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Spatiotemporal analysis of urban growth in three African capital cities: A grid-cell-based analysis using remote sensing data

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ABSTRACT

Spatiotemporal analysis of urban growth patterns and dynamics is important not only in urban geography but also in landscape and urban planning and sustainability studies. Based on remote sensing-derived land-cover maps and LandScan population data of two time points (ca. 2000 and 2014), this study examines the spatiotemporal patterns and dynamics of the urban growth of three rapidly urbanizing African capital cities, namely, Bamako (Mali), Cairo (Egypt) and Nairobi (Kenya). A grid-cell-based analysis technique was employed to integrate the LandScan population and land-cover data, creating grid maps of population density and the density of each land-cover category. The results revealed that Bamako's urban (built-up) area has been expanding at a rate of 5.37% per year. Nairobi had a lower annual expansion rate (4.99%), but had a higher rate compared to Cairo (2.79%). Bamako's urban expansion was at the expense of its bareland and green spaces (i.e., cropland, grassland and forest), whereas the urban expansions of Cairo and Nairobi were at the cost of their bareland. In all three cities, there was a weak, but significant positive relationship between urban expansion (change in built-up density) and population growth (change in population density). Overall, this study provides an overview of the spatial patterns and dynamics of urban growth in these three African capitals, which might be useful in the context of urban studies and landscape and urban planning.

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1. Introduction

Urban areas cover less than 1% of the Earth's surface, but according to the United Nations report on world urbanization, 54% of the world's population resided in urban areas in 2014 (United Nations, 2014). Although the proportion of the urban population in Africa is only 40% as a result of less urban development (United Nations, 2014), it is predicted that this region will have the highest increase rate in urban land-cover in this century (Seto et al., 2012).

With a projected high growth rate, Africa's total population will reach 1 billion by 2050, and 720 million more people will live in urban areas (Linard et al., 2013). This forecast suggests a high urban growth and rapid expansion of urban areas at an unprecedented rate that has never before been experienced in this continent (Silva, 2012). Such rapid urbanization will add great pressure to local ecosystems and pose various sustainable development challenges concerning local environments, employment, agriculture production and the water supply (Linard et al., 2013; United Nations, 2014). In this context, there is a need to understand the urban growth process and land-cover change dynamics in this region to inform landscape policy and urban planning.

Satellite imagery by remote sensing is helpful for the detection and analysis of the spatiotemporal patterns and dynamics of urban growth and land-cover changes (e.g., Maktav and Erbek, 2005; Shalaby and Tateishi, 2007; Dewan and Yamaguchi, 2009; Estoque and Murayama, 2012, 2015a). Furthermore, the increasing availability of satellite images, some of which are free, considerably helps in this endeavor (Ma and Xu, 2010). The Landsat program, for example, has been providing free continuous global-coverage satellite data with a spatial resolution of 30 m since 1982 (Bagan and Yamagata, 2014). Landsat images are useful because of their capacity to reveal land-cover changes in both natural and anthropogenic aspects in regional areas, as demonstrated in various studies (e.g., Ottinger et al., 2013; Estoque and Murayama, 2013, 2015a; Jiao, 2015).

Grid-cell-based analysis is an approach for detecting and analyzing the spatiotemporal patterns and dynamics of urban

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growth and land-cover changes. This is a relatively new method for acquiring spatial and temporal information of land-cover changes at a scale that is usually finer (i.e., 1 km grid size) than municipal boundaries. The spatial relationships between the changes in the extent of land-cover types based on a grid-cell-based approach are important for understanding urban development patterns and processes. This approach has been used in many previous studies (e.g., Bagan and Yamagata, 2014; Qian et al., 2014; Maimaitijiang et al., 2015).

Population growth and economic expansion are the primary drivers of urban land-cover changes during peacetime (Wu and Zhang, 2012). African cities are among the most rapidly urbanizing cities in the world, but their urbanization seems to be driven primarily by high population growth rates rather than by economic growth (Robson et al., 2012; Buhaug and Urdal, 2013). Thus, multitemporal monitoring of population growth and distribution might be useful in the context of urban land-cover change studies in African cities. Population data can be used to detect the possible relationships between urban land-cover patterns and population distributions, as well as the relationships between their respective changes (Liu et al., 2015). In fact, remote sensing-based urban land-cover change analysis, in combination with population data, has become popular in recent years (Ningal et al., 2008; Estes et al., 2012). However, most previous studies used population data at the municipal or county level (Robson et al., 2012; Lu et al., 2013). In this context and for the purpose of achieving more accurate and precise information about the relationship between land-cover and population changes, grid-cell-based population data, such as the LandScan data (http://web.ornl.gov/sci/landscan/), might be useful.

Population is also the most important factor in defining the size of a city (UNFPA, 2012). In this study, three types of African capital cities have been identified based on population size. African capital cities with populations of more than 5 million are classified as large-sized capital cities. Those with populations between 2 million and 5 million are classified as medium-sized capital cities, whereas those with populations of less than 2 million are classified as small-sized capital cities.

The purpose of this study is to examine the spatiotemporal patterns and dynamics of the urban growth of three African capitals of different sizes using remote sensing and LandScan population data and a grid-cell-based method. The results provide an overview of the spatial patterns and dynamics of urban growth in these three African capitals, which might be useful in the context of urban studies and landscape and urban planning. There is a growing body of literature on urban land-cover change studies in African cities (e.g., Yin et al., 2005; Vermeiren et al., 2012). However, a comparative analysis of urban land-cover changes in different African capital cities using a grid-cell-based method has not yet been conducted.

Bamako (Mali), Nairobi (Kenya) and Cairo (Egypt) were selected to represent small-, medium- and large-sized African capitals, respectively. The spatial distributions of these three capitals were also considered in the selection process. Bamako is located in West Africa, whereas Cairo and Nairobi are located in North Africa and East Africa, respectively (see Fig. 1). The time period of the analysis (ca. 2000–2014) was decided with the purpose of capturing the recent spatiotemporal patterns and dynamics of urban growth in the three cities, which are more likely to continue in the future.

2. Methodology

2.1. Study areas

2.1.1. Bamako

Bamako, the capital city of Mali, is located on both sides of the Niger River in West Africa. It has an area of approximately 252 km^2, with grassland dominating its surrounding areas. The climate here is tropical, with an average temperature of 27.8 °C and rainfall of 955 mm. The temperatures vary little during the year, with an average of 6.5 °C. However, the difference in rainfall between the driest months (December, January and February) and wettest months (July, August, and September) is as high as 291 mm (http://en.climate-data.org/location/500/).

As the major administrative center of Mali, Bamako is the seventh largest West African urban center, with economic activities including local business, international trade, tourism, agriculture and fisheries. With its active economic conditions and the rapid increase of its population, Bamako is undergoing rapid urbanization. According to the census data of 2009, Bamako had a population of approximately 1.8 million people, with an annual population growth rate of 5.4% since 1998 (http://www.citypopulation.de/Mali-Cities.html?admid=6430).

2.1.2. Cairo

Cairo, the capital city of Egypt in North Africa, is known as the oldest city in the African continent. Its total area is approximately 528 km^2. The eastern and western parts of Cairo are surrounded by non-arable, desert land. As a result, its spatial pattern of urban growth has been mainly towards the northern part, where agricultural land is dominant in the Nile Delta or, to a lesser extent, to the south along the Nile River (Yin et al., 2005). The climate here is desert, with an average annual rainfall of only 18 mm. Compared with the dry and rainless summer (June–August), Cairo's winter (December–February) is relatively moist, with few rainy days (Effat and Hassan, 2014). The annual temperature here averages 21.3 °C, with a difference of 14.5 °C between the hottest and coolest months.

As one of the largest markets in both Africa and the Middle East, Cairo accounts for two-thirds of the country's gross national product. The tourism industry is a major source of revenue for Cairo. Cairo is also known as the industrial center of Egypt, with products including textiles, refined petroleum products, plastics, building materials, electronics, paper and chemicals. According to World Population Statistics, the population of Cairo was approximately 9.12 million in 2013, which ranked second in Africa after Lagos (http://www.worldpopulationstatistics.com/cairo-population-2013/). However, the census data of Egypt (http://www.citypopulation.de/php/egypt-admin.php?adm1id=01) shows an annual population growth rate of 1.52% from 1996 to 2006 in Cairo, which is relatively low compared with other African cities.

2.1.3. Nairobi

Nairobi, the capital city of Kenya in East Africa, has a total area of 684 km^2. It lies adjacent to the eastern edge of the Great Rift Valley at an elevation of 1661 m above sea level. Mount Kenya is located north of Nairobi, and Mount Kilimanjaro lies towards the southeast. The western part of the city is occupied by the Ngong hills. Located at a high elevation, Nairobi has a subtropical highland climate, with an average temperature of 19.0 °C. Because Nairobi is situated close to the equator, temperatures vary little between different months, and the climate condition is separated by the wet season and dry season. Two distinct rainy seasons occur in Nairobi: one occurs from March to May and the other occurs from mid-October to mid-December (https://weather-and-climate.com/average-monthly-Rainfall-Temperature-Sunshine, Nairobi, Kenya).

Nairobi was founded in 1899 and has grown to become Kenya's principal economic and cultural center and the second largest city in the African Great Lakes (Mundia and Aniya, 2005). More than a thousand Kenyan businesses and more than 100 major