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A new method for evaluating the coordinated relationship between vegetation greenness and urbanization

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Understanding and measuring the link between vegetation greenness and urbanization is crucial for public health and sustainable development. However, previous methods may oversimplify urbanization indicators and fail to adequately reflect changes in their relationships. To address this, we introduced a comprehensive urbanization vegetation coordination index (CUVCI) on the basis of comprehensive urbanization and a compound annual growth rate and applied this index to the Yellow River Basin in China. We examined the spatiotemporal evolution of the NDVI, comprehensive urbanization level (CUL), and CUVCI from 2000 to 2019 and explored potential driving factors. The results indicate that: (1) from 2000 to 2019, 87.8% of the areas in the Yellow River Basin demonstrated a trend of vegetation growth, with growth levels highest in the midstream regions, followed by the upstream and downstream areas. (2) The CULs of most cities in the basin have shown an increasing trend, with the CUL levels in the middle and downstream cities being significantly higher than those in the upstream cities. (3) CUVCI from 2000 to 2019 was characterized mainly by general coordination (57.4%) and minor conflict (18.5%), with minor-conflict cities located primarily in the middle and lower basin. The coordinating relationships in most cities show signs of improvement. (4) While natural environmental factors such as precipitation, temperature, and relief have a significant impact on CUVCI, scientific researchers can promote the coordinated development of vegetation greenness and urbanization. Our findings suggest that cities in the basin are experiencing economic prosperity and increased greenery. However, strong- and minor-conflict cities should prioritize cultivating and attracting scientific research talent and learning from coordinated provincial capital cities.

Keywords Comprehensive urbanization, Vegetation greenness, Spatiotemporal evolution, Coordination, Yellow River Basin

Human society is experiencing rapid urbanization, with more than half of the global population now residing in cities. According to the[1], the global urbanization rate is projected to reach 68% by 2050, with all regions becoming more urbanized[1]. While rapid urbanization has contributed to social and economic growth, it has also led to problems such as environmental pollution, loss of biodiversity, and vegetation degradation and destruction[2,3]. As societal awareness of ecological protection increases and the need for urban governance increases, scholars are increasingly focusing on researching the impact of rapid urbanization on vegetation.

Vegetation plays a vital role in enhancing the environment and climate. Urbanization involves replacing vegetation with buildings, roads, and facilities, turning vegetated areas into impermeable surfaces[4,5]. This transformation has placed greater pressure on the ecosystem and has endangered green development. Studying the relationship between vegetation and urbanization is essential for understanding their interactions and promoting healthy, sustainable urban development, environmental protection, and biodiversity conservation[6–8].

Current research on the relationship between urbanization and vegetation has focused mainly on the impact of urbanization on vegetation cover and its effects on ecosystems and biodiversity. These studies have focused mainly on regions experiencing rapid urbanization expansion.

Vegetation coverage is not permanent, but it is dynamically changing, and these changes can be easily influenced by urbanization[9]. Some researchers have explored the influence of urban expansion on vegetation

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cover[10]. For example, Zhong et al.[11] conducted a comparative analysis of the impact of varying scales of urban expansion patterns on the net primary productivity (NPP) of vegetation in Chengdu and Hangzhou in China, as well as in Chicago and Raleigh in the United States. Other studies have shown that urbanization negatively affects vegetation cover; urban agglomeration reduces green spaces, grasslands, and agriculture and causes a significant loss of local tree cover[12,13].

Rapid urbanization impacts vegetation coverage globally, leading to a decrease in ecosystem services. Some researchers have examined the impacts of these changes on ecosystem services[14,15]. For example, Abdullah et al.[16] reported that population growth, urban land expansion, and the development of dense road networks due to urbanization are the primary causes of reduced ecosystem services in the five major cities of Bangladesh. Zeng et al.[17] highlighted that urban expansion in China has resulted in the fragmentation of ecological landscapes and the loss of environmental service value. Moreover, it is crucial to recognize that urbanization and changes in vegetation can substantially impact biodiversity. Numerous studies have shown that changes in urban land cover can result in significant modifications to urban vegetation, which can detrimentally impact the habitats of urban animals and ultimately influence urban biodiversity[18,19]. For example, Fumy and Fartmann[20] discovered that urban expansion in Germany threatens mountainous habitats and regional bird biodiversity by encroaching on forests and grasslands. Zhao et al.[21] highlighted that increased urbanization intensity in Beijing has led to a significant decrease in herbaceous plant diversity.

These studies highlight the importance of understanding the relationship between urbanization and vegetation. However, there is still much to be learned about this complex and dynamic relationship, especially in terms of coordination. Only a few researchers have addressed the coordination and conflict between urbanization and vegetation. For example, Zhao et al.[22] proposed a conceptual framework to study changes in the vegetation index in relation to urban development. They defined urbanization intensity as the ratio of urban land cover in pixels and analysed the correlation between the NDVI and urbanization intensity within urban agglomerations. Luo et al.[23] reported that urban agglomeration development is determined by the proportion of pixels representing construction land within the land cover map grid. Zhang et al.[24] studied the indirect impact of urbanization on vegetation by comparing these aspects between two major cities in China. Zhou et al.[25] introduced a coordination index between urbanization and vegetation cover, analysing 338 Chinese cities from 1990 to 2018 and characterized urbanization using urban physical entity boundary data.

These studies provide relatively narrow definitions of urbanization using construction land or urban boundaries. However, urbanization is a complex process that involves population concentration, urban expansion, and a series of economic and social changes resulting from these transitions. In this process, it is essential to comprehensively consider urban economic development, population growth, and the appropriate use of urban land. Additionally, the above research methods primarily utilize the average annual growth rate (AAGR) to measure urbanization or vegetation changes, disregarding potential data distortion due to abnormally rapid increases or decreases. In contrast, the compound annual growth rate (GAGR) can effectively filter out short-term fluctuations and disturbances during a given period.

In the past 40 years, the urban population of China has increased from 18% to almost 65%[26,27]. Consequently, there has been a significant increase in impervious surfaces[10,28]. The Yellow River Basin is essential for the ecological security and economic development of China and is closely linked to major Chinese sustainable development strategies[14,15,29]. Previous studies have suggested promoting green growth while effectively utilizing regional ecological advantages to achieve sustainable watershed development. Given the increasing resource and environmental pressures of urbanization, the primary challenge is to balance vegetation protection with economic and population development in the basin[30,31]. The coordination of urbanization and vegetation is essential for the green and high-quality development of the basin. The NDVI derived from remote sensing data can reflect vegetation greenness. Scholars have used remote sensing vegetation data to explore the evolution characteristics of vegetation greenness or urbanization in the Yellow River Basin[21,32–34]. Further research is needed to clarify the coordinated relationship between urbanization and vegetation greenness changes in the basin.

Therefore, we introduced a new metric, the comprehensive urbanization vegetation coordination index (CUVCI), to properly evaluate the connection between comprehensive urbanization and changes in vegetation greenness. Unlike previous studies, CUVCI combines comprehensive urbanization and the compound annual growth rate for the first time. It measures the dynamic relationship and degree between the rates of change of comprehensive urbanization and vegetation cover to identify the problems of inconsistency in their development process. We applied the CUVCI to the Yellow River Basin of China. By utilizing urban data from multiple sources and MOD13Q1 NDVI data from 2000 to 2019, we examined the spatiotemporal changes in the NDVI, comprehensive urbanization level (CUL), and CUVCI in the basin and identified potential influencing factors. Our study can offer valuable scientific insights to support the sustainable development of urban green spaces, contributing to the creation of a more beautiful China. In addition, this study can provide methodological reference for promoting the coordinated development of urbanization and vegetation in other regions worldwide (Fig. 1).

Materials and methods
Study area
The Yellow River Basin is situated at longitude 95° 35'–119° 5' E and latitude 32° 10'–41° 50' N and spans nine provinces in China: Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong. The western part of the basin has higher terrain, whereas the eastern part has lower terrain with significant altitude changes. The upper basin of the Yellow River extends from its starting point to Hekou town in Inner Mongolia and then continues to Taohuayu in Henan Province, serving as the demarcation line between the
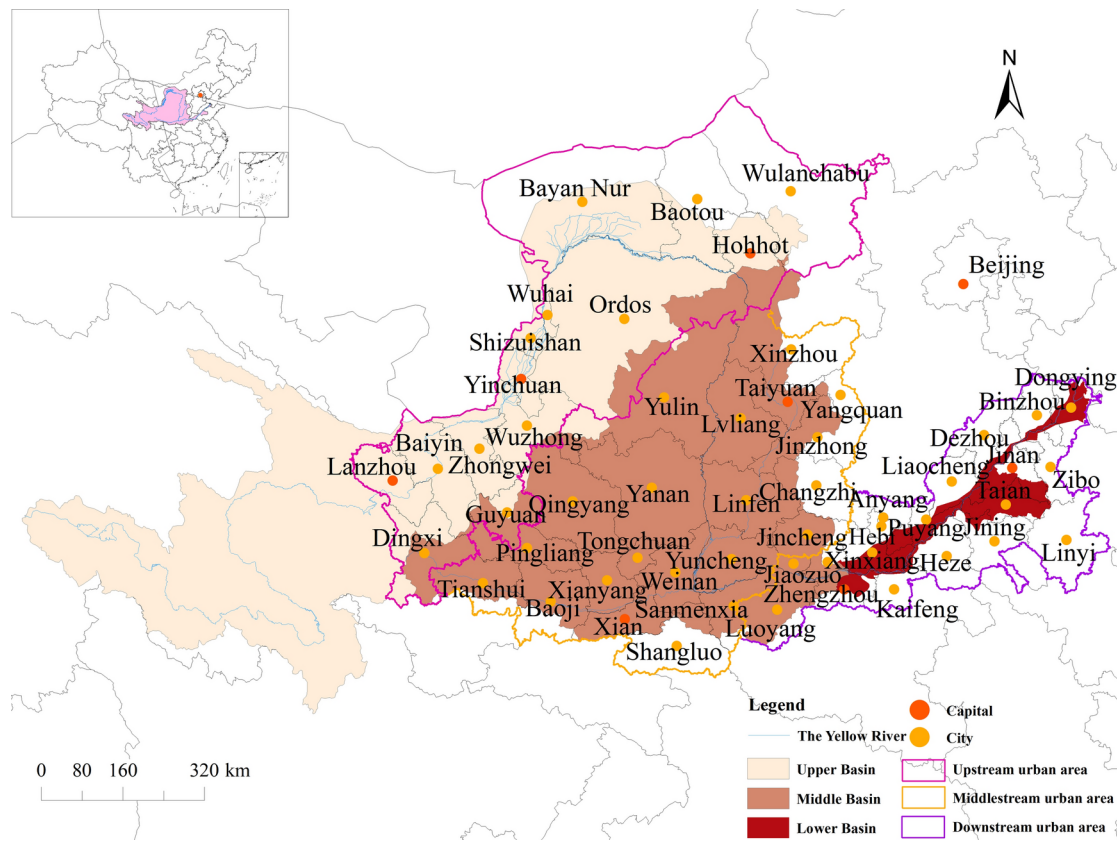
Fig. 1. The study areas (It was generated by ArcMap 10.6 software (https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview)).

Yellow River Basin	Cities
Upper Basin	Lanzhou, Dingxi, Baiyin, Guyuan, Zhongwei, Wuzhong, Yinchuan, Shizuishan, Wuhai, Ordos, Bayan Nur, Baotou, Hohhot, Wulanchabu
Middle Basin	Yulin, Xinzhou, Taiyuan, Lvliang, Yangquan, Jinzhong, Changzhi, Linfen, Yan'an, Qingyang, Pingliang, Tianshui, Tongchuan, Weinan, Yuncheng, Jincheng, Sanmenxia, Xi'an, Xianyang, Baoji, Shangluo
Lower Basin	Anyang, Jiaozuo, Jiyuan, Hebi, Xinxiang, Zhengzhou, Luoyang, Kaifeng, Heze, Puyang, Jining, Linyi, Tai'an, Jinan, Zibo, Dongying, Dezhou, Binzhou, Liaocheng

Table 1. Fifty-four major cities in the Yellow River Basin of China.

middle and lower sections of the Yellow River Basin. This study area is essential for supporting human population centres, driving economic advancement, and serving as a critical ecological buffer in China.

Referring to existing research[35], we selected 54 major cities within the Yellow River Basin as the main research objects, as shown in Table 1. There are 14 cities in the upper basin, 21 in the middle basin, and 19 in the lower basin[36].

Data

The NDVI data are sourced from the MOD13Q1 NDVI dataset provided by NASA in the United States (https://ladsweb.modaps.eosdis.nasa.gov/). The data spans from 2000 to 2019, with a temporal resolution of 16 days and a spatial resolution of 250 m. We utilized MODIS Reprojection Tools (MRT) software (https://lpdaac.usgs.gov/tools/modis_reprojection_tool) to convert the MOD13Q1 NDVI data from the original HDF-EOS format to the TIF format. This process included concatenation and projection. In ArcGIS 10.6 software (https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview), we cropped the data using the vector boundaries of the Yellow River Basin and applied the maximum value synthesis method to generate annual NDVI data. To align with the urban boundary, population density, and GDP data, we utilized ArcGIS software to crop, concatenate, and resample the NDVI data with a spatial resolution of 250 m to achieve a spatial resolution of 1 km.

The urban boundary data are sourced from the global dataset of annual urban extensions extracted from nighttime light data[37]. The population density data (POPD) are sourced from the WorldPop population density dataset, featuring a spatial resolution of 1 km and covering the time period from 2000 to 2019. The GDP density data are obtained from the 1992–2019 Global Gridded Revised Actual Gross Domestic Product and electricity

consumption, which is based on calibrated nighttime light data published by Chen et al.[38]. The spatial resolution is 1 km, and the data unit is millions of US dollars (2017 standard).

The CUVCI primarily includes vegetation and urbanization. To analyse its driving factors, we should consider potential influences from both areas. Research has indicated that temperature, precipitation, and the degree of relief are crucial natural factors impacting changes in vegetation[10,28]. With respect to urbanization, studies have shown that an increase in the number of scientific researchers can foster urban technological innovation and accelerate urbanization[39]. Furthermore, an increase in the proportion of tertiary industry and the natural growth rate indicates an optimization and upgrading of the urban economic structure, which also helps drive urbanization. As urban areas expand and the economy develops sustainably, there is a growing reliance on transportation. This has resulted in increased investment in road infrastructure, leading to a higher density of road networks to meet the travel needs of urban residents and support economic growth. The rate at which green coverage changes in built-up areas reflects the variations in vegetation coverage during urbanization. Therefore, we selected natural factors such as temperature, precipitation, and terrain undulation, along with socioeconomic factors such as the number of scientific researchers, road network density, tertiary industry, and the natural growth rate for the analysis of CUVCI driving factors.

The temperature and precipitation data were obtained from the National Science and Technology Infrastructure Platform National Earth System Science Data Center (http://www.geodata.cn). The data have a resolution of 1 km in China and cover the period from 2000 to 2019. The temperature unit is 0.1 °C, and the precipitation unit is 0.1 mm. The degree of relief data are obtained by extracting and calculating digital elevation data (DEMs) using GIS. The data for the number of scientific researchers are sourced from the "China Urban Statistical Yearbook" published by the China National Bureau of Statistics. This yearbook provides information on the number of employees in scientific research and the comprehensive technical service industry in each urban area, with an annual temporal resolution. To measure the average number of scientific researchers in each city, we aggregate the annual statistics from 2000 to 2019 and calculate the average. The proportions of the tertiary industry, the natural growth rate, and the changes in green coverage in built-up areas follow consistent data sources and processing methods utilized by many scientific researchers. The road network density is calculated by taking the ratio of the total length of roads (L) within a city to the total land area of the city (S). The total length of roads (L) data come from the "China Urban Statistical Yearbook", whereas the area of Chinese prefecture-level cities (S) is obtained from the administrative boundary data provided by the Resource and Environmental Science and Data Platform (https://www.resdc.cn/).

Methods

Theil–Sen median and Mann-Kendall test

We conducted trend analysis and significance testing on the NDVI time series data using MATLAB 2019 (https://www.mathworks.com/) and ArcGIS 10.6 software using the Theil–Sen median and Mann–Kendall (MK) test methods.

First, we applied the Theil–Sen median to examine the pixel-by-pixel changes in the NDVI time series data. The Theil–Sen median is a robust nonparametric test that does not depend on specific distribution assumptions and is less susceptible to the influence of outliers[40], making it well suited for trend analysis of long-term time series data. The calculation formula is as follows:

$$\beta = \text{Median} = \left(\frac{NDVI_j - NDVI_i}{j - i} \right), \forall j > i \tag{1}$$

In the formula, β is the median slope; if β < 0, the vegetation change shows a downwards trend. If β > 0, there is an increasing trend. $NDVI_j$ and $NDVI_i$ represent the NDVI values for different years.

We then used the Mann-Kendall method to test the significance of the trend. The Mann-Kendall test is a nonparametric method for assessing trends in time series data. The calculation formula for this test is as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\left(NDVI_j - NDVI_i\right) \tag{2}$$

$$sgn\left(NDVI_j - NDVI_i\right) = \left\{ \begin{array}{c} 1, NDVI_j - NDVI_i > 0 \\ 0, NDVI_j - NDVI_i = 0 \\ -1, NDVI_j - NDVI_i < 0 \end{array} \right. \tag{3}$$

$$Var\left(S\right) = \frac{n\left(n-1\right)\left(2n+5\right)}{18} \tag{4}$$

$$Z = \left\{ \begin{array}{c} \frac{S-1}{\sqrt{Var(S)}}, S > 0 \\ 0, \ S = 0, \\ \frac{S+1}{\sqrt{Var(S)}}, S > 0 \end{array} \right. \tag{5}$$

In the formula, *S* is the test statistic, *n* is the dataset length, and sgn is a sign function with values of − 1, 0, and 1. At a specific level of significance (α), if the absolute value of Z exceeds 1.65, 1.96, or 2.58, the trend has passed significance tests with 90%, 95%, or 99% confidence, respectively.

The comprehensive urbanization level (CUL)

Referring to existing research[41,42], we choose population growth, economic development, and urban land expansion to characterize comprehensive urbanization because of the difficulty in obtaining comprehensive and spatialized social data.

The level of urbanization is determined by measuring population density (POPD) for population urbanization, GDP density (GDPD) for economic urbanization, and the urban land use ratio (ULP) for land urbanization. Since POPD, GDPD, and ULP have very similar spatial distributions, they were analysed on a grid, standardized, and combined into a single indicator called the comprehensive urbanization level (CUL). The standardized equation for the CUL is as follows:

$$CUL = \frac{U_{POPD}\prime + U_{GDPD}\prime + U_{ULP}\prime}{3} \tag{6}$$

$$U\prime_{i,j} = \frac{U_{i,j} - X_{i,min}}{X_{i,max} - X_{i,min}} \tag{7}$$

The compound annual growth rate (CAGR)

The average annual growth rate can be divided into the average annual growth rate (AAGR) and the compound annual growth rate (CAGR). The AAGR represents the average annual growth rate, whereas the CAGR reflects the yearly growth rate of an indicator over a specific period. Notably, data may produce skewed results due to rapid abnormal increases or decreases, and as a result, the compound annual growth rate (CAGR) provides a more effective representation of the trend of indicators over a certain period than does the average annual growth rate[43]. The calculation for CAGR is Formula (8).

$$CAGR = \left(\frac{EndingValue}{BeginningValue}\right)^{\frac{1}{n}} - 1 \tag{8}$$

where *n* is the number of years in the dataset.

Comprehensive urbanization vegetation coordination index (CUVCI)

To assess the coordination between urbanization and vegetation greenness, we developed the comprehensive urbanization vegetation coordination index (CUVCI). As shown in Formula (9), this index integrates the CAGR of urbanization and the NDVI, which reflects the relationship between urbanization and vegetation greenness changes.

$$CUVCI = \frac{CAGR_{CUL}}{CAGR_{NDVI}} \tag{9}$$

According to the study by Zhou et al.[25], a 1% increase in the comprehensive urbanization level has a substantial effect on the NDVI when the positive or negative impact exceeds 1%. Otherwise, the corresponding slope for a 1% change is 1 or -1, and the impact is minor. Additionally, when the comprehensive urbanization level increases by 1%, it is not significant that the change in the NDVI is less than 0.05%, corresponding to a slope of 20 or -20. As a result, CUVCI is categorized into five categories on the basis of these findings:

(1) Strong coordination: If $0 < CUVCI < 1$, comprehensive urbanization and vegetation greenness reach an ideal coordinated development pattern and are in the strongly coordinated stage.
(2) General coordination: If $1 < CUVCI < 20$, comprehensive urbanization and vegetation greenness growth are generally coordinated, and the CUL has a specific positive impact on vegetation.
(3) Equilibrium: If the CUVCI is greater than 20 or less than -20, the comprehensive urbanization process has the most negligible impact on vegetation greenness and is in an equilibrium stage;
(4) Minor conflict: When $-20 < CUVCI < -1$, the comprehensive urbanization process hurts vegetation greenness, and the two are in a minor conflict stage.
(5) Strong conflict: When $-1 < CUVCI < 0$, the comprehensive urbanization process and vegetation greenness enter a strong conflict stage, and the improvement in the comprehensive urbanization level comes at the cost of sacrificing greenness.

To investigate the driving factors of CUVCI, we performed a Pearson correlation analysis using the potential natural (temperature, precipitation, degree of relief) and socioeconomic factors outlined in section "Data" (the number of scientific researchers, density of road network, change rate in green coverage of built-up areas, proportion of tertiary industry, and natural growth rate). Additionally, we employed Geodetector software (http://www.geodetector.cn/) to assess the explanatory power of these factors and to analyse the interactions among them.

Results
The spatiotemporal characteristics of the NDVI
Trend analysis of the NDVI
Figure 2 shows the marked variances in the spatial distribution (a) and proportion statistics (b) of the average NDVI in the Yellow River Basin from 2000 to 2019. The spatial distribution pattern clearly demonstrated a consistent increase from the northwest to the southeast.

According to the average NDVI, the NDVI values in the Yellow River Basin are divided into five categories: low (0.0–0.2), lower (0.2–0.4), medium (0.4–0.6), higher (0.6–0.8), and high (0.8–1.0). The average NDVI in the Yellow River Basin was dominated by medium and high vegetation coverage (0.4–0.8), accounting for 58.4% of the total area. The downstream vegetation coverage is the highest, followed by the middle and upstream vegetation coverage.

Figure 3 show the spatial distribution trends and statistical results of the NDVI in the Yellow River Basin. The results revealed that the vegetation in 87.8% of the Yellow River Basin exhibited an overall increasing trend from 2000 to 2019, with a significant increase of 45.7% of the basin area. Only a few areas have shown a downwards trend, accounting for approximately 11.9% of the total watershed area. The trend of vegetation growth was highest in the middle reaches, accounting for approximately 92.3%, with a dramatic increase in proportion (69.2%), followed by the upstream reaches (86%) and then the downstream reaches (63.2%). This suggests that China has achieved significant results in the management of ecologically fragile areas on the Loess Plateau (the middle basin).

The regions that did not pass the 90% confidence level were mostly not significantly reduced (22.9%), and they were mainly distributed in the northern and southwestern parts of the upper reaches of the Yellow River Basin and downstream areas. This indicates that the decreasing trend of vegetation changes has been concentrated mainly in provincial capital cities in the middle and lower reaches. This also suggests that vegetation protection should be emphasized during periods of rapid urbanization.

The spatiotemporal characteristics of the urban NDVI
The spatial distributions and interannual variation of urban areas' average NDVI from 2000 to 2019 for 54 cities in the Yellow River Basin is shown in Fig. 4. The mean annual urban NDVI within the basin can be categorized into four distinct levels on the basis of vegetation coverage: low (0–0.2), lower (0.2–0.4), medium (0.4–0.6), and higher (0.6–0.8).

It shows a noticeable increase in greenery in the 54 major cities within the basin, indicating an increase in vegetation. Compared with upstream cities, cities located in the middle and lower basin generally have significantly better vegetation. On average, the urban average NDVI of cities in the upper basin ranges from 0.2 to 0.45. The cities with higher NDVI values in this region include Dingxi (0.40), Zhongwei (0.40), and Guyuan (0.39), whereas the cities with lower NDVI values are Shizuishan (0.27), Baiyin (0.26), and Wuhai (0.21). For the midstream cities, the average NDVI was primarily concentrated between 0.35 and 0.65. Cities with higher NDVI values in this area include Shangluo (0.57), Yanan (0.57), and Tongchuan (0.52), whereas cities with lower NDVI values include Qingyang (0.39), Taiyuan (0.39), and Yulin (0.35). For the lower basin cities, the average NDVI levels are mainly within the range of 0.4 to 0.6, including the cities of Puyang (0.56), Hebi (0.54), and Binzhou (0.51) exhibiting higher mean NDVI values and cities such as Linyi (0.44), Jiyuan (0.44), and Dongying (0.41) showing lower mean NDVI values.
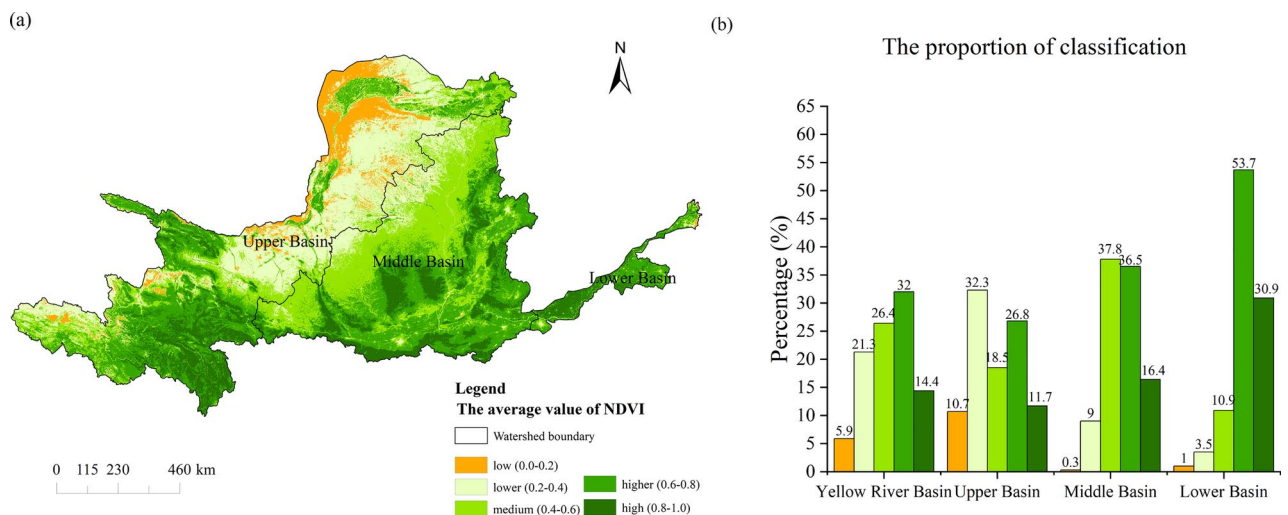

Fig. 2. Spatial distributions (**a**) and proportion statistics (**b**) of average NDVI values in the Yellow River Basin f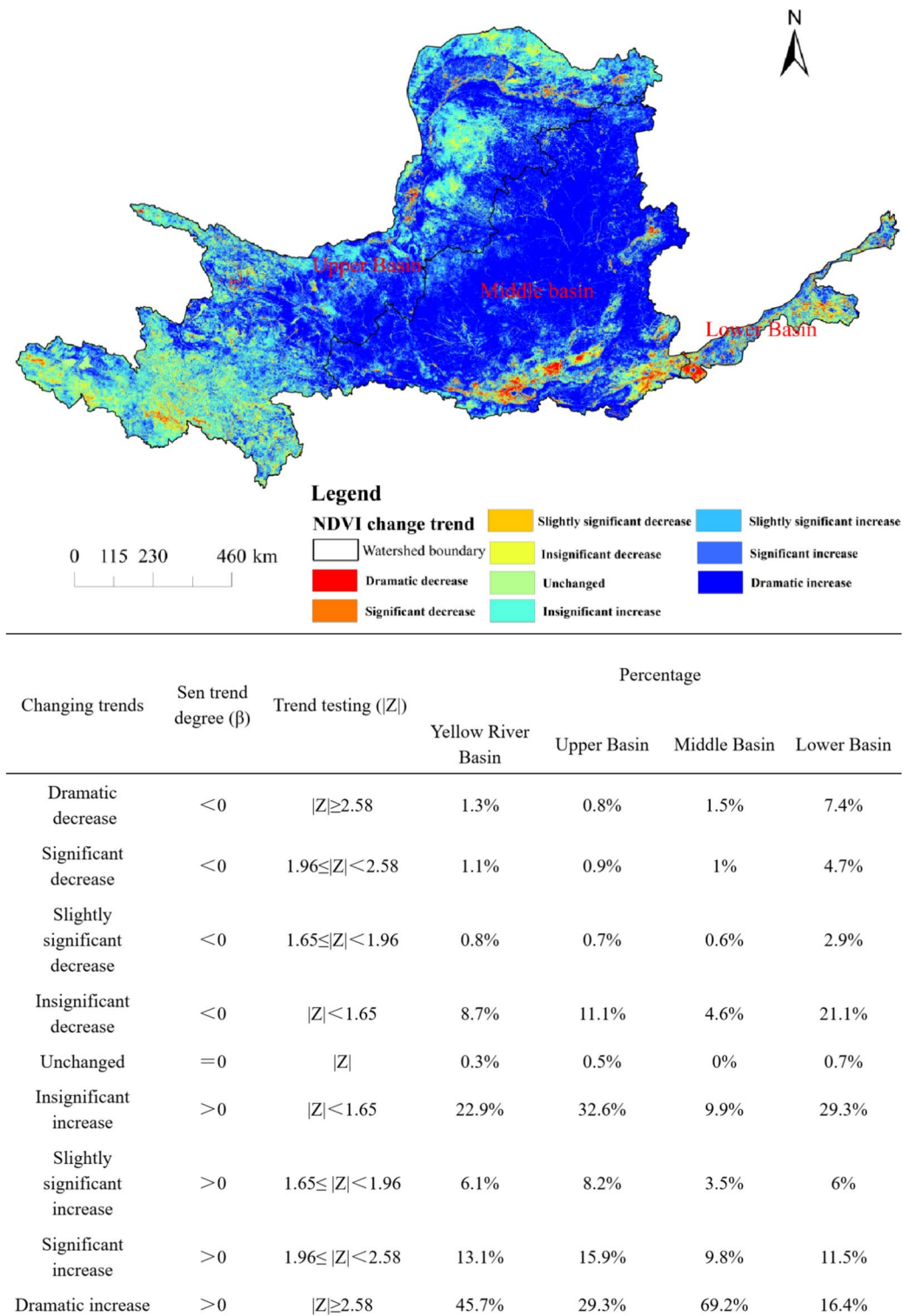rom 2000 to 2019 (It was generated by ArcMap 10.6 software (https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview)).

Changing trends	Sen trend degree (β)	Trend testing (|Z|)	Percentage			
			Yellow River Basin	Upper Basin	Middle Basin	Lower Basin
Dramatic decrease	<0	|Z|≥2.58	1.3%	0.8%	1.5%	7.4%
Significant decrease	<0	1.96≤|Z|<2.58	1.1%	0.9%	1%	4.7%
Slightly significant decrease	<0	1.65≤|Z|<1.96	0.8%	0.7%	0.6%	2.9%
Insignificant decrease	<0	|Z|<1.65	8.7%	11.1%	4.6%	21.1%
Unchanged	=0	|Z|	0.3%	0.5%	0%	0.7%
Insignificant increase	>0	|Z|<1.65	22.9%	32.6%	9.9%	29.3%
Slightly significant increase	>0	1.65≤|Z|<1.96	6.1%	8.2%	3.5%	6%
Significant increase	>0	1.96≤|Z|<2.58	13.1%	15.9%	9.8%	11.5%
Dramatic increase	>0	|Z|≥2.58	45.7%	29.3%	69.2%	16.4%

Fig. 3. Analysis of NDVI trends in the Yellow River Basin from 2000 to 2019 (It was generated by ArcMap 10.6 software (https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview)).

The spatiotemporal evolution characteristics of the comprehensive urbanization level (CUL)

The spatiotemporal distribution and interannual variation of the comprehensive urbanization level (CUL) in cities across the Yellow River Basin from 2000 to 2019 is illustrated in Fig. 5 on the basis of the measurement formula in Section "The comprehensive urbanization level (CUL)". The average annual CULs of the towns are reclassified into four levels at equal intervals: 0–0.2, 0.2–0.4, 0.4–0.6, and 0.6–0.8.
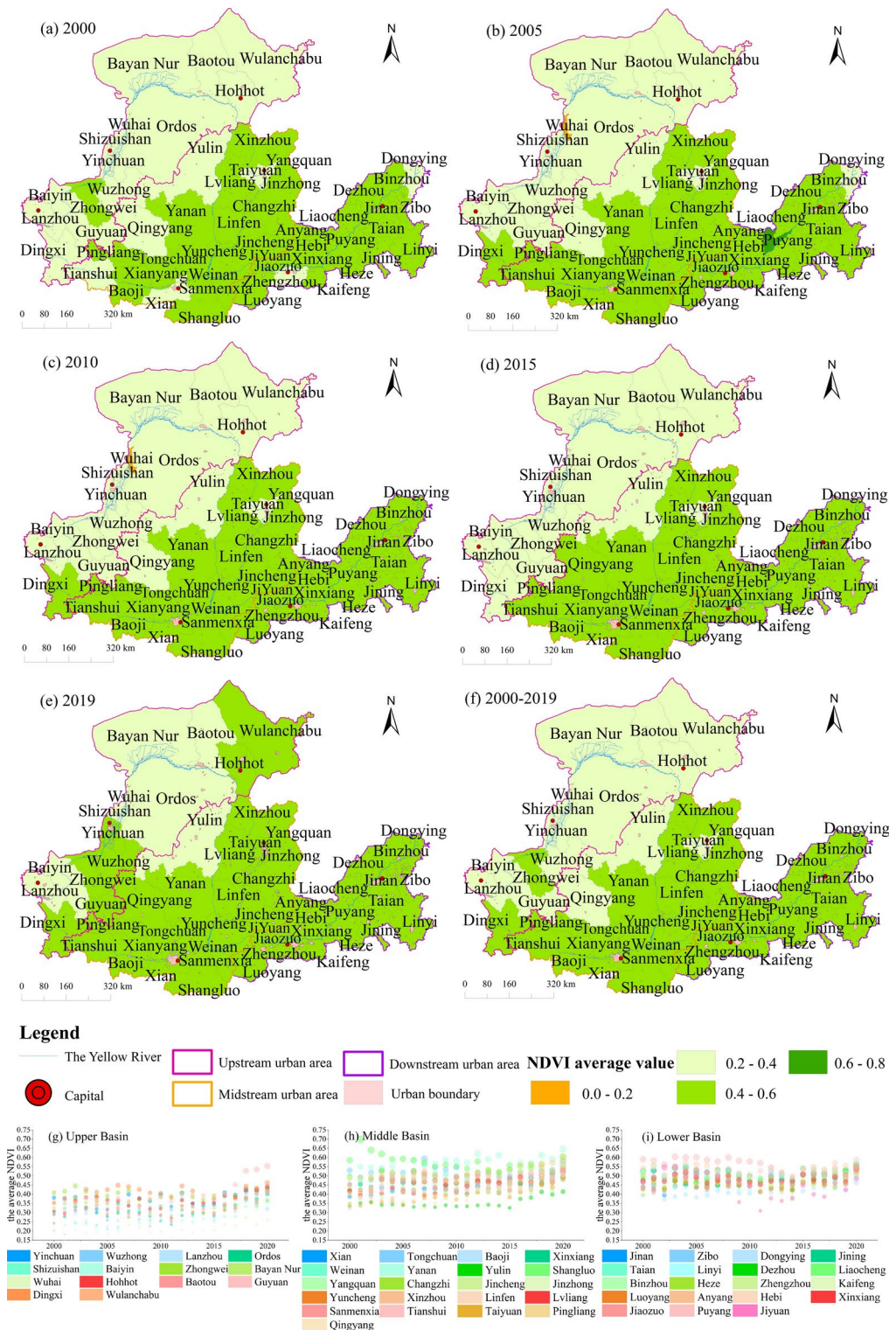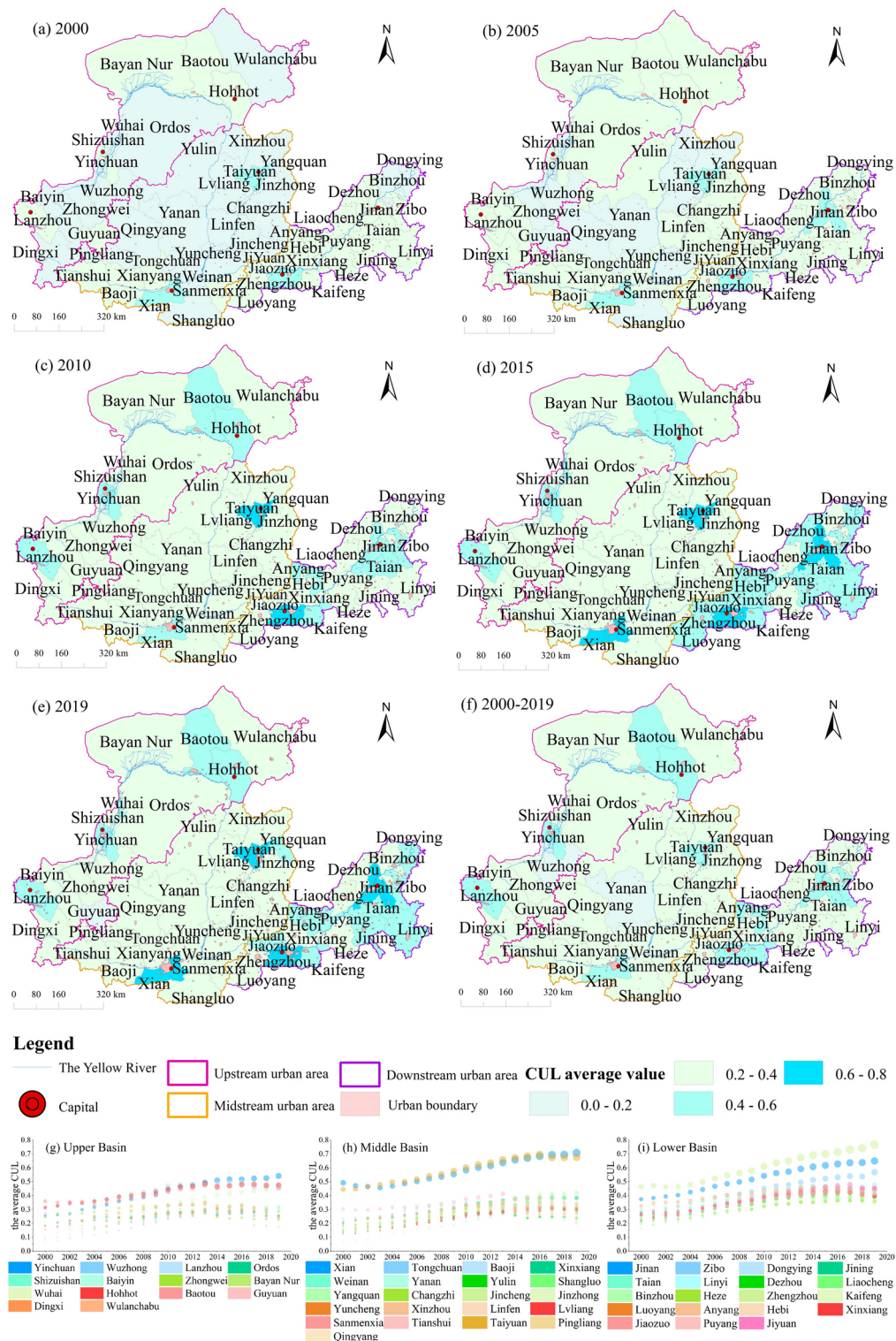
Fig. 4. The spatiotemporal distribution and interannual variation of the urban average NDVI in 54 major cities in the Yellow River Basin (They were generated by ArcMap 10.6 software (https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview)).

Most cities had a aveage CUL level between 0.2 and 0.4, accounting for 75.9% of the total, mainly in upstream and midstream areas. Cities with CULs between 0.4 and 0.8 were located mainly in the middle and lower basin, as well as in the upstream capital cities. For example, from 2000 to 2019, the average CULs greater than 0.4 in the upstream and midstream cities included mainly Taiyuan (0.58), Xi'an (0.58), Lanzhou (0.43), Hohhot (0.42),

Fig. 5. The spatiotemporal distribution and interannual variation of the average comprehensive urbanization level (CUL) of 54 major cities in the Yellow River Basin from 2000 to 2019 (They were generated by ArcMap 10.6 software (https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview)).

Baotou (0.41), and Yinchuan (0.41). In the downstream cities, the average CUL level is higher in Zhengzhou (0.60), Jinan (0.52), Zibo (0.43), Anyang (0.41), and Kaifeng (0.40).

The comprehensive urbanization level of most cities in the Yellow River Basin showed an increasing trend from 2000 to 2019, with a significantly higher CUL in the cities of the middle and lower basin than in the cities in the upper basin.

Spatiotemporal characteristics of CUVCI

Overall spatiotemporal characteristics of CUVCI

Using the comprehensive urbanization vegetation coordination index (CUVCI) proposed in Section "Comprehensive urbanization vegetation coordination index (CUVCI)", the CUVCI results for various cities in the Yellow River Basin were obtained. The overall spatial distribution and statistics of the CUVCI from 2000 to 2019 is shown in Fig. 6.

In Fig. 6, the data indicate that cities in the Yellow River Basin mostly exhibited general coordination (57.4%), followed by minor conflict (18.5%) and equilibrium (16.7%) from 2000 to 2019. The proportion of cities with strong conflicts or strong coordination is relatively small. Minor-conflict cities are situated primarily in the middle and lower basin. Most cities in the upper basin exhibited a coordinated relationship. Notably, all the provincial capital cities showed general coordination in their development, setting a valuable example for other cities to learn from.
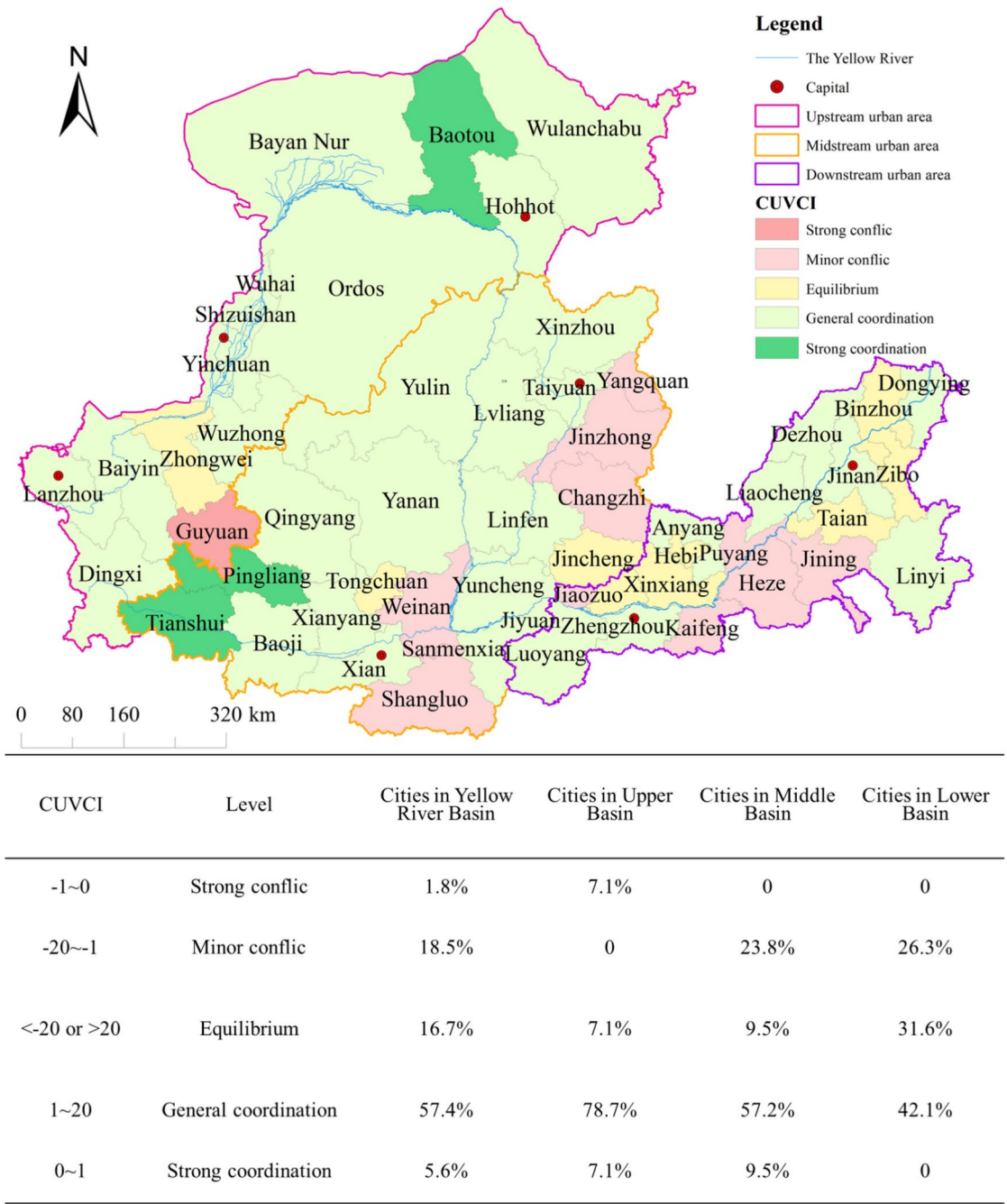

CUVCI	Level	Cities in Yellow River Basin	Cities in Upper Basin	Cities in Middle Basin	Cities in Lower Basin
-1~0	Strong conflic	1.8%	7.1%	0	0
-20~-1	Minor conflic	18.5%	0	23.8%	26.3%
<-20 or >20	Equilibrium	16.7%	7.1%	9.5%	31.6%
1~20	General coordination	57.4%	78.7%	57.2%	42.1%
0~1	Strong coordination	5.6%	7.1%	9.5%	0

Fig. 6. The spatial distribution and statistics of the CUVCI in 54 major cities within the Yellow River Basin from 2000 to 2019 (It was generated by ArcMap 10.6 software (https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview)).

In the upper basin, 85.8% of the cities have established coordinated relationships, with 78.7% showing general coordination and 7.1% showing strong coordination. The city with strong coordination is Baotou. The only city with strong conflict is Guyuan city. Guyuan city is located in the central and western parts of the Loess Plateau and is a tributary of the Yellow River. As the region with the most severe soil erosion in Ningxia, Guyuan city has been implementing the "returning farmland to forests" policy and ecological migration project since 2000. Although the ecological environment of Guyuan city has improved, it still lags behind those of other cities.

In the middle basin, 66.7% of the cities have established coordinated relationships. Among these, 57.2% exhibit general coordination, including Taiyuan, Baoji, and Xi'an, and 9.5% have strong coordination, including Tianshui and Pingliang. There has been an increase in minor-conflict cities, accounting for approximately 23.8%, such as cities in Shanxi Province—Yangquan, Jinzhong, Changzhi, Weinan, and Shangluo.

In the lower basin, there is no city with strong coordination or strong conflict. The proportion of cities showing a general coordination relationship is 42.1%, including Zhengzhou, Luoyang, and Jinan. The equilibrium relationship accounts for 31.6%, including Jiaozuo, Xinxiang, and Hebi of Henan Province and Tai 'an, Zibo, and Binzhou of Shandong Province. However, the proportion of cities with minor conflicts is also not low, accounting for 26.3% of all cities. They are located in Henan Province—Jiyuan, Kaifeng, Puyang, and Shandong Province—Heze, Jining. Compared with prefecture-level cities upstream and midstream, these cities have relatively better comprehensive urbanization levels, but rapid economic growth and urban land expansion have come at the expense of vegetation greenness and the ecological environment. Attention should be given to minimizing the negative impact of urbanization on vegetation and the urban ecological environment.

The spatiotemporal characteristics of CUVCI in different periods
The spatial distributions and statistics of the CUVCI in 54 major cities within the Yellow River Basin during various time periods are illustrated in Fig. 7.
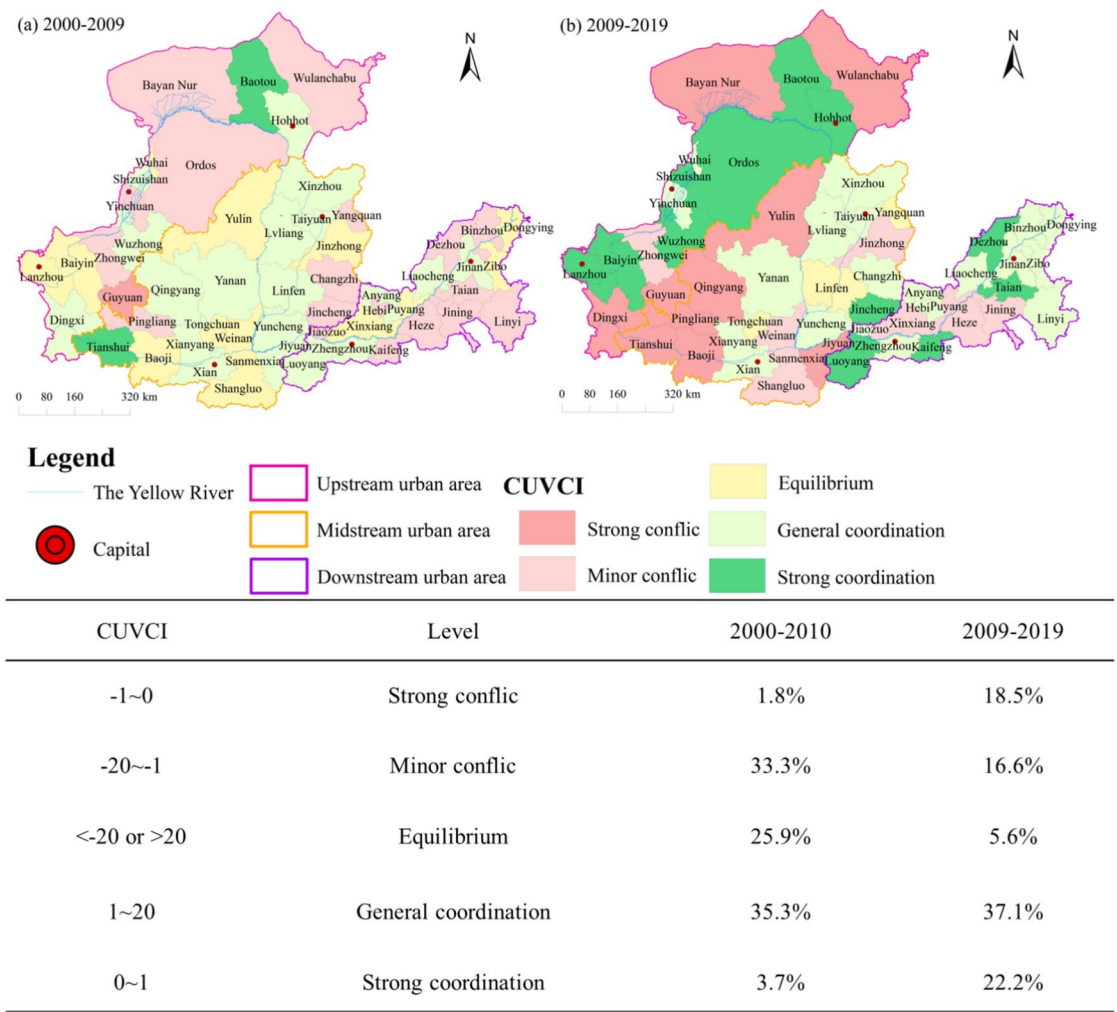

CUVCI	Level	2000-2010	2009-2019
-1~0	Strong conflic	1.8%	18.5%
-20~-1	Minor conflic	33.3%	16.6%
<-20 or >20	Equilibrium	25.9%	5.6%
1~20	General coordination	35.3%	37.1%
0~1	Strong coordination	3.7%	22.2%

Fig. 7. Spatial distributions and statistics of the CUVCI during different periods in cities within the Yellow River Basin (They were generated by ArcMap 10.6 software (https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview)).

On the basis of Fig. 7, spanning the years 2000–2009, the CUVCI indicated that 54 cities in the Yellow River Basin were characterized predominantly by general coordination (35.3%), followed by minor conflict (33.3%). Notably, the cities in conflict relationships were located mainly in the upper and lower basin. From 2009 to 2019, the CUVCI of the cities within the Yellow River Basin was characterized mainly by general coordination (37.1%), followed by strong coordination (22.2%). The cities with strong conflict relationships were predominantly concentrated in the upper and middle basin.

Compared with 2000–2009, there was a notable increase in the proportion of CUVCI with strong conflict from 2009 to 2019. Furthermore, there was an overall increase in the proportion of cities demonstrating coordination relationships, with a particularly noteworthy increase in cities showing strong coordination relationships.

The CUVCI in cities is calculated through the GAGR of the NDVI and CUL. The results are related to the rates of change in the NDVI and CUL in the city. Between 2000 and 2009, with the exception of Guyuan, all cities in conflict relationships experienced a decrease in the GAGR of the NDVI and an increase in the CUL. This indicates that the urbanization level of these cities improved during development, but the protection of vegetation was overlooked. From 2009 to 2019, the GAGR of the NDVI decreased in the cities of Jinzhong, Weinan, Shangluo, Jiaozuo, Xinxiang, Puyang, Heze, and Jining. These cities experienced minor conflicts, which were concentrated downstream and nearby. Cities showing strong conflict due to increased CUL include Bayan Nur, Wulanchabu, Yulin, Qingyang, Guyuan, Pingliang, Baoji, Tianshui, Dingxi, and Sanmenxia, and the NDVI of these cities is already relatively low compared with that of other cities. These cities are primarily concentrated upstream and nearby.

Exploration of influencing factors

To further investigate the factors influencing CUVCI in various cities within the Yellow River Basin, we used IBM SPSS Statistics 22 software (https://www.ibm.com/products/spss-statistics) to calculate the Spearman correlation coefficients between CUVCI and eight factors: temperature, precipitation, degree of relief, number of scientific researchers, density of the road network, change rate of green coverage in built-up areas, proportion of tertiary industry, and natural growth rate. We also conducted confidence tests on these factors. The results, which were visualized using Origin 2021 software (https://www.originlab.com/), are displayed in Fig. 8.

With respect to natural factors, CUVCI is found to have significant correlations with temperature, precipitation, and degree of relief. Specifically, the correlation coefficients between the CUVCI and the mean temperature and precipitation are -0.39 and -0.48, respectively, both of which are statistically significant at the 0.05 confidence level. This finding indicates that high urban temperatures and excessive precipitation are not conducive to the coordination between urbanization and vegetation, with precipitation having a more significant impact than temperature does. Human activities, such as rising global temperatures, greenhouse gas emissions, industrialization, and deforestation, have also adversely affected the coordinated development of vegetation and urbanization through frequent extreme weather events. Additionally, the correlation coefficient between CUVCI
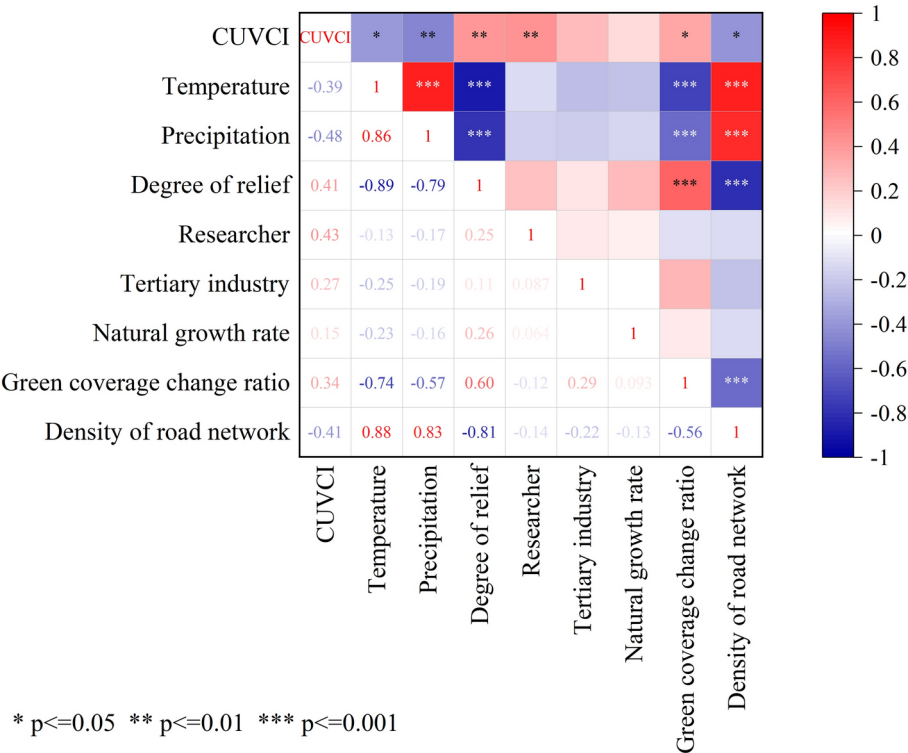

* p<=0.05 ** p<=0.01 *** p<=0.001

Fig. 8. Correlation analysis between the CUVCI and various factors in cities in the Yellow River Basin.
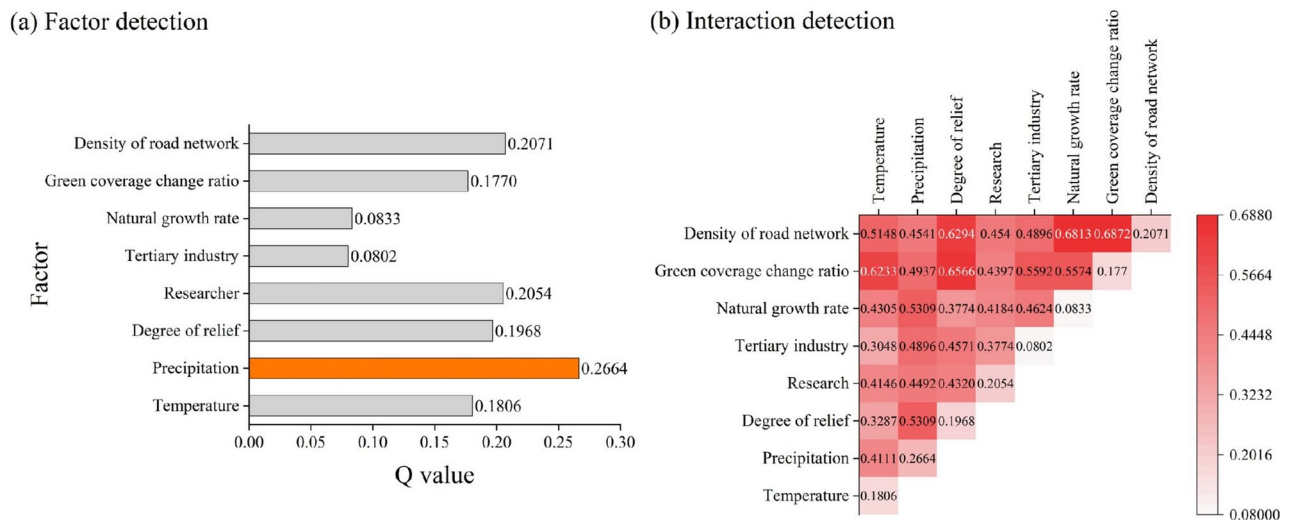
Fig. 9. Factor detection (**a**) and interaction detection (**b**) of CUVCI with factors using geographic detectors.

and the degree of relief is 0.41 (p values < 0.01), suggesting that specific topographic relief may benefit urban layout and vegetation growth, which requires further research.

In terms of socioeconomic factors, CUVCI is significantly correlated with the number of researchers (0.43), road network density (− 0.41), and the change rate of green coverage in built-up areas (0.34). All of these correlations successfully met the significance test at the 0.05 confidence level. An increase in researchers and green coverage in urban areas improves CUVCI levels, whereas a higher density of the road network is associated with better urban development. However, it is important to note that road network construction can lead to destruction of vegetation and neglect of reconstruction and protection. To enhance the coordination between urbanization and vegetation, appropriately increasing the rate of change in green coverage, encouraging more scientific researchers to actively participate in urban development and governance, and paying attention to the protection of vegetation during road construction in the Yellow River Basin are recommended.

We also conducted factor detection and interaction detection of CUVCI with the aforementioned natural and socioeconomic factors using geographic detectors. The results are displayed in Fig. 9.

The factors with the most significant explanatory power for CUVCI in Fig. 9a are precipitation, the density of the road network, scientific researchers, the degree of relief, temperature, and the change rate of green coverage in built-up areas. These six explanatory factors are relatively similar to the correlation results. The results show that natural factors are important environmental factors affecting the CUVCI spatial pattern, but the explanatory power of some social and human factors, such as the density of road networks, researchers, and the change rate of green coverage in built-up areas, is also high. These factors can help us improve the coordination between urbanization and vegetation.

In Fig. 9b, the primary interaction factors exhibit a dual factor enhancement relationship, without any nonlinear enhancement, independence, or weakening relationship. This suggests that the strength of the interaction between two factors is greater than that of each individual factor. Among them, the strongest interaction is between the density of the road network and the rate of change in green coverage of built-up areas. This is followed by the natural growth rate and the density of the road network and the interaction between the degree of relief and the rate of green coverage change in built-up areas.

The results show that natural factors are important environmental factors affecting the CUVCI spatial pattern, but the explanatory power and interaction of social and human factors, such as the density of the road network, scientific researchers, and the green coverage change rate of built-up areas, are also high. These factors can help us improve the coordination between urbanization and vegetation.

Discussion
Comparison with previous studies
Our study demonstrated that the concordance between urbanization and vegetation greenness changes has strengthened in most cities within the Yellow River Basin. According to Hu et al.[44], prioritizing the ecological environment by local governments can improve the policy environment and increase public enthusiasm for environmental protection projects. The various policies and regulations issued by the Chinese government have played a positive role in improving the coordination between urbanization and vegetation in the Yellow River Basin[45,46]. These policies demonstrate Chinese commitment to the coordinated, green, and sustainable development of the Yellow River Basin.

Our research findings share some similarities with those of existing studies. For example, Zhou et al.[25] noted that between 1990 and 2018, Chinese urbanization and vegetation growth progressed towards a more coordinated and sustainable development pattern. An increasing number of cities are evolving towards coordinated development with the implementation of urban ecological environment policies. Cities in northern

China have generally reached this coordination stage. This aligns with our conclusion that most cities in the Yellow River Basin have emphasized coordination in the comprehensive urbanization–vegetation coordination index over the past 20 years.

Additionally, Dong et al.[47] explored the coordinated relationship between urban expansion and changes in vegetation cover in 44 port cities along the Maritime Silk Road from 2000 to 2020. They reported that, overall, high-economy port cities have become more coordinated, whereas many medium- and low-economy cities still struggle with conflicts between urban expansion and vegetation cover. In our study, cities with high comprehensive urbanization levels (CUL), such as Lanzhou, Yinchuan, Hohhot, and Baotou in the upstream region; Xi'an and Taiyuan in the midstream region; and Zhengzhou and Jinan in the downstream region, demonstrated both general and strong coordination in their comprehensive urbanization–vegetation coordination index (CUVCI). In contrast, cities with lower CULs, including Guyuan upstream, Tongchuan, Shangluo, Weinan, Changzhi, and Yangquan midstream, as well as Heze downstream, exhibited weak conflicts in the CUVCI. Our measurement of comprehensive urbanization encompasses economic factors as well.

However, our study provides a more comprehensive approach to measurement methods and results analysis than do existing studies. We consider various aspects of comprehensive urbanization—urban land, economy, and population—rather than focusing solely on urban expansion or urbanization. In measuring dynamic changes, we adopted a compound annual growth rate (GAGR) instead of the average annual growth rate, which can effectively filter out short-term volatility interference. For the first time, we have revealed the explanatory power and interactive effects of potential factors influencing the coordination between comprehensive urbanization and vegetation cover. This not only enhances the theoretical and methodological framework of urbanization–vegetation coordination but also identifies key driving factors for promoting the harmonious development of urbanization and vegetation cover, offering more targeted scientific recommendations.

Implications and suggestions

On the basis of the analysis of the influencing factors of the CUCVI and the strong and minor-conflict cities identified in the research results, we further discuss and propose the following suggestions:

The upstream city of Guyuan has experienced significant challenges. Our experimental data reveal a downwards trend in the comprehensive urbanization level of Guyuan city from 2016 to 2019, primarily due to a decrease in urban population density. While the urban land area continues to expand, the population distribution remains relatively scattered, which further contributes to the decline in population density in the urban areas of Guyuan city. Historically, agriculture has been the primary industry in Guyuan, with the industrial and service sectors lagging behind. This limited industrial development restricts the ability of the city to absorb labour, making it difficult to support large-scale population agglomeration. To address these issues, we recommend that Guyuan city accelerate the transformation of its industrial structure, modernize agriculture, and develop modern service industries. Additionally, it would be beneficial to carefully manage the expansion of construction land and promote steady progress in comprehensive urbanization. Furthermore, when considering the influencing factors of CUVCI, we observed that, with the exception of Hohhot, Yinchuan, Lanzhou, and Baotou, other upstream cities—including Guyuan—had relatively few scientific research and employment personnel. To improve this situation, we suggest implementing specific policies aimed at attracting scientific research talent to participate in urban governance and environmental protection initiatives.

In the middle reaches, cities such as Yangquan, Jinzhong, Changzhi, Weinan, and Shangluo exhibit minor conflicts. Our analysis of experimental data reveals that these cities experienced a negative compound annual growth rate of the NDVI and a positive compound annual growth rate of the CUL from 2000 to 2019. This trend indicates a pressing need for stronger vegetation protection in these cities. Additionally, these cities have fewer scientific researchers than cities that are generally well coordinated or coordinated. To address these issues, efforts to restore and protect vegetation should be intensified. When roads are constructed, precautions should be taken to minimize damage to existing vegetation. Furthermore, attracting relevant researchers to engage in urban governance could provide valuable insights and suggestions for coordinated urban development.

The downstream cities that show weak conflicts include Jiyuan, Puyang, Heze, Jining, and Kaifeng. Similar to the midstream cities, these areas experienced a negative compound annual growth rate for the normalized difference vegetation index (NDVI) and a positive compound annual growth rate for comprehensive urbanization levels (CUL) between 2000 and 2019. This indicates inadequate vegetation protection within these cities. Jining and Puyang need to increase the greening rate of their built-up areas, whereas the other cities with weak conflict have relatively few scientific researchers. Additionally, the road network density should be thoughtfully arranged to balance road construction with vegetation coverage while attracting scientific research talent to engage in urban governance.

In summary, increasing the number of scientific researchers is essential for promoting the coordinated development of comprehensive urbanization and vegetation cover. Therefore, cities facing conflict should focus on attracting talent for ecological protection, scientific urban development, and vegetation conservation when creating talent attraction strategies.

Limitations and future research

In terms of limitations, our study focused on 54 major cities in the Yellow River Basin, specifically within the northern urban region, without including southern cities. Additionally, the GDP density data available to us were limited, restricting our analysis to the time frame of 2000–2019. To conduct research within the urban area, we employed a grid resolution of 1 km to standardize various data resolutions. While we explored and discussed potential factors influencing the comprehensive urbanization vegetation coordination index (CUVCI), we recognize that the results and geographical explanations require further depth.

We also attempted to analyse factors such as carbon emissions, related policies, and population inflow and outflow; however, the correlations we found were relatively low.

In future research, we plan to utilize higher-resolution data, such as nighttime light data[48], to extract more refined urban boundary information. This will allow us to conduct a more detailed examination of the coordination between urbanization and vegetation, as well as to accurately identify areas that are not conducive to coordinated development. Additionally, we will investigate the driving mechanisms behind CUVCI using multisource data and regression models.

Conclusions

This study utilized comprehensive urbanization and a compound annual growth rate to develop a comprehensive urbanization vegetation coordination index (CUVCI). This index can demonstrate the correlation between the rates of change in various systems and improve the singular quantification of urbanization in current coordination methods. The indicator was applied to the Yellow River Basin to investigate the spatiotemporal evolution characteristics of the NDVI, comprehensive urbanization level (CUL), and their coordinated relationship with CUVCI. Furthermore, this research explores and discusses the potential influencing factors of CUVCI in the basin. The findings of this study partially align with existing research and lead to several important conclusions that have yet to be revealed.

The proposed CUVCI in this study demonstrates strong applicability in reflecting the dynamic relationship and degree of change between two systems. It can be applied to various large-scale river basins and regions to identify issues of uncoordinated development between these systems. The data we utilize, including NDVI data, city boundary data, GDP density data, population density data, and statistical yearbook data, are all publicly available and easily reproducible. This accessibility facilitates faster and more detailed research and comparisons in different regions for scholars.

Our study holds significant potential for application value, providing methodological support and a decision-making foundation for sustainable regional economic development. It aids in assessing whether vegetation protection is necessary during urbanization and contributes to the stability of urban ecosystems. By clarifying the relationship between urbanization and vegetation, decision-makers can plan urban development and land use more scientifically, ensuring appropriate resource allocation and improving land use efficiency and resource utilization. The coordinated development of urbanization and vegetation also fosters a more liveable environment, enhancing the quality of life and overall happiness of residents.

Data availability

All data generated or analysed during this study are included in this published article [and its supplementary information files].

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Author contributions
W.H.M. and Y.C.W. wrote the main manuscript text and prepared all figures, S.Y. (Corresponding author) and Y.C.W. revised the manuscript, designing the data processing code, L.H.M. and L.Y.H. revised the manuscript, Y.C.W. and X.H.Q. performed visualization. All the authors reviewed the manuscript.

Declarations

Competing interests
The authors declare no competing interests.

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