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

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Research 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.

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 (Richardsson, 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 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 & 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 & Goughan, 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 to the Flanders-Brussels region. The analysis focuses on the years 1986, 2001, and 2013. As such, the development of the population time series, in combination with the sealed surface data for each time step enables us to analyse in detail the last stage of the urban flight of the late 20th century in the region, the 21st century revival of the regional cities, and the still declining population density of new built-up areas around these cities.

2. Methods

2.1 Study area and land use

The northern half of Belgium, i.e. Flanders, the Brussels Capital Region and the north of Wallonia, is a region with one of the highest proportions of built-up surfaces and fragmented landscapes in Europe, with extensive urban sprawl and ribbon development with mixed urban and rural functions (Antrop, 2004; Poelmans & Van Rompaey, 2009). This development pattern finds its origin in two 19th century government policies decided when Belgian cities were rapidly industrialising but the political elite wanted to inhibit massive migration from the rural population to the cities in order to avoid social unrest and health problems (De Decker, 2008). Firstly, a dense light railway network was built to enable fast and cheap travel from rural areas to the city (De Block & Polasky, 2011). Secondly, home ownership was promoted with beneficial tax policies for mortgages. Frequent moving is discouraged by high transaction costs, and has gradually become almost exceptional in a society where almost everybody has become used to owning a suburban house with a large garden, close to several cities and job possibilities (Meeus & De Decker, 2015). In 2013, 70% of the Flemish population lived in a unit they owned, and 85% of these units were single-family dwellings (Winters et al., 2015). From 1970 till 2000 there was still an ongoing ‘urban flight’ in Belgian cities with a declining urban population, while the rate of suburban population growth did not fall (Hertogen, 2013). At first sight, the Flemish cities and Brussels seem to have regained their attractiveness after the year 2000 due to improved spatial policies and urban revitalisation projects, yet the total picture is more complex since the main reason for urban population growth is external migration (De Decker, 2011).

Flanders has a relatively high population considering its size (6,381,859 inhabitants in 2013, or 472 per km²). The Brussels Capital Region (BCR), a territory of only 161.38 km², forms an enclave in Flanders (Figure 1). With a population of 1,154,635 inhabitants in 2013 (data of the Belgian Federal Department of Economics), it has a density of 7155 inhabitants/km². Just outside the BCR, the population density rapidly falls: in comparison with other large European capitals, Brussels has one of the highest densities in the core but one of the lowest in the zone between 8 and 15 km from the city centre (European Commission, 2014).

According to the 10 m resolution land-use map of the Flemish Institute for Technological Research (VITO) of 2013 used in this study (Figure 1, Tables 1 and 2), the 13,522 km² of the Flemish Region consist of 27.6% of built-up land uses, while the Brussels Capital Region contains 69.3% built-up land uses. Not all sources agree on the amount of built-up surfaces. The Cadastre of Belgium reports only 20.1% of built-up registered parcels for Flanders and 58.6% for the BCR in 2013 (FOD Economie, 2015) (Table 2). The big differences can be attributed to other land-use definitions: in the Cadastre, infrastructure and unbuilt parts of industrial and commercial terrains are regarded as unbuilt.

2.2 Sealed surface fraction mapping

This study uses sealed surface fraction estimates for Flanders and Brussels for the years 1987 (as a proxy for 1986), 2001 and 2013, produced from a time series of medium-resolution Landsat imagery at 30 m resolution by applying a sub-pixel mapping approach, as described in Vanderhaegen, De Munter, and Canters (2015). In this approach, the sealed surface fraction within each pixel that is part of the urban area is assumed to be the complement of the vegetation fraction. Therefore, the first step in the mapping is to determine an urban mask for each date delineating the urbanised area. The mask for 2013 was defined based on large-scale reference data sets of Flanders (GRB Vlaanderen) and Brussels (UrbIS), combined with the 10 m resolution land-use map of VITO. The masks for previous years were considered to be subsets of the 2013 mask. The Normalised Difference Vegetation Index (NDVI: see e.g. Mather, 2004) was used to exclude pixels fully covered by vegetation for each year. Based on four high-resolution IKONOS images (4 m resolution) covering part of the study area, a detailed mapping of vegetation cover was accomplished. Based on this detailed mapping, the vegetation fraction of each 30 m Landsat pixel located within the IKONOS coverage was determined. Next, a linear regression model was built with known vegetation fraction, derived from the IKONOS images as the dependent variable, and the Landsat NDVI value as independent variable:

$$VF_i = a_0 + a_N . NDVI_i + \varepsilon_i \quad (1)$$

with VF_i the reference vegetation fraction in pixel i, a_0 the model's intercept, a_N the regression coefficient for the NDVI, $NDVI_i$ the NDVI value of pixel i, and ε_i the residual for pixel i. Multiple linear regression with Landsat spectral band values as extra independent variables did not improve the model's outcome, hence the model with NDVI as the sole variable was applied to estimate the vegetation fraction for each Landsat pixel within the urban mask. Finally, as indicated above, the sealed surface fraction SSF was defined as the complement of VF:

$$SSF_i = 1 - VF_i \quad (2)$$

To produce a temporally consistent SSF series and correct for errors due to uncertainty in the estimation procedure, the SSF value of a pixel for a later time step was defined to be minimally the value of the previous step. As such, the sealed surface cover is assumed to only increase over time, which can be expected to be true for almost the entire study area. For a full description and discussion of the technique used, the reader is referred to Vanderhaegen and Canters (2016).

2.3 High-resolution mapping of population density for 2013

For each first day of the year, there exist population data made available by the Federal Department of Economics at the municipality level, and for certain years also at the more detailed level of statistical sectors. Flanders and the BCR include 327 municipalities and 9906 statistical sectors. We obtained data per statistical sector for 1981, 1991, 2001 and 2011, and made an interpolation for 1986 and an extrapolation for 2013; in both the latter cases we rescaled the statistical sector estimates so that the totals were correct for municipalities.

For the purpose of downdating, we required a detailed population density raster for 2013. The Belgian Federal Department of the Interior provided population data at 100 m resolution for 2013 which we resampled to a 30 m raster to enable computations with the sealed surface series. However, the original population raster had a number of drawbacks. The raw population data were extracted from a database of the Belgian National Population Register (Rijksregister) which contains the addresses of all inhabitants. Unfortunately, these addresses were transformed into coordinates with an unknown interpolation method. Especially in rural areas we noticed a mismatch between the built-up area in the land-use map and the sealed surface maps on the one hand, and the population map on the other. Furthermore, the totals were slightly different from those of the Federal Department of Economics.

Hence, we decided to evenly redistribute all the population living in cells without buildings, i.e. cells without an urban land use or without sealed surfaces, over nearby cells having a 'habitable' urban land use with sealed surface cover. At 10 m resolution, residential and industrial cells, commerce and services, port areas, and military buildings were considered to be 'habitable', while cells labelled as infrastructure and all rural and natural land uses were not. Thus all 30 m pixels containing at least one 'habitable' cell in the 10 m land-use map, and having $SSF_i > 0$, were defined to be 'habitable'. The redistribution was done in 5 x 5 focal neighbourhoods around the wrongly located 30 m 'inhabited' cells, and repeated with remaining erroneous locations in 11 x 11 and 17 x 17 focal neighbourhoods. The remaining very small amount of population not having 'habitable' cells within a 17 x 17 focal neighbourhood was considered to be totally wrong, and was therefore excluded. In the end, we performed a rescaling operation to equate the statistical sector totals to those obtained based on the Federal Department of Economics data. The rescaling was proportional to the population already present in a cell. The resulting map is shown in Figure 2.

2.4 Downdating of the population density map

To produce a population density map for 1986 and 2001, we developed a downdating strategy using the population raster constructed for 2013, as well as the sealed surface fractions of 1987 and 2001 and the statistical data for 1986 and 2001. The results of the downdating for 2001 served as input data for the 1986 estimates.

In the proposed strategy, cells that are not part of the urban mask in a previous time step do not receive any population. For cells with changing SSF values we hypothesise a local relationship between the evolution of the population and sealed surface cover. We do so by assuming that the local building style imposes a more or less constant population density per unit of built-up area. Therefore, increases in sealed surface cover in urban cells between an earlier and a later date can be associated with increases in population:

$$\bar{P}_{i,t-1} = P_{i,t} \times SSF_{i,t-1} / SSF_{i,t} \quad (3)$$

with $\bar{P}_{i,t-1}$ the estimated population in pixel i at an earlier time step t – 1, $P_{i,t}$ the population in pixel i at step t, and $SSF_{i,t-1}$ and $SSF_{i,t}$ the sealed surface fraction in pixel i at time steps t – 1 and t. The fact that ribbon development next to existing roads is one of the most common mechanisms of built-up area growth in Flanders supports the hypothesis that SSF increase goes along with local population growth, with little changes in population density per unit built-up area. As such, the proposed procedure seems a valid option to create rasters with spatial resolution higher than the level of statistical sectors for past decades. On the other hand, the approach does not account for large-scale major evolutions such as population decline or re-urbanisation of an entire urban core. Furthermore, enlargements of a building are not necessarily related to an increase in the number of inhabitants. As such, a rescaling of local population estimates obtained is required, accounting for these effects. The rescaling ensures correct totals at the statistical sector level:

$$P_{i,t-1} = \bar{P}_{i,t-1} \times P_{s,t-1} / \sum_{j=1}^{n} \bar{P}_{j,t-1} \tag{4}$$

with $P_{i,t-1}$ the rescaled population in pixel i at time step t – 1, $P_{s,t-1}$ the total population in statistical sector s, j a pixel in sector s, and n the number of pixels in sector s. The applied correction factor $P_{s,t-1} / \sum_{j=1}^{n} \bar{P}_{j,t-1}$ for every statistical sector serves both as a validation of the constant density hypothesis and, in case of a rejection of this hypothesis in a statistical sector, as an indicator of density changes. If the correction factor for a statistical sector is close to 1, then use of equation (3) to estimate the population seems justified. A correction factor not close to 1 indicates that population density trends in the statistical sector are not in line with the extension of the urban tissue. In that case, the factor gives an indication of population density changes in relation to the sealed surface fraction evolution within the sector. The inverse of the correction factor can be defined as a densification index $D_{s,t-1,t}$ for a statistical sector s between time steps t – 1 and t:

$$D_{s,t-1,t} = \frac{\sum_{j=1}^{n} \bar{P}_{j,t-1}}{P_{s,t-1}} \tag{5}$$

For sectors with an increasing population, D_s serves as a detection method for urban densification (if $D_s > 1$) or deteriorative sprawl (if $D_s < 1$). The index is not suited though to analyse causes for a shrinking population since there is clearly no direct link between population decrease and sealed surface growth.

2.5 Uncertainty propagation analysis

Because sealed surface mapping from remotely sensed data inevitably introduces uncertainty in the estimation of sealed surface fractions at pixel level (Cockx, Van de Voorde, &

Canters, 2014) and may be considered the most important source of error in the downdating method proposed in this study, we analysed how this uncertainty affects the computation of the historical population maps and the densification indices through Monte Carlo uncertainty propagation analysis.

The sealed surface fraction estimates obtained in this study were validated for a set of Landsat pixels, located in parts of the study area covered by the IKONOS images used for calibrating the sub-pixel mapping model (see section 2.2). For a set of validation pixels, not used in the calibration, and for which it was verified that sealed surface cover did not change between 1986 and 2013, the error in sealed surface fraction estimates was calculated, using the average sealed surface fraction in the underlying IKONOS pixels as ground truth. Validation pixels were selected with stratified random sampling: each of ten quantiles of all possible sealed surface fraction values are equally represented in the validation set. Next, random errors were drawn for all Landsat pixels from a multivariate normal distribution defined by the mean error vector and the variance-covariance error matrix, calculated from the errors observed at each time step. This way, error perturbed versions of the sealed surface maps for each of the three time steps could be produced, accounting for temporal correlation in the errors. The error simulation process was repeated 100 times, producing 100 sealed surface maps for all time steps. These maps were used to compute 100 population maps of 2001 and 1986 and 100 densification index maps for the periods 1986-2001 and 2001-2013. As such, we can analyse the uncertainty in the resulting population and densification maps.

3. Results

3.1 Population trends between 1986 and 2013

Sealed surface cover increased in Flanders and the Brussels Capital Region (BCR) from 1911km² in 1987 to 2687 km² in 2013 (Vanderhaegen & Canters, 2016), which corresponds to an overall growth of 41%. The proportions of sealed surface cover in each time step largely match the proportions of built-up land use reported by the Belgian Cadastre (Table 2). The average daily growth of sealed surfaces was 10 ha between 1987 and 2001, and 6 ha between 2001 and 2013. During the same period, the population evolved from 6,652,730 in 1986 to 7,536,494 in 2013, or a 13% overall growth (Table 3). The average annual population growth increased from 19,246 during the 1986–2001 period to 49,589 during the 2001–2013 period. In other words, while the population growth rate has risen significantly, the sealed surface growth rate has declined.

To show and analyse the trends observed, we have aggregated our 30 m population maps obtained for the three dates to a 300 m resolution. Between 1986 and 2001 the population decreased in almost all urban centres, Antwerp, Ghent and Bruges being the best examples, as well as in some rural areas (Figure 3a). In the BCR the trend was more mixed, with some neighbourhoods increasing and others decreasing in population, resulting in almost no total population change over the whole period (Table 3). Suburban areas attracted the most population, especially around Antwerp and in the north of Limburg province. Another growth zone was the Belgian coast, situated at the northwest edge of West Flanders province. Between 2001 and 2013 population in all cities increased, especially in Brussels, Antwerp and Ghent (Figure 3b). At the same time, the population increase was still considerable in suburban areas, as well as along the Belgian coast. Decreases in population were mostly limited to rural areas, with some neighbourhoods at the edges of cities as exceptions.

3.2 Population change versus changes in built-up area

We also aggregated the results obtained for the densification index of equation (5) to a 300 m resolution, and excluded all 300 m cells with a population below 10 in the start year of a time period to avoid outliers, as well as all cells with a population decline during that time period. Before 2001 the trend towards sprawl is clear in almost the whole of Flanders (Figure 4a): index values below 1 indicate that sealed surfaces grew more strongly than the population. The lower the population density of a cell, the more obvious is the trend (Table 4). There are only a few exceptions, with the Belgian coast standing out. After 2001 some regional differences appear (Figure 4b). In general, the densification index is higher for cells with a higher population density (Table 4). In most cities, the densification process brought extra population to areas where sealed surface fractions were already high. In many suburban zones, the increase of sealed surfaces was proportional to the population growth. However, in some rural areas with an increasing population, and especially in suburban areas north of Antwerp and in the centre of Limburg province, there was still a stronger increase of the built-up area than of the population. This continuing process of sprawl is also observed at the level of municipalities in the north and east of Flanders (Figure 5). Not all municipalities covering urban core areas have the highest values for the densification index, since they often are much larger than only the urban core. Some smaller municipalities in the 'Flemish Diamond', the central region between the cities of Brussels, Ghent, Antwerp and Leuven, have equally high index values.

3.3 Uncertainty propagation analysis

Since error in sealed surface maps can be substantial, we wanted to investigate if this causes a high uncertainty in the resulting population and densification maps. There is no significant bias in sealed surface error and the errors for each time step prove to be normally distributed, so 100 perturbed sealed surface maps for each time step could be produced using a multivariate normal error distribution. Like in the original procedure, the maps obtained for the three time steps in each of the 100 simulations were made temporally consistent. The standard deviation of the 100 resulting sealed surface fractions, averaged over all cells, which provides a measure of the magnitude of the uncertainty, is for all time steps around 15% (Table 5). Errors are lower in urban areas, and more specifically in the three largest cities (Brussels, Antwerp and Ghent). While these errors are significant, they seem to level each other out when sealed surface ratios are used together with other available information to produce population maps. The average standard deviation in the population maps (aggregated to the 300 m resolution used in the population and densification analysis) is only around 1 person per cell (Table 5). Absolute uncertainty values are higher in dense urban areas since the population per cell is higher and the sealed surface differences in time are mostly limited. However, the standard deviations are still relatively small with values of around 10 persons per 300 m cell (Figure 6), while most of these cells are inhabited by 1000 to 2000 persons. The densification indices have a limited uncertainty too (Table 5) in comparison with the range of observed values in Figure 4. There is only very little spatial variation in densification uncertainty, except in a few cells with changed urban functions, like old industrial terrains that were reconverted into dense residential areas.

4. Discussion

The combination of population growth with the construction of a dense road network have caused widespread sprawl in Flanders with large areas of ribbon development in between villages. This phenomenon can be seen in the land-use map (Figure 1), but is even more striking when analysing detailed population maps as produced in this study (Figure 2). A real urban flight during the last decades of the 20th century towards suburban areas caused a huge intake of natural and agricultural land uses. Sealed surfaces grew more than would be expected from population trends, as can be inferred from the low densification factor values in almost all areas with a population increase in the period 1986–2001. An exception is the Belgian coastline, which has been almost entirely filled up with high rise apartment buildings for decades. These buildings were originally intended for recreational stays but have gradually been more and more used as permanent residences, especially by the growing number of older people (Schillebeeckx, De Decker, & Oosterlynck, 2013). One of the causes of the population decline per unit of built-up area is the shrinking household size. In Belgium an average household had 2.73 members in 1981, 2.52 in 1991, and 2.31 in 2008 (Deboosere et al., 2009; FOD Economie, 2011). 30% of all households in Flanders and 50% in the BCR consisted of singles in 2008.

The massive sprawl has been made possible due to a lack of spatial planning. It was only in 1997 that Flanders adopted the general Spatial Structure Plan (Ruimtelijk Structuurplan Vlaanderen). But even in this plan residential development is still allowed in a large number of non-urban lots (De Decker, 2008). Likewise, ribbon development continues to occur along roads where building is still allowed (Verbeek, Boussauw, & Pisman, 2014).

Since 2001, the urban population has significantly increased. Household sizes are larger again in cities, especially in the BCR (FOD Economie, 2011). Migration is an important factor in this new urban revival since cities serve as an arrival station for newcomers (Schillebeeckx, De Decker, & Oosterlynck, 2013). In our analysis we see indeed that migrant neighbourhoods in Brussels and Antwerp have the largest densification index values. However, we also clearly observe population growth and a densification increase in almost all other urban neighbourhoods, including those of smaller towns and in centres of suburban municipalities, especially in the ‘Flemish Diamond’. On the other hand, most suburban areas in the north and east of Flanders and some rural areas still suffer from sprawl.

The beginning of a trend towards densification seems to be there, but many authors believe that spatial planning in Flanders still has to improve. The Spatial Structure Plan of Flanders is in the process of being replaced by the Spatial Policy Plan for Flanders (Beleidsplan Ruimte Vlaanderen), yet Boussauw and Boelens (2015) criticise the content of the plan. Among other things, they indicate the persistence of exceptions for large projects, the lack of quantification and measurable goals, the lack of cooperation between the Belgian regions, and more specifically the restrictions on the growth of the Brussels urban area in the fringe governed by the Flanders region encapsulating the city. The recent strong growth of the population in Brussels caused a rise of real-estate market prices which is leading to new suburbanisation further away from Brussels, in both Flanders and Wallonia (Boussauw, Allaert, & Witlox, 2013). Leaving the city is often not the preferred choice of young adults in Belgium who desire to acquire a home, but the prices force them to do so. Living in less attractive urban neighbourhoods or renting instead of buying can be intermediate solutions or alternatives (Slegers, Kesteloot, Van Criekingen, & Decroly, 2012). Within the cities, there is also an increasing segregation between ethnic groups. The proportion of migrants living in often poorer neighbourhoods seems to be an important negative attractiveness factor for those who can afford to live elsewhere (Schuermans, Meeus, & De Decker, 2015).

An enhanced spatial planning policy in Belgium clearly needs quantifiable goals to prevent the growing population from moving into the rural zones, and rather to house it in available space in the existing urban centres. Both long-term land use modelling and specific case studies assessing the impact of different planning scenarios can help to reach these goals. Job accessibility should again become a more important factor in residential location choices in order to decrease the average commuting distance. Such spatial visions can be examined with activity-based land-use models which need to be fed with reliable population and employment data to allow for a proper calibration. The approach proposed in this study for producing detailed historical population maps may help to do so. Between 1986 and 2001 the relation between population and sealed surface growth was not constant: for a 27% increase of sealed surface cover in Flanders, there was only a 5% increase of the population. This means that the computed population density map for 1986 may be less reliable as an input for historical calibration of the activity-based land-use model for Flanders. From 2001 densification factor values are close to 1 for the less populated cells, which suggests that the hypothesis of equation (3) is valid for this period (Table 4). A better input population raster for the most recent year (2013) would help to reduce some of the errors observed, especially in rural neighbourhoods. Within urban cores, and especially those of the largest cities, a densification trend is observed between 2001 and 2013, yet one should keep in mind that it is more difficult to examine the ratio between sealed surfaces and population in an environment that is already largely built-up. The detailed population predictions within city centres for 2001 are therefore assumed to be less reliable than the local predictions in rural areas. Since the prime purpose of an urban growth model remains the prediction of the future extension of urban land uses, the limitations of the proposed downdating approach seem acceptable for historic calibration purposes.

In summary, downdating a spatially detailed population density map has the advantage of using today's high resolution information for predicting population densities in the past, but involves the risk that errors will increase when going further back in time. To build scenarios for Flanders' and Brussels' future, a calibration based on the most recent period in the past (2001 – 2013 in this study) should give the best results since this period includes the start of the re-urbanisation process and the hypothesis of a local relationship between population density and sealed surface cover seems to hold rather well for this time frame. A modelling scenario exercise predicting possible urban futures for Flanders has already been carried out with a CA model for the Department of Spatial Planning (de Kok, Poelmans, Engelen, Uljee, & Van Esch, 2012), but could be improved with a multifunctional CA model including land use, population, employment and transport, as has been proposed by Crols et al. (2015). Downdating of population based on time series of sealed surface maps may be useful for the calibration of this model and was also the incentive for developing the mapping approach proposed in this paper.

5. Conclusion

This paper presents an approach for downdating a detailed population density map for a recent date, using a time series of sealed surface data for the past, obtained through remote sensing. The computed historical population density maps revealed spatial differences and changing trends in the relation between population and sealed surface cover in Flanders and Brussels. In the last decades of the 20th century the region experienced an urban population decline and a massive increase of urban sprawl. Since 2001 the urban population has been increasing again, primarily due to immigration, but in the centres of smaller towns also as a result of the advent of an overall spatial structure planning policy that was missing before. Nevertheless, the built-up area used per inhabitant is still increasing in some rural areas and several suburban municipalities in the north and east of Flanders.

Land-use models can help spatial planners to define objectives for the spatial allocation of the still expected population growth in the future. These land-use models should incorporate population, employment and transport data at a detailed scale level. Downdating of recent population data based on an existing high-resolution population raster and sealed surface fraction estimates of the past, as proposed in this study, may be useful for producing historical data needed for the calibration of such models.

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Table 1. Proportions of land uses (%) in Flanders and the Brussels Capital Region according to the 2013 land-use map of the Flemish Institute for Technological Research (VITO). Residential, industrial and commercial, and infrastructure are built-up land uses. Natural land covers in military terrains were moved from infrastructure to nature to produce this table.

Land use	Flanders	Brussels Capital Region
Residential	15.8	66.1
Industrial and commercial	5.4	
Infrastructure	6.4	3.2
Nature	17.8	14.9
Agriculture	48.8	3.9
Parks and recreation	2.2	9.7
Water	2.7	1.1
Other	0.9	1.0

Table 2. Proportion of built-up land use / land cover (%) in Flanders and the Brussels Capital Region for 1986, 2001, and 2013 according to the 2013 land-use map of VITO, the Belgian Cadastre, and the sealed surface time series (SSF × pixel area) used in this study.

LU/LC data	Flanders			Brussels Capital Region		
	1986	2001	2013	1986	2001	2013
LU map of VITO	-	-	27.6	-	-	69.3
LU in the Cadastre	12.7	17.8	20.1	50.9	55.8	58.6
Sealed surface data	13.5	17.2	19.1	45.2	48.3	51.3

Table 3. Population of Flanders and the Brussels Capital Region for 1986, 2001, and 2013.

Year	Flanders	Brussels Capital Region	Total
1986	5,676,194	976,536	6,652,730
2001	5,967,946	973,475	6,941,421
2013	6,381,859	1,154,635	7,536,494

Table 4. Average (Avg) densification index values and standard deviations (SD) for different categories of population per 300 m cell in the population density map for 2013. Cells with a population below 10 were excluded as outliers.

Population per 300 m cell (2013)	Densification index D_s for cells with growing population			
	1986 – 2001		2001 – 2013	
	Avg	SD	Avg	SD
10 – 30	0.866	0.187	1.006	0.139
30 – 100	0.905	0.181	1.022	0.170
100 – 300	0.948	0.201	1.043	0.170
> 300	0.990	0.152	1.098	0.169

Table 5. Standard deviation of sealed surface fraction (30 m cells), population estimate (inhabitants per 300 m cell) and resulting densification index (300 m cells), averaged over all cells, in a Monte Carlo uncertainty propagation analysis.

	1986		2001		2013
		1986-2001		2001-2013	
Sealed surface fraction	0.1560		0.1592		0.1574
Population	1.4635		1.0296		---
Densification index		0.01655		0.01589	

Figure 1. Land-use map of Flanders and Brussels in 2013 (10 m resolution map developed by VITO aggregated to a 100 m resolution), with an indication of both regions (thick black lines; Brussels Capital Region (B)), the Flemish provinces (thin black lines) and their capitals (Bruges (Bg), Ghent (G), Antwerp (A), Leuven (L) and Hasselt (H)).

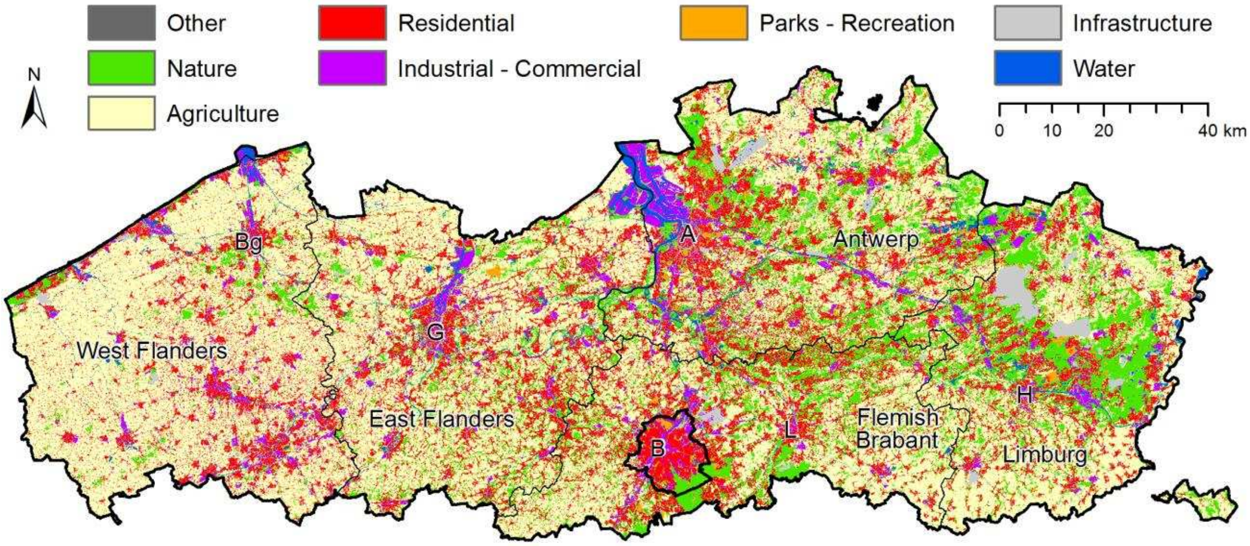

Figure 2. Population density map for 2013 (inhabitants per 30 m pixel).

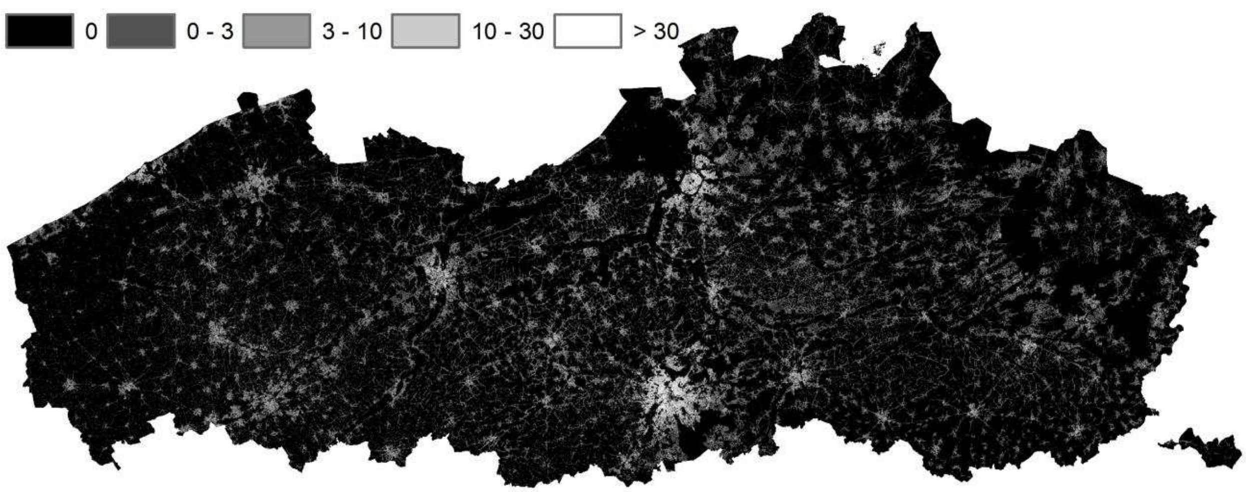

Figure 3. Population difference maps (aggregated to a 300 m resolution) for the periods (a) 1986 – 2001, and (b) 2001 – 2013.

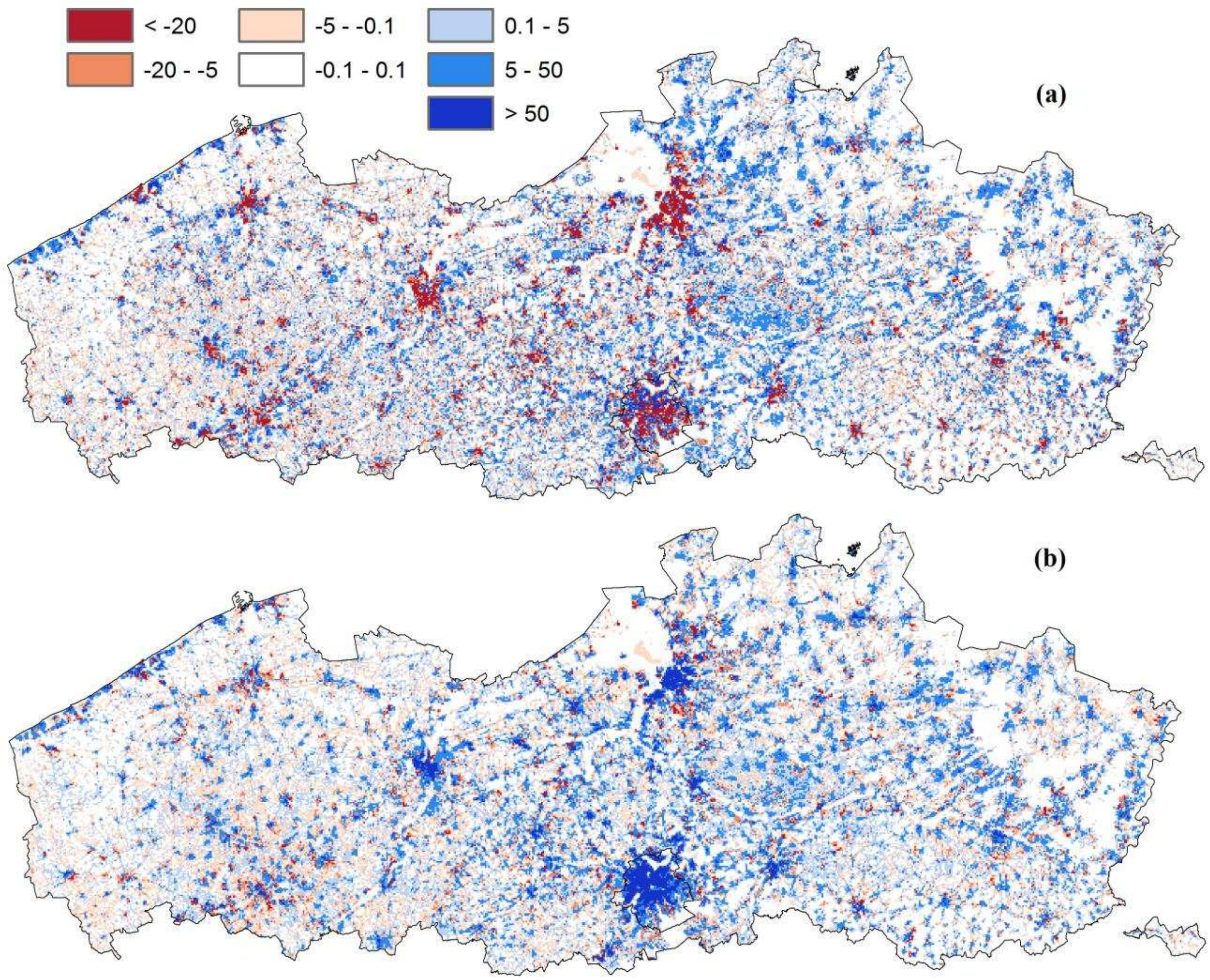

Figure 4. Densification index maps (300 m resolution) for cells with a growing population and a minimum of 10 inhabitants for the periods (a) 1986 – 2001, and (b) 2001 – 2013.

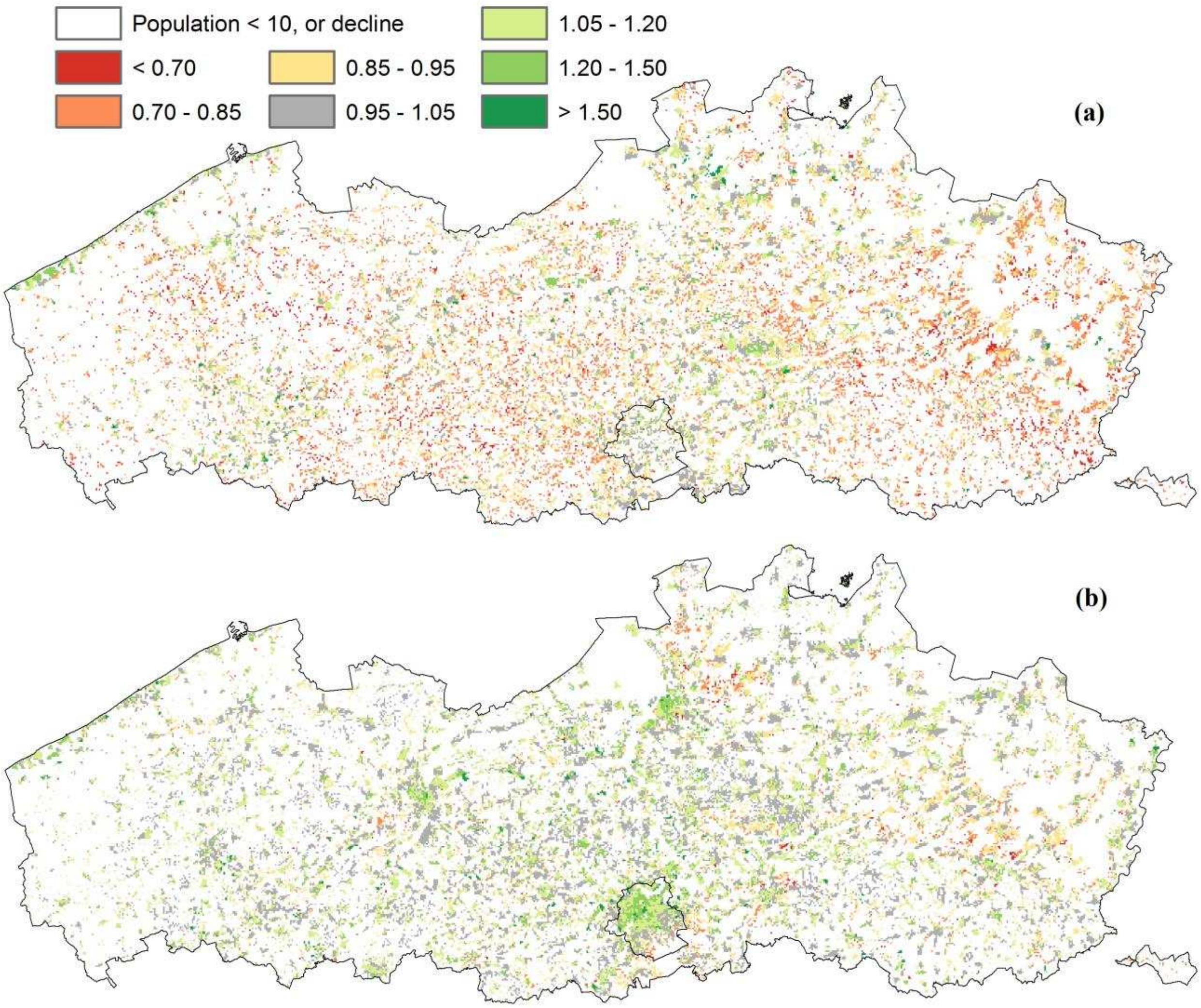

Figure 5. Average densification index values per municipality for the period 2001 – 2013. The Flemish provincial capitals are indicated: Bruges (Bg), Ghent (G), Antwerp (A), Leuven (L) and Hasselt (H).

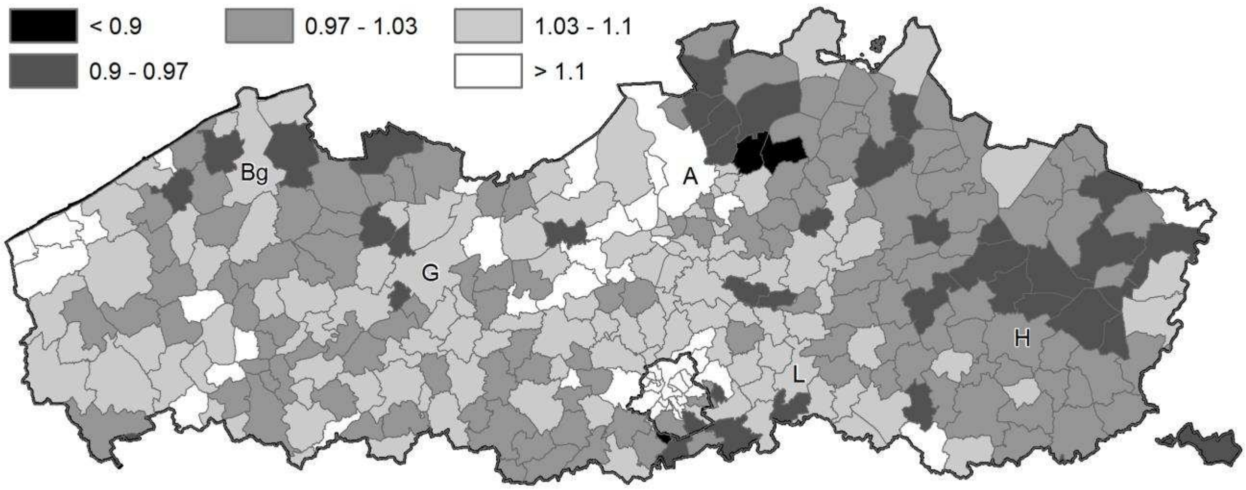

Figure 6. Standard deviation of the estimated number of inhabitants in a Monte Carlo analysis at 300 m resolution for 1986.