

Worldwide estimation of parameters for a simple reaction-diffusion model of urban growth

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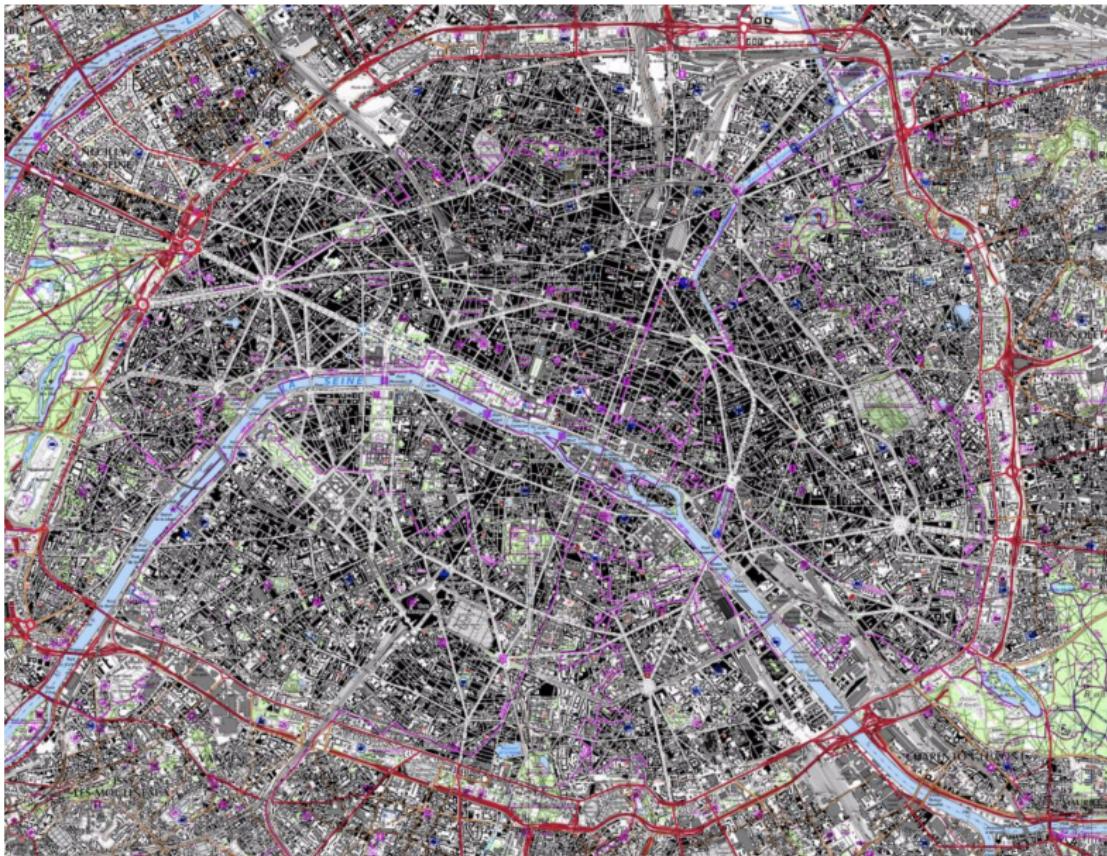
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International Land-Use Symposium 2019
3.1: Fractals and Multi-fractals
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Complex processes of Urban Morphogenesis



Complex processes of Urban Morphogenesis



[Engelen and White, 2008] calibration/validation + map comparison

[Zhou et al., 2018] urban form / emissions

→ *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*

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

A simple Reaction-diffusion model

- 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.

- 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:

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

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

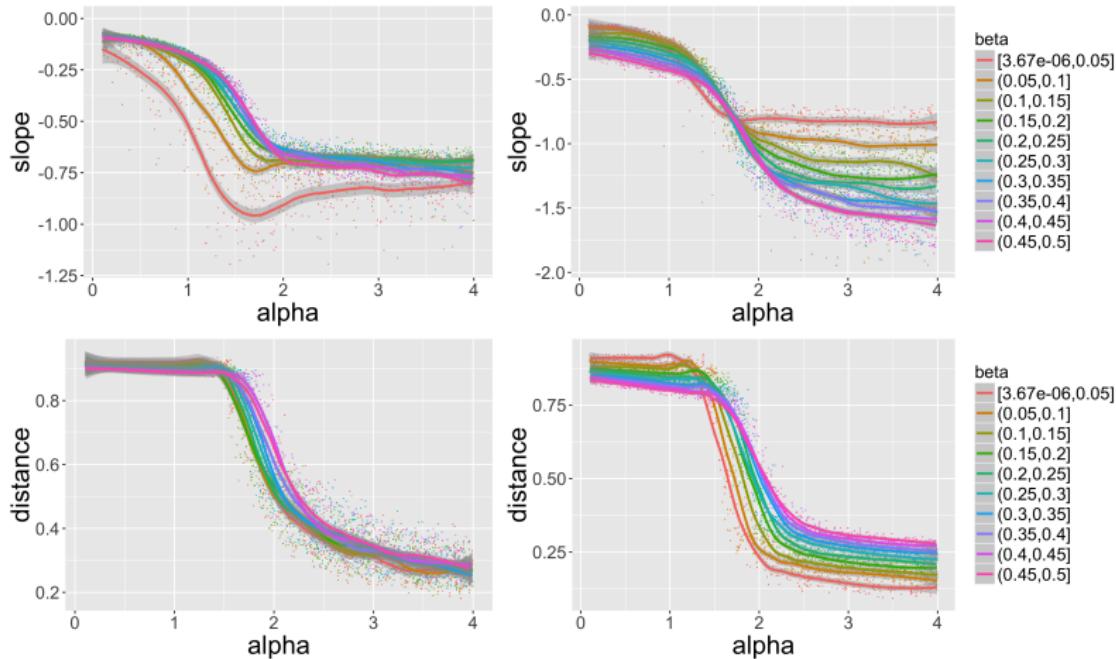
- 3 Spatial-autocorrelation given by Moran index, with simple spatial weights given by $w_{ij} = 1/d_{ij}$

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

- 4 Mean distance between individuals

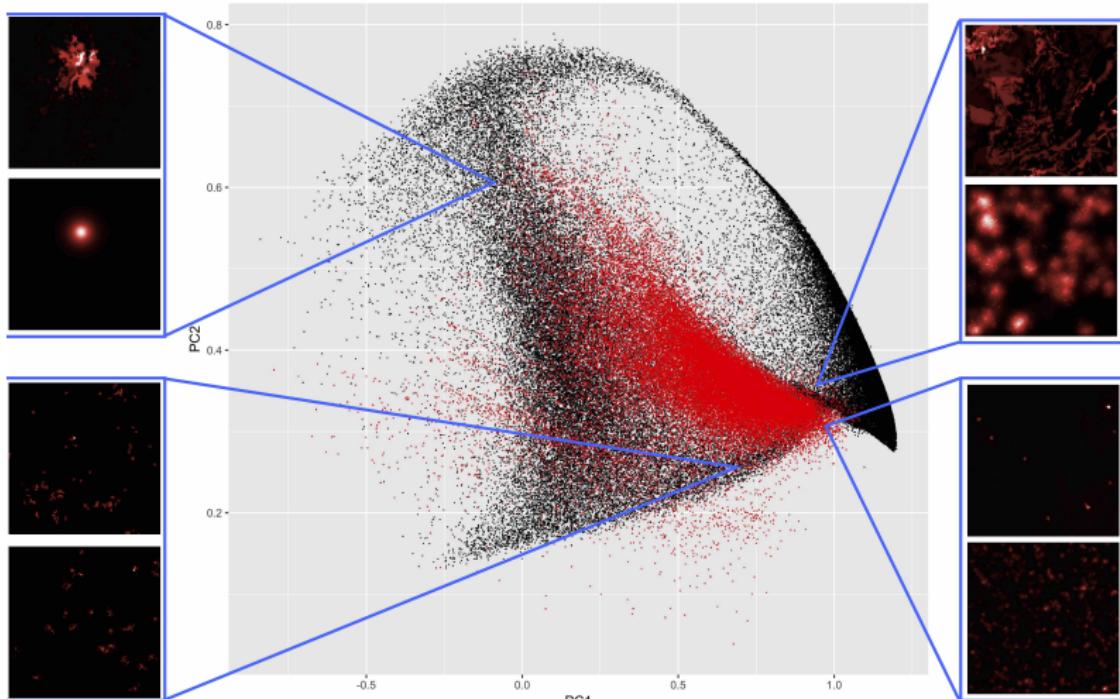
$$\bar{d} = \frac{1}{d_M} \cdot \sum_{i < j} \frac{P_i P_j}{P^2} \cdot d_{ij}$$

Model behavior (synthetic data))



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

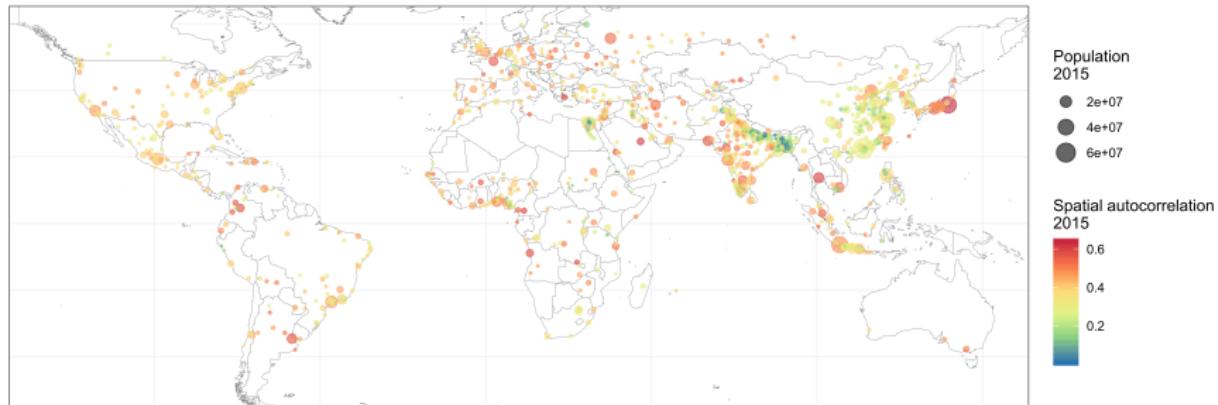
Model application on a spatial grid



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

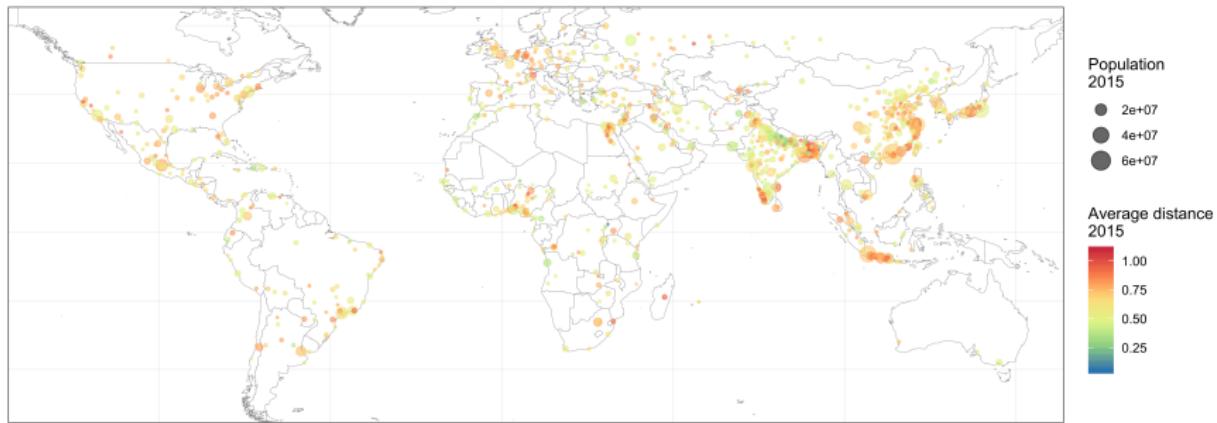
- Application on worldwide urban areas using the GHSL population grid
- Dynamical calibration on three successive time windows (1975-1990, 1990-2000, 2000-2015)
- Extraction of neighborhood (spatial span times 1.5) of 1000 larger urban areas (2015 population)
- Computation of morphological indicators on corresponding population grids

Global indicators distribution: Moran



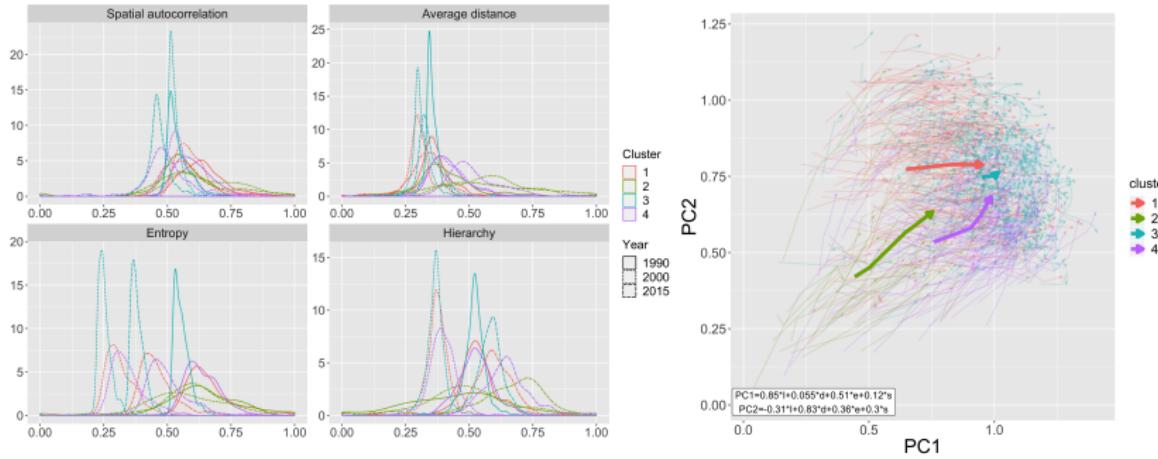
Regional patterns for Moran index

Global indicators distribution: average distance



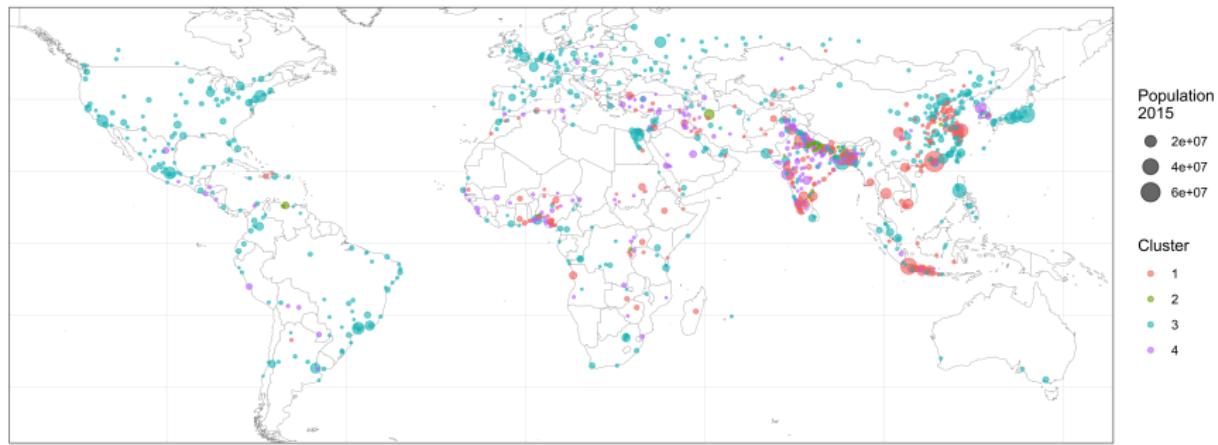
Complementarity of average distance indicator

Clustering morphological trajectories

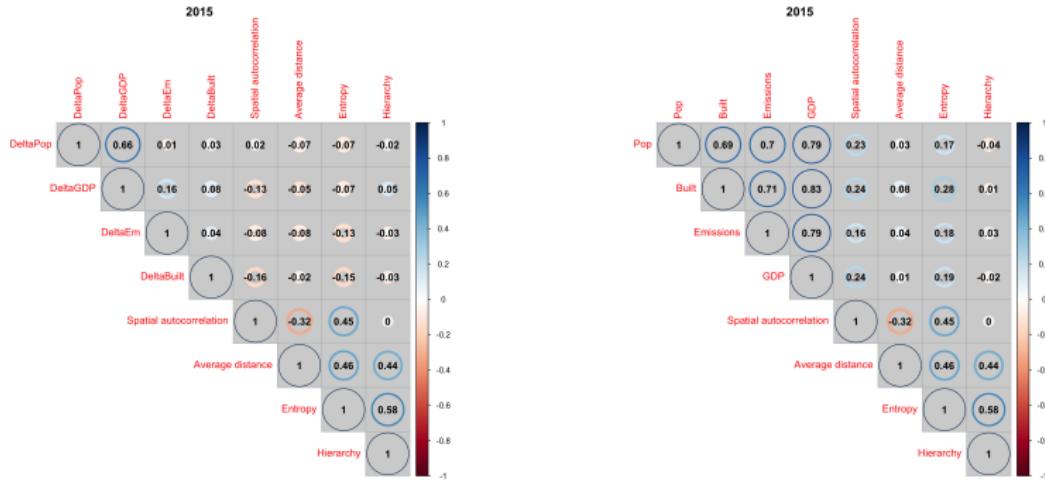


Disjoint distributions and temporal trajectories: model application is relevant

Distribution of clusters



Correlations



Calibration method

Performance constraints: simulate N mesoscopic morphogenesis models in parallel (macroscopic interactions are efficient as based on matrices)

→ model implemented in `scala` and integrated within a broader library (including implementations of [?] [Raimbault, 2018] [?] [?])

Large number of parameters and output indicators

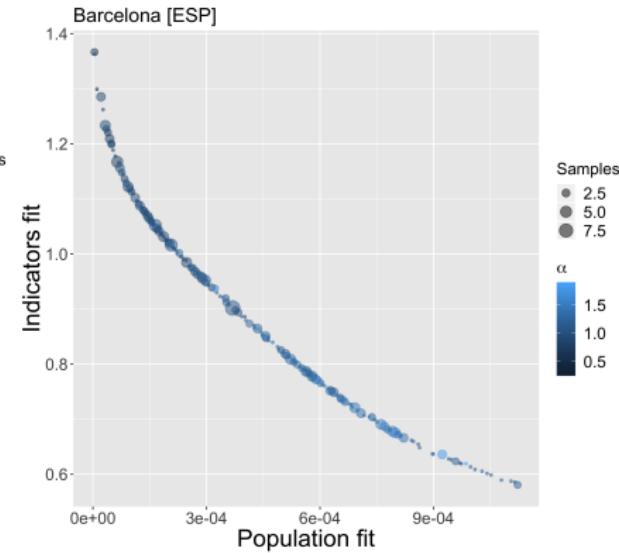
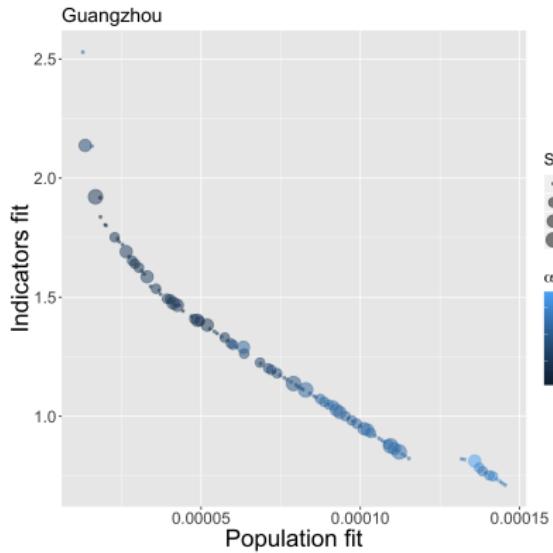
→ integration into the OpenMOLE model exploration open source software [Reuillon et al., 2013]



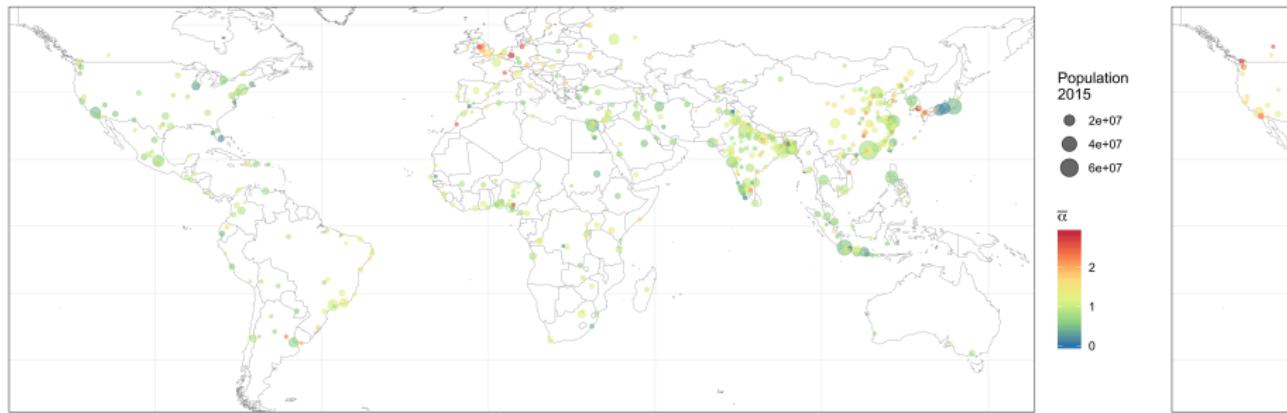
Enables seamlessly (i) model embedding; (ii) access to HPC resources; (iii) exploration and optimization algorithms

Come to the satellite *New Methods and Epistemologies to Explore Simulation Models* tomorrow afternoon in LHN-TR+05

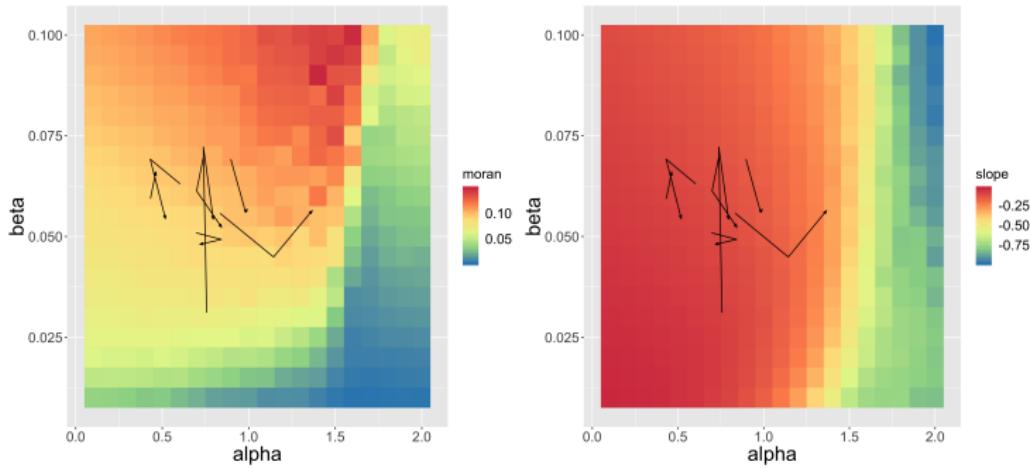
Examples of results



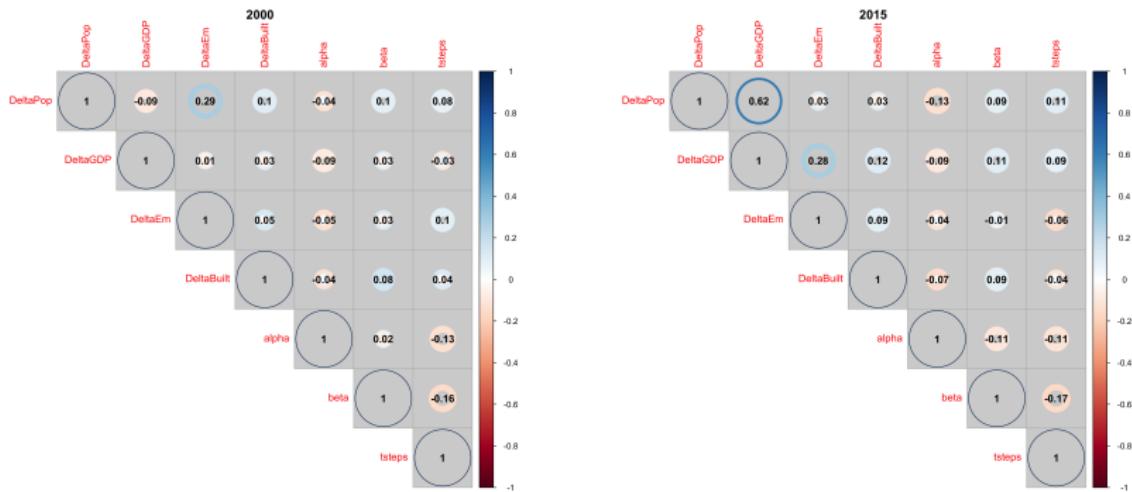
Adjusted parameters



Trajectories in phase diagrams



Correlations



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.**

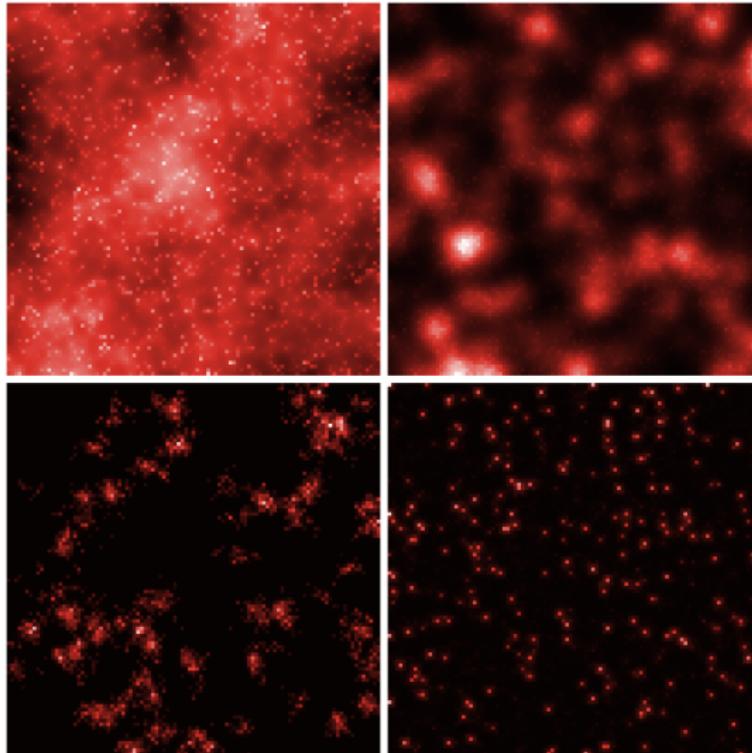
- Code, data and results available at

<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

Generating Population Distributions



Examples of generated territorial shapes

Path-dependence and frozen accidents

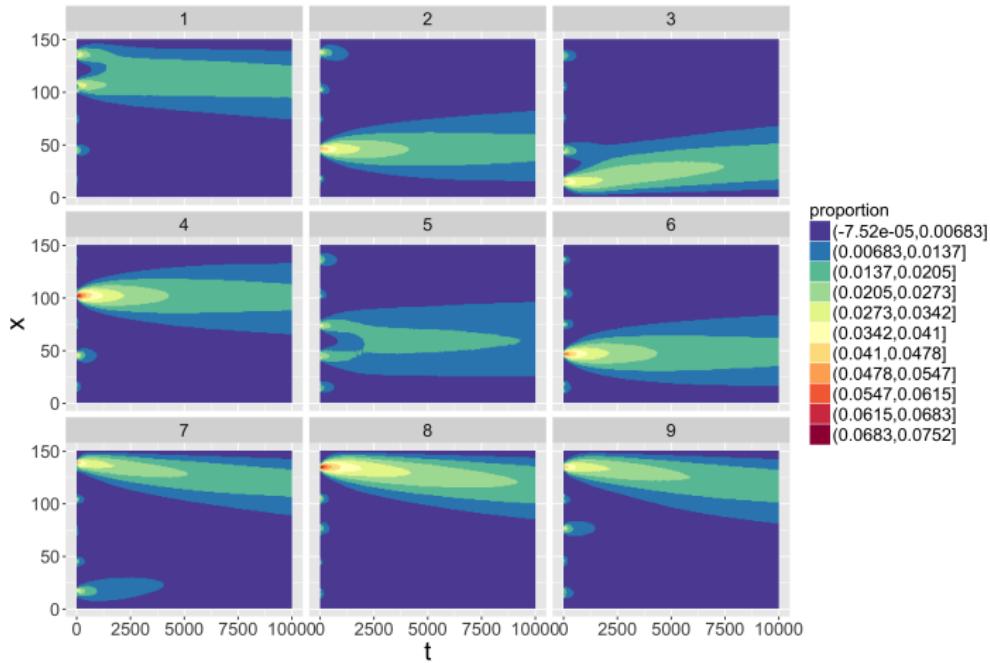
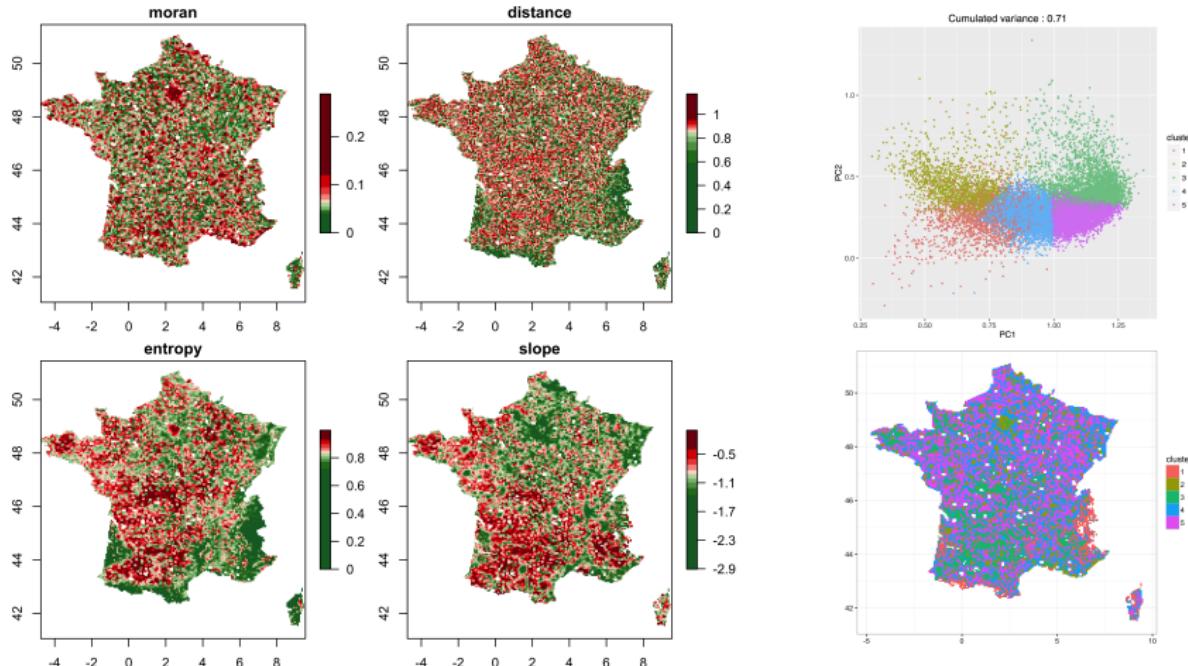


Illustration of path-dependence in a simplified one-dimensional version of the model: cell trajectories in time for 9 independent repetitions from the same initial configuration.

Empirical Data (moving window)

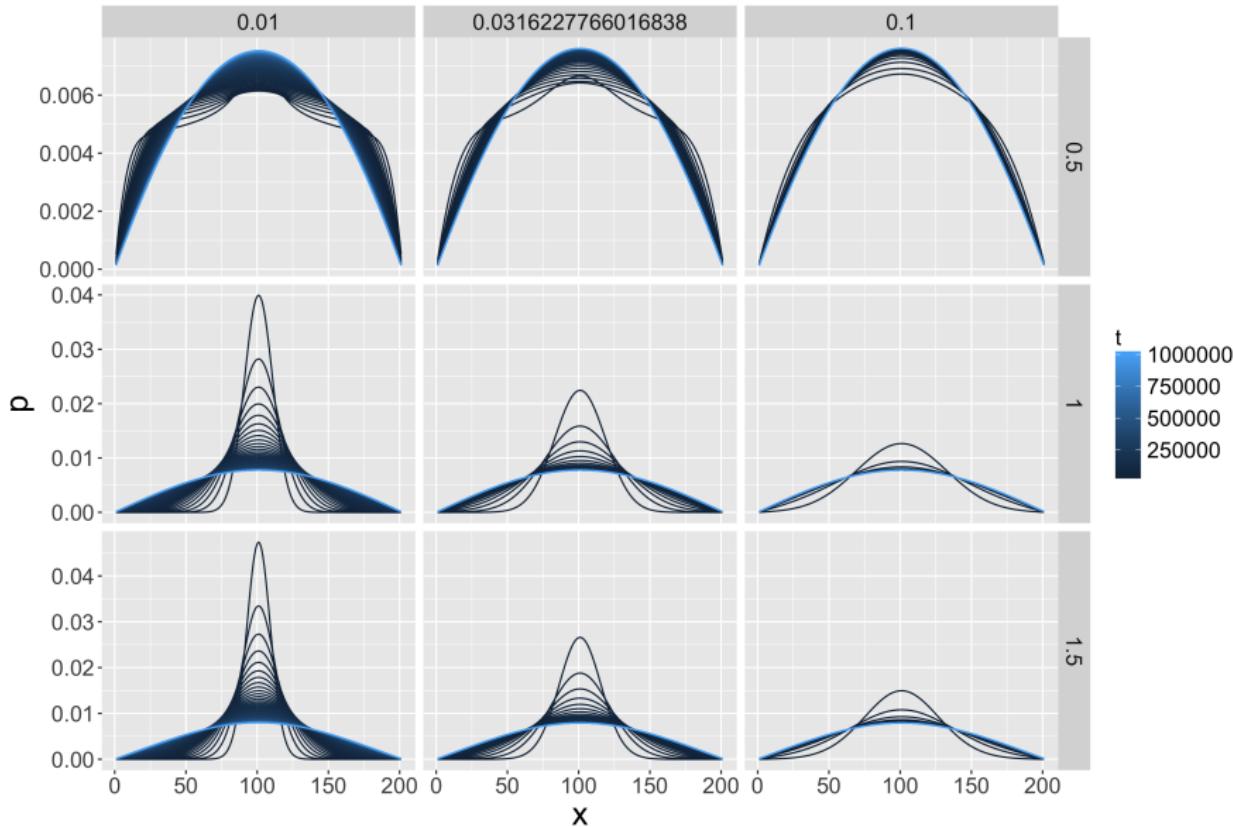


Computation of morphological indicators on population density data for Europe (shown here on France), morphological classification.

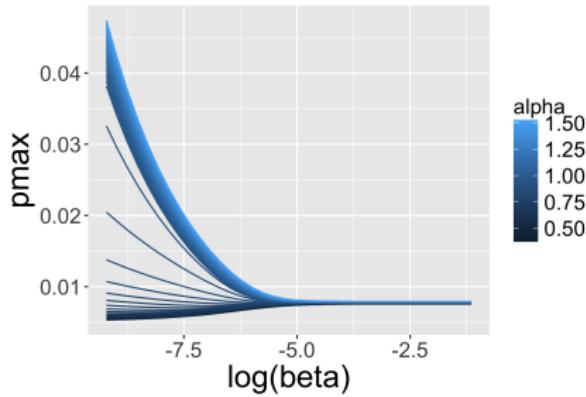
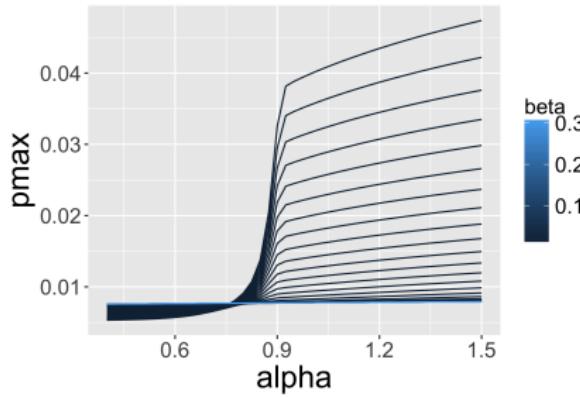
The one-dimensional model verifies the PDE :

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

Stationary behavior of 1D model

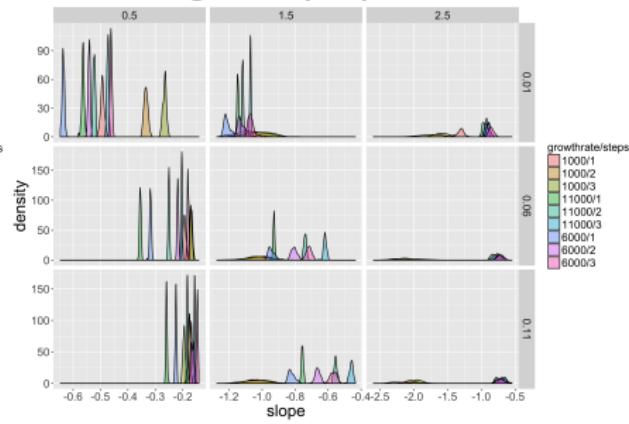
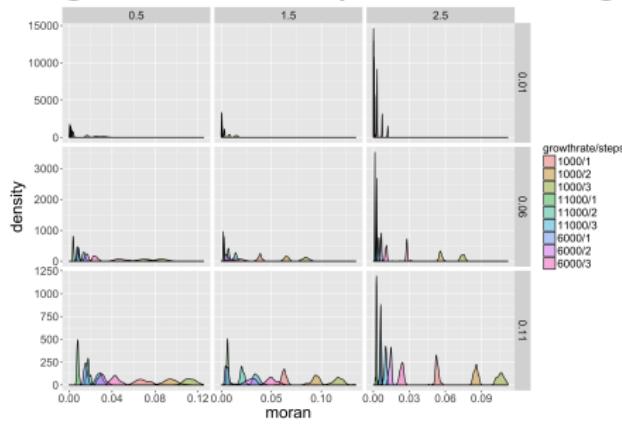


Stationary behavior of 1D model

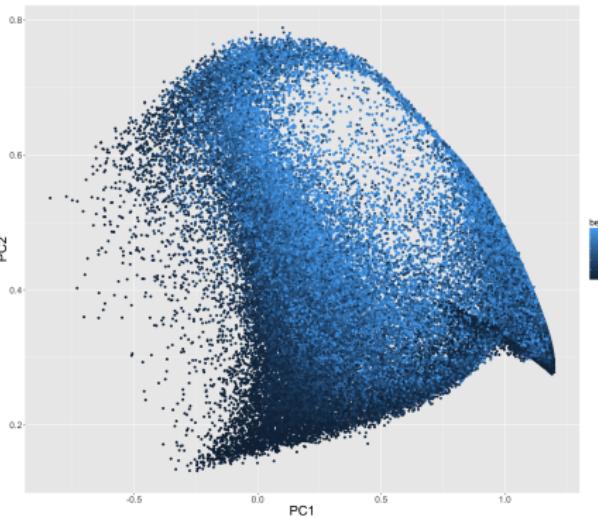
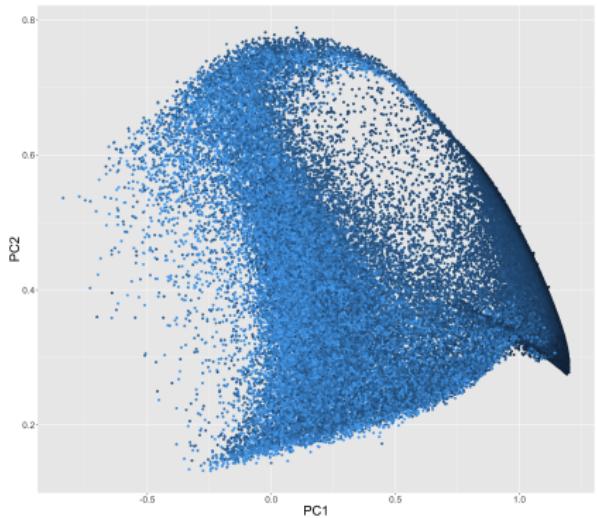


Model behavior : Convergence

Large number of repetitions show good convergence properties

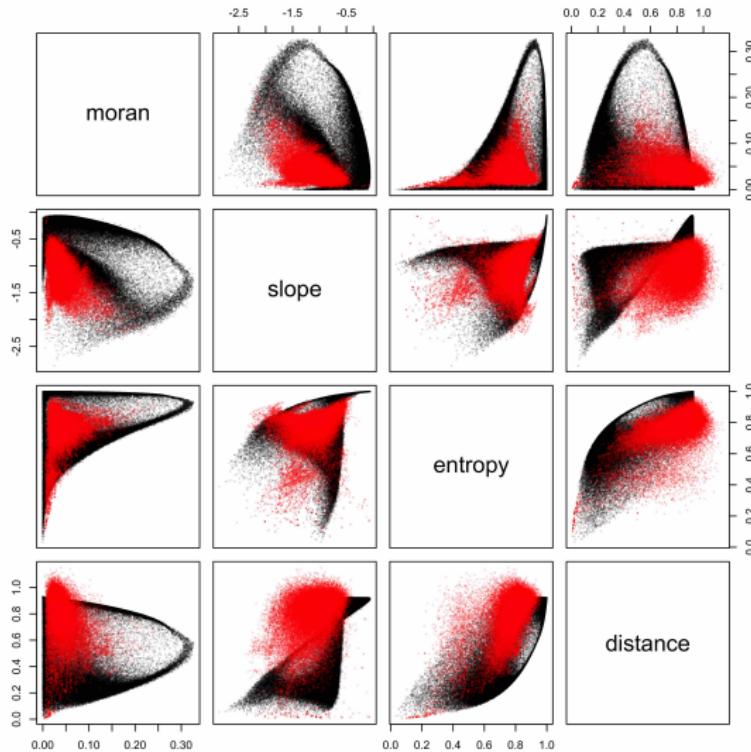


Model behavior

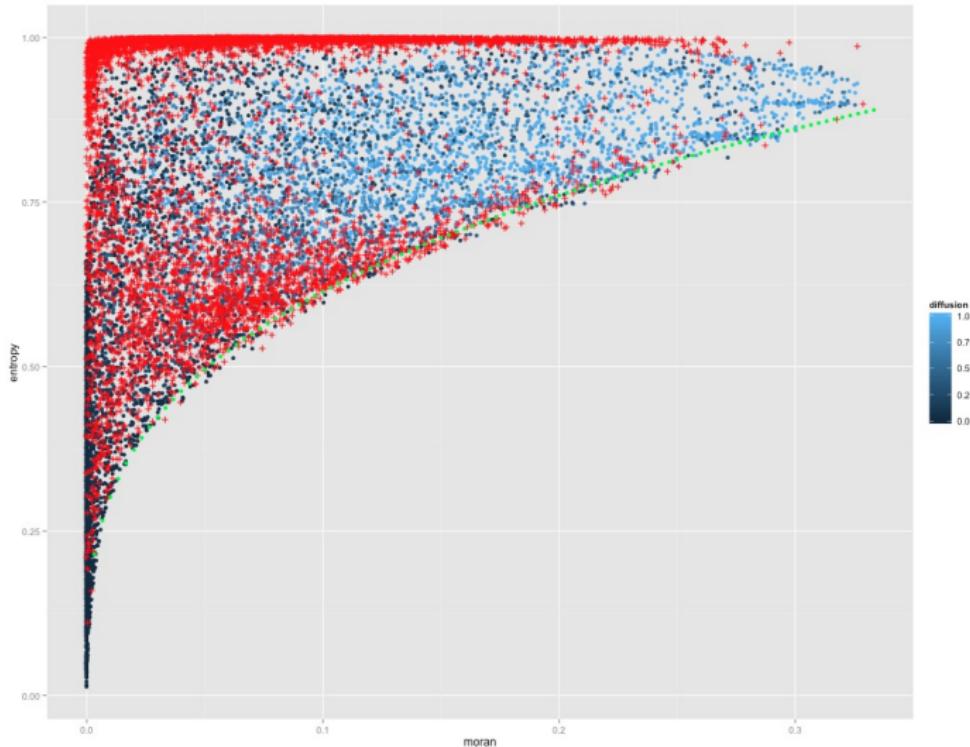


- Eurostat population density raster (100m, simplified at 500m resolution)
- Overlapping (10km offset) squares of 50km side : equivalent to smoothing, removes window shape effect. Not very sensitive to window size (tested with 30km and 100km)
- Indicators computed using Fast Fourier Transform Convolution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

Model calibration: all indicators



Model Targeted Exploration



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

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]*

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