Landscape and Urban Planning 160 (2017) 96–106

Contents lists available at ScienceDirect

Landscape and Urban Planning

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

Research Paper

Downdating high-resolution population density maps using sealed surface cover time series

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HIGHLIGHTS

- We propose an approach for downdating population maps using sealed surface data.
- We apply the method to Flanders, which is among the most sprawled regions in Europe.
- Population density increased in urban areas, while in rural areas sprawl is ongoing.
- Obtained population time series can help to calibrate activity based land-use models.

ARTICLE INFO

Article history:
Received 20 November 2015
Received in revised form
12 December 2016
Accepted 19 December 2016

Keywords:
Urban sprawl
Population growth
Sealed surfaces
Land-use modelling
Historical calibration
Densification

ABSTRACT

Many countries in Europe and North America see their natural and agricultural landscapes being replaced by a fragmented, sprawled landscape. Spatially detailed modelling of changes in land use, population and transport could help to forecast the impact of scenarios aimed at mitigating the process of urban sprawl. A common problem with land-use change models however, is the lack of historical data for proper model calibration. In this paper we describe an approach for developing historical population density maps by downdating a recent high-resolution population density raster, using a time series of sealed surface data and historical census data as an input. In the proposed approach, we hypothesise a local relationship between increasing population densities and increasing sealed surface fraction estimates, the latter obtained from remote sensing imagery. We apply the method to Flanders, Belgium, a region where population growth and improved transport networks led to a diffuse urban expansion, with ribbon development along many roads and a strong fragmentation of open space. The resulting population and sealed surface maps provide interesting data on the urban sprawl phenomenon in the past decades. By computing a densification index we observe that most urban areas witness a recent population density increase while in several rural areas the built-up area per inhabitant is still growing. The downdated time series of population maps obtained in this study will be used to set up a historical calibration for an activity-based cellular automata model for Flanders and Brussels which, among other data, needs high-resolution population maps.

1. Introduction

Many environmental problems worldwide arise from the ever growing area on Earth occupied by human activities. This urban growth often manifests itself in the form of urban sprawl, especially in large parts of North America and Europe (Ewing, 2008; Kasanko et al., 2006; Ravetz, Fertner, & Nielsen, 2013). The main causes of urban sprawl are a growing population, increased income and new fast transportation networks with decreased travel costs (Anas, Arnott, & Small, 1998; Brueckner, 2000; European Environment Agency, 2006). Other important forces leading to the diffuse growth of urban areas are economies and diseconomies of agglomeration (Richardson, 1995): while a concentration of population and companies produces advantages of proximity, a too high concentration of activity in a single location can also lead to high

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http://dx.doi.org/10.1016/j.landurbplan.2016.12.009
0169-2046/

land prices, increasing traffic congestion and environmental pollution. Extended transportation networks and diseconomies of agglomeration can both lead to a growth of suburban housing and employment. This, in turn, causes new health concerns (Jackson, 2003) and environmental problems due to high commuting distances and related congestion (Camagni, Gibelli, & Rigamonti, 2002), increased energy consumption (Newman & Kenworthy, 1989), and altered natural landscapes and loss of valuable agricultural land (Antrop, 2000). In recent times the average home-to-work travel distance has grown significantly (Boussauw, Derudder, & Witlox, 2011). For many reasons residential location choices are often determined by more than the current job location: two-worker households need housing in between both jobs, job uncertainty plays a major role, and moving costs can be substantial (Anas, Arnott, & Small, 1998; Crane, 1996). In the US, job accessibility has become less important for land prices since non-work travel for social interactions has increased (Giuliano, Gordon, Pan, & Park, 2010). Owning a suburban house is therefore often perceived as an 'ideal' living location (Batty, Besussi, & Chin, 2003). Recently, however, a number of cities and regions in both North America and Europe have started to recognise the need for more compact urban forms (Dieleman & Wegener, 2004).

To gain a spatially differentiated insight in the future evolution of urban land use and the associated population growth or decline, land-use change modelling could be beneficial. Several land-use change models have been developed over the years to simulate the spatial evolution of the urban sprawl phenomenon (Haase & Schwarz, 2009; Poelmans & Van Rompaey, 2010). One particularly successful type of highly-detailed raster based models are cellular automata (CA) (Santé, Garcia, Miranda, & Crecente, 2010). Thanks to their high resolution and regular structure, they fully integrate spatial input data and are computationally efficient for large regions. In the constrained cellular automata model of White, Engelen, and Uljee (1997), which has been widely used (e.g. Barredo, Kasanko, McCormick, & Lavalle, 2003), the neighbourhood rules are the core of the CA land-use dynamics. For each cell, they weigh the influences exerted by the land uses present in a given neighbourhood of the cell to determine its future land use. A historical calibration strategy is necessary to obtain reliable parameter estimates for this model. Efforts have been made to develop automatic calibration algorithms for the CA neighbourhood rules (Straatman, White, & Engelen, 2004; van der Kwast et al., 2012). An important problem, though, is the lack of consistent historical land-use data to serve as input for the calibration (Engelen & White, 2007). The CA model has many applications since it also deals with regional interactions between population and economic forces in its regional component. Recently, some publications have proposed an integration of the population and the economic data within the CA structure itself by using an activity-based approach (Crols et al., 2015; van Vliet, Hurkens, White, & van Delden, 2012; White, 2006; White, Uljee, & Engelen, 2012). This implies that for calibration, next to historical land-use maps, also detailed maps of population and employment for the past are required.

The development of a time series of regional land-use maps is a time consuming task, and existing series are often produced with inconsistent methodologies (van der Kwast et al., 2009; Van de Voorde et al., 2016). Remote sensing imagery can be a useful data source to build consistent land-use time series for recent decades. Spectral unmixing of medium-resolution images, available since the 70s, enables the mapping of sealed surfaces, which are an indicator of urbanised land uses (Vanderhaegen, De Munter, & Canters, 2015; Van de Voorde, De Roeck, & Canters, 2009; Weng, 2012; Wu, 2004). Van de Voorde, Jacquet, and Canters (2011) used a spectral unmixing technique to produce sealed surface maps from Landsat TM/ETM+ data, and to use these maps for distinguishing urban from non-urban land use, and even residential from non-residential urban land uses by computing spatial metrics on pixel-based sealed surface fractions for each urban block. A thematically more detailed mapping of land use though, as is often required for historical calibration of land-use models, cannot be achieved with this approach.

A possibility to obtain historical land-use maps with a higher number of urban classes is to start with present land-use information, and then move progressively back in time by defining a downdating procedure, using remote sensing data available for previous time steps to downdate the most recent map. Using this approach, Fricke and Wolff (2002) succeeded in building a land-use series for the agglomeration of Brussels ranging from 1955 until 1997. All land-use maps they produced involved manual interpretation of orthophotos or aerial photos and topographical maps. For the 1997 map, which formed the basis for downdating, extra information out of satellite remote sensing and a GIS database was used. The procedure involves much manual work, and hence is not feasible for application to larger regions. Nevertheless, downdating a present high-resolution land-use map using remote sensing data available for the past remains an interesting idea, if image interpretation for previous time steps can be automated. Time-series of sealed surface maps obtained through spectral unmixing seem promising for developing such a strategy.

In a similar way, sealed surface time-series seem also an interesting data source for downdating population maps. High-resolution population density maps are mostly constructed using dasymetric mapping approaches, which model population distribution within census units based on spatially detailed ancillary data explaining differences in population density (Wu, Qiu, & Wang, 2005). Often use is made of multiple regression analysis, with population as the dependent variable and land-use data as one of the independent variables (e.g. Eicher & Brewer, 2001; Gallego, Batista, Rocha, & Mubareka, 2011; Langford, Maguire, & Unwin, 1991; Mennis, 2003). Stevens, Goughan, Linard, and Tatem (2015) proposed nonparametric modelling to include a large set of land cover and other spatial variables. Several publications confirm that population density within a certain land use and census unit is related to sealed surface cover (Batista e Silva, Gallego, & Lavalle, 2013; Lu, Weng, & Li, 2006; Wu & Murray, 2007; Zandbergen and Ignizio, 2010). If available, information on the building type in parcels (Jia, Qiu, & Goughan, 2014; Xie, 2006) or in land-use polygons (Goerlich & Cantarino, 2013) can improve the results, and can be combined with land cover data such as sealed surface cover (Jia and Gaughan, 2016). Recently, the number of address points within a land use and census unit was suggested as the most accurate factor to compute high-resolution population density maps (Cockx & Canters, 2015; Tapp, 2010). Alternatively, nighttime mobile phone data can be used to downscale population maps (Deville et al., 2014) or to update existing outdated population maps (Douglass, Meyer, Ram, Rideout, & Song, 2015). Unfortunately, address points and mobile data are generally not available for the past. Hence, in the absence of address data, sealed surface cover can be considered the best option for estimating population density (Zandbergen, 2011).

We recently defined a workflow for downdating both land use and population maps using time series of sealed surface maps for the Flanders-Brussels region, to be used as an input for the historical calibration of the activity-based land-use model developed by White, Uljee and Engelen (2012) and Crols et al. (2015). Downdating of land-use data using sealed surface cover as ancillary data has proven to be a complex and partially ad hoc process which we do not intend to discuss in detail in this publication. The downdating of population though is more generic and has proven useful for documenting the phenomenon of urban sprawl. Therefore, in this paper we focus on the latter. Starting from a recent high-resolution population map, and using remote sensing derived sealed surface data and statistical population data for previous time steps, we demonstrate the downdating method proposed by applying it