Chin. Geogra. Sci. 2023 Vol. 33 No. 1 pp. 1−20
https://doi.org/10.1007/s11769-023-1325-5

Springer Science Press
www.springerlink.com/content/1002-0063

Urban Expansion in Major Grain Producing Area from 1978 to 2017: A Case Study of Zhengzhou Metropolitan Area, China

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Abstract: The spatial form of urbanization in China has developed from single-core city expansion to a multi-center metropolitan area. However, little attention has been paid to the growth process of the emerging metropolitan area situated in major grain producing locations in the central China. Taking the Zhengzhou metropolitan area (ZZMA) as a case study, we developed an inverse S-shape model to characterize the spatial distribution of urban land density, and constructed an urban expansion core index, urban expansion intensity index, and urban compactness index to quantify the spatial structure change that has taken place from 1978 to 2017 during the process of urban expansion. Moreover, cropland contribution rate (CR) was constructed to evaluate the impacts of urban expansion on croplands. We uncovered four key findings. First, over the past 40 yr, the ZZMA has experienced dramatic expansion, and the central city of Zhengzhou expanded faster than other cities. The gravity centers of urban expansion of surrounding cities were moving toward to Zhengzhou City. Second, the urban land density decreased with the distance from the city center to the outskirts. As the only large city, Zhengzhou has experienced the fastest and most compact centralized urban expansion, especially after 2000, while other medium- and small-sized cities have experienced low-intensity decentralized expansion. Third, the urban core has been gradually expanding outward. From 1978 to 2017, the hot-zone of urban growth has moved progressively with the acceleration of urbanization. All cities except Jiaozuo had a single peak in different periods. Forth, the cities in national core grain-producing areas has higher cropland contribution rates and lower urban expansion areas, which was closely related to cropland protection. Further analysis showed that large city was relatively better positioned than smaller cities in the efficiency of their urban infrastructure and the effectiveness of wealth creation efficiency in the urbanized area could be tested in all cities, and the policy factor seemed to play an important role in the urban expansion process.

Keywords: urban expansion; major grain producing area; inverse S-shape; cropland contribution rate (CR); policy factor; Zhengzhou metropolitan area (ZZMA)

Citation: YANG Yongju, ZHANG Hebing, QIAO Xuning, LIU Liang, ZHENG Jinchan, 2023. Urban Expansion in Major Grain Producing Area from 1978 to 2017: A Case Study of Zhengzhou Metropolitan Area, China. *Chinese Geographical Science*, 33(1): 1−20. https://doi.org/10.1007/s11769-023-1325-5

1 Introduction

Today, more than 55% of the world's population lives in cities, and by 2050 more than two-thirds of the world's population is projected to be urban with as much as 90% of the increase centered in Asia and Africa (United Na-

Received date: 2022-05-05; accepted date: 2022-10-19

Foundation item: Under the auspices of National Natural Science Foundation of China (No. 41971274), the Innovation Research Team of Henan Provincial University (No. 2021-CXTD-08, 2022-CXTD-02), the Scientific and Technological Innovation Team of Universities in Henan Province (No. 22IRTSTHN008)

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tions, 2019). Urbanization leads to the expansion of urban area and shifts in urban form, which change from point to zonal areas. When cities in these areas experience high levels of integration, metropolitan areas form (Fang et al., 2010; Fang and Yu, 2017). Metropolitan area has become the basic geographical and organizational units of global competition and international labor division for many rapidly developing and developed countries (Marcotullio et al., 2008; Levine, 2012).

Many literature studies have examined the spatial-temporal evolution characteristics and driving mechanism of urban expansion, focusing on individual cities (Li et al., 2003; Qin et al., 2015; Fei and Zhao, 2019; Tao and Ye, 2022) and urban metropolitan areas. Dadashpoor (2019) analyzed land use change and urbanization and explored their impact on changes in landscape patterns in the Tabriz metropolitan area (TMA) from 1996 to 2016. The total urban area of the Guangdong-Hong Kong-Macao Greater Bay Area (GBA) of China expanded approximately 13 times from 1986 to 2017, and the driving factors of urban expansion varied with spatial and temporal scales (Zhang et al., 2020). Jiao (2019) quantitatively analyzed the dynamic characteristics and spatial patterns of urban expansion that have emerged over the past 20 years in three metropolitan areas with different socio-economic backgrounds and urbanization levels (Tokyo, New York, and Shanghai). In different periods, urban expansion in metropolitan areas displayed different spatial-temporal characteristics, and urban spatial connection in metropolitan areas played an important role in urban expansion (Jiao et al., 2016). The rapid expansion of metropolitan areas with high population density has exerted pressure on the ecological environment system (Fang et al., 2016; Song et al., 2020; Han et al., 2022) and caused increasingly serious problems. The expansion of urban metropolitan areas as well as industrial development and population growth have also put pressure on water resources (McMichael et al., 2006). Metropolitan areas are concentrated centers of production, consumption, and waste disposal that drive land change and a host of global environmental problems (Kalnay and Cai, 2003). Understanding the process of expansion and its driving forces in metropolitan areas is thus necessary to address urgent issues related to sustainable development policies and planning (Liang et al., 2018). Concentric partitioning of cities has commonly been used in studies that focus on urban form and urban sprawl. The variation in spatial metrics or density variables from the city center outward has often been discussed (Irwin and Bockstael, 2007). For instance, Seto and Fragkias (2005) quantified the spatiotemporal patterns of cities by analyzing the spatial metrics in experientially defined buffer zones, namely, 0–3 km, 3–10 km, and 10–20 km. Taubenböck et al. (2009) analyzed urban structure based on six ring-shaped zones around the main urban center. Schneider and Woodcock (2008) defined the urban core area as a circular area with an urban land density above 50% and divided the remaining landscape into fringe, periphery, and hinterland regions with three 8-km buffers. The researchers found that urban land density generally decreased from the urban center to the outskirts. Jiao (2015) proposed using the urban land density function to measure urban compactness, urban expansion rate, and degree of urban sprawl, and in doing so, he derived an established method for concentric partitioning of urban areas.

In China, the spatial form of urbanization has developed from single-core city expansion to a multi-center metropolitan area (Xiao, 2021). However, in the past 10 years, academic research and national strategy in China have focused on the development of urban agglomeration, ignoring that the development of metropolitan area is a necessary step in the growth and development of urban agglomeration (Huang and Wu, 2021). During the 14th Five-Year Plan period, the metropolitan area will become more important because it will absorb the new urban population in China, and metropolitan areas have become the strategic core regions of national economic development in the country (Li et al., 2018). Current research mainly focuses on the spatial expansion process of mature urban agglomerations and metropolitan areas in the east, such as Beijing-Tianjin-Hebei (Yu and Zhou, 2018), Guangdong-Hong Kong-Macao Greater Bay Area (Ma and Xu, 2010), and the middle reaches of the Yangtze River (Chen et al., 2016; Zhu et al., 2021). Beijing, Tianjin, and Shijiazhuang have presented a mono-nuclear concentric polygon pattern, a double-nucleated polygon-line pattern, and a sectorial point pattern, respectively, resulting primarily from their respective topographic constraints as well as urban planning and policy (Wu et al., 2015). As the dominant cores, the metropolitan areas within Wuhan, Nanchang, and Changsha have developed well, while the macro intercity relatedness in the Yangtze River middle reaches megalopolis has not broken free from the shackles of the geographical boundaries of the provinces (Xia et al., 2019). Most of these studies focus on metropolitan areas and large cities in the eastern developed areas because the spatiotemporal characteristics of urban expansion were obvious and are clear and easy examples of the urban process. A few studies have shown urban expansion in specific regions (Research Group of Henan Provincial Academy of Social Sciences, 2021; Wei et al., 2022); however, their results ignored the impact analysis derived from regional development (Tian et al., 2011; Li et al., 2013). This bias towards large cities in urban expansion studies neglects regional processes that may include changes in smaller cities (Zhou et al., 2018). Less attention has been paid to the emerging metropolitan areas located in major grain producing areas in central China, which limits the universality of research results and reduces the successful targeting of China's new urbanization policies. Metropolitan areas, in particular, contain cities of different sizes, and some uncertainty exists about whether urban expansion still follows the same generalized growth process that can be found in large cities.

Therefore, more spatially extensive and comprehensive research on urban expansion is needed to improve our theoretical understanding of the megaregion process and its implications for policy. The Zhengzhou metropolitan area is located in the major national grain producing areas of central China. Cropland accounts for about 70% of the Zhengzhou metropolitan area, and the urban built-up area there increased from 90 km^2 in 1991 to 1181.51 km^2 in 2019, mainly from cropland. The contradiction between urban expansion and food security is prominent (Qiao et al., 2022). These circumstances make the ZZMA an ideal region to explore the spatial patterns of the urban expansion process in cities of different sizes with food security constraints. More specifically, we proposed three research questions: 1) What are the spatiotemporal characteristics of urban expansion in the metropolitan areas located in major grain producing areas? 2) What are the differences between center cities (large cities) and other cities (medium- and small-sized cities) in the urban expansion process and form? 3) Which factors play important roles in the urban expansion process? It is particularly important to analyze the urban expansion of metropolitan areas and its drivers in major national grain producing areas in order to ensure regional food security and the successful targeting of China's new urbanization policies.

2 Materials and Methods

2.1 Study area

The Zhengzhou metropolitan area is located in the transition zone between the second- and third-level landforms of central China (33°51′N–35°26′N, 112°42′E–114°50′E) (Fig. 1). It belongs to the north temperate monsoon climate, and the vegetation types are mainly cropland, forest land, and grassland. The surface cover in the region is dominated by crop cultivation, and cropland accounts for about 70% of the area. The core includes Zhengzhou as well as the four central urban areas of Kaifeng, Xinxiang, Jiaozuo, and Xuchang and the counties of Gongyi, Xingyang, Zhongmu, Dengfeng, Xinmi, Xinzheng, Wuzhi, Yuanyang, Xinxiang, Weishi and Changge, which are classified as large, medium and small-sized cities (Table 1) and make up the urban-rural integration demonstration areas. The development of the central city (Zhengzhou) and four secondary cities (Kaifeng, Xinxiang, Jiaozuo, and Xuchang) has gradually moves beyond the original boundaries and is currently in a period of accelerated growth, accounting for 9.6% of the total land area of Henan Province and gathering nearly 20% of the province's population and more than 30% of the province's total economic output. It is one of the areas in the central and western regions with the strongest economy and fastest development. As a national central city, Zhengzhou is one of the first and only airport-type national logistics hubs in China and a core demonstration area for ecological protection and high-quality development in the Yellow River Basin. In 2019, the urbanization rate of Zhengzhou was 74.6%, much higher than Henan Province's rate of 53.12%. Henan Province was identified as major grain producing area in 2001 by the State Council of China. After that, cities and counties in the ZZMA except Zhengzhou Administrative District were further divided into the national core grain-producing areas. With the acceleration of urbanization in the Zhengzhou metropolitan area, high-quality cultivated land has decreased, the quality of cropland has declined, and problems with food security,

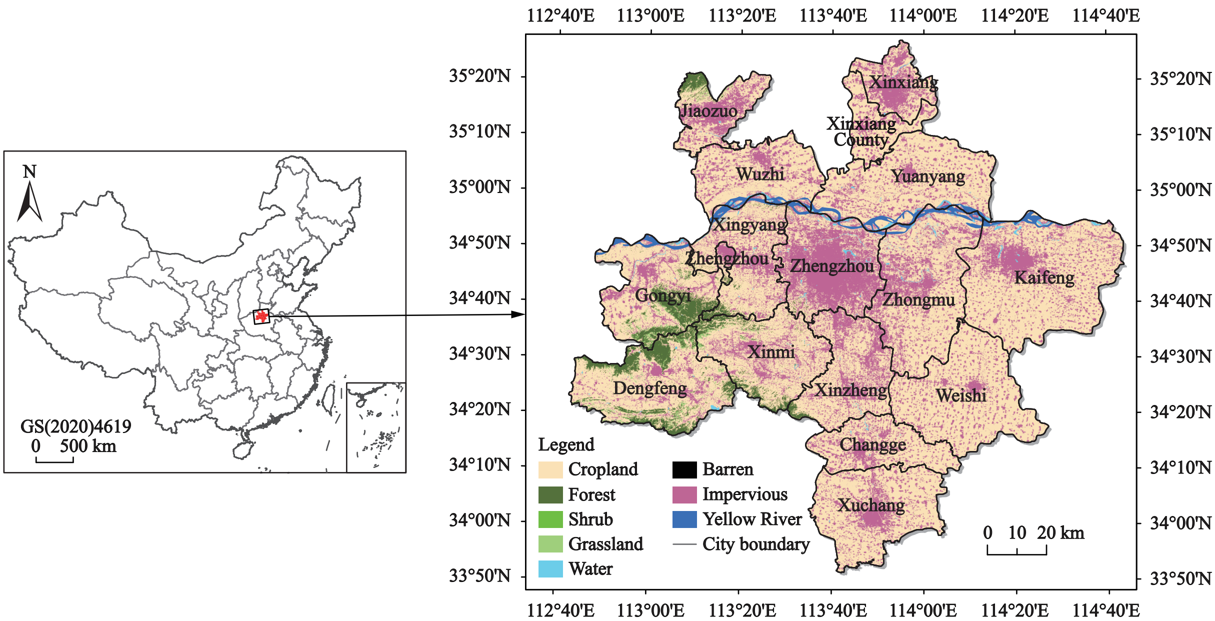

Fig. 1 The location and land use of the Zhengzhou metropolitan area (ZZMA), China

Table 1 Classification of city size

City	Size	Population standard
Zhengzhou	Large-sized city	1.00–5.00 million
Xinxiang, Jiaozuo, Kaifeng	Medium-sized city	0.50–1.00 million
Xuchang, Xingyang, Xinmi, Xinzheng, Dengfeng, Weishi, Yuanyang, Wuzhi, Changge, Zhongmu, Gongyi, Xinxiang County	Small-sized city	Less than 0.50 million

ecology, and urban space have become prominent.

2.2 Data sources

2.2.1 Impervious surface datasets

Urban area in physical terms refers to a complex of impervious surfaces and urban vegetation. Impervious surfaces, including pavement, roofs, and compacted soil, are closely associated with a built-up environment in a dominate urban area. When using remote sensing images, urban area is best defined by impervious surface area (Arnold and Gibbons, 1996). Impervious surface is the most significant feature of human settlements, and it is widely used to represent the urban area (Bounoua et al., 2018). Timely, accurate, and frequent information about urban areas is crucial for urban monitoring and management. In this study, we used a dataset of impervious surfaces in China. In particular, we examine data from 1978 with 60 m spatial resolution and data from 1985 to 2017 with annual temporal resolution and 30 m spatial resolution (Gong et al., 2019). This dataset was developed based primarily on Landsat images from NASA with an ancillary dataset of nighttime light (NTL) data and processed on the Google Earth Engine platform. It is the first dataset with annual urban area in China with high spatial details (Gong et al., 2019). In previous studies, the best maps of urban areas were only made every five years (Liu et al., 2018). The dataset was proven to be reliable with overall classification accuracies of evaluation reaching more than 90% (Gong et al., 2019). The annual dataset can provide more timely and detailed information about the urban expansion of the ZZMA.

2.2.2 Land cover datasets

The China land cover dataset (CLCD, resolution 30 m) is freely available at https://doi.org/10.5281/zenodo.4417810, and the overall accuracy of CLCD reached 79.31% (Yang and Huang, 2021).

2.2.3 Statistical datasets

The urban resident population and GDP in Zhengzhou, Kaifeng, Xinxiang, Jiaozuo, and Xuchang of the ZZMA were taken from the China City Statistical Yearbooks (DCSNBSC, 1986; DUSNBSC, 2006; 2011; 2018; USONBSC, 1991; 1996; 2001).

3 Methods

3.1 Concentric ring analysis

In each city, a series of 1-km buffers were built in an increasing, stepwise manner from the city center, which surrounded the central business district (CBD) in 1990. An outer ring was selected as defined boundary of a city based on two criteria (Jiao, 2015; Bren et al., 2017): 1) the boundary was large enough to incorporate continuous urban areas, even if they have different administrative governance structures; 2) the urban extent of a city did not include isolated small cities far from the main urban area. Partitioning has been used in a number of previous studies to define the geographical extent of each city using a standardized method (Wolman et al., 2005; Schneider and Woodcock, 2008). More information on generating buffers for polycentric cities can be found in Jiao's work (2015). For each ring, the proportion of built-up area as the urban density was calculated. Large water bodies in city areas were excluded in the calculation since it is unlikely that they would be used for urban development. For consistency, the area of large water bodies was subtracted from the total area.

3.2 Urban land density function

The urban land density function was used to characterize the urban forms and their changes (Jiao, 2015). The concentric ring partitioning and the outer boundary of Zhengzhou City are shown as an example in Fig. 2. To minimize the bias in calculation, the area of water bodies was subtracted from the total area if its influence on the urban land density of any ring was larger than 1%. The urban land density in concentric rings is defined as the proportion of urban land to the area of buildable land in each ring (Eq. (1)). The buildable land is the total land area, excluding water bodies:

$$Dens = \frac{S_{\text{ul}}}{S - S_{\text{w}}} \tag{1}$$

where *Dens* is the urban land density and *S* is the area with land use information in a concentric ring (dough-

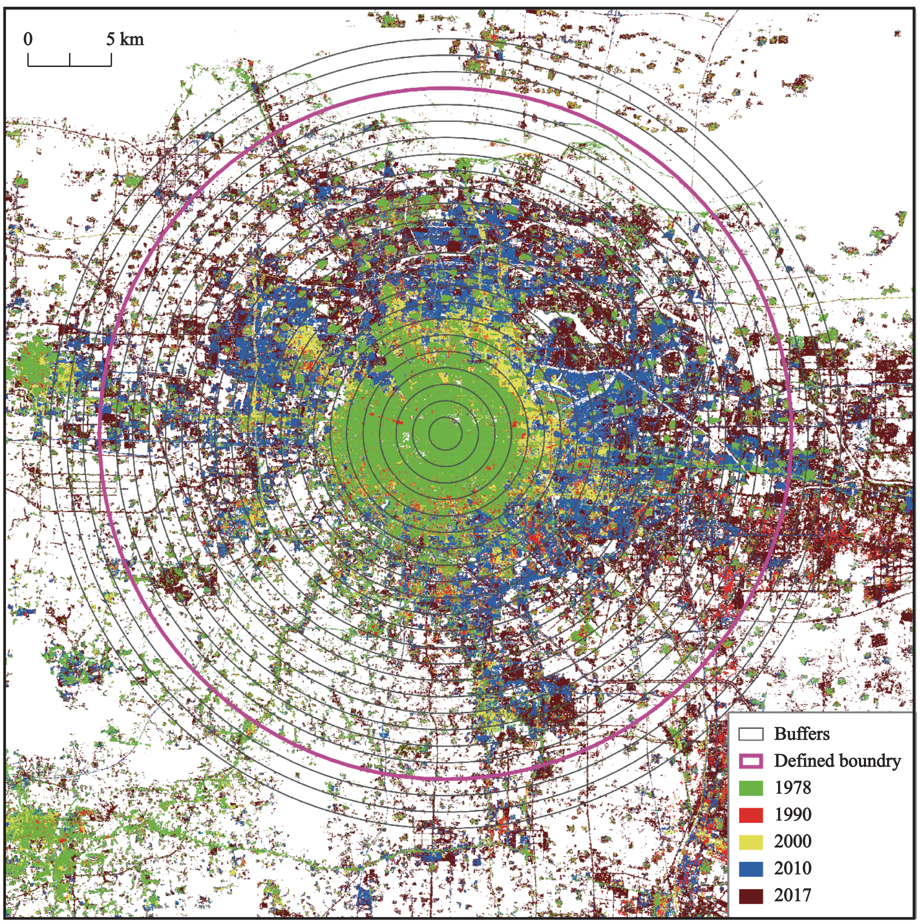

Fig. 2 The concentric ring partitioning and the defined boundary of Zhengzhou City from 1978 to 2017

nut), which is not the area of the concentric ring. S_{ul} and S_w are the areas of urban land and water bodies in a ring, respectively.

By calculating the urban land densities in a series of concentric rings in a city, Jiao (2015) found that the attenuation of urban land density has an inverse S-shape from the city center to the urban periphery. Inspired by the S-shape of the sigmoid function ($f(x) = 1/(1 + e^{-x})$), Jiao (2015) proposed a modified function with an inverse S-shape to characterize the spatial distribution of the urban land density within a city, which is shown in Eq. (2):

$$f(r) = \frac{1-c}{1+e^{\alpha((2r/D)-1)}} + c \tag{2}$$

where f is the urban land density in the concentric rings that is calculated using Eq. (1), r is the distance to the city center, and α, c, and D are parameters, which vary between cities. Parameter c represents the background value of the urban land density in the hinterland of a city, and parameter D denotes the approximate boundary between the urban fringe and the urban hinterland. Parameters c and D will increase with urban expansion. Parameter α characterizes the shape of the curve of the urban land density, which can be used to reflect the urban expansion form. Parameter α is negatively correlated with the proportion of the rapidly decreasing part of the curve, which is the part denoting the inner urban and suburban areas (Jiao, 2015). A compact city has a narrow rapidly decreasing part, resulting in a higher α. Thus, a higher α indicates a more compact urban form. Detailed explanations can be found in Jiao (2015). The fitted curves can be calculated using the nonlinear least squares in MATLAB R2018a.

3.3 Urban expansion indexes

Three indexes, urban expansion core index (UCI), urban expansion intensity index (UII), and urban compactness index (k_p), were used to quantify the dynamic change of spatial structure in the process of urban expansion. The urban expansion core index (UCI) was used to compare the compactness of urban expansion and the concentration of urban area to the urban core, which is defined as Eq. (3):

$$UCI = \frac{R_c}{R_f} \tag{3}$$

where UCI is the urban expansion core index and R_c represents the radius of the urban core area, which is the area between the city center and the circle where the density of impervious surface is greater than or equal to 50%. R_f represents the radius of the periphery of the core area, which is from the boundary of the core area to the ring where the density of impervious surface is greater than or equal to 10%.

The urban expansion intensity index (UII) indicates the percentage of the expansion area of impervious surface to the total area of a spatial unit per unit time. UII measures the intensity and speed of urban expansion, which is defined as Eq. (4):

$$UII_{i,t\sim t+n} = \frac{UA_{i,t+n} - UA_{i,t}}{TA_i} \times \frac{1}{n} \times 100 \tag{4}$$

where $UII_{i,\, t\sim t+n}$ is the urban expansion intensity index of the i buffer ring from time t to $t + n$. $UA_{i,\, t+n} - UA_{i,t}$ represents the increase of the area of impervious surface from time t to $t + n$, and TA_i represents the total area of available land in the i buffer ring.

k_p is designed as the proportion of the rapidly decreasing part of the curve (i.e., the part denoting the inner urban and suburban areas). The index, represented by k_p, can be written as Eq. (5):

$$k_p = \frac{r_2 - r_1}{D} = \frac{1.316957}{\alpha} \tag{5}$$

where α is the parameter that controls the slope of the curve of urban land density function. A compact city has a high urban land density in the urban core area, which decreases quickly to a very low value outside the urban core. A compact city has a narrow area that covers the inner urban area and the suburban area and thus has a small k_p value. On the other hand, a city with a large k_p value is a low-density or dispersed city. The k_p value is only related to α and is suitable as an index for the degree of dispersion of diverse cities with time.

3.4 Cropland contribution rate

This index was constructed to evaluate the impacts of urban expansion on croplands.

$$CR = \frac{CL_{t\to t+n}}{UE_{t\to t+n}} \times 100\% \tag{6}$$

where CR (%) denotes the contribution rate of croplands to urban expansion; $CL_{t\to t+n}$ and $UE_{t\to t+n}$ represent the area of croplands encroached by newly-expanded urban lands and the newly-expanded urban lands from time t to $t + n$, respectively; and n indicates the time interval of the monitoring period.

4 Results

4.1 Urban expansion in the ZZMA

The results showed that over the past 40 yr, the ZZMA has experienced dramatic urban expansion (Fig. 3). The urban area of the ZZMA increased from 1028.63 km^2 in 1978 to 3719.54 km^2 in 2017, accounting for 5.35% and 19.36% of the local territory area, respectively, representing an increase of 261.60% that could be well fitted with an exponential curve. The annual urban area also increased greatly, which were 18.21, 27.13, 64.56, and 222.23 km^2/yr for the three periods of 1978–1990, 1990–2000, 2000–2010, and 2010–2017, respectively, indicating that the urbanization process in the ZZMA has accelerated over the past 40 yr. Furthermore, we mapped the standard deviation ellipse of urban expansion and the spatio-temporal trends gravity center of the ZZMA from 1978 to 2017 (Fig. 4), which showed the gravity centers of urban expansion were moving toward to Zhengzhou except Xinxiang and Kaifeng in 2010–2017. By polarization and trickle effect, Zhengzhou attracted and drove the expansion of surrounding cities and promoted Zhengzhou metropolitan an integral unit in the past four decades.

All the cities experienced rapid urbanization during 1978–2017, and the urban expansion differed between cities. In 1978, the urban area of Zhengzhou was the largest (246 km^2), followed by Jiaozuo (104 km^2), Kaifeng (99.8 km^2), Xinxiang (96.8 km^2), and Xuchang (30.8 km^2) (Fig. 3). The urban area of each city in the ZZMA and its annual change rate from 1978 to 2017 are shown in Fig. 5. From 1978 to 2017, the urban area of Zhengzhou increased by 604.01 km^2, which meant that it experienced the biggest expansion, followed by Kaifeng (164.01 km^2), Xuchang (138.87 km^2), Xinxiang (119.68 km^2), and Jiaozuo (118.91 km^2), respectively. Xuchang had the smallest original urban area among cities but experienced the fastest expansion rate (450.45%) in 1978–2017. Jiaozuo, located in the south of Taihang Mountains and the north of Yellow River, had the smallest expansion (113.90%), which is closely related to physical factors. In 1990–2017, the annual expansion rate in all cities accelerated. In 2000–2017, the fastest annual expansion rates were in Xuchang. This is because Xuchang had a relatively small urban area compared to the other four cities. Though Zhengzhou had the second fastest annual expansion rates in 2000–2017,

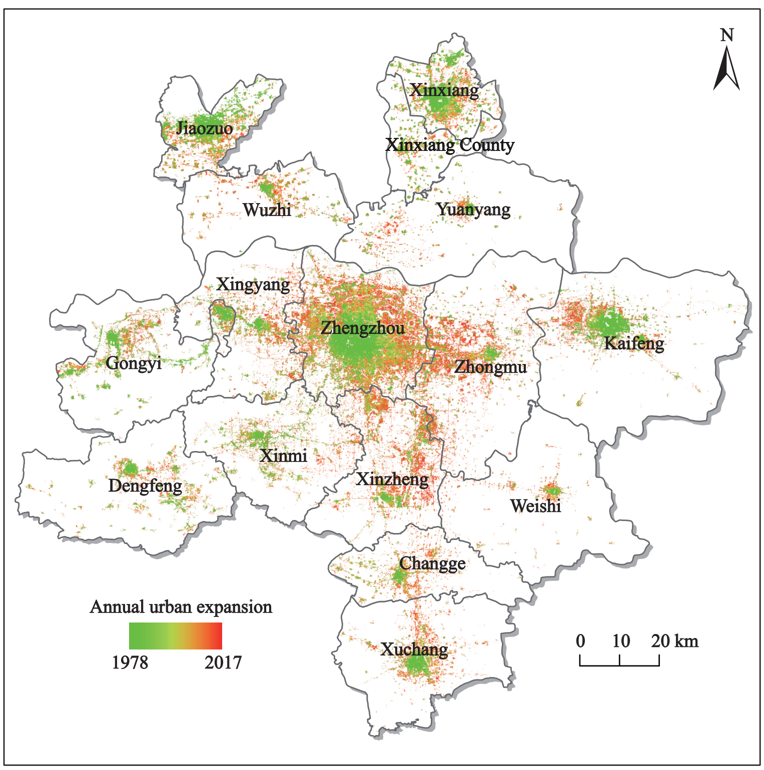

Fig. 3 The annual urban expansion process in the ZZMA from 1978 to 2017

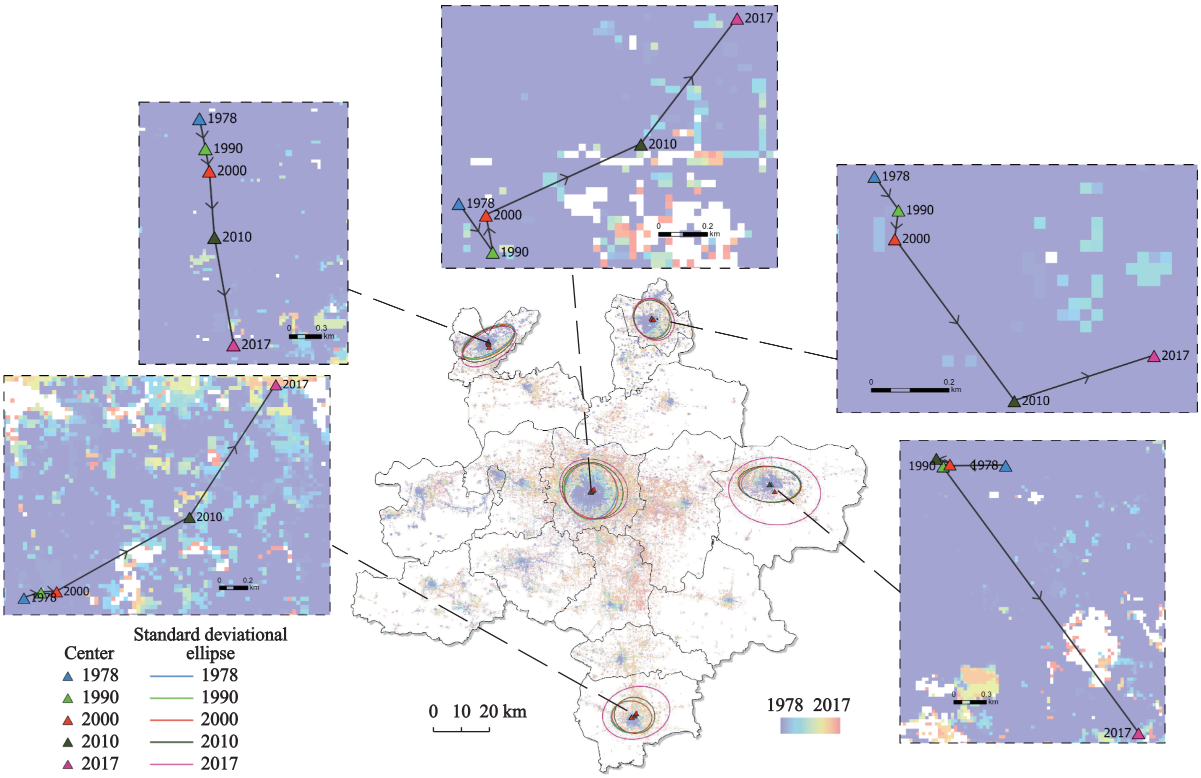

Fig. 4 The standard deviation ellipse of urban expansion and the dynamics of gravity centers of the ZZMA from 1978 to 2017

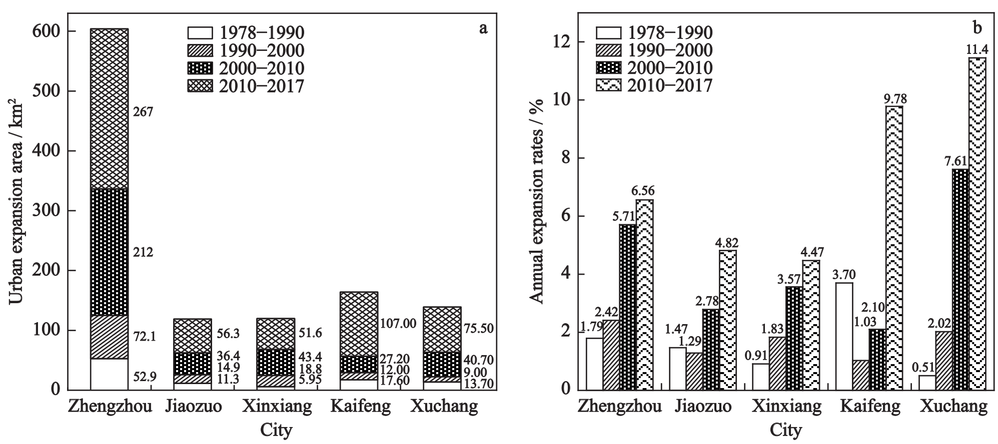

Fig. 5 Urban expansion (a) and annual expansion rates (b) in ZZMA from 1978 to 2017

it had the largest area. From 2010 to 2017, Kaifeng experienced faster expansion; the annual expansion rates increased to 9.78%, especially expanding westward.

4.2 Urban land density in concentric rings

The urban land density in each concentric ring was calculated using Eq. (1) in each city of ZZMA in 1978–2017. The fitted curves are shown in Fig. 6. Spatially, the urban land density decreased with the distance from the city center to the outskirts. More specifically, it decreased slowly at the beginning, dropped down quickly, and then decreased slowly again (Fig. 6). The growth intensity of urban land in different concentric rings of the city had spatio-temporal heterogeneity. Temporally, the fitted curves of the five cities increased with time so that the urban land density in the same circle increased with time, and the urban land expanded in each circle. The urban land density in each concentric ring increased from 1978 to 2000 and further at 2010 and 2017, indicating an apparent but differentiated urban expansion in each concentric ring.

The intervals of the urban land densities in the same

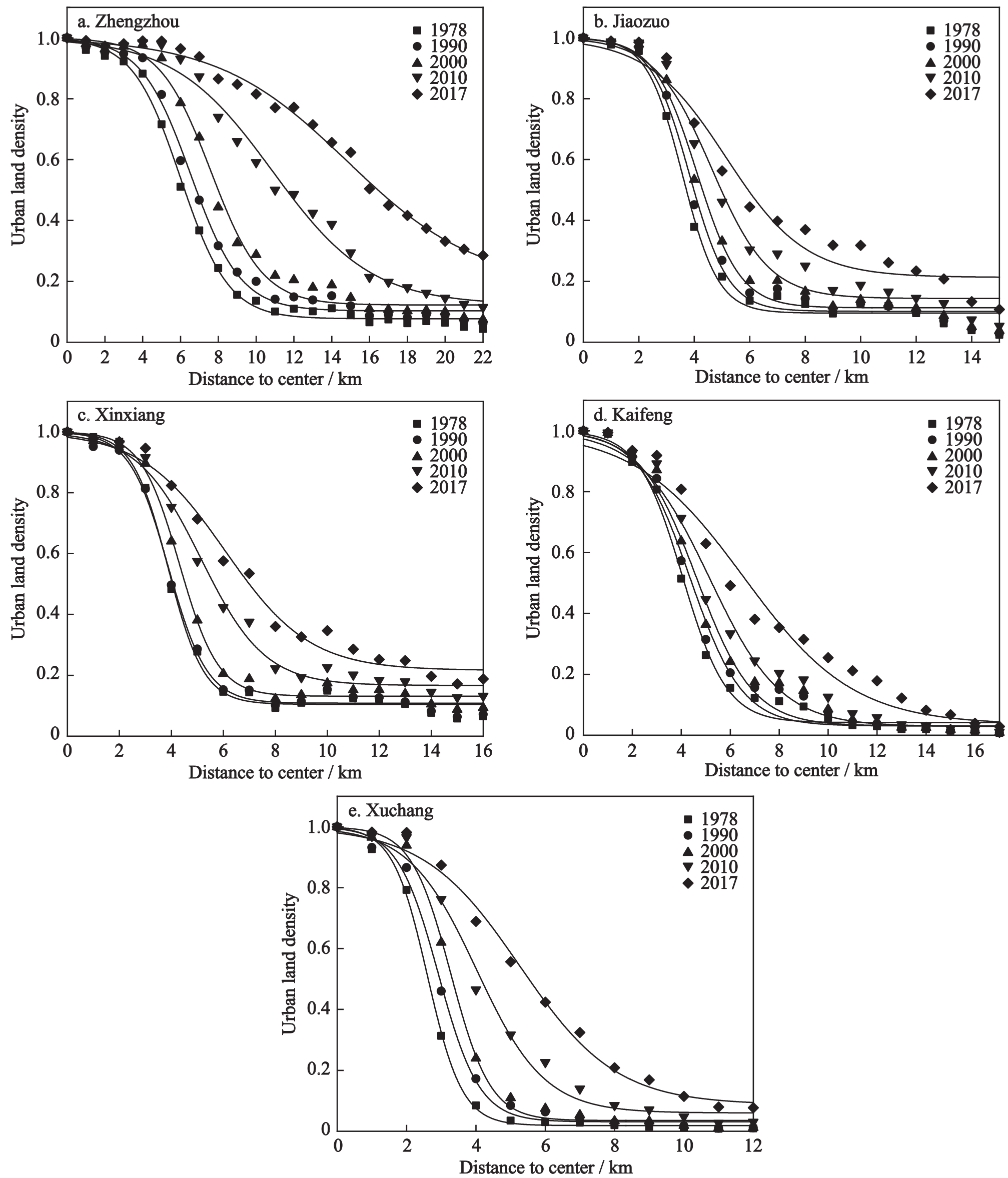

Fig. 6 The urban land density in concentric rings with the distance to the city center in 1978, 1990, 2000, 2010, and 2017

concentric ring reveal the expansion intensity at different time points, the larger the interval, the more intense the expansion. The urban expansion intensity in each city became higher with time. The intervals of fitted curves in Zhengzhou were the largest in the same period, indicating that it has experienced the fastest urban expansion in the ZZMA. During the latter periods (2000–2010, 2010–2017), the urban land density of Zhengzhou in the concentric rings increased to a very high level at approximately 10–15 km from the city center, showing that the main urban area of Zhengzhou was still experiencing faster expansion while the other four cities decreased rapidly after 10 km from the city center. The intervals of fitted curves in Kaifeng, Xuchang and Jiaozuo in 2010–2017 was higher than those in the first three periods (1978–1990, 1990–2000, 2000–2010).

4.3 Changes of urban form

The parameters of the urban land density function denote some basic characteristics of the urban form (Table 2). Parameter *D* is the boundary distance of the main urban area for a city, including the urban core, inner urban and suburban zones, and the urban fringe. Fig. 7 showed the growth rate of *D* values for 5 cities over the last 40 years. From 1978 to 2017, parameter *D* in Zhengzhou, Jiaozuo, Xinxiang, Kaifeng, and Xuchang increased by 141.10%, 66.86%, 67.85%, 62.09% and 107.51%, respectively. Parameter *D* in five

Table 2 Parameters of urban land density functions in ZZMA from 1978 to 2017

City	Year	α	c	D	R^2
Zhengzhou	1978	4.72	0.08	12.02	0.99
	1990	4.87	0.10	13.14	0.99
	2000	5.44	0.11	15.31	0.99
	2010	4.13	0.12	21.89	0.99
	2017	4.39	0.22	28.98	0.99
Jiaozuo	1978	5.57	0.08	7.00	0.99
	1990	5.00	0.07	7.83	0.98
	2000	4.77	0.08	8.42	0.98
	2010	3.84	0.10	9.74	0.97
	2017	2.83	0.13	11.68	0.96
Xinxiang	1978	5.15	0.08	7.62	0.99
	1990	4.97	0.09	7.88	0.99
	2000	5.48	0.11	8.75	0.99
	2010	3.90	0.13	10.61	0.99
	2017	3.40	0.17	12.79	0.98
Kaifeng	1978	4.50	0.03	8.10	0.99
	1990	4.09	0.03	8.73	0.98
	2000	4.01	0.03	9.26	0.98
	2010	3.55	0.03	10.33	0.98
	2017	2.94	0.04	13.13	0.98
Xuchang	1978	5.10	0.01	5.21	0.99
	1990	4.81	0.02	5.89	0.99
	2000	5.57	0.02	6.60	0.99
	2010	3.91	0.04	8.23	0.98
	2017	3.64	0.06	10.81	0.99

Notes: α characterizes the shape of the curve of the urban land density, a higher α indicates a more compact urban form, *c* represents the background value of the urban land density in the hinterland of a city, and *D* denotes the approximate boundary between the urban fringe and the urban hinterland

cities increased by 3.39% to 13.01% from 1978 to 1990 and 6.12% to 16.54% from 1990 to 2000, respectively. From 2000 to 2010, five cities rapidly increased their *D* by 11.49% to 42.98%, and three cities increased by more than 20%. Each city in the ZZMA increased by more than 20% from 2010 to 2017. The largest growth of *D* in the first period (1978–1990) was in Xuchang and in Zhengzhou during the latter three periods (1990–2000, 2000–2010, 2010–2017), which shows that the expansion intensity of the core city in the ZZMA was higher than it was in the other cities. The growth rates over the latter periods for all of the cities except Zhengzhou were almost equal to or higher than the growth rates over the previous periods from 1990 to

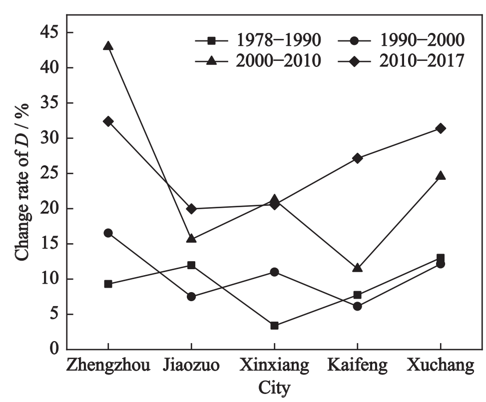

Fig. 7 Growth rate of the radius of the main urban area of cities in ZZMA from 1978 to 2017. *D* is the boundary distance of the main urban area for a city, including the urban core, inner urban, suburban zones and the urban fringe

2017. Particularly, the five cities experienced tremendous growth during the latter period; it can be inferred that the five cities in the ZZMA expanded more quickly during the latter periods.

The expansion intensity of different areas within a city varied, and the internal form changed with time. As shown in Fig. 8, the growth of the urban core and urban fringe in Zhengzhou increased by 134.08% from 1978 to 2017, followed by Xuchang (78.37.3%), Xinxiang (38.07%), Kaifeng (26.58%), and Jiaozuo (16.94%). The growth of inner urban and suburban zones in Zhengzhou, Jiaozuo, Xinxiang, Kaifeng, and Xuchang increased by 159.48%, 227.59%, 152.84%, 147.66%, and 192.25%, respectively. The result showed that the urban form of Zhengzhou was more compact than it was in the other four cities. Parameter α characterized the shape of the curve of the urban land density, and a higher α means a more compact urban form. Parameter α in Zhengzhou increased from 1978 to 2000 and then decreased during 2000 and 2010. There was a slight increase between 2010 and 2017, indicating that the urban form of Zhengzhou changed with time. On the whole, parameter α in the other four cities decreased with time, so their urban form became decentralized, especially in Kaifeng and Jiaozuo. The constant c represents the background value of urban land density in the hinterland of the city. Table 2 showed that c increased with time in five cities, indicating that urban area in the surrounding area increased due to the development of the entire region.

The urban expansion indexes can also quantitatively describe the change in the urban form. The result of UCI, UII, and k_p are shown in Fig. 9. UCI in Zhengzhou decreased slightly from 1978 to 2000 and then increased rapidly, reaching an obviously high value from 2010 to 2017, indicating that the urban core of Zhengzhou was experiencing high-intensity expansion after 2000 and that its urban form became compact. On the whole, UCI in Kaifeng and Xuchang were higher than other cities, and their UCI gradually declined after 1990 due to the faster expansion of the suburban zones. UCI in Jiaozuo and Xinxiang gradually increased from 1978 to 2017. From 1990 to 2017, UII in each city increased rapidly, and UII was much higher in Zhengzhou than it was in the other four cities. As Fig. 9 shows, all cities except Zhengzhou were dispersed from 1978 to 2017. In particular, the k_p values for Jiaozuo and Kaifeng increased significantly, which implied that these two cities experienced more dispersed urban growth.

4.4 Hot-zones of urban expansion

The spatial distribution between the growth area and its distance from the urban center revealed the hot-zone of urban expansion in ZZMA (Fig. 10). The distribution of UII as a function of increasing distance was represented as single peaked or multipeaked curves. The peaks re-

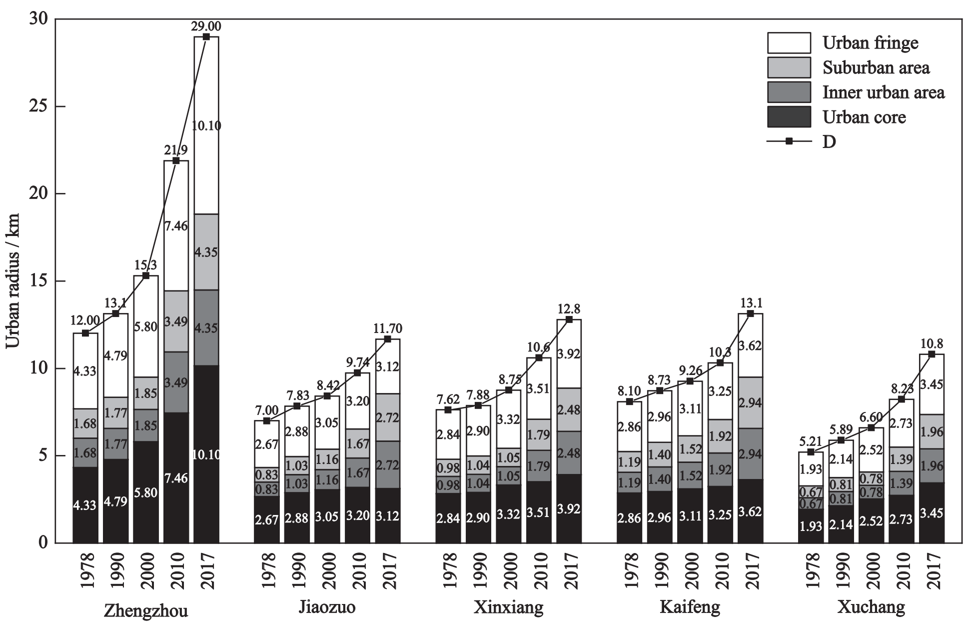

Fig. 8 Spatial variations of the extent of different urban areas in the ZZMA from 1978 to 2017. *D* is the boundary distance of the main urban area for a city, including the urban core, inner urban, suburban zones and the urban fringe

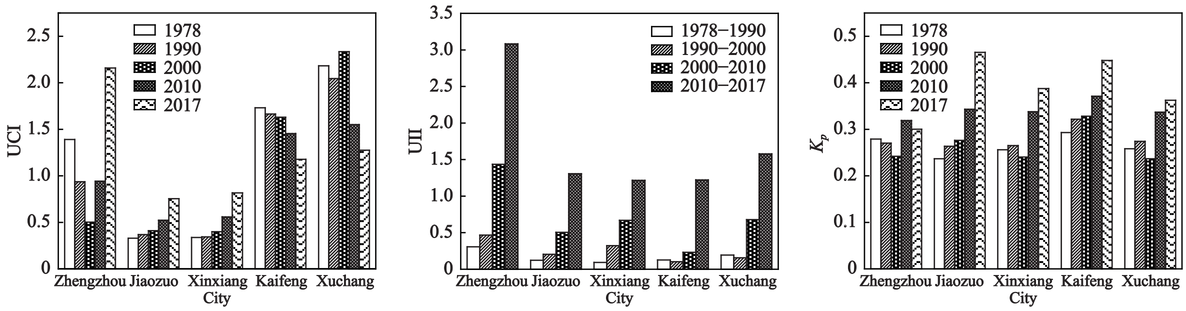

Fig. 9 Temporal variations of concentration, intensity, and compactness of urban expansion in ZZMA from 1978 to 2017. UCI, urban expansion core index; UII, urban expansion intensity index; and k_p, urban compactness index

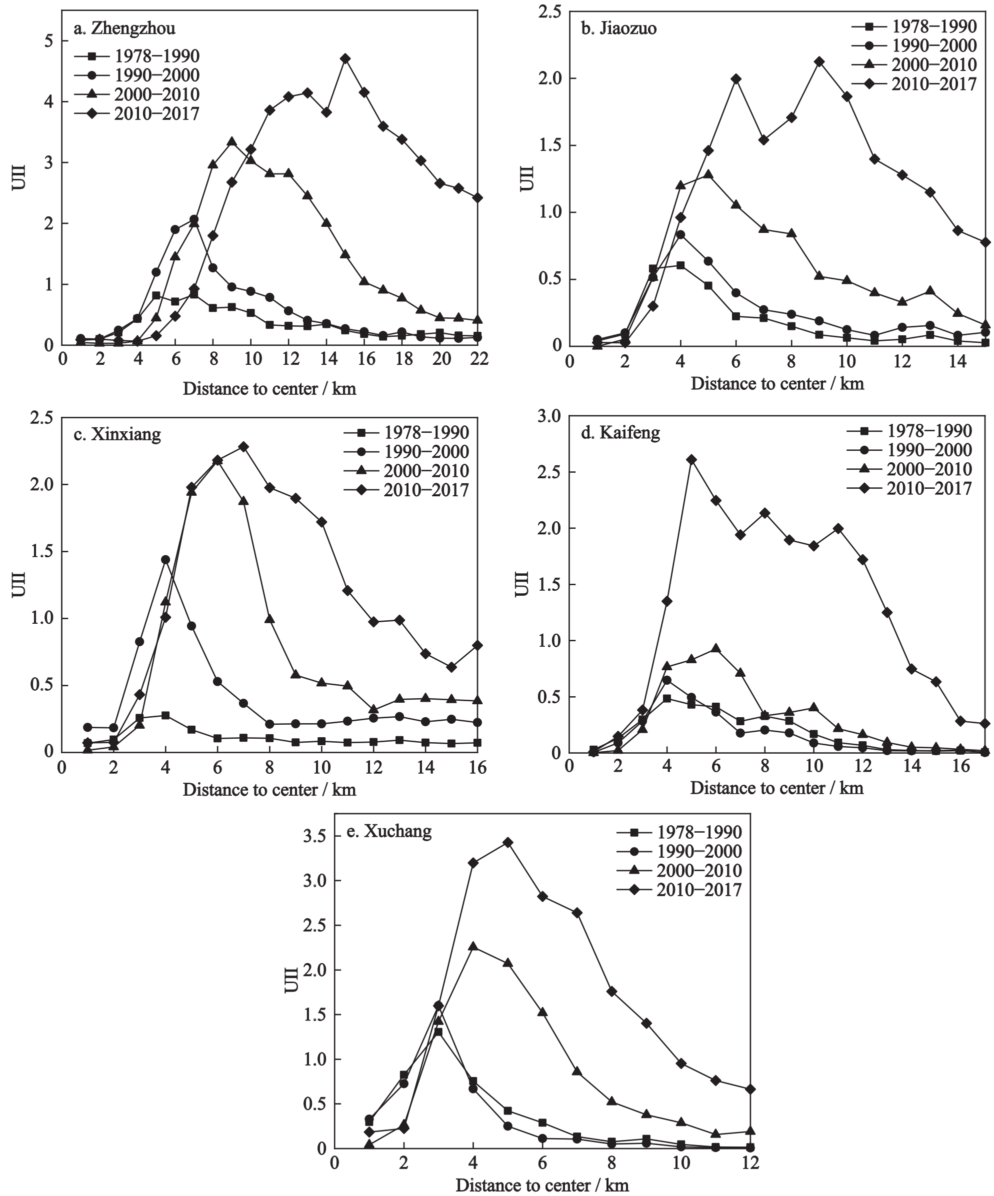

Fig. 10 Spatial distribution of urban expansion intensity with the distance to the urban center in ZZMA from 1978 to 2017. UII is urban expansion intensity index

flected the hot-zones of urban expansion in each period. In the five cities, UII increased significantly with time, and the shift of the peak extended from the urban center to the outskirts. The result showed that the urban core was gradually expanding outward. UII in Zhengzhou showed a single peak in different periods. Along with urban growth, the region at the urban fringe moved outwards. In 1978–1990 and 1990–2000, the peak occurred at 4–7 km, and in 2000–2010 the peak moved to 7–13 km, while in 2010–2017, it moved rapidly to 10–20 km. The results showed that the highest urban expansion intensity in Zhengzhou moved farther from the center with time. Jiaozuo had two peaks from 2010 to 2017, indicating that another expansion center appeared. The peak values in the ZZMA continued to increase over time. The peak of Kaifeng shifted to the left from 2010 to 2017 due to the adjustment of administrative divisions in Kaifeng city. Overall, a single peaked or multipeaked curve was the general form of the relationship between urban growth area and distance; this represented the hot-zone of urban growth moving progressively with the moving distance increasing with the acceleration of urbanization in the four periods.

4.5 The contribution rate of cropland losses due to urban expansion

We calculated the cropland contribution rate (CR) from 1990 to 2019 (Table 3). In the past three decades, more than 2340 km^2 croplands in 16 cities of ZZMA were encroached by urban lands, which accounted for 79.75% of the newly-expanded urban lands and became the primary land source of urban expansion. Among 16 cities, croplands lost with an average of 146.28 km^2 per city, which approximately equaled to the central urban lands of Xining in 2017 (152.93 km^2) (Liu, 2019). Cropland losses in ZZMA kept in step with urban expansion, of which 67.56% appeared after 2000 (Table 3). Croplands were the first land source for urban expansion in 16 cities with CRs ranging from 73.81% (Yuanyang) to 82.91% (Xuchang). CRs of the cities in national core grain-producing areas were higher than other cities, such as Changge, Weishi, and Xinxiang County. However, urban expansion areas in national core grain-producing area were lower than other cities (Fig.11), which was closely related to cropland protection. Yuanyang, with the largest wetland area and the highest forest coverage rate in Henan province, was also in national core grain-producing area, but the cropland contribution rate was lowest. In order to reveal the role what national core grain-producing area plays in urban expansion, we use binary color image method to classify the cities into four types by comparing urban expansion area and cropland contribution rate in ZZMA from 1990 to 2019. As the core area of ZZMA, Zhengzhou, Xinmi and Xinzheng that were not in national core grain-producing areas had a higher urban expansion areas and cropland contribution rates, and the cities surrounding Zhengzhou also had higher urban expansion areas but lower cropland contribution rates (Fig. 12).

Table 3 Loss areas of croplands and their contribution rates to urban expansion in ZZMA from 1990 to 2019

City/county	Loss area / km^2			CR / %	City/county	Loss area / km^2			CR / %
	1990–2000	2000–2010	2010–2019			1990–2000	2000–2010	2010–2019	
Zhengzhou	126.91	147.66	147.76	80.41	Xinmi	76.55	38.40	32.98	81.02
Jiaozuo	32.33	38.78	31.09	80.09	Xinzheng	64.61	40.51	113.50	82.37
Xinxiang	36.62	40.95	30.10	81.19	Dengfeng	45.35	39.80	23.40	80.34
Kaifeng	47.27	62.53	82.61	80.04	Weishi	32.65	19.54	32.00	82.53
Xuchang	23.36	40.97	48.61	82.91	Xinxiang County	14.63	20.37	15.36	81.68
Zhongmu	54.14	37.62	169.06	78.74	Yuanyang	42.45	17.37	42.28	73.81
Gongyi	52.51	34.23	26.92	75.80	Wuzhi	31.40	23.07	43.36	75.59
Xingyang	57.45	30.43	54.72	76.86	Changge	25.60	28.52	36.22	82.61

Note: CR is cropland contribution rate

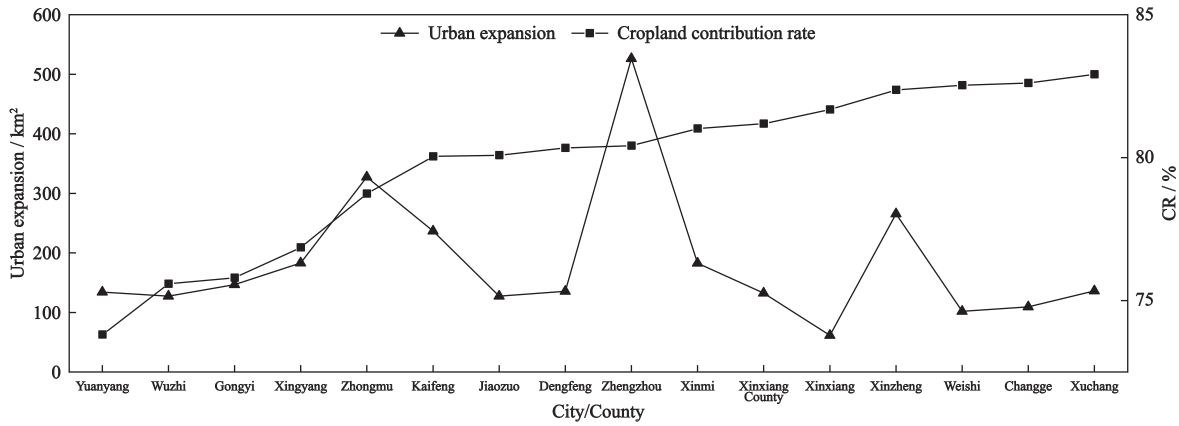

Fig. 11 Urban expansion and cropland contribution rate (CR) in ZZMA from 1990 to 2019

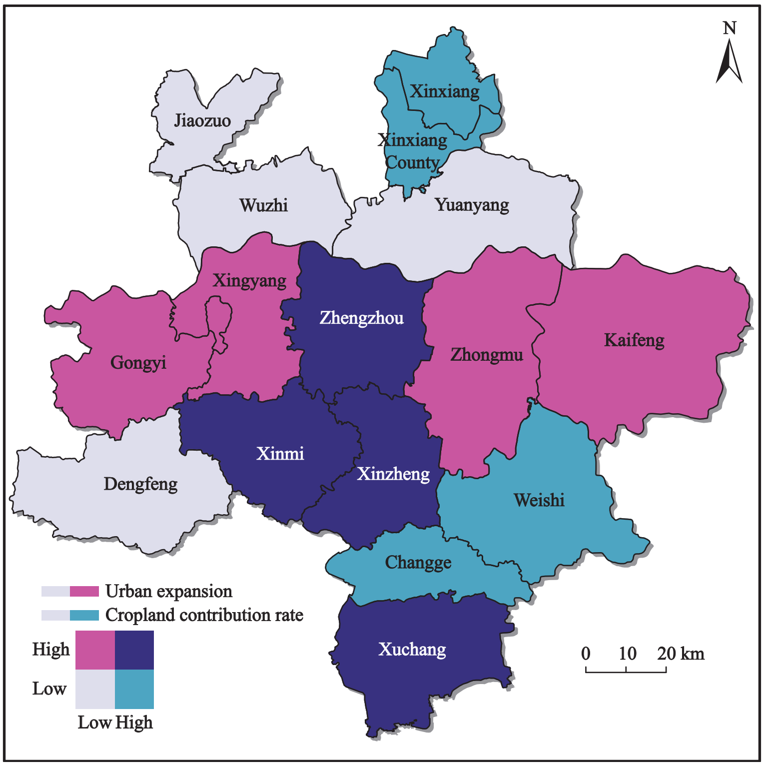

Fig. 12 Spatial distribution between urban expansion and cropland contribution rate in ZZMA from 1990 to 2019

5 Discussion

5.1 Comparisons of urban expansion in metropolitan areas

In this study, we develop models including concentric ring analysis, urban land density function, urban expansion indexes and cropland contribution rate to characterize the spatial-temporal process and form of urban expansion in major grain producing area. In the ZZMA, the urban area increased exponentially, and urban area change also exhibited a significant increase during the four periods. The urban area of the ZZMA has increased significantly over the past 40 years and could fit well with an exponential curve, which is consistent with the results of the urbanization process of the Nanjing metropolitan area (Xu et al., 2007). However, the urban area in the GBA increased about 13 times from 1986 to 2017 (Zhang et al., 2020), which could fit better with a linear curve than an exponential curve. Urban land density has an inverse S-shape from the center to periphery in the ZZMA. Relative research found that the urban land densities in three Southeast Asian megacities decrease with distance to the city centers and that their urban forms vary over time (Xu et al., 2019). Compared with medium and small-sized cities, Zhengzhou City's urban expansion was more compact. These results are in slight disagreement with the findings in Hai's (2020) study, but these differences can be explained. Hai points out that most of China's large cities became less compact and more fragmented from 1992 to 2015. These inconsistent results further reveal how the pattern of urban expansion in metropolitan areas can vary depending on the stage of urban development (Jiao et al., 2019). Jiao's study shows that the spatial-temporal process of urban expansion includes three periods: core area expansion, subcenter and new district construction, and high-density and stable multi-center formation (Jiao et al., 2019). In Hai's (2020) study, Zhengzhou is ranked as a medium-sized city, and large cities are more mature than Zhengzhou city (e.g., Shanghai, Beijing, Guangzhou, Tianjin, Wuhan, Chengdu, Chongqing, Hangzhou and Taipei). As a national center city, Zhengzhou is still in a lower stage than Shanghai, Guangzhou, and Beijing, which lead the development of the Yangtze River Delta, Pearl River Delta, and Rim Bohai Sea, respectively. From 1978 to 2017 and especially after 2000, Zhengzhou has developed rapidly and attracted a large number of people. During this time, it also experienced significant urban expansion, and the areas with adjacent surrounding space and good traffic conditions became the main areas of industrial and population spillover (21st Century, 2020). A spatial connection has formed between Zhengzhou, Kaifeng, and Xuchang, especially between Zhengzhou and Kaifeng, which was the basic condition for the spatial pattern in the ZZMA. As a small-sized city, Xuchang's highest expansion rates were associated with its initially smallest urban areas, which is consistent with the inverse relationship between urban expansion rates and city size found based on 32 major cities across China and six cities in the Yangtze River Dela Urban Agglomeration (Zhao et al., 2015; Fang and Zhao, 2018). Each city in the ZZMA is shifting from being a single city to becoming integrated with the metropolitan area.

5.2 Test of urban expansion quality in ZZMA

The ZZMA is representative of central China, which is undergoing rapid urbanization (He et al., 2019; Yang et al., 2019). Population is a distinctly important factor that triggers rapid expansion, and close links between urban expansion and GDP indicate that China's current economic growth pattern is highly dependent on resources input, especially land resources (Li et al., 2018). Accordingly, we tested the quality of urban expansion in the ZZMA by comparing urban area with urban population and GDP using the power scaling law, which has been successfully adopted to scale many urban attributes across space and time (Bettencourt et al., 2007; Zhao et al., 2018). We found that the comparison between the scaling coefficient of the urban population and the urban area was not consistent for different cities in the ZZMA (Fig. 13). The scaling coefficient was higher than 1.0 for Zhengzhou (1.39), suggesting that the growth in urban population increasingly outpaced area expansion, while it was lower than 1.0 for the rest of the cities, varying from 0.38 for Xuchang and 0.90 for Kaifeng, indicating that the urban population growth progressively lagged behind area expansion. Although diseconomies of scale existed for medium-sized cities, including Jiaozuo, Xinxiang, and Kaifeng, the scaling coefficient was larger than the global average of 0.5; however, the scaling coefficient for small-sized cities, such as Xuchang, was lower than 0.5. The global expansion of urban areas has been twice as fast on average as the growth in urban population in recent decades (Angel et al., 2011), signifying that a large city is relatively better positioned than smaller cities in the efficiency of their urban infrastructure.

The scaling coefficients of the urban GDP vs. urban area are larger than 1 for all cities, ranging from 2.39 for Xuchang to 3.72 for Xinxiang, which shows that the urban GDP growth greatly exceeds urban expansion over time. The wealth is always created efficiently in the urbanized area in all Chinese cities because urban expansion has been widely pursued as a practical tool to promote economic growth in China (Xu, 2008; Lin and Yi, 2011; Zhao et al., 2018).

5.3 Influence of policy factors to urban expansion

Government decision play an important role in urban expansion, at least macroscopically (Ma and Xu, 2010). The ZZMA is undergoing rapid urbanization (He et al, 2019; Yang et al., 2020), which is affected by land use policy and urban planning. To some extent, government policy can affect the orientation and rate of urban expansion in a macroscopic way (Ma and Xu, 2010).

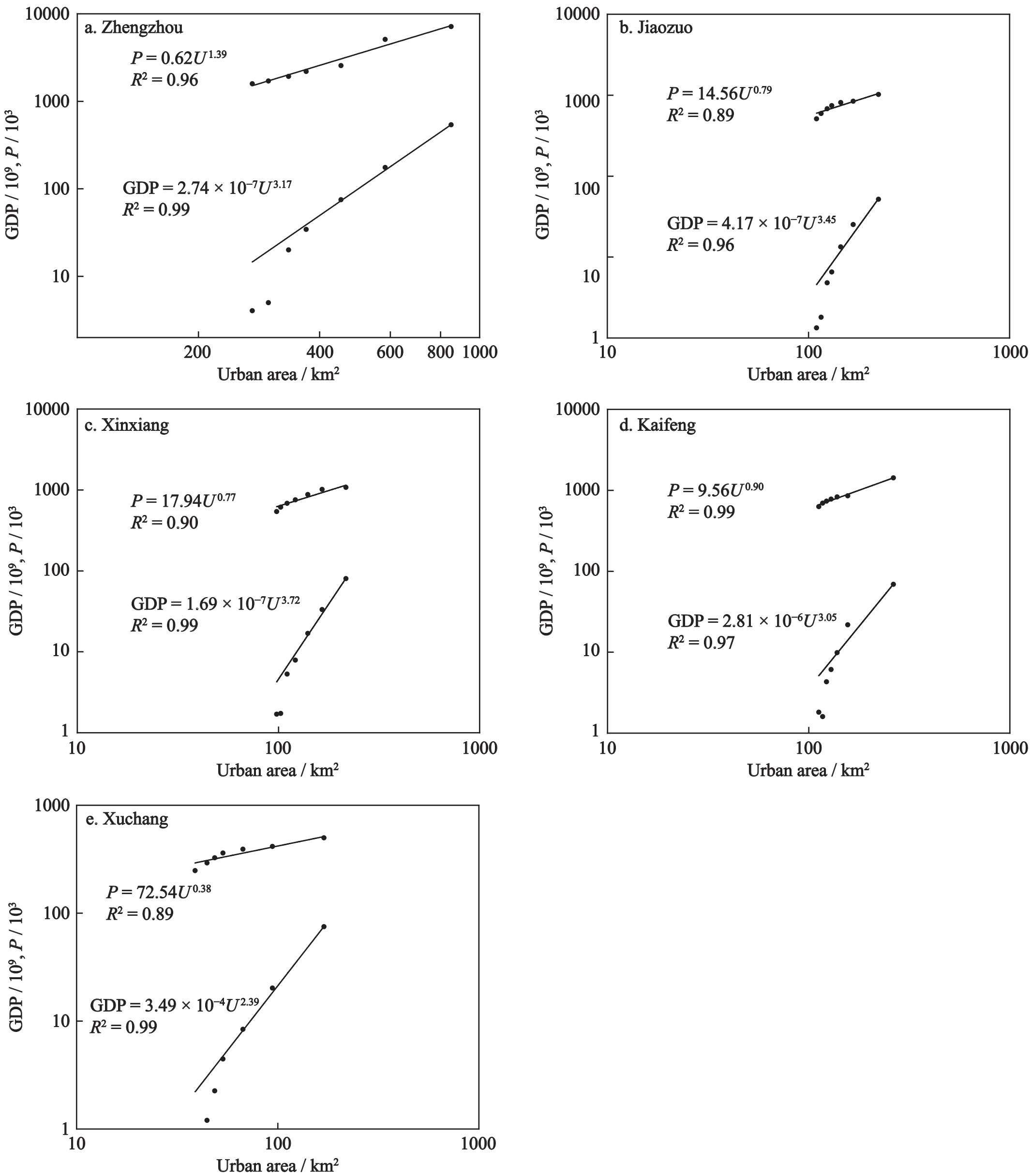

Fig. 13 Temporal coevolution of urban area with urban population and GDP in ZZMA from 1978 to 2017. P, GDP and U represent population, gross domestic product and urban area, respectively

Every five years, the central government draws up a plan called the Five-Year Plan, which could be understood as a key indicator of the direction and changes in philosophy for economic growth and social development (Yu and Zhou, 2018). In 11th Five-Year Plan Period (2006–2010), it was proposed that the urban agglomeration should be the major form for accelerating urbanization. Meanwhile, ‘*Guiding Opinions of the State Council on Supporting Henan Province to Accelerate the Construction of the Central Plains Economic Zone*’ was issued in 2011. It thus seems uncoincidental that the ZZMA’s urbanization process notably accelerated from 2010–2017.

China has implemented the strictest cropland protection system, which has led to heterogeneity in the expansion of different cities located in major grain producing areas. Cropland in the ZZMA accounts for about 70% of the area, and urban land is mainly converted from cropland. ‘*Outline of National Core Grain-producing Areas Planning in the New Era* (2021–2035)’ has been drafted to build important national core grain-producing areas in China as a means of ensuring national food security at a high level. The ZZMA is surrounded by national core grain-producing areas of the Huang-

Huai Plain and the Piedmont Plain of North and West Henan, where croplands are strictly protected. All of the cities in the ZZMA except for Zhengzhou Administrative District are located in national core grain-producing areas, so Zhengzhou has experienced faster expansion than the other four cities. The cities surrounding Zhengzhou were not in national core grain-producing areas, with a higher urban expansion, but the cropland contribution rate was lower.

Adjustment of administrative divisions can also affect the urban expansion area and form. From 2010 to 2017, Xuchang and Kaifeng had the highest annual expansion rates, and the intervals of fitted curves in Kaifeng and Xuchang in 2010–2017 were higher than they were during the first three periods (1978–1990, 1990–2000, 2000–2010). During a series of administrative divisions adjustments, Kaifeng County was incorporated into the Xiangfu District of Kaifeng City in 2014, and Xuchang County was incorporated into the Jian'an District of Xuchang City in 2016. Consequently, the peak of Kaifeng shifted left from 2010 to 2017. With the development of a new urban district, the municipal government of Jiaozuo City moved southward about 4 km from Jiefang Road of the Shanyang District to Renmin Road of the Jiefang District in 2003, which caused a new expansion center to appear in south Jiaozuo.

5.4 Limitations and uncertainties

The spatiotemporal characterization of urban form and expansion heavily relies on remote sensing data, and the quality of this data can have a huge impact on the results. In this study, we revealed the urban expansion process and form in the ZZMA by using a dataset of impervious surfaces for China. In particular, we examined data from 1978 with 60 m spatial resolution and data from 1985 to 2017 with annual temporal resolution and 30 m spatial resolution (Gong et al., 2019). This dataset was primarily developed based on Landsat images using the supervised classification method. The classification error due to mixed pixel effect in these data may influence the results of our analysis. In addition, we did not conduct the sensitive analysis of buffer intervals, which are set as 1 km. Due to a lack of data from 2018 to 2021, we also do not know what happened during this period, which was when many new policies were issued, such as '*Development Planning of Central Plains Urban Agglomeration*' in 2017, '*Spatial Planning of Zhengzhou Metropolitan area* (2018–2035)' in 2019, '*Ecological Protection and Construction Planning of Zhengzhou Metropolitan Area* (2020–2035)' in 2020, and '*Zhengzhou-Jiaozuo Integrated Development Plan* and *Traffic Integration Development Planning of Zhengzhou Metropolitan Area*' in 2021.

We analyzed possible drivers of metropolitan area expansion, including socioeconomic, land use policy, and urban planning factors, but neglected other factors such as physical characteristics, including topography,elevation, and slope (Li et al., 2013), the neighborhood factor (Li et al., 2018) , urban infrastructure construction, and resident income (Ma and Xu, 2010). Furthermore, we do not quantify the complex coupling relations among different factors and their contributions to urban expansion. These types of questions are important for understanding the mechanisms of metropolitan area expansion, especially in major national grain-producing areas. In future research, the regression model (Chen et al., 2016) or Geographical Detector model (Wang et al., 2010; Zhang et al., 2020) can be introduced to detect the contributions of different factors to urban expansion. What we should do is reveal the mechanism of different drivers and describe the process of urban expansion, which would provide new understandings that could help solve the conflict between metropolitan area expansion, cropland protection, and ecological security in major grain-producing areas.

6 Conclusions

The Zhengzhou metropolitan area (ZZMA) in the central China has experienced dramatic urban expansion. From 1978 to 2017, they increased from 1247.10 to 3719.54 km^2, which is a pattern that follows an exponential curve. The urban land density decreased with the distance from the city center to the outskirts. The ZZMA entered into a stage of significant expansion from 2000 to 2010, which triggered urban expansion in the hinterlands of core cities. The urban core gradually expanded outward, and the hot-zone of urban growth moved progressively with the acceleration of urbanization from 1978 to 2017.

There is great heterogeneity in the expansion of different cities located in major grain producing areas. The largest city (Zhengzhou) had the biggest expansion areas, and smallest city (Xuchang) had the fastest expansion rate during the 1978–2017 period. The expansion intensity of different areas within a city was different. The main urban area of the large city (Zhengzhou) experienced faster expansion at 10–15 km from the city center, while medium- and small-sized cities decreased rapidly within 10 km from the city center. The large city was more compact than medium- and small-sized cities that were decentralized and easily affected by adjustment and location change of administrative divisions. By comparing urban area with urban population and GDP using the power scaling law, the effectiveness of wealth creation efficiency in the urbanized area can be tested in all cities. It was found that the large city is relatively better positioned than smaller cities in terms of the efficiency of its urban infrastructure. In major grain producing areas, strict cropland protection system affects urban expansion significantly, the cities in national core grain-producing areas has higher cropland contribution rates (CRs) and lower urban expansion areas, however, the core area of ZZMA that were not in national core grain-producing areas had a higher urban expansion areas and cropland contribution rates. In addition, policy factors, cropland, the five-year plan, and the adjustment of administrative divisions, played important roles in the urban expansion of the ZZMA.

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