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

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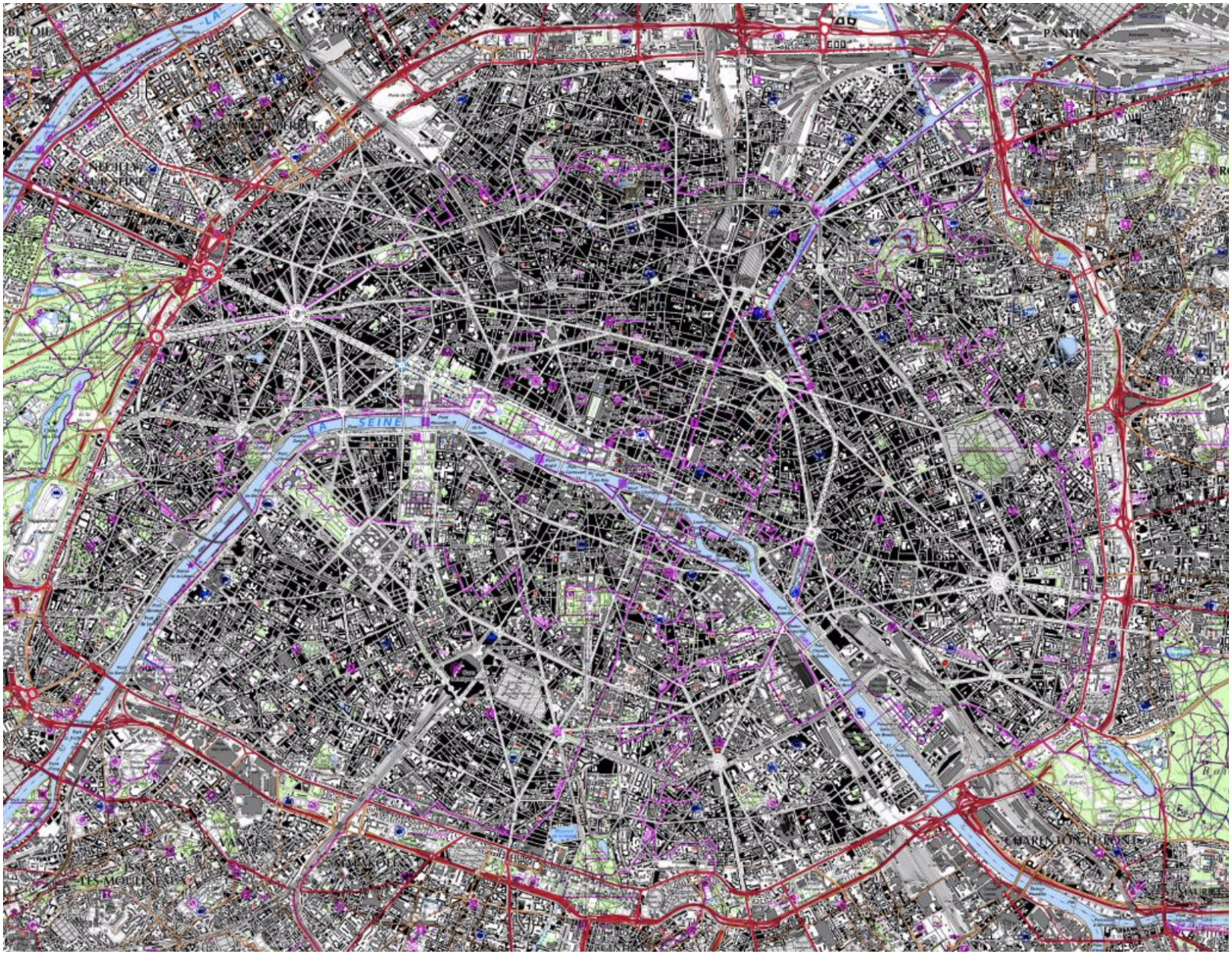
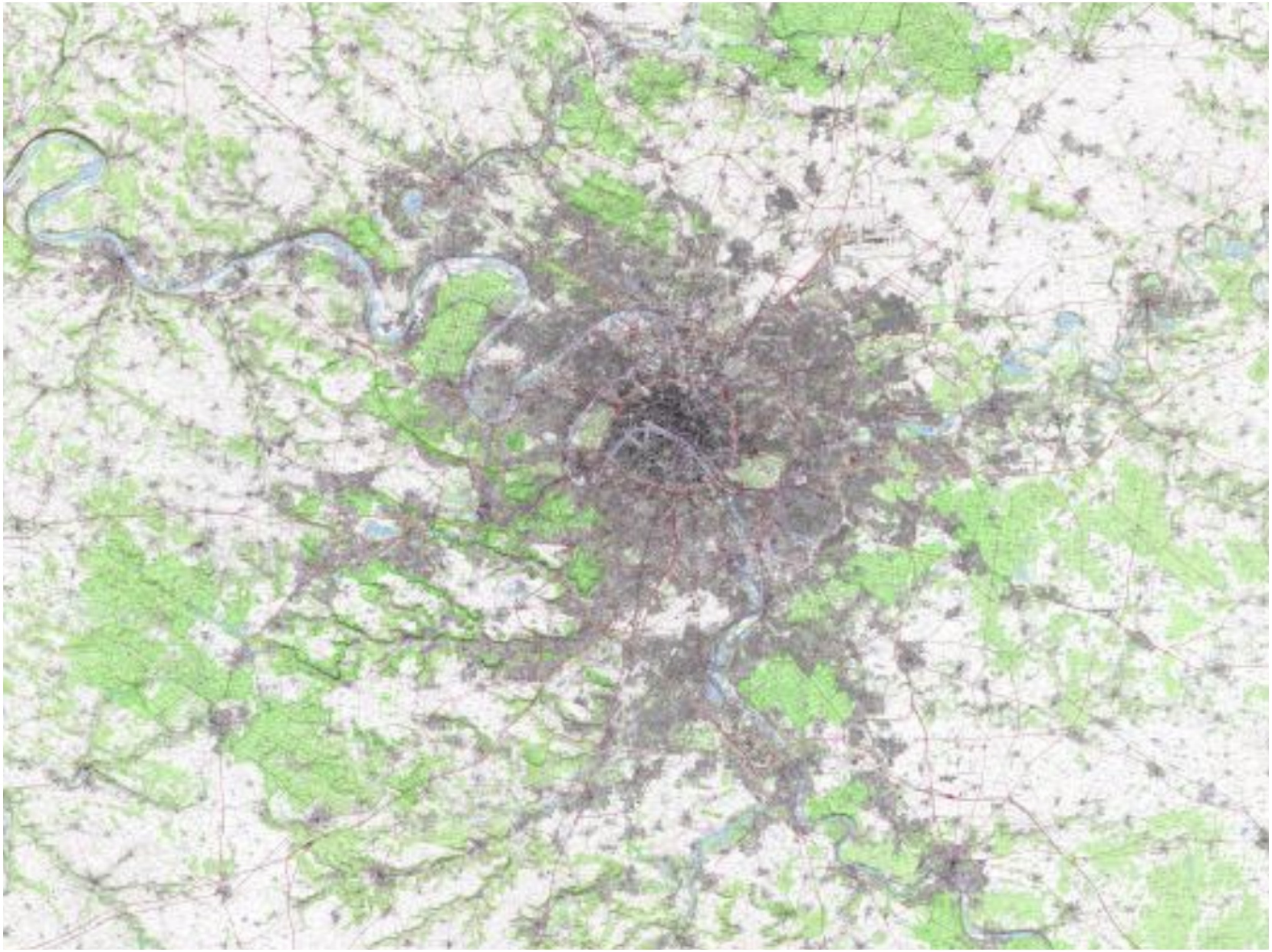
International Land-Use Symposium 2019
Session Drivers, Mechanisms, Tools
5th December 2019

Complex processes of Urban Morphogenesis



Complex processes of Urban Morphogenesis



Modeling urban growth and land-use change

$\rightarrow$ Cellular automata models or models of land-use change generally highly data-driven

$\rightarrow$ May be case-specific or conclusions difficult to generalize (see Sleuth for example [Clarke et al., 2007])

$\rightarrow$ Issues to calibrate and validate these models
[Engelen and White, 2008]

Urban morphogenesis models approach:

$\rightarrow$*At the crossroad between Urban Simulation and Artificial Life, stylized models of urban growth processes*

$\rightarrow$*Importance of parsimony: generative modeling as a tool to understand processes*

Contribution

$\rightarrow$ Explore a simple model to capture morphogenesis based on abstract representation of urban processes; test their ability to reproduce existing urban systems.

$\rightarrow$ The simple reaction-diffusion model of urban growth is calibrated worldwide using GHSL, and in time.

$\rightarrow$ Globally comparable insights into processes of concentration and dispersion.

A simple Reaction-diffusion model

$\rightarrow$ Crucial role of the interplay between concentration forces and dispersion forces [Fujita and Thisse, 1996] in keeping Urban Systems at the border of chaos

$\rightarrow$ Potentiality of aggregation mechanisms (such as Simon model) to produce power laws [Dodds et al., 2017]

$\rightarrow$ Link with Reaction-diffusion approaches in Morphogenesis [Turing, 1952]

$\rightarrow$ 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.

Model formalization

$\rightarrow$ Grid world with cell populations $\left(P_i\left(t\right)\right)_{1\leq i\leq N^2}$.

$\rightarrow$ 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

$\rightarrow$ Stopping criterion: fixed maximal population P_m.

$\rightarrow$ Output measured by morphological indicators: Moran index, average distance, rank-size hierarchy, entropy.

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

$$\mathscr{E} = \sum_{i1}^{M} \frac{P_i}{P} \cdot \ln \frac{P_i}{P} \tag{1}$$

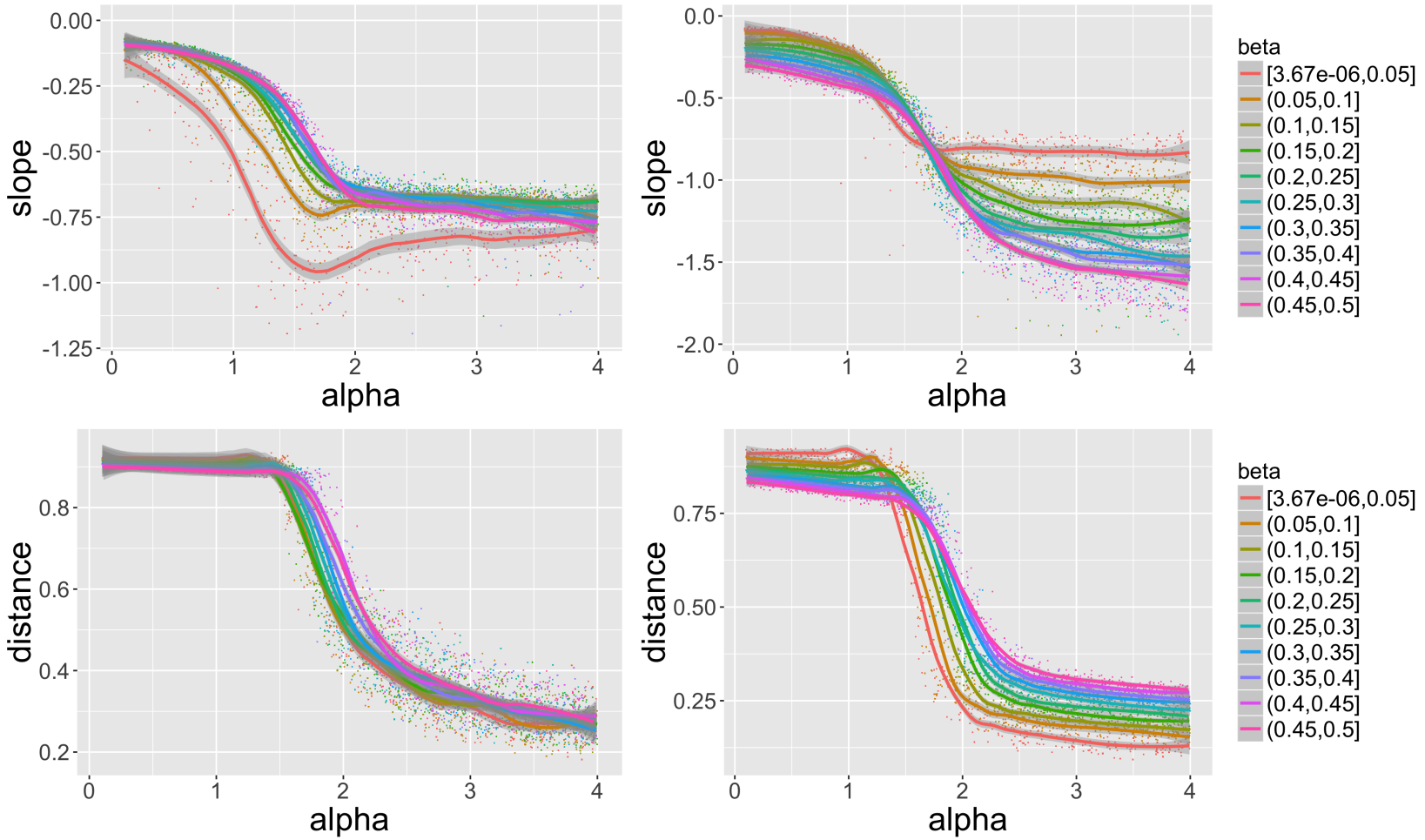
   $\mathscr{E} = 0$ means that all the population is in one cell whereas $\mathscr{E} = 0$ means that the population is uniformly distributed.
3. Spatial-autocorrelation given by Moran index, with simple spatial weights given by $w_{ij} = 1/d_{ij}$

$$I = M \cdot \frac{\sum_{ij/} w_{ij} \left(P_i - \bar{P}\right) \cdot \left(P_j - \bar{P}\right)}{\sum_{ij/} w_{ij} \sum_i \left(P_i - \bar{P}\right)^2}$$

4. Mean distance between individuals

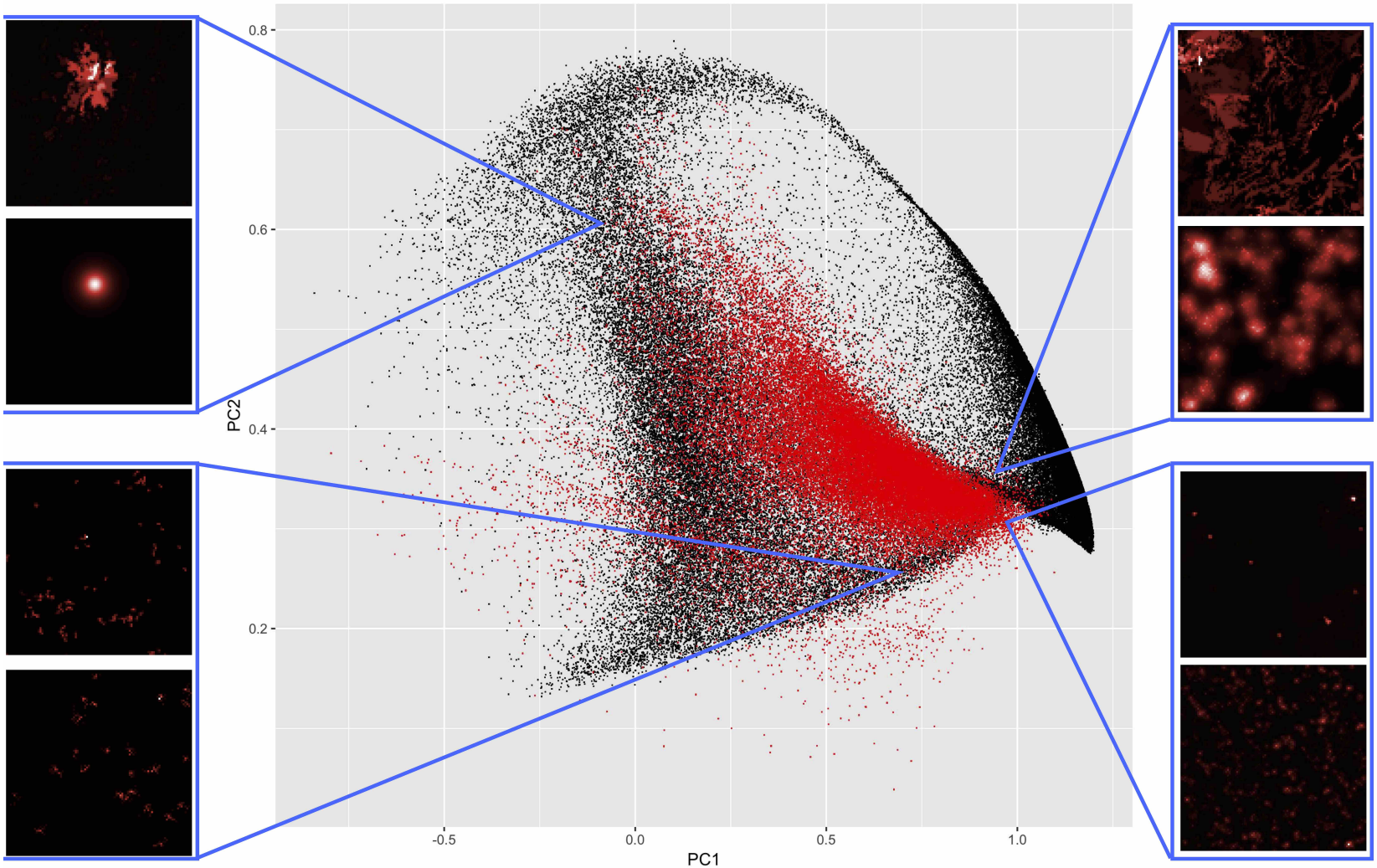
$$\bar{d} = \frac{1}{d_M} \cdot \sum_{i<j} \frac{P_i P_j}{P^2} \cdot d_{ij}$$

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).

GHSL database

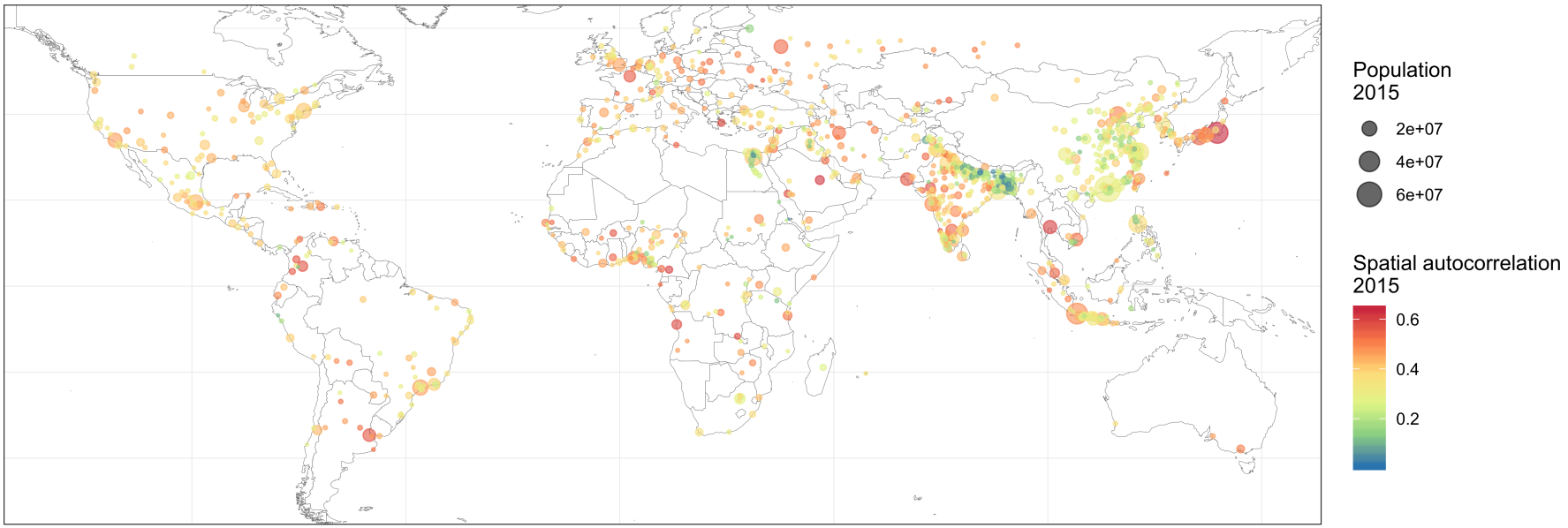
→ Application on worldwide urban areas using the GHSL population grid

→ 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)

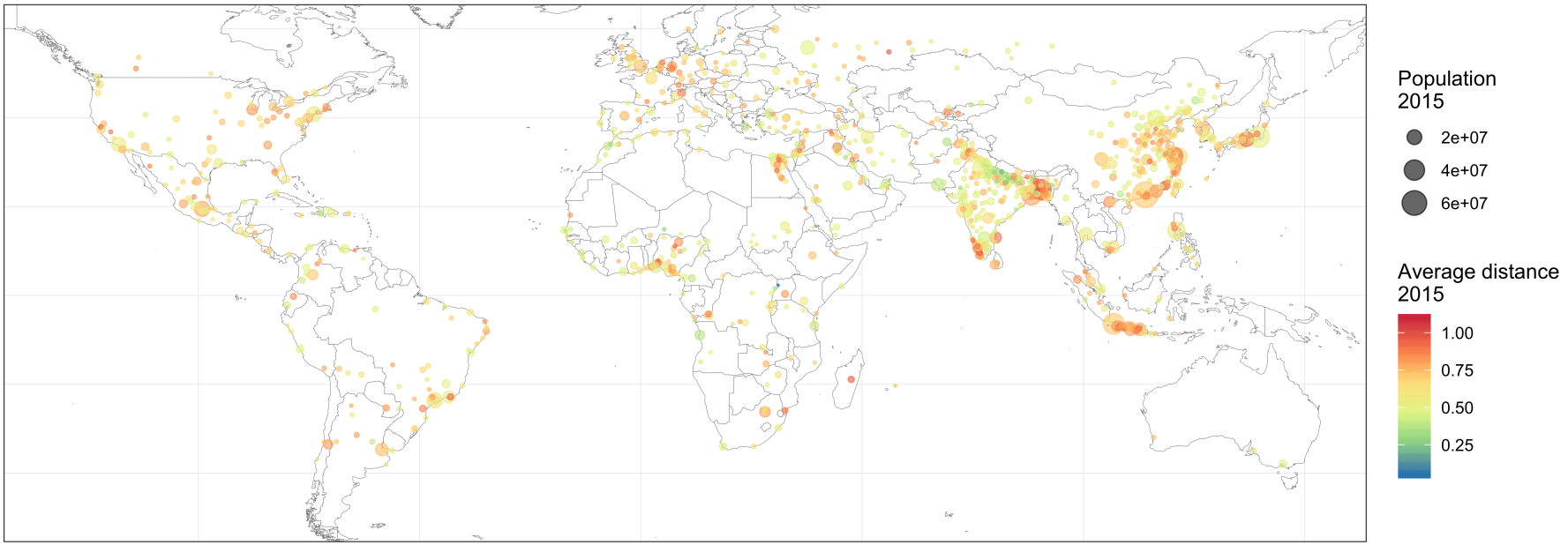
→ Computation of morphological indicators on corresponding population grids

Global indicators distribution: Moran



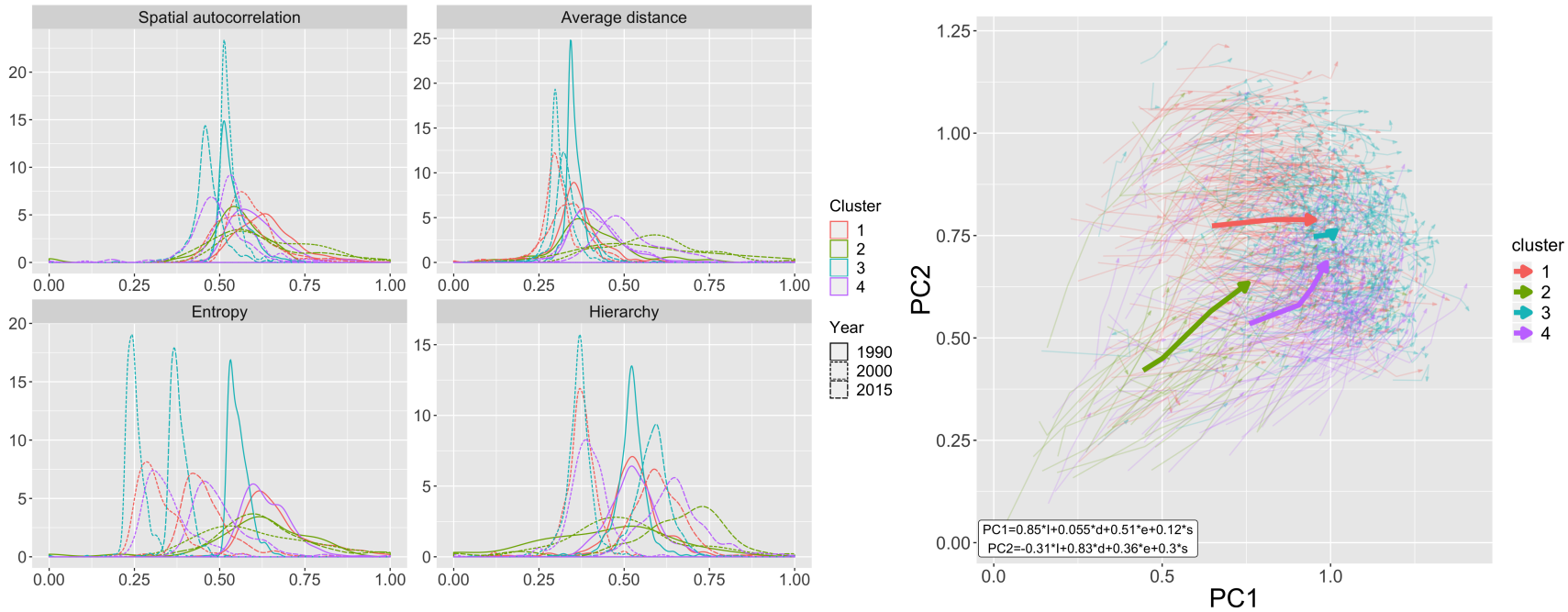
Regional patterns for Moran index

Global indicators distribution: average distance



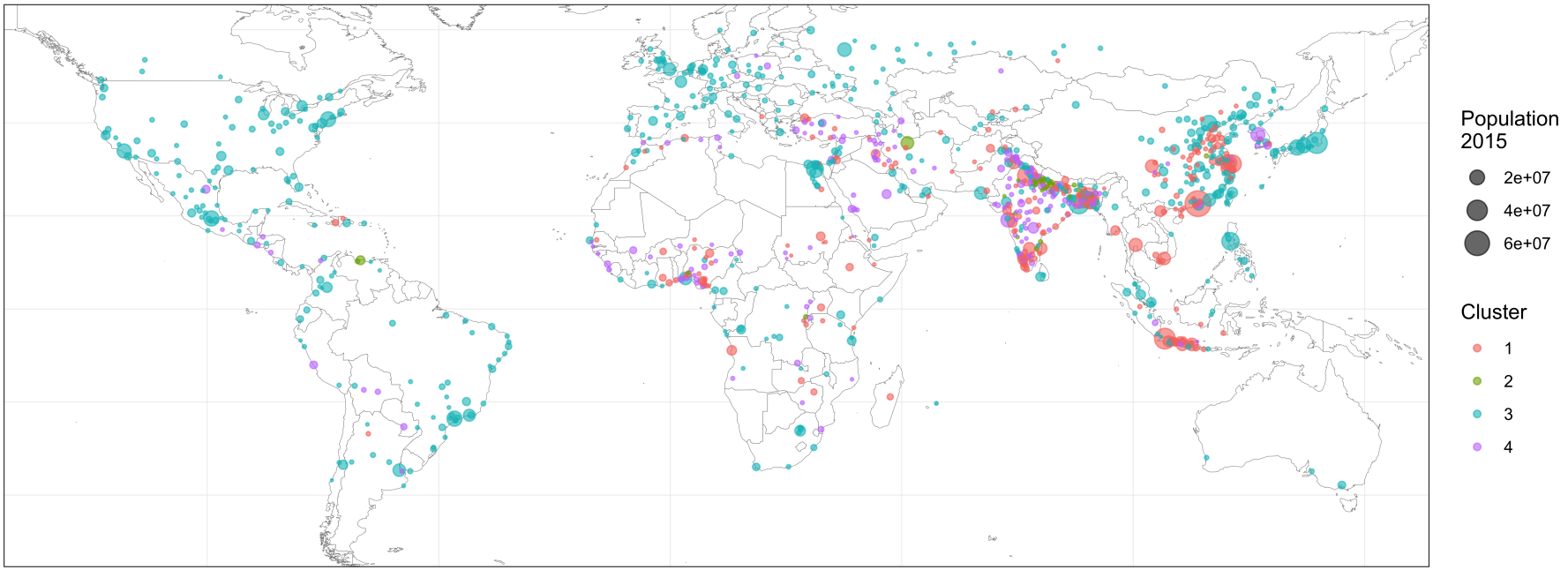
Complementarity of average distance indicator

Clustering morphological trajectories

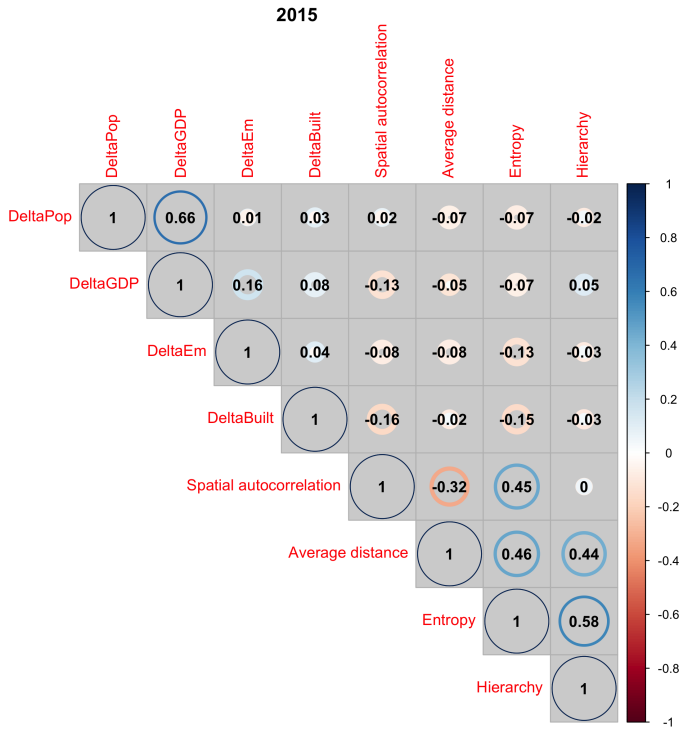


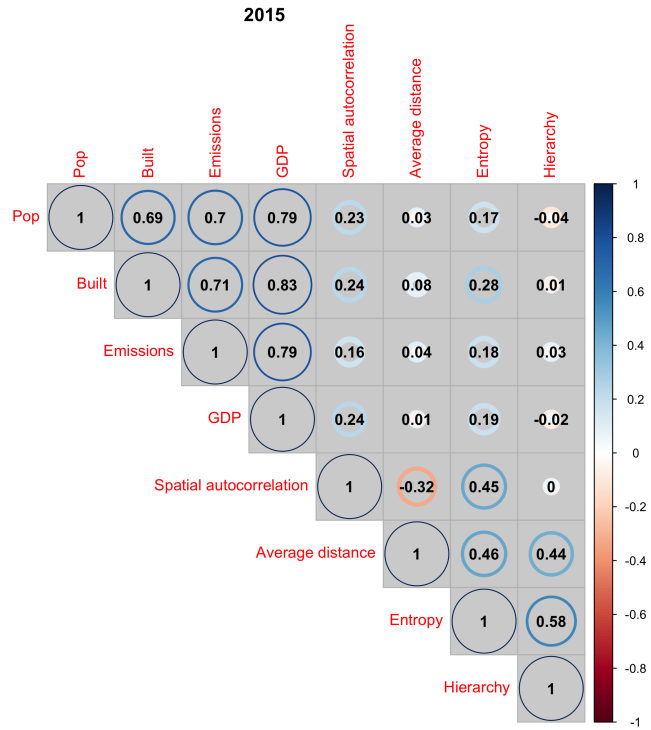
Disjoint distributions and temporal trajectories: model application is relevant

Distribution of clusters



Correlations with urban area properties





Calibration method

- For a time period $\left[t_0, t_f\right]$, model initialized with population at t_0
- Growth rate N_G is computed by constraining with actual population growth: $N_G = \left(P_i\left(t_f\right) - P_i\left(t_0\right)\right)/T$ where T is a calibration parameter
- Fitness functions: squared relative population error and squared relative morphological indicator error
- Biobjective genetic algorithm (NSGA2) run for each areas ($\sim$ 600 areas large enough) and each time windows (1000 generations, population of 100), on parameters α, β, T

Implementation

Performance constraints: large number of calibration algorithms to be run

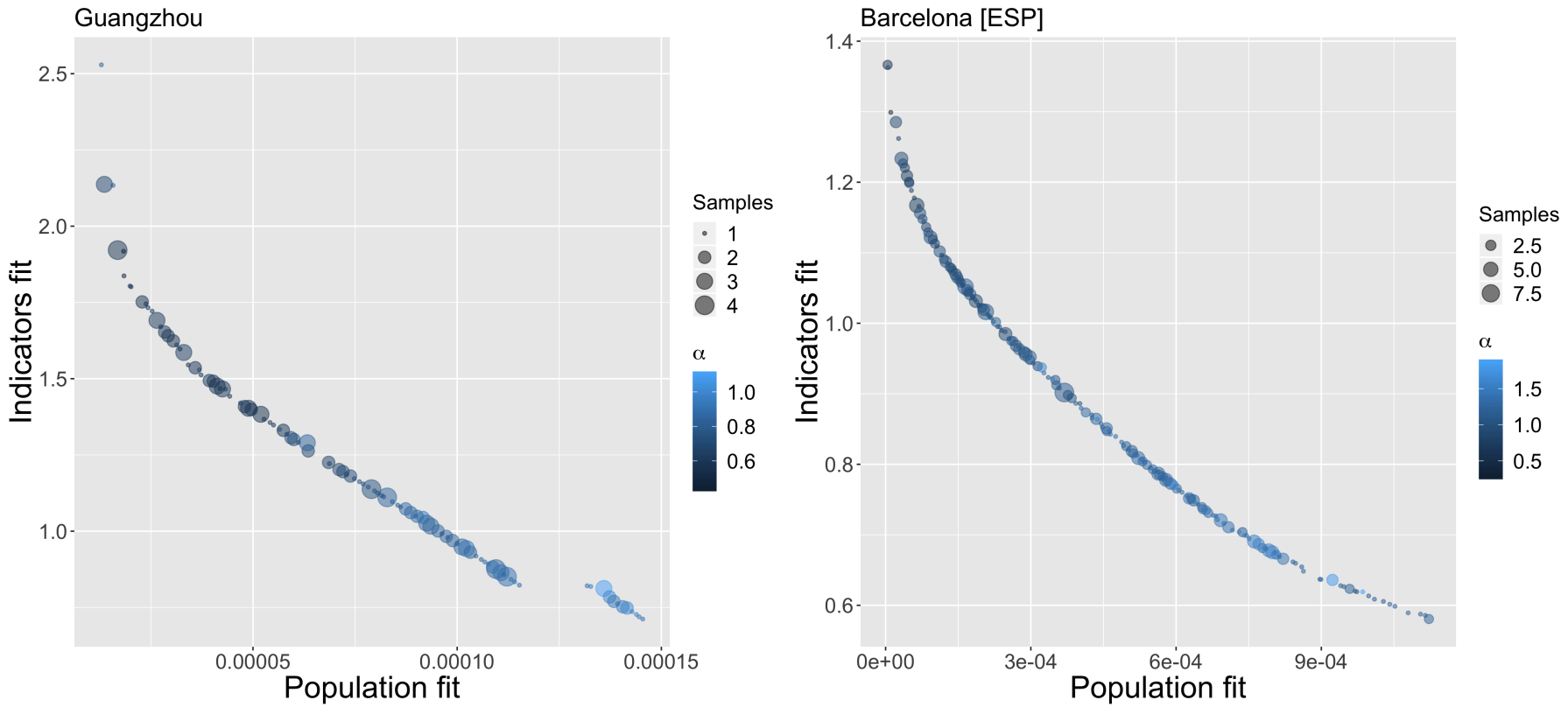
→ model implemented in `scala` and integrated within the `spatialdata` library for spatial sensitivity analysis (including implementations of [Raimbault, 2018b] [Raimbault, 2018a] [Favaro and Pumain, 2011] [Cottineau
See `https://github.com/openmole/spatialdata`

→ 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

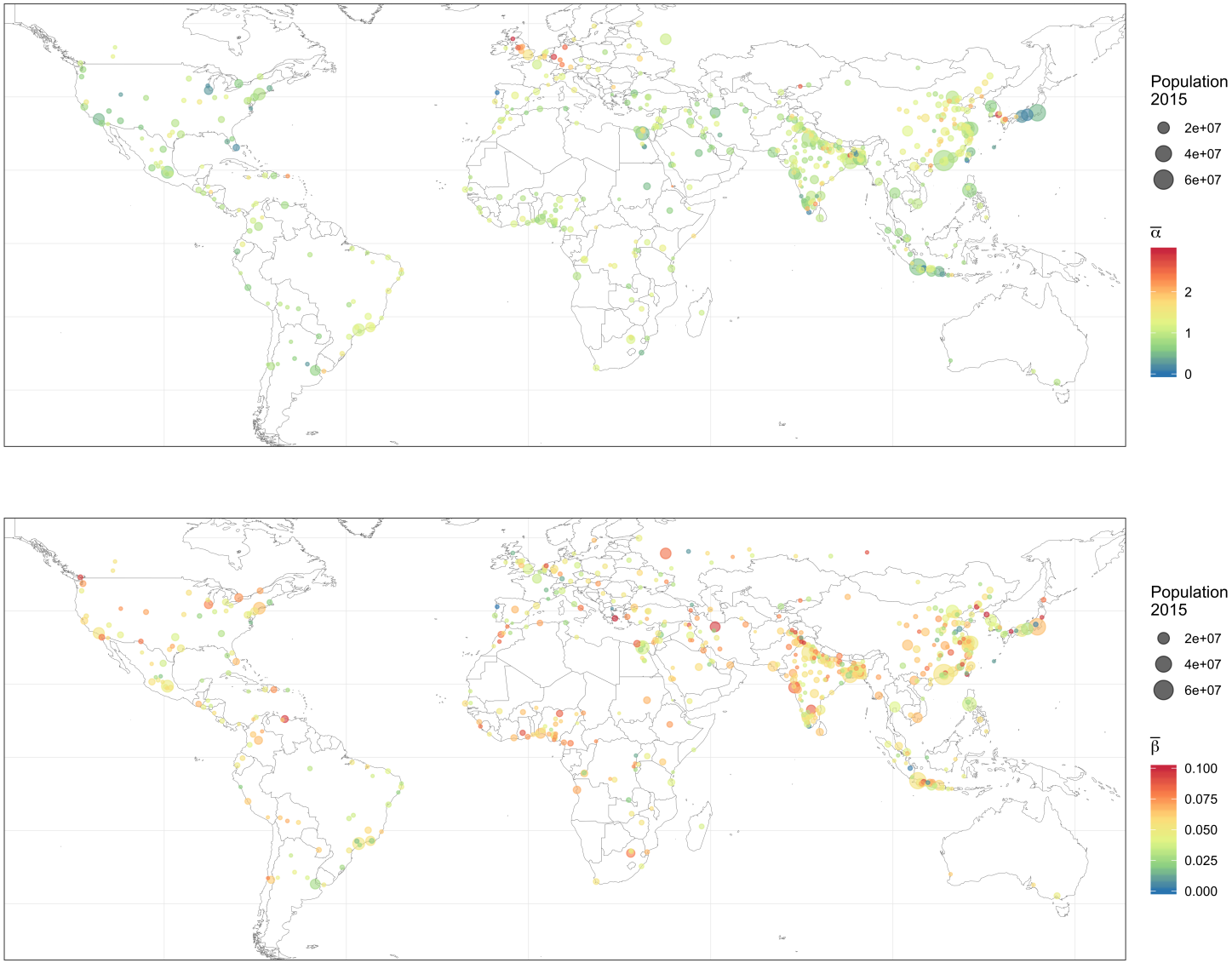
Apply for the OpenMOLE summer school before January 15th
`https://exmodelo.org/`

Examples of results

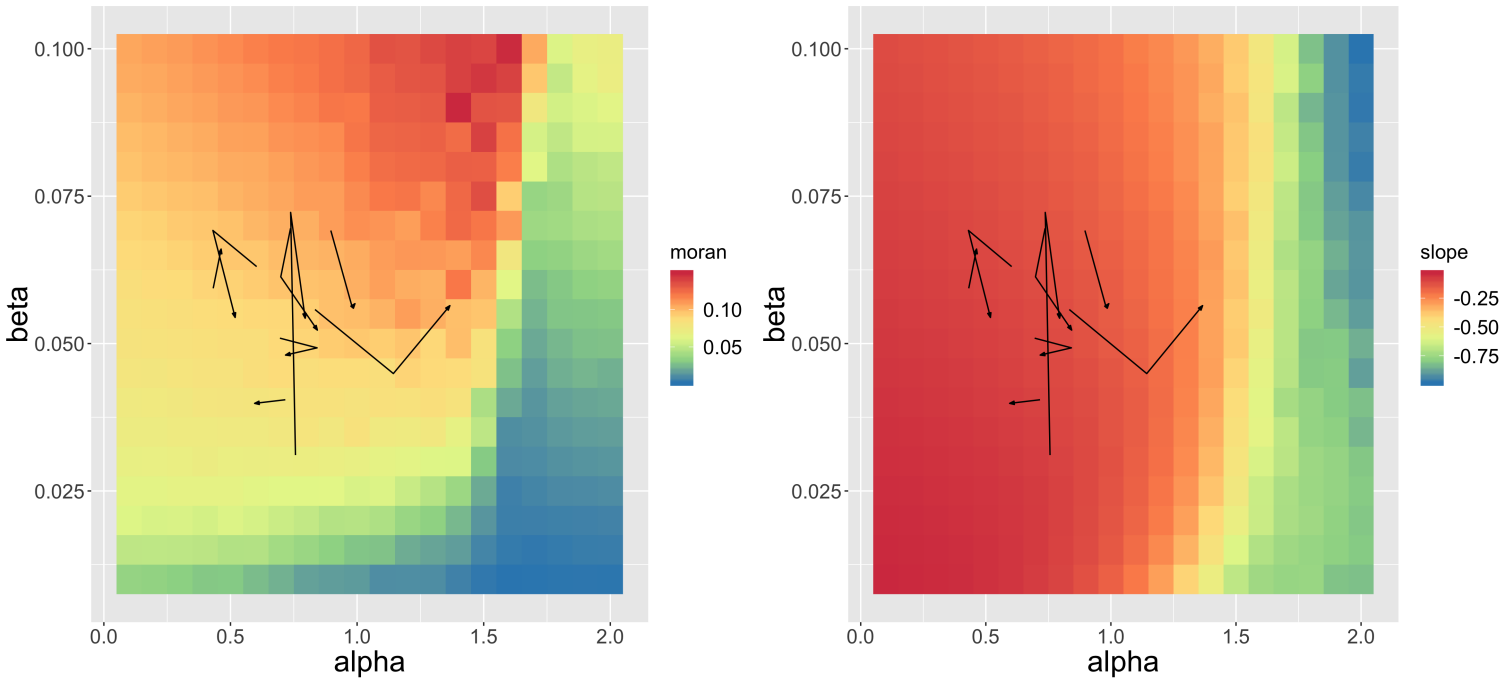


Different performance on indicator fit and forms of Pareto fronts

Adjusted parameters

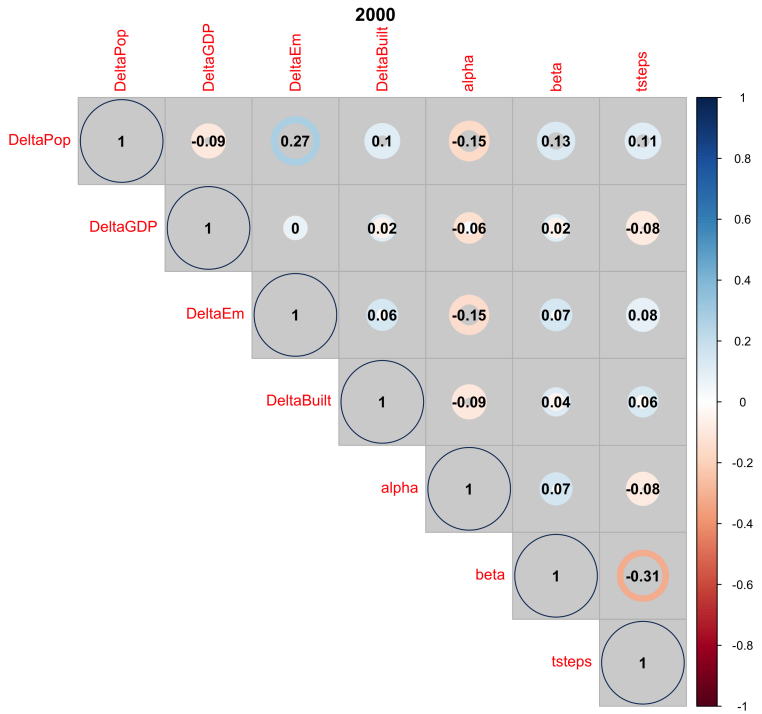


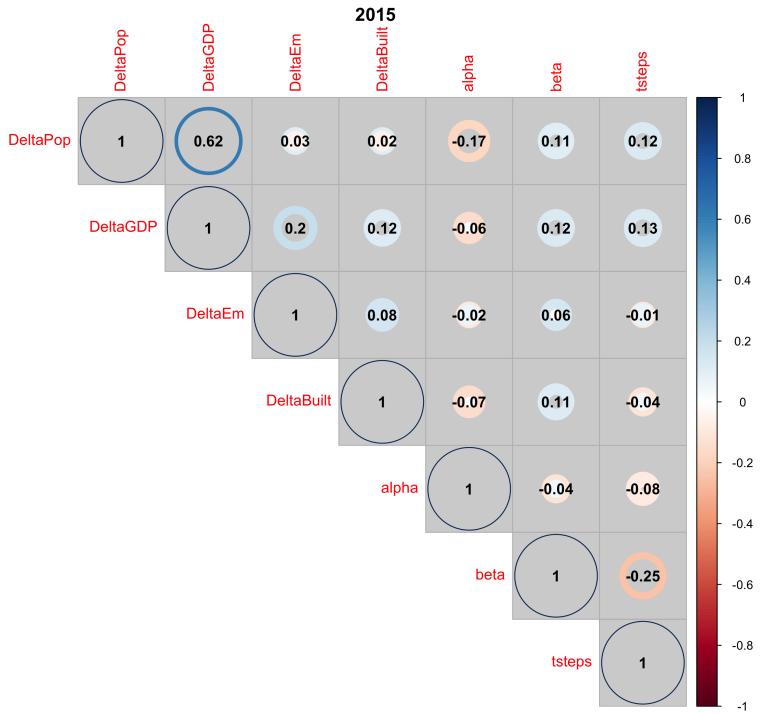
Trajectories in phase diagrams



Urban areas trajectories can be projected into model phase diagrams

Correlations





Slight significant correlations with growth rates of GHG emissions: more aggregation correlates with decreasing emissions e.g.

Discussion

Implications

→ This rather simple model can effectively be calibrated on worldwide urban areas and provide comparable growth parameters

→ Link between urban form, urban dynamics and sustainability properties

Developments

→ Benchmark with other simple models (e.g. [Li et al., 2019] presented yesterday)

→ Coupling with macro-scale model for system of cities [Raimbault, 2019a]

→ Investigate the link between spatial non-stationarity and non-ergodicity through simulation by the model

Towards policy applications

Within the same stream of modeling (complementary to more classical approaches to land-use change):

More realistic models?

$\rightarrow$ Introducing more concrete ontologies, economic processes [Bonin and Hubert, 2014], qualitative differentiation [Bonin and Hubert, 2012] governance processes [Le Néchet and Raimbault, 2015]

$\rightarrow$ 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?

$\rightarrow$ More systematic link with sustainability indicators: GHG emissions, economics, etc. [Raimbault, 2019b]

$\rightarrow$ Study models on hybrid synthetic data [Raimbault et al., 2019]: systematic conclusions for policies

Conclusion

$\rightarrow$ A simple model of urban morphogenesis at the mesoscopic scale systematically calibrated: **need for more benchmarking and comparison of models.**

$\rightarrow$ At the macro scale of the system of cities? **Need for multi-scale models.**

$\rightarrow$ With more refined urban characteristics and other dimensions ? **Need for more interdisciplinarity.**

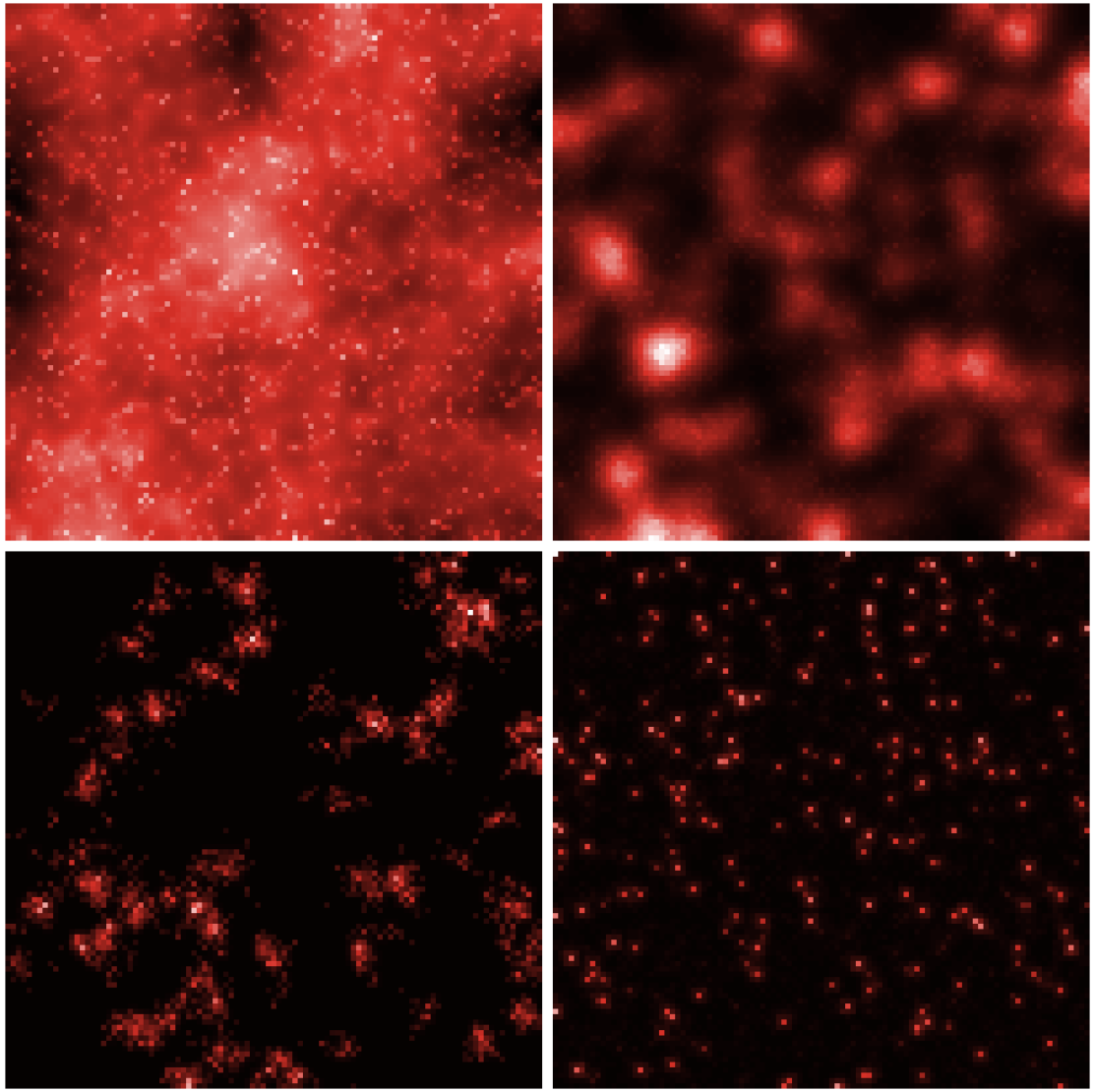
Use and contribute to OpenMOLE: `https://github.com/openmole`

Apply to the summer school: `https://exmodelo.org/`

- Code, data and results available at `https://github.com/JusteRaimbault/UrbanGrowth`
- 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

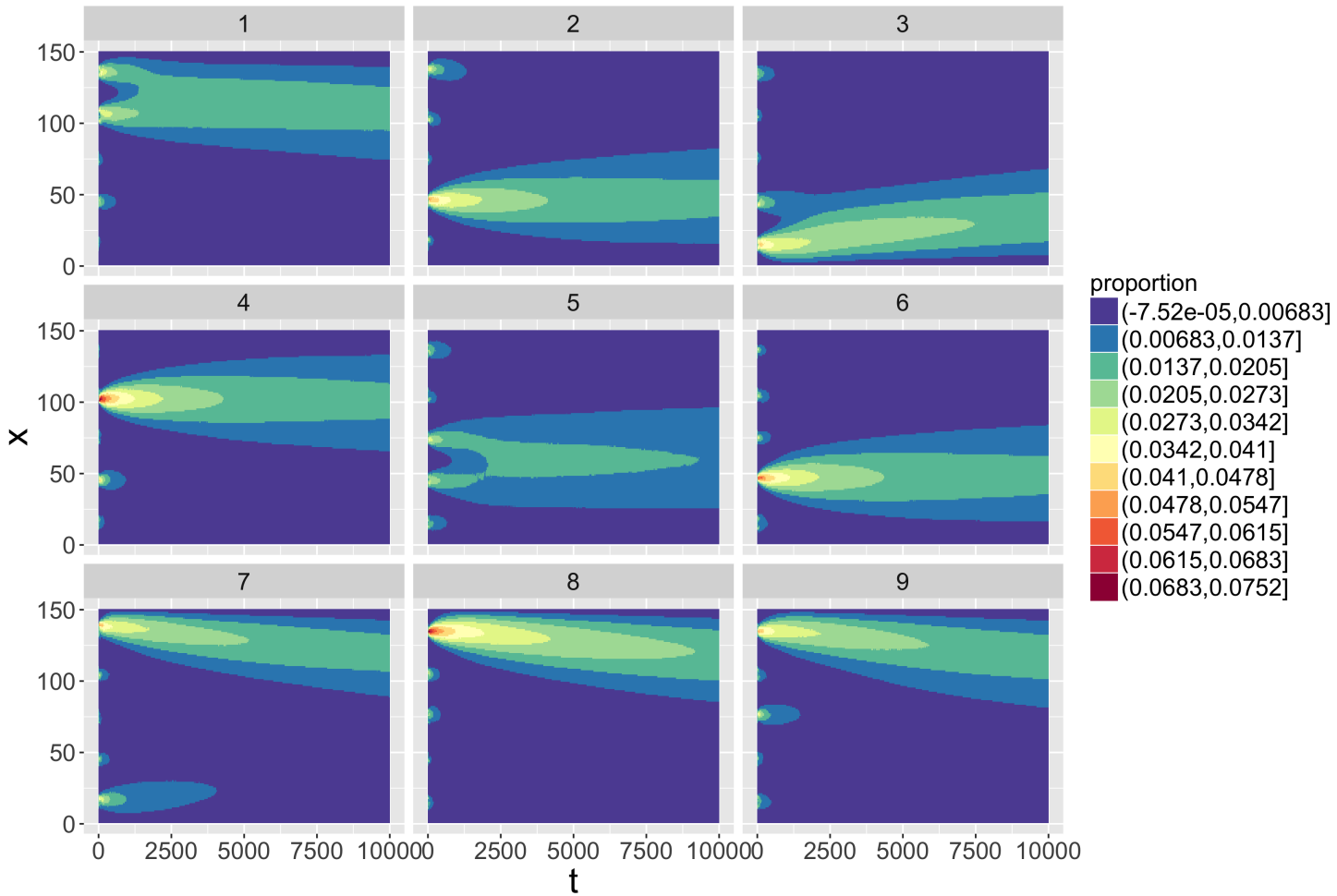
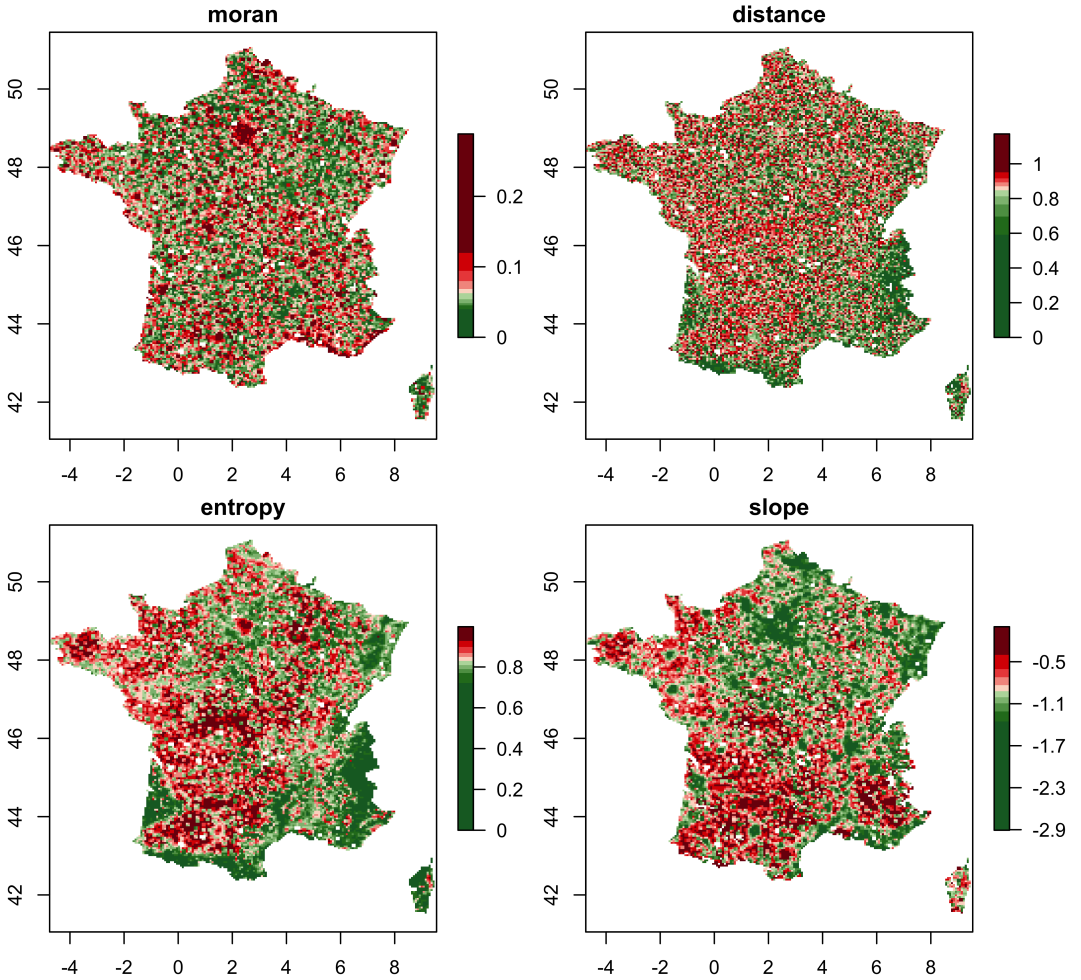
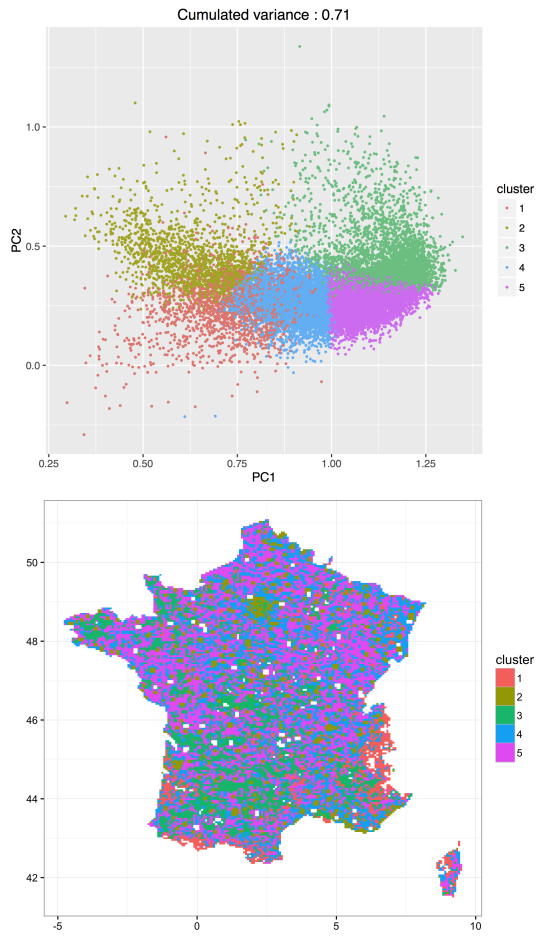


Illustration of path-dependence in a simplified one-dimensional version of the model: cell trajectories in time for 9 independent repetitions from the same initial configuration.

Empirical Data (moving window)



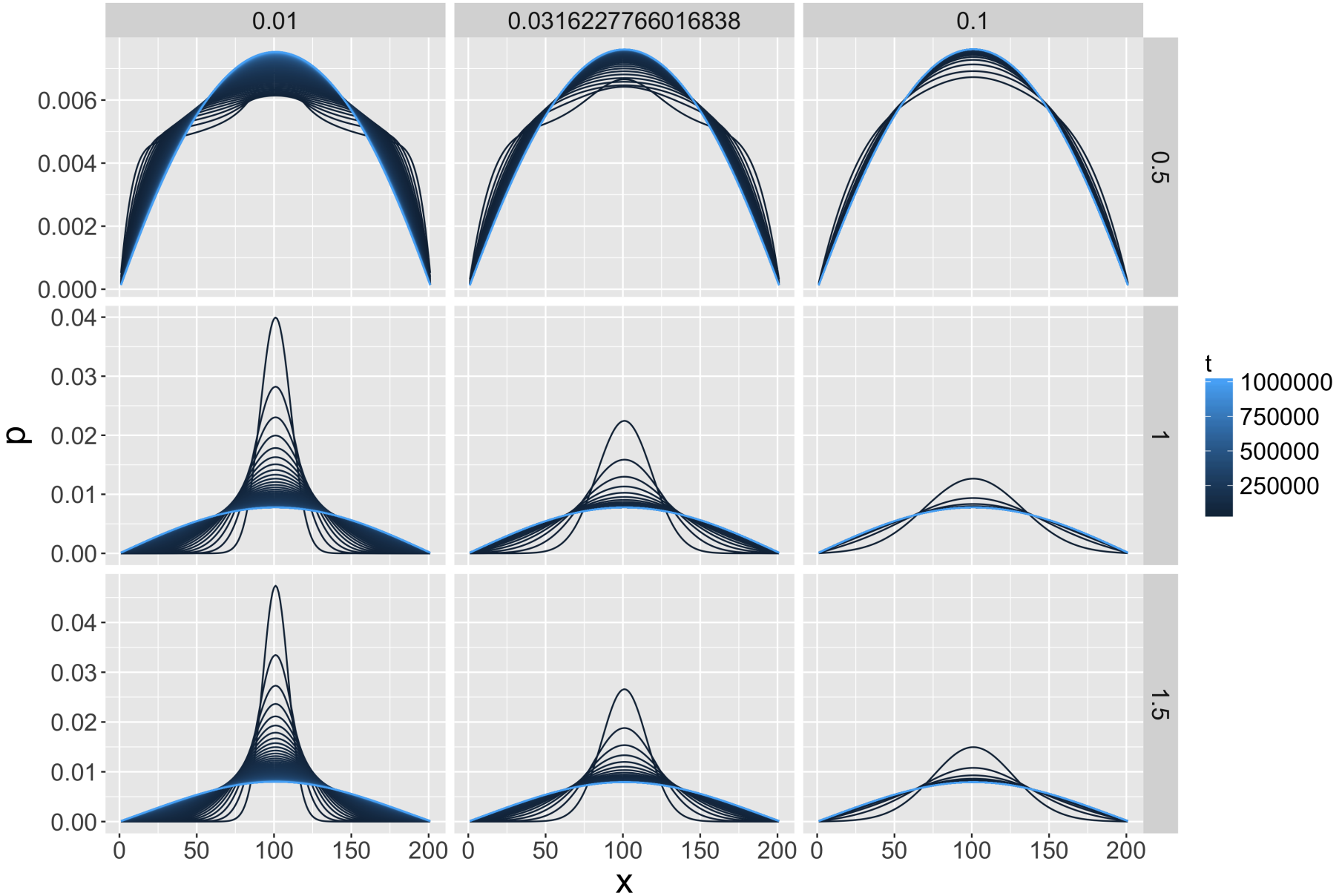


Computation of morphological indicators on population density data for Europe (shown here on France), morphological classification.

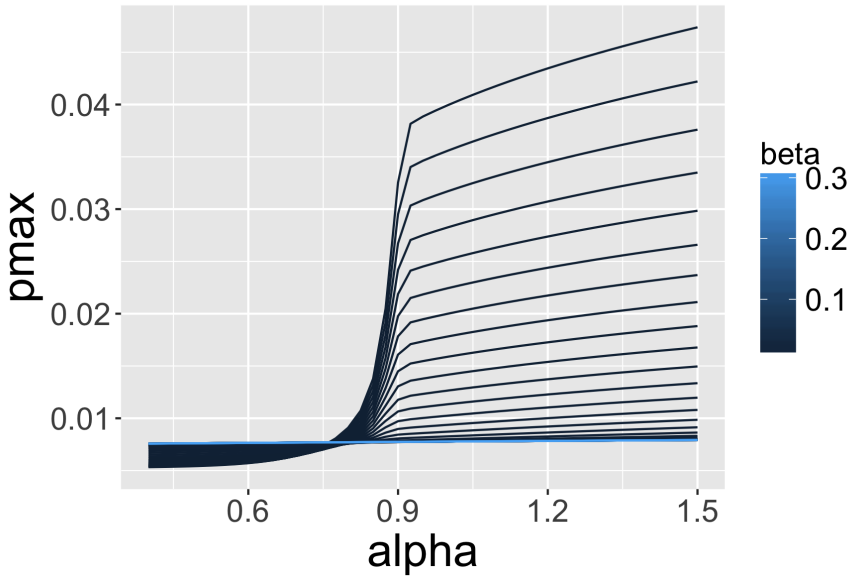
The one-dimensional model verifies the PDE :

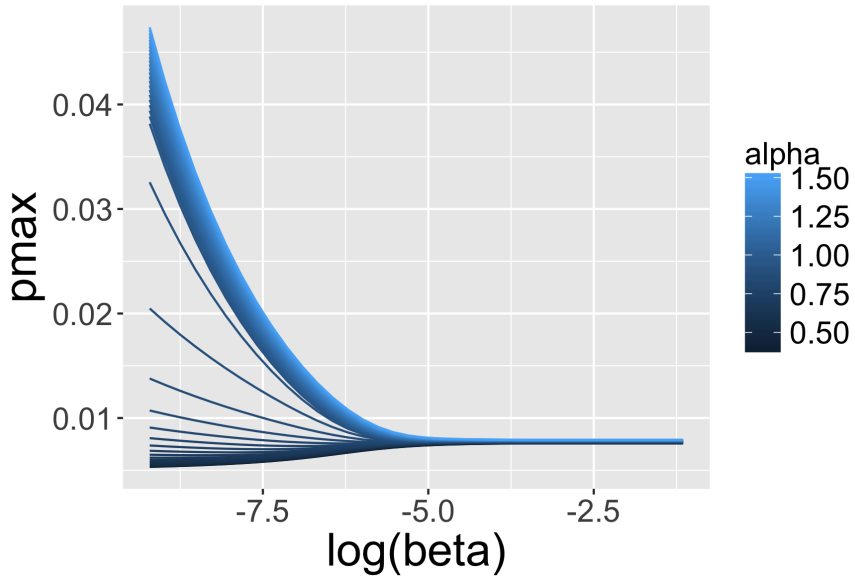
$$\delta t \cdot \frac{\partial p}{\partial t} = \frac{N_G \cdot p^{\alpha}}{P_{\alpha} t} + \frac{\alpha\beta\left(\alpha-1\right)\delta x^2}{2} \cdot \frac{N_G \cdot p^{\alpha-2}}{P_{\alpha}\left(t\right)} \cdot \left(\frac{\partial p}{\partial x}\right)^2 + \frac{\beta \delta x^2}{2} \cdot \frac{\partial^2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

Stationary behavior of 1D model



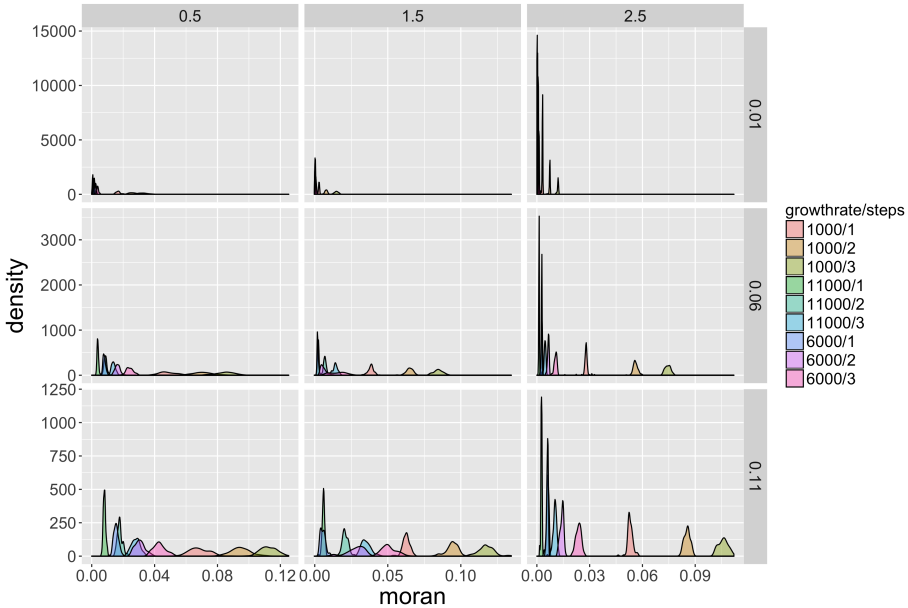
Stationary behavior of 1D model

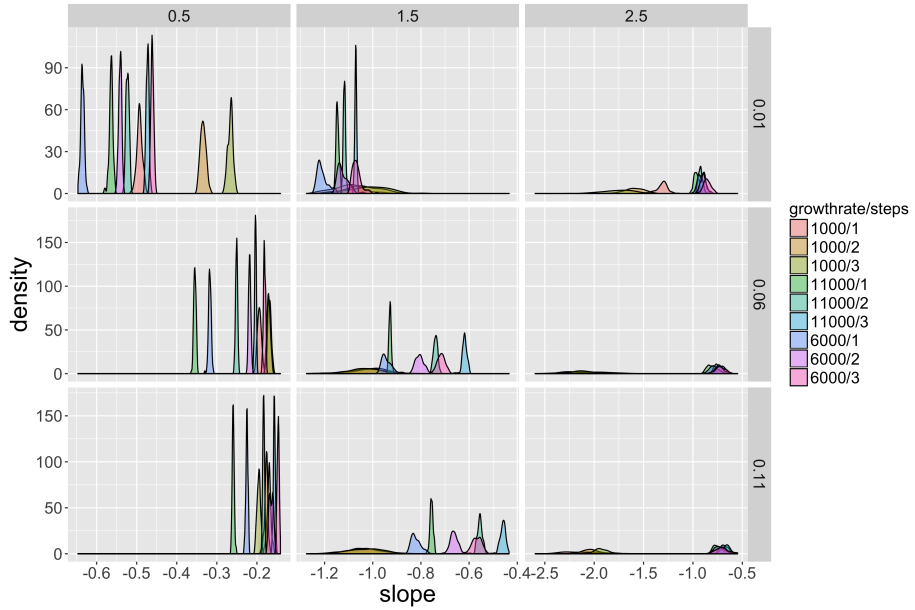




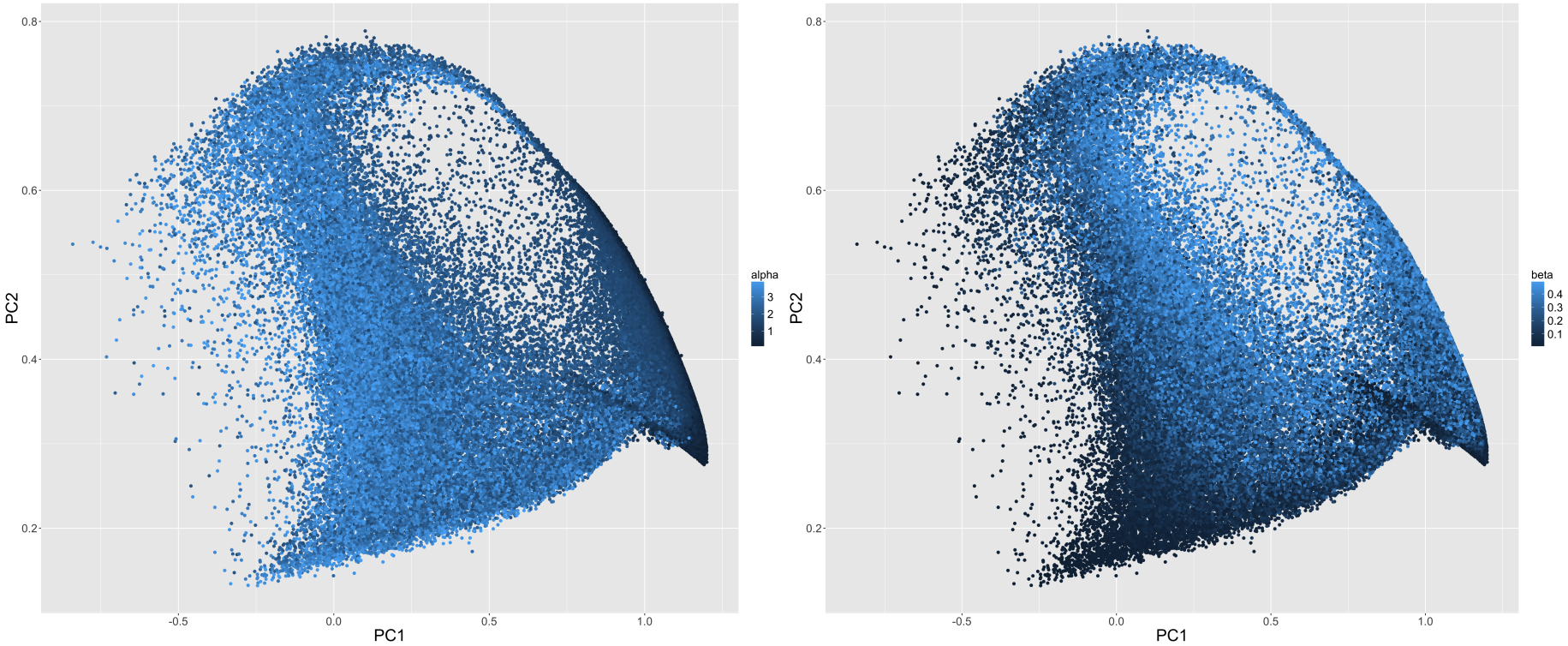
Model behavior : Convergence

Large number of repetitions show good convergence properties





Model behavior



Empirical indicators computation

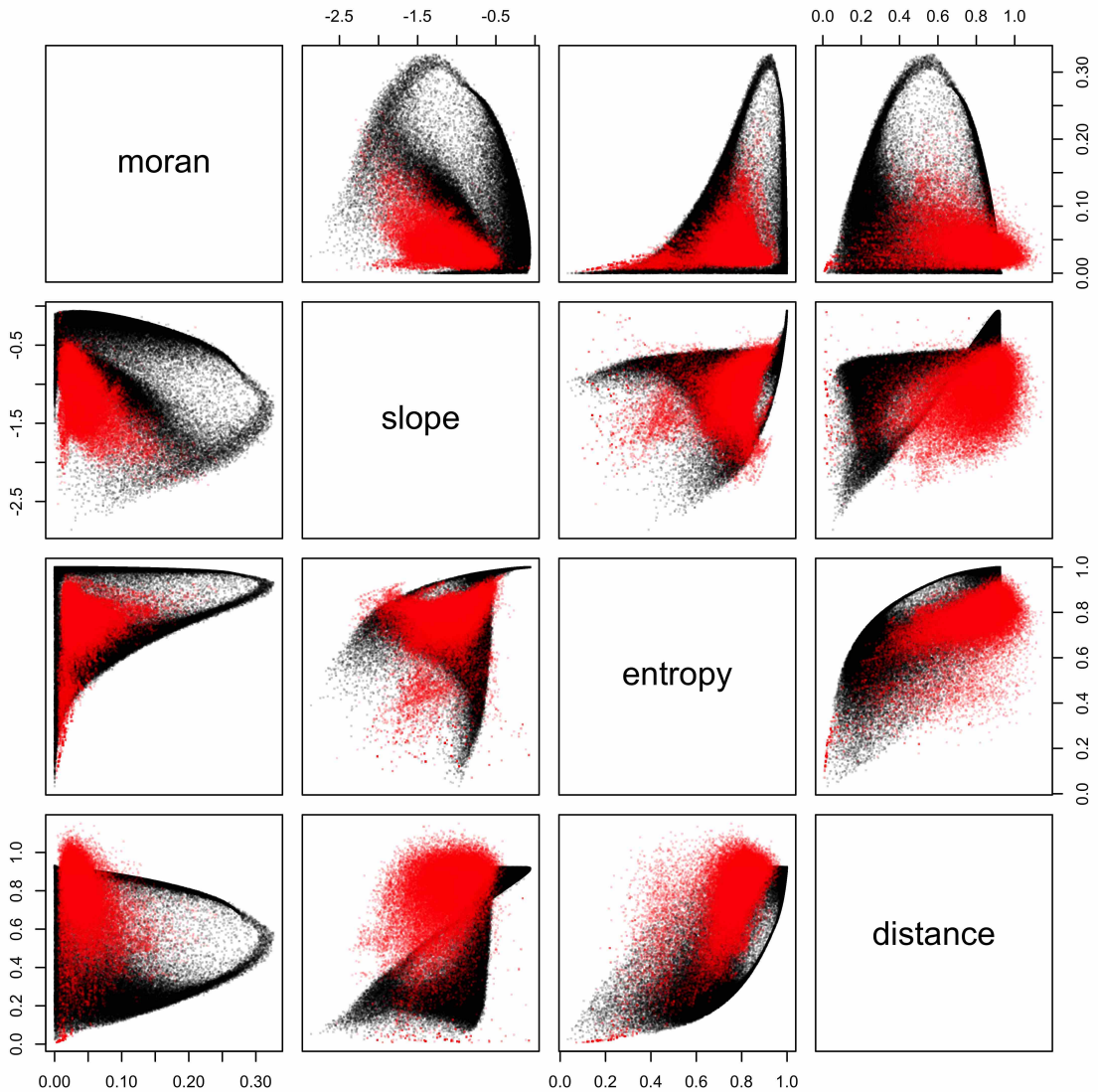
$\rightarrow$ Eurostat population density raster (100m, simplified at 500m resolution)

$\rightarrow$ 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)

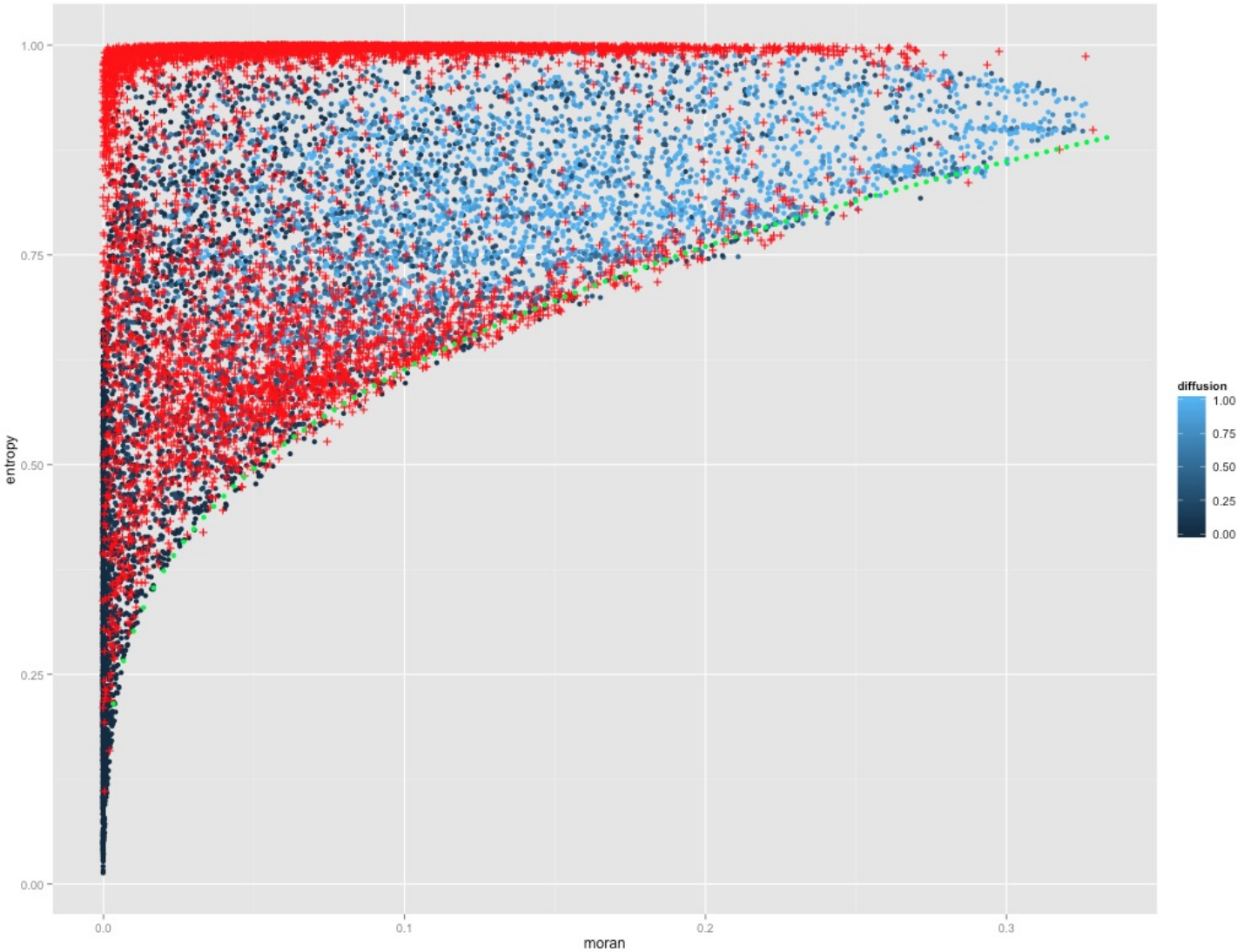
$\rightarrow$ Indicators computed using Fast Fourier Transform Convolution

$\rightarrow$ 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].

Defining Morphogenesis

Proposition of an interdisciplinary definition

Meta-epistemological framework of imbricated notions:
Self-organization $\supsetneq$ Morphogenesis $\supsetneq$ Autopoiesis $\supsetneq$ 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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