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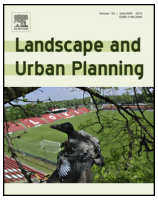

Research paper

High resolution modelling and forecasting of soil sealing density at the regional scale

Sven Vanderhaegen*, Koen De Munter, Frank Canters

Cartography and GIS Research Group, Vrije Universiteit Brussel, Brussels, Belgium

HIGHLIGHTS

- Sealed surfaces are mapped at sub-pixel level using a multi-sensor approach.
- The spatial distribution of sealed surfaces is described in relation to neighbourhood characteristics.
- Regression tree models yield best results in terms of overall estimation accuracy and a favourable error distribution.
- In residential/mixed areas, a sealed surface cover increase of 23.6% and 44.6% is forecasted by 2030 and 2050, respectively.

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ABSTRACT

The on-going growth of urban areas results in increased sealed surface cover, affecting the environment through fragmentation of the landscape, increased surface runoff and obstruction of water infiltration. Within Flanders (Belgium), which is characterized by a highly sprawled urban network and a sealed surface density much higher than in many other European metropolitan regions, there is a strong need for more accurate high-resolution forecasting of soil sealing densities. This study attempts to meet this need by developing a spatial explanatory model for soil sealing density that is applicable at the regional scale and that can be applied in combination with the Flanders cellular automata land-use change model for evaluating the impact of future land-use scenarios on soil sealing. In the modelling, neighbourhood characteristics such as land-use composition and positioning with respect to the urban network and its major transport axes are considered as attraction/repulsion factors for soil sealing. Global multiple regression and regression tree models are compared with a simple average model. The regression models yield clear improvements in overall estimation accuracy and a favourable distribution of the remaining error. Applying a two-rule partitioning model on a future land-use map, produced by the Flanders land-use change model, shows an increase of 23.6% and 44.6% of sealed surface cover within residential/mixed areas in the study area by 2030 and 2050, respectively.

1. Introduction

Approximately 80% of the Western European population currently lives in urban areas, a proportion that is expected to rise up to 85% by 2035, and even up to 90% or more within some countries (United Nations, 2011). The increase of urban population may manifest itself spatially in two ways: increasing population within – and hence a densification – of the existing urban fabric, and urban expansion. The latter goes (very often) hand in hand with highly fragmented conversion of (mainly) agricultural land into developed land in the urban fringe areas, a process commonly referred to as urban sprawl. An increasing discrepancy between cities' spatial growth and population increase, enforced by low density housing patterns, has led to a decrease of compactness of European urban areas (EEA, 2006; Kasanko et al., 2006). Monitoring different urbanization phases (urbanization, suburbanization, disurbanization and reurbanization) of functional urban regions throughout the second half of the previous century shows different patterns depending on the region one focuses on. Notwithstanding a noticeable shift in time between distinct regions, in most European urban areas a crossover point between declining urbanization and increasing suburbanization is observed (Antrop, 2004). Within Europe, the highest increases of artificial surfaces are observed in the Mediterranean Region (Spain, most of Portugal, Cyprus and some regions in Italy), Ireland, most of the northern regions in The Netherlands

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* Corresponding author. +32 26293783.
E-mail addresses: svdhaege@vub.ac.be (S. Vanderhaegen), kdemunte@vub.ac.be (K. De Munter), fcanters@vub.ac.be (F. Canters).

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and some regions in France, Austria, Estonia and Poland (Prokop, Jobstmann, & Schönbauer, 2011). Although Belgium, together with the Czech Republic, Germany, Luxembourg, Poland and Slovakia, shows a strong decrease in annual land-use take between 2000 and 2006 in comparison to the previous decade (from 2.2 to 0.4 m^2 per inhabitant per year), it is, next to Luxembourg, the only country in this list which expects a strong population growth in the next decades (Eurostat, 2008), which most likely will consolidate or even increase the current land-use take rate.

Future projections produced with the 'RuimteModel Vlaanderen', a cellular automata land-use change model developed by the Flemish Institute for Technological Research (VITO), show a strong conversion of non-urban to urban land in the next decades. The RuimteModel Vlaanderen relies on forecasts of population and activity in different economic sectors at the regional scale, and on the specification of policy scenarios impacting the spatial organization of open and built-up spaces. At a sub-regional scale, assumed trends in population and economic activity, as well as policy-related constraints are translated into a need for space for various land uses, e.g. residential, commercial, industrial or natural space. Subsequently, this need for space is allocated at the local level, i.e. 1 ha cells, based on dynamic modelling of the transition potential, which expresses the attractiveness of a cell to change from its current state into one of the other land uses (Engelen et al., 2011). Following a Business-As-Usual scenario, extrapolating currently observed trends towards the future, i.e. a decreasing density of residential and economic land use and an increasing importance of the tertiary and public sector (Engelen et al., 2011), a mean annual conversion of 3382 ha of agricultural land to built-up area is predicted till 2030 within the whole of Flanders, of which three quarters is transformed into residential and mixed use areas. Verbeek, Leinfelder, Pisman, and Allaert (2010) identify two distinct types of urban development outside the existing urban centres in Flanders: high density ribbon development, which mainly occurs in the central part of Flanders, and a highly scattered development of built-up area, which is typically present in the province of West-Flanders and in the Campine region east of Antwerp. According to Van Steertegem (2009) residential and commercial land use in the vicinity of major roads (450 m) is expected to increase up to 34% by 2030.

Apart from the negative impacts of urban sprawl on the environment (the consumption of natural resources, a less efficient use of resources, increased pollution, fragmentation and reduction of habitat space), the physical process of soil sealing, i.e. the permanent covering of the soil surface with impermeable material, is detrimental to the soil's environmental functions (e.g. safeguarding soil biodiversity and functioning as carbon sink) and affects the water balance (EEA, 2006; Scalenghe & Marsan, 2009). Soil sealing increases surface runoff and leads to a higher discharge of pollutants, accumulating over paved surfaces, into receiving water bodies, both during and immediately following storm events. It also obstructs water infiltration and recharge of groundwater bodies, and may thus contribute to groundwater drought (Dougherty, Dymond, Goetz, Jantz, & Goulet, 2004; Van Lanen & Peters, 2000; Verbeiren et al., 2013).

The conversion of natural land covers into sealed surfaces in Flanders has led to increased flooding and contributes to the process of lowering of groundwater tables. Studying these on-going processes and their impact on the environment, especially when local impacts are being assessed, requires detailed spatial information on soil sealing (Dams et al., 2013; Poelmans, Van Rompaey, & Batelaan, 2010). Previous work was done to produce a full coverage one kilometre resolution soil sealing map for Flanders, based on the presence of built-up structures as delineated on topographical maps (De Meyer, Tirry, Gulinck, & Van Orshoven, 2011). This study revealed an overall sealed surface density for Flanders of 13.5%, which is far above the average for the whole of Europe (1.8%), nearly doubling the Belgian average (7.4%), and – within Europe – only approached by Malta (13.3%) (EEA, 2010). At a regional level, similar sealed surface densities are observed only in the Randstad (The Netherlands) and the Ruhr area (Germany) (European Commission, 2012). High-resolution remote sensing data may be a useful data source for accurate and spatially more detailed mapping of sealed surface cover (De Roeck, Van de Voorde, & Canters, 2009; Hu & Weng, 2011; Lu & Weng, 2009; Van de Voorde et al., 2004; Zhou & Wang, 2008). Large-scale applications of this approach, however, may be hampered by financial constraints or by the amount of effort that is required. Multi-sensor approaches, combining medium resolution remote sensing data like Landsat or SPOT imagery with detailed high-resolution maps of sealed surface cover for a small, but representative part of the targeted area, offers the possibility to build models for full coverage estimation of the proportion of soil sealing at sub-pixel level with relatively high accuracy (Van de Voorde, De Roeck, & Canters, 2009; Yang, Huang, Homer, Wylie, & Coan, 2003; Yang & Liu, 2005). This approach will also be used in the present study to obtain a detailed map of soil sealing density within the study area.

In order to assess future impacts of land-use changes on e.g. the water balance (Verbeiren et al., 2013), it is essential to be able to forecast future changes in sealed surface cover related to processes of densification and expansion of urban areas. The RuimteModel Vlaanderen provides the possibility to assess the spatial impact of different policy scenarios by means of a large set of land-use based spatial indicators. Examples of spatial indices related to urban growth are the density and the cluster size of urbanized areas. However, the available indicators do not provide information on the physical characteristics of urbanized spaces, i.e. soil sealing density, and how these change over time. Subsequently, the research presented in this paper aims to develop an explanatory model to quantify the relationship between soil sealing density and land-use characteristics, which can be used for high-resolution forecasting of sealed surface cover in residential/mixed areas. As the growth of industrial areas in Flanders can be considered negligible (21 ha/year) (Gobin et al., 2009), one may assume that the future increase of sealed surface cover will mainly be caused by the growth of these residential/mixed areas. The model, which will describe the physical characteristics of the urbanized landscape in the form of soil sealing density, aims to complement and refine the (categorical) land-use related output delivered by the RuimteModel Vlaanderen. While much work documented in the literature focuses on sealed surface mapping, so far limited research has been conducted on explaining and predicting sealed surface cover distribution. Stankowski (1972) examined the relationship between impervious surface cover and population density within distinct land-use zones in New Jersey, proposing it as a method to quantify past, present and future urban development in hydrological models and forecasts. Reilly, Maggio, and Karp (2004) proposed the use of a stepwise regression model to relate soil sealing proportions in the northern half of New Jersey to a number of neighbourhood and land-use descriptors, demonstrating a strong correlation with employment statistics and building unit density. A recent study of Salvati (2013) emphasizes the relation between soil sealing characteristics, such as density and composition of sealed surfaces, and the distance towards the city centre for the Athens urban region. However, in these studies relationships are examined at the level of municipalities, which is a far lower scale level than required in e.g. hydrological modelling. Our work will focus on high-resolution prediction of sealed surface cover density, compatible with the 1 ha resolution of the Flanders' land-use change model. The hypothesis in our research is that variations in sealed surface density for residential/mixed areas can be explained by spatial context. For example, one may expect that high fractions of sealed