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China's urban-rural expansion and natural habitat loss since the 1980s: Retrospective analysis and future suggestions

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Natural habitats transformed to city or countryside with human activities of different intensities have reshaped regional and global landscapes, especially in those rapid developed low- and mid-income countries, like China. China's rapid shift in urban and rural expansion, which are greater than and equal to, and below county-level's artificial land expansion, and reduction in farmland and ecological land are important for determining future urban and rural development under the conservation and protection of farmland and ecosystems; however, such an understanding is still inadequate. Here, we show that both urban and rural expansions have encroached on farmland and ecological land since 1980; rural areas, with 1.33 $km^2 \times 10^5$ km^2 in 2020, remain larger than urban areas, with 0.97 $km^2 \times 10^5$ km^2 in 2020. However, urban areas (1857.5 km^2/year) increased faster than rural areas (695.0 km^2/year) during 1980–2020, rural expansion primarily occurred in the 1980s and 1990s, and urban expansion primarily occurred after 2000 especially 2000s. Farmland is the major land cover that has been occupied by urban and rural expansion for 53.7 and 39.1 thousand km^2, especially in East China's densely populated areas. And, both farmland and ecological land were primarily encroached during 2000s. Our results demonstrate imbalanced urban and rural expansion and encroachment on farmland and ecological land; thus, both forms of encroachment should be optimized at the regional scale based on the socioeconomic needs and natural conditions, and diverse policies can be designed to support local sustainable development.

KEYWORDS

urbanization, developing country, rural expansion, China, ecologial land loss

Introduction

Natural habitats transformed to city or countryside with human activities of different intensities have reshaped regional and global landscapes (Vitousek et al., 1997). Urban and rural areas are thus becoming important human footprints; however, attention to the two areas has differed. Cities have attracted much attention, as many countries promote

city expansion and development to boost their economies; however, little attention has been given to the countryside (Liu and Li, 2017).

China's urbanization strategy changes during the past four decades have increased China's urbanization rate change from 19.39% in 1980 to 63.89% in 2020 (from Nation Bureau of Statistics of China at www.stats.gov.cn). China's urbanization strategy initially set as "control the size of large cities, rationally develop medium cities, and actively develop small cities" in its 6th Five-Year Plan (FYP) during 1980–1985. It was gradually shift to "form cities mostly in form of city clusters along the two east-west axes of the Yangtze River and the Urumqi-Lianyungang railway, the three north-south axes of coast, the Harbin-Beijing-Guangzhou railway, and the Baotou-Kunming railway" after the 12th FYP during 2010–2015. (available at National People's Congress of China, www.npc.gov.cn). During this great change and urban spatial development shift, rural residents initially migrated to cities, while with the increase in those new urban residents' incomes, city nurtures countryside with the most obvious increase and improvement of rural construction areas and the living environment (Wang et al., 2016; Chen, 2020). Such changes directly occupied farmland and ecological land by both urban expansion and rural expansion (Deng et al., 2015; He et al., 2020; Zhou et al., 2020).

During the past decades, urban expansion has been attracting special attention from global, regional, to a specific administrative unit like country, province/state, prefecture, or city, especially at those regions with rapid urbanization (Sharma et al., 2016; Zhang et al., 2018). The multi-spectral, varied spatiotemporal resolution remote sensing imagery has been taking as the major data source for urban or artificial land surface extraction with visual interpretation or/and automatic/machine-learning classification (Sharma et al., 2016; Schneider et al., 2010; Seto et al., 2011). In recent years, many concerns have been given to artificial or urban imperious areas expansion; however, rare concerns have been given to rural impacts, even though China is a giant country with a large countryside (Bai et al., 2014; Zhang et al., 2018; Chen et al., 2021). This is partially due to the lack in distinguishing urban and rural areas as there is no clear boundary between them.

At national level, understand both urban and rural expansions and their occupation on farmland and ecological land would provide a better understanding of regional developmental dynamics and characteristics (He et al., 2020), provide regional development strategies for better balancing urban and rural land use efficiencies, and establish farmland and ecological land protection regulations (Jensen et al., 2019). Thus, the objectives of this research were to quantify urban and rural expansions and their occupations of farmland and ecological land. These characteristics suggest regionally specified practices to balance land occupation and development. We hope the results from this work will demonstrate land surface transmission by intensive human activities in rapidly developing mid- and low-income countries, and further provide cases and experience for other countries that are encountering the rapid urbanization to better design their urbanization strategies with the essential consideration of rural development.

Material and methods

China's prefectures

The prefecture boundary record was obtained from the National Geomatics Center of China (available at http://www.ngcc.cn/ngcc/). A total of 343 prefectures were used in this study (Suppementary Figure S1), including ninety-one prefectures in East China, thirty-six prefectures in Northeast China, eighty-four prefectures in Central China, and 132 prefectures in West China. The three urban clusters of Jingjinji, the Yangtze River Delta and the Pearl River Delta were further considered in this work. The Jingjinji urban cluster consists of thirteen prefectures in Beijing, Tianjin and Hebei Provinces, and the Yangtze River Delta urban cluster consists of fourteen prefectures in Shanghai, Zhejiang Province and Jiangsu Province.

Land cover data

The land cover data were visually interpreted with Sentinel and Landsat imagery with a spatial resolution of 30 m in 1980, 1990, 2000, 2010, and 2020. Those imageries were collected in the optimal season for the visual interpretation at different provinces of China, and then those provincial results were merged together as a national wide land cover data. The data consist of six first-level classifications and twenty-five second-level classifications (Table 1). Farmland, forest, grassland, and open water in the first-level classification were used in this work, and forest, grassland, and open water were categorized as the ecological land. Meanwhile, the urban areas and rural areas in the second-level classification were used in this research. Urban areas were defined as areas higher than the county-level constructed human residential areas, while rural areas were defined as areas below the county-level constructed human residential areas. The data had a total accuracy of 80% for the first-level classification and 85% for the urban and rural area classification (available at https://www.databox.store/Home/Index).

Urban and rural occupation identification

The farmland that changed to urban and rural areas during 1980–2020 was obtained by directly using GIS change analysis tools. Forest, grassland, and open water were taken as ecological land in 1980, 1990, 2000, 2010, and 2020. Then, the ecological land changes to urban and rural areas during 1980–2020 were obtained by overlay and change analysis with the following algorithms:

TABLE 1 Land cover classification that used in this work.

First-level classification	Second-level classification		Re-class in this work
Type	Type	Characters	
Farmland	—	Land for planting crops, including mature cultivated land, land for agricultural fruits, and beach with more than 3 years cultivation	Farmland
Forest	—	Land for forest, shrub, bamboo, and coastal mangrove	Ecological land
Grassland	—	Land with herbs grass dominated that grass coverage more than 5%, and shrub or tree coverage lower than 10%	
Open water	—	Natural or human made open water areas	
Constructed land	Urban area	Higher than county level constructed human residential areas	Urban area
	Rural area	Below county level constructed human residential areas	Rural area
	Other construction land	Land for factories, mining, oil field, saltworks, stone quarries, etc., and traffic roads, air ports and other construction land that not major for peoples' living	—
Others	—	Other types of land covers that beyond farmland, forest, grassland, open water, and constructed land	—

$$U_i = U_{i-10} + UF_{i-10} + UE_{i-10}. \quad (1)$$

$$R_i = R_{i-10} + RF_{i-10} + RE_{i-10}, \quad (2)$$

where *Ui* and *Ri* represent the urban and rural sizes in year i, Ui-10 and Ri-10 represent the urban and rural sizes in year i-10, *UFi*-10 and UEi-10 represent the urban occupation of farmland and ecological land during 10 years after year *i*, and RFi-10 and REi-10 represent the urban occupation of farmland and ecological land during the 10 years after year *i*.

Then, each period's urban and rural occupations at the prefectural level were calculated by overlaying China's prefectures.

China's urban and rural development policy

The urban and rural development policies were obtained from China's FYPs, which define the national strategies of national development. The sixth FYP to the 14th FYP were obtained from the National People's Congress of China (www.npc.gov.cn). The urban development policies and strategies were then collected as shown in Figure 1.

Results

Urban expansion and rural expansion after 1980s in China

Rural areas remained larger than urban areas, but urban areas increased faster than rural areas during 1980–2020 (Figure 2A; Table 2). Urban areas expanded from 22.4 thousand km^2 (0.2% of the China's total land area) in 1980 to 96.7 thousand km^2 (1.0% of the China's total land area) in 2020, while rural areas expanded from 105.5 thousand km^2 (1.1% of the China's total land area) in 1980 to 133.3 thousand km^2 (1.4% of the China's total land area) in 2020. Urban areas primarily expanded in the last two decades, while rural areas primarily expanded in the first two decades during 1980–2020. China's sub-regions showed three types of urban and rural expansion methods (Figure 2B; Table 2). East China mainly showed urban expansion with less rural expansion, especially after 2000. Urban area expanded from 17.7 thousand km^2 (1.8% of the East China's total land area) in 2000 to 49.6 thousand km^2 (5.1% of the East China's total land area) in 2020, with rural expansion changing from 45.8 thousand km^2 (4.7% of the East China's total land area) in 2000 to 48.4 thousand km^2 (5.0% of the East China's total land area) in 2020. Central and West China showed similar expansion as that in East China, but urban expansion had small amounts, expanding from 7.4 to 6.8 thousand km^2 (0.7% and 0.1% of the Central and West China's total land area) in 2000 to 22.4 and 19.7 thousand km^2 (2.1% and 0.3% of the Central and West China's total land area) in 2020, respectively. Meanwhile, Central China's rural areas showed a decrease from 36.6 thousand km^2 (3.5% of the East China's total land area) in 2010 to 36.2 thousand km^2 in 2020. Both urban and rural expansions in East China showed similar intensities but differed temporally. Urban expansion primarily occurred in the 2000s, while rural expansion primarily occurred in the 1980s; specifically, urban area expanded from 4.3 thousand km^2 in 2000 to 6.4 thousand km^2 in 2010, while rural area expanded from 30.1 thousand km^2 in 1980 to 33.9 thousand km^2 in 1990. The three urban clusters showed that both urban and rural areas expanded in Jingjinji, only urban areas expanded after 2000 in the Yangtze River Delta, and urban areas expanded with rural areas first and then decreased in the Pearl River Delta (Figure 2B; Table 2).

In 1980, there were no prefectures with urban sizes greater than 1,000 km^2 but there fifteen prefectures with urban sizes

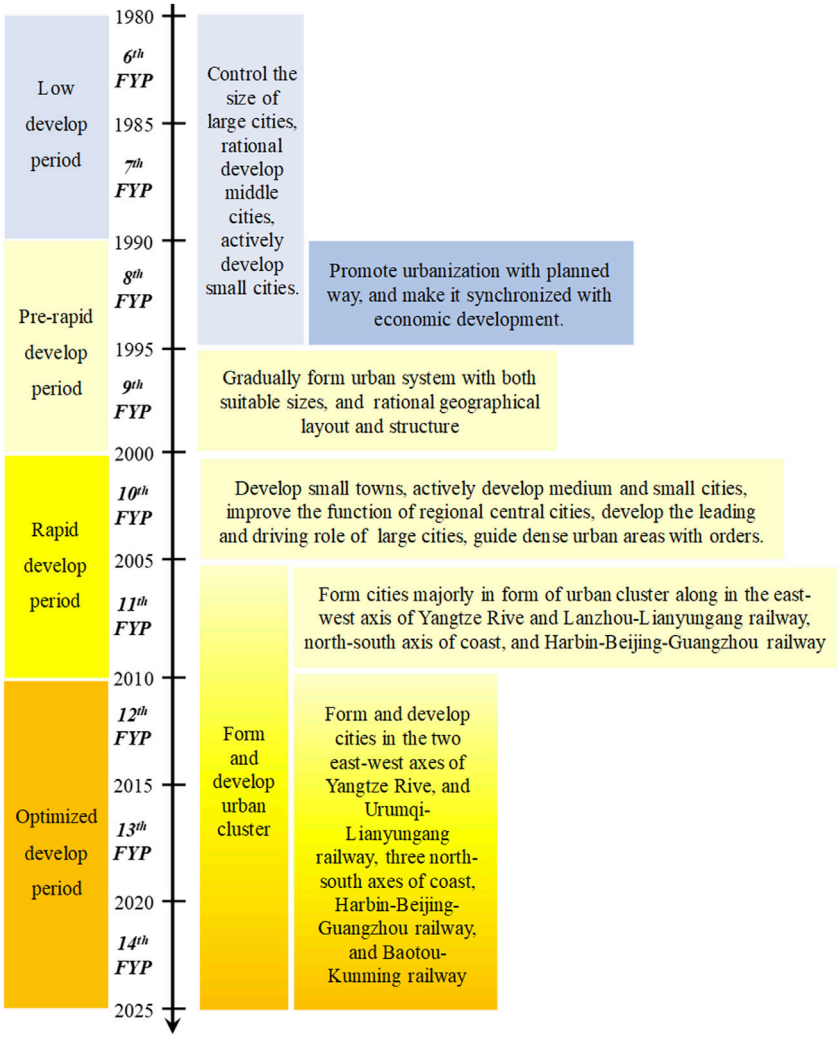

FIGURE 1
China's urban developing strategy during 1980–2025.

greater than 1,000 km^2 in 2020; however, twenty-six prefectures had rural sizes larger than 1,000 km^2 in 1980, and thirty-eight prefectures had rural sizes larger than 1,000 km^2 in 2020 (Supplementary Figure S2). Prefectures with larger urban areas were mainly found in East China's Beijing, Tianjin, Hebei, Shandong, and Jiangsu Provinces before 2000, while until 2020, all provinces of East and Central China had prefectures with urban sizes greater than 500 km^2 (Figure 3). However, prefectures with larger rural sizes were steadily found in Northeast China, east of Inner Mongolia, Beijing, Tianjin, Hebei, Shanxi, Shandong, Anhui, and Jiangsu (Figure 3). In 1980, only thirty-two prefectures had urban areas larger than rural areas, but this number sharply increased after 2000, to 144 in 2020 (Supplementary Figure S3). Prefectures with larger urban than rural areas were mainly found in West China in 1980, but they steadily increased, especially during 2000–2020, resulting in 49, 35 and 58 prefectures with urban areas larger than rural areas in East, Central and West China in 2020, respectively. These three city clusters in Jingjinji with only two prefectures are Beijing and Tianjin, and the urban areas were larger than rural areas until 2020. However, the values were twelve and seven prefectures in the Yangtze River Delta and Pearl River Delta, respectively, with urban areas larger than rural areas until 2020 (Supplementary Figure S3).

Farmland occupation by urban and rural expansion

Farmland is the major land cover that is occupied by urban and rural expansions. A total of 53.7 and 39.1 thousand km^2 (0.5% and

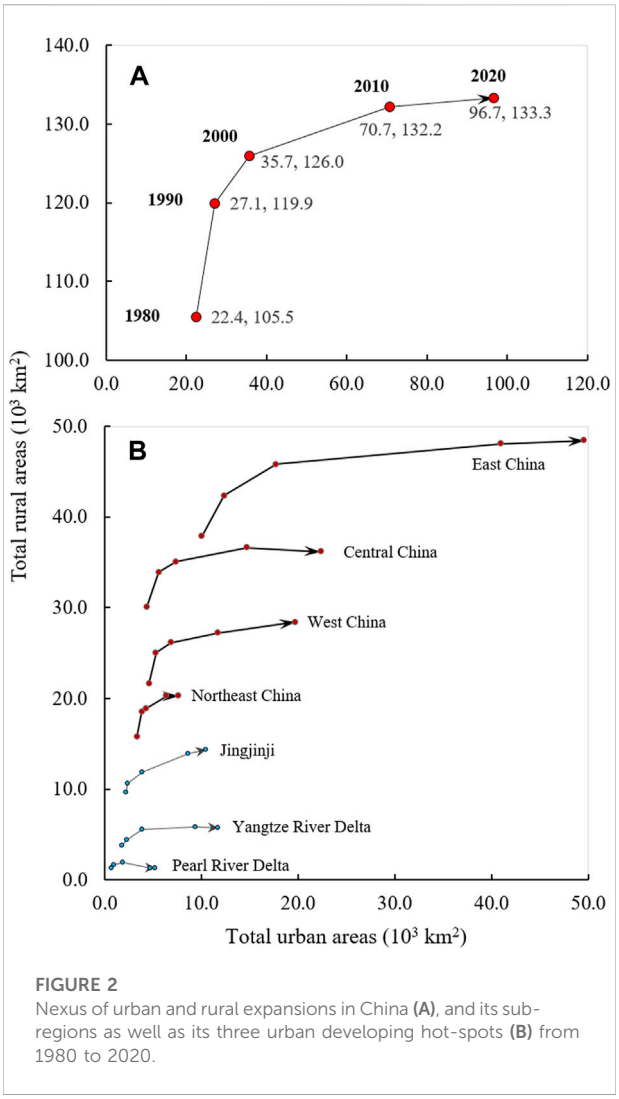

FIGURE 2
Nexus of urban and rural expansions in China **(A)**, and its sub-regions as well as its three urban developing hot-spots **(B)** from 1980 to 2020.

0.4% of China's total land area) of farmland was occupied by urban and rural expansion during 1980–2020 (Figure 4A). This area increased from 1980–1990 to 2000–2010 and then decreased. During 2000–2010, 25.3 and 35.1 thousand km^2 of farmland was occupied by urban and rural expansions, respectively (Figure 4A). As a result of the large amount of urban and rural expansions in East China, farmland also occupied a larger area. A total of 28.0 and 16.5 thousand km^2 of farmland was occupied by urban and rural expansions in East China during 1980–2020 (Figure 4B). More than half of the occupations occurred during 2000–2010, when farmland also largely occupied the rest of the subregions of China. Except for East China's farmland occupation by urban expansion rather than rural expansion after 2000, this phenomenon occurred after 2010 in the three remaining subregions of China. In the three typical urban clusters, the Pearl River Delta was found to have the smallest farmland occupation, and farmland occupation by urban expansion has been the major form in the Pearl River Delta since 1980, in the Yangtze River Delta since 2000, and in Jingjinji only after 2010 (Figure 4C).

Prefectures with larger farmland areas occupied by urban expansion were primarily found in Beijing, Chongqing, southern Hebei, Shandong, Jiangsu and northern Zhejiang Provinces during 1980–2020 (Figure 5A). Larger farmland occupation by urban expansion mainly occurred during 2000–2020, in which occupation occurred, especially during 2000–2010 (Supplementary Figure S4). In 1980–1990, very limited farmland was occupied by urban expansion. Prefectures with large farmland occupied by rural expansion were primarily found in provinces in Northeast China, east of Inner Mongolia, Beijing, Tianjin, Hebei, Shandong, Jiangsu, and Henan Provinces where large farmland area was distributed (Figure 5B). Larger farmland occupation by rural expansion primarily occurred during 2000–2020, in which occupation occurred especially during 2000–2010 (Supplementary Figure S5). In 2010–2020, a very small amount of farmland was occupied by rural expansion. A total of 232 out of 343 prefectures had more farmland occupation by urban expansion than by rural expansion during 1980–2020. This number increased from 41 prefectures in 1980–1990, 175 and 138 prefectures in 1990–2000 and 2000–2010, respectively, to 305 prefectures in 2010–2010.

Ecological land occupation by urban and rural expansion

A total of 18.2 thousand km^2 (0.2% of China's total land area) of ecological land was occupied by urban and rural expansions, with 11.4 and 6.8 thousand km^2 of ecological land occupied by urban and rural expansions, respectively (Figure 4D). The urban and rural occupation first decreased to 1.8 thousand km^2 in 1990–2000, then largely increased to 12 thousand km^2 in 2000–2010, and then decreased 5.2 thousand km^2 in 2010–2020 when occupation by urban expansion rather than by rural expansion was first observed. Similar changes were found for the four subregions of China, but more occupation by urban expansion than by rural expansion was first observed in 1990–2000 in East and Central China (Figure 4E). In the three typical urban clusters, the Yangtze River Delta was found to have the smallest ecological land occupation of only 1.7 thousand km^2, and ecological land occupation by urban expansion was the major form in the Pearl River Delta and in Jingjinji since 1990 but not in the Yangtze River Delta until 2000 (Figure 4F).

Prefectures with more ecological land areas occupied by urban expansion were primarily observed in Beijing, Tianjin, Inner Mongolia, Chongqing, Hunan and the Pearl River Delta during 1980–2020 (Figure 5C). More ecological land occupation by urban expansion primarily occurred during 2000–2020, while very limited ecological land was occupied by urban expansion during 1980–2000 (Supplementary Figure S6). Prefectures with more ecological land occupied by rural expansion were primarily found in Inner Mongolia and Xinjiang during 1980–2020 (Figure 5D), and especially during 1980–2020 (Supplementary Figure S7). In fact, 223 out of 343 prefectures had ecological land

TABLE 2 Comparison of urban (U) and rural (R) expansion rate in China, China's subregions and the three urban expansion hot-spots in percentage.

Periods	China		East China		Northeast China		Central China		West China		Jingjinji		Yangtze river delta		Pearl river delta	
	U	R	U	R	U	R	U	R	U	R	U	R	U	R	U	R
1980–1990	21	14	23	12	14	17	28	13	16	16	10	10	28	17	36	25
1990–2000	32	5	43	8	12	2	32	3	29	4	61	12	70	27	96	17
2000–2010	98	5	131	5	49	7	99	4	71	4	124	18	145	5	147	-30
2010–2020	37	1	21	1	20	0	52	-1	69	4	21	3	25	-2	12	-5

occupied by more urban expansion than by rural expansion during 1980–2020. This number increased from 39 prefectures in 1980–1990 to 128 and 174 prefectures in 1990–2000 and 2000–2010, respectively, and to 276 prefectures in 2010–2010.

Discussion

In this research, we highlighted urban areas increased faster but remain smaller than rural areas during 1980–2020, rural expansion majorly occurred during first two decades, 1980–2000, but urban expansion majorly occurred during the latest two decades, 2000–2020. Farmland loss was the majority contribution to the urban and rural expansion. Based on those results, the implication goes to urban and rural expansion should be optimized by the local socioeconomic needs, as well as land occupation needs to be adjusted with regional imbalanced development. Details followed.

Regional urbanization needs diversification as the past 4 decades' diversification

The results in our work extend temporal scale to 2020 indicated China's urbanization from low speed to pre-rapid, rapid and optimized development characterized the shape of the structure, size, and spatial pattern of cities and rural areas. Urban and rural developments in the past 40 years have shown regional diversity in both size and speed and their associated ecological land and farmland occupations. These changes also have a broad impact on China's ecosystem and the environment, providing a unique sample for the world to discover and reconsider diverse urbanizations and their impacts (Zhou et al., 2004; Zhou et al., 2021).

Other concerns remain to be further justified, such as China posting the "two east-west axes and three north-south axes" urban development strategy as early as China's 11th FYP and then further emphasizing it in its 12th and 13th FYPs; however, until the size distribution in 2020, the pattern was still not as clear as the ideal design. Furthermore, China posted the urban cluster strategy as early as the 11th FYP and emphasized that in the 12th and 13th FYPs, clusters could be identified in a smaller range of the current boundary of those clusters. Beijing, Tianjin and Tangshan could be recognized as similarly sized clusters in the current officially defined Jingjinji urban cluster; Shanghai and Suzhou could be recognized as similarly sized clusters; and Guangzhou, Dongguan and Shenzhen could be recognized as similarly sized clusters (Fang and Yu, 2017). Further justification of an urban cluster should take more consideration of the urban sizes while setting the boundary of the urban cluster, even though a cluster needs combinations of cities of multiple sizes. These results suggest that China's future urban development plan should be more diverse by considering the local urban

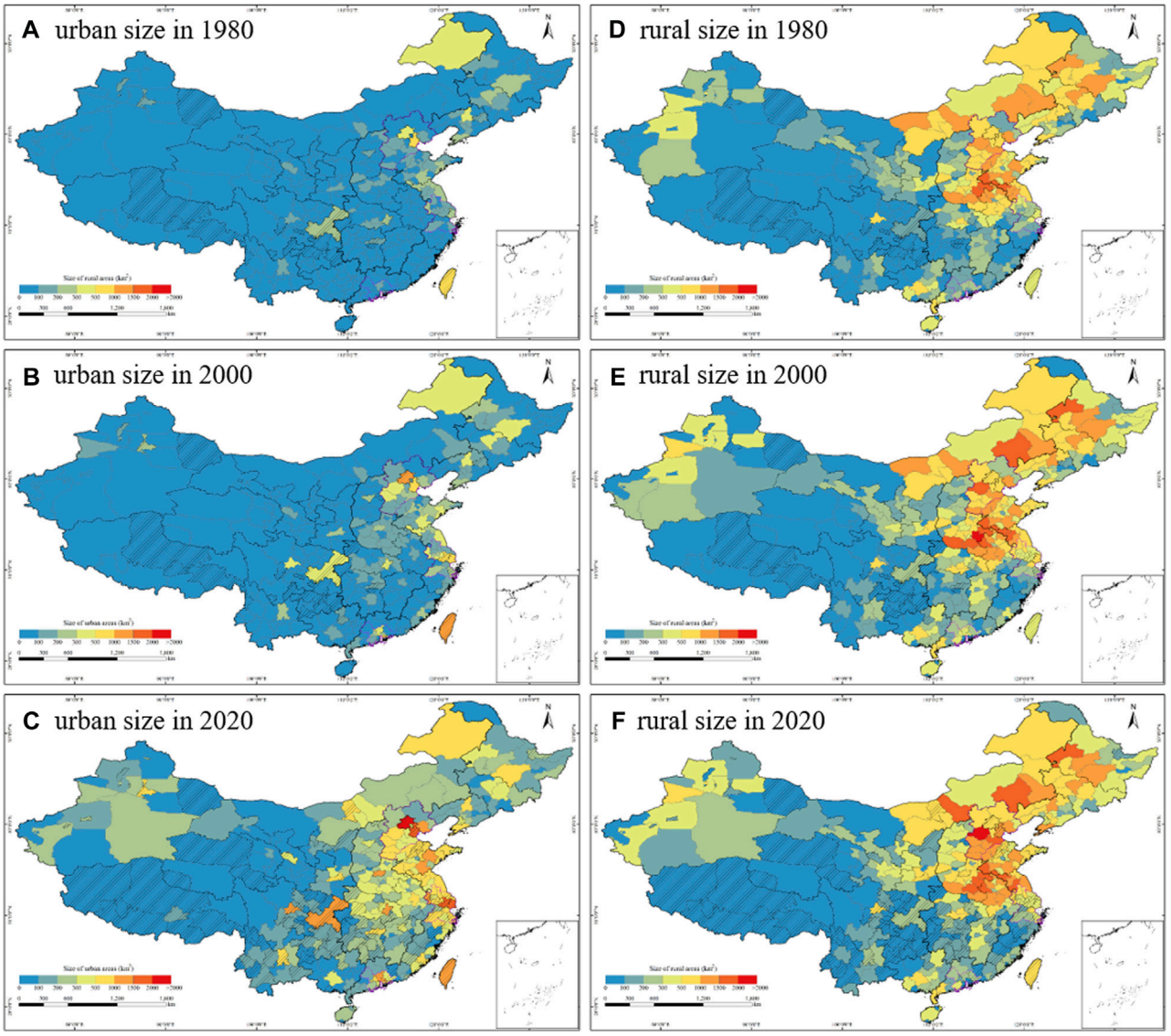

FIGURE 3
Urban and rural sizes at each prefecture of China in 1980 and 2020. Note: The shaded prefectures indicate urban size larger than rural sizes.

development form. For instance, urban cluster policy might best fit East China's plain areas, while metropolitan development might best fit elevated cities such as Chongqing and regional central cities in West China.

Rural development need optimized in regions of both rapid urbanization and remote areas

The rural expansion was carefully examined with standard of artificial surface below county-level's artificial land expansion. That could follow Chinese general understanding on the countryside or rural areas (Li et al., 2015). Through the understanding of our results, clear rural development optimization could be raised.

Before 2000, especially before 1990, rural expansion marked China's artificial land expansion. Local residents' living conditions, especially housing areas, greatly improved as China posted the rural housing construction plan with a total of 5.5 billion square meters during the 6th and 7th FYPs, which was more than five times the urban housing construction plan (China's 6th and 7th FYPs available at National People's Congress of China, www.npc.gov.cn). However, a national rural layout design and plan, such as the "two east-west axes and three north-south axes" urban development strategy, does

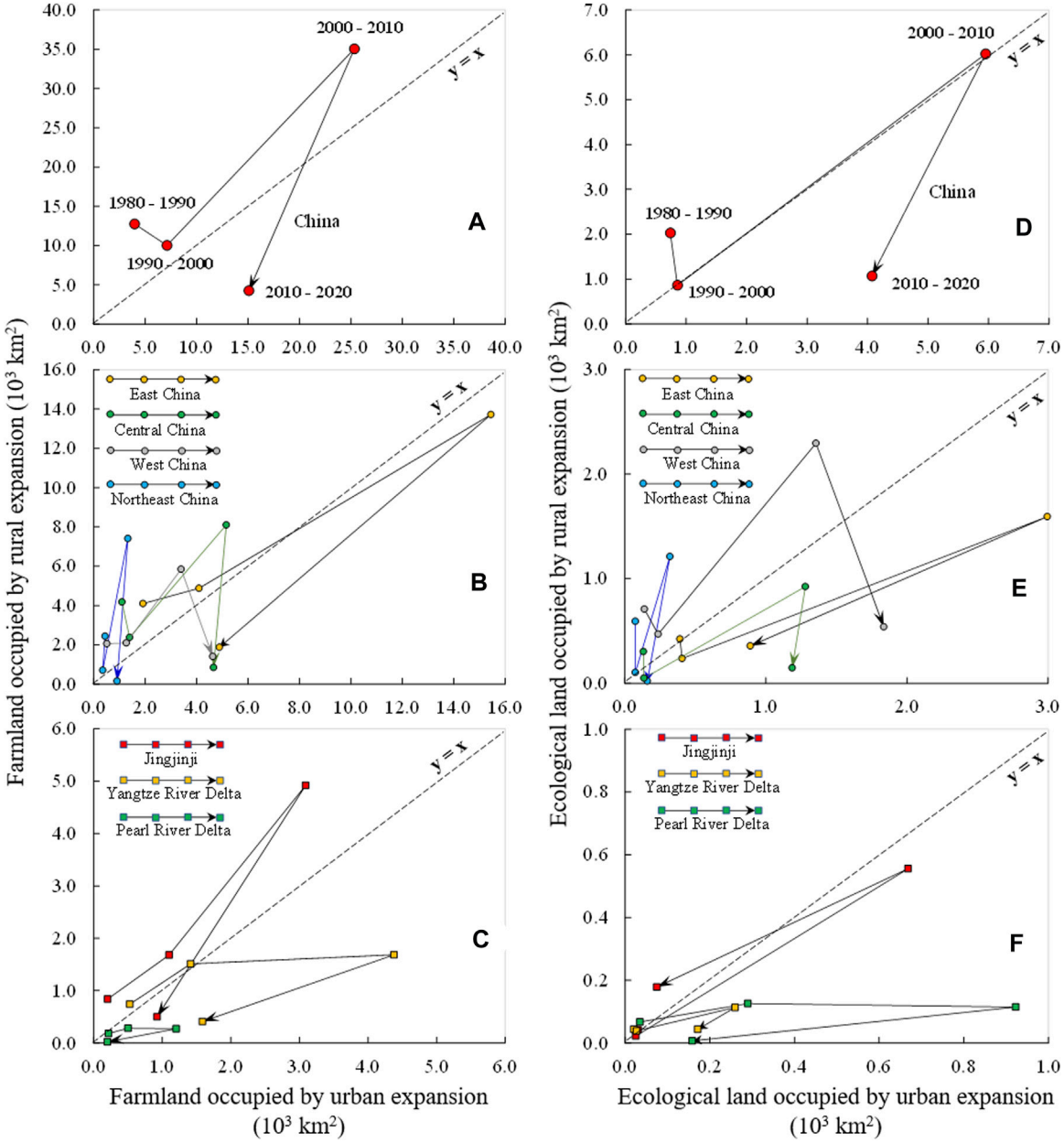

FIGURE 4
Farmland and ecological land occupied by urban and rural expansions in China during 1980–2020. **(A,D)** show farmland and ecological land occupation in China, respectively; **(B,E)** show farmland and ecological land occupation in subregions of China, respectively; **(C,F)** show farmland and ecological land occupation in China's three urban developing hot-spots, respectively.

not exist even though the rural revitalization strategy in 2017 was still not raised.

Under China's urban population, the rate reached 63.89% at the end of 2020. Moreover, the population is migrating to cities and aging, reducing artificial land use efficiency in rural areas (Wang et al., 2012). Those particular areas need both national strategies and better local adaptation to better plan rural areas for sustainable development. For instance, over 40 years, China's rural areas were primarily located in Northeast China, east of Inner Mongolia, and the East China Plain, which covers the Jingjinji urban cluster and Shandong, Henan, Jiangsu and Anhui Provinces. These areas were also China's major farmland zone, and rural development and farmland conservation were therefore as important as urbanization in those areas. Considering both urban and rural development with regional socioeconomic balance should be carefully considered.

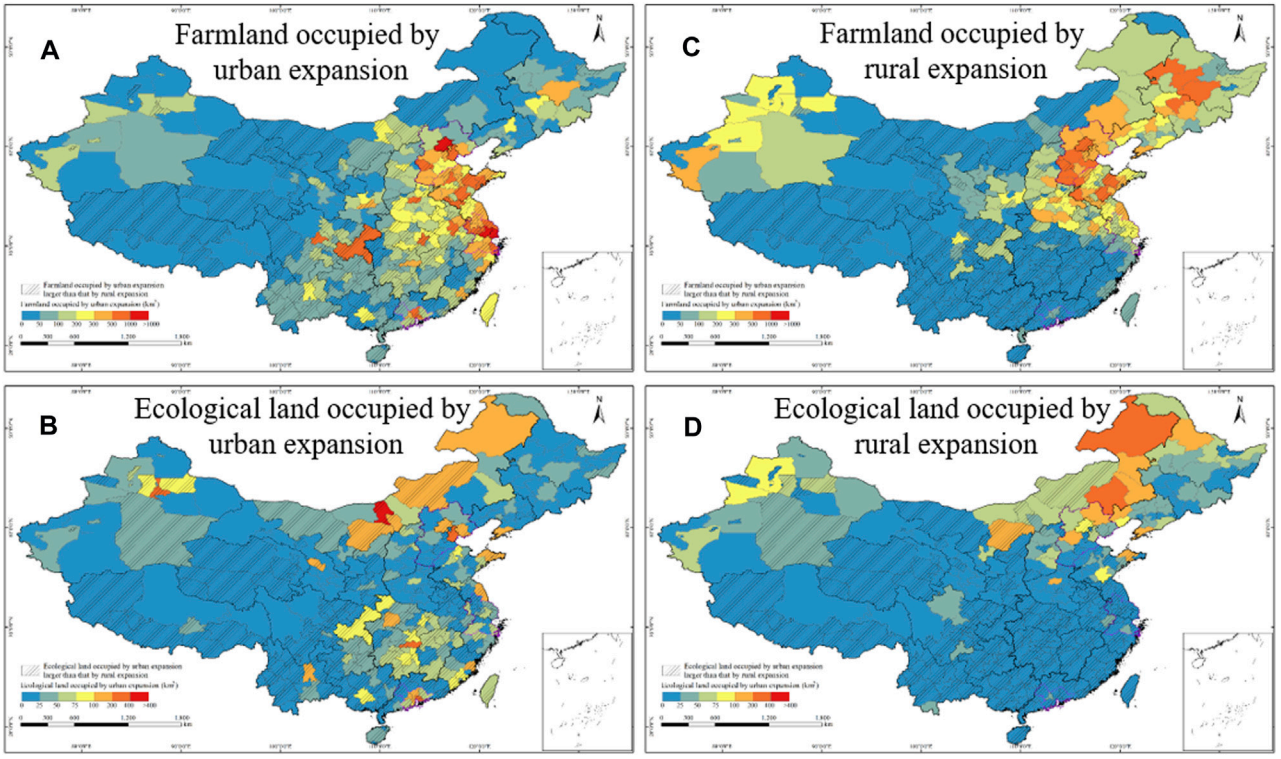

FIGURE 5
Farmland and ecological land occupied by urban and rural expansions in China during 1980–2020. Note: The shaded prefectures indicate farmland and ecological land occupied by urban expansion larger than that occupied by rural expansion.

Land occupation needs to be adjusted with regional imbalanced development

As the land cover change especially the land occupation by human dominated cover has be recognized as important factor to both the environmental dynamic and sustainability (Turner et al., 2007). Go through the past 40 years' land occupation in our findings, and under the new 14th FYP in China from 2021 to 2025, we argue that urban and rural development should cooperate with regional and local socioeconomic development. In the 14th FYP, developing urban clusters and the "two east-west axes and three north-south axes" urban development strategy were the major considerations in China's urban development; however, the balance of urban and rural areas was not well explained in the plan. We thus suggest the following regionalized urban and rural occupation based on the forty-year land occupation and socioeconomic development level.

In East China's plain areas, rural expansion should be strictly limited and prohibited and villages with low populations should be further compressed and merged to return them back to farmland. Urban population capacity is highly suggested to increase, and urban expansion is suggested to make essential expansions on the basis of improving the urban living environment. Thus, to further promote the urbanization process and attract surrounding rural residents, the urban expansion-derived small amount of farmland occupation should be exchanged for rural land returned to farmland in the large areas. In East China's non-plain or mountainous areas, both urban and rural expansions have almost reached the regional capacity by moderately converting rural land to multi-function ecological land to provide potential space for urban residents' demands for ecological recreation.

In Central China, it is highly suggested to increase the population intensive capacity of cities and ensure the areas and quality of farmland and ecological land within the region.

In West China, it is highly suggested to increase the capacity of cities with relatively better ecological and living condition areas and merge villages in the better areas and return villages in areas with harsh environments.

In Northeast China, it is highly suggested to prohibit rural expansion and further limit urban expansion but increase urban capacity and living conditions to attract rural residents. Thus, rural areas with low use efficiency can be returned to farmland and ecological land.

Conclusion

Natural habitats transformed to city or countryside with human activities of different intensities have reshaped landscapes in China, which were very unique on the planet as it introduced reform and opening-up since 1979 (Bai et al., 2014; Chen et al., 2021; Zhou et al., 2021). China's rapid shift in urban and rural expansion and reduction in farmland and ecological land are important for determining future urban and rural development under the conservation and protection of farmland and ecosystems.

In this research, we analyzed both urban and rural expansion, as well as their encroached on natural and semi-nature habitat. We found that both urban and rural expansions have encroached on a big amount of both farmland and ecological land since 1980; rural areas, with values of 1.06 $km^2 \times 10^5$ km^2 in 1980 and 1.33 $km^2 \times 10^5$ km^2 in 2020, remain larger than urban areas, with values of 0.22 $km^2 \times 10^5$ km^2 in 1980 and 0.97 $km^2 \times 10^5$ km^2 in 2020. However, urban areas increased faster than rural areas during 1980–2020, rural expansion primarily occurred in the 1980s and 1990s, and urban expansion primarily occurred after 2000 especially 2000s. Farmland is the major land cover that has been occupied by urban and rural expansion, especially in East China's densely populated areas. And, both farmland and ecological land were primarily encroached during 2000s.

Our results demonstrate imbalanced urban and rural expansion and encroachment on farmland and ecological land; thus, both forms of encroachment should be optimized at the regional scale based on the socioeconomic needs and natural conditions, and diverse policies can be designed to support local sustainable development.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: The original dataset can be obtained from https://www.databox.store/Home/Index by paying a fee. However, the results from this research are freely available upon request from the first author LH at ljhan@rcees.ac.cn.

Author contributions

LH contributed to design of the work, analysis and interpretation of data, wrote and revised the manuscript; LZ contributed to acquisition and analysis of data; WZ contributed to manuscript revise; WL and YG contributed to interpretation of data and manuscript revise.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.1065174/full#supplementary-material

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