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Urban sprawl in provincial capital cities in China: evidence from multi-temporal urban land products using Landsat data

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The onset of global urbanization has led to a population shift from rural to urban areas and the expansion of urban development [1–3]. Urban land areas are growing at faster rates than their populations in most parts of the world [4]. The urban sprawl process refers to dispersed land development characterized by low-density, unplanned, and uneven patterns of growth during urban expansion. This process can result in inefficient use of land resources contradictory to the principle of sustainable development [5]. Additionally, urban sprawl has various environmental, economic, and social consequences, including the following: loss of agricultural land, higher costs for transportation infrastructure, increased landscape fragmentation, degeneration of soil ecological functions, and reduced ecosystem resilience. It is crucial to understand the trends and patterns of urban sprawl to implement a framework for sustainable urban development in developing regions.

Satellite data can be used to monitor the evolution of urban lands on national, regional, and global scales. Most global urban land products or artificial surface layers are produced using imagery from coarse resolution sensors. The global nighttime light data collected by the US Air Force Defense Meteorological Satellite Program's Operational Linescan System (DMSP-OLS) and the Visible Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band (DNB) aboard the Suomi-NPP satellite have been used to quantify patterns of urban area growth in China to a spatial resolution of 500–1,000 m [6]. The freely available Landsat image series with 30-m spatial resolution has enhanced the ability to monitor changes in urban built-up areas. Landsat images have been used to monitor and analyse urban sprawl in large cities and urban agglomerations in China [7–9]. However, the majority of Landsat studies are conducted at the city scale, and analysis areas are mainly located in China's eastern coastal regions [8]. Continual urban expansion in China and its resulting consequences highlight the need for systematic investigation of urban sprawl at the national scale. Urban lands have been mapped using the China Land Use/Cover Dataset (CLUD) [10] and the Global Land Cover Dataset (GlobeLand30) [11] with an overall accuracy greater than 85%. The urban land products at 30-m resolution have been used to compare growth patterns across cities in previous studies, whereas manual processes were required to generate both products.

The availability of high-performance computing resources in recent years in addition to big Earth observation datasets has made large-scale urban mapping possible [12–14]. Multi-temporal urban land products have been developed from Landsat imagery using the Joint Research Centre Earth Observation Data and Processing Platform (JEODPP) framework [15]. With this data, municipalities and provincial capitals with large populations have been classified as rapidly developing areas in China [15,16], and for this study, the rates, extent, and patterns of urban sprawl were quantified and compared in China's provincial capital cities using the new urban land products in conjunction with population census data. First, the annual expansion area (AE, km^2) and annual rate of urban land expansion (AGR, %) were used to quantify the amount and rate of urban expansion. Landscape indices were used to characterize the spatial patterns of urban sprawl in each city (Table S1 online). The urban sprawl index (USI) considers the growth rate of an urban area and its corresponding urban population. Moreover, the USI is used to measure the degree of sprawl in each metropolitan area. A high USI value indicates a larger degree of urban sprawl. An overall USI representing the national average sprawl level was calculated using the total amount of urban area and population in all analysed cities.

A total of 27,861 scenes were acquired by the Landsat 4–5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), the Landsat 8 Operational Land Imager (OLI), and the Thermal Infrared Sensor (TIRS). The data were collected and organized into six data collections (1990, 1995, 2000, 2005, 2010, and 2015). Landsat data collections were used as the main input, and urban built-up areas were automatically extracted using the Symbolic Machine Learning methodology. The multi-temporal urban land products encoded the presence of built-up surfaces covering mainland China for six epochs ranging from 1990 to 2015 at a 30-m resolution. According to the per-pixel accuracy assessment, urban land classifications were in strong agreement with the manually collected referenced dataset. Moreover, the overall accuracy range was 0.79–0.96, and the Kappa value range was 0.59–0.92 (Table S2 online).

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The spatial patterns for built-up areas in 31 provincial capital cities were mapped, and the results revealed that each city experienced rapid urban expansion between 1990 and 2015 (Fig. S1 online). The change in urbanized land for each individual city was estimated at each period (Fig. S2 online). The average AE and AGR for all 31 cities were 573.33 km^2 and 5.21%, respectively, during the study period. The expansion of total built-up areas was slow in the 1995–2000 period, with an AE value of 316.89 km^2 and an AGR value of 3.89% (Table S3 online). However, the expansion rate peaked during the 2000–2005 period, with an AE of 1,269.02 km^2 and an AGR of 11.13%, followed by deceleration from 2005 to 2015. These results coincided with a CLUD-based analysis, which found slower growth rates for cities with more than 2 million residents after 2005 [17]. The AEs and AGRs for urban areas across four economic regions were compared between 1990 and 2015. The annual urban area expansion for eastern cities was 333.75 km^2, which was larger than the other regions. Western cities featured the highest AGR value (6.32%) followed by cities in central China (6.14%) and eastern China (5.11%). The cities in north-eastern China had the lowest growth rates (AGR = 3.47%). The spatial variation of AGRs in different regions was consistent with the regional urban expansion patterns reported by Xu et al. [6].

Eight landscape parameters were used to quantify spatial patterns for urban land at six time stages beginning in 1990. These parameters were calculated and combined in a spider chart (Fig. S3 online). Generally, the total urbanized area (CA) and largest patch index (LPI) exhibited increasing monotonic trends in all the cities during the urbanization process. Shanghai, Beijing, and Tianjin provided the largest CAs. Zhengzhou, Hefei, and Taiyuan had an LPI greater than 0.5, which indicated that the large built-up area patch dominated the total landscape area. The number of patches (NP) and patch density (PD) exhibited increasing trends in 19 of the 31 cities, which mirrored fragmentary urban landscapes. Low mean patch size (MPS) values (<0.2) were observed in Nanjing, Nanning, Wuhan, Urumqi, Haikou, and Lhasa. A fluctuating and increasing MPS trend was observed in the provincial capital cities. The MPS values for Shanghai, Fuzhou, Lanzhou, and Hefei increased by five times compared to 1990 values. The increasing NP and MPS for cities in central and eastern China were also revealed using the CLUD dataset [18]. Conversely, the edge density (ED) based on our products differed from the declining EDs observed in CLUD [18]. This finding may be attributed to the different approaches for urban area extraction. The urban land in CLUD included developed and non-developed lands such as grasslands and parklands. Moreover, this land was created by using the manually delineated boundaries for cities and towns. The mean shape index (MSI) and the area-weighted mean patch fractal dimension (AWMPFD) measured the complexity of patch shapes in the urban landscape. The MSI was observed to increase in most cities, which suggests that the shape of urban landscapes became more irregular with increasing urbanization.

The extent of urban sprawl was measured using an Urban Sprawl Index in 29 provincial capital cities. The growth of urban land among the cities (5.16%) generally exceeded that of the urban population (2.31%), with an overall USI of 2.85. Only 3 of the 29 cities (Shijiazhuang, Xining, and Yinchuan) did not experience sprawl (USI < 0), while 26 displayed urban sprawl (USI > 0) (Fig. S4 online). Among these cities, 9 had lower USIs than the national average (USI < 2.85), and the remaining 17 displayed sprawls exceeding the national average. The most sprawling cities included Nanjing, Chongqing, Wuhan, and Hangzhou, with USI values higher than 7. Regionally, the cities in central (average USI = 3.61) and eastern China (average USI = 3.57) had a greater degree of sprawl than those in western China (average USI = 3.41) and northeastern China (average USI = 2.54). The excessive sprawl in large cities in eastern China and high USI values in cities such as Hangzhou, Nanjing, and Chongqing were also revealed by analyzing urban areas mapped from DMSP-OLS nighttime light images [19].

The built-up area covering the mainland of China was mapped from a Landsat dataset over the 1990–2015 period with a five-year interval. The urban sprawl in provincial capital cities was measured and investigated using newly developed multi-temporal urban land products in tandem with population data. The growth rate of the urban population was 2.31%. The AGR was 5.16%, which indicated an overall trend of urban sprawl. Of the 29 provincial capital cities, 26 experienced urban sprawls with 17 showing USIs higher than the national average. An increasing degree of fragmentation was observed in most of the cities during the urban expansion process. Our results highlight the measures and efforts to curb urban sprawl and help promote resource-efficient land use in China's provincial capital cities.

Conflict of interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary data

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