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How territorial function determines CO_2 emissions in China: An approach of spatial dimension

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Abstract: Regional CO_2 emissions are closely related to their territorial function, which is the major role a region plays in sustainable processes on the earth's surface. Given that China is implementing a top-down emission allocation quota strategy, studying the impact of a territorial function on emissions addresses the research gap from a spatial integration dimension. By investigating the effects of three basic functional territories (urbanization zones (UZ), food security zones (FSZ), and ecological security zones (ESZ)), horizontal spatial structure and vertical combinations of functional territories on CO_2 emission patterns in China, we found that functional territory patterns were highly coupled with the spatial distribution of CO_2 emissions, with a ratio of CO_2 emissions from UZ–FSZ–ESZ was stable at around 5:2:1 from 2000 to 2017. Spatially, CO_2 emissions in FSZ and ESZ were 1.06–2.12 times higher than the average value within 200 km from the UZ. As territorial function combination increased with spatial upscaling, the emission characteristics attributable to functional territories became indistinct. The findings above can provide a basis for the long-term prediction of CO_2 emissions from spatial dimension, support scientific guidance for inter-zone cooperation and classified management of carbon emissions with the major function oriented zones as impetus.

Keywords: CO_2 emission pattern; functional territory; spatial structure; function combination; spatial dimension-based analysis

1 Introduction

In recent years, geoscience researchers have paid much attention to the effects of human–nature interactions on the patterns of earth surface systems and have conducted in-depth investigations of the social–natural ecosystem (Fan, 2022; Wu *et al.*, 2022). Such

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research is gaining popularity and importance, as global climate change weighs heavily on the minds of scholars and policy makers, with a majority of countries around the globe working hard towards achieving the 2030 Sustainable Development Goals (Wang *et al.*, 2019; Bruckner *et al.*, 2022). The mechanisms, effects, and management of and sustainable adaptation to climate change and CO_2 emissions are among the focal research topics (Peters *et al.*, 2017; Lamb *et al.*, 2021; Liu *et al.*, 2022). In the context of environmental sustainability, efforts to achieve the CO_2 peaking and CO_2 neutrality goals will become the core driving force of human–nature interactions. Uncovering the patterns of CO_2 emissions on the earth surface systems has become a frontier research area in the research framework of the human–nature relationship in geoscience.

IPAT model considering that the environment (I) is influenced by population (P), affluence (A), and technology (T) (Ehrlich and Holdren, 1971). The KAYA identity decomposes changes in carbon emissions into the contribution of population, economic level, technology and energy structure (Kaya, 1989). IPAT model and KAYA identity are common methods for the analysis of influencing factors of carbon emissions, and the influencing factors covered by them have become the basic template for the selection of driving factors of carbon emissions (Wang and Fan, 2022). In actual research, the above indicators have been continuously expanded, providing methodological support for analyzing the driving factors of carbon emissions (Guan *et al.*, 2018; Wu and Gu, 2021).

Research on CO_2 emissions has mainly focused on how these are affected by socio-economic factors, such as population size and structure (Zhou and Liu, 2016; Yi *et al.*, 2021), economic development and structure (Guan *et al.*, 2018; Zheng *et al.*, 2020; Li *et al.*, 2022b), and technology level (Le Quere *et al.*, 2019) and energy structure (Li and Haneklaus, 2022; Wang and Yan, 2022). Most of the related studies have centred around industrial sectors (Zheng *et al.*, 2020; Chen *et al.*, 2021), especially carbon-intensive sectors such as manufacturing (Huang *et al.*, 2020), construction (Erdogan, 2021; Zhang *et al.*, 2021), and transportation (Liu *et al.*, 2021; Li *et al.*, 2022a). In contrast, few studies have evaluated the spatial dimension of CO_2 emissions, and most of these have only analysed the regional differences in CO_2 emissions on a macro scale, while paying little attention to the effects of the spatial dimension on CO_2 emissions. In addition, studies evaluating CO_2 emissions from the spatial dimension have mainly focused on urban areas (Wang *et al.*, 2020a; Yi *et al.*, 2021; Zhang *et al.*, 2022) and seldom on other functional zones, such as agricultural and ecological areas. As a result, the overall research on CO_2 emissions at national and regional levels (including multiple functional regions) is inevitably biased.

A ‘territorial function’ is a geographical unit’s role in the sustainable development of a country, the world, or other geographical zone. The urbanisation zones (UZ), food security zones (FSZ), and ecological security zones (ESZ) (Figure S1) of Chinese Major function oriented zoning (MFOZ) considered in this study have the territorial functions of population concentration and economic agglomeration, food security, and ecological security, respectively (Fan *et al.*, 2019). Each territorial function manifests of the comprehensive integration of natural conditions and socio-economic development. Territorial function is intrinsically connected to CO_2 emissions as the former result from the natural conditions and human activities in a region (Wang *et al.*, 2019). As territorial functions are the result of long-term interactions between human society and the natural system, they are less prone to extensive changes than industrial and demographic patterns. Thus, territorial functions provide another dimension for studying and predicting changes in CO_2 emission patterns. In addition, territorial functions serve as a basis for dividing policy units and can be used as a policy instrument for spatial governance.

Spatial governance is an important instrument used by a country in its public and governance policies, especially in China (Liu *et al.*, 2022). The administrative hierarchy-based management is the core means of carbon control in China. However, if this management lacks theoretical support, the decomposition of carbon control indicators based on administrative levels will become groundless and thus dampen the effectiveness of spatial governance. Therefore, a spatial dimension-based systematic understanding of the characteristics and evolutionary patterns of CO_2 emissions is warranted as an important lens for studying human–nature interactions under the framework of earth surface systems. More importantly, such understanding is of great practical significance for coordinating regional socio-economic development and achieving CO_2 peaking and CO_2 neutrality goals.

This study was based on three basic territorial functions, namely urbanisation, food security, and ecological security. The corresponding basic spatial units are UZ, FSZ, and ESZ, which are divided by county-level administrative regions in China (Fan *et al.*, 2019). By analysing the characteristics and mechanisms of CO_2 emission patterns in the three basic functional zones and the combined functional units of spatial hierarchy levels in China from 2000 to 2017, this paper investigates the coupling relationship between CO_2 emission patterns and territorial functions based on their spatial characteristics. This paper also examines the effects of the horizontal spatial structure and vertical function combinations on this coupling relationship. Finally, this paper proves the value of studying CO_2 emissions from the spatial dimension and discusses the development of an integrated analytical approach for the spatial prediction of CO_2 emissions.

2 Theoretical framework

The population, industrial pattern and regional economic development level gradient of the three zones may lead to inter-regional differences of CO_2 emissions. First, due to their different functional positioning in the pattern of territorial space development and protection, significant differences existed among UZ, FSZ and ESZ in population and industrial scale, which will inevitably lead to amount differences in CO_2 emissions. Second, the economic development level varies strongly among the three zones, and the industrial technology level and energy use efficiency level are different in functional zones, which leads to the inter-zone differentiation of CO_2 intensity. Third, the difference in living standards of residents in UZ, FSZ and ESZ is reflected in the inter-zone difference in per capita CO_2 emissions.

The spatial structure of the MFOZ will also affect the spatial pattern of CO_2 emissions. MFOZ has a core-edge spatial structure, with UZ as the core (population weighted centroid of urban areas), and the number of FSZ and ESZ gradually decreases with the distance from the core. Regional openness leads to the flow of population, industry and other factors from zone to another zone, which bring about the spatial interaction of functional zones will affect inter-zone CO_2 emissions. Theoretically, FSZ and ESZ adjacent to UZ have higher frequency and scale of population and economic factors flow than other zones farther away from UZ, and are more significantly affected by UZ CO_2 emissions.

The MFOZ characteristics of CO_2 emissions gradually blur as the spatial upscaling to the high-level administrative region. The MFOZ are county-level units with corresponding CO_2 emission characteristics. Comprehensive functional sub-regions and Comprehensive functional regions are the combination of MFOZ. Therefore, the CO_2 emission differences among provincial units can be regarded as the result of different combination modes of MFOZ. The CO_2 emission characteristics of MFOZ are transmitted along with upscaling, and the degree of deviation varies according to the complexity of the combination of MFOZ. Theoretically, the CO_2 emission characteristics of comprehensive functional sub-regions and Comprehensive functional regions are gradually blurred.

Starting from the social and economic pattern contained in the scientific process of the formation of MFOZ, the CO_2 emission characteristics of MFOZ are revealed. And the theoretical analysis framework of the effects of MFOZ on CO_2 emission characteristics is constructed considering the type of MFOZ, the impact of MFOZ combination and MFOZ interaction on CO_2 emission characteristics (Figure 1).

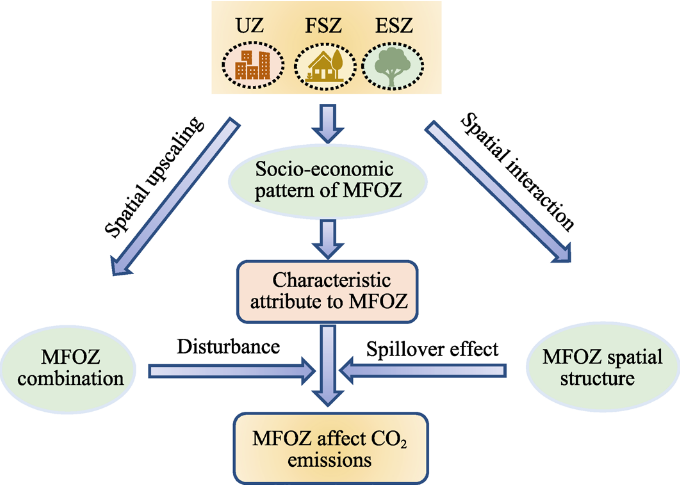

Figure 1 Theoretical framework of research on the impact of MFOZ on CO_2 emissions

3 Methods

3.1 Data sources

3.1.1 CO_2 emissions data

Carbon emission account datasets (CEADs) that use two sets of night light data (Defence Meteorological Satellite Program/Operational Linescan System (DMSP/OLS) and National Polar-Orbiting Partnership/Visible Infrared Imaging Radiometer Suite (NPP/VIIRS)) provided by the National Geophysical Data Center (NGDC) were used to invert CO_2 emissions at county level from 2000 to 2017. These datasets provide high-quality long time series CO_2 emission data for districts and counties. After fitting these data with national and provincial carbon emission data on fossil energy consumption, accuracy was as high as 0.998 and 0.985, respectively (Chen *et al.*, 2020). This paper used carbon emission data for each county from

2000 to 2017 provided by the CEADS database. In the districts and counties with low human activity intensity levels (mainly ecological security counties), the night light index could not invert the corresponding CO_2 emission data. This paper compared the kriging interpolation results with the inverse distance weight (IDW) interpolation results and combined with the verification of energy consumption in some county-level units, the kriging interpolation results were more accurate. Kriging interpolation was used to complete the missing CO_2 emission data for 39 districts and counties.

3.1.2 Socio-economic data

Based on our previous publication (Fan *et al.*, 2019), we collected and sorted the national list of major county-level functional zones. Combined with the relevant county-level administrative boundary map of China from the work of Chen *et al.* (2020), we obtained the national major functional zone vector map. Considering adjustments to the administrative divisions of the districts and counties, especially adjustments to the boundaries of municipal districts; the availability of social and economic data; and the consistency of statistical data, all the municipal districts were merged accordingly, and finally, 2271 districts and counties were obtained, of which 791 units were UZ, 750 units were FSZ, and 730 units were ESZ.

Population migration is an important factor related to CO_2 emissions; however, a permanent population can better reflect the actual population distribution pattern. Therefore, permanent population data from districts and counties in 2017 were collected and sorted by province and city based on the fifth (2000) and sixth (2010) census data. The GDP and three industrial output values were obtained from the *China Statistical Yearbook* (*County Level*) (*2001*, *2011*, and *2018*), while those of municipal districts were obtained from the *China City Statistical Yearbook* (*2001*, *2011*, and *2018*). Taking the year 2000 as the base year, all economic data were converted to comparable prices in 2000 for the calculations to avoid the effects of inflation.

The GDP, three industrial output values, permanent population size, urbanization rate, actual utilization of foreign capital, and energy consumption amount of case areas were obtained from the *Beijing Regional Statistical Yearbook* (*2011–2020*), *Xingtai Statistical Yearbook* (*2011–2020*), *Hengshui Statistical Yearbook* (*2011–2020*), and *Xilingol League Statistical Yearbook* (*2011–2020*). All economic indicator were converted to comparable prices in 2010 for the calculations to avoid the effects of inflation. CO_2 intensity is calculated by CO_2 emissions divided by GDP.

3.2 Research methods

1) Theil index

The Theil index was introduced to measure intergroup and intragroup differences and reflect the imbalance degree of CO_2 emissions within and between functional zones. The index investigates inequalities and differences using the concepts of information amount and entropy. It divides the overall difference into the difference between various parts and the difference within each part and has been widely used in analysing and dissolving differences and inequalities (Zhang *et al.*, 2021).

$$T = T_b + T_w = \sum_{k=1}^{k} y_k \log \frac{y_k}{n_k / n} + \sum_{k=1}^{k} y_k \left(\sum_{i \in g_k} \frac{y_i}{y_k} \log \frac{y_i / y_k}{1 / n_k} \right) \tag{1}$$

where T represents the Theil index of China's terrestrial CO_2 emissions, and y_i is the CO_2 emissions of a certain area. T can be decomposed into intragroup differences (T_w) and intergroup differences (T_b). Divide all samples of n into K groups, each group is g_k (k = 1, 2, …, K), n_k is the sample number of g_k in group k, and y_k is the CO_2 emissions of group k.

2) Further subdivide the territorial functional zone

Based on previous research results, GDP and the proportion of secondary industries (secondary industries are the main source of energy-CO_2 emissions) were selected as classification indicators (Ramaswami *et al.*, 2017; Shan *et al.*, 2018), using the K-means clustering method to further subdivide UZ and ESZ. See Table S3 for specific classification of statistical information.

3) Functional combination diversity characterization

Based on the land diversity index, the richness and complexity of the functional zones in provincial units were described, and the functional combination degree of provincial units was described as follows:

$$H = -\sum_{K=1}^{n} Mk \ln\left(Mk\right) \tag{2}$$

where Mk is the proportion of the k zone area to the total, and n is the type of functional zone.

4) Core-periphery structure measure

According to *Outline of the 14th Five-Year Plan* (*2021–2025*) *for National Economic and Social Development* and *Vision 2035 of the People's Republic of China*, 20 national urban agglomerations were established: Beijing-Tianjin-Hebei urban agglomeration, Yangtze River Delta urban agglomeration, the Pearl River Delta urban agglomeration, Chengyu urban agglomeration, an urban agglomeration in the middle reaches of the Yangtze River, Shandong Peninsula urban agglomeration, coasts of Guangdong urban agglomeration, Fujian and Zhejiang urban agglomeration, Zhongyuan urban agglomeration, Guanzhong Plain urban agglomeration, Beibu Gulf urban agglomeration, Harbin-Changchun urban agglomeration, central-southern Liaoning urban agglomeration, central Shanxi province urban agglomeration, central Guizhou urban agglomeration, central Yunnan urban agglomeration, Hohhot-Baotou-Ordos-Yulin urban agglomeration, Lanzhou-Xining urban agglomeration, Ningxia urban agglomeration along the Yellow River, and an urban agglomeration on the north slope of Tianshan Mountains. The urbanization strategy proposed in the 20-city cluster plan is highly consistent with that in the major functional zone plan. The population weighted centres of the 20 urbanized areas were extracted as the cores of the core-periphery structure. A core-based multibuffer analysis was used to generate a 50 km equally spaced buffer zone from the core. The base map of the major functional zones was superimposed on the buffer zone; the CO_2 emissions, population size and gross economic output value of various functional zones in different buffer zones were calculated; and the carbon emission intensity was determined.

5) Type division

The UZ, FSZ, and ESZ were ranked in descending order, and the proportion of their accumulated area in 60% of the corresponding functional zones in China was taken as the threshold value (Fan *et al.*, 2019). The thresholds of the UZ, FSZ, and ESZ were 21.62%, 28.14% and 65.42%, respectively. That is, if the area of the corresponding functional area in a province exceeds the threshold, it was considered the dominant functional zone. Using the provincial area threshold as a basis, combined with national and provincial spatial planning and urban agglomeration planning expert experience, a comprehensive analysis of the structures of the functional zones was conducted, and provincial units were divided into several types (Tables S3 and S4). In a province, urbanization function is superior to food security function, ecological function is superior to food security function, as area proportion of the two function zones was similar.

4 Results

4.1 CO_2 emission characteristics of territorial functional zones

The structure of total CO_2 emissions was stable across different territorial functions. From 2000 to 2017, the proportion of CO_2 emissions in the UZ, FSZ, and ESZ was around 5:2:1. The proportion of UZ decreased slightly from 65.56% to 63.14% during the period, while the proportion of CO_2 emissions from FSZ and ESZ increased, fluctuating from 22.77% to 23.41% in FSZ and from 11.67% to 13.45% in ESZ (Figure 2j).

The relationship between per capita CO_2 emissions and CO_2 intensity remained stable among the three functional zones. The CO_2 intensity in all three functional zones decreased steadily, and CO_2 emission intensity value could be ranked: UZ<FSZ<ESZ, the CO_2 intensity in the UZ were significantly lower than in the ESZ and FSZ (Figure 2k). The descending order according to value of CO_2 emissions per capita was: UZ > ESZ > FSZ, and the CO_2 emissions per capita in the UZ was significantly higher than those in the FSZ and ESZ (Figure 2l).

The spatial distribution pattern of CO_2 emissions was high coupled with that of territorial function from 2000 to 2017. Being a major source of CO_2 emissions, the UZ accounted for approximately 64% of the total CO_2 emissions in China in this period. Approximately 75% of the top one fourth of CO_2-emitting districts and counties were located in the UZ. Nevertheless, the FSZ and ESZ also accounted for large amounts of CO_2 emissions, approximately 23% and 13%, respectively. Among the greenest one fourth of districts and counties, approximately 70% were located in the ESZ (Figure S1 and Table S1).

4.2 Effect of the vertical upscaling of territorial function combinations on CO_2 emission patterns

The basic territorial function units correspond to county-level administrative regions. By vertically combining two levels of territorial function, this study examined the effects of territorial functions of different spatial scales on CO_2 emissions. Based on territorial function consistency within regions and inter-territorial functional differences, multiple county units were combined into 75 comprehensive functional sub-regions and 30 comprehensive functional regions through spatial clustering (see the method and Table S3 for details). The comprehensive functional sub-regions became spatial units between county-provincial level in spatial scale. The comprehensive functional regions were the same as the provincial administrative regions in China (excluding Hong Kong, Macao and Taiwan). The comprehensive function sub-types were divided into 7 types: UZ, UZ-FSZ, UZ-ESZ, FSZ,

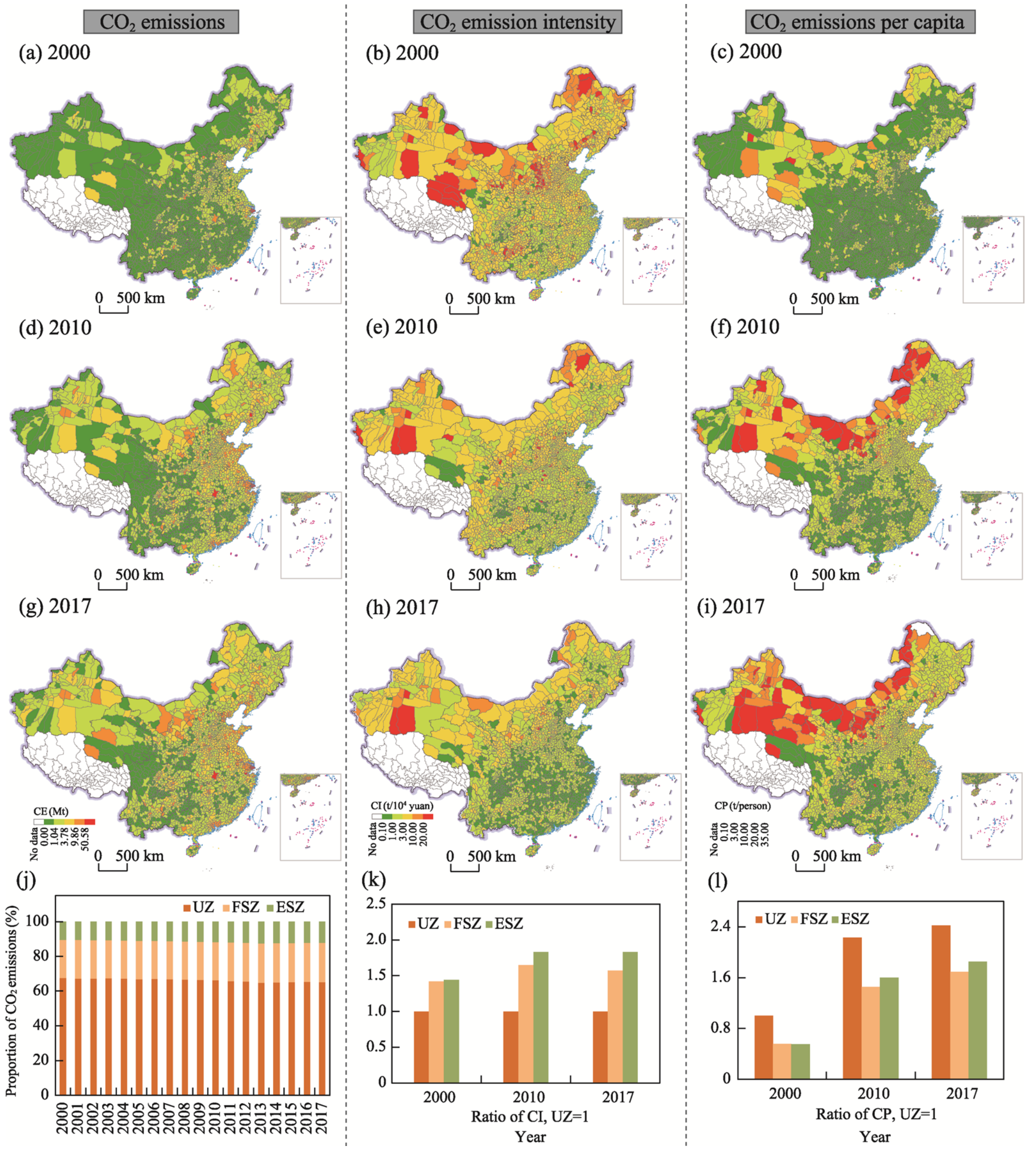

Figure 2 Changes in CO$_2$ emissions, CO$_2$ intensity, and CO$_2$ emissions per capita in the UZ, FSZ, and ESZ in 2000, 2010, and 2017. CE is CO$_2$ emissions, CI is CO$_2$ intensity, and CP is CO$_2$ emissions per capita.

FSZ-ESZ, ESZ, and UZ-FSZ-ESZ (Figure S2 and Table S3). The comprehensive functional regions (provincial units) were divided into four types: UZ, UZ-FSZ, UZ-ESZ, and UZ-FSZ-ESZ, base on the proportion of their functional zones (represented by area), population size, land area, and economic development level (Table S4).

As the spatial scale increased, large-scale regional units featured more complex territorial functions and greater internal differences in CO$_2$ emissions. The theil index was used to measure the inter-group and intra-group differences in CO$_2$ emissions. The results in Table 1 show that the intra-group differences gradually increased. Whereas the inter-group differences continuously decreased, and the intra-group differences in CO$_2$ emissions of units from the first and second combinations were larger than the inter-group differences. Therefore, it can be concluded that as the spatial scale increased, more territorial functions were involved, the degree of disturbance to the CO_2 emission characteristics of territorial functions increased, and the difficulty in uncovering the CO_2 emission characteristics of territorial functions also increased.

Table 1 Differences in CO_2 emissions of functional zones in 2000, 2010, and 2017

Spatial scale	Year	Intra-group difference	Inter-group difference
Basic territorial function units	2000	0.311	0.365
	2010	0.269	0.344
	2017	0.241	0.301
Comprehensive functional sub-regions	2000	0.437	0.239
	2010	0.377	0.239
	2017	0.346	0.198
Comprehensive functional regions	2000	0.431	0.245
	2010	0.386	0.230
	2017	0.386	0.159

Note: Basic territorial functions are classified as UZ, FSZ, and ESZ.

Despite the combination increase along with spatial upscaling, CO_2 emission characteristics of dominant units were found to greatly depend on the territorial function. However, the CO_2 emission characteristics became non-obvious for units with complex territorial function combinations. After the second combination, the CO_2 intensity values of units dominated by single territorial functions were closer to the average CO_2 intensity values of corresponding functional zones. For instance, this was observed for Shanghai, Tianjin, Jiangsu, and Zhejiang, which are dominated by UZ, and for Hainan and Jilin, where the FSZ is the dominant functional zone. In Heilongjiang, Gansu, and Qinghai, where ESZ are dominant, the CO_2 intensity and CO_2 emissions per capita of the ESZ were high. In addition, when county-level units were combined with provincial-level units, the characteristics of higher CO_2 intensity and CO_2 emissions per capita continued to accumulate, which significantly exceeded the corresponding average values for ESZ (Figure 3). For multi-functional provincial-level units that featured complex territorial function combinations, their CO_2 emission statistics were between those of the UZ and ESZ and their CO_2 emission characteristics were non-obvious. It is worth noting that industrial structure affects provincial CO_2 intensity and per capita CO_2 emissions. For example, in important energy bases such as Inner Mongolia and Xinjiang, as well as important industrial bases such as Hebei and Shanxi, the proportion of industry, especially heavy industry, in the economic structure is relatively high (the proportion of heavy industry in the industrial structure of the four provinces is more than 70%). Its CO_2 intensity and per capita CO_2 emissions are much higher than the CO_2 emission value of corresponding major functions.

4.3 Effect of the horizontal spatial distribution of territorial functions on CO_2 emission patterns

We next evaluated the effect of the spatial structure of territorial function on the CO_2 emission

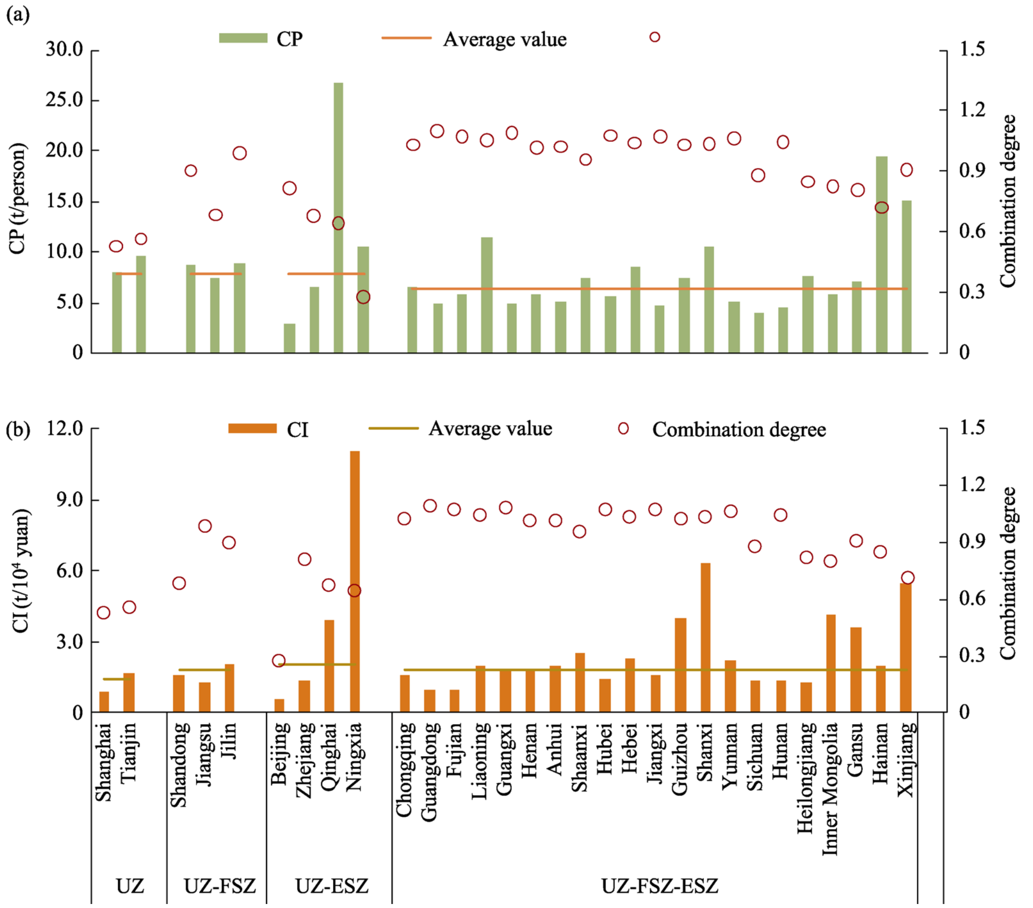

Figure 3 CP (a) and CI (b) of the second combination units. Territorial function complexity, CO_2 intensity (CI), and CO_2 emissions per capita (CP) of different types of provincial-level units in 2017; average values refer to the average CO_2 intensity and CO_2 emissions per capita of the nationwide UZ, FSZ, and ESZ.

pattern to unveil the effect of the horizontal spatial dimension. The spatial structure of territorial function refers to the spatial distribution patterns of the UZ, FSZ, and ESZ. The spatial distribution patterns of the UZ, FSZ, and ESZ are characterised by concentric circle-shaped spatial differentiation from the outer circle to the core (UZ population-weighted centroid); that is, the proportion of UZ gradually decreases from the core to the outer circle, while the proportions of FSZ and ESZ gradually increase (Wang and Fan, 2020) (Figure S4). In addition to territorial functions, their spatial structures (from the core to the outer circle) were also found to affect the CO_2 emission pattern. Generally, the amount of CO_2 emissions decreased as the distance to the core increased, and the CO_2 emission intensity increased as the distance to the core increased, demonstrating the spatial characteristics of regional CO_2 emissions (Figure S5).

The horizontal spatial structures of China's provincial administrative units were classified into three types: a) UZ–FSZ –ESZ (with Guangdong province as an example). Guangdong is a densely populated, highly urbanised region with a buoyant economy. The UZ accounts for a large part of the province, which represents the territorial functional structure of UZ–FSZ–ESZ that is mainly found in economically advanced regions. As shown in Figure 2, the CO_2 emissions in Guangdong first increase and then decrease from the central UZ to UZ–FSZ fringes. With the common centre as the core, the CO_2 emissions in Guangdong form a parabola with the vertex on the left. CO_2 emissions obviously increase from the core to the urban periphery, and a CO_2 emission peak is formed between 0 km and 150 km from the core, which then drops sharply beyond 150 km and remains stable. The CO_2 emission intensity shows the opposite tendency. It increases sharply at 150 km and remains stable (Figure 4a); b) UZ–FSZ (with Jilin province as an example). The FSZ is widely distributed in Jilin province. Owing to the modern industrial layout of China, a UZ with Changchun as the centre has taken shape, with a typical spatial structure of the UZ–FSZ territorial function. With the common centre as the core, the CO_2 emission curve is divided into two sections. The CO_2 emission peaks within the range of 0–150 km from the core and then falls rapidly, but the rate of decrease is lower than that in the UZ–FSZ–ESZ structure. The CO_2 intensity curve is also a two-section curve but shows the opposite trend (Figure 4b); c) UZ–ESZ (with Qinghai province as an example). Qinghai province is a major component of China's ecological security pattern. The ESZ is concentrated and continuous in this region. The development of mineral resources and easily accessible locations of some basins and valleys have accelerated urbanisation and industrialisation in this province. Figure 3c shows a spatial pattern featured by a vast ESZ and a separated UZ, which is a typical UZ–ESZ structure. The CO_2 emission curve shows the shape of a negative power function. CO_2 emissions dramatically decrease within the range of 0–150 km and are maintained at a low level at 200 km and beyond. In contrast, the CO_2 intensity shows fluctuations with no obvious patterns (Figure 4c).

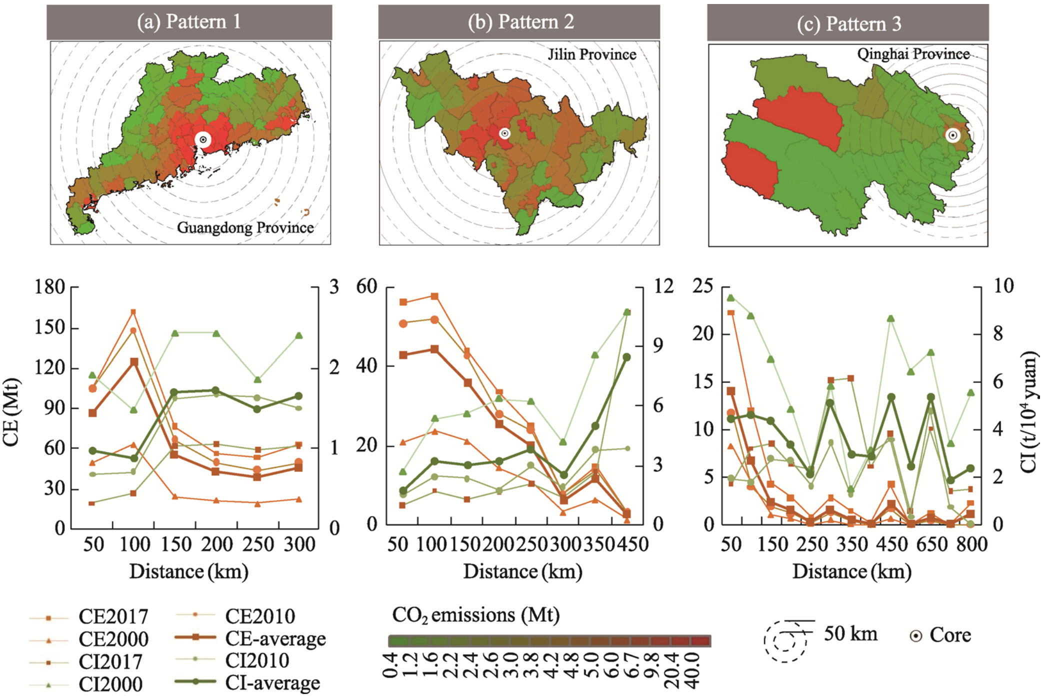

Figure 4 Changes in CO_2 emissions and CO_2 intensity based on the distance to the core. Four spatial structures of territorial function: UZ–UZ–FSZ/ESZ (a), UZ–FSZ (b), UZ–ESZ (c), and UZ–FSZ–ESZ (d). CE stands for CO_2 emissions, and CI stands for CO_2 intensity.

The abovementioned features reflect the spatial spillover effects of CO_2 emissions in UZ. As UZ are subject to restraints on CO_2 emissions, high-emitting companies move to neighbouring FSZ and ESZ to reduce their costs, causing CO_2 leakage (Song *et al*., 2020; Zhou *et al*., 2021). As a result, CO_2 emissions are generally high in FSZ and ESZ, which are adjacent to UZ. The GDP of ESZ was less than half of that of FSZ, indicating a weaker economic base than the former. Therefore, the spatial spillover effect of CO_2 emissions in the UZ was observed over a longer distance and showed a wider range of variation in the ESZ than in the FSZ. Within the range of 200 km from the core, the ESZ CO_2 emissions showed 1.13–2.12 times magnification, whereas the FSZ CO_2 emissions showed 1.06–1.12 times magnification within the range of 100 km from the core (Figure S6 and Table S2).

4.4 The drivers variation of three territorial function zones

4.4.1 Dominant factors influencing CO_2 emissions of the three territorial functions

The UZ, FSZ, and ESZ were found to differ not only in terms of total CO_2 emissions and CO_2 intensity but also in terms of the factors influencing CO_2 emissions. The level and direction of influence that socio-economic factors had on CO_2 emissions also changed in line with the territorial function. To minimise the influence of regional differences, Beijing, Xingtai-Hengshui, and Xilingol league in northern China, which have nearly consistent development backgrounds, were selected as case zones to analyse the dominant factors influencing CO_2 emissions from 2010 to 2020 (Figure S7). The results showed that the CO_2 emissions in UZ, especially in prosperous and highly urbanised zones, were mainly driven by population growth and economic development. Population size and GDP per capita were among the most significant contributors to CO_2 emissions, with the former wielding a slightly greater effect on CO_2 emissions than the latter. The proportion of secondary and tertiary industries is also an important factor driving CO_2 emissions. Energy intensity is the most important CO_2 emission-reducing factor, whereas the amount of utilised foreign investment plays a limited role in reducing CO_2 emissions. In the FSZ, energy intensity, GDP per capita, population size, and the amount of utilised foreign investment contribute to the growth of CO_2 emissions. In the urbanisation process, the industrial structure improves and the population increases, which improve the level of industrial production and housing intensification and effectively inhibit the growth of CO_2 emissions. In the ESZ, with an energy structure dominated by coal power and an industrial structure with manufacturing as the pillar industry, Xilingol league has an economic growth mode featuring high energy intensity and high CO_2 emissions. The population size, energy intensity, GDP per capita, urbanisation rate, and proportion of secondary and tertiary industries were found to be the main factors driving the increase in CO_2 emissions in this region. In the extensive urbanisation mode, the scale effect was the major factor driving the increase in CO_2 emissions (Table 2).

4.4.2 Mechanism underlying the effects of territorial functions on CO_2 emission patterns

The population and industrial scale, as well as the structure, vary across the UZ, FSZ, and ESZ. As a result, CO_2 emissions show inter-zone differences. Since the UZ, FSZ, and ESZ play different roles in spatial land development and protection, the industrial structure and demographic distribution in these zones also vary. The UZ is a major zone for population growth and economic activities in China. Secondary and tertiary industries account for a

Table 2 Results of the panel data regression model

	UZ			FSZ			ESZ		
	Coef.	St. err	t	Coef.	St. err	t	Coef.	St. err	t
ln$P$	1.255***	0.33	3.81	0.821***	0.267	3.08	1.185***	0.072	16.53
lnUR	0.167*	1.244	1.73	–0.634***	0.145	–4.36	0.608***	0.120	5.08
ln$A$	0.781***	0.098	7.96	0.930***	0.074	12.54	0.768***	0.085	9.06
ln$S2$	0.315**	0.138	2.28	0.011	0.040	–0.27	0.301**	0.187	1.98
ln$S3$	0.303*	0.227	1.34	–0.056	0.035	–1.62	0.220*	0.156	1.71
lnEI	–1.358***	0.122	–11.15	0.938***	0.019	48.59	0.861***	0.020	42.01
lnFDI	–0.024	0.015	–0.55	0.009**	0.004	2.01	–0.002	0.031	–0.55
R^2	0.679			0.936			0.988		

Note: *, **, *** denote significant levels at 10%, 5%, and 1%, respectively.

large part of the economic activities in this zone, resulting in a large amount of energy consumption and anthropogenic CO_2 emissions. This result is consistent with the research findings of other scholars (Ribeiro *et al.*, 2019; Wang *et al.*, 2020b). In 2017, the permanent population, GDP, and CO_2 emissions of the UZ accounted for 55.29%, 74.33%, and 63.14% of the corresponding totals across all zones of China, respectively (Table S5). CO_2 intensity in the UZ is low as energy efficiency has increased sharply due to mass production across industrial sectors. In contrast, as residents enjoy high living standards, this contributes to an increase in energy consumption and CO_2 emissions, resulting in higher CO_2 emissions per capita than those in the FSZ and ESZ. The FSZ is a national land space whose main function is supplying agricultural products and ensuring food security in China. Although this zone is also urbanised to some extent, its population size is usually smaller and economic development is lower than those in the UZ. In 2017, the resident population, GDP, and CO_2 emissions of the FSZ accounted for 29.32%, 17.14%, and 23.41% of the corresponding national totals, respectively (Table S5). The ESZ is the main ecological security space in China, and its main function is to protect the ecosystem and provide ecological products. Large-scale industrialisation and urbanisation are restricted in this zone. Therefore, CO_2 emissions in the ESZ are generally low. In 2017, the resident population, GDP, and CO_2 emissions accounted for 15.39%, 8.53%, and 13.45% of the corresponding national totals, respectively (Table S5).

Agglomeration of the UZ population and economic activities has a reduced effect on emissions. The UZ is characterized by an increasing population (51.33% to 55.29% of the national total from 2000 to 2017) and rising economic output (from 72.83% to 74.33% of the national total). During the same period, CO_2 emissions decreased steadily from 65.56% to 63.14% of the national total (Table S5). The proportion of CO_2 emissions from the UZ to the national total did not increase year-on-year in line with the economic output, remaining more stable than that in the ESZ and FSZ. Before China became a middle-income country, its economic development depended mainly on energy investment and high-polluting enterprises with high energy intensity (Zheng et al., 2020). The industrial clusters in the UZ help to facilitate technological innovation, promote clean manufacturing, and increase energy efficiency (He *et al.*, 2017). The efforts to constantly improve the industrial structure and reduce structural emissions and CO_2 intensity have effectively inhibited the growth of CO_2

emissions in the UZ (Guan *et al*., 2018). Furthermore, the UZ boasts a more reasonable functional zoning and more efficient use of buildings than the other zones (Ouyang *et al*., 2008). Electricity, heat, water, and other essential resources in the UZ are serviced by central supply systems to maximise the use of public facilities and share emission reduction facilities, which has contributed to efficient energy utilisation (Li and Haneklaus, 2022).

The FSZ, on the other hand, has become a shelter for polluting enterprises. Since China launched an initiative to develop low-CO_2 cities in 2010, it has tightened its CO_2 emission control policies, which has increased the costs of environmental governance and pollutant emission control for enterprises. To maximise their profits, high-polluting enterprises have begun to move out of the UZ. However, moving enterprises to ESZ has been difficult due to restrictive policies. In contrast, the environmental policies in FSZ are more lenient than those in the UZ and ESZ, which has led many high-polluting enterprises in UZ to move their operations to FSZ. Considering consumption preferences and the minimisation of transportation costs, polluting enterprises in UZ, such as Xingtai and Hengshui, tend to move to neighbouring areas (Zhou *et al*., 2021). The Beijing–Tianjin–Tangshan region is an important industrial base in China. However, energy-intensive industries have moved out of this region due to the tightening of environmental policies and the restructuring of industrial structures in large cities in recent years. Under the guidance of China's strategies for the development of large-scale regions, such as the efforts to move 'non-capital functions' out of Beijing, a large number of enterprises have moved out of Beijing into the neighbouring FSZ.

Some ESZ feature high CO_2 emissions due to their resource and energy endowment. Most China's energy and mineral resources are distributed in ESZ. For example, the ESZ in Inner Mongolia accounts for more than 70% of the total land area in the region. In 2017, Inner Mongolia ranked first among Chinese provinces in terms of coal output, accounting for more than one fourth of the total coal output in China (NBO, 2019). The energy development-related industries relying on the resource endowment of ESZ are highly energy-intensive (Liu *et al*., 2019). However, economic development and energy utilisation technology in ESZ tend to lag behind those in UZ. Therefore, high CO_2 emissions from these high-CO_2 industries lead to high CO_2 emissions per capita and CO_2 intensity in ESZ.

5 Discussion

5.1 Spatial dependence of CO_2 emissions

The spatial dependence of CO_2 emissions can be explained as follows: CO_2 emissions comprehensively reflect regional manufacturing and human activities, and their evolution has distinct regional characteristics. If the space in which each human activity occurs can be identified, it would be possible to uncover the spatial pattern of CO_2 emissions based on these activities. However, it is difficult to identify the spatial locations of CO_2 emission sources based on each human activity due to the high cost associated with this approach and the unavailability of required technology. Therefore, research on CO_2 emissions is generally carried out via two approaches: CO_2 emissions are (1) analysed according to industrial sectors, such as transportation, manufacturing, and construction, and (2) spatially identified according to the UZ, FSZ, and ESZ (Figure 5).

Different governments worldwide have adopted spatial planning as an important tool for environment management. It would be the main policy impetus to implement a top-down emissions control strategy and allocation quota to achieve the climate mitigation goals in China. In the future, spatial planning will be an important entry point for the long-term prediction of CO_2 emissions. Existing CO_2 emission prediction models that adopt the economic scale, industrial structure, population growth, and other socio-economic indicators as key parameters feature a sector planning period (Steckel *et al.*, 2020; Xu *et al.*, 2020; Bruckner *et al.*, 2022). In contrast, the integrated path developed in this study for spatial CO_2 emission prediction features a planning period for territorial function control, enabling prediction of the spatial pattern of CO_2 emissions. This approach is a potential complement to the widely used prediction method that is based on industrial structures and sectors.

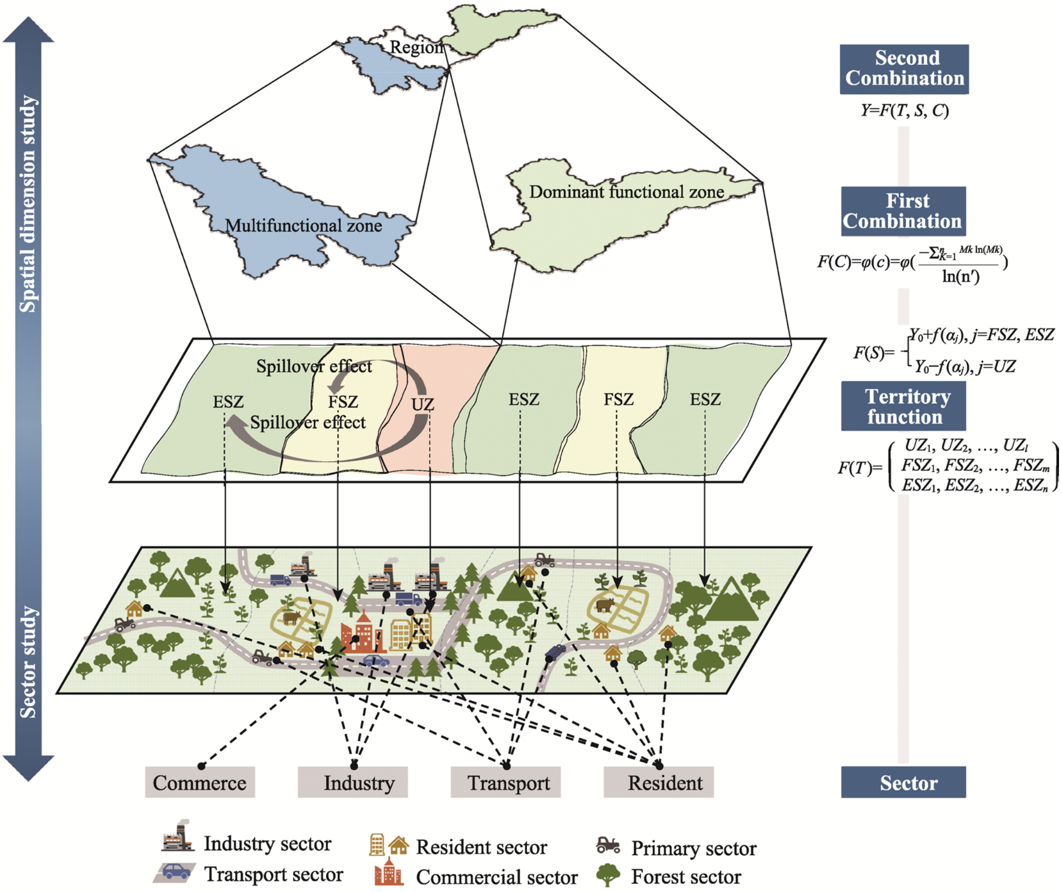

Figure 5 Diagram of sector study and spatial dimension study on CO_2 emissions

5.2 Spatial dimension-based integrated analysis of CO_2 emission patterns

Evaluation of the effect of the spatial dimension on CO_2 emission patterns according to territorial functions is complex and challenging. As mentioned before, this is because the dominant factors and mechanisms of influence differ spatially across functional zones. Furthermore, the horizontal spatial structure, the vertical function combinations, and the additional effects of UZ and FSZ all add to the complexity of the evaluation. Therefore, developing an integrated path for future spatial CO_2 emission prediction has become an important research topic. Based on the results of spatial dimension-based analysis, this study developed an integrated approach for the long-term spatial prediction of CO_2 emissions (Figure 5).

Based on the foregoing analysis of the effects of territorial function types, horizontal spatial structure, and vertical function combinations on CO_2 emissions, a spatial model for CO_2 emission prediction was developed. The formula is provided below:

$$Y = F\left(T,S,C\right) \tag{3}$$

$$F(T)=\begin{pmatrix} UZ_1,UZ_2,\ldots,UZ_l \\ FSZ_1,FSZ_2,\ldots,FSZ_m \\ ESZ_1,ESZ_2,\ldots,ESZ_n \end{pmatrix} = f\left(q\right) \qquad (l,\, m,\, n \geqslant 0) \tag{4}$$

$$q = 1 - \frac{\sum_{s=1}^{L} N_s \sigma'^2}{N\sigma^2} \qquad q \in \left(0,1\right) \tag{5}$$

$$F = \frac{N-L}{L-1}\frac{q}{1-q} \sim F\left(L-1, N-L, \lambda\right) \tag{6}$$

$$\lambda = \frac{1}{\sigma^2}\left[\sum_{s=1}^{L}\overline{Ys}^2 - \frac{1}{N}\left(\sum_{s=1}^{L}\sqrt{Ns}\,\overline{Ys}\right)^2\right] \tag{7}$$

where the amount of CO_2 emissions by a regional unit Y is the function of territorial function type T, horizontal spatial structure S, and vertical function combination C. The territorial function type T is UZ, FSZ, or ESZ, and their corresponding numbers of units are l, m, and n. CO_2 emission Y varies with the territorial function. q represents the efficiency with which a territorial function type can account for the CO_2 emissions, and it has a noncentral F-distribution after a simple transformation; $s = 1, \ldots, L$ represents the basic unit zone in the region; Ns and N represent the number of units in zone s and the whole region, respectively; and σ'^2 and σ^2 are the variances of CO_2 emissions in zone s and the whole region, respectively. λ is a non-centrality parameter, and $\overline{Ys}$ is the average value of CO_2 emissions in zone s.

The function of the horizontal spatial structure S and vertical function combination C may be expressed according to the following formula:

$$F\left(S\right) = \begin{cases} Y_0 + f\left(\alpha_j\right), j = FSZ,\ ESZ \\ Y_0 - f\left(\alpha_j\right), j = UZ \end{cases} \tag{8}$$

$$I = \frac{\sum_l \sum_j \omega_{lj}\left(Y_l - \bar{Y}\right)\left(Y_j - \bar{Y}\right)}{\sum_l \left(Y_l - \bar{Y}\right)^2} \qquad I \in \left(0,1\right) \tag{9}$$

$$F\left(C\right) = \varphi\left(c\right) = \varphi\left(\frac{-\sum_{K=1}^{n} Mk \ln\left(Mk\right)}{\ln\left(n'\right)}\right) \qquad c \leqslant 1, \text{ when } c \to 1, F\left(C\right) \to \bar{U}, \bar{E}, \bar{F} \tag{10}$$

where $F(S)$ is the amount of CO_2 emissions influenced by the horizontal spatial structure S;

Y_0 stands for the initial emissions in the UZ, FSZ, and ESZ; and α_i stands for the parameters corresponding to different spatial structure patterns of CO_2 emissions (i.e., UZ–FSZ–ESZ, UZ–FSZ, UZ–ESZ, and UZ–FSZ–ESZ). I represents the correlation between CO_2 emissions and the UZ, FSZ, and ESZ; ω_{lj} stands for the spatial connectivity matrix; and Y stands for the average value of CO_2 emissions in a regional unit. $F(C)$ stands for the amount of CO_2 emissions influenced by the vertical function combination C; c stands for the diversity index of territorial function types; Mk stands for the proportion of the k type land area to the total area; and n' stands for the number of function types. The diversity index $c \leqslant 1$; when c is close to 1, $F(C)$ tends towards the CO_2 emission pattern of zones with a single dominant territorial function.

6 Conclusions and policy

6.1 Policy recommendations

Aiming at the goal of carbon peaking and carbon neutrality, we are committed to controlling total carbon emissions and reducing carbon intensity. Combined with regional functional positioning, the carbon emission reduction policies and measures of the three functional areas should have different focuses.

With the guidance of the Major function zone planning, further guide the population to gather in UZ, give full play to the role of urbanization in the agglomeration effect, and improve the efficiency of CO_2 emissions. FSZ should strictly comply with industrial access standards, undertake industrial transfer in UZ, and strengthen the screening of high-polluting enterprises, to avoid FSZ becoming “havens” for high-polluting enterprises. ESZ should continue to implement a strict exit mechanism for polluting enterprises, adopt policies and tax measures, move out polluting enterprises that do not meet the functional positioning, and strictly restrict the entry of polluting enterprises.

To strengthen inter-zone cooperation, FSZ and ESZ actively introduce advanced production technologies from UZ, effectively improve production efficiency and reduce energy intensity (Figure 6).

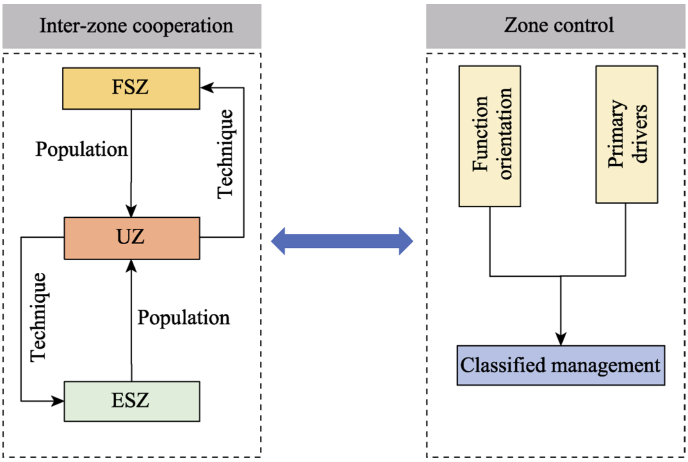

Figure 6 Diagram of CO_2 emission control measures of three functional zones

6.2 Conclusions

Spatial dimension-based study of CO_2 emissions can accurately reveal the impact of regional development on carbon emission patterns, which would be a research path alongside sectoral studies. This study developed a spatial dimension-based approach to investigate the effects of three basic functional territories, horizontal spatial structure and vertical combinations of functional territories, and typical functional territories on CO_2 emission patterns in China during 2000–2017. The results show that regional CO_2 emissions are spatial dependent due to the effects of territorial function. Firstly, the proportion of emissions from UZ, FSZ, and ESZ has been stable at approximately 5:2:1 for a long time. Meanwhile, the core-periphery spatial structure of the UZ, FSZ and ESZ led to internal fluctuations in FSZ and ESZ through the spillover effect of UZ emissions. The CO_2 emissions of FSZ and ESZ adjacent to UZ are 1.06–2.12 times higher than the average value within 200 km from the UZ, and the ESZ is more significantly affected by UZ radiation due to its weak economic foundation. However, the emission characteristics attributable to functional territories would become indistinct due to the functional combination along with upscaling.

Further analysis of influence factors indicates that highly variable of CO_2 emission patterns across territorial zones are mainly due to the distinct characteristic differentiation in industry and population among UZ, FSZ and ESZ. The CO_2 emissions in UZ were mainly driven by population size and economic development level, while energy intensity was the most important inhibiting factor. CO_2 emissions in FSZ were mainly affected by energy intensity and economic development level, while urbanization rate exhibited an inhibiting effect on CO_2 emissions. CO_2 emissions in ESZ were mainly driven by population size, energy intensity, economic development level. The county-level unit is the basic administrative unit for policy implementation in China and better captures the regional heterogeneity of emissions. Therefore, studying the impact of spatial scales on emissions based on function territory in China is scientific and feasible.

Based on the spatial analysis, this study developed an integrated approach for the spatial prediction of CO_2 emissions by taking the basic space attributes of region as an important dimension of carbon emission targets allocation. The emission prediction based on territorial functions is a supplement to the current sector prediction. By comprehensively using the prediction method of industry sectors and the territorial functions, emissions can be controlled from both spatial administrative and departmental perspectives. This approach improves control policies and measures, facilitating the implementation of carbon emission reduction goals.

This study has the following limitations. First, the structure of territorial function-based CO_2 emissions was stable from 2000 to 2017. The proportions of population and economic output in the UZ to the corresponding national totals increased steadily during the same period (Huang and Matsumoto, 2021). However, the mechanism of emission reduction resulting from population and industrial agglomeration in the UZ needs to be further investigated in future studies. Second, China's land area was spatially divided into UZ, FSZ, and ESZ in this study. Further studies are warranted to investigate whether the subdivided functions improve the accuracy of the identified spatial CO_2 emission patterns and to develop optimal methods to subdivide the functions. Finally, using territorial function-based CO_2 emission analysis, this study proposed an integrated path for the long-term prediction of regional CO_2 emissions. Further empirical research is warranted to determine the dominant factors driving CO_2 emissions in different functional zones and to investigate their use as parameters in our spatial prediction model; this will help to shed light on the potential practical applications of the proposed integrated path for CO_2 emission prediction.

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