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Spatio–temporal dynamics and human–land synergistic relationship of urban expansion in Chinese megacities

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ABSTRACT

Megacities play important roles in countries' politics, economy, culture, etc. Exploring the law of urban expansion of megacities has important reference for sustainable urbanization. Here, the spatiotemporal dynamics of urban expansion were quantified analyzed in 21 Chinese megacities from 2000 to 2020 with quantitative measurement indicators and explored the human–land synergistic relationship used the decoupling model. Results are as follows: (1) China's megacities experienced significant expansion, and urban expansion characterized as rapid initially but slowed down thereafter. (2) Urban expansion in megacities was characterized as having significant spatial differences, and rapidly expanding megacity centers moved from eastern to mid-western China. (3) Urban spatial expansion of megacities was mainly an enclave type in 2000–2010 and marginal type in 2010–2020. (4) The main type of human–land synergistic relationship in megacities were weak decoupling, there is a significant increase in expansive coupling and expansive negative decoupling in 2010–2020; (5) Lastly, human–land synergy relationship in most megacities was uncoordinated based on the per capita urban land area and decoupling type. The findings of this study can deepen the understanding of the characteristics and quality of urbanization evolution, and provides reference for high-quality development planning and decision-making in megacities.

1. Introduction

The world is increasingly becoming urbanized. The proportion of urban population in the world's total population has increased from 36.6% in 1970 to over 56% currently; this proportion is projected to increase to 68% by 2050 [1]. The mass population rush toward cities has led to continuous urban expansion and megacities emerging globally. Megacities carry a huge amount of human activity and their numbers continue to increase, which brought a multitude of complex and diverse changes to land use and land cover in urban areas, these changes will pose immense challenges and present opportunities for sustainable development.

The advantages of economic development and population agglomeration have led to the significant expansion of megacities, which has caused widespread ecological and social problems, such as traffic congestion [2], greenhouse gas emissions [3], urban heat islands

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[4,5], health diseases caused by smog [6,7], and shrinking ecological land [8,9]. Megacities, as the most developed urban form, have experienced the most intense urban expansion, huge population growth and large–scale encroachment of ecological land, causing them to face serious resource and ecological problems that pose a considerable challenge to sustainable urbanization [10]. Therefore, the premise of recognizing the evolution of megacity is quantifying the spatiotemporal dynamics of their urban expansion which is conducive to the sustainable development of human society and high–quality urbanization.

Urban expansion is an important manifestation of urbanization and a popular topic in urban research. Previous studies systematically explored the measurement and governance of urban expansion. Scholars used geoscience information technology to quantitatively analyze the spatial heterogeneity of urban expansion [9,11]. They have mainly focused on measuring urban expansion from the perspective of land use landscape morphology, and proposing a series of quantitative measurement indicators, such as urban expansion intensity [12], population–urban expansion index [13], compactness index [14] and urban sprawl index [15]. As the introduction of technical methods, such as geographic information system and computer algorithms, studies on the drivers, simulation and optimization of urban expansion have been conducted to explore the mechanism of urban expansion [16–18]. Physical expansion of urban land is an indispensable process for accommodating increasing populations and improving the average living space of urban dwellers. However, a lack of f scientific planning guidance has often led to excessive urban spatial expansion, mainly manifested as land expansion faster than population growth [19] and urban sprawl [20], thereby threatening the security of ecology, food, and biodiversity [21–23]. Evaluation the rationality of urban expansion based on the synergistic relationship of human–land or economy–land has attracted the expanding interest of urban planners and managers [24]. Megacities are the most advanced and developed cities, and play important roles in countries' politics, economy, culture. Their development model and ecological problems in the urbanization process have significance guiding and reference values for other cities [25,26]. Understanding the laws of megacity expansion is vital to achieving high–quality urban development in the increasingly urbanized world. The existing research on urban expansion of megacities mainly focused on a single megacity or several typical megacities to explore their expansion characteristics and evolution patterns, but lacks comparative research on the expansion of megacities with different levels of development over a long period of time.

Since the 1980s, China has experienced a huge rural–urban population migration, resulting in the continuous urban expansion, and the emergence of megacities with global influence, such as Shanghai, Shenzhen, and Guangzhou. According to the Notice of the State Council on Adjusting the Criteria for Urban Classification issued by the Chinese government in 2014, megacities are defined as those with a resident population of over 5 million in central urban areas [27]. Data of the seventh national census show that China has 21megacities in 2020 [28]. China's urbanization rate is more than a dozen percentage lower than those of developed countries. Therefore, China's urbanization has immense potential, and the number and scale of its megacities will continue to increase. However, due to the long-term extensive urban development model in the past, most of China's megacities have experienced disorderly expansion, which has led to issues such as farmland occupation, soaring land prices, and deteriorating living environments [29,30]. Megacities dominate the socio-economic development of Chinese cities, and the negative ecological effects of urban expansion are

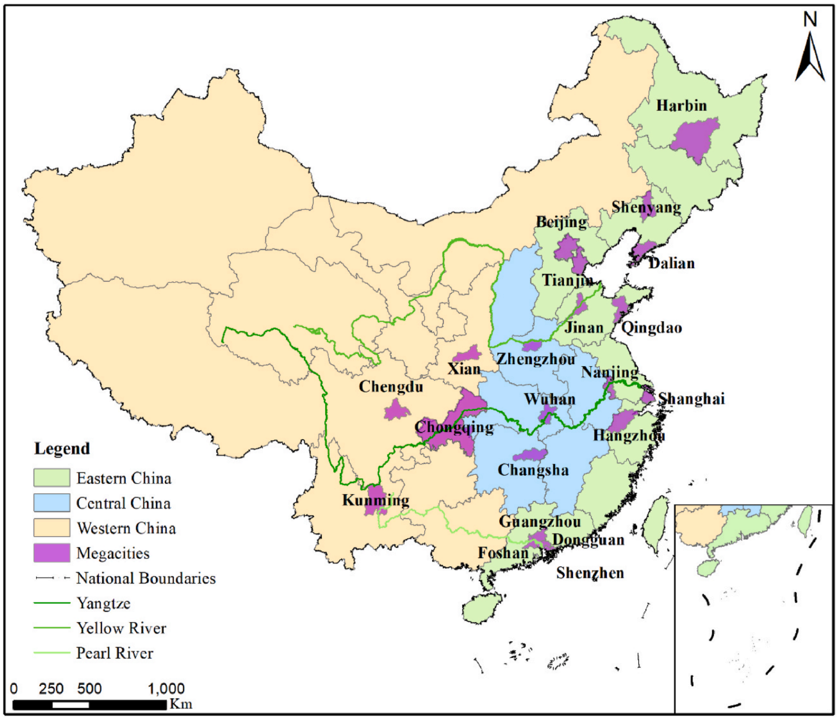

Fig. 1. Location of 21 Chinese megacities.

substantially severe. As the most populous and largest developing country in the world, China's urbanization is regarded by international observers as one of the major events affecting the world's development trends. The urban expansion of China's megacities has global representative significance and provides reference for the development of megacities in developing countries. Systematic studies on the pattern, speed, and human–land relationship of urban expansion in China's megacities in a relatively long period remain lacking. Particularly limited are quantitative studies on the similarity and difference in urban expansion among all megacities in China. Knowledge of the changes and interrelationships of urban land and population in urban expansion during urbanization will help to gain a deeper understanding of the evolution of megacities [31,32], and to formulate targeted strategies to enhance the sustainability of urbanization.

In this study, we used multi–temporal remote sensing images to map and quantify the spatiotemporal dynamics of urban expansion in 21 Chinese megacities from 2000 to 2020. Thereafter, this study analyzed the human–land synergistic relationship. The main purposes of this research are as follows: (1) quantitative analysis and mapping of the spatiotemporal dynamics of urban expansion in megacities, (2) compare and analyze the similarities or differences in urban expansion among 21 Chinese megacities, (3) discuss the types of human–land synergistic relationship in urban expansion of megacities based on the decoupling model, and (4) propose urban expansion governance measures in megacities and strategies for high–quality urban development.

2. Study area and datasets

2.1. Study area

According to the data from the 7th National Population Census of China in 2020, there are a total of 21 megacities with a permanent population of over 5 million in central urban areas in China. On the bases of geographical location and socio-economic development conditions, China is divided into Eastern, Central and Western China (Fig. 1). Of the 21 megacities, 14 are located in Eastern China (i.e., Harbin, Shenyang, Dalian, Beijing, Tianjin, Jinan, Qingdao, Nanjing, Shanghai, Hangzhou, Guangzhou, Dongguan, Foshan, Shenzhen), 3 are in Central China (i.e., Zhengzhou, Wuhan, Changsha), and 4 are in Western China (i.e., Xi'an, Chongqing, Chengdu, Kunming). Of the 21 megacities, 4 (i.e., Beijing, Shanghai, Tianjin, Chongqing) are national municipalities directly under the central government, 5 megacities are China's special economic zones or important coastal open cities (i.e., Shenzheng, Dalian, Qingdao, Foshan, Dongguan), and the remaining megacities are provincial capitals.

The 21 megacities only account for 7.5% of China's land area, but they gathered over one-fifth of the population and created nearly one-third of GDP in 2020. In 2020, the total GDP of China's mega cities exceeded 4.83 trillion US dollars, with an average of 230.2 billion US dollars; The total urban population reaches 210.43 million, with an average of 10.02 million people; There are significant differences in the urbanization of mega cities, including Shenzhen, which is close to complete urbanization, with an urbanization rate of 99.54%, and Chongqing, which is in the stage of rapid urbanization development, with an urbanization rate of only 69.46% (Table 1). These megacities have huge economic and population scales; are important political, economic, or transportation centers in China; and are core cities for national or regional development. Moreover, the megacities are the backbone of China's economic development and participants in international competition, and play leading and exemplary roles in the urbanization development of other small–medium cities.

Table 1
Social and economic development of Chinese megacities in 2020.

Megacities		GDP (Billion US dollars)	Urban Population (Million)	Urbanization (%)
Eastern China	Beijing	523.28	17.75	87.55
	Shanghai	560.93	19.87	89.30
	Guangzhou	362.63	14.88	86.19
	Shenzheng	401.05	17.44	99.54
	Tianjing	204.13	10.93	84.70
	Shenyang	95.25	7.07	84.52
	Dalian	101.89	5.21	82.35
	Haerbing	75.14	5.50	70.61
	Nanjing	214.77	7.91	86.80
	Hangzhou	233.44	8.74	83.30
	Jinan	146.98	5.88	73.46
	Qingdao	179.74	6.01	76.34
	Foshan	156.77	8.54	95.20
	Dongguan	139.87	9.56	92.15
Central China	Zhengzhou	173.99	5.34	78.40
	Wuhan	226.34	9.95	84.31
	Changsha	176.00	5.55	82.60
Western China	Chongqing	362.39	16.34	69.46
	Chengdu	256.79	13.34	78.77
	Kunming	97.60	5.34	79.67
	Xi'an	145.23	9.28	79.20
Total		4834.21	210.43	82.88

2.2. Datasets

The satellite remote sensing images of every 5 years from 2000 to 2020 we used sourced from Landsat TM/ETM+ with a spatial resolution of 30 m, and generated through manual interpretation of land use cover data by the Institute of Geography, Chinese Academy of Sciences. The land use classification system adopted divides land use into six categories: arable land, forest land, grassland, waters, construction land, and unused land, and further subdivides them into 25 subcategories [33]. The urban land defined in this study refers to industrial and mining land, residential land, and roads in urban areas. Thereafter, spatial pattern of urban expansion in megacities were mapped. Data of urban land area and urban population used were mainly extracted from the annual *China Urban Construction Statistical Yearbook* to quantify the extent of urban expansion and human–land synergistic relationship.

3. Methodology

3.1. Urban expansion measurement models

(1) Urban expansion intensity index

Urban expansion intensity index (UEI) refers to the intensity of urban land expansion in different periods of the same megacity, reflecting the expansion situation of the same megacity in different time periods [34,35]. UEI can be used to analysis the urban expansion intensity of megacities and compare the urban expansion dynamics in different periods. The specific calculation formula is as Eq. (1).

$$UEI_n = \frac{A_n^{t_2} - A_n^{t_1}}{A_n^{t_1} \times \Delta t} \tag{1}$$

where UEI_n refers to the urban expansion intensity of the nth megacity; $A_n^{t_1}$ and $A_n^{t_2}$ refer to the area of urban land of the nth megacity in time periods t_1 and t_2, respectively; Δt refer to the interval year from t_1 to t_2.

(2) Urban expansion intensity differentiation index

The urban expansion intensity differentiation index (UEDI) is the ratio of the urban land expansion change intensity of a megacity to the urban land expansion change intensity of all megacities, reflecting the differences in the urban expansion intensity of different megacities [34,35]. UEDI can be used to compare urban expansion between megacities during the same period, exclude the influence of the size of megacities. The index is calculated is as Eq. (2).

$$UEDI_n = \frac{\left|A_n^{t_2} - A_n^{t_1}\right| \times A^{t_1}}{\left|A^{t_1} - A^{t_2}\right| \times A_n^{t_1}} \tag{2}$$

where $UEDI_n$ refer to urban expansion intensity differentiation index of the nth megacity; A^{t_1} and A^{t_2} refer to the urban land area of the

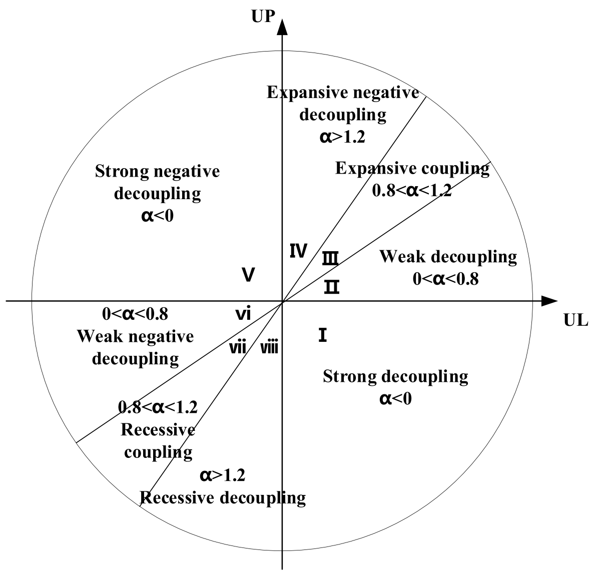

Fig. 2. Decoupling types of urban population and urban land.

all megacities in time periods t_1 and t_2.

3.2. Human–land synergistic relationship

This study explored the synergistic relationship between population and urban land use during urban expansion under a decoupling framework. To determine the decoupling state, we constructed a decoupling formula for population and urban land based on the Tapio's model [36]. The specific calculation formula is as Eq. (3).

$$\beta = \frac{(UP_{t2} - UP_{t1}) \times UL_{t1}}{(UL_{t2} - UL_{t1}) \times UP_{t1}} \tag{3}$$

where β refer to the decoupling elasticity value of population and urban land; UP_{t2} and UP_{t1} refer to the urban population at the beginning and end of a time period, respectively; UL_{t2} and UL_{t1} refer to the urban land area at the beginning and end of a time period, respectively.

The classification of decoupling types is determined by the decoupling elasticity calculated by formula 3. The three forms of human–land synergistic relationship are coupling, decoupling and negative decoupling [36]. To avoid overinterpreting small changes as significant, a ±20% change in elasticity value approximately 1.0 is still considered coupled. Thus, the coupling is defined as the elastic coefficient value in the interval 0.8–1.2. Moreover, coupling is further divided into expansive or recessive coupling based on the positive or negative growth of variables. As shown in Fig. 2, decoupling can be divided into eight types with different meanings. For example, strong decoupling means negative changes in urban land indicators and positive changes in urban population. Other decoupling types can have similar interpretations.

4. Result

4.1. Spatio–temporal dynamics of urban expansion

4.1.1. Temporal differences in urban expansion intensity

Urban land of all megacities clearly expands, and presents an initially first fast and slow change trend thereafter (Table 2). With the continuous expansion of urban areas, the area of urban land in megacities increased significantly, but expansion intensity varied across megacities. From 2000 to 2020, UEI of all megacities was 10.96. The highest UEI was Dongguan, which was as high as 207.28, followed by Shenzhen, Nanjing, Qingdao, Zhengzhou, and Chongqing, which all exceeded 20. The lowest UEI was Shanghai with a value of 1.67, followed by Guangzhou, Tianjin, Dalian, Harbin and Changsha, which were all below 10. UEI of all megacities decreased from 13.67 in 2000–2010 to 3.49 in 2010–2020, and the speed of urban expansion slowed down significantly. In 2000–2010, 15 megacities had UEI of over 10, but only 3 in 2010–2020. Among them, Dongguan had the largest decline in EUI (i.e., from 329.43 to 2.51), and that of Shenzhen also decreased (i.e., from 51.28 to 1.67). This result indicates that after the two megacities experienced large–scale urban

Table 2
The urban expansion intensity index in Chinese megacities.

Megacities		Urban expansion intensity Index		
		2000–2020	2000–2010	2010–2020
Eastern China	Beijing	10.01	18.28	0.62
	Shanghai	1.67	2.55	0.64
	Guangzhou	4.36	7.06	0.98
	Shenzheng	30.76	51.28	1.67
	Tianjing	8.48	7.80	5.15
	Shenyang	10.52	9.86	5.63
	Dalian	5.28	8.92	0.86
	Haerbing	8.22	11.43	2.34
	Nanjing	21.08	30.15	2.99
	Hangzhou	18.06	17.25	6.93
	Jinan	18.42	19.01	6.14
	Qingdao	22.34	13.57	13.20
	Foshan	15.78	35.14	−0.79
	Dongguan	207.28	329.43	2.51
Central China	Zhengzhou	22.26	17.65	9.72
	Wuhan	12.90	20.32	1.81
	Changsha	8.97	12.92	2.19
Western China	Chongqing	20.10	19.57	6.98
	Chengdu	16.89	11.26	10.59
	Kunming	10.83	18.27	1.20
	Xi'an	14.99	5.82	15.27
Total		10.96	13.67	3.49

expansion in 2000–2010, that in 2010–2020 was effectively controlled, and urban land began to develop toward intensive use.

4.1.2. Spatial differences in urban expansion intensity

The UEDI value of each megacity was calculated separately. Thereafter, the natural discontinuity method of ArcGIS 10.6 software was used to divide the urban expansion intensity in 21 megacities into three types: low, moderate, and rapid expansions (Fig. 3). Evidently, there were differences in urban land expansion between megacities, and spatial distribution was uneven. During the study period, the rapidly expanding megacities migrated from Eastern China to Central and Western China. In 1990–2010, rapid expansion megacities were all distributed in Eastern China, and moderate expansion ones were concentrated in Midwest China (Fig. 3(a)). Urban expansion speed of Dongguan, Shenzhen, Foshan and Nanjing in Eastern China was twice as high as that of all megacities. In particular, Dongguan had a maximum UEDI value of 24.1. In 2010–2020, megacities with rapid urban expansion were concentrated in Central and Western China, and megacities with moderate expansion were concentrated in Eastern China (Fig. 3(b)). The UEDI values of Xi'an, Chengdu and Zhengzhou, which are located in Central and Western China, exceeded that of all megacities by 2.5 times. UEDI values of the most developed megacities, namely, Beijing, Shanghai, Guangzhou, and Shenzhen were below 0.5. Moreover, these megacities were in the stage of ultra–low–speed urban expansion.

4.1.3. Spatial pattern of urban expansion in megacities

The spatial pattern of urban expansion in megacities showed marginal and enclave coexistence, but there were evident differences between them (Fig. 4). Megacities dominated by the marginal–type urban expansion spatial pattern were Beijing, Shanghai, Guangzhou, or Harbin, Shenyang located in the old industrial bases in Northeast China. These megacities are important national economic central or old industrial cities. Their urban development started early, urban spatial expansion was mainly carried out along the edge of t the original urban area, and urban land was relatively compact. Megacities dominated by the enclave–type urban expansion spatial pattern include Tianjin, Hangzhou, Nanjing, Jinan, Qingdao, Foshan, and Dongguan. These megacities are growing or emerging megacities, the urban expansion of which has mainly occurred in the past two decades. Their urban spatial pattern has undergone a diffusion process, and most new urban land has developed within a certain distance from old urban areas. In terms of the urban expansion stage, enclave–style urban expansion mainly occurred in 2000–2010, and marginal–type urban expansion dominated most megacities in 2010–2020. The urban expansion of most megacities has gone through a process of diffusion to agglomeration, forming a spatial pattern of urban land use from disorder to compactness.

Urban expansion of megacities was substantially affected by such factors as physical geography or traffic. Urban expansion of Nanjing, Hangzhou, and Wuhan, along the Yangtze River was clearly affected by the Yangtze River, forming a bipolar expansion pattern blocked by the Yangtze River. Urban expansion of Zhengzhou, Jinan, and Changsha, was mainly distributed in strips, primarily affected by traffic, and urban development expanded along main railway lines. Shenzhen and Dongguan are respectively important special economic zone and manufacturing base, respectively, in China; they developed from small towns into megacities. After rapid urban expansion in recent decades, land suitable for construction has been developed, and space for urban development was close to saturation.

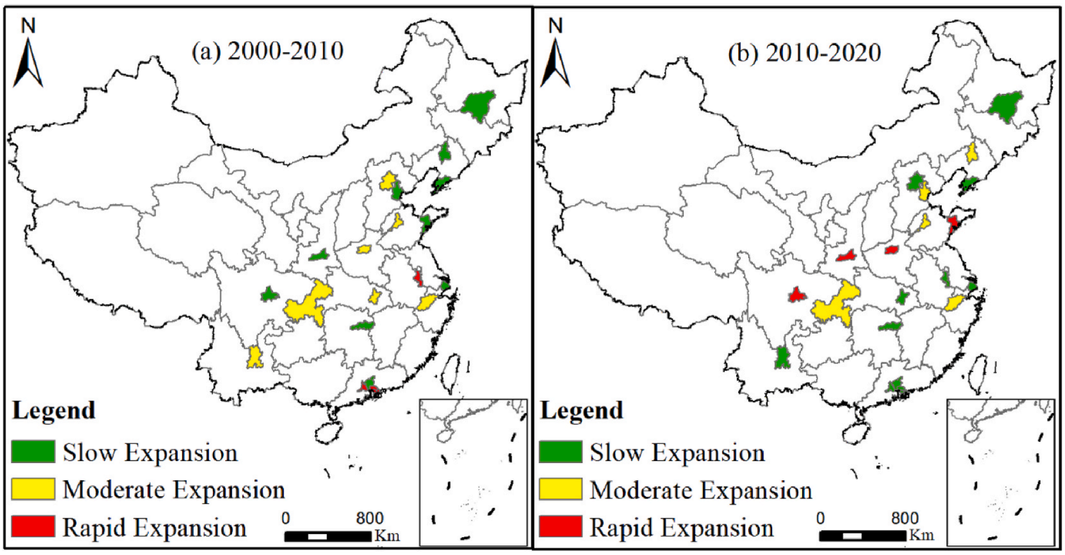

Fig. 3. Distribution of urban expansion differentiation index.

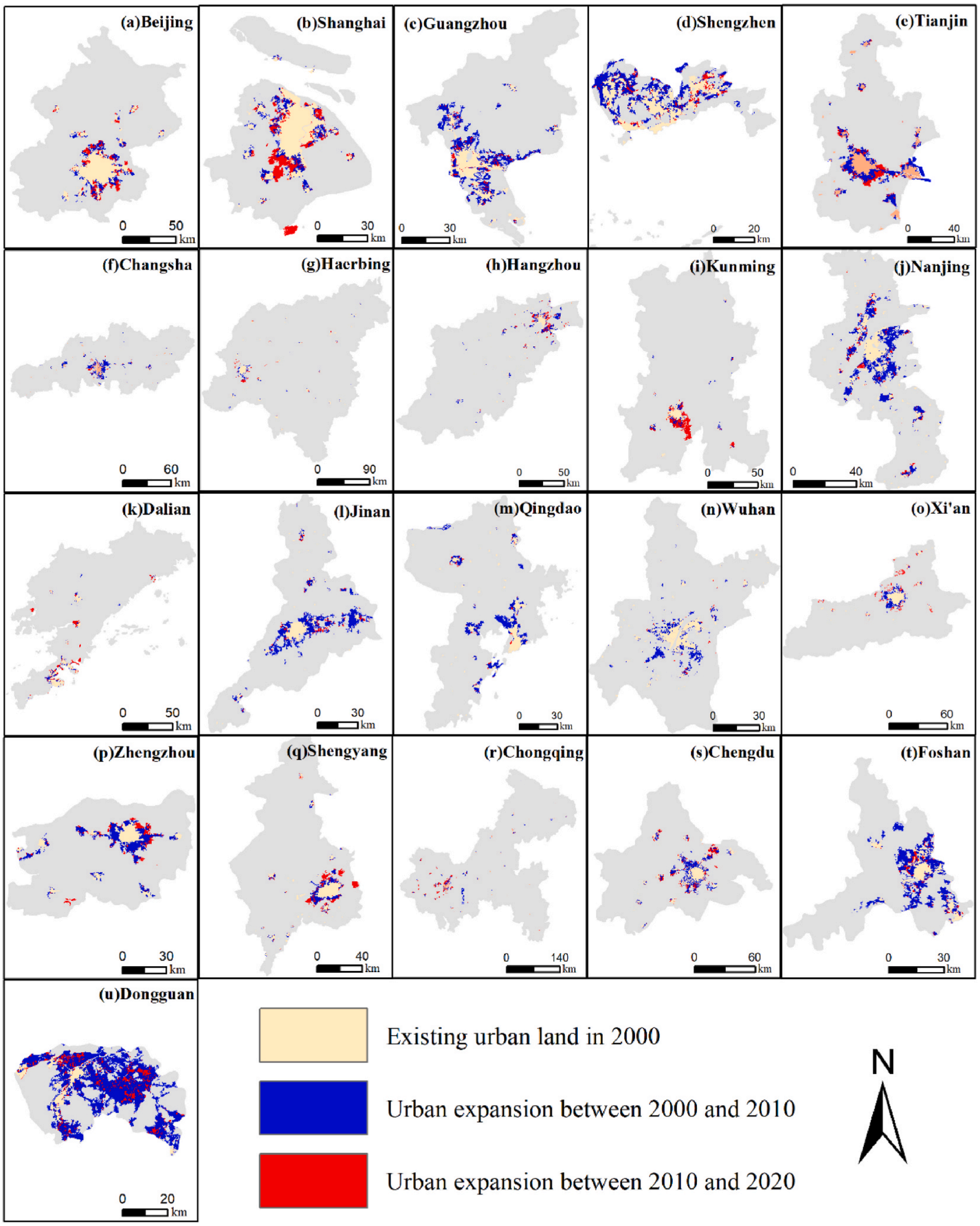

Fig. 4. Change of urban expansion in different periods of Chinese megacities.

Table 3
Decoupling between urban expansion and population growth in 2000–2020.

Types	Number	Megacities
Expansive coupling	4	Beijing. Tianjin, Changsha, Guangzhou
Weak decoupling	16	Shengyang. Dalian, Nanjing, Hangzhou, Shengzhen, Chengdu, Chongqing, Dongguan, etc.
Expansive negative decoupling	1	Shanghai

4.2. Human–land synergistic relationship of urban expansion

4.2.1. The human–land coupling relationship in urban expansion

From 2010 to 2020, urban land area of Chinese megacities increased by 2.19 times, from 5337.58 km^2 to 17,041.68 km^2. In the same period, urban population of megacities increased by 1.54 times, from 61.37 million to 156.02 million. The decoupling relationship between urban land area and population growth was weak decoupling, with a decoupling elasticity value of 0.7, indicating that urban land expansion was faster than population growth, the megacities were over–expanded, and urban land use tends to be extensive. Types of decoupling in Chinese megacities were: expansive coupling (4 of 21 units), weak decoupling (16 of 21 units), and expansive negative decoupling (1 of 21 units) (Table 3). In the study period, the urban expansion speed of most megacities exceeded population growth. Only the four megacities of Beijing, Tianjin, Changsha and Guangzhou have the same pace of urban land expansion and population growth. Shanghai was the only city with a population growth rate exceeded the urban expansion.

From 2000 to 2010 to 2010–2020, the number of megacities with expansion connection type increased from 2 to 4, the number of weak decoupling types decreased from 19 to 8, and the number of expansion negative decoupling types increased from 1 to 7 (Table 4). This result means that in the process of urban expansion in Chinese megacities, the trend of urban land expansion being faster than population growth has been significantly changed. The number of megacities with faster urban expansion than population growth has decreased from the vast majority (i.e., 19 of 21) to 8, and the number of megacities with population growth being faster than urban land expansion has increased significantly (i.e., 1 to 7). Harbin is the only megacity to be strongly decoupling in 2010–2020. With the economic recession in Northeast China, Harbin's urban population decreased by 21,400 in 2010–2020. Foshan's urban construction land area decreased by 13.22 km^2 from 2010 to 2020, and this was the only strong negative decoupling.

4.2.2. Coordination of human–land relationship in urban expansion

Population is an important indicator of human activities, and the per capita urban land area (PCULA, ratio of urban construction land area to population) is one of the core contents of urban construction land expansion research. It can not only reflect the trend of urban expansion, but also measure the flow of population in the process of socio-economic development, thereby revealing the evolution of human land-relationship in the process of urbanization, and providing theoretical guidance for coordinating regional human-land relationship and urban expansion regulation. PCULA is considered the basic indicator in measuring urban land use intensity and national urban land use guideline for promoting the "construction of a resource–efficient society" in China [37,38]. In 2020, the average PCULA in China's megacities was 105.18 m^2, with the lowest and highest being 70.99 m^2 and 152.44 m^2 in Shenzhen and Hangzhou, respectively. We define that when a megacity's PCULA exceeds the average value, its urban land use is relatively extensive; otherwise, it is relatively intensive. As shown in Fig. 5, only five megacities have PCULA below the average value (i.e., Shenzhen, Beijing, Shanghai, Changsha, Tianjin, and Guangzhou) in 2020, and their land use was relatively intensive, while the land use of other megacities was extensive.

To make the analysis of human–land relationship in urban expansion considerably targeted for land use decisions, we classified the coordination of human–land relationship into four types based on the analysis of decoupling and PCULA (Table 5).

Type I: Human–land relationship was coordinated. PCULA of these megacities was lower than the average value, urban expansion was slower than population growth, or the two were the same. Urban land use is increasingly intensive. Five megacities were of this type: Beijing, Changsha, Guangzhou, Shanghai, and Tianjin. In the future, urban expansion of these megacities should adhere to existing strategies and intensively utilize urban land.

Type II: Human–land relationship was relatively coordinated. PUCLA of these megacities was lower than the average value, urban expansion was faster than population growth, and the utilization of urban land was intensive but tends to be extensive. Shenzhen was the only megacity of this type. In the future, such megacities should appropriately control the speed of urban expansion to avoid extensive use of urban land.

Type III: Human–land relationship was relatively uncoordinated. PUCLA was between the average value and 120 m^2, urban expansion was faster than population growth, and the utilization of urban land was close to intensive but tends to be extensive. Seven megacities were of this type, including Chengdu, Chongqing, Foshan, and Harbin. In the future, these megacities should strictly limit the speed of urban land expansion below that of population growth, and reverse the trend of extensive utilization of urban land.

Type IV: Human–land relationship was uncoordinated. PUCLA exceeds 120 m^2, urban land use was highly extensive, the speed of urban expansion was faster than that of population growth, and urban land use tends to be more extensive. This type of megacity had the highest number (i.e., 8), including Zhengzhou, Wuhan, Shenyang, and Qingdao. In the future, urban development of such megacities should focus on the development of stock urban land, and strictly limit new urban construction land.

Table 4
Changes in decoupling types from 2000 to 2010 to 2010–2020.

Decoupling Types	Number	
	2000–2010	2010–2020
Expansion coupling	2	4
Weak decoupling	19	8
Expansive negative decoupling	1	7
Strong decoupling	0	1
Strong negative decoupling	0	1

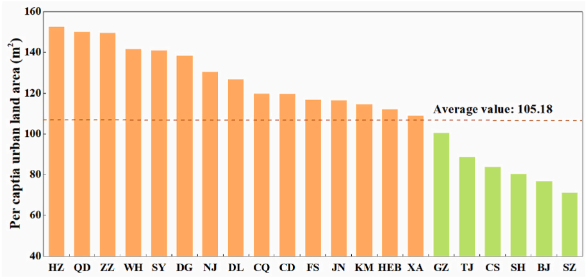

Fig. 5. Per capita urban land area of Chinese megacities in 2020.

Table 5
Coordination types of human-land relationship.

Type	Decoupling	PCULA	Number	Instruction
I	Expansion coupling Expansive negative decoupling	PCULA<105.18	5	Urban land use was intensive and tends to be more intensive
II	Weak decoupling	PCULA<105.18	1	Urban land use was intensive but tends to be extensive
III	Weak decoupling	105.18<PCULA<120	7	Urban land use was close to intensive but tends to be extensive
IV	Weak decoupling	PCULA>120	8	Urban land use was extensive and tends to be more extensive

5. Discussion

5.1. Adjustment of urban expansion regulation

Long–term excessive expansion of large cities in China has caused immense pressure on the regional environment, and widened the development gap with small–medium cities, resulting in unbalanced regional development [39]. Since 2010, the Chinese central government has implemented an urban development strategy oriented to "rationally constrain the expansion of large cities and prioritize the development of small–medium cities" to achieve balanced urban development [40]. However, existing studies have proven that the scale of urban expansion in Chinese megacities has consistently been higher than that of other cities [41,42], indicating that the original urban expansion restriction strategies for megacities have not been well implemented, and urban expansion management should be adjusted.

Our research results show that the average urban expansion intensity index of megacities in Eastern China from 2000 to 2010 was 40.12, which is much higher than the 16.96 and 13.73 of megacities in Central and Western China. However, the situation from 2010 to 2020 was the opposite, with an average urban expansion intensity index of 3.49 for megacities in Eastern China, lower than 4.57 and 8.51 for megacities in Central and Western China. The urban expansion of megacities in Eastern China has slowed down significantly after experiencing high speed in the early stage. Moreover, megacities with rapid urban expansion, such as Zhengzhou, Xi'an, Chengdu, have moved to the Central and Western China. The imbalance of urban expansion of megacities was mainly caused by the difference in urbanization. As shown in Fig. 6, urbanization rate of megacities such as Beijing, Shanghai, and Shenzhen, was approximately 90% in 2020, with the highest reaching 99.54% (i.e., Shenzhen, which was already highly urbanized). However, urbanization rates of Chongqing, Chengdu, Zhengzhou, and Xi'an were in the 70–80% range, which was substantially behind the highly urbanized megacities. Urbanization of midwestern megacities still has immense potential. With the national strategies of "Rise of Central China" and "West Development" proposed, midwestern megacities, which are the engines of regional development, will

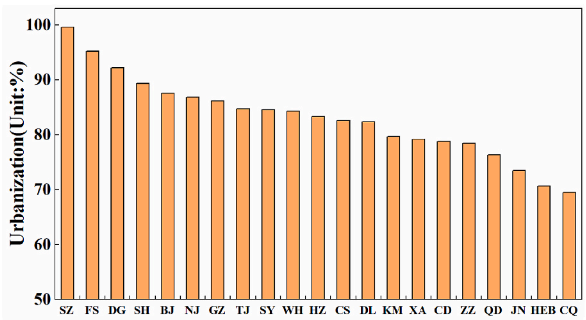

Fig. 6. The urbanization rate of Chinese megacities in 2020.

continue to rapidly develop in economically, thereby driving their urban expansion. Therefore, urban expansion management strategy of megacities in the future should be changed from comprehensive restrictions to constraints of eastern developed megacities and reasonable guidance of midwestern megacities.

5.2. Differences in the hierarchy and developmental strategies of megacities

The 21 megacities showed significant differences in terms of urban expansion intensity and coordination of human land relationships. High urbanization cities such as Shanghai and Shenzhen had lower values of urban expansion intensity index and coordinated types of human-land relationships, while cities with lower urbanization levels such as Zhengzhou and Xi'an had higher values of urban expansion intensity index and uncoordinated types of human-land relationships. The megacities can be classified into three development types (i.e., mature, growing, and emerging megacities) based on the research results and referring to the related research [30,43]. The development patterns of various types of megacities are as follows:

Mature megacities: Early urban expansion, stable urban spatial structure, highly urbanized, speed of urban expansion has slowed, and urban spatial expansion was mainly marginal and infill. Human–land synergistic relationship was coordinated. Representative megacities include Beijing, Shanghai, Shenzhen, and Guangzhou.

Growing megacities: Urban spatial structure tends to be stable, relatively highly urbanized, urban expansion was at a medium–low speed, and urban spatial expansion was mainly marginal and accompanied by enclaves. Certain contradictions exit in the human–land synergistic relationship. Representative megacities include Dongguan, Nanjing, Hangzhou, and Changsha.

Emerging megacities: Urban spatial structure has not yet stabilized, relatively low urbanization, and urban expansion was still at a rapid speed. Numerous enclaves were in urban spatial expansion. Human–land synergistic relationship was uncoordinated. Representative megacities include Zhengzhou, Xi'an, Qingdao, and Jinan.

Mature megacities are China's most developed cities with global influence [25]. Their urban spatial form was compact with highly intensive urban land use, and urban spatial expansion was stagnant, and improvement of spatial quality has become the main goal of urban development. Growing megacities are the second tier of China's urban hierarchy and have important national influence and regional driving effects [44]. Their urban spatial expansion is transforming from disorderly sprawl to intensive utilization and compact form, and are developing into world–renowned cities. Emerging megacities are an important force in the development of China's megacities [45]. Their urban spatial expansion was disordered and land use were relatively extensive. However, emerging megacities have immense development potential and are important growth poles for China's economic development. Development patterns and urban expansion of different megacities levels vary widely. Moreover, differentiated development strategies should be adopted to guide the high–quality and coordinated development of megacities.

5.3. Recommendations for future study

This study used the LUCC data and urban development statistics as bases to quantitatively and comparatively analyze the spatiotemporal characteristics and human–land synergistic relationship of urban expansion in 21 megacities. This study has made up for the lack of research on the expansion characteristics and comparison of different levels of megacities over a long period of time, and deepened the understanding of the spatial structure and evolution of Chinese megacities. However, a few limitations should be explored in future research. First, an empirical comparative analysis of urban expansion between megacities and small–medium cities should be conducted to provide targeted reference for formulating differentiated urban development strategies. Second, this study only conducted a qualitative classification of megacities, quantitative assessments should be performed in the future to deepen the understanding of the development in Chinese megacities.

6. Conclusions

This study used long–term land use vector data and urban statistics to explore the spatiotemporal dynamics and human–land synergistic relationship of urban expansion in 21 Chinese megacities during 2000–2020. We revealed the temporal evolution and spatial pattern of urban expansion in megacities, and then divided the types of human land collaborative relationships in urban expansion based on decoupling models, corresponding urban development strategies proposed. The main conclusions are as follows.

(1) In the study period, Chinese megacities experienced significant expansion, and urban expansion presented an initially first fast and slow change trend thereafter. Expansion intensity index of all megacities decreased from 13.67 in 2000–2010 to 3.49 in 2010–2020, and nearly all megacities had a marked slowdown in urban expansion.
(2) Spatial distribution of urban expansion in megacities was significantly uneven. Rapidly expanding megacity centers moved from Eastern China to Central and Western China in the study period. All megacities that expanded rapidly in 2000–2010 were located in Eastern China, while those in 2010–2020 were mainly concentrated in Central and Western China.
(3) The spatial patterns of urban expansion in megacities showed marginal and enclave coexistence. Enclave–type urban expansion mainly occurred in 2000–2010. Meanwhile, urban expansion of most megacities was dominated by marginal–type in 2010–2020. Early–developed megacities mainly experienced marginal–type expansion, and their urban spatial pattern were compact. Emerging megacities mainly experienced enclave–type expansion, and their urban spatial pattern were disordered.
(4) The type of human–land relationship in megacities was mainly weak decoupling. That is, the speed of urban expansion was faster than that of population growth. However, the trend of excessive urban land expansion in megacities had been curbed in

the study period. The number of weak decoupling megacities decreased significantly in 2010–2020 compared with 2000–2010. Meanwhile, population growth was faster than urban land expansion, and the number of megacities with negative decoupling markedly increased.

(5) Human–land synergistic relationship in most megacities was uncoordinated based on PCULA and the number of decoupling types growth. The human–land synergistic relationship in 15 megacities was uncoordinated owing to rapid urban expansion and extensive land use. The other 6 megacities were coordinated because of their intensive land use and the synergy of urban expansion and population growth.

Author contribution statement

Enxiang Cai: Conceived and designed the experiments; Performed the experiments; Wrote the paper. Shengnan Zhang: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data. Weiqiang Chen: Analyzed and interpreted the data. Ling Li: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

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Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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