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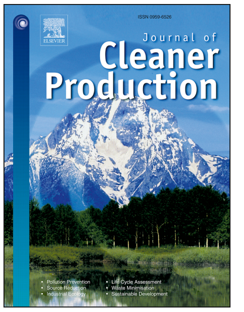

Urban expansion and form changes across African cities with a global outlook: Spatiotemporal analysis of urban land densities

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Urban Expansion and Form Changes across African Cities with a Global Outlook: Spatiotemporal Analysis of Urban Land Densities

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Abstract: Africa has been experiencing rapid urbanization, yet limited studies have systematically investigated urban growth dynamics across African cities. Using 25 cities as cases, we quantified urban growth and form changes in Africa via spatiotemporal analysis of urban land densities in concentric rings over three time points (1990, 2000, and 2014). The results show that African cities have rapidly grown both in population and built-up areas, which increased by about 4% and more than 5% per annum, respectively. Urban land density (defined as the proportion of the built-up area to the buildable area) in each concentric ring decreases from the city center to the urban periphery with diverse patterns among cities. Comparatively, small cities have a lower urban land density and a more dispersed urban form than medium-sized and large cities in Africa. The international comparisons between cities with over one million population in Africa, Asia (e.g., China and India), Europe, and North America (i.e., the United States) reveal that African cities have a relatively less compact urban form. Implications of these findings for the future of African cities are further proffered.

Key words: urban expansion; population growth; urban land density; urban form; urban sustainability; Africa

1 Introduction

As the world continues to urbanize, sustainable development challenges will be increasingly concentrated in cities, particularly in the lower-middle-income countries where the pace of urbanization is rapid and mostly unplanned (Cobbinah et al., 2015; Nagendra et al., 2018). In Africa, a huge number of people are and will continue migrating to cities. The increase in population forces cities to spatially expand, and the impacts of these changes may be considerable (Cobbinah and Darkwah, 2016; Linard et al., 2013). Understanding the characteristics of urban expansion in African cities has the potential to promote sustainable urban development now and into the future. With the United Nations sustainable development goals (SDGs) providing a global development pathway (Anderson et al., 2017; Nilsson et al., 2016), an appreciation of urban expansion dynamics in Africa has become increasingly important and tenable.

A number of studies have examined urban expansion and form changes (Chai and Li, 2018; Seto et al., 2011; Zeng et al., 2015). With the emergence of remotely sensed imagery, spatial metrics or landscape indices have been widely used to characterize urban dynamics, which are usually combined with the gradient analysis (Ramachandra et al., 2012). Another widely used method is the grid-cell-based analysis, which can unify population growth and urban land expansion and further investigate their correlations (Bagan and Yamagata, 2012; Hou et al., 2016). Spatial modeling in the geographical information system (GIS), like the cellular automata (CA), is able to reconstruct the discontinuous historical time series of the urban land use, supporting the analysis of urban growth and form changes (Basse et al., 2014; Cosentino et al., 2018; Herold et al., 2003; Li and Yeh, 2002; Pontius et al., 2007). As for the urban form, shape and density have proven to be the two most important aspects (Angel et al., 2018; Angel et al., 2010a). The exploration of the urban land density can not only characterize urban expansion, but also distinguish the dispersed pattern from the compact form (Jiao, 2015; Schneider and Woodcock, 2008). Additionally, the emerging big data has raised new methods to understand cities and quantify urban expansion (Jiang, 2018; Long et al., 2018; Song et al., 2018).

Compared to widespread studies on urban land-use changes and expansion in Europe, North America (e.g., the United States), as well as Asia, particularly in China and India (Liu et al., 2017; Sahana et al., 2018; Schneider and Mertes, 2014; Sumari et al., 2017; Zeng et al., 2017), limited studies have focused on urban development in African cities. Similarly, available studies on urban land-use changes and expansion in Africa do not provide a comprehensive basis for comparison as they focused on a city in detail (Cobbinah and Aboagye, 2017; Coulter et al., 2016; Kleemann et al., 2017; Simwanda and Murayama, 2018) or few cities in some countries (Adhikari and de Beurs, 2017; Hou et al., 2016; Linard et al., 2013). In many cases, these previous studies focused on urban expansion in large cities (Schneider and Woodcock, 2008), neglecting urban dynamics in small and medium-sized cities. Regrettably, urban growth data across African cities are limited, making holistic assessment of urban development dynamics across African cities difficult.

In this study, using 25 African cities as cases, we systematically and comprehensively investigate the characteristics and processes of urban expansion and form changes from 1990 to 2014, from the perspective of spatio-temporal analysis of urban land densities. We compare urban expansion and form changes among different sized cities, and further compare them between these African cities and those in Europe, Asia (e.g., India and India) and North America, particularly the United States.

2 Study Area and Data

2.1 Study area

The Atlas of Urban Expansion (*2016 Edition*) program was published online, including urban population and built-up areas in 200 global cities in 1990, 2000, and 2014 (Angel, 2016). The 200 global cities were constructed with three strata, world regions, city population sizes, and the number of cities in their countries. Cities were selected at random from eight world regions in proportion to the urban population in each region (United Nations, 2015). Finally, a sample of 200 cities was chosen from the entire 4,231 cities and metropolitan areas that had 100,000 people or more in 2010. The spatial distribution of 200 sample cities is presented in Figure 1a.

There are 25 African cities in this dataset, with seven cities in North Africa and eighteen cities in Sub-Saharan Africa (Figure 1b). The city sizes vary across the 25 cities, including large ones, such as Cairo (Egypt) and Johannesburg (South Africa), as well as small cities with only 100 thousand people. According to their population in 2014, we divided sample cities into three groups: large cities (> 5 million people in 2014), medium-sized cities (1-5 million people), and small cities (< 1 million people), shown in Table A1. The group of large cities includes three megacities, Cairo (Egypt), Lagos (Nigeria), Kinshasa (Congo Dem. Rep.), which have more than 10 million people in 2014.

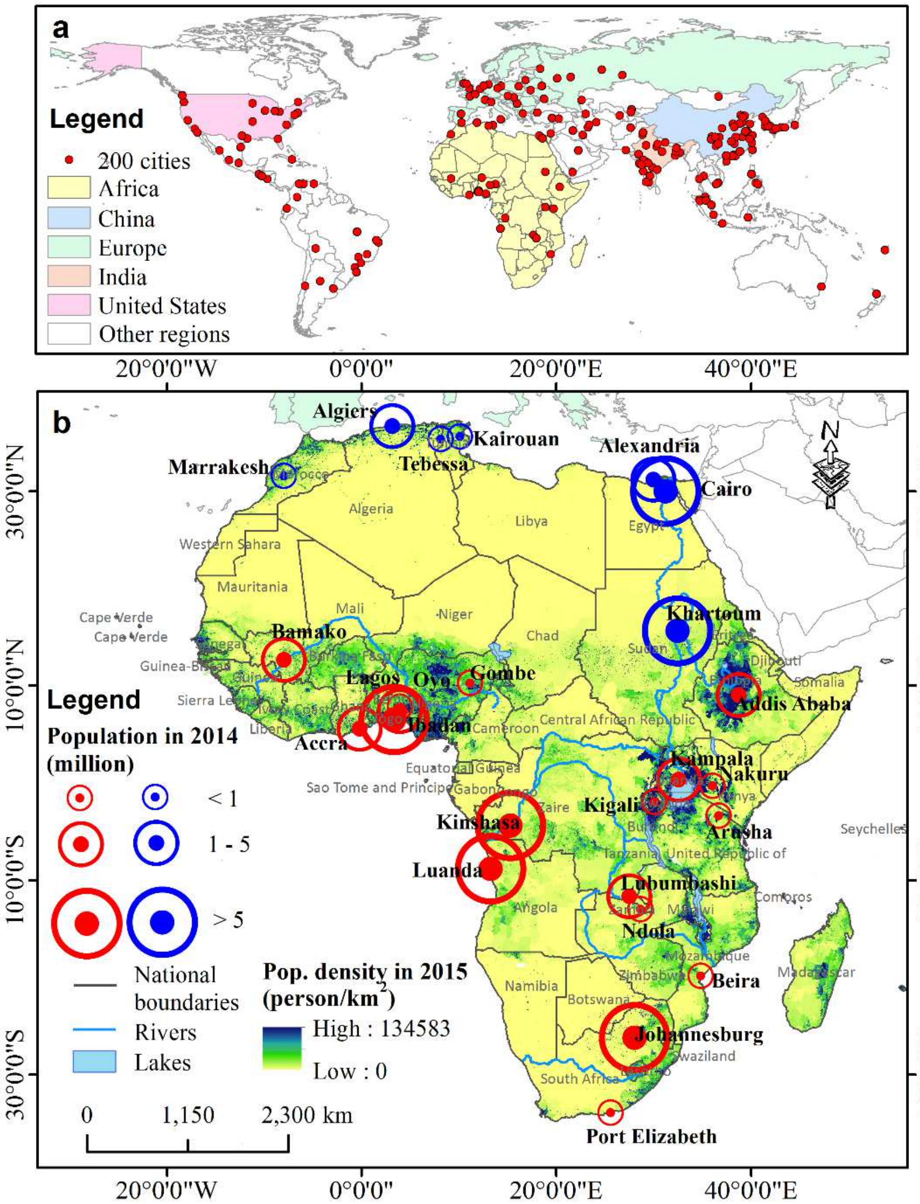

Figure 1. Spatial distribution of 200 global cities (a) and 25 African cities and their population sizes in 2014 (b). Seven cities located in North Africa are in blue and eighteen cities located in Sub-Saharan Africa are in red. According to their population in 2014, these 25 cities are divided into three groups: small cities, medium-sized cities, and large cities. The base map of population density in Africa comes from the world pop (http://www.worldpop.org.uk/).

2.2 Data source

The data used in this study were generated from *The Atlas of Urban Expansion* (*2016 Edition*) (http://www.atlasofurbanexpansion.org), including population data and land use maps at three time points (circa 1990, 2000, and 2014, hereinafter T1, T2, and T3). The population estimates are constructed from available census data. They used the unsupervised classification method to classify the Landsat imagery (spatial resolution: 30 m) into three classes: built-up, open space, and water bodies (Angel, 2016). They define the urban cluster as built-up areas together with the urbanized open space. The largest urban cluster in a given study area is recognized as the main city. The main city and surrounding urban clusters make up the urban extent of the city. The spatial distribution of urban land and urban extent in three years (circa 1990, 2000, and 2014) and open space and water bodies in 2014 in each city is presented in Figure 2. See Angel et al. (2016) for detailed explanations for data acquiring and processing and detailed land use classification procedures can be found in Hurd (2015).

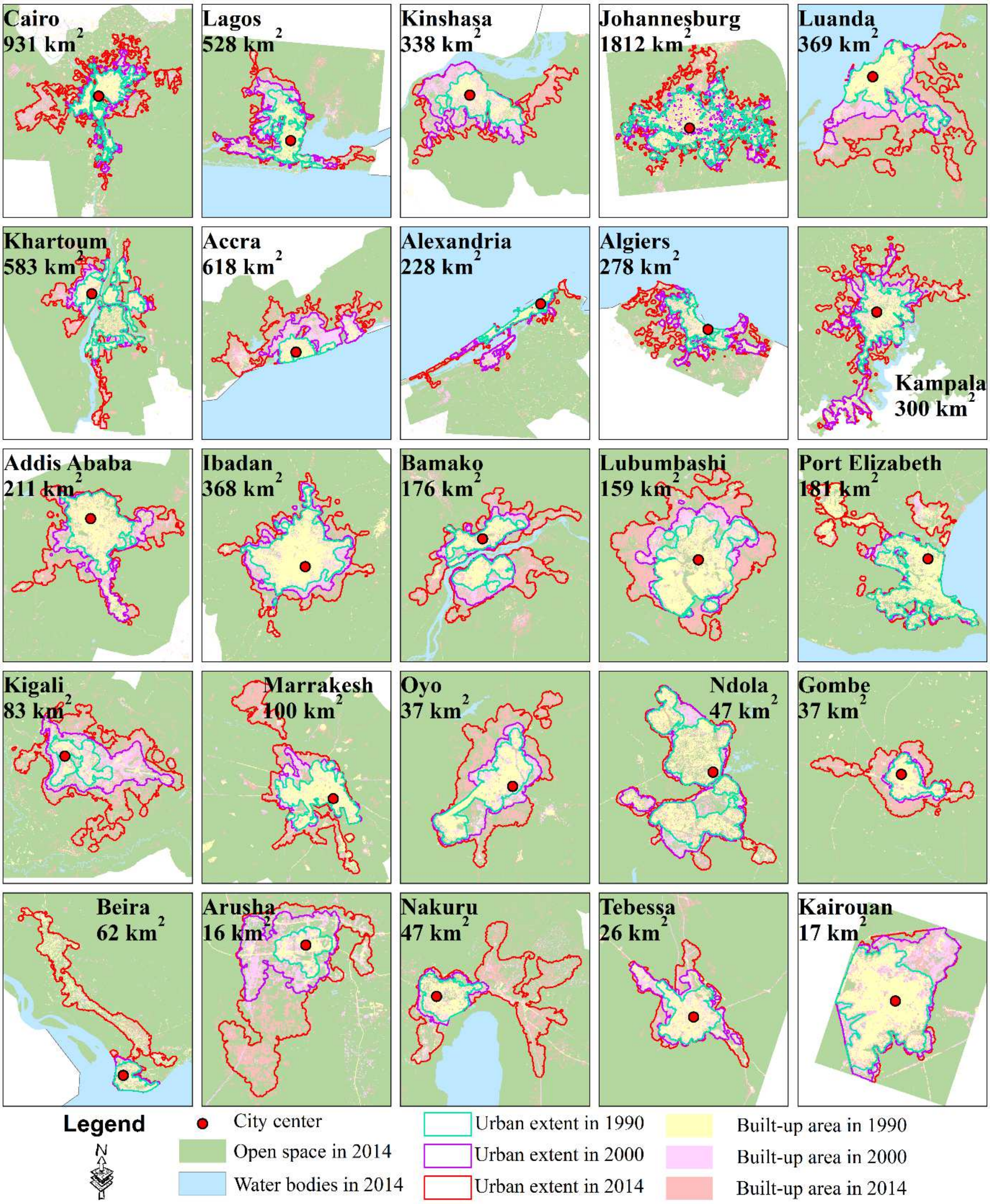

Figure 2. Spatial distribution of land use and urban extent in 25 African cities at three time points (1990, 2000, and 2014). Cities are organized in descending order of population in 2014. Sub-plots are under different scales and sizes of urban extents can be compared by their built-up areas in 2014 shown in sub-plots.

3 Methods

3.1 Concentric rings analysis

The concentric rings analysis divides urban areas into series of concentric rings from the city center (Jiao et al., 2017b; Schneider and Woodcock, 2008). It is of significance as to where the city center is defined, usually, this is taken as the birthplace of the city or the central business district (CBD) of the city. *The Atlas of Urban Expansion* (*2016 Edition*) provides CBD locations in each city. We inspect and verify these CBD locations using Google high-resolution imagery. We first generate a series of equidistant concentric rings from the city center until the outmost ring covers the entire urban extent in T3 (2014). Taking Cairo (Egypt) as an example, the series of 1-km equidistant buffer rings is shown in Figure 3a.

The urban land density in concentric rings is defined as the proportion of urban land to buildable areas. The buildable area refers to the land that is, and has the potential to be converted into, the urban land. Among the three land use types (built-up, open space, and water bodies) obtained from Landsat imagery, water bodies are usually protected and are considered not to be converted into the urban land. Finally, the urban land density in each ring is calculated using formula (1):

$$Dens = \frac{S_{\text{urban land}}}{S - S_{\text{water}}} \tag{1}$$

where *Dens* is the density of urban land (built-up area). S is the total land area in a ring, excluding areas without land cover in a ring. $S_{\text{urban land}}$ and S_{water} are the areas of built-up areas and water bodies in a ring, respectively.

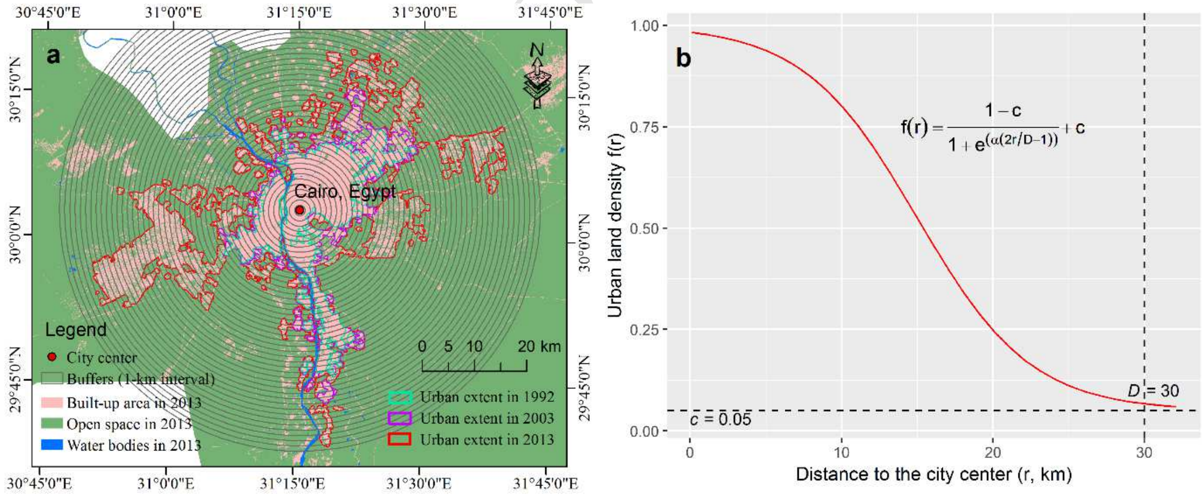

Figure 3. A series of concentric rings with a 1-km interval until the outmost ring covering the entire urban extent in 2013 in Cairo, Egypt (**a**) and a graph of the urban land density function with $\alpha = 4$, $c = 0.05$, and $D = 30$ (**b**).

3.2 Urban land density function

By calculating urban land densities in series concentric rings in Chinese cities, Jiao (2015) found that the urban land density decreases slowly with increasing distance from the city center in the urban core area, decreases relatively quickly in the inner urban and suburban areas, and then decreases slowly again in the urban fringe and periphery, presenting an inverse *S*-shape. Inspired by the *S*-shape of sigmoid function ($f(x) = 1/(1+e^{-x})$), Jiao (2015) proposes a modified function (*urban land density function*) with an inverse *S*-shape to characterize the distance decay of urban land density within a city. The urban land density function with an inverse *S*-shape is defined in formula (2):

$$f(r) = \frac{1-c}{1+e^{\alpha(2r/D-1)}} + c \tag{2}$$

where *f* is the urban land density calculated using formula (1), *r* is the radius from the city center to a concentric ring, *e* is Euler's number, and α, *c* and *D* are parameters. A graph of the urban land density function is shown in Figure 3b with $\alpha = 4$, c = 0.05, and D = 30.

The significant scientific value of urban land density function is not only that the function can fit the spatial variation of the urban land density in a city very well, but also the function can generate indicators to characterize urban form and dynamics of urban expansion (Jiao, 2015). The parameter *c* represents the background density of urban land in the hinterland of a city and the parameter *D* denotes the urban extent, an approximate of the boundary between the urban fringe and the hinterland. The parameter α is negatively correlated with the proportion of the rapidly decreasing part of the curve, i.e., the part denoting the inner urban and suburban areas (Jiao, 2015). A compact city has a narrow area for the rapidly decreasing part, resulting in a higher α. Thus, a higher value of α indicates a more compact urban form (see detailed explanations in Jiao (2015)).

4 Results

4.1 Urban population growth and land expansion

The population and built-up areas of the 25 African cities at three time points (1990, 2000, and 2014), and their annual change rates (geometric growth rate) during two periods (1990-2000, 2000-2014) are presented in Figure 4. City sizes vary considerably among the 25 cities, both from the perspective of population and built-up areas. Cairo (Egypt) has the largest population in 2014, which is more than 100 times greater than the smallest city, Kairouan (Tunisia). The biggest size in terms of built-up area is Johannesburg (South Africa). All cities have been growing both in population and built-up areas. The average population of 25 cities increased from 1.44 million in 1990 to 3.43 million in 2014, suggesting an increase of 2.4 times in the past 24 years. The average built-up areas of 25 cities increased from 99 km^2 in 1990 to 302 km^2 in 2014, which is a 3.1 fold increase from the initial size.

On average, the urban population grew by 4.19% per year and urban land expanded by 5.97% per year from 1990 to 2000. During 2000-2014, the average annual growth rates of population and built-up area are 4.04% and 5.13%, respectively. In terms of the disparities among different sized cities, the average annual growth rates of population in small, medium-sized, and large cities are 3.74%, 4.28%, and 4.35%, respectively, during 1990-2014. Correspondingly, the average annual growth rates of the built-up areas in 1990-2014 are 5.41%, 5.28%, and 5.42% in small, medium-sized, and large cities, respectively. The faster-growing of urban land than that of population results in a widespread decline in urban population densities (Angel et al., 2010b; Xu et al., 2019b). For instance, the average urban population densities of the 25 cities decreased from 17273 person/km^2 (1990) to 11949 person/km^2 (2014).

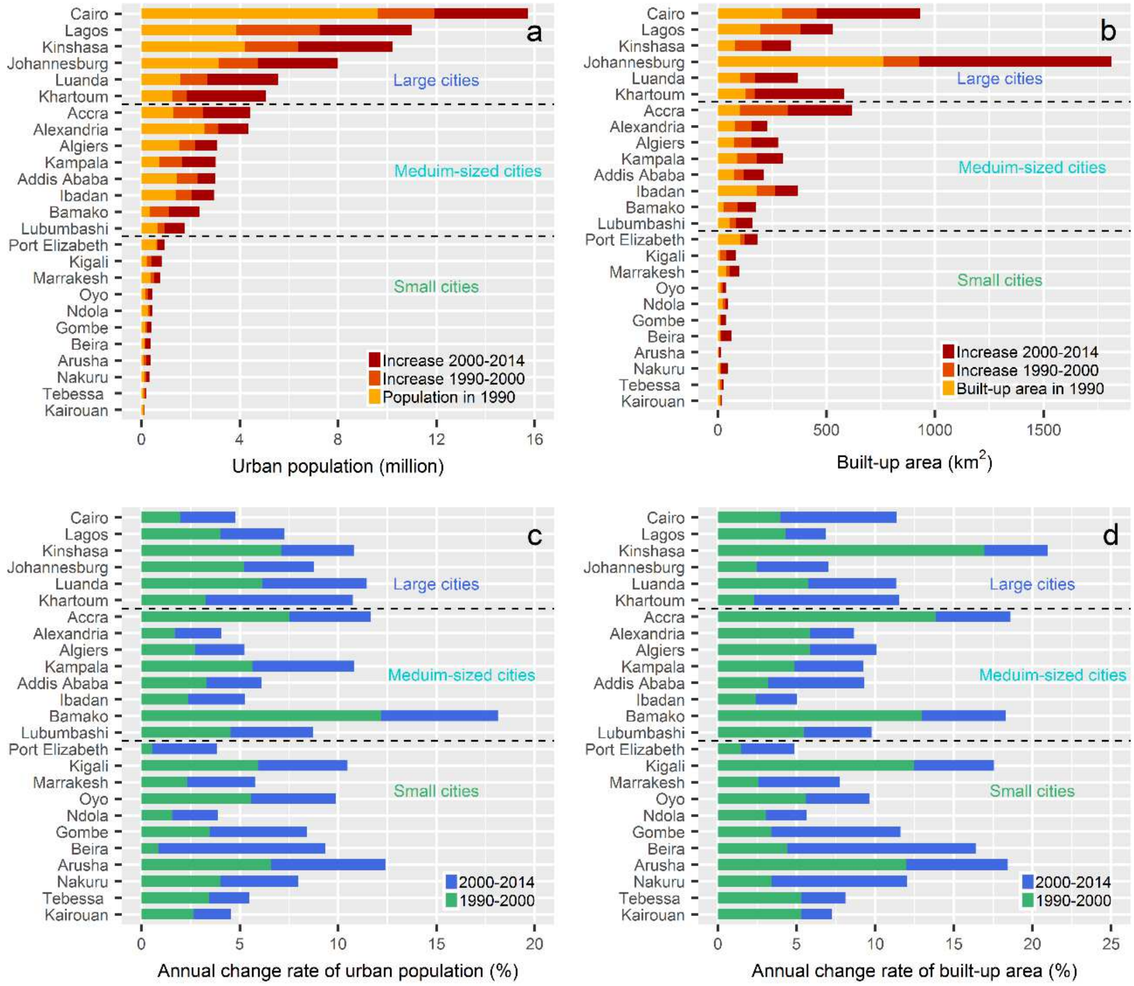

Figure 4. Urban population (**a**) and built-up areas (**b**) in 1990, 2000, and 2014 and annual change rates of urban population (**c**) and built-up areas (**d**) during 1990-2000 and 2000-2014 in 25 African cities.

4.2 Distance decay of urban land density

We calculate the proportion of built-up area to the buildable area in each concentric ring, which is defined as the urban land density. We fit the distance decay of the urban land density using the urban land density function (formula (2)) proposed by Jiao (2015). Scatter plots and fitted curves at three time points in each city are shown in Figure 5, and the estimated parameters for the model are shown in Table A2. Spatially, urban land densities in concentric rings decreased from the city center to the urban periphery. Overall, the urban land density function can fit the distance decay of densities very well (with a high adjusted R^2, Table A2). Temporally, urban land densities increased in all concentric rings from 1990 to 2000, and then from 2000 to 2014, revealing the persistent and spatially wide expansion in all cities.

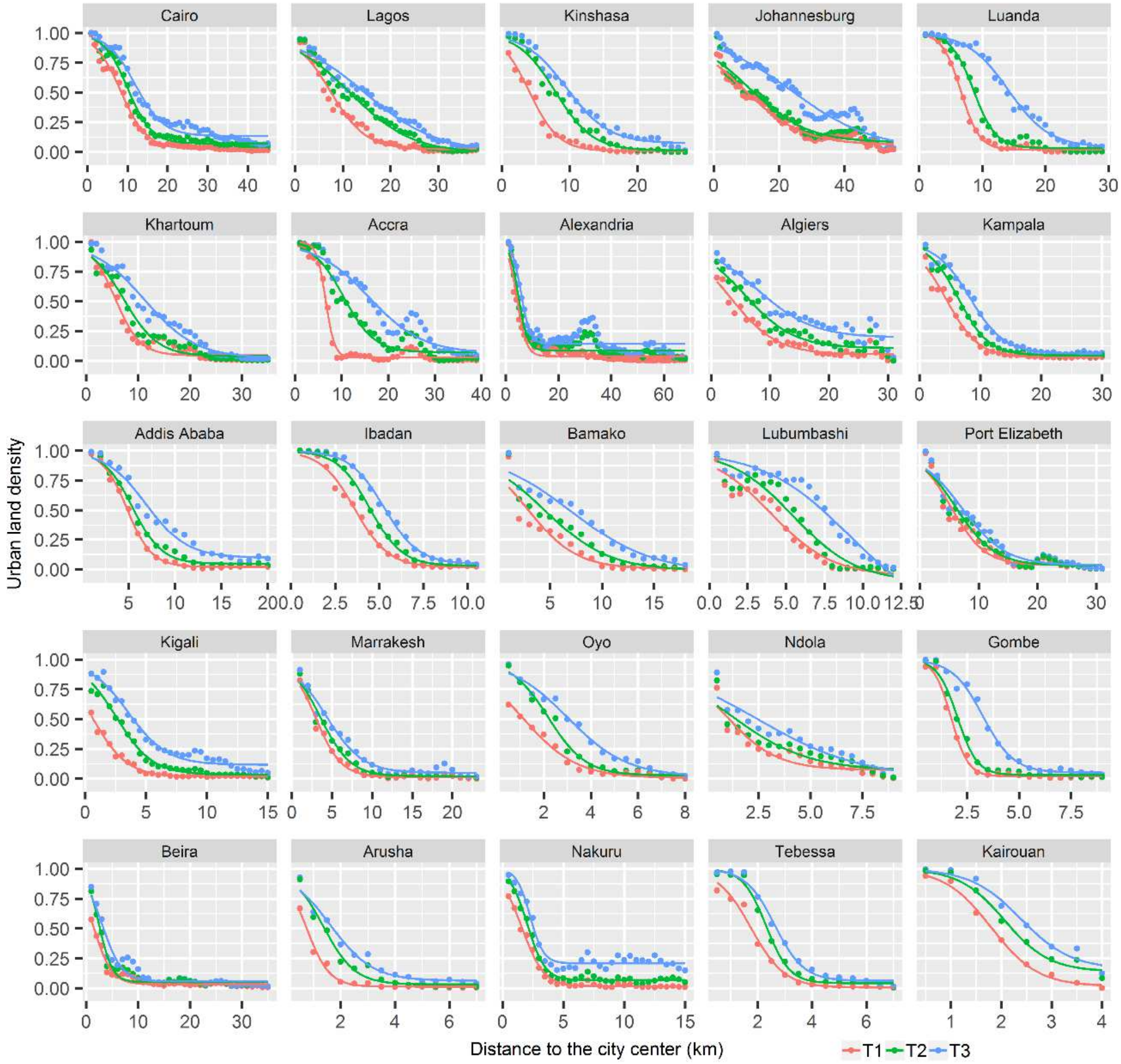

Figure 5. **The distance decay of the urban land density in concentric rings at three time points.** Cities are organized in descending order of their population in 2014. See parameters and goodness of fit of the urban land density function in Table A2.

Parameters of the urban land density function indicate the temporal variations and disparities of urban dynamics in different sized cities (Figure 6). Parameter α reflects urban form and changes and a higher α represents a more compact urban form. Generally, large cities and medium-size cities have a higher α than small cities from the perspective of median values (black thick line), indicating the urban form is relatively dispersed in small cities. Parameter α increases over time in large and medium-sized cities, showing a more compact urban form as city expand. Parameter c represents the background density of urban land and its values for large, medium-sized, and small cities increase from 3%, 3%, and 2% in 1990 to 5%, 8%, and 8% in 2014, respectively, indicating the increase of the urban land density in the hinterland. The average boundaries of urban fringe (represented by parameter D) for large, medium-sized, and small cities in 1990 are 13.7 km, 8.8 km, and 3.6 km, respectively, which increased to 28.5 km, 16.0 km, and 6.5 km in 2014, respectively.

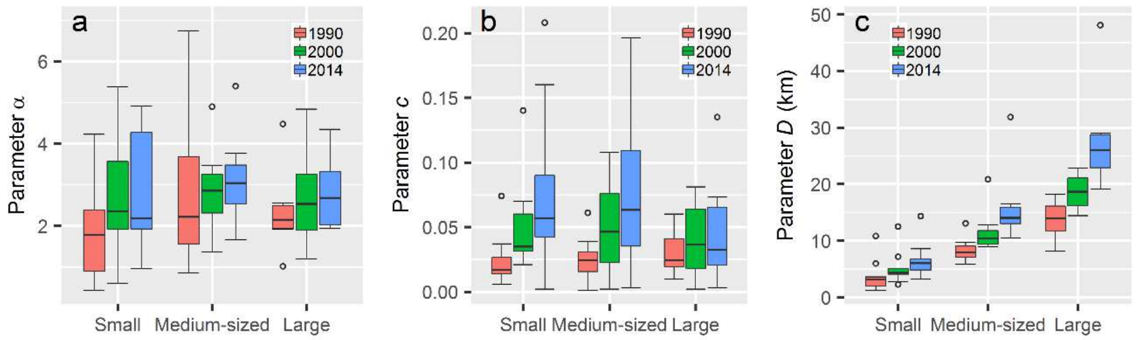

Figure 6. Boxplots of parameters α, c, and D of the urban land density function in three sized cities in 1990, 2000, and 2014.

There are considerable disparities of the distance decay of the urban land density in diverse cities (Figure 5). To further compare the differences of urban expansion and urban forms in different sized cities, we obtained the distance decay of the urban land density in three aggregated cities (large, medium-sized, and small cities), where the urban land density is the average densities of cities from the same group (Figure 7). The parameters and goodness of fit of the three aggregated cities using the urban land density function are presented in Table A3. Distance decay curves of the urban land density vary among different sized cities, which reveals the disparities of urban expansion and urban form among them. The curve of the aggregated large city is the closest to the inverse S-shape, where the urban land density is high and decreases slowly near the city center. However, the inverse S-shape is not obvious in small cities, where the urban land density tends to decrease in a linear mode until to a stable density. Urban land densities are more than 90% around city centers in large cities, but densities near the center in small cities are less than 80%. This reflects that small cities are still in the primary stage of urban development and the urban core areas have not yet formed. As a result, the curves of the urban land density in small cities do not present an inverse S-shape. In addition, large cities have experienced a much rapider urban expansion because the intervals between curves are greater in the averaged large city.

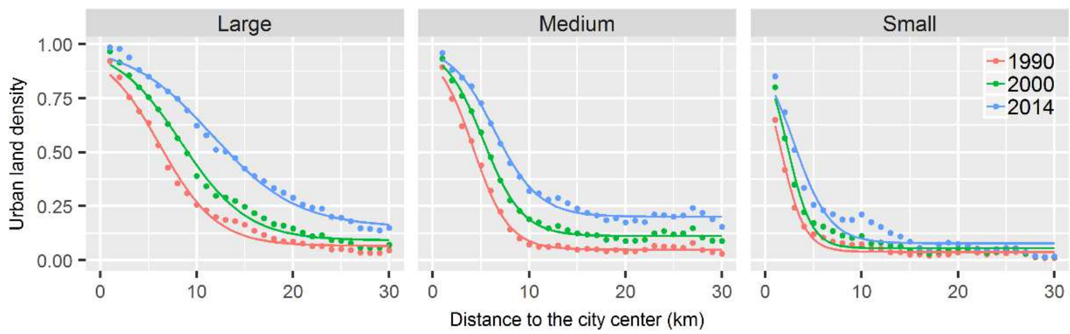

Figure 7. The distance decay of the urban land density in three aggregated cities in Africa. The urban land density in an aggregated city is the mean of densities of cities from the same group. For instance, the urban land density in a concentric ring in the aggregated large city is the mean of densities in concentric rings (with the same distance to the city center) of the all six large cities (Figure 1, Table A1).

4.3 International comparisons of urban expansion and forms

For the comparisons of urban expansion and urban forms between African cities and cities in other regions, we selected cities with more than one million (2014) population in Africa, Europe, the United States, China, and India from *The Atlas of Urban Expansion-2016 Edition* (See Table A4 for detailed city names). We first calculate the urban land density in concentric rings in each city (Figure A1) and then summarize the average densities in concentric rings in cities from the same country or region, resulting in an aggregated city in each of the five regions. The fitted distance decay curves are presented in Figure 8 (see parameters and goodness of fit in Table A5).

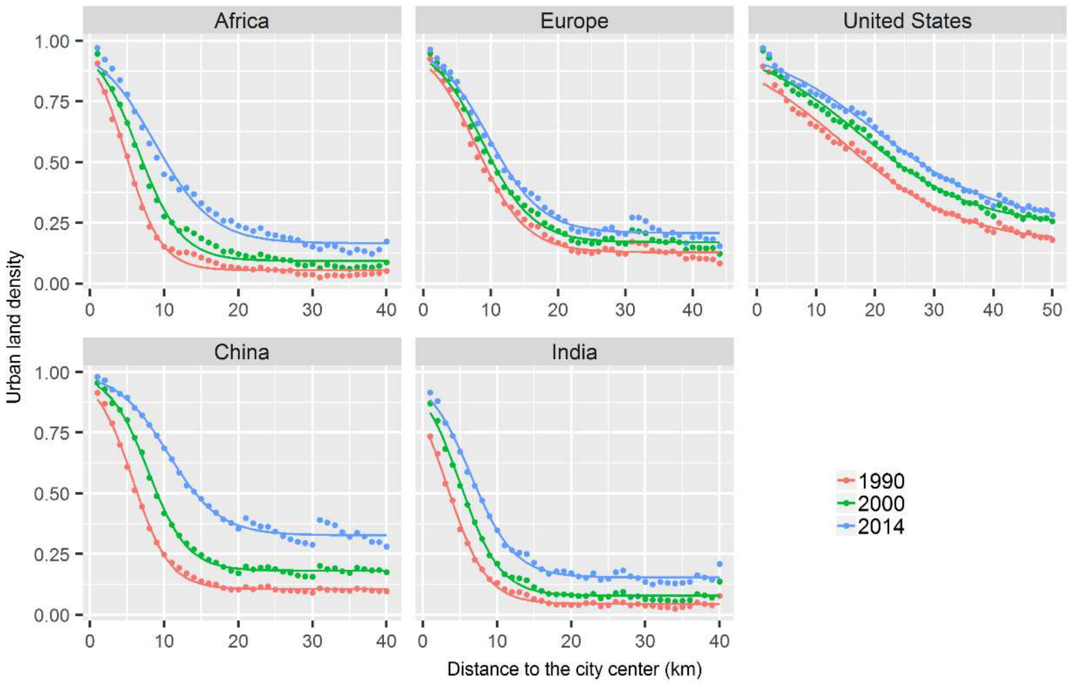

Figure 8. **Comparisons of the distance decay of the urban land density in the aggregated cities in Africa, the United States, Europe, China, and India.** These are aggregated cities whose urban land densities in concentric rings are summarized from cities with over one million population in 2014 in each region. The detailed names of city samples from the five regions are shown in Table A4. The distance decay curves of the urban land density in an individual city in Europe, the United States, China, and India are shown in Figure A1.

Comparatively, there are three patterns of distance decay of the urban land density, namely, the inverse S-shape, two stages of linear decay, and the linear decay, which are represented by the Chinese city, the European city, and the American city, respectively (Figure 8). The Chinese city has the most obvious inverse *S*-shape of the distance decay of the urban land density. The European city nearly experiences two stages of linear decay of the urban land density, which has been reported (Guérois and Pumain, 2008). The urban land density in the American city tends to decline in a linear mode. The pattern of distance decay in the African city is between the inverse S-shape and the two stages of linear decay.

The pattern of distance decay of the urban land density reflects urban form and its changes. Overall, cities in China, Europe, and India have a more compact urban form in 2014 because they have a higher α (Table A5). On contrast, α of the African city and the American city is relatively low in 2014, indicating a more dispersed urban form. The African city and the Chinese city have larger intervals of the urban land density in concentric rings, indicating the relatively rapid urban expansion in the two regions.

5 Discussion

Previous literature presents conflicting positions on rapid urbanization or urban growth in Africa (Cobbinah et al., 2015; Potts, 2005; Watson, 2009). On the one hand, there is optimism that the rapid urbanization in Africa provides a fertile ground for industrialization, skill development, improved infrastructure and economic growth (Group, 2014; Turok and Borel-Saladin, 2014). On the other hand, others believe that Africa's urbanization is problematic, population-driven, and without development (Boadi et al., 2005; Todes, 2012; Turok and Borel-Saladin, 2014). While each of the foregoing positions may, to some extent, be true, the known reality is that African cities are growing, both in population and spatial extent, although the dynamics across cities are unknown. It is within this context that there is even a greater urgency to understand the dynamics of Africa's urbanization or urban growth (Pieterse, 2011).

In this study, we have quantified the urban growth in 25 African cities from 1990 to 2014. Findings show that all cities have experienced considerable growth in population and built-up area. Urban population averagely increased by about 4% per annum, while built-up area averagely increased by more than 5% per annum during 1990-2014. Urban expansion is relatively occurring faster compared to population growth, which often leads to low urban population density and sprawl over time (Angel et al., 2010b). Urban land densities in African small cities are lower than in large or medium-sized cities, predominantly near the city center, and small cities have a more dispersed urban form (Figure 7). International comparisons reveal that urban form in African cities are less compact than cities in Europe and China (Figure 8). We used the urban land density function within a global context, verifying its applicability across global cities. The comparison of global urban patterns can also provide useful references for studies on urban expansion and form changes.

Our findings have implications for urban environment and sustainability in Africa. The challenge of incongruence nature of urban expansion and population growth forms the basis of urban sustainability (Angel et al., 2018; Angel et al., 2010b). The relatively dispersed urban form in small cities needs to be given attention, and controlling measures should be implemented in the future urban planning. Policies and strategies promoted to compact growth are encouraged in Africa within the sustainable development thinking. Urban expansion inevitably influences the urban environment, increasing uncertainties of urban sustainability (Jiao et al., 2017a; Kaur and Garg, 2019; Martellozzo et al., 2018; Nagendra et al., 2018; Xu et al., 2016). Rapid and massive land-use/land-cover change (LUCC) strongly affects ecosystem services (Wang et al., 2018). Many African cities are in environmentally sensitive and vulnerable areas or near biodiversity hotspots, and the urban environment should be extraordinarily protected while developing the city.

This study also has some exceptions. For instance, urban land densities are decreasing monotonically in most cities, but in Accra and Alexandria, urban land densities increase in suburban areas. Bumps of densities away from the city center indicate influences of significant sub-centers. Accra and Alexandria are typical coastal cities (Figure 2), showing a long and narrow ribbon form, which are sensitive to sub-centers in the distance decay of the urban land density. For instance, the Mobarak town (satellite town) and Alexandria Borg el Arab Airport are included in the calculation of urban land densities for Alexandria, resulting in two obvious bumps in densities, about 17 km and 30 km away from the city center, respectively (Figure 5). Adopting polycentric scenarios can alleviate the abnormal fluctuation of urban land densities (Jiao, 2015; Xu et al., 2019a). In addition, the method we used can well quantify the macro pattern of urban expansion (Xu et al., 2019a), but it may neglect micro dynamics of urban sprawl and urban sprinkling (Jiao et al., 2018; Romano et al., 2017a; Romano et al., 2017b; Saganeiti et al., 2018).

6 Conclusions

African cities are experiencing extraordinary urban transformation, and the region remains one of the fastest urbanization zones in the world. This study provides a comprehensive analysis of urban expansion dynamics and urban forms across 25 African cities with a global outlook. All 25 African cities have grown both in population and built-up areas, which increased by around 4% and more than 5% per annum, respectively. The spatiotemporal variations of urban land densities in concentric rings reflect urban expansion processes and form changes. Different sized African cities experience diverse urban expansion with distinguished urban forms. Small African cities feature a lower urban land density and a more dispersed urban form, which are usually ignored and should be taken into consideration in further urban planning. The international comparisons of cities among Africa, Asia (e.g., China and India), Europe, and North America (i.e. the United States) indicate that African cities are in a less compact urban form. Compact growth policies and strategies are encouraged for the sustainable urbanization in Africa.

Results from this study provide researchers, policy- and decision-makers insights into the reality of urban dynamism across African cities; the similarities, and variations, and their implications for future urban planning. An understanding of the urban complexities, and conscious awareness and application of the findings from this research in African cities would provide a better policy, planning and management response in containing the urban growth or urbanization phenomenon. Considering that Africa’s urbanization level is estimated to rise, further studies linking urban growth and economic transformation can improve the quality of urbanization and promote the sustainable development (Gollin et al., 2015). This is particularly important especially in this era that there is a global movement towards achieving sustainability expressed through the sustainable development goals.

Declarations of interest: none.

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Highlights

- We analyze variations of urban land densities to quantify Africa's urban expansion.
- Urban population and land grew by about 4% and over 5% annually from 1990 to 2014.
- Small African cities have a lower urban land density and a more dispersed form.
- African cities have a less compact form than cities in China, Europe, and India.