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

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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.

1　**Does cropland threaten urban land use efficiency in the peri-urban area? Evidence from**

2　**metropolitan areas in China**

3

4　**Abstract**

5　In recent decades, cropland policies have been recognized as crucial tools for ensuring food

6　security and managing urban growth. However, whether cropland conservation undermines

7　urban land use efficiency (ULUE) in peri-urban areas has not been adequately studied. This

8　study investigated the impact of cropland on ULUE in the peri-urban areas of 36 rapidly

9　urbanizing metropolitan areas in China. Multiple open-source datasets were used, including

10　land use, land cover, three-dimensional building structure, and nighttime light (NTL) data.

11　Urban construction land patterns (infilling, edge, outlying) were categorized to examine the

12　intermediate role of urban form in the correlation between cropland and ULUE. The findings

13　indicated that: (1) high proportion of cropland area within the peri-urban areas significantly

14　undermined ULUE; (2) although the conservation of cropland is conducive to compact urban

15　growth, the infilling expansion pattern that compelled by cropland conservation would not

16　sustain intensive human activity; and (3) reducing the spatial separation between conserved

17　cropland and urban construction land was conducive to the dual objectives of protecting

18　cropland and promoting ULUE. This study contributed to the development of a nuanced

19　understanding of cropland protection policies that balance national food security and

20　urbanization efficiency.

21

22　**Keywords:** Cropland conservation; Urban land use efficiency; Urban expansion; Land

23　cover; Metropolitan area; Land use and land cover change

24

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

50 dynamically balanced cropland protection system stipulates the total amount of cropland in

51 each administrative unit, restricting the conversion from cropland to urban construction land.

52 Second, the dynamically balanced cropland protection system allows cropland displacement

53 under the premise of keeping the total amount of cropland constant, which further promotes

54 compact urban growth. Third, in the quality management of cropland, basic cropland zoning

55 defines the spatial boundaries of the most fertile cropland that cannot be converted (Wu et al.,

56 2017), which leads to fragmented patches of urban construction land.

57   The newly increased urban function is expected to be sustained by the limited amount of

58 urban construction land, which emphasizes the need to promote urban land use efficiency

59 (ULUE). Previous studies of ULUE have regarded urban construction land as a scarce

60 resource (Lambin & Meyfroidt, 2011), which is expected to facilitate economic production

61 (Cao et al., 2019; Jingxin et al., 2022). Accordingly, ULUE represents the efficiency of the

62 transformation from urban construction land to economic benefits such as GDP contributions

63 and the number of employees (Yu et al., 2019). In line with this definition, the input-output

64 function is widely used to define ULUE and urban construction land has been considered one

65 of the input elements to evaluate its role in socio-economic development (Y. Chen et al.,

66 2016). The related literature commonly applied the Data Envelopment Analysis (DEA) model

67 for the ULUE analysis and evaluation. This model was developed based on a relatively

68 efficient concept and assesses and sorts the relative effectiveness of various decision-making

69 units when considering multiple input and output factors (Olesen, 2006). Other studies,

70 following the goals outlined under SDG 11 (Agenda, 2017; Zitti et al., 2015; Chakraborty et

71 al., 2022), have defined ULUE as an indicator of the ratio between urban area expansion

72 (land consumption) and population growth rate (Corbane et al., 2017; Zhang et al., 2020).

73 Essentially, this definition regards the population carrying capacity as the output in terms of

74 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).

100   As the strict land use regulations imposed by cropland protection policies interfere with

101   spontaneous urban growth and increase the fencing of land, social and economic networks

102   between urban construction land are weakened, and the functional isolation of the dispersed

103   urban built-up land patches is further exacerbated. However, the effect of cropland

104   protection on ULUE has not received adequate attention. Specifically, an examination of this

105   relationship requires the mediated role of the spatial pattern of urban sprawl to be

106   investigated, which has been a contentious subject in previous studies. Some studies have

107   indicated that cropland constraints are essential for enhancing ULUE by preventing the

108   dispersed expansion of urban construction (T. Liu et al., 2015; Qianwen et al., 2017).

109   Conversely, other studies have argued that strict agricultural zoning policies may trigger a

110   "leapfrog" effect on urban expansion and threaten ULUE (McConnell et al., 2006; Yin &

111   Sun, 2007; Zhong et al., 2018). This contradiction suggests that quantitative and qualitative

112   cropland protection policies would result in diverse landscapes of urban construction land

113   (Vyn et al., 2012). In other words, the strict land use regulation of cropland leads to various

114   urban expansion consequences, including compact and dispersed growth. Thus, their

115   combined influence on the urban landscape needs to be further explored.

116   The investigation of the correlation between cropland protection and ULUE also require

117   finer methods used to evaluate ULUE (Guastella et al., 2017). Essentially, the conventional

118   ULUE concept focuses on the external benefits that accrue from urban land use. Thus,

119   evaluation methods including DEA are commonly associated with input-output models that

120   employ the "black box" concept (Jingxin et al., 2022). In detail, these methods measure the

121   ratio of the input and output factors of land use, which commonly proceeded in

122   administrative units and is correlated with various external background factors, such as

123   population, globalization, transportation networks, urbanization, and marketization (S. He et

124   al., 2020; C. Wu et al., 2017). However, this ULUE evaluation ignores the process of land

125　use, which is propelled by internal human activities and is characterized by physical land

126　utilization intensity. Human activities are associated with artificial and physical land use

127　processes and act as a necessary link between land consumption and benefits production. In

128　this sense, human activity intuitively reflects the ULUE in a "white box" method.

129　Importantly, the intensity of human activities is largely determined by the compactness of

130　urban form in the peri-urban area (Ye et al., 2018; Xia et al., 2020), which is affected by

131　cropland proportion. The conserved cropland surrounding the construction area reduces the

132　street connectivity and blocks the traffic network, which is confirmed to be an adverse factor

133　in the visit frequency of urban facilities (Chiang & Li, 2019). In this sense, the conserved

134　cropland potentially threatens human activities in the peri-urban area.

135　　　An evaluation of human activity intensity is therefore required in the ULUE

136　measurement. Correspondingly, in this study, ULUE was defined as the actual amount of

137　human activity loaded per unit of urban construction land. Specifically, the human activity

138　associated with land use consists of two parts: construction activity and urban socio-

139　economic activity. This definition aligns with urban vitality theory and conceptualizes ULUE

140　as the raw power and energy of a city (Jane, 1961). It primarily depends on a well-developed

141　urban morphology and extensive urban activities. Therefore, we specifically measured ULUE

142　using a composite indicator that combined urban land construction intensity and urban socio-

143　economic activity. To measure these two factors at a finer scale, we used building volume

144　density (BVD) data and nighttime light (NTL) data (Deng et al., 2009b; Q. He et al., 2018;

145　Xia et al., 2020; Zheng et al., 2017b). These two human activity indexes presented the three-

146　dimensional building structure (M. Li et al., 2020) and spatial distribution of intra-urban

147　socio-economic activities (Zheng et al., 2023), which indicate physical urban construction

148　land use intensity in different dimensions. The high spatial resolution of these data allowed us

149　to adequately identify the ULUE of urban land patches in diverse landscape patterns.

150   Additionally, as the central government intensified cropland protection around urban areas

151   (SCP, 2017), we incorporated the proportion of cropland (PC) in the peri-urban area to assess

152   the influence of cropland protection on the landscape patterns of urban built-up land. To

153   achieve this, we used micro-scale geographical open-access product data to detect urban

154   construction land (Gong et al., 2020) and cropland with a resolution of 30 m (Potapov et al.,

155   2022).

156   The primary objective of this study was to better understand the impact of cropland

157   protection on the ULUE in peri-urban areas. We aimed to provide strategies for land use

158   regulation and sustainable planning that would promote ULUE (Chakraborty et al., 2021; B.

159   Chen et al., 2021). To achieve these objectives, we examined the relationship between

160   conserved cropland and ULUE in 36 metropolitan areas within peri-urban regions.

161   Subsequently, we addressed the following research questions. (1) How does cropland

162   preservation influence the spatial pattern of urban construction land? (2) What are the

163   differences in ULUE among urban construction land in various spatial patterns? (3) How

164   does the ULUE of urban land patches in different landscape patterns vary with different

165   cropland preservation policies? The structure of the paper is as follows. Section 2 provides an

166   overview of the data collection process and research methodology employed in this study.

167   Section 3 presents the empirical findings derived from the analysis. In Section 4, we discuss

168   the pathways through which cropland affects ULUE. Finally, the concluding section

169   summarizes the key points of the paper and highlights its theoretical implications.

170

2 Data collection and research methodology

### 2.1 Study area

173   In recent decades, China's metropolitan areas have undergone significant urbanization

174   and spatially heterogeneous urban expansion. In this study, we selected specific metropolitan

175 areas based on the city classification scheme provided by Fang (2021) (Fig. 1). The selected

176 metropolitan areas were subject to direct authorization and supervision by the central

177 government in terms of spatial planning (Zhong et al., 2018). Consequently, these areas have

178 implemented relatively stringent cropland protection policies and thus, significant land use

179 conflicts have arisen between cropland and constructed land.

180   Previous literature has not reached a consensus on the spatial boundaries of metropolitan

181 areas in China. Therefore, we used the Major Functional Oriented Zoning as a framework to

182 determine the boundaries of the metropolitan areas (Wang & Fan, 2020). This national zoning

183 determines the function that each county-level administrative unit should undertake in the

184 national sustainable development system. By combining the central cities of the metropolitan

185 areas with the urbanization zones defined by Major Functional Oriented Zones, we were able

186 to establish the boundaries for 36 metropolitan areas based on the following rules (Fig. 2).

187 We included all county-level units located within the administrative boundaries of the central

188 cities. Then, we incorporated the urbanization zones that spatially adjoined the administrative

189 boundaries of the central cities. Based on the regional classification scheme proposed under

190 regional economics (Kuang et al., 2016), we divided the metropolitan areas into four broad

191 geographical categories: eastern, central, western, and northeastern areas (Fig. 1, Table. 1).

192 Furthermore, we refined 588 county-level units by removing those which has no more than

193 5% impervious surface areas in the peri-urban areas. All these county-level units are in the

194 selected metropolitan areas.
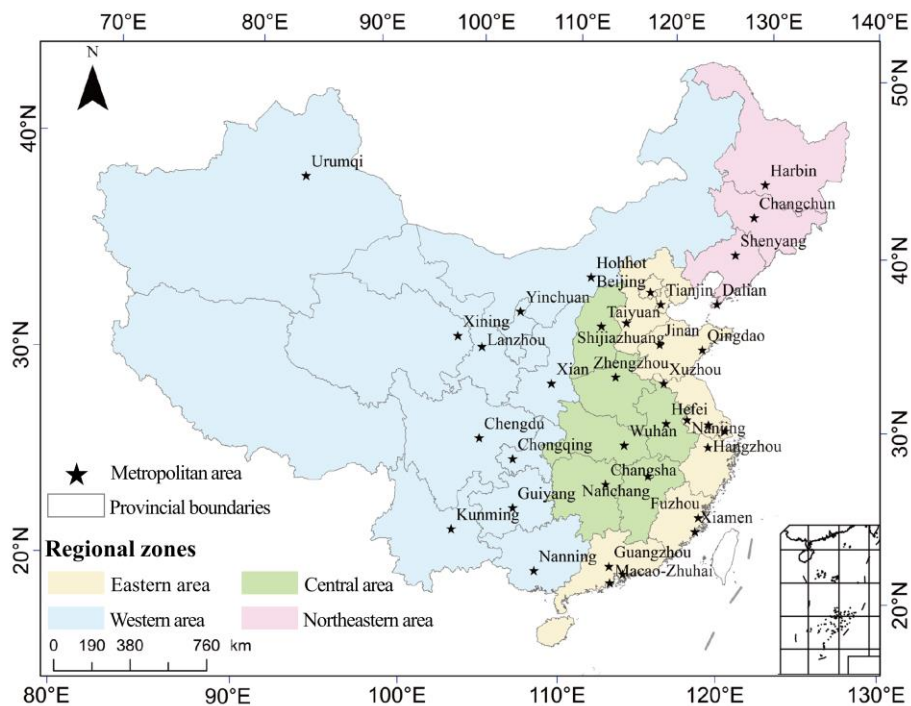
195
196 **Figure 1.** Regional zoning of the selected metropolitan areas
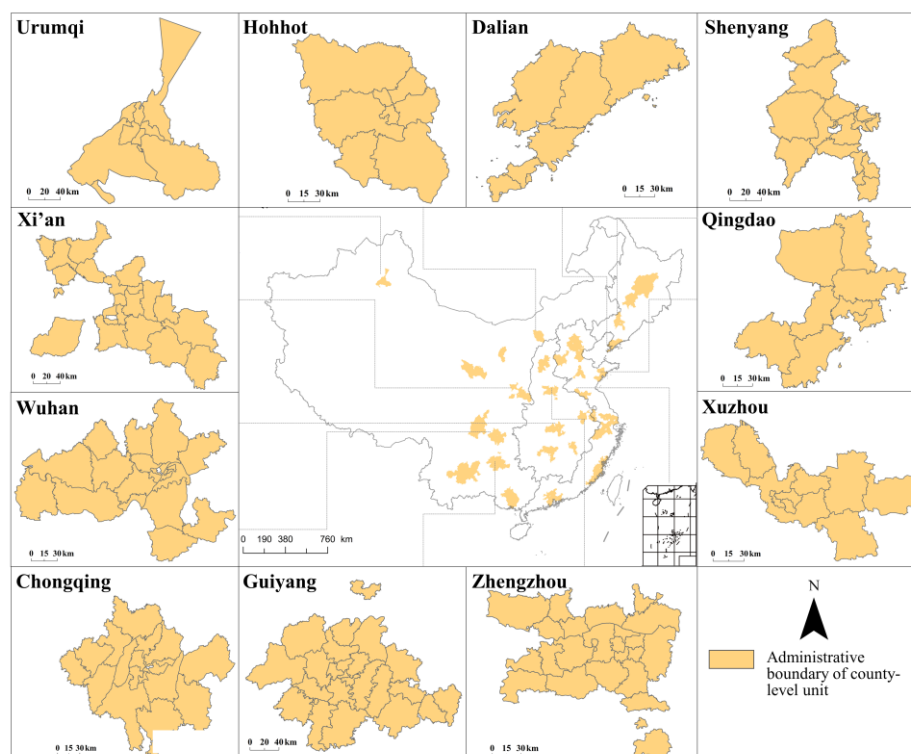
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198 **Figure 2.** Selected metropolitan areas and administrative boundaries of the county-level units

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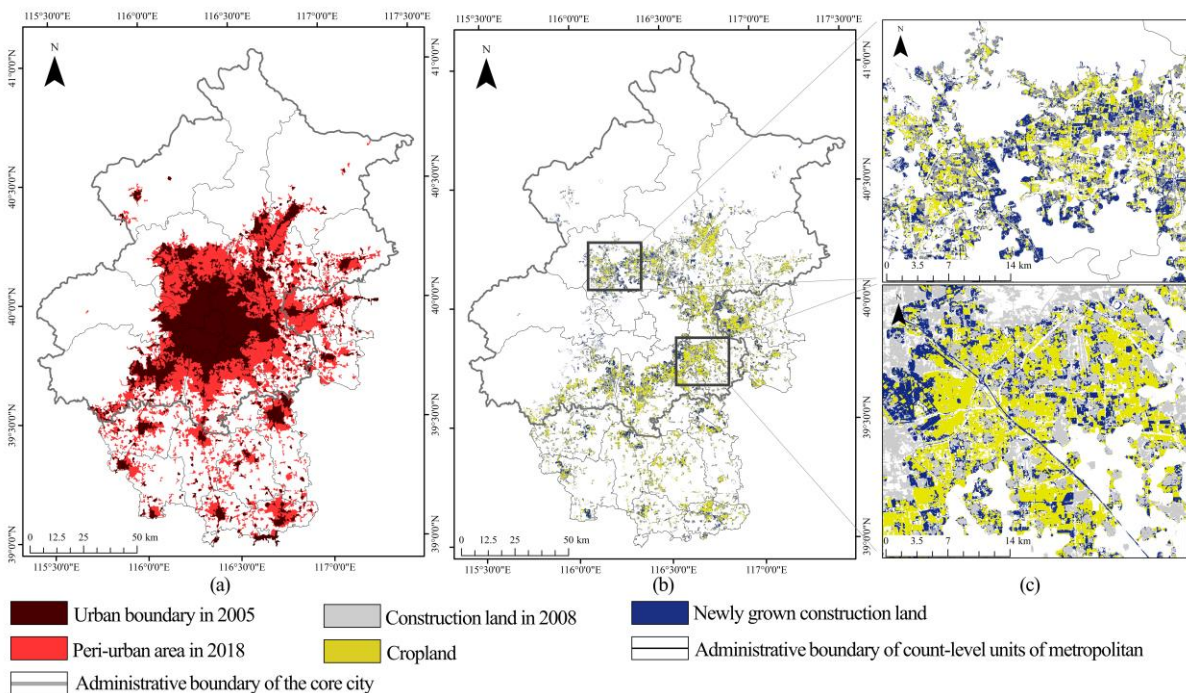202   **Table 1.** Metropolitan areas and the number of county-level units in different regions

	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

203

204   **2.2 Data preprocessing**

205   Global artificial impervious area (GAIA), which is an open-source database published

206   by Gong et al (2020), was used to extract urban construction land for this study. GAIA

207   provides global artificial impervious area data with a resolution of 30 m. It also maps the

208   global urban boundaries derived from the artificial impervious area data (X. Li et al., 2020).

209   The wide coverage scope and resolution of GAIA are superior to other similar datasets,

210   such as CORINE land cover data (Aune-Lundberg & Strand, 2021), which only covers the

211   European region with a resolution of 100m. In this study, a two-step procedure was used to

212   prepare for newly grown urban construction land. First, we identified the peri-urban area in

213   2018 by extracting the urban boundaries of 2005 from those of 2018 (Fig. 3a). The peri-urban

214   area refers to the region that was previously agricultural land but has experienced peri-

215   urbanization (Tian, 2015). In this study, the average distance between peri-urban areas and

216   related urban cores is 68.83 km^2 (Appendix. A). Second, we applied the GAIA database to

217   extract the new areas with an impervious surface within the peri-urban area (Fig. 3b, c). In

218   order to draw a clear figure, we convert the raster data to shapefile in ArcGIS.

219   A global cropland map of the four-year period of 2016–2019 at 30 m spatial resolution

220   provided by Potapov et al. (2022) was used to extract cropland for this study (Fig. 3b, c). This

221   widely-used dataset used the global 16-day normalized surface reflectance Landsat Analysis

222   Ready Data as input data for cropland mapping. Moderate Resolution Imaging

223   Spectroradiometer (MRIS) surface reflectance was applied as a normalization target to

224   normalize the Landsat top-of-atmosphere reflectance. The cropland map accuracy was

225   examined by a sample analysis, which randomly selected 100 sample units (Landsat data

226   pixels) from each stratum. Then, we extracted the cropland within peri-urban areas (Fig. 3a)

227   and calculated the PC in the peri-urban area for all county-level units.

Urban boundary in 2005   Construction land in 2008   Newly grown construction land
Peri-urban area in 2018   Cropland   Administrative boundary of count-level units of metropolitan
Administrative boundary of the core city

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.

228   The calculation of ULUE involved the use of NTL and BVD data with a spatial

229   resolution of 500 m (Table 2). For the NTL data, we used the 2018 data from the extended

230   time series (2000 to 2018) of the National Polar-orbiting Partnership Visible Infrared

231   Imaging Radiometer Suite (NPP-VIIRS) NTL dataset constructed by Z. Chen (2021). The

232   BVD data was provided by M. Li et al. (2020) and had a resolution of 500 m. This dataset

233   enabled us to extract information regarding urban 3D building structure, including building

234   footprints, heights, and volumes. In order to identify the NTL and BVD values of the urban

235   construction land, we resampled the impervious surface area derived from GAIA with

236   30m*30m grids in all the county-level units' peri-urban area, which aligned with the spatial

237   resolution of the impervious area and cropland data. Then, we combine a GIS analysis with a

238   sub-pixel method to calculate BVD and NTL of all the county-level units, which is a

239   powerful tool for calculating and describing some properties of environmental data within an

240   area (Valjarević et al., 2018). We first recognize different index values of the resampled girds

241   at 30 m resolution within the impervious surface area in all the county-level units' peri-urban

242   areas. Then, we calculate the area-weighted NTL and BVD value of the grids in each county-

243   level unit, which is the analysis unit of this study. The area-weighted NTL and BVD values

244   of the analysis units are prepared for further ULUE evaluation.

245   Furthermore, we accounted for the influence of other socio-economic indicators on

246   ULUE, as outlined in Table 2. Two additional indicators were considered. (1) Average land

247   GDP was used to assess the economic development level of all 588 county-level units. The

248   data for average land GDP were obtained from an open-source database published by the

249   Resource and Environment Science and Data Center (Gong et al., 2020). The land GDP data

250   at a resolution of 1 km per pixel were used to calculate the average land GDP values for all

251   county-level units. (2) Average population densities of all 588 county-level units were

252   calculated using data from the sixth national census and the China land cover dataset

253   provided by Yang and Huang (2021).

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

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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

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270 pattern type of the newly grown built-up patches for the 588 county-level units is

271 programmed and then conducted in Google Earth Engine (GEE) platform.

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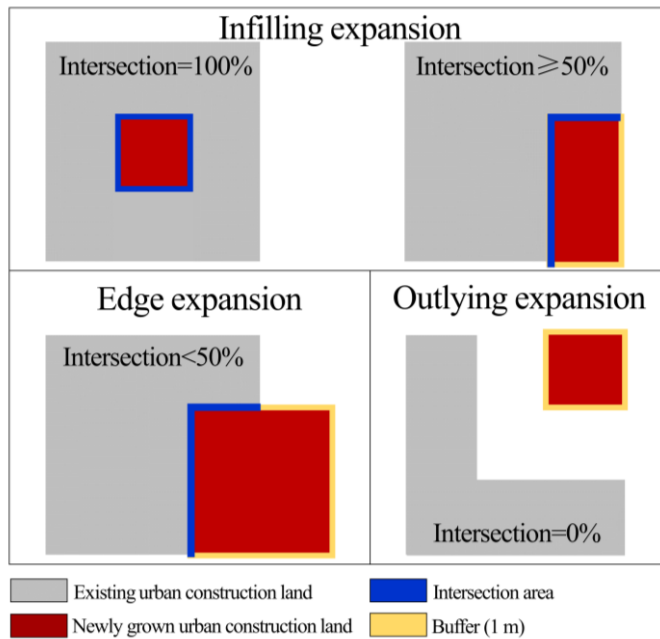
273 **Figure 4.** Graphical depiction of the spatial rules for the identification of urban

274 construction land patterns

275 **2.3.2 Normalized difference expansion index (NDEI)**

276 The NDEI has been used to assess the compactness of urban expansion and identify the

277 extent of infilling, edge, and outlying expansion (Chakraborty et al., 2022). It quantifies the

278 dominance of urban construction land under the infilling mode in the total new built-up land

279 in the peri-urban area (Eq. 2).

280 $$\text{NDEI} = \frac{Area\ under\ infilling - Sum\ area\ under\ edge\ expansion\ and\ outlying}{Area\ under\ infilling + Sum\ area\ under\ edge\ expansion\ and\ outlying} \text{(Eq. 2)}$$

281 The value of the NDEI ranges from -1 to $+1$, signifying the compactness of urban

282 expansion. A positive NDEI value indicates the dominance of inward urban expansion,

283 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:

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

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.

$$\text{ULUE} = \text{NTL}_{mn} \times \text{BVD}_{mn} \quad (\text{Eq. 5})$$

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

309 ULUE for different types of urban construction land patterns, including infilling, edge, and

310 outlying expansion.

3 Results

3.1 Spatial variations of the PC and urban construction land pattern

313   The PCs of the 588 county-level units were used to map the regional differences across

314 China (Fig. 5). The intensity of the cropland distribution in the peri-urban areas increased

315 gradually from the southwest to the northeast. The northeastern region had the highest

316 average PC of 0.23, which was twice as high as that of the western region. The eastern region

317 had an average PC of 0.17, while the western region had a lower average PC of 0.11. Among

318 the 36 metropolitan areas studied, those located in the north, such as Tianjin, Harbin, and

319 Beijing, had the highest PCs (Appendix A). In contrast, metropolitan areas in the southern

320 region tended to have lower PCs, including Shenzhen-Hong Kong, Guangzhou, and Macau-

321 Zhuhai.

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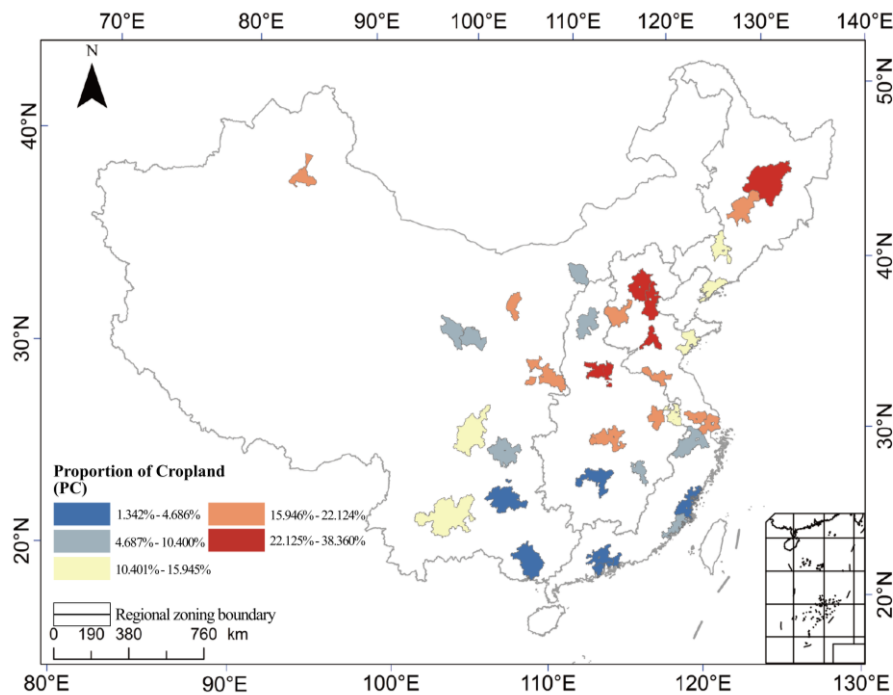
323 **Figure 5.** The proportion of cropland (PC) in the metropolitan areas

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325   We categorized the expanded construction land into three growth modes: infilling

326   expansion, edge expansion, and outlying expansion (Fig. 6). Infilling and edge expansion

327   accounted for most of the total urban expansion. Specifically, infilling expansion accounted

328   for 44.54% of the total, while edge expansion represented 51.57%. In contrast, outlying

329   expansion accounted for only a small proportion of 3.89%. Accordingly, 22 of the 36

330   metropolitan areas had an NDEI larger than 0 (Appendix. A, Fig. 7). The metropolitan areas

331   with the highest NDEI values were primarily located in the eastern region, including Suzhou-

332   Wuxi-Changzhou, Shanghai, and Nanning. The remaining 14 metropolitan areas had negative

333   NDEI values, with Guiyang, Changsha, and Hohhot being among the areas with the lowest

334   values.
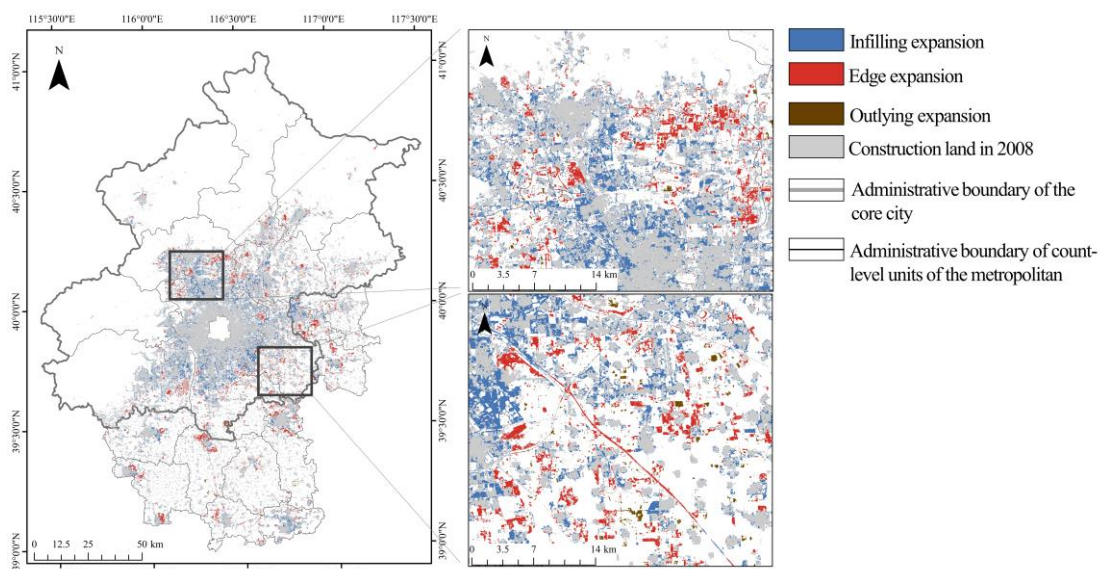
335 **Figure 6.** The different types of urban expansion (infilling, edge, outlying expansion)
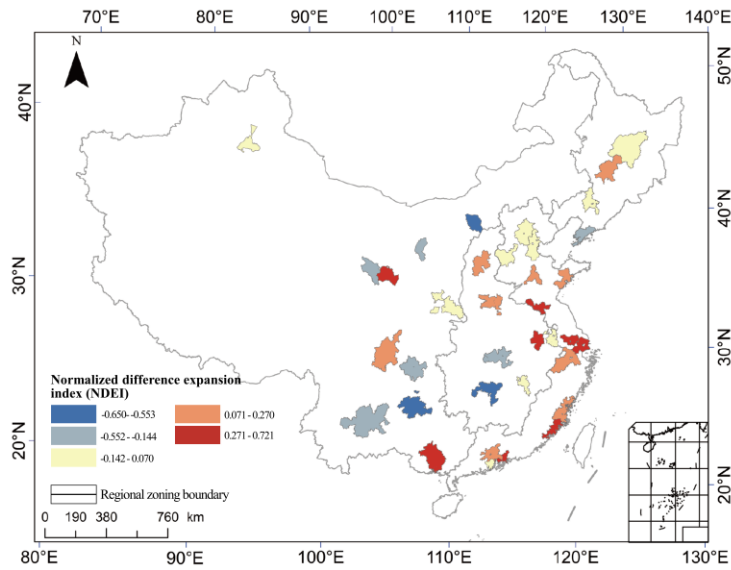
Figure 7. Normalized difference expansion index (NDEI) of the metropolitan areas

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.

19
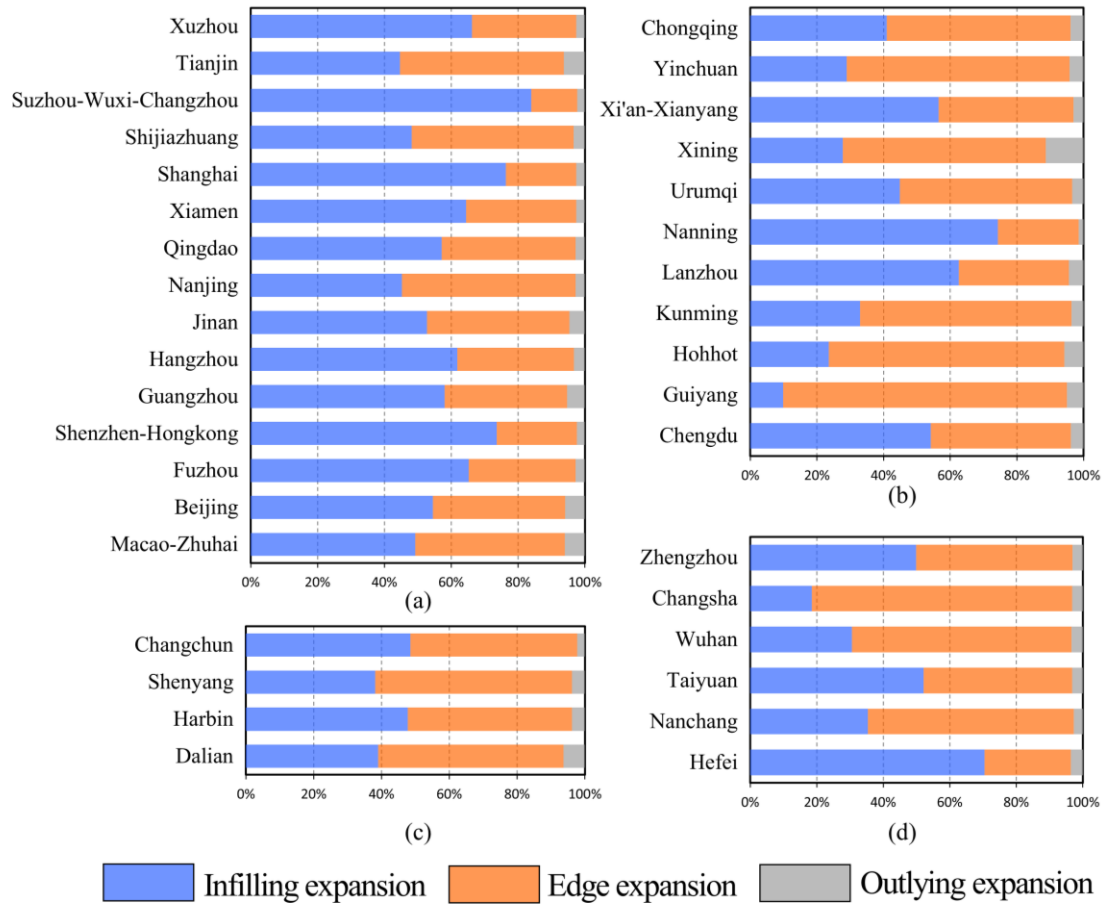
Figure 8. Percentage of different urban expansion types: (a) eastern area; (b) western area; (c) northeastern area; (d) central area

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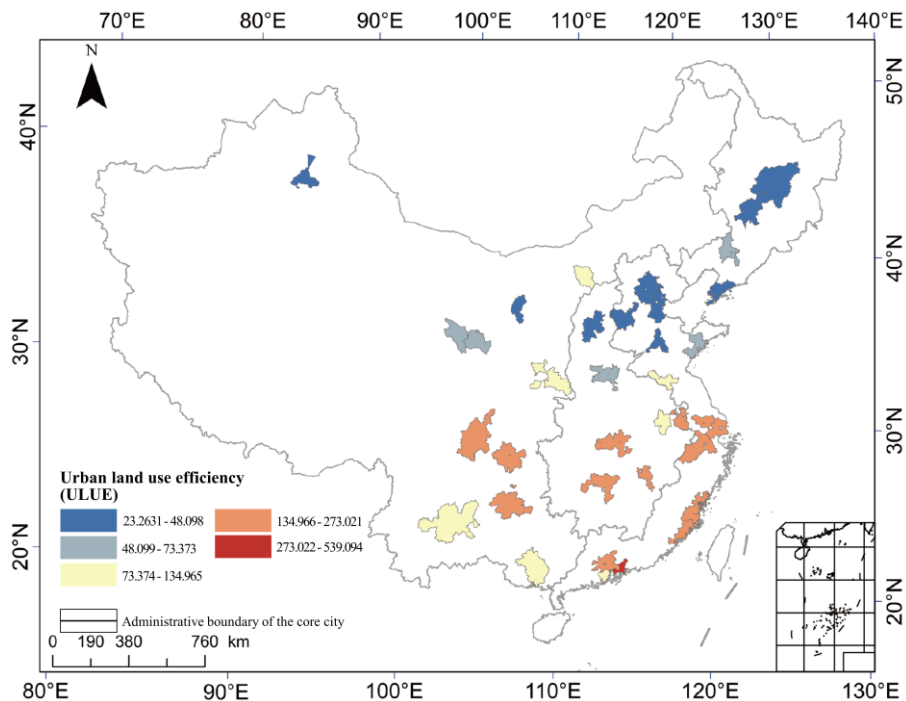
Figure 9. Urban land use efficiency (ULUE) of the metropolitan areas

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

362

363   Urban construction land patterns in different expansion models exhibited differences in

364 ULUE (Table 5). The ULUE of the infilling expansion pattern was significantly higher than

365 the edge and outlying expansion patterns, reaching 293.709 nationwide. The outlying

366 expansion patterns demonstrated the lowest ULUE. Nationwide, the ULUE of infilling

367 expansion patterns was approximately three times higher than that of edge expansion patterns

368 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

370 **3.3.1 Impact of cropland on the urban construction land pattern and ULUE**

371 The correlations between the PC and urban expansion compactness were investigated. The

372 results showed that PC and NDEI were significantly correlated at the national scale, with a

373 Pearson correlation coefficient of 0.107 (Table 6). Furthermore, we investigated the

374 correlations between the PC and the proportion of different urban construction land patterns.

375 The results showed that the PC was positively correlated with the proportions of infilling and

376 outlying expansion areas but negatively correlated with the proportion of edge expansion

377 area (Table 6). Considering that the outlying expansion only accounted for a small fraction of

378 the new built-up land (Figure. 8), it was concluded that the increase in cropland area was

379 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.

380

381 The Pearson correlation results indicated a significant negative correlation between the

382 PC and ULUE. Table 7 and Figure. 10 shows that the PC and ULUE were negatively

383 correlated in different regions. The Pearson correlation coefficients were -0.338, -0.369,

384 -0.157, and -0.487 for the eastern, central, western, and northeastern areas, respectively. All

385 the correlation results are in a confidence interval at 1% level (Table 7). However, with the

386 highest PC in the peri-urban area, the ULUE of urban construction land tended to be low.

387 These results confirmed the significant and negative relationship between the PC and ULUE.

388 Nevertheless, a small number of samples in the 30% to 60% interval has a very low ULUE

389 (Figure. 10). Meanwhile, there is not a particularly large difference in the PC from 0 to

390 30%. These results indicate the linear correlation between the PC and ULUE is not

391 persistently stable in line with the variation of PC. In detail, the land use efficiency of some

392 fragmented construction land patches surrounded by large areas of cropland may lead to

393 extremely low ULUE. In addition, human activity remains intensive in compact urban areas

394 and has not been affected by a slight increase of cropland within a certain degree. Therefore,

395 ULUEs are not in line with the variation of PC in the range from 0 to 30%.

396

397 **Table 7.** Results of a Pearson correlation analysis between the proportion of cropland (PC)

398 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***

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

400
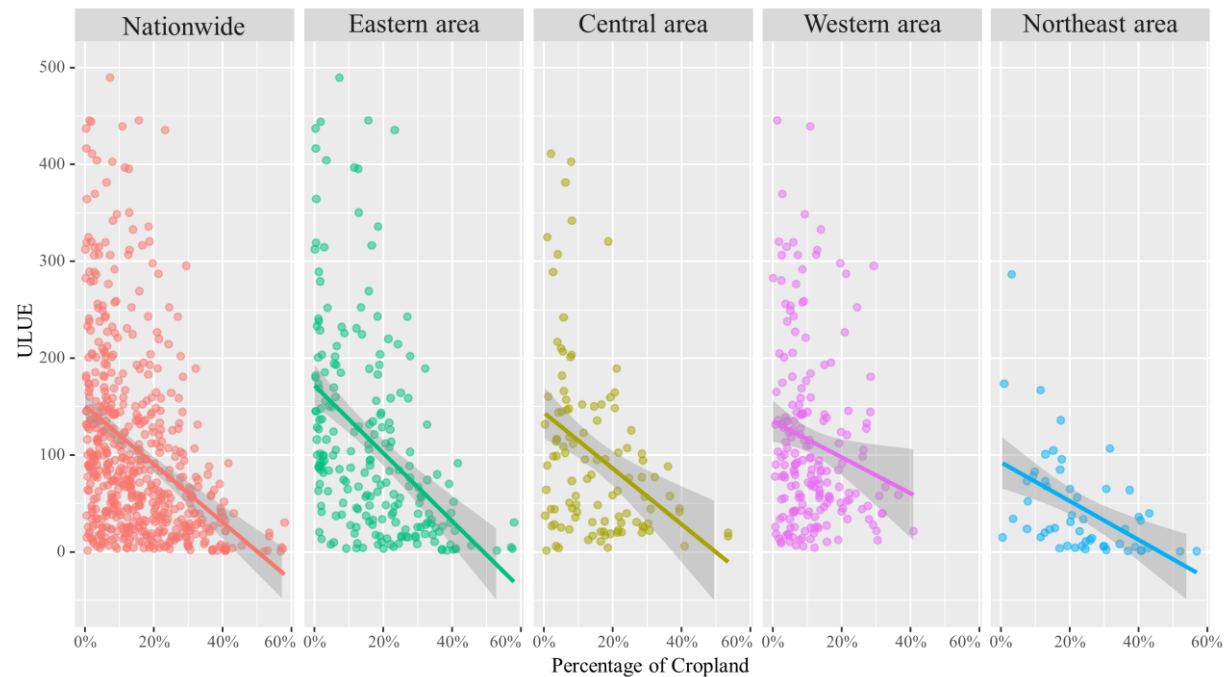
401 **Figure 10.** Scatter plot of the proportion of cropland (PC) and urban land use efficiency (ULUE)

402 nationwide and in the eastern, central, western, and northeastern areas

403

404   A multiple regression analysis was applied to examine the net contribution of the PC to

405 ULUE when other contributing factors were controlled, including population density and per-

406 land GDP. The correlations between the PC and ULUE obtained in all models were

407 significantly negative (Appendix. B). This result confirmed that the PC had a negative effect

408 on ULUE, even when accounting for other contributing factors.

409

410 **3.3.2 Impacts of cropland on the ULUE of different urban construction land**
411 **patterns**

412   Table 8 presents the relationships between the PC and ULUE of infilling, edge, and

413 outlying expansions. The results indicate significant negative effects of cropland on the

414 ULUE of infilling and edge expansions. The Pearson correlation coefficients between the PC

415 and ULUE of infilling and edge expansions were -0.338 and -0.266, respectively, on a

416 nationwide scale. This suggests that the ULUE of infilling expansion was more adversely

417 affected by the increase in cropland than edge expansion. Similar significant effects of the PC

418 on the ULUE of infilling expansion were observed in the eastern, central, and northeastern

419 regions. These findings imply that infilling expansions occurring in peri-urban areas with a

420 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

432   conflicts (Platt, 2004; Zou et al., 2019; Dunk et al., 2011; Vaske et al., 2007). Urban growth

433   primarily took place on cropland and turned into the primary threat to food security in China

434   (Jiang et al., 2012). This competition for land resources is a result of conflicting spatial

435   regulation approaches between the central and local governments. The central government

436   promotes cropland protection as a means to control urban sprawl driven by local governments

437   and in an attempt to mitigate cropland degradation (T. Liu et al., 2015). Two decades ago,

438   such competition between the central and local governments led to another land use conflict

439   in China. Woodland and grassland achieved a certain degree of growth due to the conversion

440   of cultivated land on slopes for the purpose of improved protection against soil erosion settled

441   by the central government (G. Q. Chen & Han, 2015b). Also, the land use conflicts triggered

442   by urbanization are different in China and Africa, where sustainable development depends on

443   forest preservation (Valjarević et al., 2018). In this sense, land use conflicts around the world

444   are reflections of the land use competition between various stakeholders. Specifically, the

445   essential cause of China's land use competition is commonly traced back to the contended use

446   regulation between the central and local government.

447   While cropland conservation is a nationwide policy in China, the intensity of its

448   implementation varies across different regions, as reflected in the spatial variation of the PC.

449   Specifically, basic farmland preservation areas, which is the primary cropland protection

450   policy, positively drive cropland landscape fragmentation changes (Penghui et al., 2021). The

451   PC values of peri-urban areas in the northern regions were significantly higher than those in

452   the southern regions, suggesting that cropland conservation is effective in the northern area.

453   Additionally, urban expansion in the eastern region tends to be more compact compared to

454   other areas, suggesting that the replacement of existing cropland with newly grown

455   construction land is preferable in land use regulation. This situation suggests that local

456   governments in the eastern region have prioritized urbanization and have adopted a cropland

457 conservation policy that emphasizes a dynamically balanced system allowing cropland

458 displacement (Y. Wu et al., 2017).

459 **4.2 The intermediate role of the urban construction land pattern in the impact of**

460 **cropland on ULUE**

461 Our findings revealed an interesting relationship between the PC and ULUE. While an

462 increase in the PC promoted compact urban expansion and enhanced ULUE, we also

463 observed a negative impact of the PC on ULUE. This seemingly contradictory result suggests

464 a complex influencing mechanism. Specifically, the conservation of cropland areas reduces

465 the intensity of human activities in infilling urban expansion patterns. Therefore, although

466 cropland conservation contributes to compact urban growth, it can also reduce the ULUE in

467 certain expansion patterns. This highlights the need for a comprehensive understanding of the

468 intricate relationship between the conservation of cropland area and urban expansion

469 dynamics.

470 Moreover, our analysis suggested that the passive infilling expansion resulting from the

471 conservation of cropland may not be as efficient as spontaneous infilling expansion in land

472 use. Previous studies have highlighted the positive relationship between compact urban

473 expansion and ULUE (Xu et al., 2020; Chakraborty et al., 2022). Our study suggested that

474 spontaneous compact urban expansion is the main driving force promoting ULUE, rather

475 than the passive infilling expansion triggered by land use regulations established by cropland

476 protection policies. This may be because spontaneous compact urban expansion would create

477 more social connections and a greater urban vitality, which is a good match with the

478 surrounding socio-economic environment and land use functions that achieve a functional

479 coordination between existing built-up areas and new built-up land (Fernández-Aracil &

480 Ortuño-Padilla, 2016, Xia et al., 2020, Ewing et al., 2016). The benefit of the spontaneous

481 compact urban expansion is probably more obvious in large cities, as it takes advantage of the

482   existing social network and creates more social connections. This assumption is evidenced by

483   an empirical study that found physical urban form with high patch density and large urban

484   patch size is conducive to enhancing land use efficiency in large cities, while not in small

485   cities (S. He et al., 2020). In comparison, the infilling expansion compelled by the

486   conservation of cropland in the peri-urban area may not take full advantage of existing public

487   services and infrastructure support, requiring additional investments to sustain adequate

488   facility provision. Understanding the mechanisms by which cropland impacts ULUE will

489   improve our understanding of the intermediate role of the urban construction land pattern on

490   cropland conservation on ULUE.

491   **4.3 Policy implications from the perspective of a coordination between cropland**

492   **conservation and ULUE**

493   In developing countries, policies aiming at protecting cropland often strive to find a

494   balance between resource security and economic development (Valjarević et al., 2018).

495   Correspondingly, coordinating the relationship between food security and the fast-growing

496   population is a crucial issue in China (Y. Wu et al., 2017). Despite the central government

497   releasing numerous edicts to protect agricultural land from conversion, cropland in China

498   continues to be converted (Jiang et al., 2012). Empirical studies show that strict regulations

499   on urban growth have limited benefits for cropland protection (Xi et al., 2012). In this sense,

500   the policies concerning urban growth management and cropland protection should recognize

501   the importance of maintaining agricultural productivity while accommodating urban growth.

502   Therefore, it is important to carefully consider the cooperation between preserving cropland

503   and promoting urbanization efficiency.

504   Previous studies have viewed cropland as a vulnerable component in urban expansion

505   (Song et al., 2015; Y. Wu et al., 2014). However, the reality is that due to the pressing issue

506   of food security, spontaneous urban expansion is now substantially restricted by conserved

507 cropland and is converted into passive infilling patterns, which has a negative effect on

508 ULUE. The efficient utilization of urban construction land in China has been evidenced by

509 the fact that China is a net importer of built-up land use, especially an importer of industrial

510 land use such as petroleum processing, nonmetal mineral products, and electric power (G. Q.

511 Chen & Han, 2015). In the orientation of low carbon policy, the enhancement of the

512 interaction between existing facilities should be encouraged for China's further urban land

513 use efficiency improvement. On this account, land use planning concerning the spontaneous

514 and compact urban expansion in the peri-urban area is demanded.

515 China's population has reached its peak value in recent years. It means that the demand

516 for increasing urban land use would decline, as well as urban growth. Based on this

517 consensual prediction, the spatial extent of urban areas and peri-urban areas would tend to

518 stabilize. In other words, the conversion from peri-urban areas to urban areas would gradually

519 slow down. Such prediction indicates that the land use optimization method in the peri-urban

520 area has a profound significance. China's accelerating urbanization in the past has resulted in

521 fragmented urban construction land patches in the metropolitan area, which is negatively

522 related to ULUE (Dadashpoor et al., 2019; S. He et al., 2020) and, in return, fuels urban

523 sprawl and fragmentation (Koroso et al., 2021). An optimized cropland conservation

524 protection policy will avoid a fragmented landscape pattern, with the spatial interspersion of

525 cropland and construction land.

526 Our study confirmed the positive impact of cropland areas on compact urban expansion,

527 but relying solely on increasing the PC to promote ULUE is not advisable. Instead, we

528 propose implementing a spatial separation between cropland and new built-up land to achieve

529 the goal of cropland protection while maintaining a high ULUE. Conserved cropland should

530 be concentrated outside the built-up area rather than dispersed in small patches within it.

531 Such optimization of the land cover landscape is also conducive to improving cropland

532 utilization efficiency by means of technical development and resource reallocation (G. Q.

533 Chen & Han, 2015). Hence, the current cropland preservation policy, which emphasizes

534 "supplementing permanent basic cropland in the peri-urban area according to the order from

535 close to far" (MPA, 2016), may not be appropriate.

5 Conclusion

537   Developing countries face a dilemma due to the conflict between food security and

538 urbanization. The rapid urbanization process has led to the peri-urban areas surrounding

539 metropolitan regions becoming the primary sites for urban expansion. This has resulted in the

540 scarcity of land resources and an emphasis on ULUE. The knowledge of the interaction

541 between urban expansion and cropland is vital, given the potential large-scale land conflicts

542 between agriculture and urban uses in an era of rapid mega-urbanization (Bren et al., 2017).

543 In this study, building volume density data and nighttime light data were used to evaluate

544 ULUE, which quantifies the extent of the artificial utilization during the land use process in a

545 certain sociometric background. The method of urban construction land classification and

546 NDEI measurement enables us to quantify the urban growth compactness, which further

547 explicit the intermediate role of the urban construction land pattern in the impact of cropland

548 on ULUE. Also, the correlation analysis confirms the significant impact of PC on ULUE.

549 The findings of this study confirmed that while cropland conservation contributed to compact

550 urban growth, it did not promote ULUE. In fact, an extensive cropland area within the peri-

551 urban areas of metropolitan regions significantly undermined the ULUE of urban

552 construction land. Although the conservation of cropland tended to drive compact urban

553 growth, the infilling expansion pattern that results from a high PC would not sustain

554 intensive human activity. In contrast, an extensive cropland area within the peri-urban area

555 markedly diminished the ULUE of compact urban construction land. Furthermore, we argue

556 against relying solely on strict cropland protection measures to promote ULUE. Instead, we

557 emphasize the intermediate role of urban construction land landscape and suggest a clear

558 spatial separation between cropland and urban construction land. An optimized cropland

559 protection policy should achieve a balance between cropland preservation and ULUE. Such a

560 balanced approach is crucial for sustainable urbanization.

561   The theoretical and practical contributions to urban planning of this study are as follows.

562 Theoretically, this study proposed a new ULUE concept concerning the processes of land use,

563 which is measured by human activity intensity. This new evaluation method explains the

564 actual utilization intensity of urban construction land during the land use process and reflects

565 the extent of the artificial utilization of urban construction land, which was supposed to be

566 superior to the conventional method following the "black box" concept. The results obtained

567 have improved our understanding of the mechanisms influencing the relationship between

568 land cover and ULUE. While previous studies have stressed the benefits of the compact

569 urban form (Mahtta et al., 2019b; Chakraborty et al., 2022; Xu et al., 2020b), our study

570 indicated that the impact of compactness on the efficiency of the land use process depends on

571 the driving force. We demonstrated that when compact urban expansion is compelled by strict

572 cropland conservation, it is incapable of sustaining intensive human activity.

573   Practically, this study provided a novel ULUE evaluation measurement that quantifies

574 the actual intensity of land use processes. Although urban land use efficiency mainly depends

575 on the population size of the city and the level of economic development, such social and

576 economic factors are somehow difficult to change. On this account, we explore the pathway

577 to promote ULUE by land use planning. The results of this study are useful for land use

578 planning to tackle the conflict between cropland protection and urbanization in developing

579 countries with the idea of a balance between food security and economic development. The

580 results can assist urban planners and policymakers in avoiding the unintended consequences

581 of cropland conservation that might undermine ULUE.

582   This study has several major limitations that should be acknowledged. First, the

583   cropland data used in this study were not based on the official designation of permanent basic

584   cropland, which would have provided a more accurate reflection of cropland protection

585   policies. This limitation may have affected the robustness of the findings regarding the

586   impact of cropland on ULUE. Second, according to the multiple regression analysis result in

587   Appendix B, we have to admit the net contribution of the PC to ULUE is relatively weak.

588   The probable reason for this is that the influencing factors on ULUE is various. Third, the

589   resolution of the BVD and NTL is not high enough, which probably reduces the accuracy of

590   ULUE evaluation. Fourth, the boundaries of the metropolitans should be settled by uniformed

591   standard and further examined.

Notes

Color should be used for all the figures in print

592

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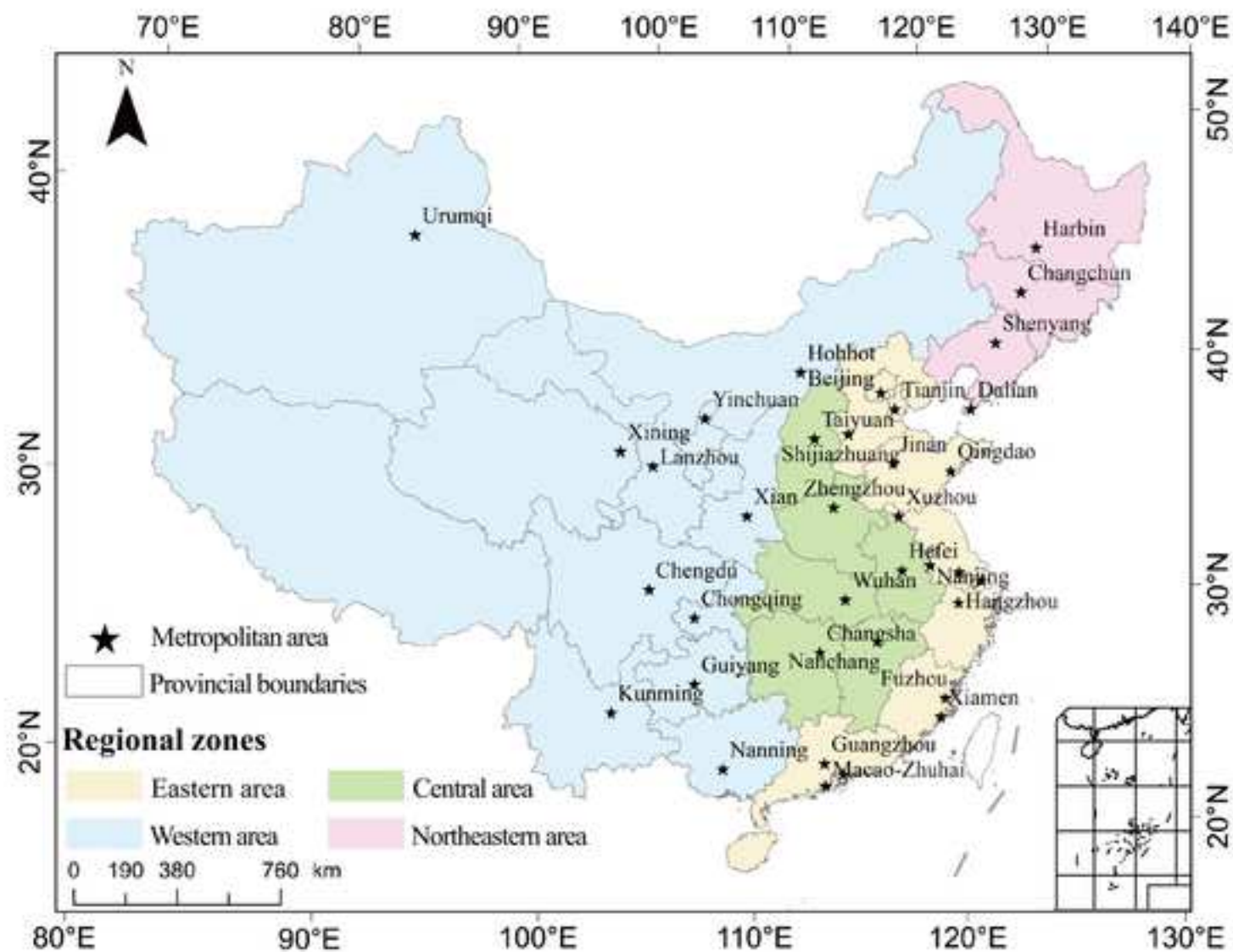
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864

Figure. 1

(a) (b) (c)

Urban boundary in 2005   Construction land in 2008   Newly grown construction land

Peri-urban area in 2018   Cropland   Administrative boundary of count-level units of metropolitan

Administrative boundary of the core city

Infilling expansion

Intersection=100%

Intersection≥50%

Edge expansion

Outlying expansion

Intersection<50%

Intersection=0%

Existing urban construction land   Intersection area

Newly grown urban construction land   Buffer (1 m)

Figure. 5

Figure. 6

Figure. 8

Urban land use efficiency (ULUE)

(dark blue)	23.2631 - 48.098	(orange)	134.966 - 273.021
(grey)	48.099 - 73.373	(red)	273.022 - 539.094
(pale yellow)	73.374 - 134.965		

Regional zoning boundary

0 190 380   760 km
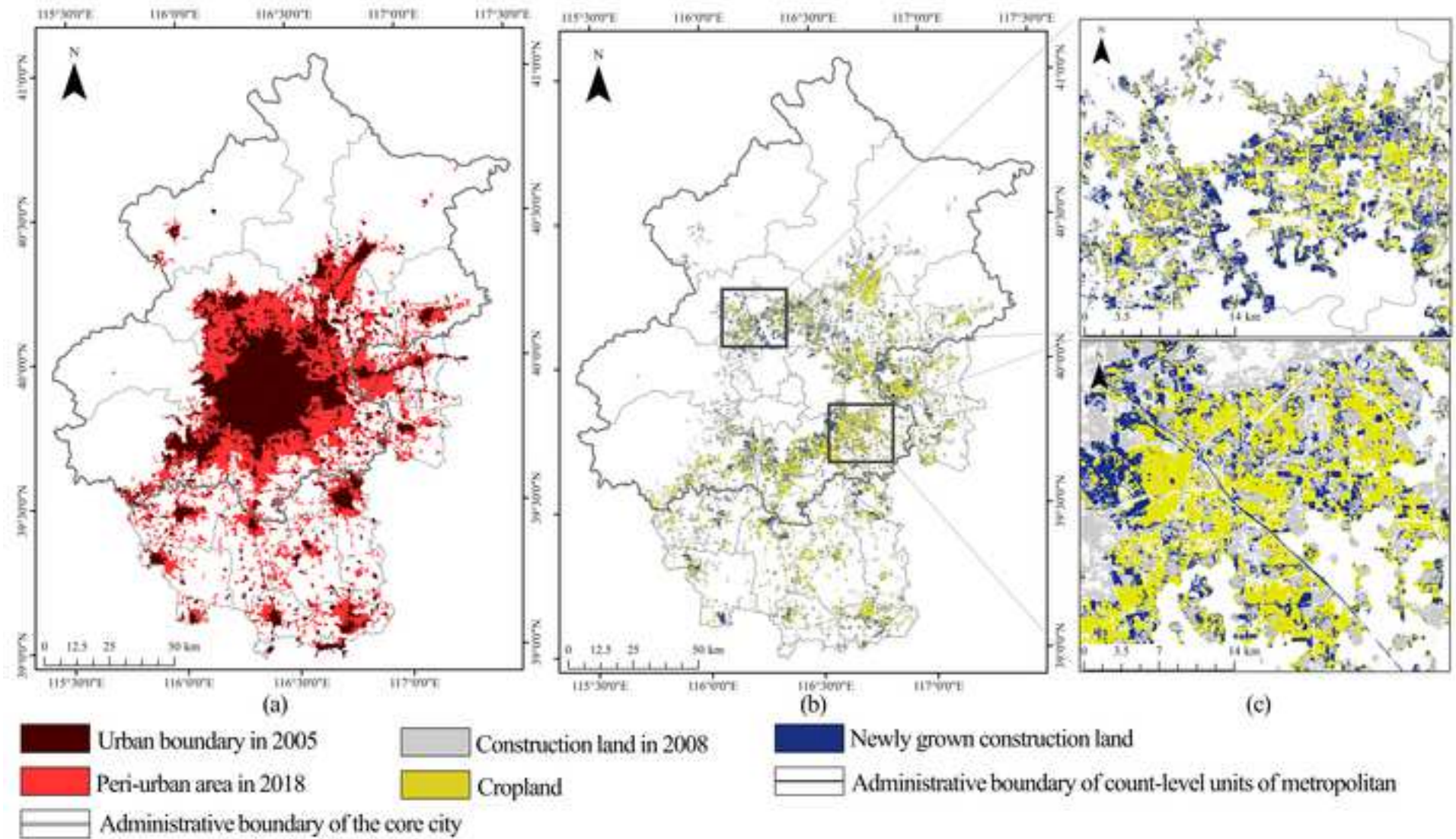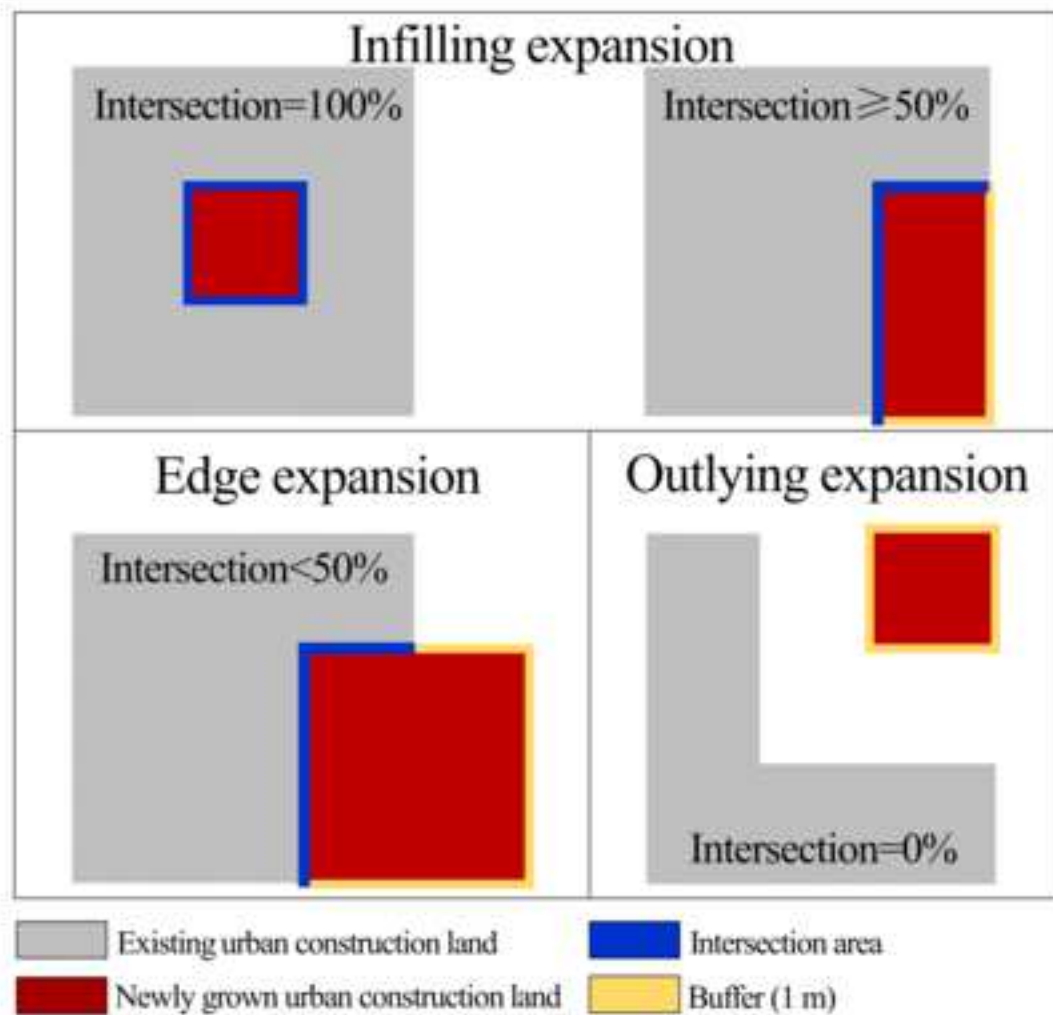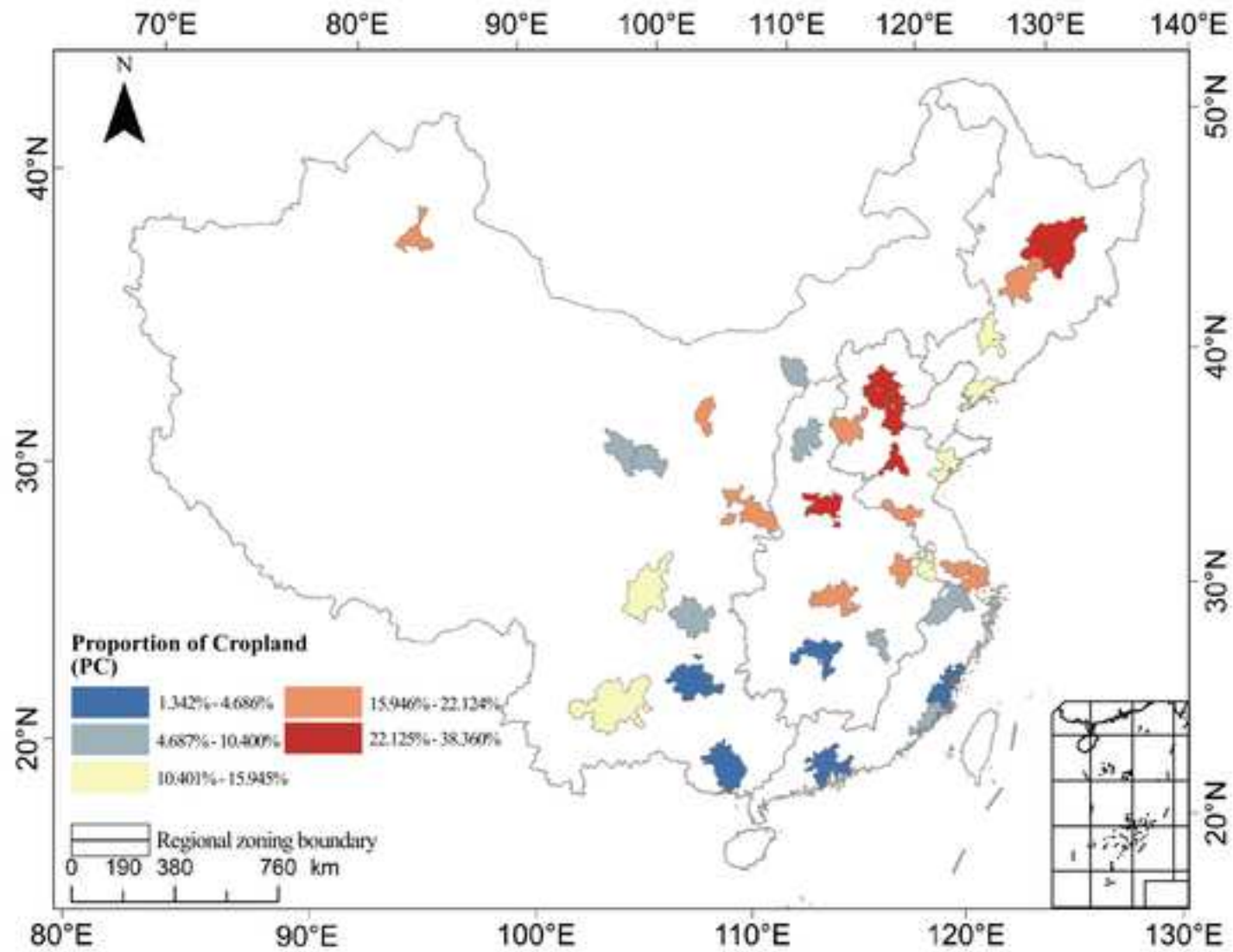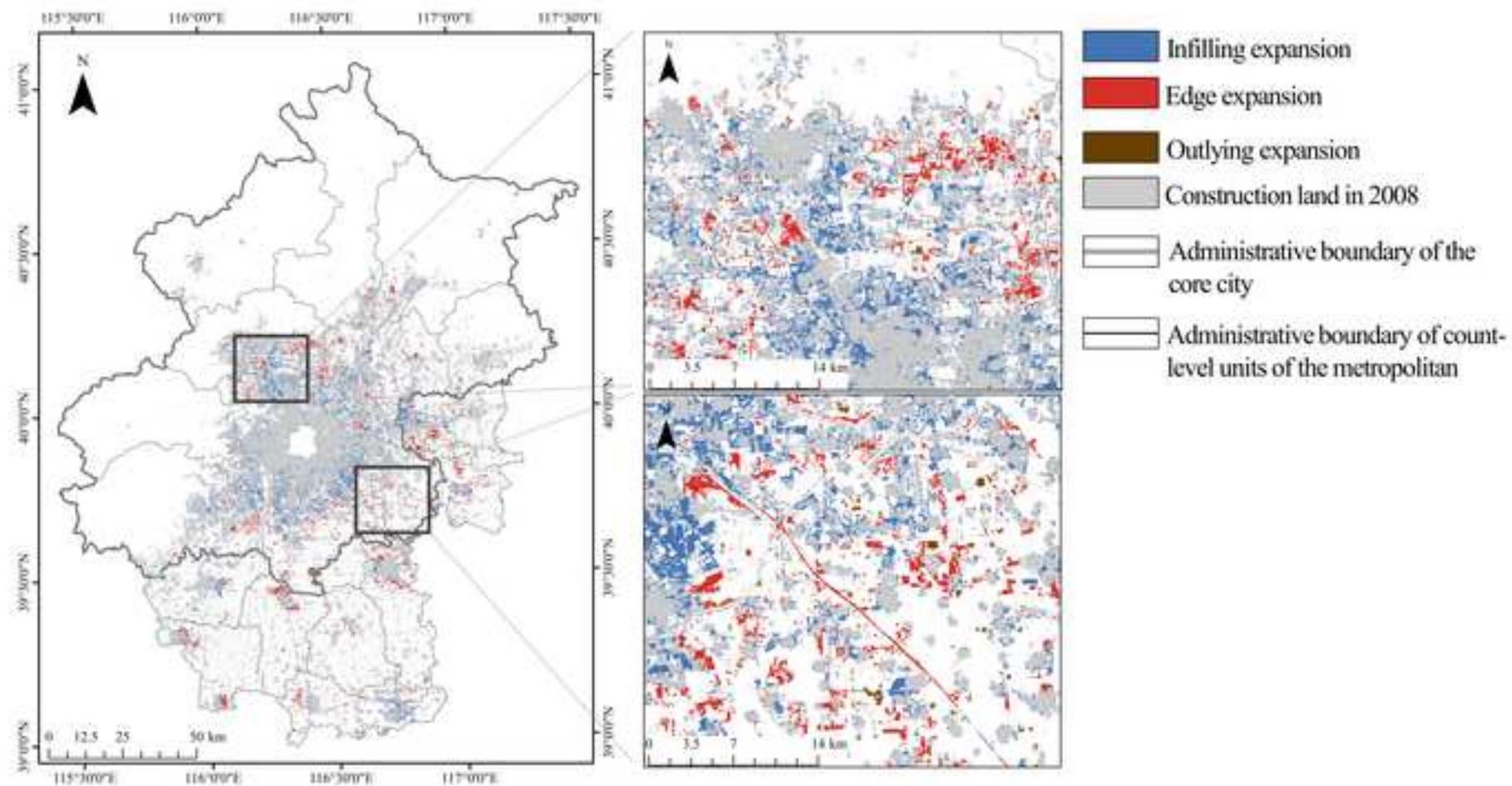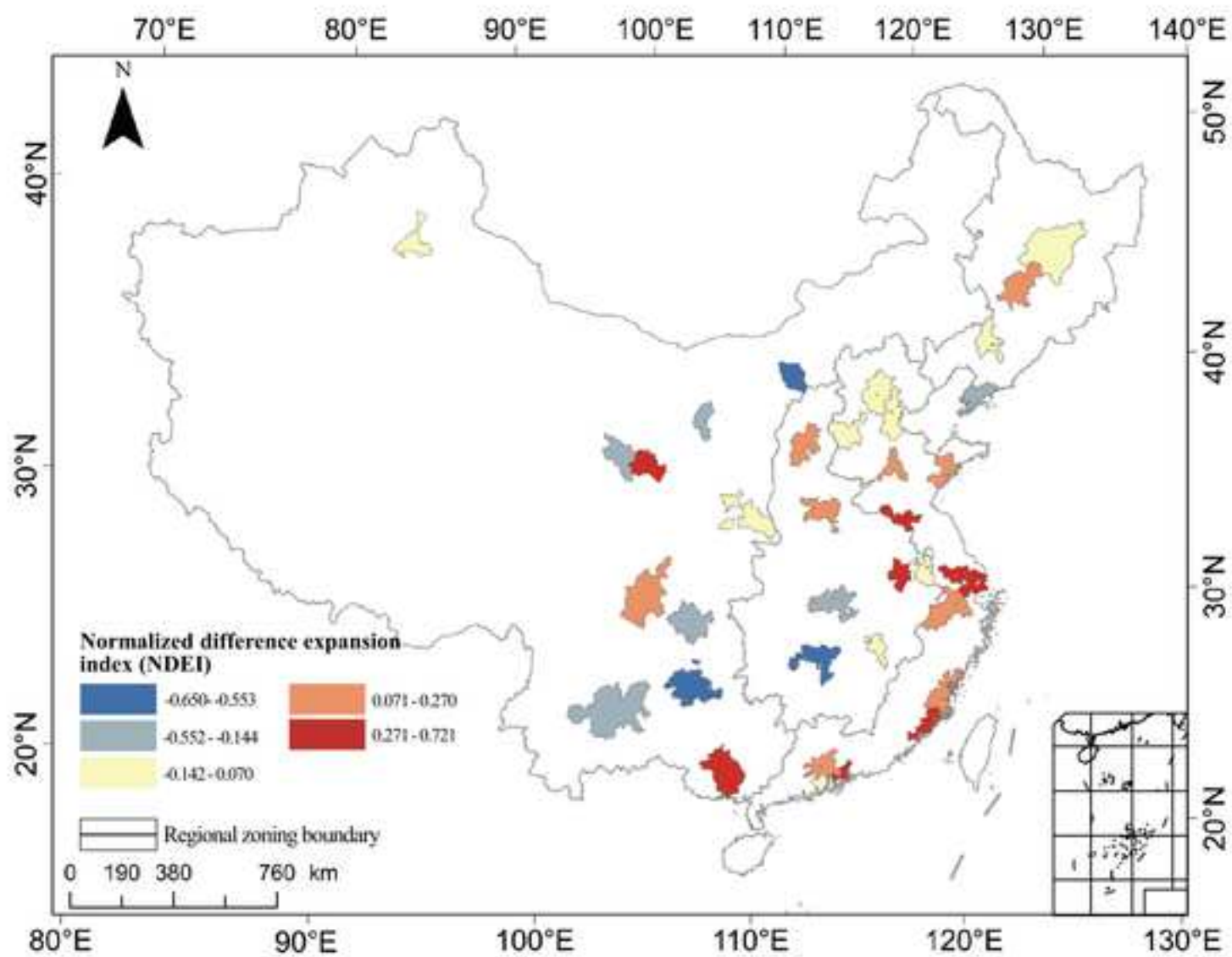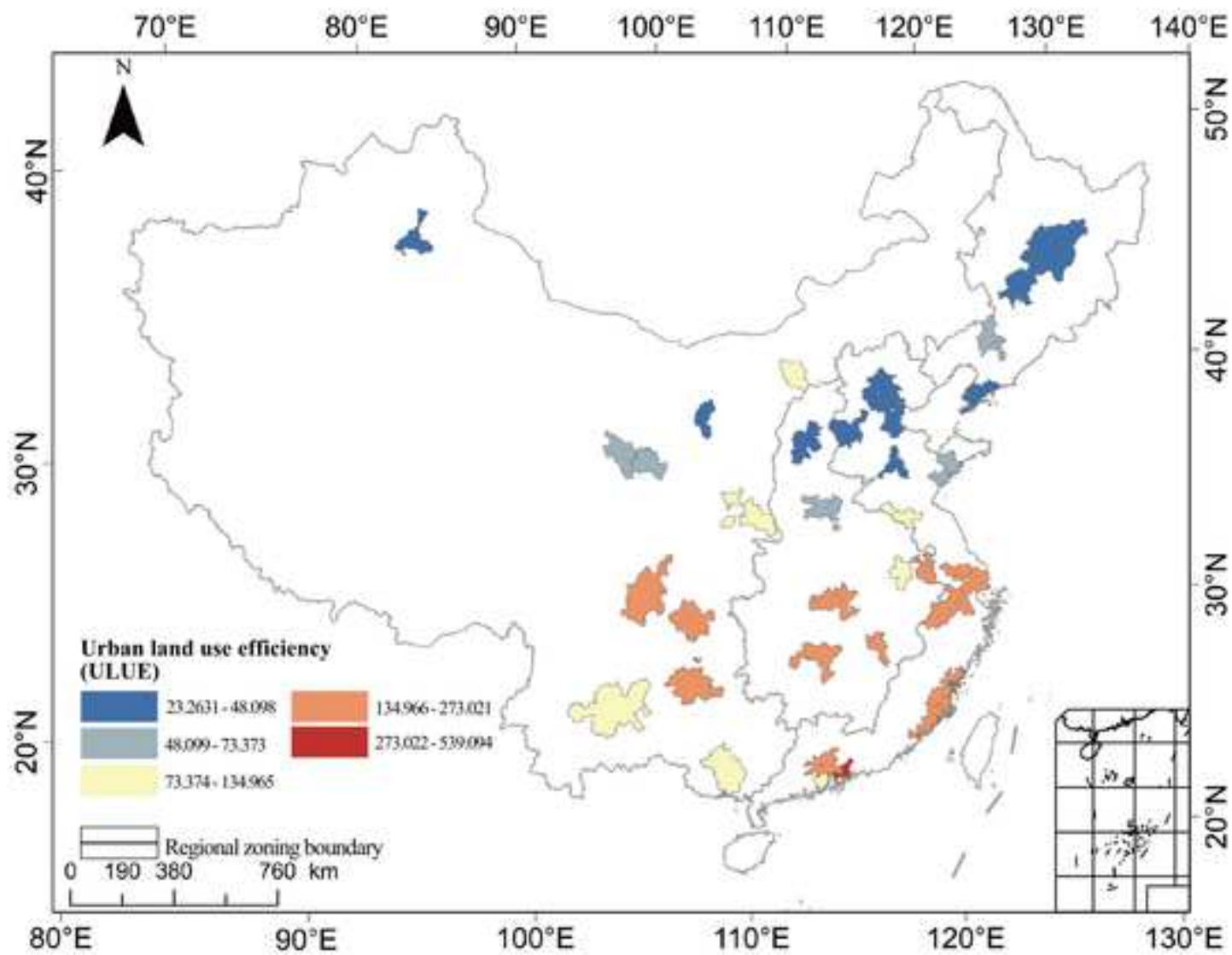
Figure. 10
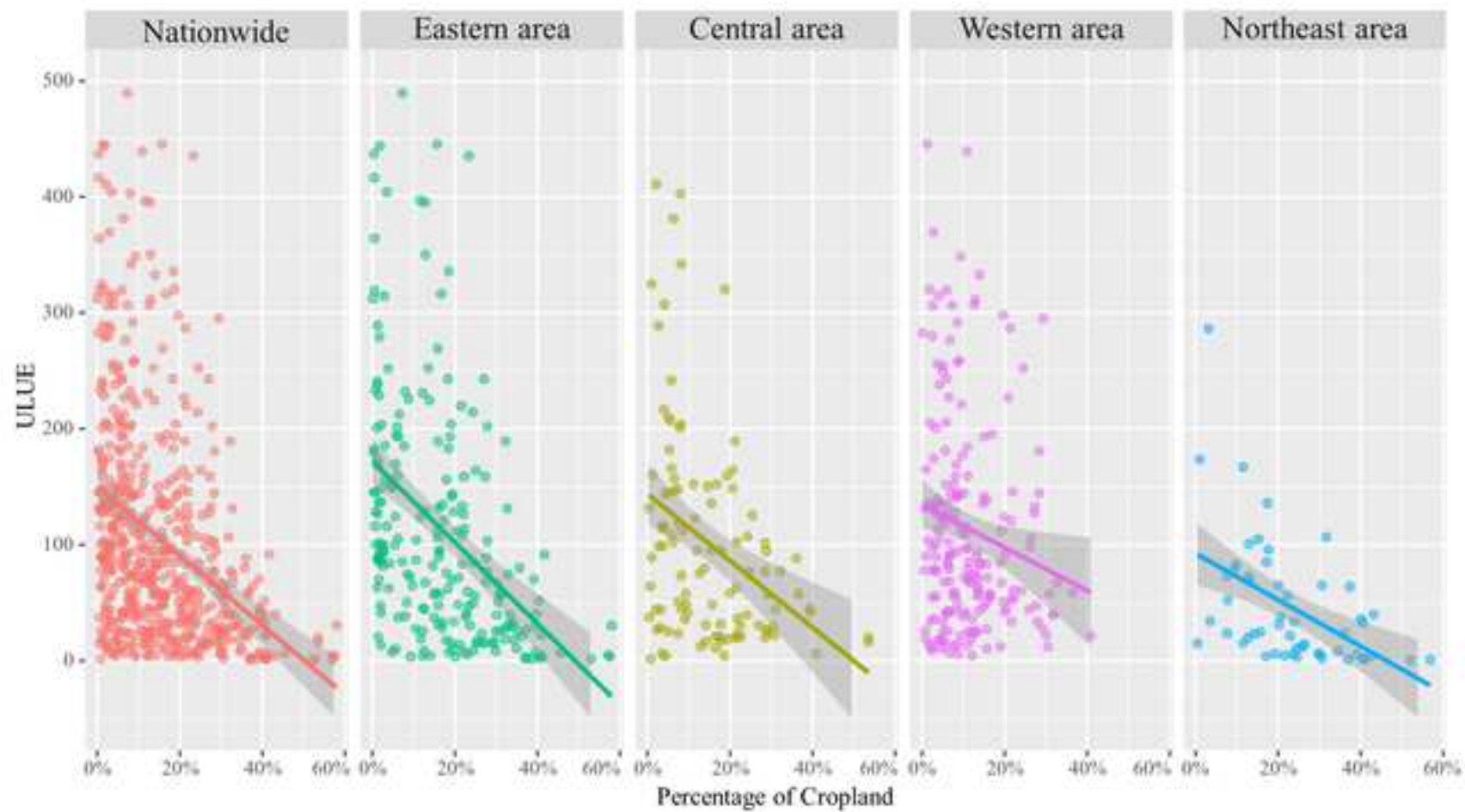
Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: