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Dimensioning urbanization – An advanced procedure for characterizing human settlement properties and patterns using spatial network analysis

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ABSTRACT

The ongoing global phenomenon of people migrating to cities is referred to as urbanization and primarily manifests itself in the continuous and often rapid spatial expansion of urban agglomerations. Nevertheless, the dimension and structuring behind this process can be considered as a spatial continuum ranging from rural to urban settlements. Accordingly, gathering a detailed global knowledge about the size, form (e.g., compact or spread) and spatial distribution (e.g., dispersed or nucleated) of different types of settlements represents a major issue to better understand urbanization and develop effective mitigation, adaptation and management strategies. In such context, this paper introduces a novel procedure specifically designed to characterize settlement properties and patterns, which can be applied at high spatial resolution (hence being capable of accounting even for single villages and dwellings) from the local up to continental or global scale using binary maps (i.e., figure-ground diagrams describing the spatial distribution of built-up and non-built-up areas) derived from Earth observation (EO) products. Starting from a binary mask depicting built-up and non-built-up areas over a given study region, the proposed method first delineates settlement objects. Next, a spatial network is created where the nodes correspond to the centroids of the extracted objects and the edges connect neighboring objects lying within a prefixed Euclidean distance from each other. Suitable attributes describing the geometrical properties of the associated objects are then computed for all the nodes and specific weights of interest are assigned to the edges of the network. Finally, indexes modeling the relationships between different nodes are calculated to properly characterize the relevance of different settlements within the spatial network. Several experimental results obtained on the basis of figure-ground diagrams derived from existing EO-based geo-information layers from local to continental level assess the capabilities of the presented approach and demonstrate its potential to provide key information to quantitatively and qualitatively characterize settlement properties and patterns in any spatial detail (depending on the spatial resolution of the input data) and at arbitrary spatial scales.

Introduction

The rapid global urbanization with its manifold environmental, economic and social impacts poses one of the major challenges to the sustainable development of the human habitat and therewith to humankind in general. To date, the increasing amount of people living in or migrating to cities results in a steady spatial expansion of urban agglomerations. As a consequence, more than half of the world's population currently consists of urban dwellers and this proportion is predicted to increase to more than two-thirds by the year 2030 with peaks in Africa and Asia (UN, 1996). However, the phenomenon is not solely limited to the sprawl of cities and towns, but also includes the spreading emergence and expansion of rural settlements such as villages and hamlets. Accordingly, urbanization ultimately manifests itself as a subtle transformation from natural and semi-natural environments to increasingly urbanized landscapes. Hence, the spatial dimension and structuring behind urbanization can be considered as a continuum from rural to urban settlements (Rain, 2007; Simon, 2008).

Since settlements – and urban areas in particular – represent the centers of human activity, the environmental, economic, political, societal and cultural impacts and effects of urbanization are

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far-reaching. On the one hand, there are negative aspects such as the loss of natural habitats, biodiversity and fertile soils, climate impacts, waste, pollution, crime, social conflicts or transportation and traffic problems. On the other hand, urbanization is associated with positive developments including protection, employment, rising living standards, prosperity, societal values, well-being, trade or education. The benefits and challenges of urbanization are comprehensively discussed in Daily and Ehrlich (1992), Johnson (2001), Cieslewicz (2002), Crane and Chatman (2003), Dye (2008), and Seto, Fragkias, Güneralp, Reilly, and Anel (2011).

Seto (2009) stresses that profound knowledge of the status and development of settlements is fundamental to address pressing aspects of urbanization (e.g., impacts on and of urban form and growth patterns, the use of resources, infrastructure and transport needs, ecosystems and biodiversity, human health, food security or socioeconomic development). Potere and Schneider (2007), Batty (2008) and Potere, Schneider, Angel, and Civco (2009) emphasize that large-scale regional to global assessments of settlement patterns and their spatiotemporal development are still rare. Therefore, there is still a high demand of spatially detailed,[1] accurate and up-to-date geo-information on the settlement forms, patterns and their transformations.

To present no consensus or generally agreed perception concerning the appropriate theoretical, conceptual and methodological specification of the complex spatial and physical manifestation of urbanization has yet been reached. Nevertheless, almost all previous works presented in the literature somehow relate to the form (e.g., compact or spread) and spatial pattern (e.g., nucleated or dispersed) of human settlements as key features when addressing this phenomenon and analyzing mitigation, adaptation and management strategies (Batten, 1995; Breheny, 1992; Brueckner, 2000; De Roo & Miller, 2000; Dieleman & Wegener, 2004; Florida, Gulden, & Mellander, 2008; Johnson, 2001; Kloosterman & Musterd, 2001; Lee, 2007; Pacione, 2009). In this framework, most of the practical and application-oriented studies are, however, carried out only at regional scale in a specific cultural and/or geographical context, most frequently North America, Europe or Asia (Beatley, 2000; Conzen, 2001; Deng, Huang, Rozelle, & Uchida, 2010; Ewing, Pendall, & Chen, 2002; Fishman, 1990; Van Houtum & Lagendijk, 2001). On the one side, this is due to the still existing lack of reliable, spatially detailed, and up-to-date information about the location and extent of human settlements at continental and global scale, which currently hinders a comprehensive study of key large-scale urbanization phenomena and forms (e.g., city regions, mega-cities, mega-regions, urban corridors or networks and systems of settlements). Instead, the actual analyses of continental and global urbanization basically rely on demographic data such as those collected by the UN Population Division (UN, 2013), amongst others reflecting the status of the rural and urban population. However, such statistical figures are often outdated or exhibit a spatial resolution that is not sufficient to properly characterize small-scale settlement patterns and related population distributions typical for rural areas (Linard, Gilbert, Snow, Noor, & Tatem, 2012). On the other side, so far none of the methods proposed in the literature allows an effective and concurrently spatially detailed characterization of the degree of urbanization at different spatial scales (which then prevents standardized quantitative and qualitative comparison studies).

One of the most promising approaches to overcome the lack of appropriate geo-information on the spatial structure and spatiotemporal development of human settlements is the analysis of Earth observation (EO) imagery (Esch et al., 2010). A comprehensive overview of the currently available EO-based and EO-supported global geo-information layers on human settlements is provided by Potere et al. (2009) and Gamba and Herold (2009). Actually, the vast majority of these data sets are generated from medium resolution (MR) optical EO data, as for instance the largely-established MODIS 500 (Schneider, Friedl, & Potere, 2010) and GlobCover 2009 (ESA, 2013) land-cover maps with a spatial resolution of ~500 m and ~300 m, respectively. Nevertheless, their capability to accurately detect and delineate small and scattered villages and towns is quite limited. Therefore, recent initiatives have started with the aim of providing more accurate human settlements layers based on high resolution (HR) EO data. In this context, NASA (2012) released in 2013 a new global nighttime light product derived from imagery of the Visible Infrared Imaging Radiometer Suite (VIIRS) on board of the Suomi NPP satellite. Pesaresi, Ehrlich, Caravaggi, Kauffmann, and Louvrier (2011) presented a procedure for an automatic extraction of built-up areas by analyzing HR optical and/or radar data, whereas Miyazaki, Shao, Iwao, and Shibasaki (2013) proposed a method based on the integrated analysis of ASTER satellite images and GIS data to produce a new global HR settlement mask. By means of Envisat-ASAR radar imagery, Gamba and Lisini (2012) derived a built-up area layer that aims at improving the GlobCover 2009 urban class. In this framework, Esch et al. (2012, 2013) presented an initiative based on a novel methodology which aims at producing a global map of built-up areas at the unique spatial resolution of 12 m, namely the Global Urban Footprint (GUF). Specifically, the GUF is derived from very high resolution (VHR) data acquired by the TerraSAR-X and TanDEM-X German satellites between 2011 and 2013 and is currently under production at the Earth Observation Center (EOC) of the German Aerospace Center (DLR). The full-resolution product will only be available open and free for scientific uses, whereas for non-profit users a public domain version with a downscaled spatial resolution of ~3 arcsec (i.e., ~50–75 m) is planned.

Recently, some approaches have been presented to characterize the spatial pattern and spatiotemporal dynamics of urbanization from EO-based built-up area layers (Herold, Couclelis, & Clarke, 2005; Ji, Ma, Twibell, & Underhill, 2006; Schneider & Woodcok, 2008; Seto & Fragkias, 2005; Taubenböck et al., 2012, 2014). In particular, most of them make use of spatial metrics derived from information theory and fractal geometry (e.g., the total percentage of urban area, the density of urban area patches, the total length and density of the edges of urban area patches, etc.). However, although spatial metrics are an effective means to quantitatively describe the spatial structure and fragmentation of landscapes, they exhibit limitations with respect to the evaluation of the relevance and relations (e.g., in terms of betweenness, closeness, etc.) within a hierarchical system or network of objects or patches (e.g., settlements) with varying granularity and spatial extent (Saura, 2004; Urban, 2005; Wu, 2004).

Here, spatial network analysis shows a great potential. In particular, by representing different settlements as nodes of a spatial network[2] and properly establishing edges between them, graph theory allows to characterize local relationships and, hence, to quantitatively and qualitatively assess their significance (Barnsley & Barr, 1997; Barthelemy, 2010; Freeman, 1979; Newman, 2010). Nevertheless, to our knowledge such an approach has never been documented before in the literature for modeling settlement patterns

[1] Please note that hereinafter we use the term *spatially detailed* for referring to the capability of detecting and characterizing both, large urban settlements (e.g., cities and towns) as well as the small-scale rural structures (e.g., villages, dwellings, hamlets).

[2] Spatial networks are networks for which the nodes are located in a spaced equipped with a metric. For most practical applications, the space is the two-dimensional space and the metric is the usual Euclidean distance (Barthelemy, 2010).