Land Use Policy 49 (2015) 332–340

Contents lists available at ScienceDirect

Land Use Policy

journal homepage: www.elsevier.com/locate/landusepol

Simulating urban growth driven by transportation networks: A case study of the Istanbul third bridge

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ARTICLE INFO

Article history:
Received 7 July 2014
Received in revised form 4 August 2015
Accepted 11 August 2015

Keywords:
Urban growth
Cellular automata
LULC change
Istanbul
Third bridge
Transportation network

ABSTRACT

Increasing populations and the related transport volumes are problematic for metropolitan regions in Istanbul especially due to the separation of the city by the Bosphorus strait, which creates significant congestion, delays, and carbon dioxide emissions. A third bridge north of the two existing bridges that will bypass the urban areas in Istanbul is under construction to address these challenges. The new Yavuz Sultan Selim Bridge project will transect the most important natural areas. The main purpose of this paper is to investigate urban growth driven by transport networks as observed after the construction of the two existing bridges and the probable impact the third bridge will have on land use and land cover (LULC) via a cellular automata (CA) based simulation technique. The time periods selected for model calibration were 1972, 1987, 2002, and 2009 because the first bridge (Bosphorus Bridge) was built in 1973 and the second bridge (Fatih Sultan Mehmet Bridge) in 1988. An urban growth simulation model was generated for the year 2030, and a change detection analysis was performed between 1972–2009 and 2009–2030 to determine the probable natural areas threatened by urbanization. According to the results, Istanbul will continue to grow northward with 41% of forested areas and 28% of fragile ecosystem areas transforming into urban areas between 2009 and 2030.

1. Introduction

According to the European Environment Agency (EEA), approximately 75% of Europeans currently live in urban areas, and by 2020, this population will increase another 5% (EEA, 2006). This on-going urbanization, triggered by expected urban benefits for immigrating populations, is accompanied by an increased demand for residential areas that need to be connected to the existing infrastructure (Batty, 2007; Herold et al., 2005). New residential and infrastructural areas, such as roads and the increase of areas for economic development (including commercial and industrial areas, public, and private services), cause rapid changes in the LULC with notable environmental effects both in and around cities. These effects can involve soil sealing and loss of green spaces along with their associated ecological functions and services, which can have negative societal effects regarding the quality of life, e.g., due to heat island effects or increased environmental burden (Alberti, 2008; EEA, 2010; Scherer et al., 2013). Other social effects of urbanization are changes in lifestyle and demography. For example, the number of single households increases and both birth rates and segregation or cohesion decrease due to high cultural mixing (Hossain Khan, 2012; Lauf et al., 2012b). Related economic effects might include economic growth due to locational advantages, tax revenues and general social welfare in the city (Douglas, 2012; Orfield, 2002). In addition to consequences related to LULC changes, increasing populations and the consequent increase in human activities generates more traffic that might collapse an overstretched transport system (Nagel and Paczuski, 1995; Sheller and Urry, 2000). When this increase is accompanied by the continual increase of individual transport, as is the case in Turkey (ITMP, 2011), the number of added

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http://dx.doi.org/10.1016/j.landusepol.2015.08.016
0264-8377/

cars increases even more rapidly, which creates more congestion, decelerates traffic, increases time spent in traffic, increases CO_2 emissions (increasing health risks) and impacts regional outputs including tax revenues, which all can affect the quality of personal and economic life (Baur et al., 2014; Sheller and Urry, 2000; Yang and Huang, 2004).

Because these potential effects have some sensitive mechanisms of actions related to urban growth, urban decision makers seek to control or at least monitor urban growth to increase the quality of life and productively use urban and environmental resources (Engelen et al., 1997; Häkkinnen, 2005; Rizzoli et al., 2008). The drivers, direction, and speed of urban sprawl are of particularly interest to limit a number of accompanied environmental effects (e.g., Catalán et al., 2008). To that end, urban growth models seem promising (Ayazli et al., 2014; Lauf et al., 2012a).

Several urban growth models have been developed since the 19th century (An, 2012; Batty, 2007; von Bertalanffy, 1968; von Thünen, 1826). The most popular theoretical model, "The Isolated State", was created by Johann Heinrich von Thünen (1826) and forms the basis for the following model concepts. Because urban growth is accepted as resulting from a dynamic (urban) system consisting of a number of non-linear, dynamic, and complex sub-systems, the system theory approach has been suggested for urban planning studies since the 1950s (Clarke et al., 1997; von Bertalanffy, 1968). Cellular automata (CA)-based simulation methods were developed in the 1980s when processing spatial data came to prominence because of increased computer power and are predominantly used in current spatial simulation modelling to determine and simulate future urban growth (Barredo et al., 2003; Batty, 2007; Silva and Clarke, 2002). Urban growth modelling based on CA runs on subdivided cells that characterize urban areas within a regular grid, where each cell is defined by the minimum of one discrete cell state (Batty, 2007; Benenson and Torrens, 2004). Various CA-based models have been developed to determine urban growth around the world; the most famous being GeoDynamica, METROnamica in the Netherlands, SLEUTH in the USA, and DUEM in the United Kingdom. The cell state depends on the state of adjacent cells and can change during the simulation. Accordingly, CA models consist of five main elements, space, state, neighborhood, transition rules and time, which all must be predefined. The defined neighborhood (distance) and transition rules are especially decisive for the dynamics of the CA model (Benenson and Torrens, 2004). One commonly used CA modeling software is the SLEUTH UGM. The pioneering study was implemented in the San Francisco Bay area by Clarke et al. in 1997 (Clarke et al., 1997). The model achieved important success for simulating urban growth between 1900 and 1990 on a regional scale and has subsequently been applied in various studies (Akın et al., 2014; Ayazli et al., 2014; Heinsch et al., 2012; Jantz and Goetz, 2005; Rafiee et al., 2009; Silva and Clarke, 2002; Wu et al., 2009; Dietzel et al., 2005). Transportation networks trigger urban growth and are a major factor of urbanization (EEA, 2006). The SLEUTH model provides a conclusive representation of one of the main factors influencing urban growth, transportation accessibility (Antrop, 2004; Geurs and van Wee, 2004). Road (or rail) networks provide access to areas of human activity, such as living, working and leisure, and thus affect their attractiveness. Due to this causal linkage, the influence of transportation networks must be integrated in urban simulation models (Kucukmehmetoglu and Geymen, 2009; Müller et al., 2010; Geymen, 2013).

Istanbul is one of Europe's most rapidly expanding and crowded cities. The city joins two continents, Asia and Europe, and has always attracted people because of its cultural, natural, and environmental heritages. The population has risen dramatically from 3.5 million in 1973 to over 14 million (14,160,467) in 2013, while private car ownership has simultaneously increased 40-fold (TSI, 2014; ITMP, 2011). To overcome the resultant transportation problems, two bridges were built over the Bosphorus to connect the Asian and European parts of Istanbul, one in the seventies and the other at the end of the eighties. The construction of a third bridge started in May 2013, and this bridge will bypass urban areas in Istanbul to the north of the two existing bridges. Although zone plans made in the 1960s suggested an east to west urbanization pattern for Istanbul, the Bosphorus and Fatih Sultan Mehmet (FSM) bridges have catalyzed northward urban growth (Ayazli et al., 2010; Geymen, 2013; Kubat et al., 2007; Kucukmehmetoglu and Geymen, 2009; Sahin and Ersoy, 2005). New settlements will presumably spread next to the access road of the third bridge as planned in the 'New Istanbul Project' (Stevens, n.d.; Strickland, n.d.). This expansion of the city will radically threaten the fragile northern ecosystems of the Turkish metropolis, which are defined in 1:100,000 scaled environmental plan reports as dunes, sandy beaches, grasslands, pastures, flood areas, reeds, marshes, and shrubberies (IEP, 2009).

Therefore the main goals of this paper are:

- To determine the urbanization process inducing LULC changes caused by the three Bosphorus bridges in the mega-urban regions of Istanbul.
- To assess the probable impact the third bridge will have on natural ecosystems.

In so doing, we propose a CA-based urban growth simulation model using the SLEUTH simulation software to simulate LULC changes until the year 2030. The LULC data needed for this simulation was generated from Landsat imagery and classified for the years 1972, 1987, 2002, and 2009. A digital elevation model (DEM) and the transport networks for the years 1997 and 2009, and the third bridge were included in the model. The LULC changes were obtained from the SLEUTH software for the years 1972–2009 and 2009–2030.

2. Study area

Istanbul is located in northwestern Turkey (41°00′49″N 28°57′18″E) and is the largest city in Turkey, defining the country's economic, cultural, and historical heart. Istanbul has long been an attractive global center because of its natural, cultural, historical, social, and economic potential, not least of which is its geographical location connecting Europe and Asia. The city is connected to ancient business locations and is a melting pot of cultures, ethnicities, religions, and knowledge. After a long period of population increases and declines (since its foundation over 2600 years ago) with its highest level being at the end of the nineteenth century with over 1 million people, Istanbul's population began increasing rapidly in the beginning of the second half of the twentieth century (Sahin and Ersoy, 2005). This population growth has caused complex transportation problems.

Today, Istanbul is one of the largest urban agglomerations in Europe. The entire urban area covers 5461 km^2 (IMM, 2013) with half of the city in Europe and Asia separated by the Bosphorus strait (Fig. 1). The study area is dominated by urban areas that are mainly located in the south accompanying the existing road network. A mixture of rural patterns with agriculture and forested lands characterizes the northern part of the studied region. Today, two bridges connect the eastern and western parts of the city. These two bridges across the Bosphorus were constructed in 1973 and 1988 but did not adequately solve the increased traffic volume. On the contrary, they created their own traffic and new urban problems including unplanned population growth, decreased forested areas, both air and water pollution, wild life destruction, and increased flood, and erosion risks (Geymen, 2013; Kucukmehmetoglu and