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Original Research

How Urbanisation Affects Carbon Dioxide Emissions: A Case Study of the Yellow River Basin

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Abstract

The Yellow River basin is a key region to study carbon peaking and carbon neutralisation owing to its high ecological and economic importance in China. To achieve this dual carbon goal, the relationship between carbon emissions and anthropogenic factors, such as urban land use, night light intensity, population density, and urban economic activities, should be elucidated. This study aimed to understand how urban construction land, urban economic activity intensity, and spatial population density patterns impact the CO_2 concentrations in the Yellow River basin using remote sensing data, and how urbanisation impacts the ecological environment of the basin with respect to land, economy, and population. The remote sensing satellite observation data was processed and subjected to coupling analysis, spatial analysis, and spatial econometric model. We found that during the study period, the lower reaches of the Yellow River basin exhibited a clear shift from construction to non-construction land, whereas the middle and upper reaches showed the reverse trend. Moreover, the bivariate clustering spatial patterns of construction land, night light intensity, and population with CO_2 concentration values had some similarities and partial differences. The coupling area of population and night light with CO_2 concentration was concentrated in the downstream, midstream, and upstream traffic trunk areas, and the construction land strongly impacted some areas in the upstream and midstream regions. The coupling and coordination of CO_2 concentration, construction land, and -economic activity intensity of cities in the Yellow River basin showed a ladder-like spatial pattern of increasing coordination degree from upstream to downstream. Furthermore, the ecological environment in the study area was affected by economic as well as population urbanisation. Urban construction land is one of the reasons for the CO_2 concentration in the Yellow River basin. This study suggests that high-quality development should be focused on ensuring regional economic development and ecological environment security

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according to the different directions of the impact of urbanisation and industrialisation on the ecological environment in different regions.

Keywords: Yellow River basin, land use change, coupling and coordination, correlation mechanism

Introduction

Carbon emissions is a global environmental problem, and its effective reduction is a common challenge for humankind. In the general debate of the 75th United Nations General Assembly, China committed to carbon peaking and carbon neutralisation and put forward requirements for the sustainable development of the Chinese nation and the construction of a community with a shared future for mankind. After 2012, as China's economy entered the new normal and began to promote the urbanisation strategy, urbanisation has become an important factor affecting regional carbon emissions. It affects carbon emissions and carbon sinks through land use change and economic activity agglomeration. Land use change is an important global environmental change and a key factor affecting the sustainable development of cities and regions; it has important mutual feedback on the regional ecological environment [1]. Therefore, studying the spatio-temporal coupling relationship between urbanisation and carbon emissions can help elucidate the patterns of urbanisation and carbon emissions in a region.

As a heavy industrial base and a rapidly developing economy and society, the Yellow River basin in China is an ideal region to study the change in urban construction land and is a difficult but key area to consider for carbon peaking and carbon neutralisation. It accounts for 75% of the country's basic coal reserves, 36% of the country's cumulative proven geological reserves of oil resources, 60.5% of the country's total energy production, and 31% of the country's total energy consumption. Energy consumption per unit of GDP in the basin is 25% higher than the national average. It is also a major carbon emission area in China. Moreover, the symposium on ecological protection and high-quality development of the Yellow River basin has designated the basin as an important ecological barrier and economic zone in China and has clarified the relationship between protection and development and the major strategic tasks required in the future [2-3]. Therefore, to achieve the dual carbon goal, it is necessary to scientifically identify the spatio-temporal relationship of industrialisation and urbanisation with carbon emissions in the Yellow River basin and the regional heterogeneity of these parameters.

Urban construction land is an important carrier of human production and life and a major dynamic indicator of land expansion in the process of urbanisation [4-6]. Both domestic and foreign scholars have previously discussed about the environmental problems caused by urban construction. In recent years, they have also conducted relevant research on urban land use from various perspectives. Foreign scholars have mainly focused on the relationship between urban economic development and land use efficiency, urban land intensive use, and efficiency evaluation [7-9]. Domestic scholars have conducted multi-scale measurement and evaluation of several elements, such as urban land use efficiency, regional differences, and influencing factors [10-12]. Additionally, research on the ecological and environmental effects of urban land use has gradually increased. The factors affecting carbon emissions mainly include economic development scale, industrial structure, energy consumption structure, urbanisation rate, technical level, and other factors, and the leading factors affecting carbon emissions are different depending on the time and region [13-17]. Some authors argued that, industrialization and urbanization are the main factors affecting China's carbon emissions. Especially after 2012, urbanization became an important factor affecting regional carbon emissions with a new normal of the Chinese economy and promotion of urbanization strategy. And it affects carbon emissions and sinks through land use change and agglomeration of economic activities. Therefore, it could scientifically understand the regularity of the two with studying the spatiotemporal coupling relationship between urbanization and carbon emissions. As an important component of global environmental change, land use change is a key factor affecting sustainable development of cities and regions, and has essential mutual feedback on regional ecological environment. However, the existing research on the ecological environment effect of urban land use has mainly focused on the analysis of the influencing factors, and the analysis of the interaction and correlation mechanism is limited.

Regarding "ecological protection and high-quality development of the Yellow River basin", "carbon neutralisation", and "carbon peaking", understanding the changes in urban construction land and its ecological and environmental effects in the Yellow River basin has many practical implications. Moreover, it is of academic value to analyse the contradictions between regional economic and social development and the ecological environment, and to coordinate the problems between regional high-quality development and environmental requirements and policies. In addition, this study reduces the scale of research to the kilometre grid scale, for accurately identifying spatial differences. It is innovative to analyze urban land use, regional economic activity intensity and its ecological environment effects based on remote sensing, and further analyze the coupling and correlation mechanism. In response to the requirements of high-quality development in the Yellow River basin, this paper takes cities in the Yellow River basin as the study area, and discusses the change of urban construction land, the intensity of urban economic activities and the distribution of CO_2 concentration based on remote sensing satellite data, and further researches the ecological environmental effects of urban land use using methods such as coupling analysis, spatial analysis research and spatial econometric models.

Materials and Methods

Variable Selection and Data Source

The Yellow River basin was selected as the research area in this study (Fig. 1), and satellite remote sensing observation data were used to avoid human errors in the statistical data and ensure the authenticity of the research data. The Yellow River flows through nine provinces and autonomous regions, including Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shanxi, Shaanxi, Henan, and Shandong. Considering the integrity of the administrative boundaries of the regions through which the river basin passes, this study selected 5 counties in 89 cities (autonomous prefectures) of the 9 provinces as the study areas.

The annual average concentration of CO_2 in 2020 was selected as the explained variable. It was obtained from two observation satellites, GOSAT and OCO-2, through spatio-temporal and geostatistical interpolation processing. The spatial resolution was 0.01° × 0.01°, and the CO_2 concentration was measured in ppm. Since CO_2 is a major greenhouse gas and one of the main causes of global climate problems, it can directly reflect the ecological environmental effects of production and living conditions of an area. CO_2 satellite remote sensing observation data can more reasonably reflect the global CO_2 concentration level in an area, avoid statistical errors caused by uneven site distribution, and eliminate the endogeneity problem of the original carbon emission data calculated from energy consumption.

Land use, night light data [18], and population distribution per spatial kilometre grid data in 2020 [19] were selected as the core variables, and land use type change, night light intensity, and population spatial distribution density in 2020 were selected as the measurement standards of land, economy, population, and other multi-dimensional urbanisation parameters. Among these, land use type change is the most intuitive measure of urbanisation. We comprehensively analysed the changes in the ecological environment effects in the process of urbanisation in the study area. We selected 1-km grid data based on the LandsatTM image of the United States, which is the national land use type remote sensing monitoring spatial distribution data generated by manual visual interpretation. Land use data were identified as construction land and non-construction land through preprocessing, which improved the accuracy of the land use data and intuitively interpreted the characteristics of land urbanisation. Night light remote sensing data is an important indicator of human activities such as social economy and energy consumption, which can more clearly reflect the intensity of regional economic activities and the characteristics of economic urbanisation. The nighttime lighting data used in this study were derived from China's long time series artificial nighttime lighting dataset yearly. The nighttime light convolutional long short-term memory (NTLSTM) network was applied to the prolonged artificial nighttime light dataset (PANDA). As another important measure of urbanisation, the proportion of the urban population is an important indicator of multi-dimensional urbanisation, and the distribution of population density is a direct manifestation of the

Fig. 1. The geographical range of Yellow River Basin in China.

spatial pattern of urbanisation. The kilometre grid data of population spatial distribution were selected, and the population density was used as the regional population urbanisation indicator, which avoids the shortcomings of traditional urban population measurements and usually takes administrative regions as the statistical unit. The above data used the spatial statistical unit to replace the traditional administrative statistical unit, avoiding the error impact of administrative divisions to more accurately discuss the spatial pattern of the study area and the internal driving mechanism. In addition, reducing the scale of the study area to a kilometre grid scale and refining the analysis unit into a spatial grid allowed more accurate identification of spatial differences.

Bivariate Spatial Correlation Analysis

Spatial autocorrelation refers to the potential interdependence between the observed data of some variables in the same area. Bivariate global spatial autocorrelation was used to explore and study the spatial correlation characteristics between different variables in this study and to analyse the overall spatial distribution correlation among variables. Its expression is

$$I = \sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(x_i - \bar{x})(y_j - \bar{y})/s^2 \sum_{i-1}^{n}\sum_{j=1}^{n} W_{ij} \tag{1}$$

where x_i and y_j are the observation values of different geographical attributes of regions i and j, respectively, and w_{ij} is a spatial weight matrix based on the proximity criteria.

The local spatial autocorrelation of two variables was used to explore the local correlation between different variables, and its expression is given as

$$I = Z_i \sum_{i=1}^{n} W_{ij} Z_j \tag{2}$$

where z_i and z_j are the normalised values of the variance of the observations in regions i and j.

In this study, the land use, night light, and population kilometre grid data were considered as one attribute observation value and CO_2 concentration value was considered as the other attribute observation value in the study area. Consequently, bivariate correlation analysis was conducted to explore the interaction between multidimensional urbanisation indicators and the ecological environment.

Coupling Analysis

To further explore the interaction and intensity between the ecological environment effect and land use change in the Yellow River basin, the concept of coupling was used to explain the mutual correlation and feedback between various elements. We attempted to explain the coupling degree and impact intensity between the ecological environment and land use, economic activity intensity, population, and other elements in the study area.

Table 1. Classification criteria of coupling strength.

D value interval	Coordination level	Coupling degree
(0.0~0.2)	1	Weakest coupling
[0.2~0.4)	2	Weaker coupling
[0.4~0.6)	3	Coupling
[0.6~0.8)	4	Stronger coupling
[0.8~1.0)	5	Strongest coupling

The concept of coupling originates from physics, which refers to the phenomenon in which two or more systems or two forms of motion affect each other through interaction and thus unite. In social science research, the phenomenon of interaction and function among various elements is called coupling and is used to express the mutual relevance and feedback of various elements [20, 21].

The degree of coupling coordination has been derived from the capacity coupling coefficient model of physics. The coupling degree is the degree of mutual influence and connection between various elements. Its formula is as follows:

$$C = \left\{ \frac{f(x) \times g(y)}{\left[\frac{f(x) + g(y)}{2}\right]^2} \right\}^{\frac{1}{2}} \tag{3}$$

where C is the coupling degree and f (x) and g (y) represent the different elements in the study area. The coupling degree C lies between 0 and 1. The larger the value, the stronger the interaction between the subsystems.

The coupling degree between land use data, night light data, and population kilometre grid data and CO_2 concentration value was analysed to further explore the impact intensity of how the land, economy, and population interacts with the ecological environment.

Spatial Econometric Model

The spatial lag model is used to study the influence of the behaviour of a region on the behaviour of its neighbouring regions, that is, to study whether there is spatial dependency, and the dependency intensity of the variables. It is expressed as:

$$Y_i = \alpha + \rho W Y_j + \beta X_i + \varepsilon_i \tag{4}$$

Where W is the spatial weight matrix, α is a constant, and ε is a random error. The spatial correlation of the spatial error model is reflected in the random disturbance term, that is, the spatial disturbance term is related to the spatial population. The disturbance in one region will affect other regions with a spatial effect, and its form can be expressed as:

$$y = \alpha + \beta X + \varepsilon \quad (\varepsilon = \lambda W + \mu) \tag{5}$$

where λ is used to measure the impact of the error on the local observations of the interpreted variables in the adjacent areas.

Results

Distribution of Construction Land in the Yellow River Basin is Gradually Increasing from Upstream to Downstream

In 2020, the spatial distribution of the urban construction land area in the Yellow River basin showed obvious spatial differences (Fig. 2). Construction land was densely distributed in the lower reaches, relatively densely distributed in the middle reaches, and sparsely distributed in the upper reaches. This was related to the natural environment of each region. There are many unused land types, such as mountains and sandy land in the upper reaches, cultivated land, forest land, and other non-construction land types in the middle reaches, and flat main plains and hills in the lower reaches, which are mainly composed of cultivated land and construction land. In addition, the area of urban construction land is related to the urban development level of each region. Taking the upstream region as an example, the areas with relatively concentrated construction land were clearly distributed along the main railway lines (Beijing Baotou Lanzhou line and Longhai Lanzhou new line).

Through comparative analysis of remote sensing monitoring data from 2010, it was found that land use types in the Yellow River basin have changed significantly in different regions (Fig. 3). Among them, the land use type change status of Ordos and Yulin at the border between the middle and upper reaches and Lanzhou and Hainan Tibetan Autonomous Prefecture in the upstream have changed from non-construction land to construction land. The clear expansion of urban construction land in these areas further confirms the rapid development of local urbanisation. However, some

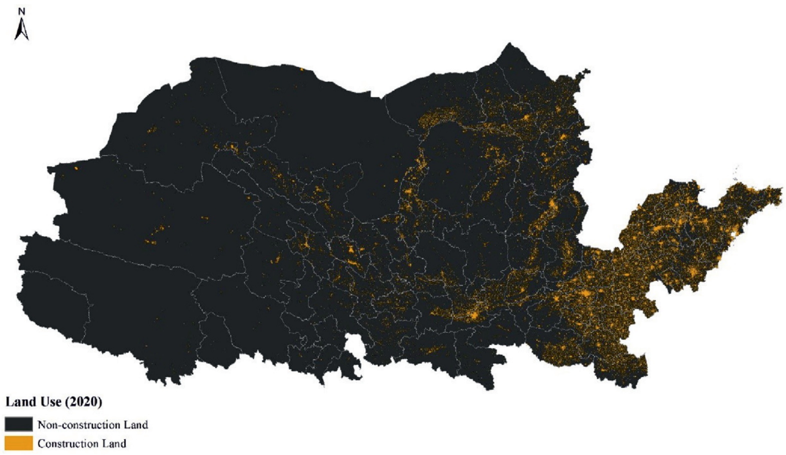

Fig. 2. Land use status of the Yellow River basin (2020).

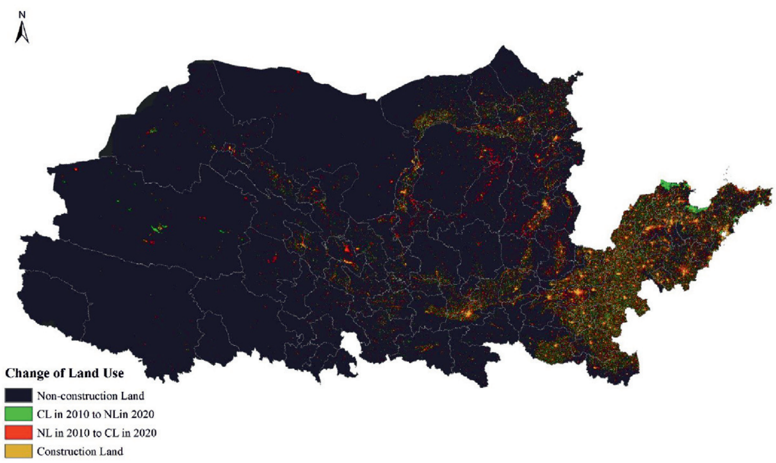

Fig. 3. Change of land use types in the Yellow River basin (2010-2020). CL, construction land; NL, non-construction land.

coastal areas in the cities Binzhou and Weifang in the lower reaches have changed from construction land to non-construction land, which is attributed to a series of policies and measures proposed by Shandong Province to promote the ecological protection and restoration of the Yellow River basin and protect the Yellow River Delta, such as restoring farmlands to wetlands, returning farmlands to the sea, and restoring farmlands to beaches.

There Are Clear Differences in the Ecological Environment Effects of Construction Land, Economy, and Population in the Yellow River Basin

As shown in Fig. 4, the areas with significant correlation between construction land and CO_2 concentration value in the study area accounted for 65.2% of the entire Yellow River basin, among which high-high (HH) cluster areas accounted for 10.6%; low-high (LH) cluster areas, 35.9%; high-low (HL) cluster areas, 10.8%; and low-low (LL) cluster areas, 42.7%. HH and LH cluster areas were mainly concentrated in the middle and lower reaches of the basin, and HL and LL cluster areas were mainly concentrated in the upper reaches and some parts of Inner Mongolia in the middle reaches. In general, the spatial distribution of the HH and LH aggregation areas were similar to the HL and LL aggregation areas, respectively. The HH and LH aggregation areas were staggered in the middle and lower reaches of the study area, whereas the HL and LL aggregation areas were staggered in the upper reaches of the study area and the middle reaches of Inner Mongolia. The bivariate aggregation distribution of construction land and CO_2 concentration value was related to the overall distribution state of the CO_2 concentration value, and the ecological environmental effect of construction land needs further investigation.

As an important indicator of urban economic activity intensity, night light intensity plays a significantly leading role in the regional ecological environment effect. The bivariate Moran's I of night light and CO_2 concentration value was 0.437, indicating a clear correlation between them. As shown in Fig. 5, the HH, LH, LL, and HL cluster areas for CO_2 concentration value and night light intensity accounted for 28.3%, 18.2%, 52%, and 1.5% of the total cluster areas, respectively. HH aggregation areas were mainly concentrated in the lower reaches and some parts of the middle reaches of the Yellow river basin, LH aggregation areas were mostly concentrated in the middle reaches, and LL aggregation areas were mainly distributed in the upper reaches of the basin and middle reaches of Inner Mongolia. Thus, the Yellow River basin showed a clear spatial differentiation from upstream to downstream. The lower reaches exhibited high night light intensity with high CO_2 concentration values, the middle reaches exhibited low night light intensity with high CO_2 concentration values, and the upper reaches mainly showed low night light intensity with low CO_2 concentration values.

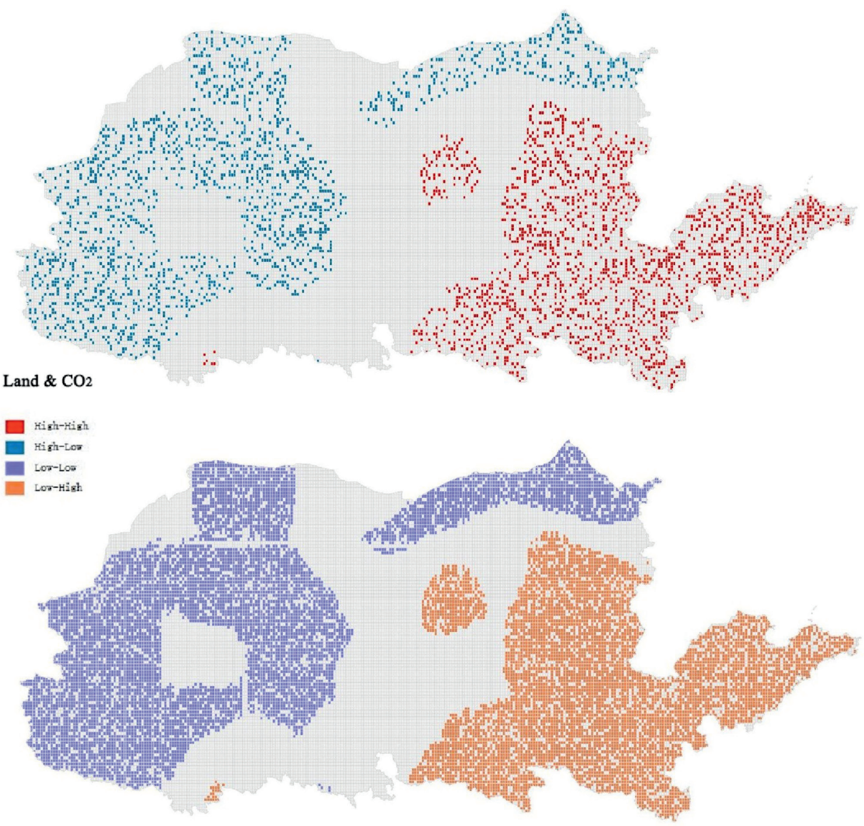

Fig. 4. Bivariate clustering of CO_2 concentration value and construction land in the Yellow River basin (2020).

The bivariate spatial autocorrelation distribution pattern of the regional population and CO_2 concentration values was similar to that of nighttime light intensity and CO_2 concentration values (Fig. 6). The population in the Yellow River basin was significantly correlated with the CO_2 concentration value. The bivariate Moran's I was 0.426, and the HH, LH, LL, and HL cluster areas accounted for 29.4%, 17.1%, 52.9%, and 0.6%, respectively. The HH aggregation areas were mainly concentrated in the lower reaches of the Yellow River basin, LH gathering areas were concentrated in the middle reaches of the basin, and LL aggregation areas were mainly distributed in the upper reaches of the basin and middle reaches of Inner Mongolia. In general, the aggregation and distribution of the population and CO_2 concentration values also showed obvious spatial differentiation characteristics. Compared with the aggregation and distribution of light intensity and CO_2 concentration values at night, the clustering and distribution of population and CO_2 concentration values were more homogeneous in the HH and LH aggregation areas.

Through the spatial correlation analysis of construction land, night light intensity, and population with CO_2 concentration values, it was found that there are some similarities and partial differences in the bivariate clustering spatial pattern. Among them, the bivariate spatial autocorrelation of the LL cluster areas of construction land, nighttime light intensity, and population with CO_2 concentration values had the same distribution pattern, which was concentrated in the upper reaches of the Yellow River basin and the middle reaches of Inner Mongolia. The HL clustering of construction land and CO_2 concentration values was mainly distributed in the upper and middle reaches of the study area in Inner Mongolia. However, this cluster type was absent in the bivariate spatial autocorrelation distribution pattern of nighttime light intensity and population with CO_2 concentration values.

Coupling Effects of Various Elements of the Ecological Environment in the Yellow River Basin Are Different

The coupling of CO_2 concentration and economic activity intensity of cities in the Yellow River basin showed clear spatial differences (Fig. 7), and the overall spatial pattern was ladder-like with increasing coupling degree from upstream to downstream. The nighttime light and CO_2 concentration in the lower reaches of the Yellow River basin were mostly in a strong coupling state, with mainly medium and high coupling degree, whereas the nighttime light and CO_2 concentration in the middle and upper reaches were mostly in a weak coupling state. The spatial difference between the CO_2 concentration and the coupling degree of urban night light clearly revealed that the intensity

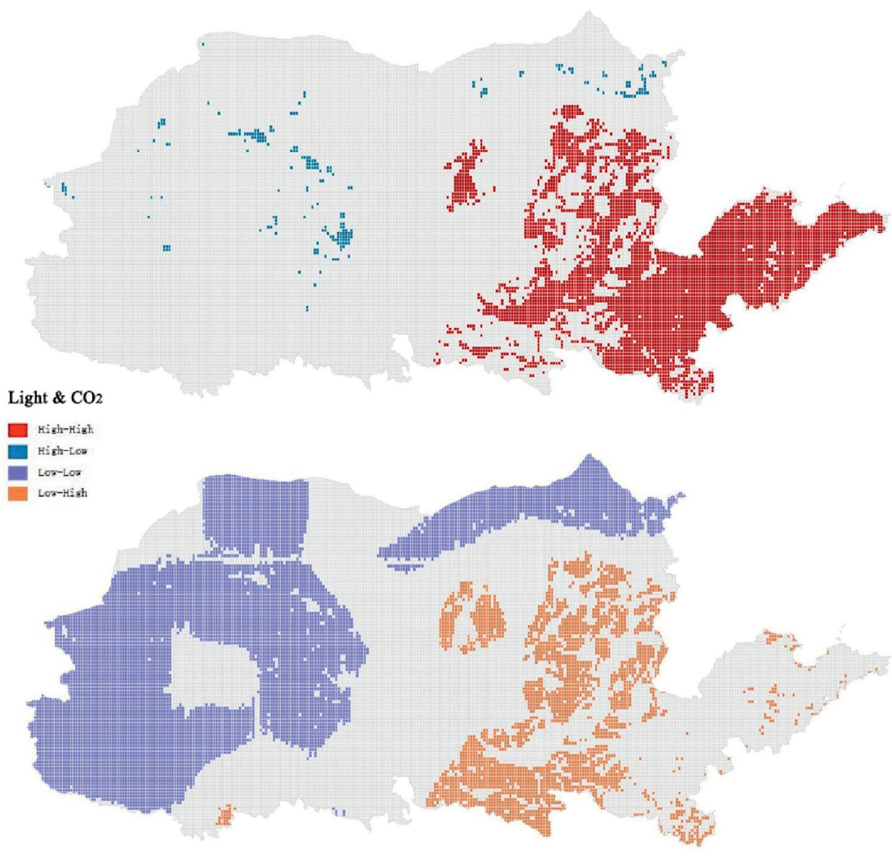

Fig. 5. Bivariate clustering of CO_2 concentration value and night light intensity in the Yellow River basin (2020).

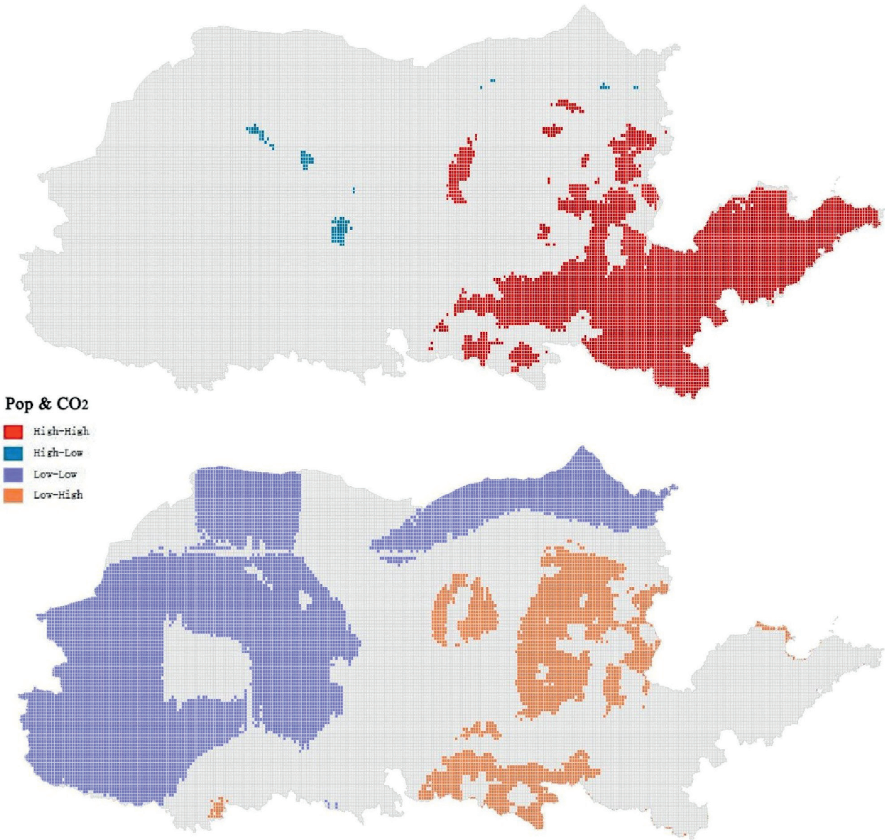

Fig. 6. Bivariate clustering of CO_2 concentration value and urban population in the Yellow River basin (2020).

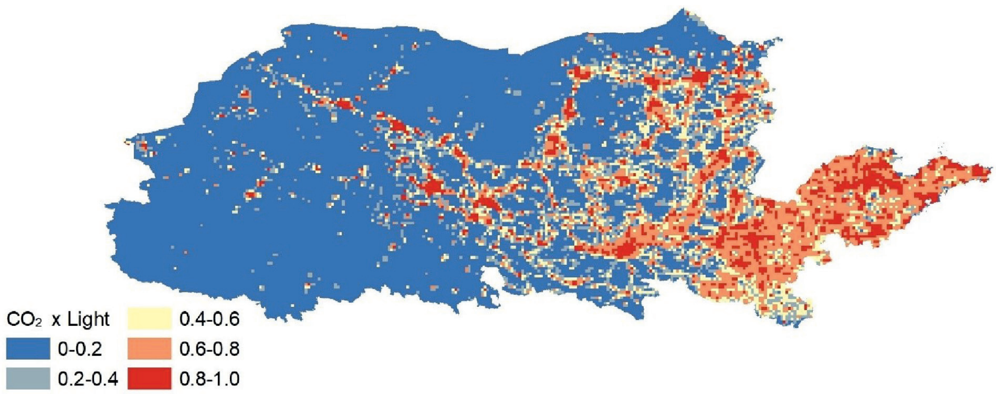

Fig. 7. Coupling degree of night light and CO_2 concentration in the Yellow River basin (2020).

of urban economic activities in the downstream area considerably impacted the CO_2 concentration, whereas that in the upstream area had a limited impact on the CO_2 concentration.

As shown in Fig. 8, the CO_2 concentration in the middle and lower reaches of the Yellow River basin showed a strong coupling with the population, especially in the lower reaches. This indicated that the population in the middle and lower reaches had a strong impact on CO_2 concentration. The CO_2 concentration in the upper reaches of the basin was not strongly coupled with the population, which indicated that the CO_2 concentration in the upper reaches of the basin was not completely affected by urbanisation.

Further, the multi-dimensional coupling relationship between CO_2 concentration and construction land, economic activity intensity, and population in the Yellow River basin showed that the multi-dimensional coupling state had an obvious spatial difference pattern similar to the two-dimensional coupling state. Considering the existence of a strong coupling degree as the classification standard, through the comprehensive classification of the coupling intensity of each element in each cell of the study area, the coupling types of the

Yellow River basin in this study were divided into seven categories based on the three elements of construction land, night light, and population; the dual elements of construction land and night light, and population and night light; the single element of construction land, night light, and population, and the regional types with weak coupling effects of the above elements. As shown in Fig. 9, the regions with weak coupling strength of construction land, night light, population, and CO_2 concentration were mainly located in some parts of the upper and middle reaches of the study area. The areas with a strong coupling relationship of the single element of night light were mainly distributed downstream and in the traffic trunk areas of the middle and upper reaches. In the middle reaches, there was an area from Taiyuan to Xi'an (passing through Taiyuan, Luliang, Jinzhong, Linfen, Yuncheng, Weinan, Xianyang, Xi'an, and Baoji) that exhibited a strong coupling relationship. The upstream area also showed a strong coupling relationship along the main railway trunk lines (Beijing Baotou Lanzhou and Longhai Lanxin lines) and from Lanzhou to Xining. The areas with strong single-element coupling relationships of construction land were scattered in the upstream and some areas of the middle reaches and were mixed with areas with weak coupling strength of the three elements.

In the regional type dominated by dual elements, the strong coupling areas dominated by construction land and night light were relatively concentrated in the traffic trunk areas of the middle and upper reaches, and the areas with strong coupling relationships between single elements of night light were distributed downstream. There were few strong coupling areas dominated by night light and population, and they are scattered around the traffic trunk lines in the middle reaches and upstream, as well as in the central areas downstream. The regional types with strong coupling intensity of construction land, night light, population, and CO_2 concentration were hardly continuous and were relatively scattered in the lower reaches and the traffic trunk areas of the middle and upper reaches.

Thus, the coupling effect of population, night light, and CO_2 concentration was concentrated in the downstream, midstream, and upstream traffic trunk areas. In addition to the above areas, construction land also had a strong impact on some upstream and midstream areas.

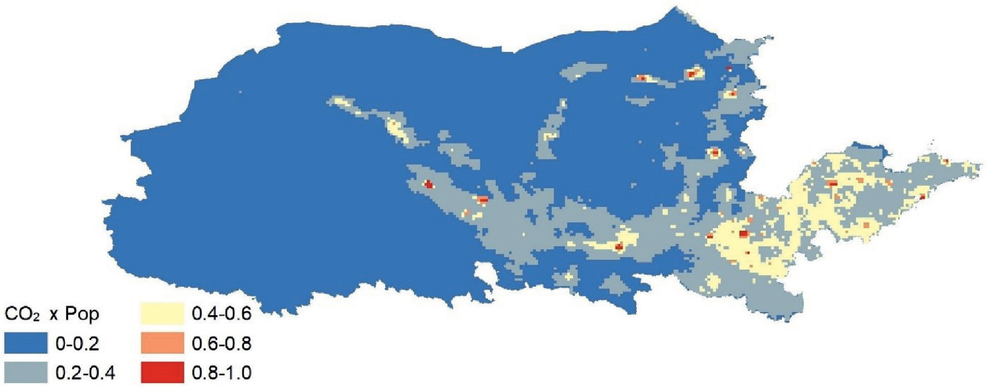

Fig. 8. Coupling degree between urban population and CO_2 concentration in the Yellow River basin (2020).

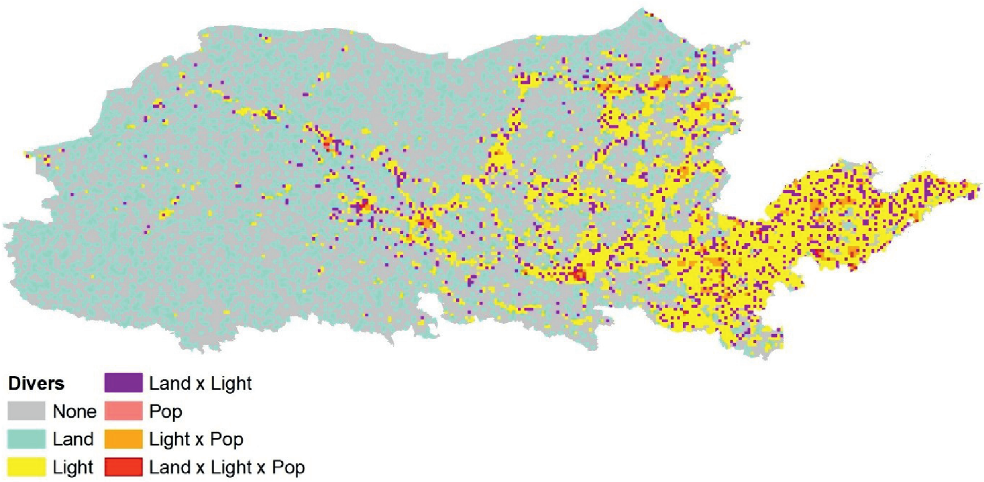

Fig. 9. Coupling type of the Yellow River basin (2020).

Regional Heterogeneity Exists in the Impact Mechanism of the Ecological Environment Effect in the Yellow River Basin

We further explored the different impacts of construction land, night light intensity, and population on CO_2 concentration. Based on the above research, spatial correlation was observed in the system; therefore, we investigated the impact mechanism of the ecological environment effect in the study area through a spatial econometric model. The model was judged according to indicators, such as Log Likelihood, AIC, and SC. The larger the Log Likelihood, the smaller the AIC and SC, and the better the model. Therefore, the spatial lag model was optimal for this study area.

The coefficient of the spatial lag term was significantly positive, with a value of 0.995 (Table 2), indicating that there was a significant positive spatial correlation between CO_2 concentrations in the Yellow River basin. The nighttime light intensity coefficient was significantly positive, with a value of 0.004, indicating the negative ecological environment effect of urban economic activity intensity in the basin; that is, the greater the nighttime light intensity, the greater the regional CO_2 concentration. The population coefficient was significantly positive, with a value of 0.013, indicating that the population in the Yellow River basin had a negative effect on the ecological environment. However, the impact of construction land on the ecological benefits of the study area was not significant, which may be due to the fact that construction land is not synchronised with economic activities and population aggregation, so the impact mechanism on the ecological environment is different.

Table 2. Measurement model results of construction land, night light, and population on CO_2 concentration.

Var	OLS	SLM	SEM
Land	0.004	-0.0002	0.00006
Light	0.678^{***}	0.004^{***}	0.0001
Population	3.105^{***}	0.013^{*}	0.001
Con	0.431^{***}	0.003^{***}	0.650^{***}
W		0.995^{***}	
R^2	0.216	0.997	0.999
log L		71157.5	98592.564
AIC		-142305	-197177
SC		-142264	-197145

Discussion

Coupling Relationship between Land, Economy, and Population Urbanisation and Ecological Environment in the Yellow River Basin

The CO_2 concentration value in the Yellow River basin was separately coupled with the multi-core variables of construction land, economic activity intensity, and population density. Based on the classification of the coupling intensity of each spatial unit, the spatial unit with prominent single-element coupling intensity was considered as the dominant factor. The coupling type in the study area was divided into seven categories, which were comprehensively dominated by construction land, night light and population, and construction land and night light. The two elements of population and night light were dominant, the single element of construction land, night light, and population was dominant, and the coupling effect of the above elements was weak.

In the lower reaches and the traffic trunk areas of the middle and upper reaches of the basin, the regional types with strong coupling strength of construction land, night light, population, and CO_2 concentration were relatively scattered, indicating that the pace of land, economic, and population urbanisation was relatively consistent in these regions, and there were obvious negative ecological environmental effects in the process of urbanisation in these regions. In the upper and middle reaches of the study area, the regions with weak coupling strength of construction land, night light, population, and CO_2 concentration were relatively concentrated. The CO_2 concentrations in these regions were less affected by land, economy, and population urbanisation, and there are other influencing factors besides local production and living conditions on its ecological environment.

The CO_2 concentration in the lower reaches of the Yellow River basin was strongly coupled with nighttime light intensity and population density. There was a weak coupling region in the middle reaches, whereas the CO_2 concentration in the upper reaches was mainly weakly coupled with the economic and population urbanisation indicators. In contrast to the coupling state of economy and population, the regions with strong single-element coupling relationships of construction land were scattered in the upstream and some regions of the middle reaches, and were mixed with regions of weak coupling strength of the three elements. This indicated that the impact of the economic activity intensity and population density in urban cities of the upstream region on CO_2 concentration was limited. Furthermore, the impact of economic and population urbanisation on the ecological environment in the upstream region was minimal, and the process of land urbanisation preceded the process of economic and population urbanisation. Therefore, the ecological environment effect in the upstream region is currently affected by the process of land urbanisation, and not population urbanisation.

Analysis of the Coupling and Correlation Mechanisms between Urban Land Use and Eco-Environmental Effects in the Yellow River Basin

The coupling analysis revealed that the intensity of economic activities in the downstream areas was directly proportional to the CO_2 concentration. The upstream CO_2 concentration was affected by nighttime light data, but they were not intuitively positively correlated. Meanwhile, the aggregation distribution of the CO_2 concentration value and population also presented spatial differentiation characteristics similar to the nighttime light intensity aggregation, and the highly correlated area of the aggregation distribution of the population and CO_2 concentration value was more homogeneous, which was related to the selection and processing of the population data.

In the process of quantifying the impact of land, economy, and population urbanisation on the ecological environment in the study area, it was found that night light intensity and population density had a negative impact on the regional ecological environment. This indicated that the ecological environment effect produced by the production and living conditions in the process of economic and population urbanisation in the study area was in a negative stage. However, the impact of construction land on the ecological benefits of the study area was not significant, which may be due to the fact that construction land is not synchronised with economic activities and population aggregation, so the impact mechanism on the ecological environment is different. The intensity of regional economic activities, urban population aggregation, and construction land use patterns were related to the natural environment and urban development level of each region. As the first step of urbanisation, the development process of urban construction land use patterns occurs prior to the stage of urban economic activities and urban population aggregation. Therefore, as a pioneering step in urbanisation, land urbanisation has little impact on the regional ecological environment. The key to solving ecological environmental problems in the study area is to avoid the negative effects of production and lifestyle choices in the process of economic and population urbanisation.

Conclusion

This study investigated the changes in urban construction land, the intensity of urban economic activities, and the impact of population spatial patterns on the intensity and mechanism of CO_2 concentration in the Yellow River basin using remote sensing satellite observation data, and reports the impact of urbanisation on the ecological environment of the study area from multiple dimensions of land, economy, and population. The conclusions of the present study are as follows.

(1) In 2020, construction land was densely distributed in the downstream area, relatively densely distributed in the middle reaches, and sparsely distributed in the upstream area. During the study period, the downstream area was evidently changed from construction land to non-construction land, whereas the middle and upstream areas showed an obvious change from non-construction land to construction land.

(2) The bivariate clustering spatial patterns of construction land, night light intensity, and population with CO_2 concentration values has some similarities as well as differences. The LL gathering areas were concentrated in the upper reaches of the basin and in Inner Mongolia of the middle reaches. The lower reaches showed high night light intensity, population density, and CO_2 concentration.

(3) The coupling area of population, night light, and CO_2 concentration was concentrated in the downstream, midstream, and upstream traffic trunk areas. Additionally, construction land also had a strong impact on some upstream and midstream areas.

(4) Urban construction land was one of the reasons for the CO_2 concentration in the Yellow River basin. The ecological environment in the study area was affected by economic and population urbanisation. High economic activity intensity and high population density had negative effects on the CO_2 concentration in the basin.

Based on the impact of urban construction land and nighttime lighting data on CO_2 concentration, this study found that the ecological environment effect and multi-dimensional urbanisation in the lower reaches of the Yellow River basin have strong mutual feedback, whereas the middle and upper reaches have weak mutual feedback. This shows that in addition to urban construction land and nighttime lighting data, there are other factors that influence the CO_2 concentration in the upper reaches. Further studies should take into account the large differences in the industrial structure of each region and the different degrees of environmental load, and explore the factors that affect the ecological environment in different regions.

This study suggests that high-quality development should be adopted measures suiting local conditions according to the different conditions in the basin. It is effective to structure stricter rules of economic-ecosystem in the lower reaches and the traffic trunk areas of the middle and upper reaches of the basin, for the negative ecological environmental effects in the process of urbanisation in these regions. On the basis of the existing industrial structure and economic development of the Yellow River basin, and on the premise of "ecological protection and high-quality development of the Yellow River basin", "carbon neutralisation", and "carbon peaking", high-quality development needs to focus on ensuring regional economic development and ecological environment security, setting reasonable carbon peaking goals, attracting high-quality talents and investing more R&D funds, maintaining regional innovation vitality, making good use of the double circulation pattern and the Belt and Road Economic Development Belt, eliminating backward production capacity, promoting the upgrading of the industrial structure, and achieving the goals of energy conservation and emission reduction from the two aspects of technological development and industrial structure upgrading.

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Conflict of Interest

This manuscript has not been published or presented elsewhere in part or in entirety and is not under consideration by another journal. We have read and understood your journal's policies, and we believe that neither the manuscript nor the study violates any of these. There are no conflicts of interest to declare.

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