Does cropland threaten urban land use efficiency in the peri-urban area? Evidence from metropolitan areas in China

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THIS IS THE ACCEPTED VERSION OF THE ARTICLE PUBLISHED AS:

Lu, Y., He, T., Yue, W., Li, M., Shan, Z., & Zhang, M. (2023). Does cropland threaten urban land use efficiency in the peri-urban area? Evidence from metropolitan areas in China. Applied Geography, 161, 103124. https://doi.org/10.1016/j.apgeog.2023.103124

Highlights

- High percentage of cropland in peri-urban area threatens urban land use efficiency (ULUE).
- Intensive cropland occupation tends to drive compact urban growth.
- Compact urban expansion compelled by cropland conservation does not present high ULUE.
- Cropland significantly undermines the ULUE of infilling expansion patterns.
- A balanced policy approach for cropland conservation and urbanization is advisable.

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Abstract

In recent decades, cropland policies have been recognized as crucial tools for ensuring food security and managing urban growth. However, whether cropland conservation undermines urban land use efficiency (ULUE) in peri-urban areas has not been adequately studied. This study investigated the impact of cropland on ULUE in the peri-urban areas of 36 rapidly urbanizing metropolitan areas in China. Multiple open-source datasets were used, including land use, land cover, three-dimensional building structure, and nighttime light (NTL) data. Urban construction land patterns (infilling, edge, outlying) were categorized to examine the intermediate role of urban form in the correlation between cropland and ULUE. The findings indicated that: (1) high proportion of cropland area within the peri-urban areas significantly undermined ULUE; (2) although the conservation of cropland is conducive to compact urban growth, the infilling expansion pattern that compelled by cropland conservation would not sustain intensive human activity; and (3) reducing the spatial separation between conserved cropland and urban construction land was conducive to the dual objectives of protecting cropland and promoting ULUE. This study contributed to the development of a nuanced understanding of cropland protection policies that balance national food security and urbanization efficiency.

Keywords: Cropland conservation; Urban land use efficiency; Urban expansion; Land cover; Metropolitan area; Land use and land cover change

1 Introduction

Unprecedented urban expansion has occurred globally in recent decades (Alcock et al., 2017; Shahbaz et al., 2017; Son et al., 2015). The urban area has grown almost twice as fast as the urban population on average (Angel et al., 2011; X. Liu et al., 2020; Seto & Shepherd, 2009), and it is predicted that the global urban area in 2030 will be three times larger than that of 2000 (Seto et al., 2012). Rapid urban expansion has caused a significant loss of cropland in most developing countries (Vitousek et al., 1997; Fazal, 2000; Turner et al., 2007; Song et al., 2015). By 2030, 80% of the global cropland reduction due to urban expansion is expected to occur in Asia and Africa (Bren et al., 2017). Given that over 60% of the world's irrigated croplands are situated near urban areas, there is growing potential for land competition between agricultural and urban uses in the peri-urban areas of metropolitan areas (Thebo et al., 2014; Dadashpoor & Somayeh, 2019; Ann et al., 2015).

In China, cropland protection policies play a significant role in managing urban growth in peri-urban areas (Feng et al., 2015; Zhong et al., 2018). From 1990 to 2006, China's construction land increased by 54080 km^2, while cropland was reduced by 131140 km^2 (T. Liu et al., 2015). 44.1% of newly added construction land is converted from cropland. Another study indicates $930*10^4$ km^2 of cropland were converted to built-up areas during 2000-2018 (Chang et al., 2022). The early peri-urban areas of major Chinese cities converted to urban areas rapidly with dense construction land in the past decades (Jiao, 2015). As a result, the peri-urban area is considered to be a transitional zone between fully urbanized land in cities and predominantly agricultural areas (Rakodi, 1998) and is characterized by land transitioning from rural to urban use (Network, 2008). The cropland protection policy in these areas comprises the establishment of a dynamically balanced system and basic cropland zoning. As a result, the cropland protection policy not only restricts the amount of urban construction land growth but also has a complex influence on its landscape pattern. First, the dynamically balanced cropland protection system stipulates the total amount of cropland in each administrative unit, restricting the conversion from cropland to urban construction land. Second, the dynamically balanced cropland protection system allows cropland displacement under the premise of keeping the total amount of cropland constant, which further promotes compact urban growth. Third, in the quality management of cropland, basic cropland zoning defines the spatial boundaries of the most fertile cropland that cannot be converted (Wu et al., 2017), which leads to fragmented patches of urban construction land.

The newly increased urban function is expected to be sustained by the limited amount of urban construction land, which emphasizes the need to promote urban land use efficiency (ULUE). Previous studies of ULUE have regarded urban construction land as a scarce resource (Lambin & Meyfroidt, 2011), which is expected to facilitate economic production (Cao et al., 2019; Jingxin et al., 2022). Accordingly, ULUE represents the efficiency of the transformation from urban construction land to economic benefits such as GDP contributions and the number of employees (Yu et al., 2019). In line with this definition, the input-output function is widely used to define ULUE and urban construction land has been considered one of the input elements to evaluate its role in socio-economic development (Y. Chen et al., 2016). The related literature commonly applied the Data Envelopment Analysis (DEA) model for the ULUE analysis and evaluation. This model was developed based on a relatively efficient concept and assesses and sorts the relative effectiveness of various decision-making units when considering multiple input and output factors (Olesen, 2006). Other studies, following the goals outlined under SDG 11 (Agenda, 2017; Zitti et al., 2015; Chakraborty et al., 2022), have defined ULUE as an indicator of the ratio between urban area expansion (land consumption) and population growth rate (Corbane et al., 2017; Zhang et al., 2020). Essentially, this definition regards the population carrying capacity as the output in terms of ULUE measurement, which is consistent with the concept of an input-output function.

Because the amount and spatial configuration of new urban construction land is restricted by conserved cropland, the impact of the landscape pattern of urban growth on ULUE plays a significant role. Urban form is related to the spatial patterns of human activities and is closely associated with economic productivity(S. He et al., 2020b). Most previous studies have attributed efficient land use to a compact urban form. For example, Xu et al., 2020 proved that a compact urban form and expansion patterns can slow down the decline in population density based on 200 global cities. Correspondingly, higher degrees of dispersion led to relatively low economic productivity measured by per capita GDP in a case study of 306 Chinese cities (Y. Li & Liu, 2018). The impact of a fragmented urban landscape on ULUE was also confirmed by the negative correlation between edge type-based metrics, such as patch density, and the added value of secondary and tertiary industries (S. He et al., 2020a). Such a dispersed urban landscape is likely to be a consequence of fast urban growth and the over-supply of urban construction land (Koroso et al., 2021; Y. Liu et al., 2018). Simultaneously, the negative effect of dispersion on ULUE could be attributed to weak scale economies effect and more restrictions in international production networks (Kimura & Ando, 2003). A fragmente d urban landscape is common in China's peri-urban areas due to the mismatch between rapid urban expansion and the spillover of urban functions (Zheng et al., 2017a; T. Li et al., 2010). Moreover, the existing fragmented land use pattern is difficult for redevelopment due to the uncertainty caused by volatile redevelopment policies, absence of trust between local government and villagers, long-time reliance of villages on land leasing income, and high transaction costs to achieve consensus among villages (Boyi et al., 2018). In comparison, a continuous and regular shape of urban construction land will reduce the construction costs of transportation networks and local public services (Yan et al., 2022). As a consequence, a compact urban form could promote ULUE by increasing urban patch cohesion as well as reducing edge fragmentation (Kii & Doi, 2005; S. He et al., 2020).

As the strict land use regulations imposed by cropland protection policies interfere with spontaneous urban growth and increase the fencing of land, social and economic networks between urban construction land are weakened, and the functional isolation of the dispersed urban built-up land patches is further exacerbated. However, the effect of cropland protection on ULUE has not received adequate attention. Specifically, an examination of this relationship requires the mediated role of the spatial pattern of urban sprawl to be investigated, which has been a contentious subject in previous studies. Some studies have indicated that cropland constraints are essential for enhancing ULUE by preventing the dispersed expansion of urban construction (T. Liu et al., 2015; Qianwen et al., 2017). Conversely, other studies have argued that strict agricultural zoning policies may trigger a “leapfrog” effect on urban expansion and threaten ULUE (McConnell et al., 2006; Yin & Sun, 2007; Zhong et al., 2018). This contradiction suggests that quantitative and qualitative cropland protection policies would result in diverse landscapes of urban construction land (Vyn et al., 2012). In other words, the strict land use regulation of cropland leads to various urban expansion consequences, including compact and dispersed growth. Thus, their combined influence on the urban landscape needs to be further explored.

The investigation of the correlation between cropland protection and ULUE also require finer methods used to evaluate ULUE (Guastella et al., 2017). Essentially, the conventional ULUE concept focuses on the external benefits that accrue from urban land use. Thus, evaluation methods including DEA are commonly associated with input-output models that employ the “black box” concept (Jingxin et al., 2022). In detail, these methods measure the ratio of the input and output factors of land use, which commonly proceeded in administrative units and is correlated with various external background factors, such as population, globalization, transportation networks, urbanization, and marketization (S. He et al., 2020; C. Wu et al., 2017). However, this ULUE evaluation ignores the process of land use, which is propelled by internal human activities and is characterized by physical land utilization intensity. Human activities are associated with artificial and physical land use processes and act as a necessary link between land consumption and benefits production. In this sense, human activity intuitively reflects the ULUE in a “white box” method. Importantly, the intensity of human activities is largely determined by the compactness of urban form in the peri-urban area (Ye et al., 2018; Xia et al., 2020), which is affected by cropland proportion. The conserved cropland surrounding the construction area reduces the street connectivity and blocks the traffic network, which is confirmed to be an adverse factor in the visit frequency of urban facilities (Chiang & Li, 2019). In this sense, the conserved cropland potentially threatens human activities in the peri-urban area.

An evaluation of human activity intensity is therefore required in the ULUE measurement. Correspondingly, in this study, ULUE was defined as the actual amount of human activity loaded per unit of urban construction land. Specifically, the human activity associated with land use consists of two parts: construction activity and urban socio-economic activity. This definition aligns with urban vitality theory and conceptualizes ULUE as the raw power and energy of a city (Jane, 1961). It primarily depends on a well-developed urban morphology and extensive urban activities. Therefore, we specifically measured ULUE using a composite indicator that combined urban land construction intensity and urban socio-economic activity. To measure these two factors at a finer scale, we used building volume density (BVD) data and nighttime light (NTL) data (Deng et al., 2009b; Q. He et al., 2018; Xia et al., 2020; Zheng et al., 2017b). These two human activity indexes presented the three-dimensional building structure (M. Li et al., 2020) and spatial distribution of intra-urban socio-economic activities (Zheng et al., 2023), which indicate physical urban construction land use intensity in different dimensions. The high spatial resolution of these data allowed us to adequately identify the ULUE of urban land patches in diverse landscape patterns.

Additionally, as the central government intensified cropland protection around urban areas (SCP, 2017), we incorporated the proportion of cropland (PC) in the peri-urban area to assess the influence of cropland protection on the landscape patterns of urban built-up land. To achieve this, we used micro-scale geographical open-access product data to detect urban construction land (Gong et al., 2020) and cropland with a resolution of 30 m (Potapov et al., 2022).

The primary objective of this study was to better understand the impact of cropland protection on the ULUE in peri-urban areas. We aimed to provide strategies for land use regulation and sustainable planning that would promote ULUE (Chakraborty et al., 2021; B. Chen et al., 2021). To achieve these objectives, we examined the relationship between conserved cropland and ULUE in 36 metropolitan areas within peri-urban regions. Subsequently, we addressed the following research questions. (1) How does cropland preservation influence the spatial pattern of urban construction land? (2) What are the differences in ULUE among urban construction land in various spatial patterns? (3) How does the ULUE of urban land patches in different landscape patterns vary with different cropland preservation policies? The structure of the paper is as follows. Section 2 provides an overview of the data collection process and research methodology employed in this study. Section 3 presents the empirical findings derived from the analysis. In Section 4, we discuss the pathways through which cropland affects ULUE. Finally, the concluding section summarizes the key points of the paper and highlights its theoretical implications.

2 Data collection and research methodology

2.1 Study area

In recent decades, China's metropolitan areas have undergone significant urbanization and spatially heterogeneous urban expansion. In this study, we selected specific metropolitan areas based on the city classification scheme provided by Fang (2021) (Fig. 1). The selected metropolitan areas were subject to direct authorization and supervision by the central government in terms of spatial planning (Zhong et al., 2018). Consequently, these areas have implemented relatively stringent cropland protection policies and thus, significant land use conflicts have arisen between cropland and constructed land.

Previous literature has not reached a consensus on the spatial boundaries of metropolitan areas in China. Therefore, we used the Major Functional Oriented Zoning as a framework to determine the boundaries of the metropolitan areas (Wang & Fan, 2020). This national zoning determines the function that each county-level administrative unit should undertake in the national sustainable development system. By combining the central cities of the metropolitan areas with the urbanization zones defined by Major Functional Oriented Zones, we were able to establish the boundaries for 36 metropolitan areas based on the following rules (Fig. 2). We included all county-level units located within the administrative boundaries of the central cities. Then, we incorporated the urbanization zones that spatially adjoined the administrative boundaries of the central cities. Based on the regional classification scheme proposed under regional economics (Kuang et al., 2016), we divided the metropolitan areas into four broad geographical categories: eastern, central, western, and northeastern areas (Fig. 1, Table. 1). Furthermore, we refined 588 county-level units by removing those which has no more than 5% impervious surface areas in the peri-urban areas. All these county-level units are in the selected metropolitan areas.

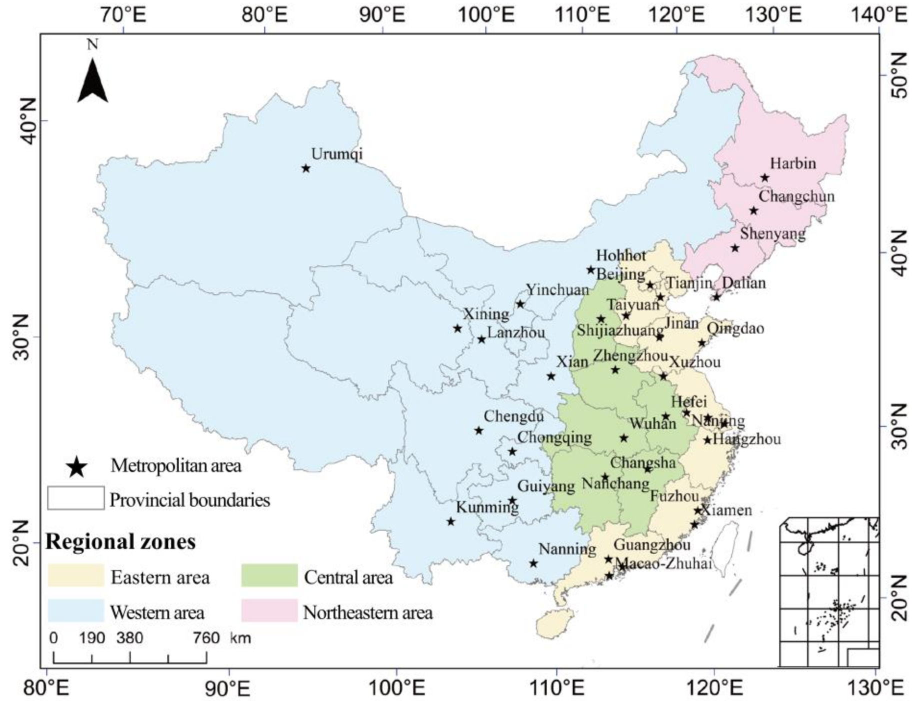

Figure 1. Regional zoning of the selected metropolitan areas

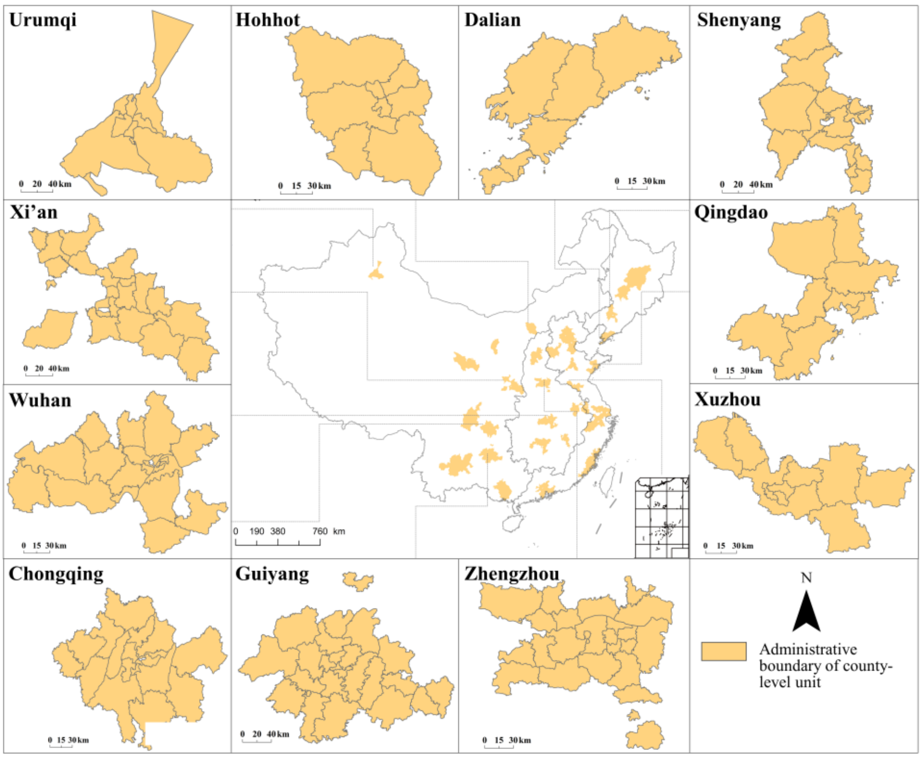

Figure 2. Selected metropolitan areas and administrative boundaries of the county-level units

Table 1. Metropolitan areas and the number of county-level units in different regions

	Metropolitan areas	Number of county-level units
Eastern area	Macao-Zhuhai, Beijing, Fuzhou, Shenzhen-Hongkong, Guangzhou, Hangzhou, Jinan, Nanjing, Qingdao, Xiamen, Shanghai, Shijiazhuang, Suzhou-Wuxi-Changzhou, Tianjin, Xuzhou	223
Western area	Chongqing, Chengdu, Guiyang, Xi'an-Xianyang, Lanzhou, Kunming, Xining, Hohhot, Yinchuan, Urumqi, Nanning	202
Central area	Changsha, Nanchang, Wuhan, Hefei, Zhengzhou, Taiyuan	110
Northeastern area	Shenyang, Harbin, Changchun, Dalian	53

2.2 Data preprocessing

Global artificial impervious area (GAIA), which is an open-source database published by Gong et al (2020), was used to extract urban construction land for this study. GAIA provides global artificial impervious area data with a resolution of 30 m. It also maps the global urban boundaries derived from the artificial impervious area data (X. Li et al., 2020). The wide coverage scope and resolution of GAIA are superior to other similar datasets, such as CORINE land cover data (Aune-Lundberg & Strand, 2021), which only covers the European region with a resolution of 100m. In this study, a two-step procedure was used to prepare for newly grown urban construction land. First, we identified the peri-urban area in

2018 by extracting the urban boundaries of 2005 from those of 2018 (Fig. 3a). The peri-urban area refers to the region that was previously agricultural land but has experienced peri-urbanization (Tian, 2015). In this study, the average distance between peri-urban areas and related urban cores is 68.83 km^2 (Appendix. A). Second, we applied the GAIA database to extract the new areas with an impervious surface within the peri-urban area (Fig. 3b, c). In order to draw a clear figure, we convert the raster data to shapefile in ArcGIS.

A global cropland map of the four-year period of 2016–2019 at 30 m spatial resolution provided by Potapov et al. (2022) was used to extract cropland for this study (Fig. 3b, c). This widely-used dataset used the global 16-day normalized surface reflectance Landsat Analysis Ready Data as input data for cropland mapping. Moderate Resolution Imaging Spectroradiometer (MRIS) surface reflectance was applied as a normalization target to normalize the Landsat top-of-atmosphere reflectance. The cropland map accuracy was examined by a sample analysis, which randomly selected 100 sample units (Landsat data pixels) from each stratum. Then, we extracted the cropland within peri-urban areas (Fig. 3a) and calculated the PC in the peri-urban area for all county-level units.

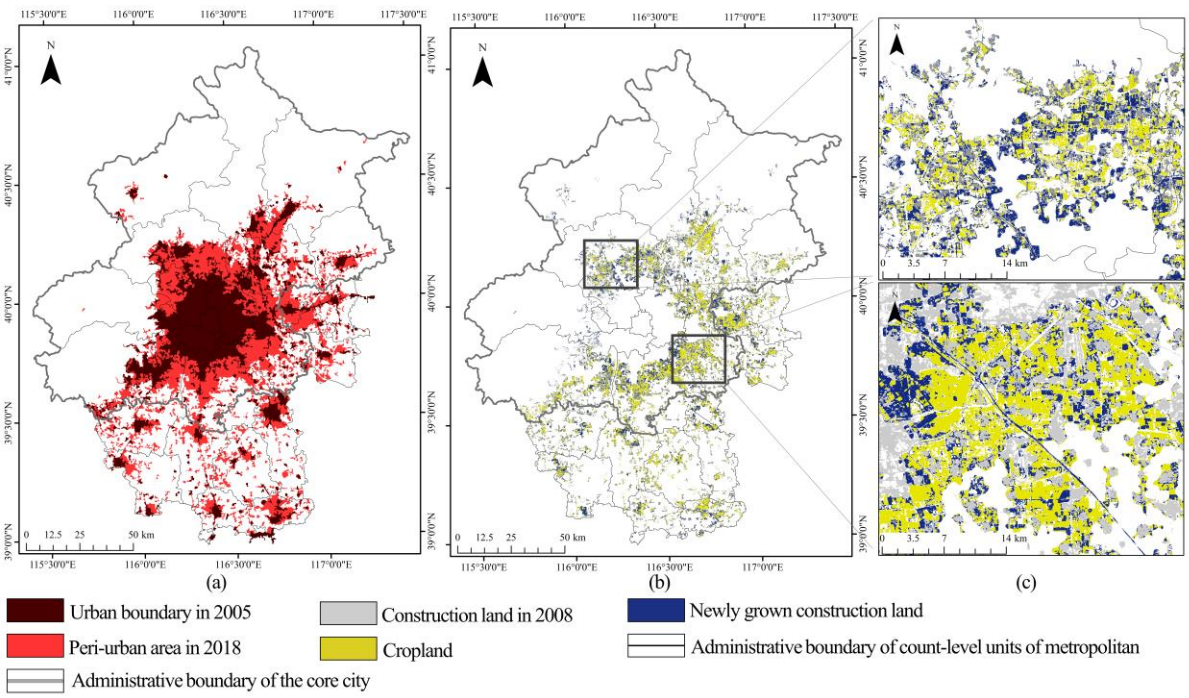

Figure 3. The peri-urban area and urban construction land extraction process. (a) Peri-urban area of Beijing metropolitan area. (b) Cropland and urban construction land within the peri-urban area of Beijing. (c) Zoom-in image showing the details of cropland and urban construction land in a fragmented landscape pattern.

The calculation of ULUE involved the use of NTL and BVD data with a spatial resolution of 500 m (Table 2). For the NTL data, we used the 2018 data from the extended time series (2000 to 2018) of the National Polar-orbiting Partnership Visible Infrared Imaging Radiometer Suite (NPP-VIIRS) NTL dataset constructed by Z. Chen (2021). The BVD data was provided by M. Li et al. (2020) and had a resolution of 500 m. This dataset enabled us to extract information regarding urban 3D building structure, including building footprints, heights, and volumes. In order to identify the NTL and BVD values of the urban construction land, we resampled the impervious surface area derived from GAIA with 30m*30m grids in all the county-level units' peri-urban area, which aligned with the spatial resolution of the impervious area and cropland data. Then, we combine a GIS analysis with a sub-pixel method to calculate BVD and NTL of all the county-level units, which is a powerful tool for calculating and describing some properties of environmental data within an area (Valjarević et al., 2018). We first recognize different index values of the resampled girds at 30 m resolution within the impervious surface area in all the county-level units' peri-urban areas. Then, we calculate the area-weighted NTL and BVD value of the grids in each county-level unit, which is the analysis unit of this study. The area-weighted NTL and BVD values of the analysis units are prepared for further ULUE evaluation.

Furthermore, we accounted for the influence of other socio-economic indicators on ULUE, as outlined in Table 2. Two additional indicators were considered. (1) Average land GDP was used to assess the economic development level of all 588 county-level units. The data for average land GDP were obtained from an open-source database published by the Resource and Environment Science and Data Center (Gong et al., 2020). The land GDP data at a resolution of 1 km per pixel were used to calculate the average land GDP values for all county-level units. (2) Average population densities of all 588 county-level units were calculated using data from the sixth national census and the China land cover dataset provided by Yang and Huang (2021).

Table.2 Datasets information (Abbreviation)

Description	**Time**	**Spatial resolution**	**Dataset and data source**	**Reference**
Urban construction land data	2018	30m	Global Artificial Impervious Area (GAIA) http://data.ess.tsinghua.edu.cn/gaia.html	Gong et al., 2020
Cropland data	2016–2019	30m	Global cropland expansion dataset https://glad.umd.edu/dataset/croplands/	Potapov et al. (2022)
Nighttime light data (NTL)	2018	500m	Global NPP-VIIRS-like nighttime light data https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/YGIVCD	Z. Chen (2021)
Building volume density (BVD)	2018	500m	Continential-scale 3D Building Structure Data https://www.landbigdata.info/cscproject/	M. Li et al. (2020)

GDP data			China GDP spatial distribution kilometer grid dataset https://www.resdc.cn/DOI/DOI.aspx?DOIID=33	(Gong et al., 2020)
Population density data	2018	100m	The sixth national census and China land cover dataset https://doi.org/10.5281/zenodo.4417810	Yang and Huang (2021)

2.3 Analysis of the urban construction land pattern

2.3.1 Urban construction land pattern classification

Urbanization is a multifaceted process that involves an interplay between urban expansion and urban dispersion, with various growth modes (Aguilera et al., 2011; C. Li et al., 2013). Therefore, we divided the urban construction land pattern into infilling expansion, edge expansion, and outlying expansion according to the spatial relationship between the new growth urban construction patterns and original patterns (Forman, 2014). The data source of urban construction land is the raster impervious surface patch derived from GAIA. Infilling expansion is a compact and intensive pattern that normally infills within the main urban built-up area while edge and outlying expansion away from the main existing urban built-up (Sun et al., 2013). To differentiate between these three urban expansion models, we used a classification method based on the intersection between existing and newly grown urban construction land (Fig. 4). This classification method was proposed by X. Liu et al. (2010) and has been widely used in research studies. The distinguishing analysis of the spatial pattern type of the newly grown built-up patches for the 588 county-level units is programmed and then conducted in Google Earth Engine (GEE) platform.

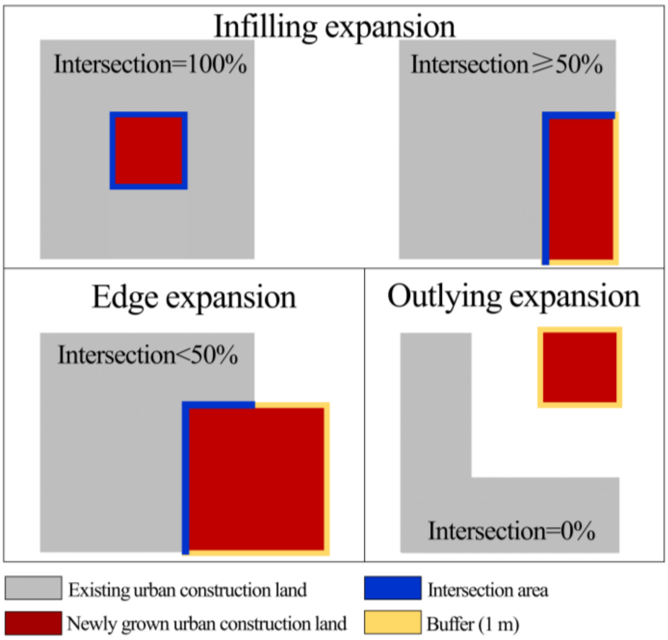

Figure 4. Graphical depiction of the spatial rules for the identification of urban construction land patterns

2.3.2 Normalized difference expansion index (NDEI)

The NDEI has been used to assess the compactness of urban expansion and identify the extent of infilling, edge, and outlying expansion (Chakraborty et al., 2022). It quantifies the dominance of urban construction land under the infilling mode in the total new built-up land in the peri-urban area (Eq. 2).

$$\mathrm{NDEI} = \frac{Area\ under\ infilling - Sum\ area\ under\ edge\ expansion\ and\ outlying}{Area\ under\ infilling + Sum\ area\ under\ edge\ expansion\ and\ outlying} \quad \text{(Eq. 2)}$$

The value of the NDEI ranges from – 1 to +1, signifying the compactness of urban expansion. A positive NDEI value indicates the dominance of inward urban expansion, whereas a negative NDEI value indicates the dominance of outward urban expansion.

2.4 Identification of ULUE and correlation analysis

Urban density and functional intensity are considered to be strong indicators in the assessment of ULUE (Q. He et al., 2018; Xia et al., 2020; Zheng et al., 2017b). We therefore calculated ULUE using the area-weighed NTL and BVD (Eq. 3, Eq. 4). These two indexes enable us to evaluate the extent of the artificial utilization of urban construction land with visible human activities, which is a “white box” method. The quantification method of each criterion for a certain evaluation unit was as follows:

$$\mathrm{NTL}_{mn} = \frac{\sum_{i=1}^{n} NTL_i}{n} \quad \text{(Eq. 3)}$$

where NTL_{mn} represents the mean NTL of the units, which equals the ratio of the accumulated illumination intensity to the number of evaluation pixels (n). n is the number of lit urban built-up land pixels in the selected area with a positive NTL value.

$$BVD_{mn} = \frac{\sum_{i=1}^{n} BVD_i}{n} \quad \text{(Eq. 4)}$$

where BVD_{mn} represents the mean BVD of the units, which equals the ratio of the accumulated building volume to the number of evaluation pixels (n). n is the number of urban construction land pixels in the selected area with a positive building volume value.

$$\mathrm{ULUE} = \mathrm{NTL_{mn}} \times \mathrm{BVD_{mn}} \quad \text{(Eq. 5)}$$

To examine the relationship between cropland conservation and ULUE, several correlation analyses were performed. First, a Pearson correlation analysis was conducted to assess the impact of cropland on urban construction land patterns and ULUE. A positive correlation indicated that a higher PC was associated with more infill expansion. Second, based on the significant correlation between the PC and ULUE in the Pearson correlation analysis, we further confirmed the influence of PC on ULUE by multiple linear regression. The average land GDP and average population densities of all 588 county-level units were applied as control variables. Third, the impacts of cropland on ULUE in different urban construction land patterns were examined. The NTL and BVD were used to calculate the

ULUE for different types of urban construction land patterns, including infilling, edge, and outlying expansion.

3 Results

3.1 Spatial variations of the PC and urban construction land pattern

The PCs of the 588 county-level units were used to map the regional differences across China (Fig. 5). The intensity of the cropland distribution in the peri-urban areas increased gradually from the southwest to the northeast. The northeastern region had the highest average PC of 0.23, which was twice as high as that of the western region. The eastern region had an average PC of 0.17, while the western region had a lower average PC of 0.11. Among the 36 metropolitan areas studied, those located in the north, such as Tianjin, Harbin, and Beijing, had the highest PCs (Appendix A). In contrast, metropolitan areas in the southern region tended to have lower PCs, including Shenzhen-Hong Kong, Guangzhou, and Macau-Zhuhai.

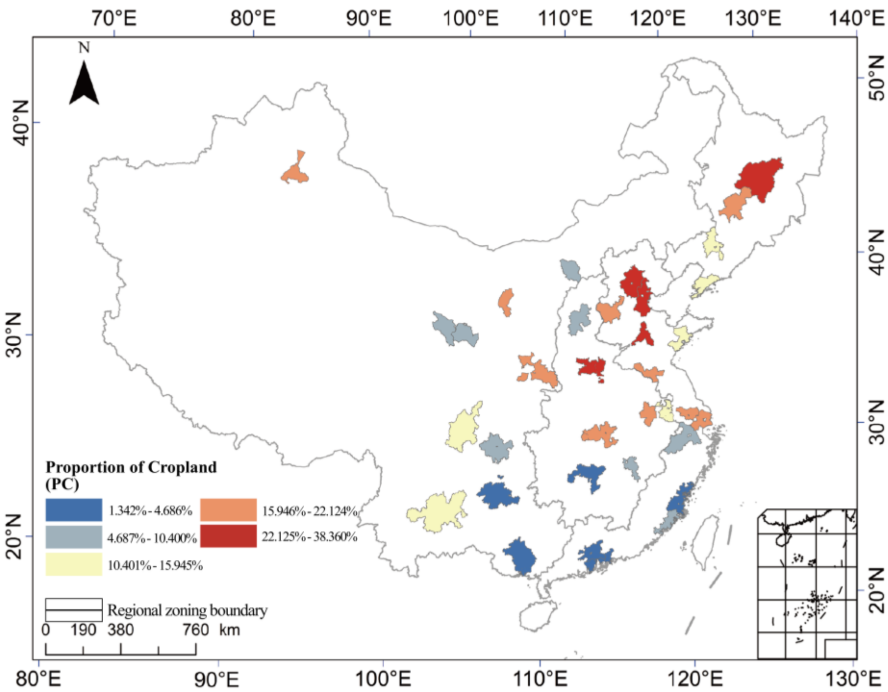

Figure 5. The proportion of cropland (PC) in the metropolitan areas

We categorized the expanded construction land into three growth modes: infilling expansion, edge expansion, and outlying expansion (Fig. 6). Infilling and edge expansion accounted for most of the total urban expansion. Specifically, infilling expansion accounted for 44.54% of the total, while edge expansion represented 51.57%. In contrast, outlying expansion accounted for only a small proportion of 3.89%. Accordingly, 22 of the 36 metropolitan areas had an NDEI larger than 0 (Appendix. A, Fig. 7). The metropolitan areas with the highest NDEI values were primarily located in the eastern region, including Suzhou-Wuxi-Changzhou, Shanghai, and Nanning. The remaining 14 metropolitan areas had negative NDEI values, with Guiyang, Changsha, and Hohhot being among the areas with the lowest values.

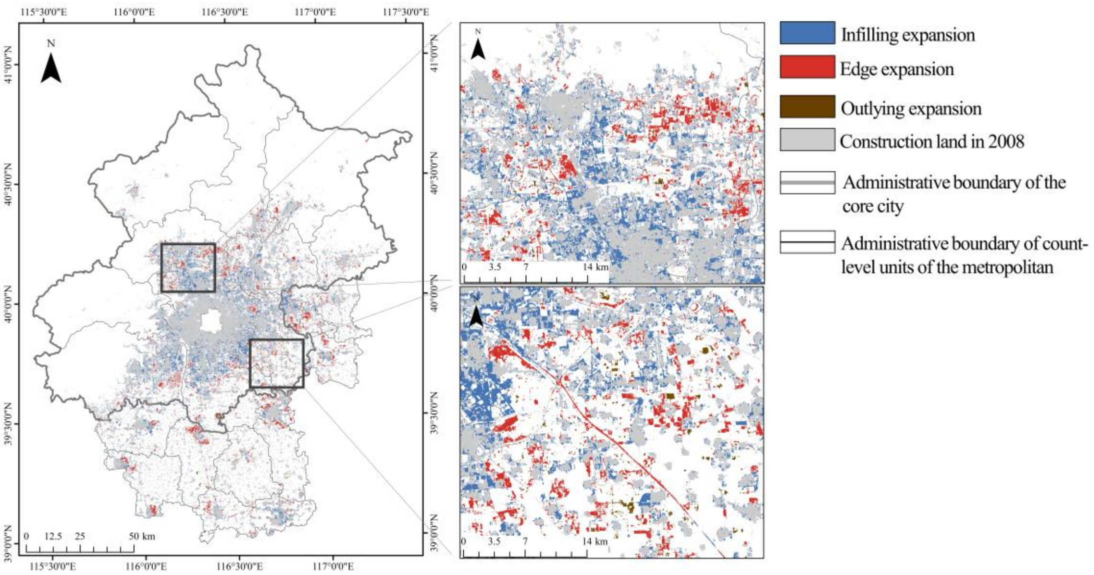

Figure 6. The different types of urban expansion (infilling, edge, outlying expansion)

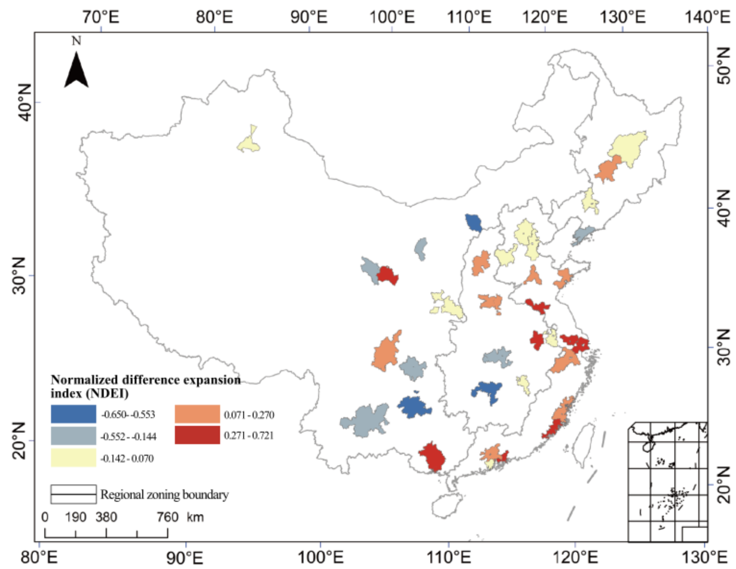

Figure 7. Normalized difference expansion index (NDEI) of the metropolitan areas

The analysis of the average NDEIs in different geographical regions provides an insight into the variation of urban construction land patterns across the country (Fig. 8). The average NDEI of the eastern area was 0.216 (Table 3), which was significantly higher than that of other regions. This finding indicates that metropolitan areas in the eastern region exhibited a more compact urban construction land pattern, characterized by a higher proportion of infilling expansion. In contrast, the western area had a dispersed urban construction land pattern, which was evidenced by its average NDEI of -0.111. The average NDEIs of the northeastern and central areas were close to 0, indicating that compact infilling and dispersed expansion are relatively equal.

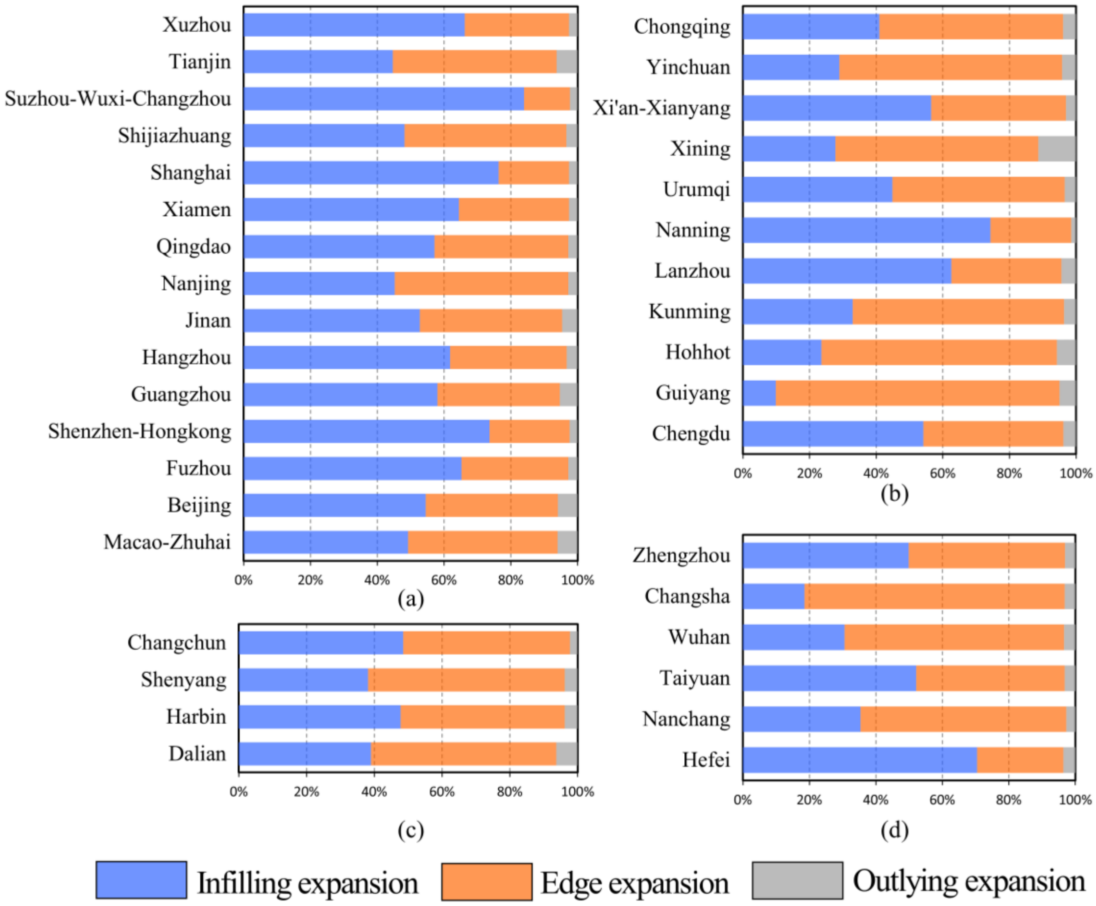

Figure 8. Percentage of different urban expansion types: (a) eastern area; (b) western area; (c) northeastern area; (d) central area

Table. 3 Average proportion of cropland (PC) and normalized difference expansion index (NDEI) values of county-level units in different regions

	PC	NDEI
Northeastern area	0.232	0.001
Eastern area	0.166	0.216
Western area	0.111	-0.111
Central area	0.145	-0.066

3.2 The spatial variation of ULUE

There was significant variation in ULUE among the 36 metropolitan areas (Fig. 9). Metropolitan areas in the southern region had higher NDEI values, with the Shenzhen-Hongkong metropolitan area having the highest ULUE, followed by Suzhou-Wuxi-Changzhou. Guiyang and Nanchang ranked third and fourth, respectively. In contrast, metropolitan areas in the northern region tended to have a lower ULUE, including Harbin, Urumqi, and Jinan. The ULUE of Shenzhen-Hongkong was nearly 23 times higher than that of Harbin, which had the lowest ULUE. The ULUE also differed among different regional zones (Table 4). Moreover, the ULUE varied across different regional zones (Table 4). Eastern metropolitan areas had the highest ULUE, with average NTL and BVD values of 9.963 and 10.325, respectively. Western metropolitan areas had a slightly higher ULUE compared to central metropolitan areas, ranking second after the eastern areas.

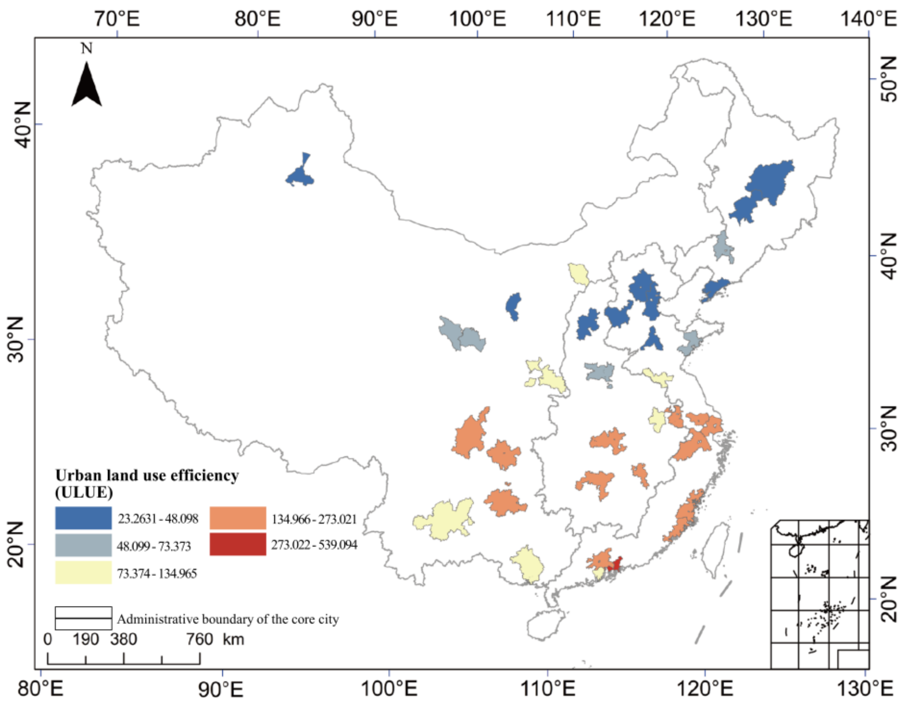

Figure 9. Urban land use efficiency (ULUE) of the metropolitan areas

Table 4. The average used building volume density (BVD) data and nighttime light (NTL), and urban land use efficiency (ULUE) of county-level units in different regions

	NTL	BVD	ULUE
Northeastern area	7.776	4.722	46.365
Eastern area	9.963	10.325	131.994
Western area	11.629	9.635	124.304
Central area	10.176	9.471	115.770

Urban construction land patterns in different expansion models exhibited differences in ULUE (Table 5). The ULUE of the infilling expansion pattern was significantly higher than the edge and outlying expansion patterns, reaching 293.709 nationwide. The outlying expansion patterns demonstrated the lowest ULUE. Nationwide, the ULUE of infilling expansion patterns was approximately three times higher than that of edge expansion patterns and about thirty times higher than that of outlying expansion patterns.

Table. 5 The urban land use efficiency (ULUE) of different urban built-up land expansion patterns

	Nationwide	Eastern	Center	Western	Northeast
ULUE of Infilling	293.709	282.098	324.429	321.594	172.525
ULUE of Edge	98.074	93.068	119.609	107.622	38.058
ULUE of Outlying	10.331	52.652	18.341	16.006	37.675

3.3 Correlation analysis

3.3.1 Impact of cropland on the urban construction land pattern and ULUE

The correlations between the PC and urban expansion compactness were investigated. The results showed that PC and NDEI were significantly correlated at the national scale, with a Pearson correlation coefficient of 0.107 (Table 6). Furthermore, we investigated the correlations between the PC and the proportion of different urban construction land patterns. The results showed that the PC was positively correlated with the proportions of infilling and outlying expansion areas but negatively correlated with the proportion of edge expansion area (Table 6). Considering that the outlying expansion only accounted for a small fraction of the new built-up land (Figure. 8), it was concluded that the increase in cropland area was conducive to compact urban growth.

Table 6. Pearson correlation analysis between the proportion of cropland (PC) and the percentage of infilling, edge, and outlying expansion

	Percentage of infilling expansion	Percentage of edge expansion	Percentage of outlying expansion
PC	0.107^{***}	-0.124^{***}	0.082^{**}

Note: ***, **, and * indicate significance at the 1%, 5% and 10% levels, respectively.

The Pearson correlation results indicated a significant negative correlation between the PC and ULUE. Table 7 and Figure. 10 shows that the PC and ULUE were negatively correlated in different regions. The Pearson correlation coefficients were -0.338, -0.369, -0.157, and -0.487 for the eastern, central, western, and northeastern areas, respectively. All the correlation results are in a confidence interval at 1% level (Table 7). However, with the highest PC in the peri-urban area, the ULUE of urban construction land tended to be low. These results confirmed the significant and negative relationship between the PC and ULUE.

Nevertheless, a small number of samples in the 30% to 60% interval has a very low ULUE (Figure. 10). Meanwhile, there is not a particularly large difference in the PC from 0 to 30%. These results indicate the linear correlation between the PC and ULUE is not persistently stable in line with the variation of PC. In detail, the land use efficiency of some fragmented construction land patches surrounded by large areas of cropland may lead to extremely low ULUE. In addition, human activity remains intensive in compact urban areas and has not been affected by a slight increase of cropland within a certain degree. Therefore, ULUEs are not in line with the variation of PC in the range from 0 to 30%.

Table 7. Results of a Pearson correlation analysis between the proportion of cropland (PC) and urban land use efficiency (ULUE)

	Nationwide	Eastern area	Central area	Western area	Northeastern area
PC	-0.338^{***}	-0.383^{***}	-0.369^{***}	-0.157^{**}	-0.487^{***}

Note: ***, **, and * indicate significance at the 1%, 5% and 10% levels, respectively.

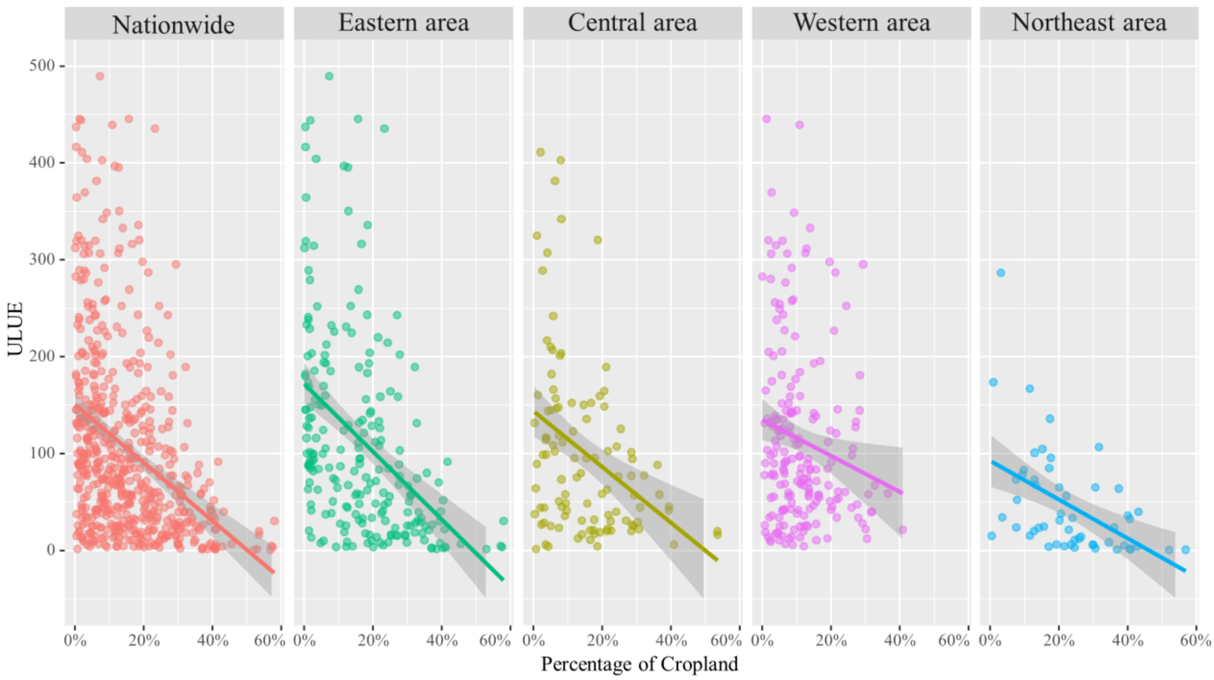

Figure 10. Scatter plot of the proportion of cropland (PC) and urban land use efficiency (ULUE) nationwide and in the eastern, central, western, and northeastern areas

A multiple regression analysis was applied to examine the net contribution of the PC to ULUE when other contributing factors were controlled, including population density and per-land GDP. The correlations between the PC and ULUE obtained in all models were significantly negative (Appendix. B). This result confirmed that the PC had a negative effect on ULUE, even when accounting for other contributing factors.

3.3.2 Impacts of cropland on the ULUE of different urban construction land patterns

Table 8 presents the relationships between the PC and ULUE of infilling, edge, and outlying expansions. The results indicate significant negative effects of cropland on the ULUE of infilling and edge expansions. The Pearson correlation coefficients between the PC and ULUE of infilling and edge expansions were -0.338 and -0.266, respectively, on a nationwide scale. This suggests that the ULUE of infilling expansion was more adversely affected by the increase in cropland than edge expansion. Similar significant effects of the PC on the ULUE of infilling expansion were observed in the eastern, central, and northeastern regions. These findings imply that infilling expansions occurring in peri-urban areas with a high PC tended to have a relatively lower urban functionality per unit area.

Table 8. The results of a Pearson correlation analysis between the proportion of cropland (PC) and urban land use efficiency (ULUE) of different urban built-up land patterns in different regions

	PC of country units nationwide	PC of country units in the eastern area	PC of country units in the central area	PC of country units in the western area	PC of country units in the northeastern area
ULUE of Infilling	-0.338***	-0.444***	-0.433***	-0.038	-0.397***
ULUE of Edge	-0.266***	-0.354***	-0.260***	-0.188***	-0.138
ULUE of Outlying	-0.074	-0.118	-0.029	-0.113	0.138

Note: ***, **, and * indicate significance at the 1%, 5% and 10% levels, respectively.

The correlations between the PC and the factors contributing to ULUE, such as NTL and BVD, were also examined (Appendix C). The results showed that an increase in the PC had a significant negative impact on the NTL and BVD of infilling and edge expansions. The strongest correlation was observed for the relationship between the PC and BVD of infilling expansion, suggesting that a higher PC would lead to a noticeable decrease in the building density of infilling expansion areas.

4 Discussion

4.1 Land use conflicts between cropland and urban expansion

In China, the land use conflicts that arise in peri-urban areas differ from those in Western countries. These conflicts primarily stem from land resource competition between cropland conservation and urbanization rather than being driven by social values and interpersonal conflicts (Platt, 2004; Zou et al., 2019; Dunk et al., 2011; Vaske et al., 2007). Urban growth primarily took place on cropland and turned into the primary threat to food security in China (Jiang et al., 2012). This competition for land resources is a result of conflicting spatial regulation approaches between the central and local governments. The central government promotes cropland protection as a means to control urban sprawl driven by local governments and in an attempt to mitigate cropland degradation (T. Liu et al., 2015). Two decades ago, such competition between the central and local governments led to another land use conflict in China. Woodland and grassland achieved a certain degree of growth due to the conversion of cultivated land on slopes for the purpose of improved protection against soil erosion settled by the central government (G. Q. Chen & Han, 2015b). Also, the land use conflicts triggered by urbanization are different in China and Africa, where sustainable development depends on forest preservation (Valjarević et al., 2018). In this sense, land use conflicts around the world are reflections of the land use competition between various stakeholders. Specifically, the essential cause of China's land use competition is commonly traced back to the content of land use regulation between the central and local government.

While cropland conservation is a nationwide policy in China, the intensity of its implementation varies across different regions, as reflected in the spatial variation of the PC. Specifically, basic farmland preservation areas, which is the primary cropland protection policy, positively drive cropland landscape fragmentation changes (Penghui et al., 2021). The PC values of peri-urban areas in the northern regions were significantly higher than those in the southern regions, suggesting that cropland conservation is effective in the northern area. Additionally, urban expansion in the eastern region tends to be more compact compared to other areas, suggesting that the replacement of existing cropland with newly grown construction land is preferable in land use regulation. This situation suggests that local governments in the eastern region have prioritized urbanization and have adopted a cropland conservation policy that emphasizes a dynamically balanced system allowing cropland displacement (Y. Wu et al., 2017).

4.2 The intermediate role of the urban construction land pattern in the impact of cropland on ULUE

Our findings revealed an interesting relationship between the PC and ULUE. While an increase in the PC promoted compact urban expansion and enhanced ULUE, we also observed a negative impact of the PC on ULUE. This seemingly contradictory result suggests a complex influencing mechanism. Specifically, the conservation of cropland areas reduces the intensity of human activities in infilling urban expansion patterns. Therefore, although cropland conservation contributes to compact urban growth, it can also reduce the ULUE in certain expansion patterns. This highlights the need for a comprehensive understanding of the intricate relationship between the conservation of cropland area and urban expansion dynamics.

Moreover, our analysis suggested that the passive infilling expansion resulting from the conservation of cropland may not be as efficient as spontaneous infilling expansion in land use. Previous studies have highlighted the positive relationship between compact urban expansion and ULUE (Xu et al., 2020; Chakraborty et al., 2022). Our study suggested that spontaneous compact urban expansion is the main driving force promoting ULUE, rather than the passive infilling expansion triggered by land use regulations established by cropland protection policies. This may be because spontaneous compact urban expansion would create more social connections and a greater urban vitality, which is a good match with the surrounding socio-economic environment and land use functions that achieve a functional coordination between existing built-up areas and new built-up land (Fernández-Aracil & Ortuño-Padilla, 2016, Xia et al., 2020, Ewing et al., 2016). The benefit of the spontaneous compact urban expansion is probably more obvious in large cities, as it takes advantage of the existing social network and creates more social connections. This assumption is evidenced by an empirical study that found physical urban form with high patch density and large urban patch size is conducive to enhancing land use efficiency in large cities, while not in small cities (S. He et al., 2020). In comparison, the infilling expansion compelled by the conservation of cropland in the peri-urban area may not take full advantage of existing public services and infrastructure support, requiring additional investments to sustain adequate facility provision. Understanding the mechanisms by which cropland impacts ULUE will improve our understanding of the intermediate role of the urban construction land pattern on cropland conservation on ULUE.

4.3 Policy implications from the perspective of a coordination between cropland conservation and ULUE

In developing countries, policies aiming at protecting cropland often strive to find a balance between resource security and economic development (Valjarević et al., 2018). Correspondingly, coordinating the relationship between food security and the fast-growing population is a crucial issue in China (Y. Wu et al., 2017). Despite the central government releasing numerous edicts to protect agricultural land from conversion, cropland in China continues to be converted (Jiang et al., 2012). Empirical studies show that strict regulations on urban growth have limited benefits for cropland protection (Xi et al., 2012). In this sense, the policies concerning urban growth management and cropland protection should recognize the importance of maintaining agricultural productivity while accommodating urban growth. Therefore, it is important to carefully consider the cooperation between preserving cropland and promoting urbanization efficiency.

Previous studies have viewed cropland as a vulnerable component in urban expansion (Song et al., 2015; Y. Wu et al., 2014). However, the reality is that due to the pressing issue of food security, spontaneous urban expansion is now substantially restricted by conserved cropland and is converted into passive infilling patterns, which has a negative effect on ULUE. The efficient utilization of urban construction land in China has been evidenced by the fact that China is a net importer of built-up land use, especially an importer of industrial land use such as petroleum processing, nonmetal mineral products, and electric power (G. Q. Chen & Han, 2015). In the orientation of low carbon policy, the enhancement of the interaction between existing facilities should be encouraged for China's further urban land use efficiency improvement. On this account, land use planning concerning the spontaneous and compact urban expansion in the peri-urban area is demanded.

China's population has reached its peak value in recent years. It means that the demand for increasing urban land use would decline, as well as urban growth. Based on this consensual prediction, the spatial extent of urban areas and peri-urban areas would tend to stabilize. In other words, the conversion from peri-urban areas to urban areas would gradually slow down. Such prediction indicates that the land use optimization method in the peri-urban area has a profound significance. China's accelerating urbanization in the past has resulted in fragmented urban construction land patches in the metropolitan area, which is negatively related to ULUE (Dadashpoor et al., 2019; S. He et al., 2020) and, in return, fuels urban sprawl and fragmentation (Koroso et al., 2021). An optimized cropland conservation protection policy will avoid a fragmented landscape pattern, with the spatial interspersion of cropland and construction land.

Our study confirmed the positive impact of cropland areas on compact urban expansion, but relying solely on increasing the PC to promote ULUE is not advisable. Instead, we propose implementing a spatial separation between cropland and new built-up land to achieve the goal of cropland protection while maintaining a high ULUE. Conserved cropland should be concentrated outside the built-up area rather than dispersed in small patches within it. Such optimization of the land cover landscape is also conducive to improving cropland utilization efficiency by means of technical development and resource reallocation (G. Q. Chen & Han, 2015). Hence, the current cropland preservation policy, which emphasizes "supplementing permanent basic cropland in the peri-urban area according to the order from close to far" (MPA, 2016), may not be appropriate.

5 Conclusion

Developing countries face a dilemma due to the conflict between food security and urbanization. The rapid urbanization process has led to the peri-urban areas surrounding metropolitan regions becoming the primary sites for urban expansion. This has resulted in the scarcity of land resources and an emphasis on ULUE. The knowledge of the interaction between urban expansion and cropland is vital, given the potential large-scale land conflicts between agriculture and urban uses in an era of rapid mega-urbanization (Bren et al., 2017). In this study, building volume density data and nighttime light data were used to evaluate ULUE, which quantifies the extent of the artificial utilization during the land use process in a certain sociometric background. The method of urban construction land classification and NDEI measurement enables us to quantify the urban growth compactness, which further explicit the intermediate role of the urban construction land pattern in the impact of cropland on ULUE. Also, the correlation analysis confirms the significant impact of PC on ULUE. The findings of this study confirmed that while cropland conservation contributed to compact urban growth, it did not promote ULUE. In fact, an extensive cropland area within the peri-urban areas of metropolitan regions significantly undermined the ULUE of urban construction land. Although the conservation of cropland tended to drive compact urban growth, the infilling expansion pattern that results from a high PC would not sustain intensive human activity. In contrast, an extensive cropland area within the peri-urban area markedly diminished the ULUE of compact urban construction land. Furthermore, we argue against relying solely on strict cropland protection measures to promote ULUE. Instead, we emphasize the intermediate role of urban construction land landscape and suggest a clear spatial separation between cropland and urban construction land. An optimized cropland protection policy should achieve a balance between cropland preservation and ULUE. Such a balanced approach is crucial for sustainable urbanization.

The theoretical and practical contributions to urban planning of this study are as follows. Theoretically, this study proposed a new ULUE concept concerning the processes of land use, which is measured by human activity intensity. This new evaluation method explains the actual utilization intensity of urban construction land during the land use process and reflects the extent of the artificial utilization of urban construction land, which was supposed to be superior to the conventional method following the "black box" concept. The results obtained have improved our understanding of the mechanisms influencing the relationship between land cover and ULUE. While previous studies have stressed the benefits of the compact urban form (Mahtta et al., 2019b; Chakraborty et al., 2022; Xu et al., 2020b), our study indicated that the impact of compactness on the efficiency of the land use process depends on the driving force. We demonstrated that when compact urban expansion is compelled by strict cropland conservation, it is incapable of sustaining intensive human activity.

Practically, this study provided a novel ULUE evaluation measurement that quantifies the actual intensity of land use processes. Although urban land use efficiency mainly depends on the population size of the city and the level of economic development, such social and economic factors are somehow difficult to change. On this account, we explore the pathway to promote ULUE by land use planning. The results of this study are useful for land use planning to tackle the conflict between cropland protection and urbanization in developing countries with the idea of a balance between food security and economic development. The results can assist urban planners and policymakers in avoiding the unintended consequences of cropland conservation that might undermine ULUE.

This study has several major limitations that should be acknowledged. First, the cropland data used in this study were not based on the official designation of permanent basic cropland, which would have provided a more accurate reflection of cropland protection policies. This limitation may have affected the robustness of the findings regarding the impact of cropland on ULUE. Second, according to the multiple regression analysis result in Appendix B, we have to admit the net contribution of the PC to ULUE is relatively weak. The probable reason for this is that the influencing factors on ULUE is various. Third, the resolution of the BVD and NTL is not high enough, which probably reduces the accuracy of ULUE evaluation. Fourth, the boundaries of the metropolitans should be settled by uniformed standard and further examined.

Notes

Color should be used for all the figures in print

Acknowledgments

This work was supported by the National Natural Science Foundation of China (NO. 52208088) and Humanity and Social Science Youth Foundation of Ministry of Education of China (22YJCZH113).

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