

Models of urban morphogenesis to link urban form and function

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TQG Debates 2019

3.1: Fractals and Multi-fractals

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Source: Geoportail

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Morphogenesis (*Oxford dictionary*)

- 1 *Biology* : The origin and development of morphological characteristics
- 2 *Geology* : The formation of landforms or other structures.

History of the notion

- Started significantly with embryology around 1930 [Abercrombie, 1977]
- Turing's 1952 paper [Turing, 1952], linked to the development of Cybernetics
- first use in 1871, large peak in usage between 1907-1909, increase until 1990, decrease until today. *Scientific fashion* ?

What is Morphogenesis ? Examples

Sources (in order by column). Ants, Erosion, Game of Life: NetLogo Library; Arbotron [Jun and Hübner, 2005]; Industrial design [Aage et al., 2017]; Swarm chemistry [Sayama, 2001]

Proposition of an interdisciplinary definition

Meta-epistemological framework of imbricated notions:

Self-organization \supseteq Morphogenesis \supseteq Autopoiesis \supseteq Life

Properties:

- Architecture links form and function
- Emergence strength [Bedau, 2002] increases with notion depth, as bifurcations [Thom, 1974]

Definition of Morphogenesis : *Emergence of the form and the function in a strongly coupled manner, producing an emergent architecture [Doursat et al., 2012]*

Which models for Urban Morphogenesis ?

Example: a basic hybrid model based on elementary processes for density and network
[Raimbault et al., 2014]

→ *At the crossroad between Urban Simulation and Artificial Life, few models try to integrate and explain the link between Urban Form and Function*

→ *Importance of parsimonious, stylized models: modeling as a tool to understand processes*

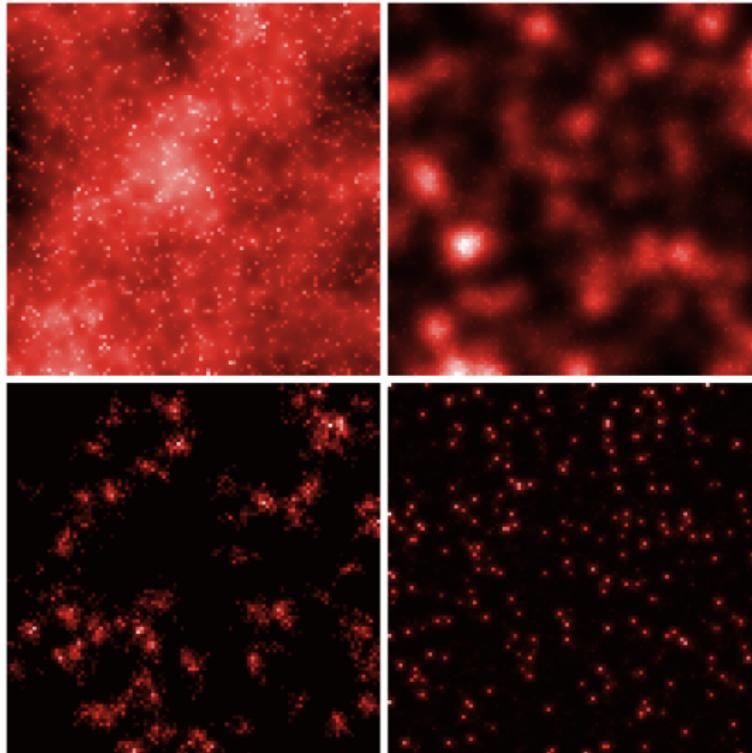
Research Objective : Explore simple models to capture morphogenesis based on abstract representation of urban processes; test their ability to reproduce existing urban systems.

- Crucial role of the interplay between concentration forces and dispersion forces [Fujita and Thisse, 1996] in keeping Urban Systems at the border of chaos
- Potentiality of aggregation mechanisms (such as Simon model) to produce power laws [Dodds et al., 2017]
- Link with Reaction-diffusion approaches in Morphogenesis [Turing, 1952]
- Extension of a DLA-type model introduced by [Batty, 1991], with simple abstract processes of population aggregation and diffusion

Raimbault, J. (2018). Calibration of a density-based model of urban morphogenesis. PloS one, 13(9), e0203516.

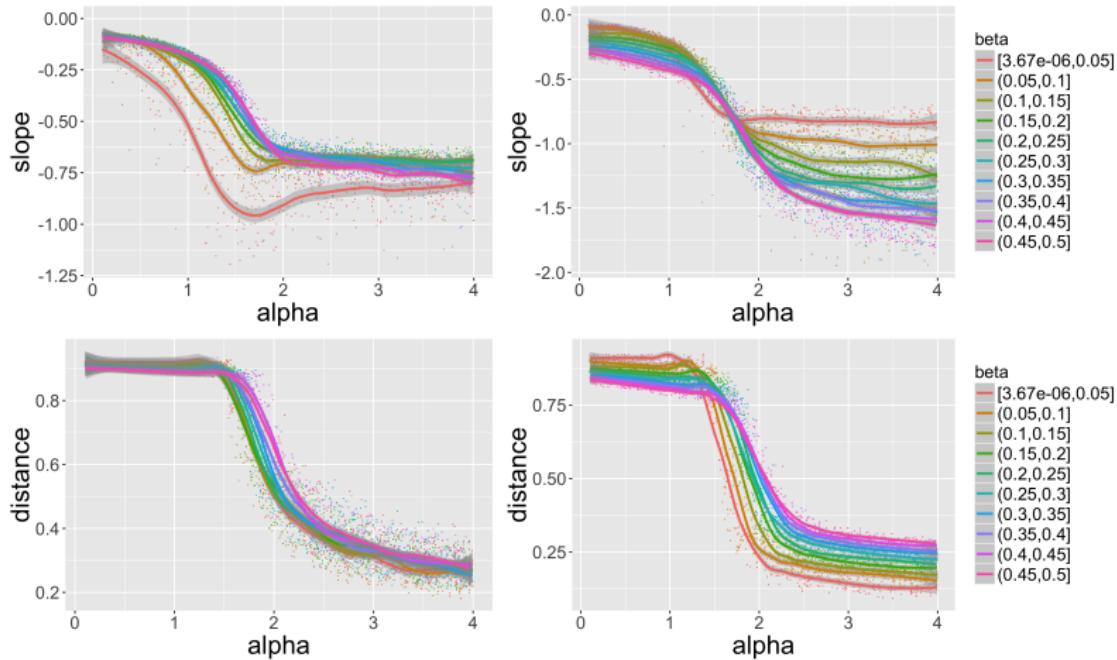
- Grid world with cell populations $(P_i(t))_{1 \leq i \leq N^2}$.
- At each time step:
 - 1 Population growth with exogenous rate N_G , attributed independently to a cell following a preferential attachment of strength α
 - 2 Population is diffused n_d times with strength β
- Stopping criterion: fixed maximal population P_m .
- Output measured by morphological indicators: Moran index, average distance, rank-size hierarchy, entropy.

Generating Population Distributions



Examples of generated territorial shapes

Model behavior



Phase transitions of indicators unveiled by exploration of the parameter space (80000 parameter points, 10 repetitions each)

Path-dependence and frozen accidents

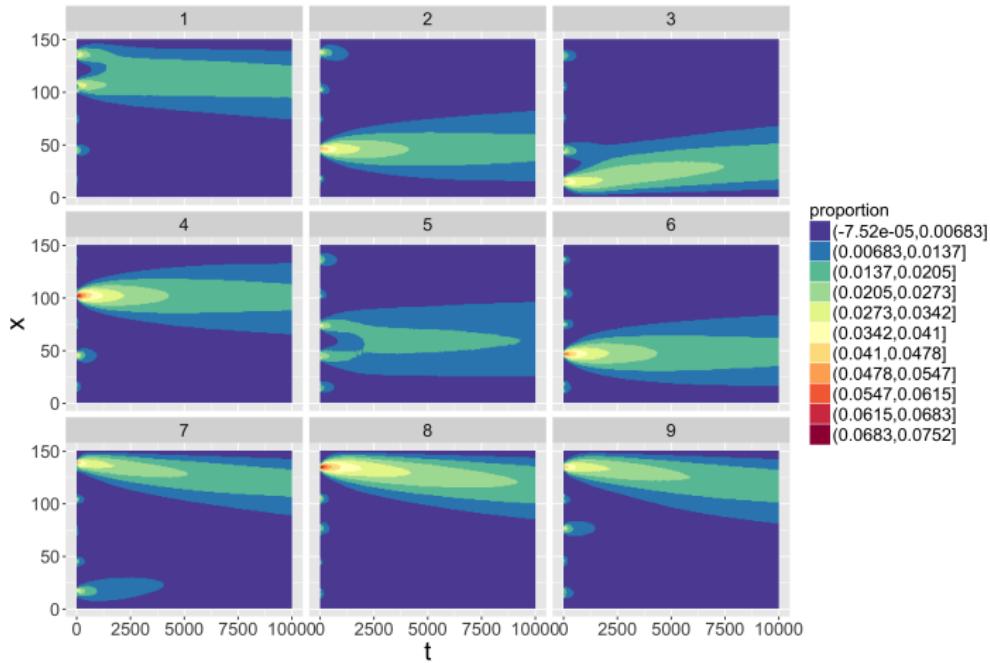
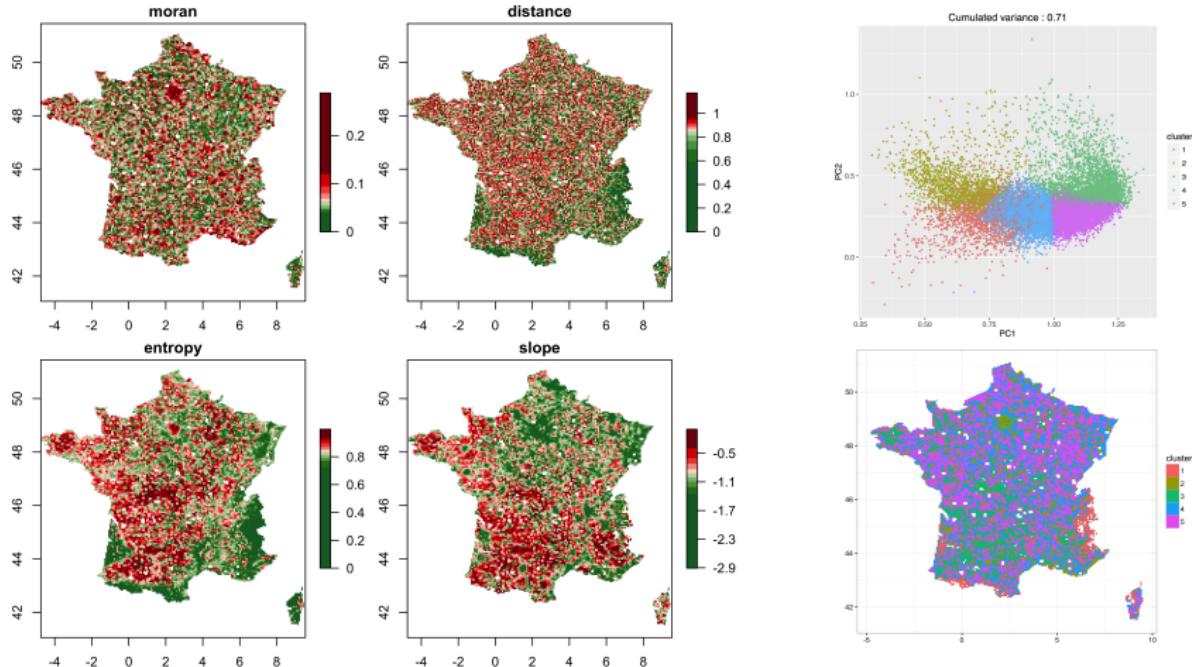


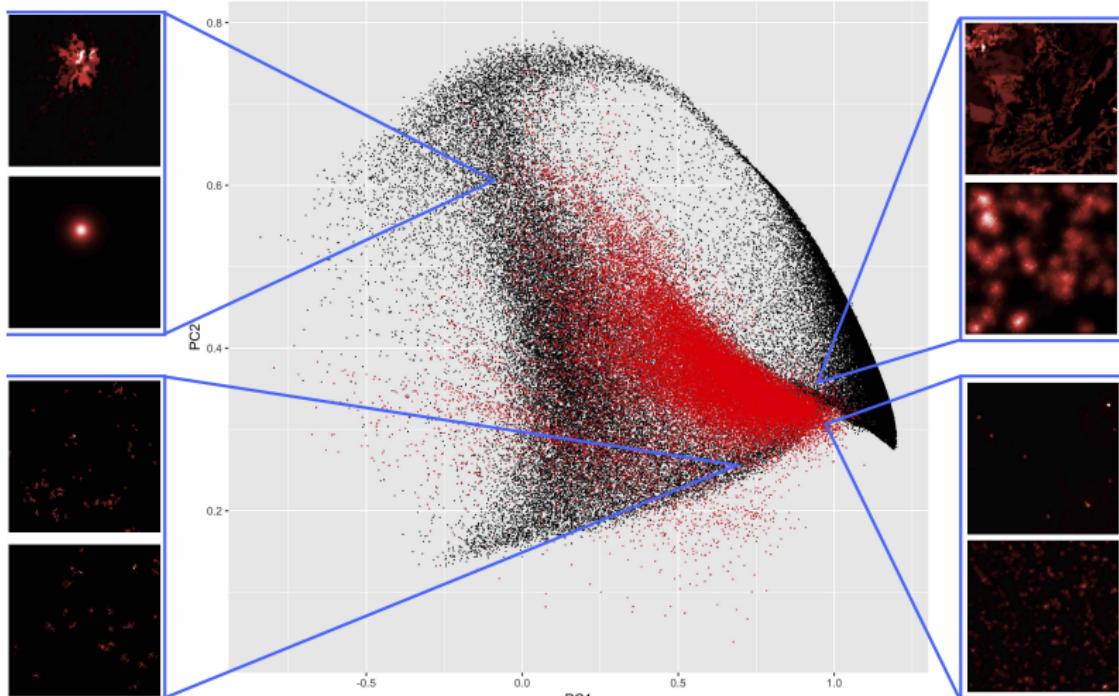
Illustration of path-dependence in a simplified one-dimensional version of the model: cell trajectories in time for 9 independent repetitions from the same initial configuration.

Empirical Data for Calibration



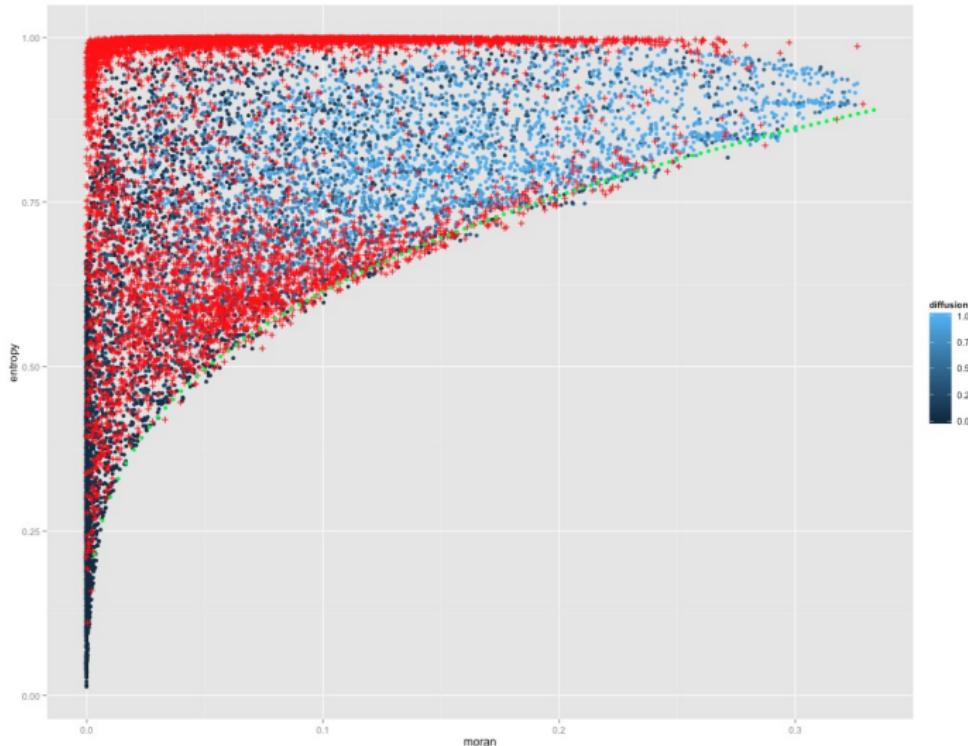
Computation of morphological indicators on population density data for Europe (shown here on France), morphological classification.

Model Calibration



Brute force calibration by exploring the parameter space. Reproduction of most existing configuration in the morphological sense (here in principal plan).

Model Targeted Exploration



Potentialities of targeted model explorations: here feasible space using Pattern Space Exploration algorithm [Chérel et al., 2015].

Which ontology to include more complex functional properties ?

- Territorial systems as the strong coupling between territories and (potential and realized) networks [Dupuy, 1987].
- Networks convey functional notions of centralities and accessibility, among others; have furthermore proper topological properties.

Implications

- This rather simple model reproduces most of existing urban forms in Europe for both population distribution and road network : which intrinsic dimension to the urban system and its morphological aspect ?
- Ability to reproduce static correlations and a variety of dynamical lagged correlation regimes suggests that the model captures some of the processes of co-evolution

Developments

- Towards a dynamical calibration ? Need of dynamical data
- Investigate the link between spatial non-stationarity and non-ergodicity through simulation by the model
- Compare network generation in a “fair” way (correcting for additional parameters, open question for models of simulation)

More realistic models?

- Introducing more concrete ontologies, economic processes [Bonin and Hubert, 2014], qualitative differentiation [Bonin and Hubert, 2012] governance processes [Le Néchet and Raimbault, 2015]
- Possible bridges with Land-use change models/Land-use Transport models [Wegener and Fürst, 2004], with systems of cities models [Pumain and Reuillon, 2017]

More data-driven models?

- Work in progress: calibration of the reaction-diffusion model on world urban areas with the Global Human Settlements Layer database
- Link with sustainability indicators: GHG emissions, economics, etc. [Raimbault, 2019]
- Study models on hybrid synthetic data [Raimbault et al., 2019]: systematic conclusions for policies

- A novel model of urban morphogenesis at the mesoscopic scale systematically explored: **need for more coupling and comparison of models.**
- At the macro scale of the system of cities? **Need for multi-scale models.**
- With more refined urban characteristics and other dimensions ? **Need for more interdisciplinarity.**

- Code, data and results available at

<https://github.com/JusteRaimbault/CityNetwork>

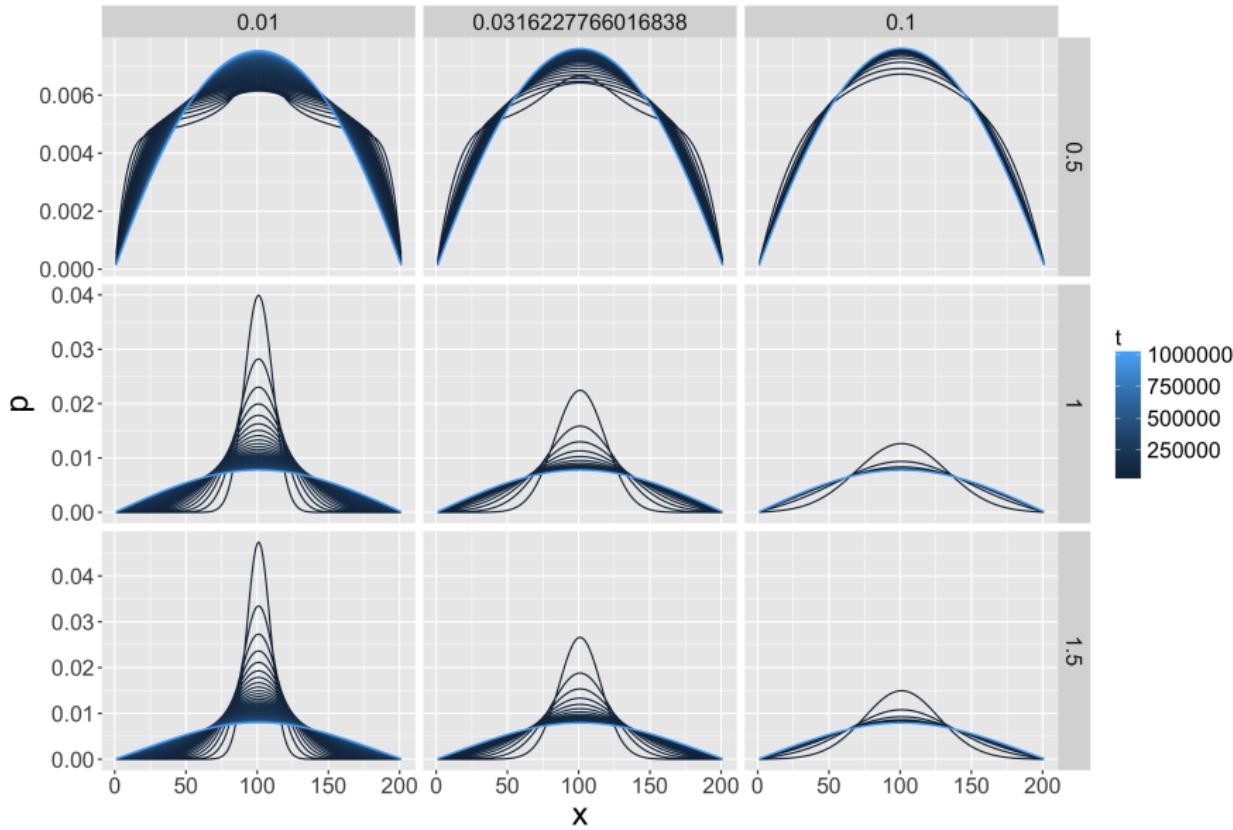
- Acknowledgments: Thanks to the *European Grid Infrastructure* and its *National Grid Initiatives* (*France-Grilles* in particular) to give the technical support and the infrastructure.

Reserve Slides

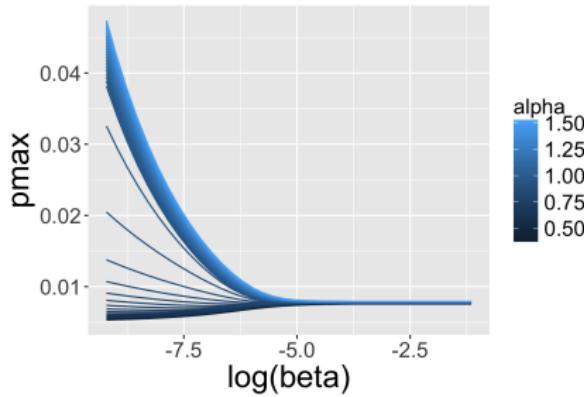
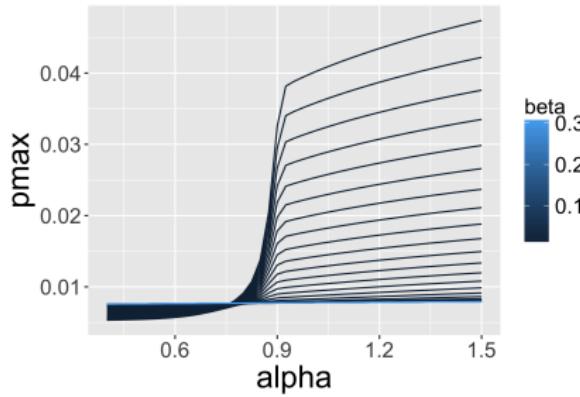
The one-dimensional model verifies the PDE :

$$\delta t \cdot \frac{\partial p}{\partial t} = \frac{N_G \cdot p^\alpha}{P_{\alpha t}} + \frac{\alpha \beta (\alpha - 1) \delta x^2}{2} \cdot \frac{N_G \cdot p^{\alpha-2}}{P_\alpha(t)} \cdot \left(\frac{\partial p}{\partial x} \right)^2 \\ + \frac{\beta \delta x^2}{2} \cdot \frac{\partial^2 p}{\partial x^2} \cdot \left[1 + \alpha \frac{N_G p^{\alpha-1}}{P_{\alpha t}} \right] \quad (1)$$

Stationary behavior of 1D model



Stationary behavior of 1D model



- 1 Rank-size slope γ , given by $\ln(P_{\tilde{i}}/P_0) \sim k + \gamma \cdot \ln(\tilde{i}/i_0)$ where \tilde{i} are the indexes of the distribution sorted in decreasing order.
- 2 Entropy of the distribution:

$$\mathcal{E} = \sum_{i=1}^M \frac{P_i}{P} \cdot \ln \frac{P_i}{P} \quad (2)$$

$\mathcal{E} = 0$ means that all the population is in one cell whereas $\mathcal{E} = 0$ means that the population is uniformly distributed.

- 3 Spatial-autocorrelation given by Moran index, with simple spatial weights given by $w_{ij} = 1/d_{ij}$

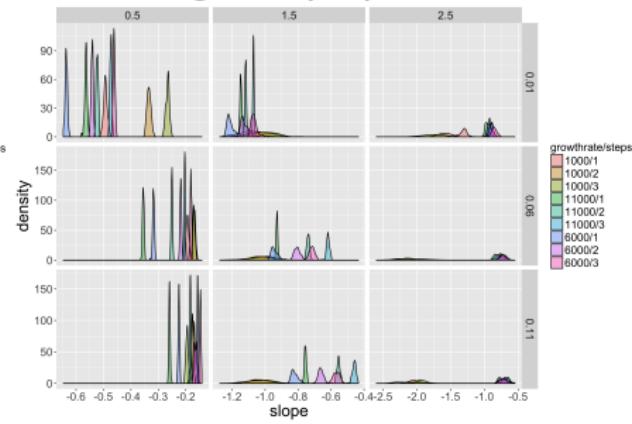
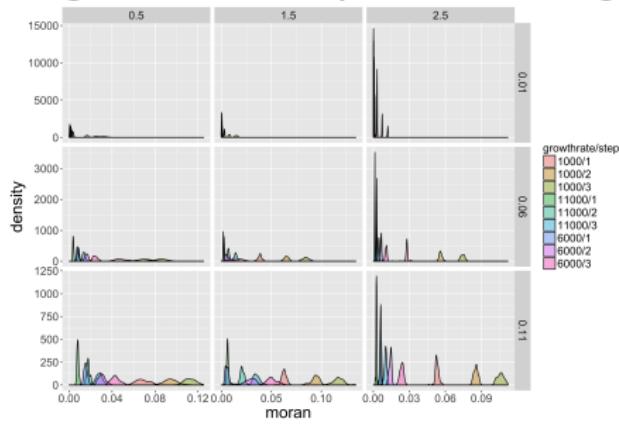
$$I = M \cdot \frac{\sum_{i,j} w_{ij} (P_i - \bar{P}) \cdot (P_j - \bar{P})}{\sum_{i,j} w_{ij} \sum_i (P_i - \bar{P})^2}$$

- 4 Mean distance between individuals

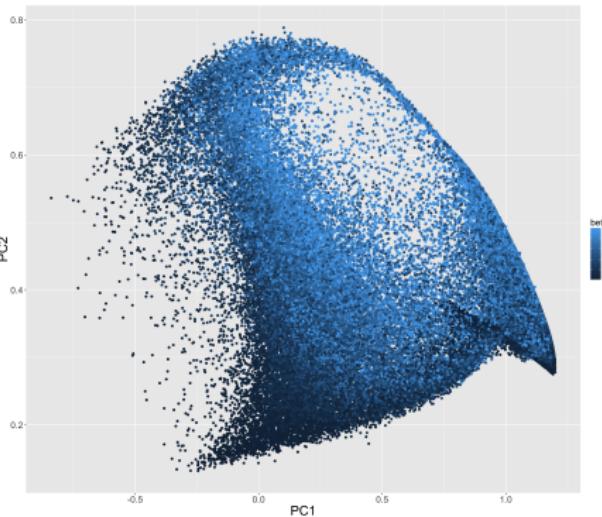
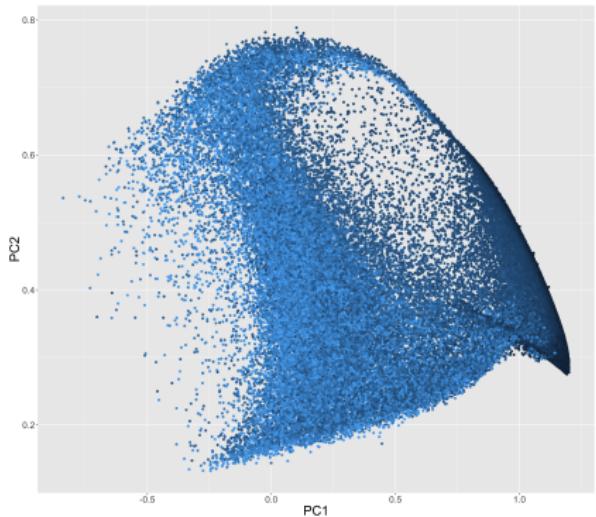
$$\bar{d} = \frac{1}{d_M} \cdot \sum_{i < j} \frac{P_i P_j}{P^2} \cdot d_{ij}$$

Model behavior : Convergence

Large number of repetitions show good convergence properties

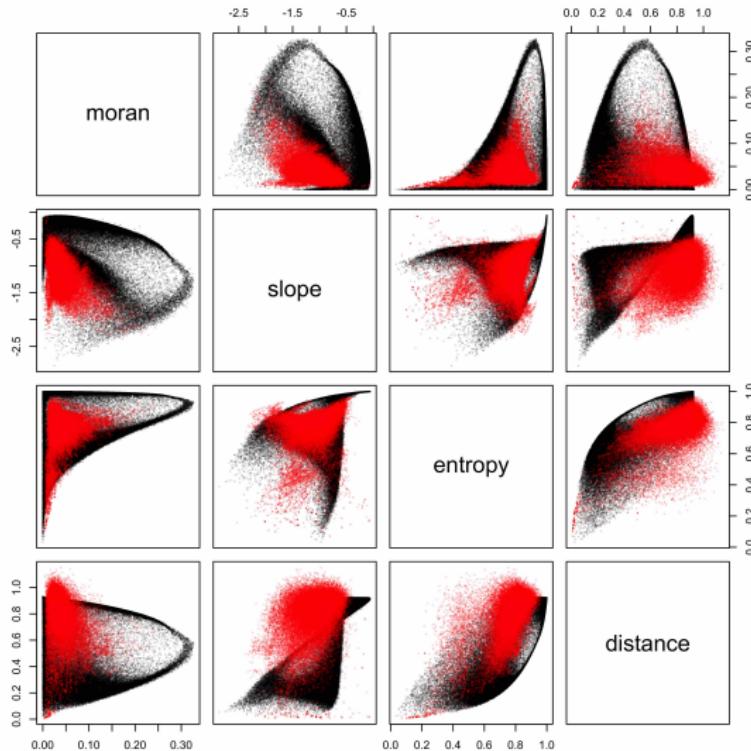


Model behavior



- Eurostat population density raster (100m, simplified at 500m resolution)
- Overlapping (10km offset) squares of 50km side : equivalent to smoothing, removes window shape effect. Not very sensitive to window size (tested with 30km and 100km)
- Indicators computed using Fast Fourier Transform Convolution
- Classification using repeated k-means ; number of clusters taken at transition in clustering coefficient.

Model calibration: all indicators



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