A cellular automata model of urban growth for two built density classes: a study of urban growth in the Thames Basin

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Abstract

The categorical nature of land use classes in Cellular Automata models of urban growth and the weak coupling of these models to population growth means density is usually not well accounted for. This paper presents an approach that uses a linear regression model to elicit relationships between population and two land cover classes with different built densities. Furthermore the paper develops a densification index that quantifies the balance of densification and expansion of the urban envelope. The findings, for the Thames Basin over the period 1984-2015, provide important pointers to future CA model development. Firstly, the model benefits from having multiple built density land cover classes, as their spatial dynamics are distinct and the CA is effective in representing them. Secondly, the historic data shows substantial fluctuation in the degree to which population growth is manifested by densification or urban growth. These fluctuations reflect change in socio-economic conditions that are exogenous to the CA model, but do have substantial impact on the evolving urban landscape. The aspect of densification in urban growth studies should no longer be neglected, and become an integral part of scenario development.

Keywords: Land use, Land Cover, Cellular Automata, Density

1. Introduction

Climate change and urbanisation are causes of increasing flood risks in many parts of the world. It is therefore of interest to understand and be able to foresee how urban growth affects catchment characteristics. This article is concerned with the analysis of past urban growth of the Thames Basin in the London hinterland. For further hydrological analysis, which is not reported here, we require separately the area of dense and sparsely built urban land (Kjeldsen, 2010), also referred to as *urban* and *suburban* land. Over the past 35 years the population of this region has grown steadily and rather uniformly. However, the changes in land use have been more varied. Over time, the degree to which population growth has been either accommodated by growth in urban extent or by densification has varied considerably, moreover the spatial distribution of growth is far from uniform.

This poses immediate challenges for forecasting future urban growth patterns. Existing tools are relatively well-suited for capturing spatial heterogeneity. In particular, Cellular Automata (CA) based land use change models account for heterogeneity in planning constraints, accessibility, physical suitability and socio-economic potential of land to sustain different forms of land use. The categorical nature of land use classifications makes CA less suited for representing the balance between densification and expansion of the urban extent. Constrained CA (White et al., 1997) take exogenous scenarios of the area demand of different land use categories and thus are not intrinsically linked to population growth. Other CA, including SLEUTH (Clarke and Gaydos, 1998) do have an endogenous driver of urban growth, however this endogenous driver of is generally calibrated on historic growth patterns and not tied to demographic change. Activity based CA (White et al., 2012) and some agent based models (Filatova et al., 2009) have a more direct representation of the interaction between population, density and land use.

The aim of this article is to investigate the applicability of the Constrained Cellular Automata framework for the development of spatial land use change scenarios, for the case of multiple (two) classes of built density. Earlier models have applied density based land cover classes, however to our knowledge, this article is the first to present methods for the development of consistent scenarios of urban change differentiated by density classes based on demographic trends and past urbanisation patterns.

2. Study area and data

The study covers the Thames river basin in the London hinterland in the UK. The area covers 9947 km^2 and some of the major towns and cities within the area are Oxford, Reading, Guildford, Basingstoke, Bracknell and Swindon. It does not include London itself but the area lies fully in the London commuting catchment and partially within the ring of the M25, the major ring road around London.

The main source of data is a time series of land cover classifications (1984, 1990, 2001, 2003, 2007, 2010, 2013, 2015) prepared by the UK Centre for Ecology and Hydrology as part of the POLLCURB project. The land cover data were derived from Landsat imagery using polygon based supervised classification. For the purpose of CA modelling, the data were rasterized to a 200 m grid and the land cover categories thematically aggregated to 5 classes: urban, suburban, agriculture, nature and water. A multi-temporal classification process was deployed that promoted temporal consistency of the classification making it more appropriate for change analysis.

A second source of data is the UK Census of Population. The variable used from the census is Usual Resident Population which is available at the finest level of aggregation called Output Area (2001, 2011) and Enumeration District (1981, 1991). These geographies are not consistent over time, and to facilitate multi-temporal analysis we rasterized the census data to the 200 m grid also deployed used for the land cover classification.

Further data that was used is the map of Risk of Flooding from River and Sea published by the UK Environment Agency and English Local Authority Green Belt Land published by the Department for Communities and Local Government. These two maps represent the main planning constraints for the study area. For future population projections we used the base line projections of the Office for National Statistics.

3. Method

The model applied for simulating land use change over time is based on the widely used Contrained Cellular Automata model as introduced by White, Engelen and Uljee (1997). The model is included in various land use change software packages, most notably MOLAND and METRONAMICA. However, we implemented a new open source version of the model. In this application there are five land categories: urban, suburban, agriculture, nature and water. The application only considers urban growth: an increase in urban and suburban land at the expense of agriculture and nature. Land taken by water remains so over the simulation. The change in urban and suburban area over time is given. New locations for urban and suburban land are selected based on the transition potential, which is a function of the land cover classes found within a 1600 m neighbourhood of each location as well as green belt and flood risk status.

Changes in landscape pattern are analysed using landscape metrics of composition (Shannon diversity) and configuration (patch size and edge density) in a multi-scale moving window approach

(Hagen-Zanker 2016). These metrics are used to analyse historical land cover change as well as to validate the calibrated land use model.

The relationship between usual resident population and urban and suburban land cover over time is investigated by means of cross-sectional regression models for different moments in time. In these models the usual resident population is the dependent variable and the area of urban and suburban land are independent variables. The regression models are based on regional aggregates (local authority, n=46). The reason for regression based on regional aggregates rather than pixels is that the land cover classes cover a wide diversity of urban activities beyond residential area, e.g. commercial, business and industrial. The rationale is that at the aggregate level these are servicing the resident population even if they are not housing people directly.

For each 10 year time period a densification index is calculated. This index expresses, informed by the aforementioned regression coefficients how much of the population growth is accommodated by densification and how much by growth in urban extent. The densification index observed for different periods in the past is combined with population growth forecasts and the calibrated urban growth model to develop urban growth scenarios.

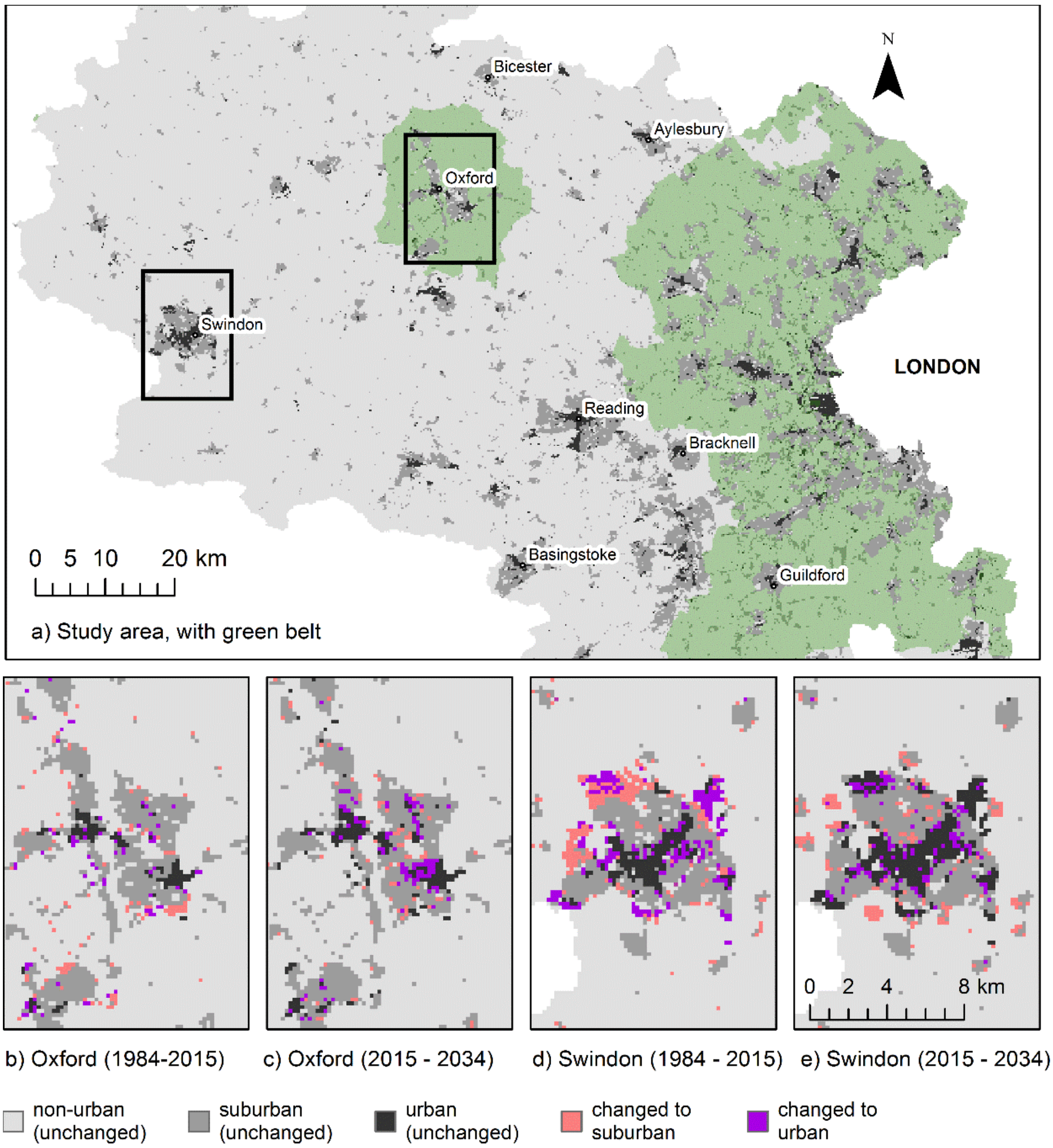

Figure 1: Pattern of urban growth 1984-2015 and 2015-2035 (business as usual scenario)

4. Results

The analysis of historical growth patterns confirmed the effectiveness of the green belt in preventing urban growth occurred outside of the green belt (Figure 1). There, growth has concentrated on mid-size towns. Over time the population associated with a unit of suburban land has remained constant, whereas there has been a steady increase for urban land (Figure 2). The uncertainty for urban land is considerably greater, possibly because this land cover type is associated with a wider range of activities (residential, commercial, industry) than suburban, which predominantly is residential. Over time there has been substantial fluctuation in the degree to which population growth was associated with increased intensity of land use, or growing the urban boundary (Table 1).

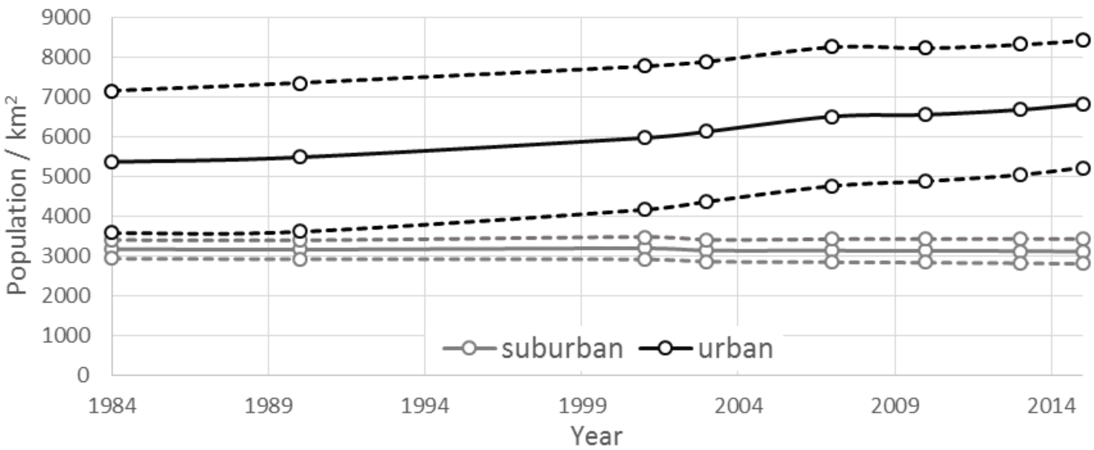

Figure 2: Population associated with land cover types *suburban* and *urban* with 95% confidence interval

Table 1: The densification index is the share of population growth that is accommodated by densification, in contrast to growing the urban envelope.

Period	Densification index
1984-1990	18%
1990-2001	23%
2001-2003	18%
2003-2007	59%
2007-2010	45%
2010-2013	47%
2013-2015	47%

5. Conclusion

Our analysis of spatial and temporal urbanization patterns in the study areas showed that spatial and temporal trends of land use change were relatively stable, except for the balance between urban expansion and densification which fluctuated substantially. The Constrained Cellular Automata, or any other land use model that we are aware of, is not suited to represent or foresee such fluctuations. Therefore possible future directions need to be represented in the form of scenarios, differentiated by degree of densification.

Regression analysis can be used to derive relationships between population growth and land area by density class. In our study these relationships proved to be stable even when the nature of urban growth changed considerably, we therefore recommend this analysis for the development of realistic, consistent and diverse scenarios for future urban growth.

Spatially the patterns of growth for sparse and dense urban area are clearly distinct and well captured by the Constrained Cellular Automata. This is not only because there is a difference in density of activities in these areas but also because of the nature of the activities found there.

6. Acknowledgements

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