Habitat International 59 (2017) 32–43

Contents lists available at ScienceDirect

Habitat International

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

Measuring urban agglomeration using a city-scale dasymetric population map: A study in the Pearl River Delta, China

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ARTICLE INFO

Article history:
Received 15 July 2016
Received in revised form
23 September 2016
Accepted 11 November 2016

Keywords:
Dasymetric population map
City scale
Megacities
Limiting variable algorithm
Urban agglomeration
Connectivity metrics
Pearl River Delta

ABSTRACT

The rates of urbanization and increase in urban sprawl that have occurred in China over the past thirty years have been unprecedented. This article presents a new city-scale dasymetric modelling approach that incorporates historical census data for 28 cities in the Pearl River Delta area of southern China. It combines Landsat imagery (from 2000, 2005, 2010, and 2015) with a 'limiting variable' estimation algorithm to generate a gridded estimate of population density. These gridded population patches are organized as a city-network to reveal the influence of urban agglomeration on population spreading processes. We then combine population patches and graph-based connectivity metrics to describe the spatial-temporal evolution of each city within the urban agglomeration. Our population disaggregation results yield accuracy improvements of 40%–60% over three traditional population disaggregation methods, to reflect the population distribution characteristics more explicitly and in greater detail. The probability of connectivity metrics from dasymetric population maps in Pearl River Delta (1) outline the role of urban agglomeration in population spread, (2) simulate the evolution of 'polycentric' urban agglomeration, and (3) outline the individual components of the polycentric megaregion. Our outlined approach is a transferable and an improved means of producing city-scale dasymetric population maps. Our case study provides practical guidance on wide applications of the medium resolution remote sensing data in delineating, measuring, and quantifying the evolution of urban agglomeration across different jurisdictional boundaries and time periods.

1. Introduction

Urbanization has become a worldwide phenomenon over recent decades (Taubenböck, Wegmann, Roth, Mehl, and Dech, 2009). Economic activities and services, transportation development, and traffic flow all have profound implications for international networks of cities. Cities are often no longer isolated but increasingly concentrated and inextricably linked together in the evolutionary term-'megaregion', sharing infrastructure systems, environmental systems, economic linkages, land use patterns and culture (Robinson, 2006; Ross & Woo, 2011). This phenomenon is known as urban agglomeration (Yue, Zhang, & Liu, 2016; Zhou, Xu, Wang, & Lin, 2015). Urban agglomeration is generally characterized by the size of the territory associated with continuity between separate urbanized areas, contiguous economic and social relationships, and a population concentration (He et al., 2016; Lang, Chen, & Li, 2016; Listengurt, 1975). Nevertheless, urban agglomeration remains a diffuse and elusive concept and there is no general agreement on what agglomeration means, how it can be recognized, or how to delineate the spatially contiguous regions (Frankhauser, 1998; Glaeser, 2008).

Commonly used approaches to delineating urban agglomeration are mainly based on subjective perceptions of the growth rates for different forms of land use, on socio-economic aspects of specific areas (Poyil and Misra, 2015; Salvati, 2014), on quantifications of urban landscape configurations and estimates of the structure characteristic of each urban form through spatial metrics (Taubenböck and Wiesner, 2015), or on accessibility as defined by a variety of transportation models (Kim and Han, 2016). Studies of urban agglomeration also generally take into account population densities. Studying population distributions has been shown to be useful for urban demographic and geographic investigations, urban planning, and environmental protection, as well as for other applications (Brennan, 1999). Researchers have studied relationships

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http://dx.doi.org/10.1016/j.habitatint.2016.11.007

between population distribution characteristics and the evolution of urban agglomerations (Schleicher, Biedermann, and Kleyer, 2011; Urban, Minor, Treml, and Schick, 2009; Plowright et al., 2011; Schumaker, 1996). However, the current understanding of the different effects of clustered populations versus dispersed populations is limited. Likewise, we know little about the effects of monocentric habitats versus polycentric habitats on urban agglomeration, as well as how urban agglomeration processes influence population spatial distributions along the gradient of decreasing population density from an urban center to its periphery (Arthur and McNicoll 1975; Wilson et al., 2001).

To overcome this deficiency it may be helpful to use real-world spatial and temporal dasymetric population models to disaggregate population distributions into multi-scale spatial population density patches (Foltête and Giraudoux 2012). These population density patches can provide a spatial framework within which to elucidate and spatially quantify the evolution of urban agglomeration through graph-based connectivity metrics (Foltête and Giraudoux 2012; Saura and Pascual-Hortal 2007). Moreover, a series of graph-based connectivity metrics, like the probability of connectivity metrics (Saura and Pascual-Hortal, 2007), the landscape coincidence probability metric (Pascual-Hortal and Saura, 2006), etc., have led to an increasing interest in considering connectivity for urban planning purpose (Nazara and Hewings 2003). With the advantages of measuring the connectivity, resilience and competition of landscape patches in the network, these well-applied graph-based connectivity metrics can also provide a valuable way of incorporating the spatial structure of spatial population density patches into an urban agglomeration analysis (Vaz, Zhao, and Cusimano, 2016). The challenge is therefore to establish a meaningful and useful spatial dasymetric population model with suitable scale and to add quantitative information that will help to identify the evolution of spatial population patches under the urban agglomeration.

With the development of Remote Sensing (RS) and Geo-informatics Science (GIS), the acquisition ability of population dasymetric maps derived by the integration of multi-disciplinary data, namely global remote sensing, human settlement and socio-economic has greatly improved (Wu, Qiu, and Wang 2005; Langford and Unwin, 2013). Previously well-cited coarse-scale (1 km–100 m) population maps include, for example, the Gridded Population of the World (GPW) method (Deichmann, Balk, and Yetman, 2001), the Landscan method (Dobson, Bright, Coleman, Durfee, and Worley, 2000), WorldPop (Stevens, Gaughan, Linard, and Tatem, 2005), amongst others. These methods establish a co-relationship between mean population densities and RS/GIS-based population distribution information (including land use types, DEMs, transportation, night-time images, various landmarks, slope) to disaggregate the population from province-scale or national-scale administrative unit into each cell of the (satellite) Geodata (L.Imhoff, Lawrence, Stutzer, & Elvidge, 1997; Zeng, Zhou, Wang, Yan, & Zhao, 2011). They are able to accurately express the inner cities' divergence within each country. However, most of these models are constrained by the coarse resolution of remotes sensing data, making the generation of city-scale (taking the city administrate boundary but not the province/national administrate boundary as the specific areal unit) dasymetric population maps a challenging research topic.

The Limiting Variable (LV) method, therefore, has been proposed by Martin (1996) and Gallego, Batista, Rocha, and Mubareka (2011) to integrate the pycnophylactic method into the population disaggregation. This method starts with a homogeneous population density in each initial zone, which is modified by applying upper limits to the less populated land-cover classes and redistributing the excess population to the more populated classes. This means that the LV method, when combined with reliable census data and finer resolution of satellite imagery, can evaluate the population density at a variety of regional scales (Mennis, 2003; Gallego et al., 2011). Therefore, the LV method makes it become possible to integrate medium-resolution of imageries with the city-scale administrate boundary into disaggregating the population density.

In summary, the sheer magnitude of population growth is an important factor affecting the evolution of urban agglomeration. It has a direct effect on the spatial concentration of urban agglomeration, as well as other causes of environmental stress (Tan et al. 2008). We therefore propose that city-scale dasymetric population maps are one crucial approach suited for the identification and delineation of spatial population characteristics, and for tracing its spatial evolution. For our investigations we chose an area covering the Pearl River Delta (PRD) megaregion in southern China and adopted a combined form of Landsat data (in 2000, 2005, 2010 and 2015) with the LV algorithm to delineate the city-scale dasymetric population maps. Then we integrate the population density patches with a series of graph-based connectivity metrics, to address the following question:

- How can city-scale dasymetric population maps delineate the city-network of the PRD megaregion and the spatial and temporal evolution of its urban agglomeration?

2. Methods

2.1. Case study

The PRD is one of the most densely urbanized regions in the world, and one of the most populous, rapidly commercialized and urbanized economic regions in China (shown in Fig. 1). The average annual precipitation in PRD is over 1500 mm, with an average annual temperature of 23 °C. The humid subtropical climate, fertile alluvial soils, and a water system good for year-round irrigation and transportation in PRD have supported more than 56 million people. According to the World Bank Group (2015), the PRD have become

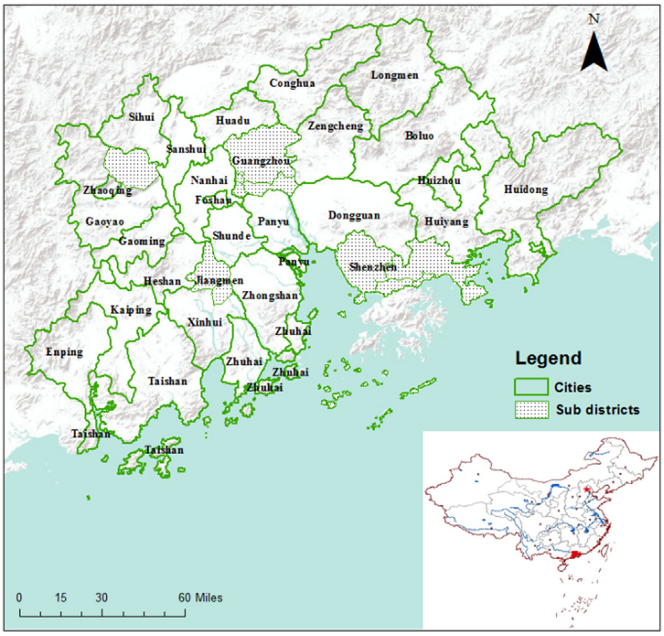

Fig. 1. Study area-the Pearl River Delta megaregion area.