An analysis of the distribution of urban settlements in Africa

Rafael Prieto Curiel[1], Carmen Cabrera-Arnau[*1] and Steven Richard Bishop[†2]

[1]Centre for Advanced Spatial Analysis, University College London, London, United Kingdom
[2]Department of Mathematics, University College London, London, United Kingdom

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Summary

City population size is a crucial measure to understand urban life. Here, we analyse the impact of city population size on the emergence of nearby cities. Based on a road network, we construct the region of influence of African mainland cities. We then use urban scaling models to describe the relationship between city population size and the number of cities or the total population within each region of influence. For small values of the radius of the constructed regions of influence, we observe a sublinear scaling behaviour, but as the radius is increased, this behaviour becomes closer to linear.

KEYWORDS: urban scaling, central places, urbanisation in Africa, road network

1. Introduction

The world is undergoing an urbanisation process which shows no signs of ceasing. By 2021, 56.2% of the world's population lived in urban areas, but this percentage is expected to keep growing up to 68% by 2050. 90% of the projected growth will be concentrated in just a few countries from Asia and Africa, with China, India and Nigeria accounting for 35% of the total growth (Population Division of the UN, Department of Economic and Social Affairs, 2018). The transition to an urban society will result in profound but still poorly understood consequences and will likely spread to the area of influence of the cities.

To understand the nature and extent of urbanisation, it is necessary to investigate the patterns formed by urban settlements, including the relations of the individual settlements within the urban system. Here, we develop a modelling framework to understand some structural aspects of the patterns formed by urban settlements. Given that Africa will be one of the regions most affected by the urbanisation process in the coming decades, the focus of our analysis is on African cities. The study is based on an urban road network that helps determine the region of influence of the cities and entails the application of urban scaling models. We observe a significant scaling behaviour that goes beyond the cities themselves, involving their region of influence.

[*] c.cabrera-arnau@ucl.ac.uk

2. Methods

We begin with an urban road network (Prieto Curiel et al., 2021), where the nodes are the African mainland cities with more than 100,000 inhabitants and the edges of the network were created based on the road infrastructure from OpenStreetMaps. Additional "transport nodes" are added to the network as they help describe possible routes between cities.

Then, we propose the following algorithm to construct the "region of influence" corresponding to the cities in the network. We consider the list of cities forming the network in decreasing order according to their population. The first city is labelled as C_1. All the cities at a road distance smaller than some influence "radius" δ, with $\delta > 0$, are considered to be within the region of influence $R_1(\delta)$ of C_1. From the list, all cities in $R_1(\delta)$ are removed, including city C_1. Then, the largest city remaining in the list is labelled as C_2 and its region of influence $R_2(\delta)$ is constructed likewise. The procedure finishes when the list of cities is empty. As shown in Figure 1, the result gives a number M of regions of influence, which depends on the chosen value of the radius δ, and each of these is identified by its "centre" C_i, with $i=1, \ldots, M$, corresponding to the largest city of that region of influence.

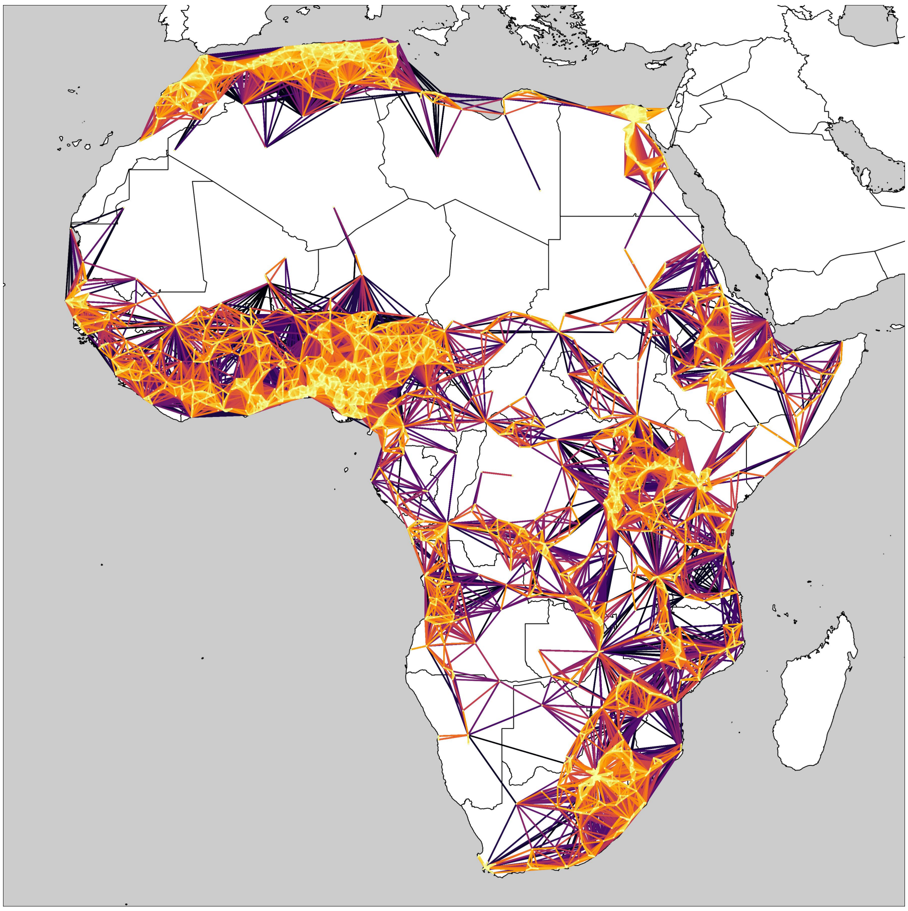

Figure 1 Distinct regions of influence are constructed for different values of δ, each identified using a colour.

For each region of influence, two quantities are measured: the *number of cities* $\kappa_i(\delta) > 0$, corresponding to the number of cities in $R_i(\delta)$ including city i, and the *population of influence* $\phi_i(\delta) \geq 0$, corresponding to the urban population inside region $R_i(\delta)$, but now without considering the population of city C_i. By not counting the population of city C_i, then a large value for $\phi_i(\delta)$ is not due to a large population in C_i directly.

Urban scaling models are then applied to describe the relation between city population size and either $\kappa_i(\delta)$ or $\phi_i(\delta)$. According to the scaling hypothesis, for each region of influence, $\kappa_i(\delta)$ or $\phi_i(\delta)$ are related to the population of the central city C_i in each region of influence, denoted by P_i, through a power law given by

$$\kappa_i(\delta, P_i) = \alpha_\delta P_i^{\beta_\delta}, \tag{1}$$

or

$$\phi_i(\delta, P_i) = a_\delta P_i^{b_\delta}, \tag{1}$$

where the scaling exponents $\beta_\delta > 0$ and $b_\delta > 0$ are, in general, different from 1 and α_δ and a_δ are proportionality constants. By fitting the observed data from the road network of African cities, we can estimate the value of the parameters α_δ, a_δ, β_δ and b_δ for different values of the radius δ. The scaling behaviour will be linear, superlinear or sublinear, depending on whether the value of the scaling exponent β_δ is equal, larger or smaller than one.

Finally, due to the design of the algorithm to construct the regions of influence, regions of influence with larger centres will be more likely to have higher values of $\kappa_i(\delta)$ and of $\phi_i(\delta)$ since they appear early on the list. To detect if the results of applying the urban scaling models are only due to the algorithm, we consider the following random permutation of the nodes in the network: we keep the structure of nodes and edges, but we permute the city size among its nodes, so a large city takes up a random location in the network. We then follow the same algorithm to construct regions of influence and measure the number of cities $\kappa_i(\delta)$ and the population of influence $\phi_i(\delta)$. If the observed scaling behaviour of $\kappa_i(\delta)$ and $\phi_i(\delta)$ are different when the network is permuted, then we can ensure that it is the position of large cities in the network that creates that observed urban scaling.

3. Results

We estimate the parameters α_δ, β_δ in equation (1) and a_δ, b_δ in equation (2) via a Poisson regression for different values of δ. The results are displayed in Figure 2.

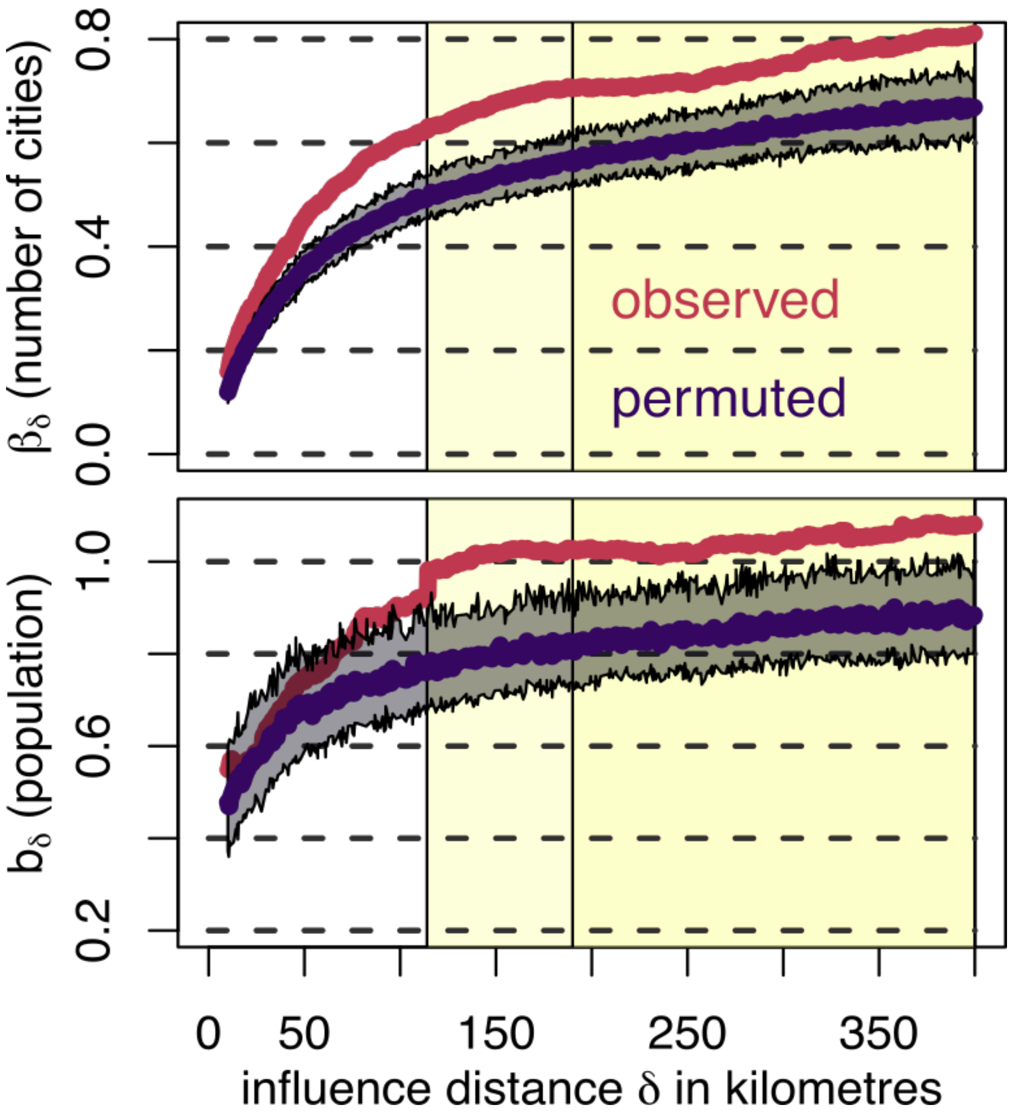

Figure 2 Observed and permuted values of β_δ (top) and b_δ (bottom) for the number of cities and the population in the region of influence of cities. The horizontal axis is the influence distance δ in kilometres. The red lines are the observed values and the purple line and the shaded interval around the permuted results give the range of values obtained from the permuted network. Intervals are obtained for some value of δ by permuting 100 times the population size of cities and removing outliers.

The observed scaling parameters β_δ and b_δ remain above and outside the intervals obtained with a permuted network. Thus, the number of cities within the regions of influence scales with city population size in a significant manner. Therefore, the structure of the network plays a role, and large cities tend to be surrounded by numerous cities. The observed scaling parameter for the total population corresponding to the cities within each region of influence b_δ also remains above the permuted values. However, for small distances, it has values inside the interval of the permuted network, suggesting that cities attract smaller towns rather than big cities.

Our findings reveal some non-trivial patterns in the urban system formed by African cities. For example, we find that cities with larger population size are surrounded by more and larger cities, meaning that large cities tend to cluster, whereas small cities are more likely to be isolated. This has some practical implications given that isolation is one of the main contributors to poverty (Linard et al., 2012) and our results show that some cities, especially the smaller ones, are highly isolated.

There are some issues in our analysis that open questions for future work. In particular, i) our study ignores the cost of crossing international borders, which might effectively lengthen the distances in the road network, ii) even though we assigned each city to a unique region of influence, some urban areas might interact with several cities, perhaps in a hierarchical manner and iii) we considered the same radius of influence δ for all the cities, but other techniques could be considered such as modelling δ as a distance-decay function depending on population size, for example, by setting $\delta(P_i) = \rho {P_i}^{\gamma}$ for some values of ρ and γ.

4. Acknowledgements

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Biographies

Rafael Prieto Curiel is a postdoctoral researcher at the Centre for Advanced Spatial Analysis (CASA), University College London. He works developing mathematical models as part of the project Peak Urban, which aims to aid decision-making on urban futures.

Carmen Cabrera-Arnau is a Research Fellow in Urban Mobility at the Centre for Advanced Spatial Analysis (CASA), University College London. Her work is on mathematical models of socioeconomic data in the context of urbanisation. Specifically, she works in a project called realTRIPS, focused on urban mobility models.

Steven Richard Bishop is a Professor in Nonlinear Dynamics in the Department of Mathematics at University College London. He is an applied mathematician seeking to solve problems of practical interest, while at the same time educating others and allowing them to reach their own potential.