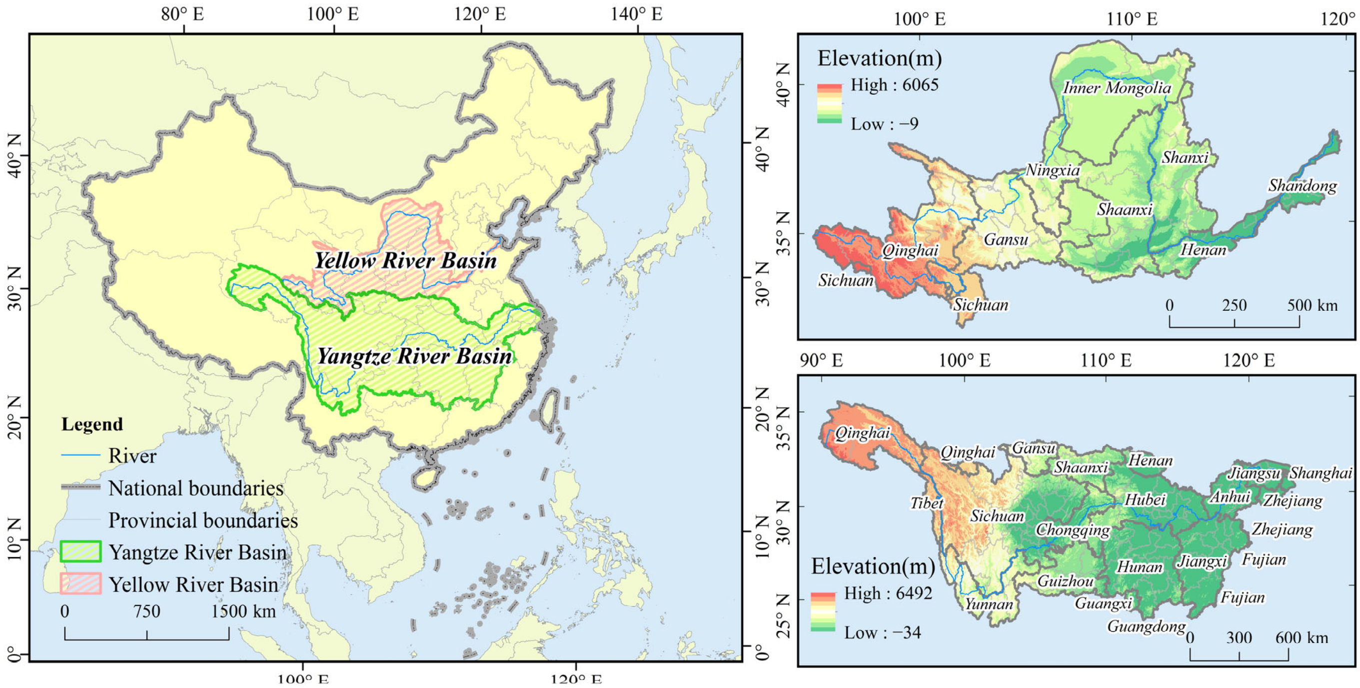

Figure 1. Location map of the YYRBs.

2.2. Data Sources and Processing

The high-resolution EEQ data used in this study, spanning the period from 2001 to 2020, were derived from the National Earth System Science Data Center, National Science & Technology Infrastructure of China (http://www.geodata.cn, accessed on 15 September 2024). This dataset has a spatial resolution of 500 m and includes indicators such as land surface temperature, normalized difference vegetation index, habitat quality index, normalized difference built-up index, and wetness. To mitigate subjective influences, these indicators underwent standardization, synthesis, and principal component analysis. Additionally, the data on DEM, GDP, and population at a resolution of 1 km, along with the proportion of the construction land area, were obtained from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn, accessed on 15 September 2024).

2.3. Change Trend Analysis

In this study, a simple linear regression model was used to calculate the annual trend in the grid-scale EEQ for the YYRBs in a continuous time series from 2001 to 2020, thereby revealing the dynamic trend in EEQ within long time series. The slope of the linear regression equation is the annual variation rate of the EEQ [6]. The equation was as follows:

$$Slope = \frac{n \times \sum_{i=1}^{n}(i \times EEQ_i) - \sum_{i=1}^{n} i \sum_{i=1}^{n} EEQ_i}{n \times \sum_{i=1}^{n} i^2 - \sum_{i=1}^{n} i} \quad (1)$$

where *Slope* signifies the slope of the simple linear regression equation fitting *EEQ* against the time variable. i represents the time variable ranging from integers 1 to n, where n equals the number of years in the study period, which is 20. *EEQ* denotes the average *EEQ* during the growing season of the i-th year. *Slope* < 0 indicates a decreasing trend in *EEQ* over time, while *Slope* > 0 indicates an increasing trend. The magnitude of the *Slope* reflects the rate of change in terms of *EEQ*.

2.4. UL Measurement

The UL is typically characterized by four key aspects: population urbanization, economic urbanization, land urbanization, and social urbanization [30]. These four dimensions represent different aspects of urbanization, with population growth being the core. This typically measured by population density. Economic urbanization serves as the driving force, and is usually represented by economic density. Land urbanization acts as the spatial carrier, and is typically measured by the proportion of construction land; and social urbanization serves as the ultimate goal [31]. Due to the difficulty of quantifying and spatializing social urbanization, this study did not incorporate it. Therefore, this study measured the comprehensive UL based on the three standardized indicators.

2.5. Bivariate Spatial Autocorrelation Model

This study employed the bivariate Moran's *I* to examine the spatial agglomeration and dispersion patterns of the EEQ and UL [30]. The bivariate spatial autocorrelation can reveal their spatial dependence and mutual influence, thereby facilitating an understanding of the interactive coercive relationship between the two variables in space. Specifically, the global bivariate Moran's *I* was employed to assess the overall association and significance between EEQ and UL, while the local bivariate Moran's *I* was utilized to identify potential spatial correlation patterns at varying spatial locations, thereby capturing the agglomeration and differentiation characteristics of local spatial elements [32]. The equations were as follows:

$$Global\ \ Moran's\ I = \frac{n\sum_{i=1}^{n}\sum_{j1i}^{n} w_{ij}\, UL_i^e EEQ_j^u}{(n-1)\sum_{i=1}^{n}\sum_{i1j}^{n} w_{ij}} \tag{2}$$

$$Local\ \ Moran's\ I = UL_i^e \sum_{j=1}^{n} w_{ij}\, EEQ_j^u \tag{3}$$

where n is the number of spatial samples; w_{ij} is the spatial weight matrix based on spatial adjacency relationships; UL_i^e is the comprehensive *UL* of the i-th research unit; and EEQ_j^u is the *EEQ* index of the j-th research unit. Furthermore, local Moran's *I* was visualized through Local Indicators of Spatial Association (LISA) maps to identify clustering patterns in space. A high–high cluster pattern indicates areas with high *UL* and high *EEQ*, while a low–low pattern indicates the opposite, and both exhibit positive spatial correlations; a low–high cluster pattern represents areas with low *UL* and high *EEQ*, while a high–low pattern represents the opposite, with both exhibiting negative spatial correlations.

2.6. CCD Model

The concept of coupling is an effective means of characterizing the interactions between different systems, including those influenced by the external environment. The CCD model is a methodology employed to assess the extent of the mutual influence between two or more systems and the nature of their interaction. This study intended to draw on this model to measure the interaction between UL and EEQ to identify the potential coercive risks between the two systems. Therefore, we established the CCD model for UL and EEQ to reveal their coupling coordination process and evolution rules [21]. First, the coupling degree (*C*) between UL and EEQ systems was measured, which reflected the degree of their mutual influence (Equation (4)). Second, with the help of the intermediate variable comprehensive coordination index (*T*) (Equation (5)) and the coupling degree, the CCD of UL and EEQ indices was jointly evaluated, reflecting the degree of coordination development between them (Equation (6)). The calculation equations were designed as follows:

$$C = \{UL \cdot EEQ/[(UL + EEQ)/2]^2\}^{1/2} \quad (4)$$

$$T = \alpha UL + \beta EEQ \quad (5)$$

$$D = \sqrt{C \cdot T} \quad (6)$$

The *UL* and *EEQ* subsystems have comparable levels of influence and exist in a mutually constraining and interacting relationship, where $\alpha + \beta = 1$. Therefore, the undetermined coefficients are determined to be such that $\alpha = \beta = 0.5$. The CCD (*D*) is divided into four stages: when $0 < D \leq 0.2$, it is classified as exhibiting extreme incoordination; when $0.2 < D \leq 0.4$, it is classified as exhibiting moderate incoordination; when $0.4 < D \leq 0.6$, it is classified as exhibiting basic coordination; when $0.6 < D \leq 0.8$, it is classified as exhibiting moderate coordination; and when $0.8 < D < 1.0$, it is classified as exhibiting high coordination.

3. Results

3.1. Spatiotemporal Patterns of EEQ in the YYRBs

The distribution of EEQ in the YLRB showed a pattern of higher values in the southeastern and southwestern regions and lower values in the central region (see Figure 2). The average EEQ values for the YLRB in 2001, 2010, and 2020 were 0.330, 0.329, and 0.353, respectively. This demonstrated an overall trend of decreasing and then increasing, with an average quality increase of 6.97%. From 2001 to 2020, the proportion of units exhibiting an increase in the EEQ was 69.96%, while the proportion of units displaying a decline was 30.04% (see Figure 3). The EEQ in the upper reaches initially exhibited a decline, followed by an increase, while the lower reaches demonstrated relatively stable growth (see Figure 3). In particular, the EEQ of the Loess Plateau has risen across the board. However, a decline was observed in 2020. The Guanzhong Plain exhibited a sustained elevation in EEQ, accompanied by a consistent expansion. The regions exhibiting the highest EEQ values were primarily situated in Nanyang, Hanzhong, Ankang, and Shangluo, whereas those displaying the lowest EEQ values were located in Alxa League, Wuhai, Ordos, and Zhongwei.

In the YTRB, the EEQ exhibited a distribution pattern whereby it was relatively low in the western regions and comparatively high in the central and eastern regions (see Figure 2). The average EEQ values for the YTRB in 2001, 2010, and 2020 were 0.540, 0.535, and 0.547, respectively. The results indicated a downward and then upward trajectory of overall quality at the prefecture-level city scale, with an average increase of 1.28%. From 2001 to 2020, 59.40% of the area was exhibiting an increase in EEQ, while 40.60% of the area was exhibiting a decrease (see Figure 3). The mainstream area of the YTRB generally demonstrated a high level of EEQ, exhibiting a high-value diffusion effect. However, the EEQ in the Yangtze River Delta showed a negative growth trend, with quality declining year by year (see Figure 3). The areas with high EEQ values were predominantly concentrated in Heyuan, Longyan, Qingyuan, and the Shennongjia Forest District, whereas the areas with low EEQ values were located in regions such as the Haixi Mongolian and Tibetan Autonomous Prefecture, the Yushu Tibetan Autonomous Prefecture, Shanghai, and Zhoushan. Overall, the EEQ value demonstrated a gradual increase. In contrast, the EEQ of the YLRB and YTRB demonstrated an overall increasing trend, but the spatial distribution pattern was quite different. Among these areas, the EEQ of the YLRB was significantly higher than that of the YTRB, and the EEQ of the YLRB increased significantly, while that of the YTRB increased relatively slowly.

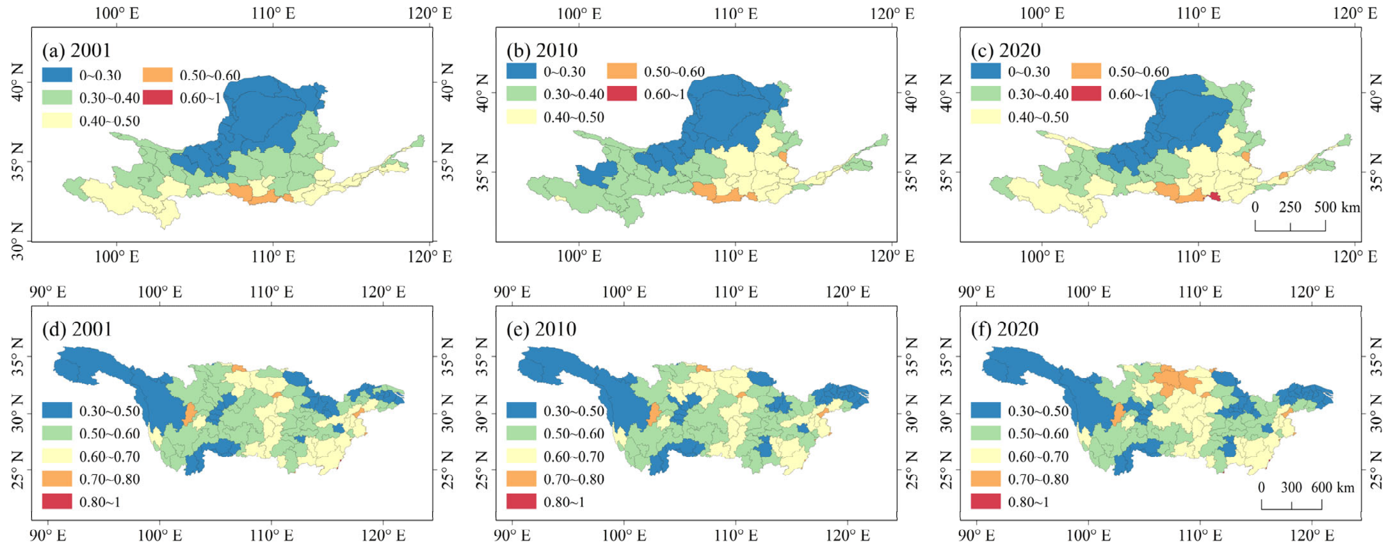

Figure 2. Spatiotemporal patterns of EEQ in the YYRBs in 2001, 2010, and 2020. Note: (a)–(c) represent the spatiotemporal patterns of EEQ in the YLRB in 2001, 2010, and 2020, respectively; (d)–(f) represent the spatiotemporal patterns of EEQ in the YTRB in 2001, 2010, and 2020, respectively.

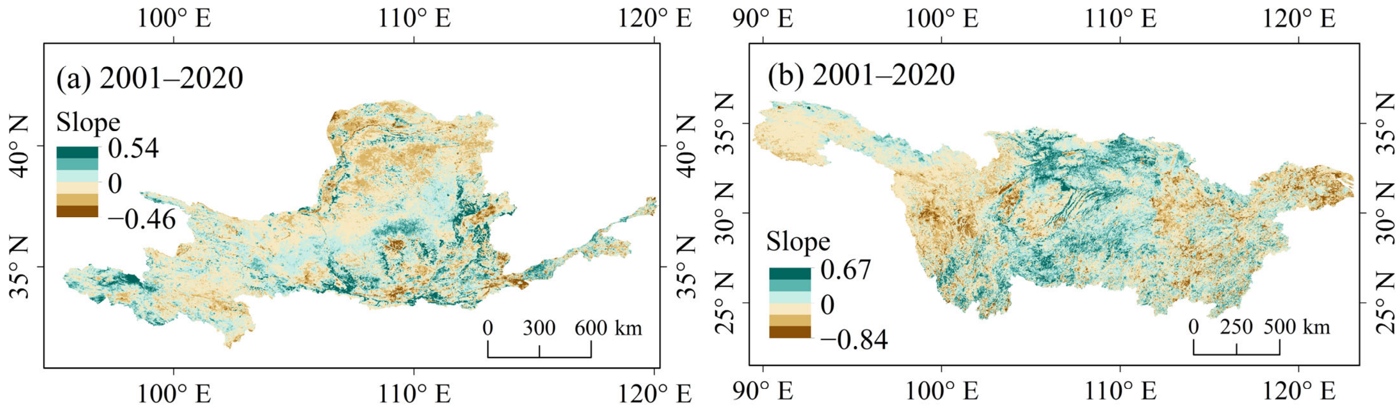

Figure 3. Changing trend in EEQ in the YYRBs during the period of 2001–2020. Note: The slope of the linear regression equation is considered to be the annual variation rate of the EEQ. (a) indicates the trend of EEQ in the YLRB from 2001 to 2020, and (b) indicates the trend of EEQ in the YTRB from 2001 to 2020.

3.2. Spatiotemporal Patterns of UL in the YYRBs in 2001, 2010, and 2020

The UL in the YLRB exhibited a spatial distribution pattern of high in the east and low in the west (see Figure 4), and the overall UL in the lower reaches was significantly higher than that observed in the middle and upper reaches. The average UL values of the YLRB were 0.06, 0.08, and 0.10 in 2001, 2020, and 2020, respectively. This demonstrated an overall increasing trend, with an average increase of 66.67% over the period under review. In particular, the UL increased in northwestern Gansu, southern Shaanxi, and southern Shanxi. Specifically, Qinghai and Sichuan, in the upper reaches, demonstrated a consistently low UL. The middle reaches exhibited rapid growth and significant increases, though the overall UL remained relatively low. The lower reaches maintained a relatively high UL, with minimal changes during the study period. Overall, areas with high UL were clustered in regions such as Zhengzhou, Xi'an, Jiaozuo, and Taiyuan.

The UL in the YTRB was gradually declining from east to west (see Figure 4). In general, the UL in the upper and middle reaches was not high, and the few areas with high UL values were mainly gathered in the lower reaches of the YTRB. The average UL values for the YTRB were 0.03, 0.04, and 0.06 in 2001, 2010, and 2020, respectively, doubling the UL from 2020 to 2001. The UL of the YTRB was generally on an upward trajectory from

2001 to 2020, with significant growth in the middle reaches and relatively higher UL values in the lower reaches (see Figure 4). In comparison to the national urbanization rate of 63.89% seen in 2020, several provinces, including Anhui, Jiangxi, Hunan, Sichuan, Yunnan, and Guizhou, exhibited urbanization rates that were below the national average. This suggested that there was considerable scope for advancement in the process of urbanization in the upper and middle reaches of the YTRB. Overall, areas with high UL values were clustered in regions such as Shanghai, Wuxi, Hangzhou, and Suzhou. In conclusion, the UL values of the YLRB and YTRB were at a low level and demonstrated an upward trajectory, exhibiting a comparable spatial distribution pattern. The UL values of units in the upper reaches were considerably lower than those of cities in the lower reaches, and the UL values of the YTRB were lower than those of the YLRB.

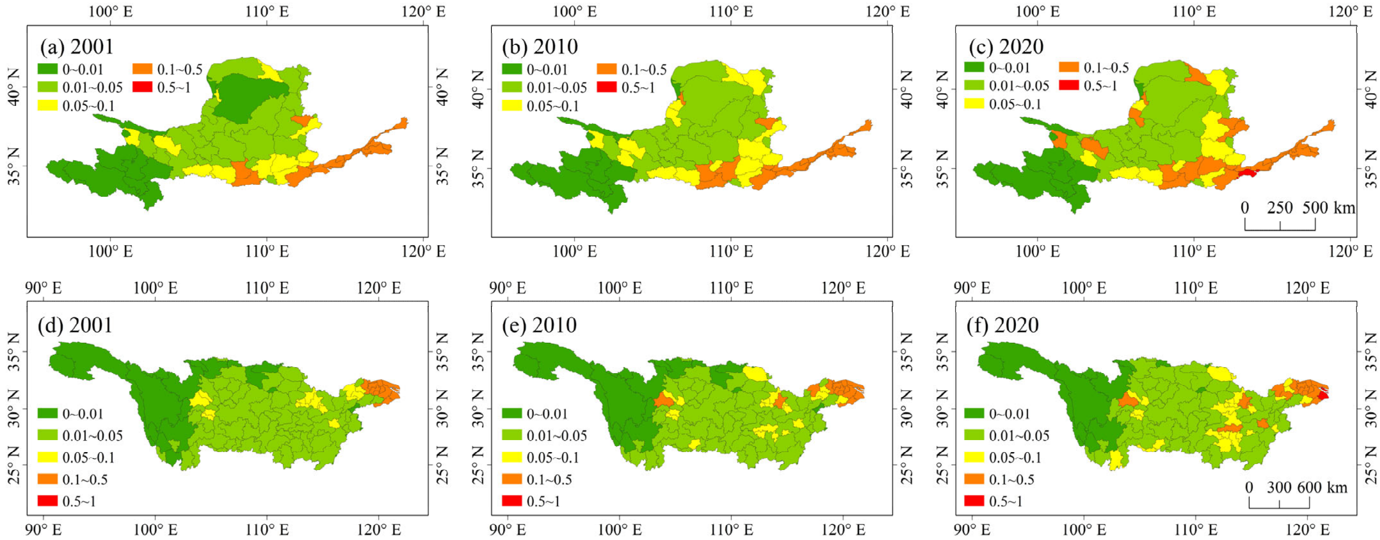

Figure 4. Spatiotemporal patterns of UL in the YYRBs in 2001, 2010, and 2020. Note: (a)–(c) represent the spatiotemporal patterns of UL in the YLRB in 2001, 2010, and 2020, respectively; (d)–(f) represent the spatiotemporal patterns of UL in the YTRB in 2001, 2010, and 2020, respectively.

3.3. Bivariate Spatial Autocorrelation Between UL and EEQ

In 2001, 2010, and 2020, the overall Moran's *I* values of UL and EEQ in the YLRB were positive but showed a decreasing trend, with values of 0.305, 0.235, and 0.194, respectively. Both types were found to be statistically significant at 0.001 level, indicating that their change values exhibited significant spatial clustering characteristics. The low–low type constituted the largest proportion, comprising nearly one-third of the area of the YLRB. It exhibited a trend of initial decline and subsequent increase over time, reaching 35.36% in 2020. The high–high type constituted the second most prevalent type, exhibiting a trend of initial increase followed by subsequent decline. The low–high and high–low types were less prevalent, exhibiting minimal alterations in their spatial distribution patterns over time. The area proportion of the low–high type exhibited an increase ranging from 0.36% to 2.39% on an annual basis, while the proportion of the high–low type demonstrated an increase ranging from 0.20% to 2.24% annually (see Figure 5). In the YLRB, high-value agglomerations were primarily concentrated in Shaanxi and Henan, whereas low-value agglomerations were predominantly situated in Inner Mongolia, Ningxia, and Gansu (see Figure 5). The relationship between UL and EEQ was positive. However, the number of high-value areas exhibited a gradual decline from 2001 to 2020. The upper and middle reaches of the region were characterized by clusters with low UL and low EEQ values. Nevertheless, as urban land coverage expands in specific regions, the surrounding EEQ exhibits a decline on an annual basis.

In 2001, 2010, and 2020, Moran's *I* of UL and EEQ in the YTRB exhibited negative values and an increased trend, with respective values of −0.185, −0.262, and −0.311. Both values were found to be statistically significant at the 0.001 level, indicating that their change values exhibited significant spatial clustering characteristics. No evidence was found regarding the largest proportion, and the area proportion exhibited a decline followed by an increase throughout the study period, reaching 12.40% in 2020. The second most prevalent type was the low–low type, which demonstrated a downward and then upward trend. The high–low type exhibited the smallest distribution area, with proportions ranging from 1.89% to 5.01%, demonstrating an annual increase (see Figure 5). In the YTRB, the distribution of aggregation areas was observed to exhibit a scattered pattern. The Qinghai segment in the upper reaches demonstrated a consistent pattern of low UL and low EEQ values, with these values remaining relatively stable over time. As the upper limits of the study area were reached, the surrounding regions also exhibited a decline in the EEQ. Meanwhile, the extent to which clusters displayed a combination of low UL and high EEQ values in the northern part of the basin and Jiangxi gradually reduced.

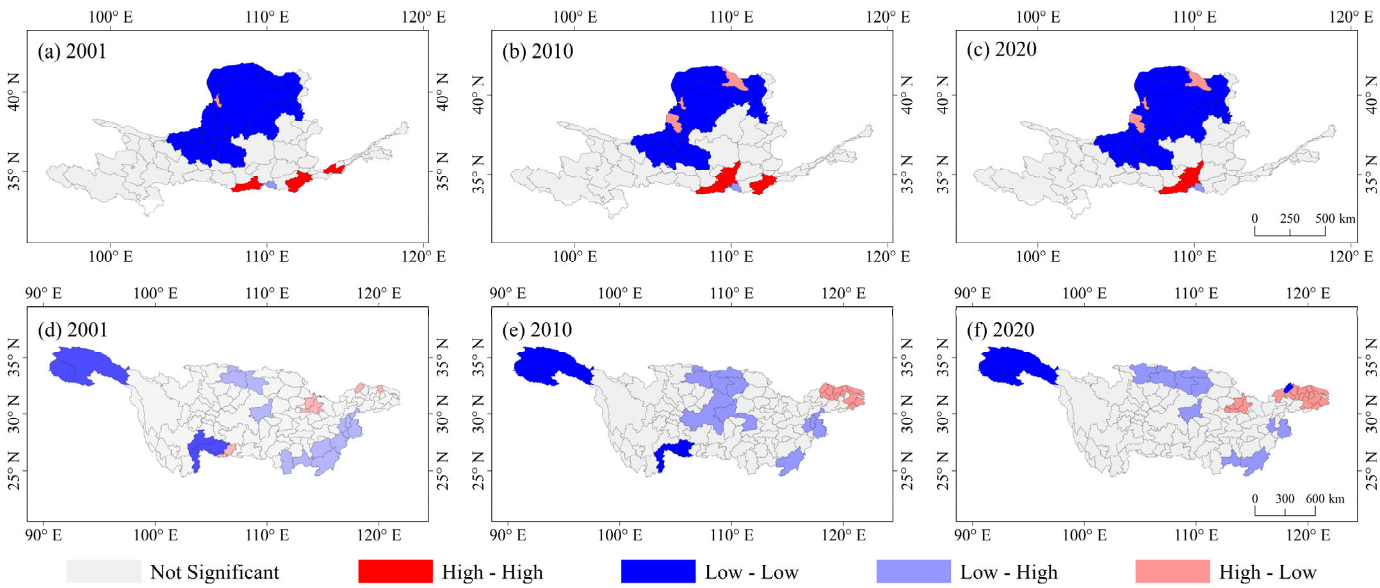

Figure 5. LISA map between UL and EEQ in the YYRBs in 2001, 2010, and 2020. Note: (a)–(c) represent the LISA map between UL and EEQ in the YLRB in 2001, 2010, and 2020, respectively; (d)–(f) represent the LISA map between UL and EEQ in the YTRB in 2001, 2010, and 2020, respectively.

3.4. CCD Between UL and EEQ

The CCDs of the YLRB in 2001, 2010, and 2020 were 0.34, 0.36, and 0.39, respectively, indicating a gradual increase over time. The percentages of areas with extreme and moderate incoordination were 68.57%, 60.43%, and 47.07%, respectively. In general, the area of extreme and moderate incoordination between UL and EEQ in the YLRB decreased, and the CCD increased (see Figure 6). Specifically, the overall CCD in the middle and lower reaches was higher than that in the upper reaches, and the degree of coordination increased, with most areas in Inner Mongolia and Qinghai rising from a state of extreme incoordination in 2001 to one of moderate incoordination in 2020, and some areas in Shaanxi and Henan rising from a state of basic coordination in 2001 to one of moderate coordination in 2020. In particular, parts of Sichuan in the upper reaches of the YLRB continued to show extreme incongruence.

The CCDs of the YTRB in 2001, 2010, and 2020 were 0.33, 0.34, and 0.36, respectively, showing a more gradual increase compared to the YLRB. The percentages of extreme and moderate incoordination areas were 79.81%, 69.36%, and 63.00%, respectively. It can be seen that, although the CCD between UL and EEQ in the YTRB slowly increased, most of the areas still showed extreme or moderate incoordination. The lower reaches showed relatively higher CCDs, showing basic and moderate coordination by 2020. In particular, Qinghai and Tibet, located in the upper reaches of the YTRB, and parts of western Sichuan remained in states of extreme incoordination; Chongqing rose from a state of extreme incoordination in 2001 to one of moderate incoordination in 2020; and parts of Jiangsu rose to a state of moderate coordination. Overall, despite the increasing CCDs of both the YLRB and YTRB, most of the areas remained at extreme and moderate uncoordinated levels.

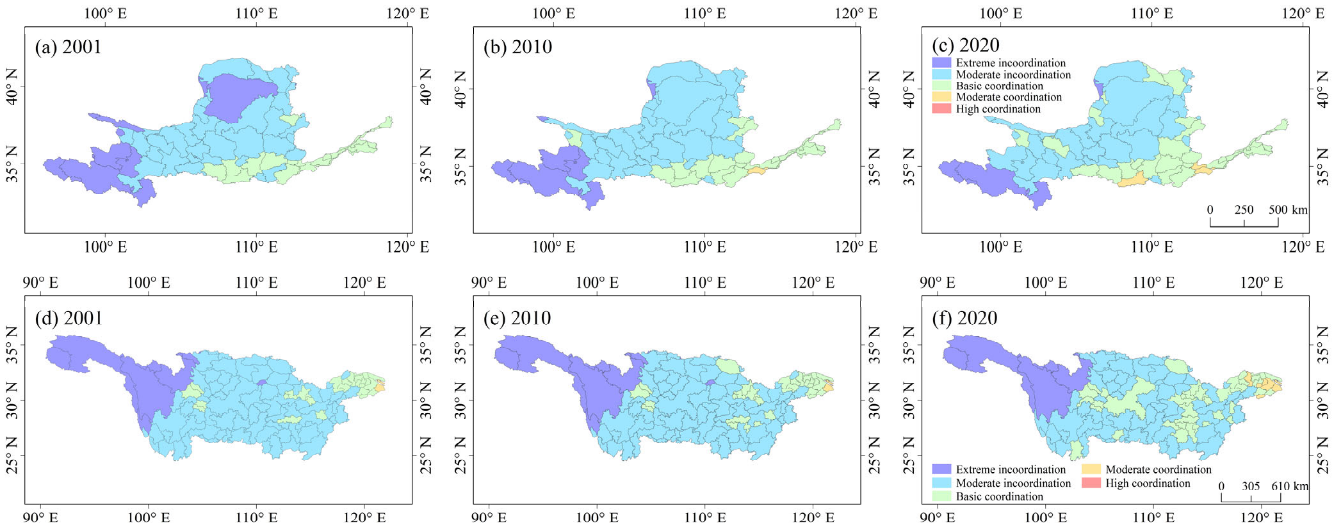

Figure 6. Spatiotemporal CCDs between UL and EEQ in the YYRBs in 2001, 2010, and 2020. Note: (a)–(c) represent the spatiotemporal CCDs between UL and EEQ in the YLRB in 2001, 2010, and 2020, respectively; (d)–(f) represent the spatiotemporal CCDs between UL and EEQ in the YTRB in 2001, 2010, and 2020, respectively.

4. Discussion

4.1. Interpretation of Findings

The overall EEQ of the YYRBs exhibited a slight decline from 2001 to 2010. It is noteworthy that the annual growth rate of EEQ in the Yangtze River Delta region remained negative, despite the low level at which it was already situated. In contrast, the regions in the upper reaches (especially Qinghai) not only exhibited low EEQ values but also demonstrated slower UL growth rates. The overexploitation and pollution of water resources in the YTRB have significantly impacted EEQ, and numerous studies indicate that climate change and human activities are severely threatening the aquatic ecosystem. Key issues such as water degradation, habitat deterioration, and resource overexploitation collectively contribute to the decline in EEQ [33,34]. Although UL drives economic growth, it simultaneously poses challenges to ecological integrity, resulting in water source pollution, air quality deterioration, and soil degradation, which ultimately hinder sustainable development in the region [35].

From 2010 to 2020, the EEQ of the YLRB showed a clear upward trend. Since the 18th National Congress of the Communist Party of China, YLRB management has entered a novel phase, with the construction of an ecological civilization now integrated into the comprehensive framework of the “five-in-one” socialist cause with Chinese characteristics (which encompasses economic, political, cultural, social, and ecological dimensions). The Loess Plateau underwent four distinct phases of eco-environment management—slope management, ditch–slope joint management, comprehensive small watershed management, and ◎Grain-for-Green◎projects—each producing significant positive outcomes [36]. Similarly, the YTRB has introduced targeted protection policies, including special inspections for shoreline protection, a year-round fishing ban in key areas, and enhancements to sewage treatment mechanisms [37]. These initiatives aimed to bolster eco-environmental protection and restoration efforts across the YTRB.

During the study period, a notable correlation was observed between UL and EEQ in the YLRB, highlighting a positive relationship and spatial synergy. However, regions with both high UL and EEQ values experienced a decline, suggesting that, despite various policies aimed at promoting environmental protection and green development, achieving a balance between economic growth and ecological integrity remains a significant challenge [38]. Additionally, the CCD model of urban agglomerations in the upper YLRB was less effective than that in the middle and lower reaches and significant coordination issues persist due to lower levels of economic development and slow ecological protection efforts [35]. As UL increases and the awareness of eco-environmental issues grows, the coercive impact of urbanization diminishes while the constraining influence of EEQ on UL becomes more pronounced. Insufficient policy implementation and regulatory mechanisms have hindered the resolution of ecological problems, particularly as the YLRB's fragile ecosystem is highly sensitive to long-term development. Grassland degradation in areas in upper reaches has led to decreased water conservation, while regions in middle reaches face severe soil erosion [28]. These challenges underscore the necessity of prioritizing eco-environmental protection during urbanization to achieve harmonious development.

There was a negative correlation between UL and EEQ in the YTRB, showing a spatial mismatch. The CCDs between UL and EEQ in the YTRB during the study period were mainly characterized by extreme incoordination. While there was a trend towards increased coordination, the overall level remained low, particularly in the upper reaches, which significantly impeded economically and socially beneficial development. In contrast, the lower and middle reaches showed higher overall coordination despite the persistent extreme incoordination in the upper reaches. This disparity reflects ongoing challenges, such as lower levels of economic development and the slower rate of environmental protection progress in the upper YTRB, resulting in increased variability in terms of coupling strength and diminished coordination capacity. Furthermore, environmental degradation and geological disasters in the mountainous upper Yangtze region, along with the reduction in lakes and wetlands in the middle reaches and the declining water quality in lower reaches, pose significant threats to the Yangtze's status as a strategic national water source [39].

4.2. Interactive Coercive Relationship Between UL and EEQ

The interactive coercive relationship between the UL and EEQ is a crucial aspect of the complex human–land dynamic in the YTRB. This relationship reveals a clear gradient across the basin, which is likely linked to varying degrees of ecological disturbance caused by urbanization in different regions [1]. As urbanization accelerates due to population growth and economic development, the landscape undergoes significant transformation, putting ecosystems under increasing pressure. Rapid urban expansion has led to the replacement of agricultural land and natural habitats with infrastructure, resulting in extensive land use changes that further exacerbate the coercive dynamics between UL and EEQ [21].

Land conversion disrupts ecological processes, fragments habitats, and reduces biodiversity, negatively impacting the stability of native species and ecosystems. Concurrently, the growth of urban populations and economic activities increases the demand for water resources, exacerbating issues of water scarcity and pollution. Urban centers in these basins contribute significantly to air and water pollution, with industrial and traffic emissions degrading air quality, while wastewater discharges harm aquatic ecosystems. Additionally, urban infrastructure alters hydrological patterns, leading to increased surface runoff, soil erosion, and sedimentation in water bodies, heightening flood risk and damaging the ecosystems of the lower reaches [22]. Collectively, these changes diminish the capacity of natural ecosystems to provide essential services such as water purification, flood regulation, and habitat support, challenging sustainable urban development and environmental protection efforts. Therefore, it is crucial to balance the benefits of urbanization with its environmental impacts. Effective management strategies should focus on integrated planning, green infrastructure, pollution control, and ecosystem restoration to protect EEQ and ensure the resilience and sustainability of these vital watersheds in China [23].

4.3. Policy Implications

In light of the disparities between the YLRB and the YTRB concerning physical, social, and economic conditions, we present for consideration a series of recommendations tailored to the specific circumstances of each region.

The YLRB, shaped by its distinctive geographical landscape, has been constrained by the lack of natural conditions conducive to the emergence of expansive urban settlements. This has resulted in a narrowing of opportunities for growth and development across various domains [40]. However, recent years have seen indications of improvement. The YLRB is situated in a pivotal location within the "Belt and Road Initiative", with the Hexi Corridor serving as a crucial transportation hub. It would be prudent to seize this opportunity and utilize the available advantages for the advancement of the region.

There is a notable discrepancy between the current state of urbanization development and the EEQ of the YLRB. The development of industry is uneven and insufficient [41]. To advance a unified approach to development, it is important to establish a comprehensive and harmonious development mechanism that encourages the growth of diverse industries. It is recommended that the upper reaches of the YLRB facilitate the provision of assistance from well-developed enterprises with advanced technologies in the middle and lower reaches to achieve collective development. Concurrently, the upper reaches must capitalize on their advantages, enhance their appeal, and construct a connected industrial development model across the upper, middle, and lower reaches, establishing long-term development mechanisms. Concurrently, the coordinated development strategy of the YYRBs is founded upon the principle of ecological priority. Consequently, throughout the process of urbanization, it is imperative to adhere to the principle of ecological priority and to implement the concept of green development in all areas. In response to eco-environmental issues such as soil erosion and reduced biodiversity, some significant ecological restoration projects should be implemented. By increasing investment in the research and development of eco-environmental protection and governance technologies and supporting universities, scientific research institutions, and enterprises in their efforts to carry out joint research, pivotal technologies and essential equipment should be developed. The transformation and application of scientific and technological achievements should be promoted to enhance the efficiency and effectiveness of eco-environment management.

To facilitate the integrated development of the YTRB, it would be prudent for the relevant authorities to establish a coordinated regional linkage mechanism. Furthermore, guidance should be provided about the support and coordination mechanisms between urban agglomerations and the lower reaches regarding inland and western regions. This would facilitate regional coordinated development and mitigate the eco-environmental pressures associated with urbanization. During the "14th Five-Year Plan" period, it is imperative to pursue unrelenting advancement in terms of EEQ. It is crucial to intensify the endeavors to avert and regulate pollution, construct a robust environmental governance apparatus, and facilitate meticulous, scientific, lawful, and systematic pollution control. Reducing pollutant emissions through green transformation is a key strategy for enhancing EEQ. Meanwhile, it is recommended that the scale of financial expenditure on the subjects of energy conservation and environmental protection be increased. Furthermore, it is advised that the fiscal system be improved in a manner that aligns rights and spending responsibilities. Additionally, environmental protection taxes and preferential tax policies should be perfected, and a performance-based fund allocation mechanism should be established. An increase in financial input and policy support serves to enhance the capability and impetus for the protection of EEQ. The establishment of a robust ecological compensation system is essential to provide fair and adequate financial compensation to regions and individuals who contribute to environmental protection. The implementation of an ecological compensation system would provide incentives for the upper and lower reaches and left and right bank areas within the basin to enhance the protection and management of the eco-environment, thereby facilitating the sustainable advancement of the basin's eco-environment as a whole.

The YYRBs cover a vast area, exhibiting considerable variation in natural conditions, economic development levels, and UL. In terms of spatial distribution, the CCD of the YYRBs exhibits a pattern of higher elevation in the central–eastern region than in the western region. This distribution is primarily attributable to the rapid economic development and elevated UL seen in the central and eastern regions, as well as the relatively robust eco-environmental protection measures. Conversely, the western region confronts heightened pressure on EEQ due to its comparatively lagging economic development and gradual urbanization. Consequently, when formulating a coordinated development strategy, it is essential to adhere to the principles of adapting to local conditions and classifying policies. To achieve precise policy application, targeted policy measures should be formulated to the characteristics and problems of different regions within the basin. For instance, in ecologically vulnerable regions, priority should be given to enhancing ecological protection and restoration. In economically underdeveloped areas, policy support should be intensified to facilitate industrial upgrading and urbanization. Furthermore, this study revealed that prefecture-level cities with high-quality coordination grades exert considerable influence, or "radiate" effects. The coupled coordination status of these cities has the potential to disseminate and radiate to the periphery, thereby enhancing the CCD of the surrounding areas. This finding offers a crucial policy implication: when promoting the coordinated development of UL and the EEQ in the YYRBs, priority should be given to upgrading the CCD of key cities, thereby driving the synergistic development of the peripheral areas through their radiation effect.

4.4. Limitations and Future Research

This study provided a robust basis for understanding the interrelationship between UL and EEQ in the YTRB; it is essential to acknowledge the constraints imposed by the data and indices employed. Firstly, a higher spatial and temporal resolution would be more effective in terms of capturing the intricate relationship between urbanization dynamics and ecological factors. This would allow future studies to be more micro-level, enabling them to be based on higher-scoring datasets. Furthermore, the EEQ is a comprehensive indicator that may not fully reflect the ecological complexity of a given area. For instance, key factors such as biodiversity, ecosystem services, and resilience may be overlooked. It is recommended that future research acknowledge this limitation and suggest the use of the EEQ in conjunction with other ecological indicators to achieve a more comprehensive assessment of ecological conditions. Additionally, future research could incorporate additional models and methods to more comprehensively investigate the non-linear relationships and interactions between UL and EEQ. Additionally, it should conduct a more detailed analysis of the causal relationship between UL and EEQ. By examining the causal relationships and feedback loops between UL and EEQ, key insights into the sustainability of urban development can be obtained.

5. Conclusions

This study employed a multidisciplinary approach, integrating a simple linear regression model, a bivariate spatial autocorrelation model, and a CCD model using multi-source remote sensing data, to investigate the interactive coercive relationships between UL and EEQ in the YYRBs. Key findings include that, from 2001 to 2020, the YLRB exhibited higher EEQ values in the southeastern and southwestern regions and lower values in the central region, with an average improvement of 6.97%, while the YTRB showed low EEQ values in the western region and high values in the central and eastern areas, with a modest average increase of 1.28%. Notably, the Yangtze River mainstream maintained consistently high EEQ, whereas the Yangtze River Delta experienced a continuous decline, with varying growth trends among tributaries. Between 2001 and 2020, the UL in the YLRB gradually increased, with Qinghai and Sichuan, located in the upper reaches, showing consistently low UL values. There was significant growth in the middle reaches, and relatively high UL values in the lower reaches; the YTRB also experienced notable increases in UL, particularly in the middle reaches. In the YLRB, high–high-value agglomeration areas were mainly concentrated in Shaanxi and Henan, where UL and EEQ were generally positively correlated, while low–low agglomeration areas were found in Inner Mongolia and Shaanxi, indicating high spatial correspondence. In contrast, the YTRB displayed a dispersed pattern, with Qinghai maintaining low UL and EEQ values, and there were significant low–high and high–low agglomerations, indicating spatial mismatches. The CCD between UL and EEQ in the YLRB showed a general improvement, particularly in the middle and lower reaches, contrasting with the upper reaches, where extreme incoordination persisted; in the YTRB, while some areas exhibited improved CCDs, many still faced extreme or moderate incoordination. Overall, future development in river basin cities should focus on promoting coordinated UL and EEQ while considering the region's eco-environmental carrying capacity.

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