Spatiotemporal changes of built-up land and population distribution patterns in China during 1990-2010

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Abstract. With the population growth, built-up land is expanding constantly in China. The paper aims to analyse spatiotemporal pattern of built-up land and population, and their relationship in China mainland from 1990 to 2010. With population census data and built-up land data, it calculates population density of counties, built-up surface proportion and population density by built-up land, as measures of population and built-up land distribution. The result shows that, the total population and built-up area have increased by 17.5% and 33.9%, respectively, in China mainland from 1990 to 2010. Meanwhile, the population density of built-up land has decreased by 12.0%, indicating that built-up land growth has outpaced population growth overall. However, such changes are not evenly distributed in space and time. Change in the later decade is much more significant than that in the earlier decade. For built-up land, the increases don't show obvious characteristics of spatial aggregation. Correspondingly, most increases in population density of counties and population density of built-up area are in the northwest area, divided by Aihui-Tengchong line, while most decreases are in the southeast area. These analyses help to explain the overall impact of political-economic environment and the policy changes on urbanization processes for China mainland.

1. Introduction

China is the most populous country in the world, with nearly 19 percent of the world’s population. The estimated population in China mainland was 1.368 billion in 2014, about 2.5 times of its population in 1949. Indeed, during 1949-1990, the population of China mainland increased at a rate of 1.8% annually and no less than 1.5% for almost every year. However, the rate dropped down to 0.5-1.5% a year during 1990-2014, and basically stable at 0.5% after 2005.

With the population growth, built-up land has experienced rapid extension in China mainland over the last three decades. From 2000 to 2010, the area of built-up land in urban and rural has increased 1.61×104 kilometers and the growth rate is 11.17% [1]. In particular, the built-up land in urban has extended significantly. A study based on remote sensing images indicates that the urban built-up land have tripled in China mainland from 1990 to 2010 [2]. This urbanization has inevitably caused a series of resource and environmental problems and protection issues throughout China [3]. In addition, urban growth has caused unprecedented changes in land use patterns, especially loss of arable land [4].

Satellite-based remote sensing observation with various spatial, temporal and spectral resolutions has been extensively applied in investigations of urban dynamics and land cover changes, because remote sensing can provide timely and spatially explicit information for land cover change processes. Zhang et al. used the Landsat images to study the annual dynamics of impervious surface in the Pearl River Delta, China, from 1988 to 2013 [5]. The result showed that the Pearl River Delta had experienced a dramatic urban expansion from 1988 to 2013 and impervious surfaces increased more than ten times.
The population problem is an important part of the relationship between human and land which is the eternal theme of geography study. Simultaneously, studying the spatial and temporal characteristics of built-up land growth in China has important significance for promoting urban sustainable development and maintaining ecological safety. Therefore, with the built-up land data from remote sensing images and census data, the aim of this paper is to analyse the spatiotemporal distribution patterns of population and built-up land quantitatively in China mainland during 1990-2010, and reveal the relationship between these two issues, utilizing GIS spatial analysis combined with statistical analysis method.

2. Materials

2.1. Remote sensing image and built-up land map
Since the beginning of the Landsat program in the early 1970s, it has become one of the most widely used remote sensing imagery. Thematic Mapper (TM) images, with 30 m ground resolution and seven spectral bands, have proven to be a very effective tool in regional-scale land use/cover and urban studies [6]. The later series of Landsat satellite with Enhanced Thematic Mapper (ETM+) and Operational Land Imager (OLI) improve in spectral resolution and number of band.

Landsat 5 TM images and Landsat 7 ETM+ images during later years of 1980s, 2000 and 2010 are collected and used to acquire the built-up land distribution in 1990, 2000 and 2010, respectively. All the images are classified based on automatic classification combining with visual interpretation method, and then the land cover maps in 30 m resolution are obtained. We define all man-made surfaces as built-up surfaces, representing all types of land uses for urban and rural development. Because of China's vast expanses, the land cover data are resampled to 1 km resolution. Then, the built-up land density maps are produced in different years for built-up land change analysis, in which the value for each pixel represents the area proportion of built-up land in the pixel.

2.2. Population data and county map
Population census data are the most reliable data for population distribution study in China. The population data used in this study include data from the 1990, 2000 and 2010 censuses conducted by the State Council of the People's Republic of China. The census data are collected at the smallest possible census unit-the county. There are permanent and registered population, male and female population, and some others information. Because of a large number of floating populations, the population of permanent residents more than census register population can reflect the actual distribution of the population. Here, we mainly use the permanent population for each county. Since there is no information for Taiwan province in population census data, this study take China mainland as study area.

County map is not only the basis of spatial distribution of statistical population, but also the basis of relation analysis between population and built-up land. However, we have only collected the 2008 county map of China mainland at 1:1,000,000 scale from the State Bureau of Surveying and Mapping (SBSM) of China. For the reason of administrative division readjustment, the number and boundaries of counties are not completely equivalent. Creation of the polygons for counties of China mainland for 1990, 2000 and 2010 is done with vectorization method by reference to historic cadastral maps.

3. Methods

3.1. Spatial association of population data and county map
In order to analyse spatial pattern of population, the distribution map of population should be produced firstly. Since there are counties with same names, county name can’t be used as the index field. According to the county name and its location, the county code is added to the population record for each county. With the county code, the population census data are associated with vector county map. Then, the population distribution vector data are produced for the year 1990, 2000 and 2010.

3.2. Calculation of population density
Population density is distribution of population in relation to land resources, which is a widely used measure of population spatial distribution and urbanization intensity. Population density generally
defines as population of unit area of land. The most common unit of population density is the permanent population per hectare or per square kilometre. In this paper, it assumes population equally distributed within each county unit, and the population density for each county is calculated with formula as follow:

\[ D_i = \frac{P_i}{S_i} \]  

(1)

where \( D_i \) is population density of county \( i \) (unit: person per square kilometre), \( P_i \) is total permanent population of county \( i \) (unit: person), and \( S_i \) is area of county \( i \) (unit: square kilometre).

With the population distribution vector data which contain the information of permanent population and area for each county, the population density map of counties in China mainland are produced.

### 3.3. Space matching of population distribution data in different periods

As mentioned, the number and boundaries of counties change over time. For comparative study of population distribution in different periods, it takes county map in 2010 as standard and adjusts the population data of counties in 1990 and 2000. Taking population distribution data in 2000 as an example, the procedure of space matching of population distribution data is shown as follows in detail.

1. For the counties whose boundaries are completely equivalent in 2000 and 2010, assign the permanent population in 2000 to the counties.
2. For the counties whose boundaries are not completely equivalent in 2000 and 2010, convert the population density maps of counties in 2000 from vector to raster in resolution 1 kilometre firstly. Next, perform zonal statistical analysis on the population density data in raster with the county map in 2010 to get adjusted value of population for each county.

### 3.4. Calculation of built-up land proportion

Built-up land proportion defines as area of built-up land per unit area, which is another measure of urbanization intensity. In some studies, proportion of built-up land is called density of built-up land. In this paper, the built-up land proportion is calculated with formula as follow:

\[ p_i = \frac{SB_i}{S_i} \times 100\% \]  

(2)

where \( p_i \) is built-up land proportion of county \( i \), \( SB_i \) is built-up land area in county \( i \) (unit: square kilometre), and \( S_i \) is area of county \( i \) (unit: square kilometre).

Once appropriate county maps are constructed, the proportion of built-up surface, based on image classification, is summarized for each county during study period.

### 3.5. Calculation of population density of built-up land

Although population density by census units is the typical measure of population distribution, it may not fully reflect the population distribution pattern because different land uses may have significantly different distribution of population. To illustrate the dynamics in both population and built-up land growth, it calculates population density by built-up surface with the aid of satellite imagery in this project. This indicator is especially important for understanding population change in outskirt of cities, where census units still contain much undeveloped or agricultural land. The population density of built-up land is defined as population per unit area of built-up surface. It is a measure of intensity of urban expansion. The calculation formula is shown as follow:

\[ DB_i = \frac{P_i}{SB_i} \]  

(3)

where \( DB_i \) is population density of built-up land in county \( i \) (unit: person per square kilometre), \( P_i \) is total permanent population in county \( i \) (unit: person), and \( SB_i \) is built-up land area in county \( i \) (unit: square kilometre).

### 3.6. Spatiotemporal change analysis of population and built-up land

With all the data of population density, proportion of built-up land and population density of built-up land at different periods, it analyses the spatiotemporal distribution patterns of population and built-up land quantitatively in China mainland during 1990-2010 using geographic information system (GIS)
spatial analysis combined with statistical analysis method. Especially, it compares population density by total area of the census unit and that by built-up area to reveal the relationship between spatiotemporal change of population and built-up.

4. Result

4.1. Spatiotemporal pattern of population distribution

Hu Huanyong pointed to a line from Aihui in Heilongjiang province to Tengchong in Yunnan province as population density boundary of China in 1935. This line is called Aihui-Tengchong Line or Hu Line. The population density, geographical structure, the human lifestyle and economic development all show significant differences on different sides of this line. Figure 1 shows the population density by counties of China mainland in 1990, 2000 and 2010. It indicates that the population distributes densely in southeast and sparsely in northwest of China mainland, divided by Aihui-Tengchong Line, as Hu Huanyong proposed in 1935 [7]. The population density is less than 50 persons per kilometre for most of the counties on the northwest side of Aihui-Tengchong Line. On the southeast side, the population density is mainly more than 50 persons per kilometre and there are several larger population centers, such as North China Plain, Yangtze River Delta, Pearl River Delta, Sichuan Basin and the Central Shaanxi Plain, where the population density is more than 400 persons per kilometre. Although the overall pattern of population distribution is unchanged, changes of population distribution still have taken place. For the entire study area, population density has increased by 17.5% from 120 to 141 persons per kilometre from 1990 to 2010.

Figure 2 shows the changes of population density of China mainland during 1990 to 2010. Section (a) shows 2000 population density as ratios of the 1990 population density. Section (b) shows 2010 population density as ratios of the 2000 population density and section (c) shows 2010 population density as ratios of the 1990 population density. There are 1401 counties, about half of all the 2869 counties, presenting significant increase in population density during 1990-2010. The 2010 population density for these counties, when expressed as a ratio with 1990, commonly has change values above 1.10. These counties mostly locate at the large cities such as Beijing, Shanghai, Guangzhou, as well as areas northwest of Aihui-Tengchong Line where populations were so few in 1990. Counties with increasing population density are perhaps the clearest indicator of the driving forces of centralization in the east regions and development of the west regions in China mainland.

However, even more remarkable, it finds decreasing population density for many counties, especially in the southeast area of China. There are 495 counties presenting significant decline in population density during 1990-2010. The 2010 population density for these counties, when expressed as a ratio with 1990, commonly has change values below 0.90. Compared with period of 1990-2000, the number of counties with decreasing population has increased from 311 to 371 during 2000-2010. Many of these counties locate across Yangtze River economic belt, south of Qinling-Huaihe line, outside of big cities. It means populations have gathered from suburb to central cities and from peripheral area to the core of urban agglomeration. This is a performance of urban-rural dual structure effect and core- periphery structure effect. There are also some other areas with significant population decline, such as Inner Mongolia surrounding Hulunbuir and the three northeast provinces of China.

Figure 1. Population density by counties of China mainland in 1990, 2000 and 2010.
4.2. Spatiotemporal pattern of built-up land growth

Figure 3 shows the proportion of built-up land of counties in China mainland in 1990, 2000 and 2010. The overall distribution pattern of built-up proportion is similar to that of population density. The high values of built-up land proportion mainly distribute at the Northeast Plain, the North China Plain and the Middle-Lower Yangtze Plain, where are generally flat and suitable for built-up land development. For the areas on the northwest side of Aihui-Tengchong Line, the built-up proportion is generally low.

Figure 4 shows the change of built-up land proportion during the study period. Section (a) shows 2000 built-up land proportion as ratios of the 1990 built-up land proportion. Section (b) shows 2010 built-up land proportion as ratios of the 2000 built-up land proportion and section (c) shows 2010 built-up land proportion as ratios of the 1990 built-up land proportion. In the figure, the change value less than 0.85 means decrease of built-up land, while the value greater than 1.15 means increase of built-up land. The value between 0.85 and 1.15 means no significant change. The figure shows a significant growth of built-up land in China mainland during the study period and the growth during 2000-2010 have been even more pronounced than that during 1990-2000. The total area of built-up surface was 142,944 kilometres in 1990, 157,213 kilometres in 2000 and 191,385 kilometres in 2010, respectively. The area of the built-up surface has increased by 33.9% from 1990 to 2010. Of the total built-up area in 2000, 14,369 km² or 10.0% were converted from other land cover from 1990 to 2000, while 34,172 km² or 21.7% were converted from 2000 to 2010.

776 counties, about a quarter of all the counties, has experienced growth of built-up land proportion during 1990-2000, scattered the central core of big cities like Beijing, Shanghai, Chongqing, Guangzhou, Shenzhen, and so on. Correspondingly, 1630 counties, more than a half of all the counties, show obvious expansion of built-up land during the later decade, distributed nationwide. There are some counties showing very significant expansion of built-up land, with the change value greater than 1.5, 185 and 650 counties for 2000/1990 map and 2010/2000 map, respectively. While the central core of the city possessed high proportions of built-up surface, the greatest changes are seen along the peripheral areas.

Figure 3. Proportion of built-up land images of China mainland in 1990, 2000 and 2010.
4.3. Analysis of population density of built-up land

Figure 5 shows the population density of built-up surface in 1990, 2000 and 2010. There are 36 counties that can’t be calculated the population density of built-up land, since the built-up land area of these counties is equal to zero. It assigns ‘nodata’ to these counties. Unlike the spatial pattern of population density by counties, the population density by built-up land presents high in the south and low in the north of China mainland, mainly divided by Qinling-Huaihe-Qilian Mountains-Altun Mountain line. The high values generally locate in Qinghai-Tibet Plateau, Loess Plateau, Sichuan Basin, Yunnan-Guizhou Plateau and Jiangnan hilly land. In these areas, the surface condition is very complicated, landform undulates terribly and it is not suitable for built-up land development.

Figure 6 shows the changes of population density of built-up surface during the study period. Section (a) shows 2000 population density of built-up land as ratios of the value in 1990. Section (b) shows 2010 population density of built-up land as ratios of the value in 2000 and section (c) shows 2010 population density of built-up land as ratios of the value in 2000. In the figure, the value less than 0.90 means decrease of population density of built-up land, while the value greater than 1.10 means increase. The value between 0.90 and 1.10 means no significant change. Quantitative analysis shows that, population per square kilometres of built-up surface has decreased from 7913 in 1990 to 7901 in 2000 and 6964 in 2010, taking China mainland as a whole. There are 805 counties undergone decrease and 644 counties undergone increase of population density of built-up land during 1990-2000, while during 2000-2010 the number of county changes to 1592 and 411 for decrease and increase of population density of built-up respectively. Such changes reflect that, built-up land expands at a much faster rate than population growth for most of the time, and the level of intensive land utilization has reduced in China mainland.

The spatial change pattern of population density of built-up area is similar to that of population density of counties, but there exists more significant differences between northwest and southeast of China mainland. On the northwest side of Aihui-Tengchong line, the value of population density of built-up area is mostly increased, while on the southeast side, the value is mostly decreased.

Figure 5. Population density of built-up land of China mainland in 1990, 2000 and 2010.
Figure 6. Changes of population density of built-up land in China mainland during 1990-2010.

According to causes, the changes of population density of built-up area may be roughly grouped to the following four types.

1. Population density of built-up area declines, owning to decrease of population and no significant change of built-up land. There are some counties at the juncture of Hebei and Inner Mongolia provinces, falling into this type. Because these counties are generally the poverty county of national level, population move out of these areas.

2. Population density of built-up area declines, owning to significant growth of built-up land and no significant change of population. These areas mainly locate around the central cities. In these areas, the speed of land urbanization is very rapid, but there is not enough attraction to population because of the lack of public service, poor transportation and some other reasons.

3. Population density of built-up area declines, owning to decrease of population and growth of built-up land. As expected, counties located across Yangtze River economic belt south of Qinling-Huaihe line—which exhibit a decline in population density by census unit—also exhibit a decline in population density by built-up area. However, the area undergone a decline of population density by built-up area extends significantly comparing to that of population density by census unit.

4. Population density of built-up area increases, owning to more significant increase of population than that of built-up land. These areas mainly locate in the northwest area and the core of big cities.

5. Conclusion and discussion

By integrating remote sensing and GIS technologies, the relationships between built-up surface and population are quantified. During 1990-2010, the rate of built-up surface growth in China mainland has outpaced the rate of population growth rate. This project results in a more detailed understanding of the relationship between change of land use and population. The analysis of population density patterns, by two different measures, census unit and built-up area, allow a better understanding of reducing of intensive land utilization in China mainland. The population density of built-up area offers a different measure from the traditional calculation of population density and provides a measure of living environment by reflecting the dynamics of both population and urban land use growth.

For the entire study area, population density has increased by 17.5% from 120 to 141 persons per kilometre during 1990–2010. In the meantime, the total built-up area has increased by 33.9% from 142,944 to 191,385 kilometres, while population per kilometre of built-up land has decreased by 12.0% from 7913 to 6964 persons per kilometre. This indicates that built-up land growth may have outpaced population growth in China mainland overall.

However, such changes are not evenly distributed in space and time. The rate of increase or decrease is much higher during the later decade than that during the earlier decade. For the change of built-up land, the increases in built-up surface don't have the characteristics of spatial aggregation. Correspondingly, most increases in population density are found in the northwest area of China mainland, divided by Aihui-Tengchong line, while most decreases are found in the southwest area, especially across Yangtze River economic belt south of Qinling-Huaihe line. The spatial change pattern of population density of built-up area is similar to that of population density of counties, but there exists more significant difference between northwest and southeast of China mainland. On the northwest side of Aihui-Tengchong line, the population density of built-up area is mostly increased, while on the southeast side, it is mostly decreased. Such changes reflects the nature of housing demand and the mechanisms that governed the urbanization process in China mainland.
Such analyses shed light on the overall impact of political-economic environment and policy changes on urbanization processes for China mainland. The information of land cover conditions and changes over time obtained through this study can be used in formulating management policies of the national and municipal governments.

Since the change pattern of population and built-up land are not the same in urban and in rural, we seek to assess changes in the spatial extent of built-up land and changes in population distribution patterns in urban and in rural respectively in the future work.

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