Journal of Interdisciplinary Methodologies and Issues in Science

Identifying European Sustainable Mega-city Regions with Multi-dimensional Network Percolation

Juste RAIMBAULT[1,2,3,*]

[1]UPS CNRS 3611 ISC-PIF, France
[2]CASA, UCL, UK
[3]UMR CNRS 8504 Géographie-cités

*Corresponding author: juste.raimbault@polytechnique.edu

DOI: 10.18713/JIMIS-ddmmyy-v-a
Submitted: Month-in-letters Day Year - Published: Month-in-letters Day Year
Volume: **N** - Year: **YYYY**
Issue: **Title of the interdisciplinary issue**
Editors: *First-name*-1 *Family-name*-1, *First-name*-2 *Family-name*-2, *First-name*-k *Family-name*-k...

Abstract

Territorial structure significantly conditions the sustainability of human settlements. Recent forms of urbanization, in particular integrated mega-city regions, may imply different patterns of economic and transportation flows and thus exhibit various performances regarding different indicators of sustainability. This paper proposes to reconstruct endogenous urban regions from the bottom-up using network percolation, in a multi-dimensional way to take into account both urban form (spatial distribution of population) and urban function (properties of transportation networks). Variable parametrizations allows to consider patterns of optimization for two stylized contradictory sustainability indicators (economic performance and greenhouse gases emissions). This suggests a customizable spatial design of policies to develop sustainable territories.

Keywords

Road network; multilayer percolation; mega-city region

I INTRODUCTION

The structure of road networks both translates its past growth dynamics and has a significant impact on the sustainability of territories it irrigates. Diverse methods to characterize the structure of spatial networks, and more particularly road networks, have been developed in that context.

A method to characterize topologies of these spatial networks is network percolation. Such approaches have been applied to the modeling of urban growth (Makse *et al.*, 1998) and to the analysis of street networks for example to extract endogenous urban regions (Arcaute *et al.*, 2016) or to characterize the spatial morphology of point patterns Huynh *et al.* (2018).

Existing heuristics however generally focus on a single morphological dimension of networks, and leave out the functional properties of urban systems (Burger and Meijers, 2012).

This paper addresses such a gap by introducing a multi-dimensional percolation heuristic.

We percolate the population density layer with a network characteristic layer, that we test among number of edges, number of vertices, cyclomatic number and euclidian efficiency, which capture functional properties especially for the two last.

II METHODS

2.1 Multi-dimensional percolation

Given discrete spatial fields, site percolation is operated between two cells given a threshold parameter for each dimension and a distance threshold. This heuristic is similar to multilayer network percolation Boccaletti *et al.* (2014).

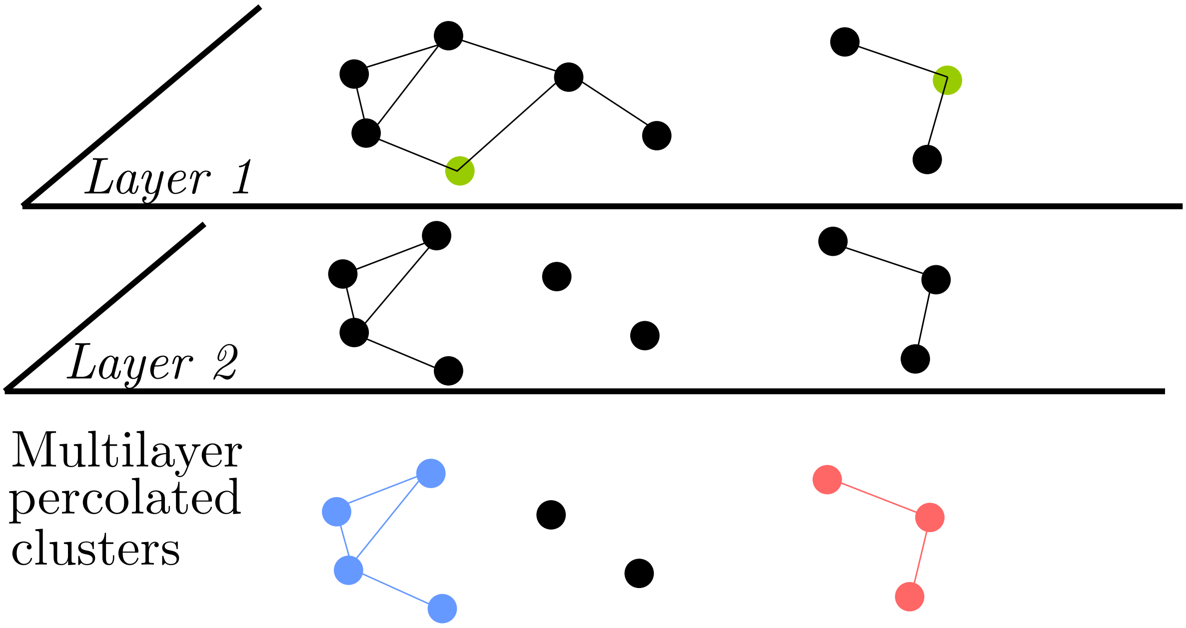

Figure 1: Schematic representation of the multi-dimensional network percolation heuristic.

2.2 Empirical data

We apply the heuristic to urban morphology and road network topology measures in Europe. More precisely, a grid with resolution 50km of population density morphology indicators and road network topology indicators, has been computed on spatial moving windows for all European Union by Raimbault (2018).

2.3 Sustainability indicators

We use this endogenous definition of regional urban systems produced by the percolation algorithm to evaluate their sustainability, in terms of conflicting objectives of economic integration and greenhouse gases emissions. The definition of sustainability, or sustainable development, is by essence multi-dimensional (Viguié and Hallegatte, 2012). Its characterization as quantitative indicators is even more subject to numerous degrees of freedom. We work here with two stylized indicators for two conflicting dimensions, as a proof-of-concept.

The EDGAR database (Janssens-Maenhout *et al.*, 2017) (version 4.3.2) is used for local estimates of greenhouse gases emissions.

Applying a gravity model to each region, we estimate abstract transportation flows within each and extrapolate emissions by coupling with the Edgar emission database (Janssens-Maenhout *et al.*, 2017) and economic activities with a scaling law of population. More precisely, greenhouse gases emissions derived from economic and transportation flows are estimated with the following expression

$$\phi_{ij} = \left(\frac{v_i v_j}{(\sum_k v_k)^2}\right)^{\gamma} \cdot \exp\left(\frac{-d_{ij}}{d_0}\right) \qquad (1)$$

where v_k are either effective local GHG emissions or population. Indeed, the economic activity follows relatively well scaling laws of populations Bettencourt *et al.* (2007), the exponent being dependant on the activity and the definition of areas on which it is estimated (Cottineau *et al.*, 2017).

The sum of all flows within the geographical span of the cluster (that we approximate as the convex Hull envelope of its points), allows us to approximate the cumulated potential emissions and economic activity.

III RESULTS

3.1 Implementation

In practice, the analysis is implemented using R and the igraph package. The network is constructed by superposing the population density layer with the network layer.

The experience plan is a full grid, for parameters r_0, θ_P, θ_N and the network variable considered.

We systematically explore the clusters obtained for 4800 parameter configurations.

3.2 Extracting endogenous mega-city regions

Maps reveal that most configurations resemble the actual distribution of European mega-city regions, which are functionally integrated polycentric urban areas (Hall and Pain, 2006). These are here defined endogenously from the bottom-up.

3.3 Pareto fronts for sustainability

We show therein that different population, network and distance thresholds yield different performances in terms of sustainability, exhibiting a Pareto front. This suggests policies in terms of regional integration to increase the sustainability of mega-city regions.

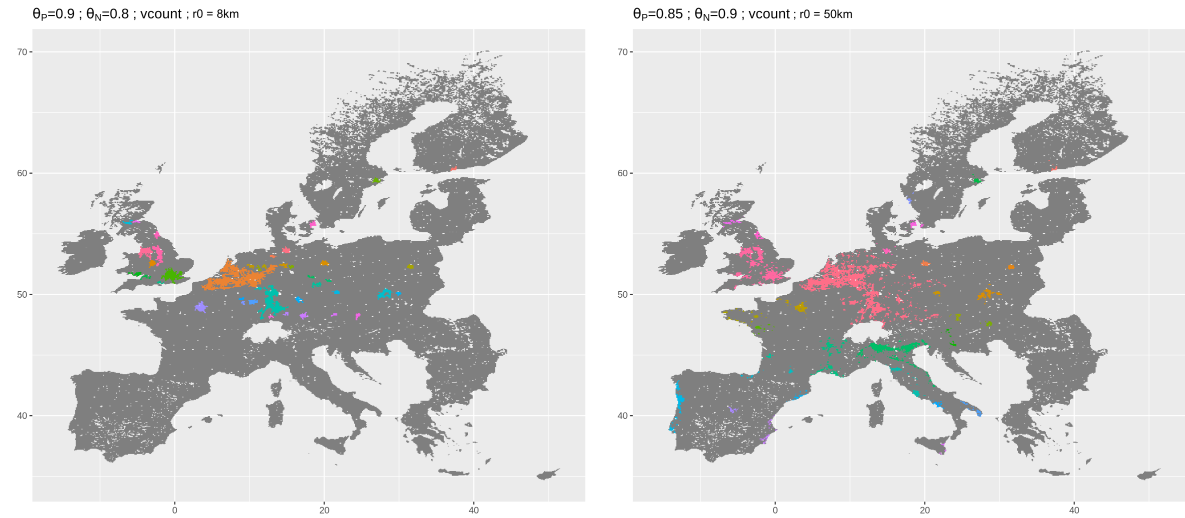

Figure 2: Two examples of obtained clusters for different parameter values.

3.4 Linking urban morphology and sustainability

When considering the aggregated indicators for a parametrization of endogenous city regions, one can relate them to morphological indicators, computed by , that we average on areas. This establishes a link between urban morphology and sustainability. A principal component analysis on considered points yield 96% of variance with two components, and 73% explained by the first component alone. The first component relates to a level of monocentricity ($PC1 = -0.3 \cdot I + 0.54 \cdot \bar{d} + 0.51 \cdot \varepsilon + 0.59 \cdot \alpha$). As shown in Fig. ??, there seems to exist an optimal intermediate level of monocentricity regarding emissions only, except for long-range and low-hierarchy interactions. However, when considering both emissions and economic indicators, urban form then acts as a compromise variable, moving points on Pareto fronts, as shown in Fig. ??. In some case, highly monocentric areas can be a good compromise, whereas the intermediate optimal for emissions may yield highly inefficient areas.

IV DISCUSSION

Further work can consist in the use of calibration heuristics (Reuillon *et al.*, 2013) to find in a more robust way optimal parameter values.

The use of calibration algorithms

Extrapolating transportation flows with a spatially explicit gravity and flow model can allow to compare these with actual transportation flows in the emission database, and yield a possible calibration. These extrapolated parameters could then be used within the economic and emissions potentials.

An other potential development would imply crossing our endogenous definitions of urban regions with socio-economic databases, and compute indicators implied in other dimensions of sustainability, for example related to socio-economic inequalities, spatial distribution of accessibilities, activities with different scaling exponents.

V CONCLUSION

References

Arcaute E., Molinero C., Hatna E., Murcio R., Vargas-Ruiz C., Masucci A. P., Batty M. (2016). Cities and regions in britain through hierarchical percolation. *Royal Society open science 3*(4), 150691.

Bettencourt L. M., Lobo J., Helbing D., Kühnert C., West G. B. (2007). Growth, innovation, scaling, and the pace of life in cities. *Proceedings of the national academy of sciences 104*(17), 7301–7306.

Boccaletti S., Bianconi G., Criado R., Del Genio C. I., Gómez-Gardenes J., Romance M., Sendina-Nadal I., Wang Z., Zanin M. (2014). The structure and dynamics of multilayer networks. *Physics Reports 544*(1), 1–122.

Burger M., Meijers E. (2012). Form follows function? linking morphological and functional polycentricity. *Urban studies 49*(5), 1127–1149.

Cottineau C., Hatna E., Arcaute E., Batty M. (2017). Diverse cities or the systematic paradox of urban scaling laws. *Computers, environment and urban systems 63*, 80–94.

Hall P. G., Pain K. (2006). *The polycentric metropolis: learning from mega-city regions in Europe*. Routledge.

Huynh H. N., Makarov E., Legara E. F., Monterola C., Chew L. Y. (2018). Characterisation and comparison of spatial patterns in urban systems: A case study of us cities. *Journal of computational science 24*, 34–43.

Janssens-Maenhout G., Crippa M., Guizzardi D., Muntean M., Schaaf E., Dentener F., Bergamaschi P., Pagliari V., Olivier J., Peters J., *et al.* (2017). Edgar v4. 3.2 global atlas of the three major greenhouse gas emissions for the period 1970–2012. *Earth Syst. Sci. Data Discuss*.

Makse H. A., Andrade J. S., Batty M., Havlin S., Stanley H. E., *et al.* (1998). Modeling urban growth patterns with correlated percolation. *Physical Review E 58*(6), 7054.

Raimbault J. (2018). An urban morphogenesis model capturing interactions between networks and territories. *arXiv preprint arXiv:1805.05195*.

Reuillon R., Leclaire M., Rey-Coyrehourcq S. (2013). Openmole, a workflow engine specifically tailored for the distributed exploration of simulation models. *Future Generation Computer Systems 29*(8), 1981–1990.

Viguié V., Hallegatte S. (2012). Trade-offs and synergies in urban climate policies. *Nature Climate Change 2*(5), 334.

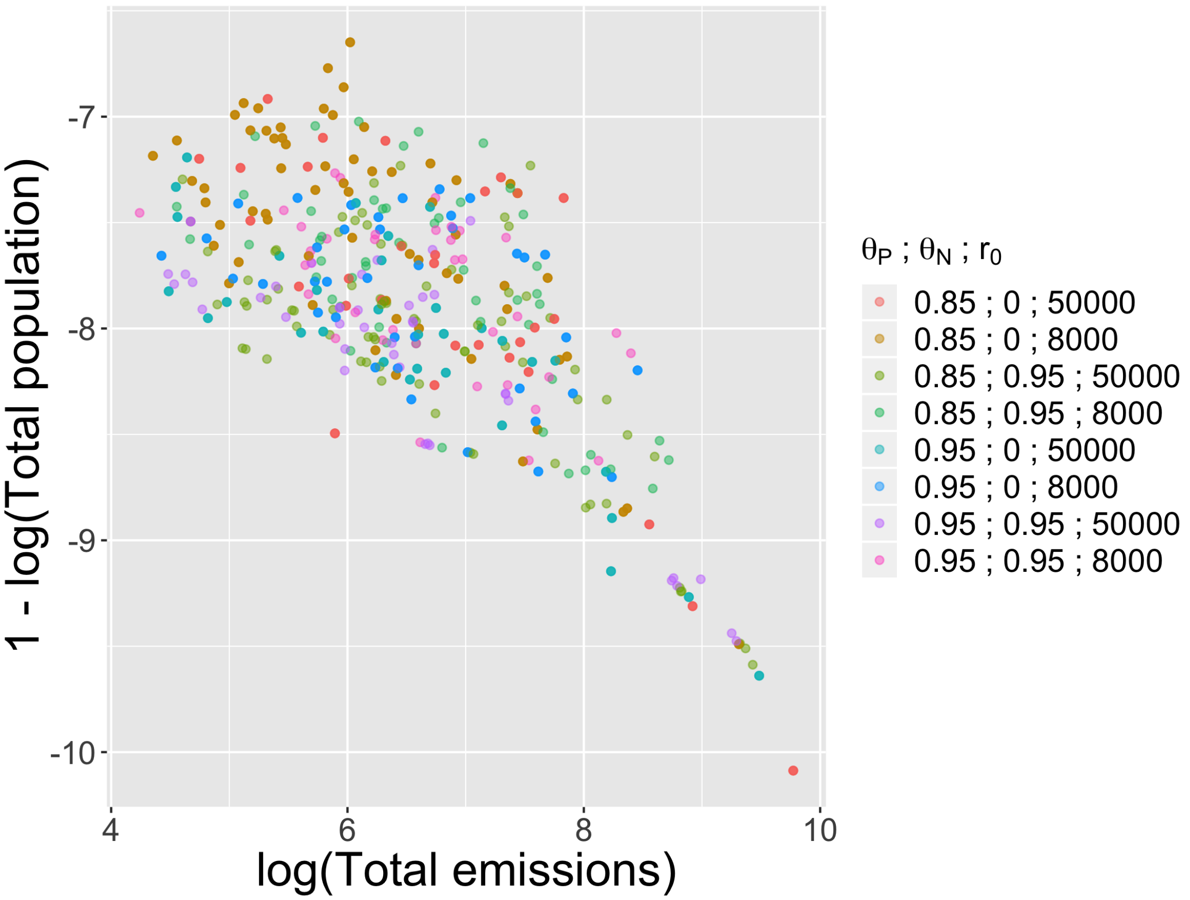

Figure 3: Point clouds of region-level indicators, namely population and emissions, for different parametrizations.

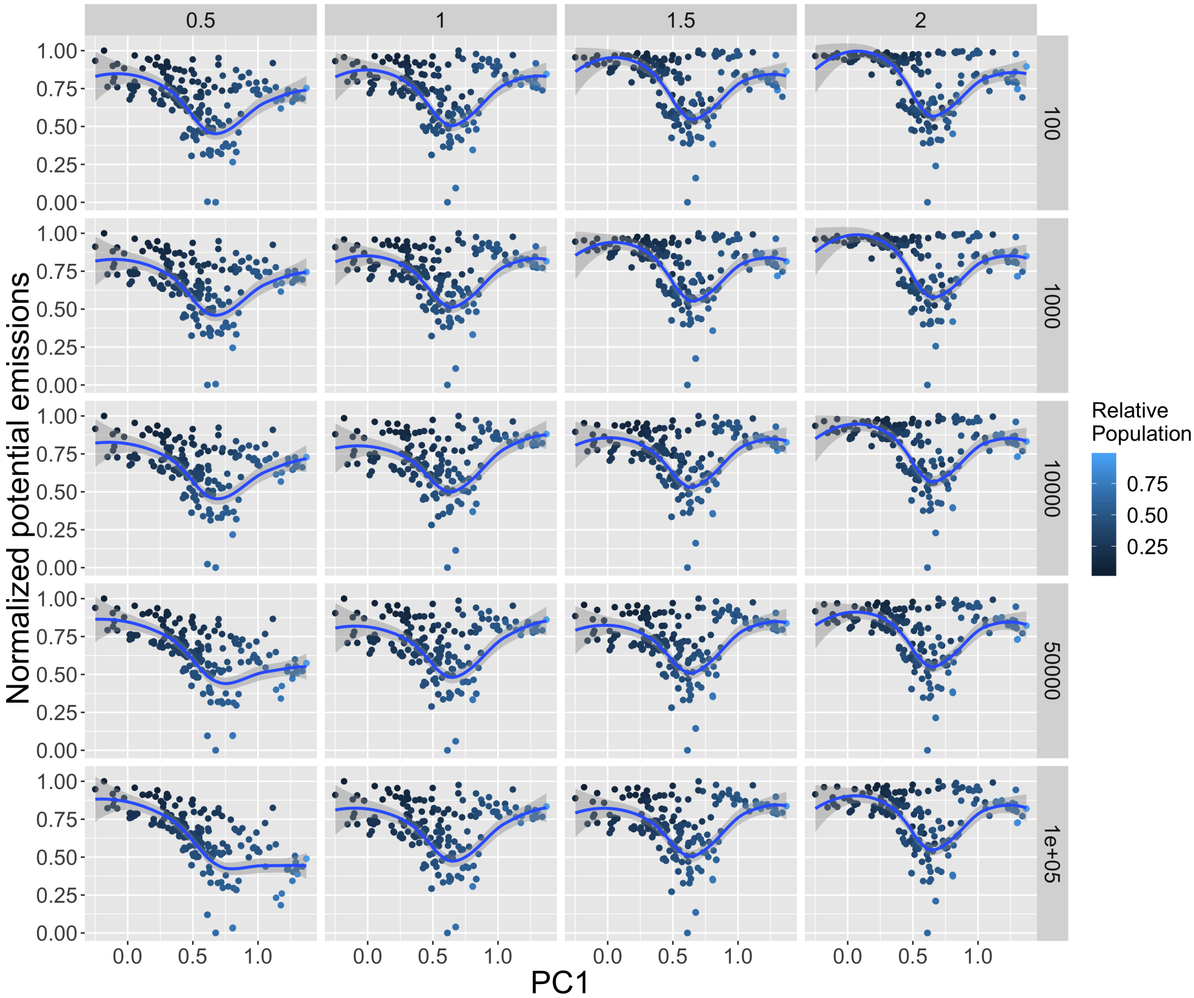

Figure 4: Aggregated values of normalized potential emissions, as a function of the first morphological principal component (PC1), for varying values of parameters d_G and γ_G. As PC1 is mainly linked to monocentricity, there seems to exist an optimal intermediate level of monocentricity for emissions alone.

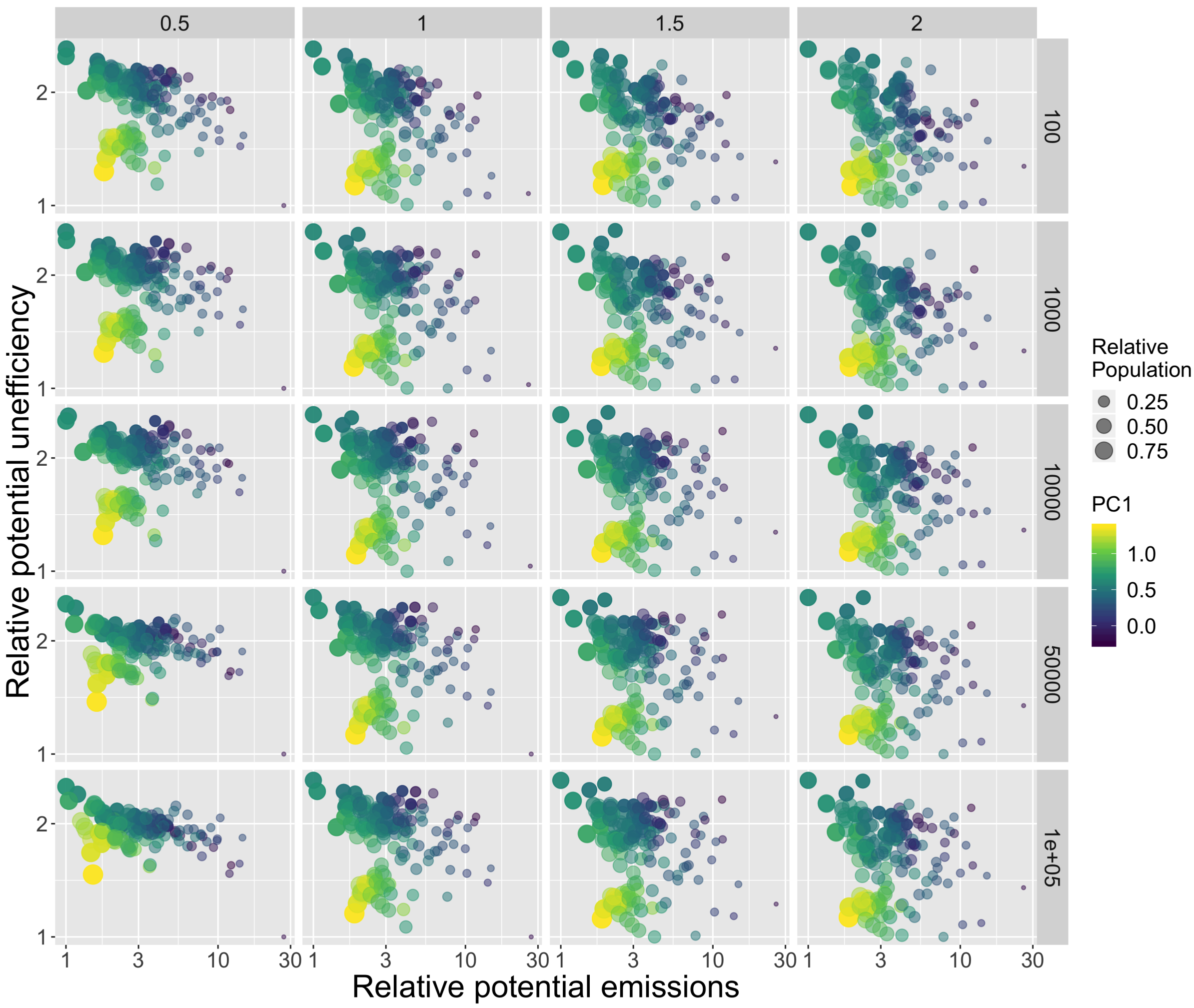

Figure 5: Relative potential emissions against relative potential economic unefficiency (both indicators should be minimized), for varying values of γ_G (columns) and d_G (rows). Color level gives the value of PC1, whereas point size gives the share of total population contained within considered areas.