Radial Urban Forms:
Lessons from Land Profile Scaling Analyses & Spatial-Explicit Models

Geoffrey Caruso

geoffrey.caruso@uni.lu

LISER LUXEMBOURG INSTITUTE OF SOCIO-ECONOMIC RESEARCH

uni.lu UNIVERSITÉ DU LUXEMBOURG

Quantitative Urban Analytics & Spatial Data Research Luxembourg www.quadtrees.lu

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Acknowledgements

I acknowledge that we are in an existential human-induced climate crisis caused by excessive CO2 emissions from a variety of human activities.

While I recognize that our day-to-day transportation, energy use, materialistic consumption, animal-based diets and excessive flying impact the climate crisis, individual mitigation alone is no substitute for policy reform.

https://acknowledge-the-climate-crisis.org/

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https://showyourstripes.info ***Ed Hawkins (University of Reading)***

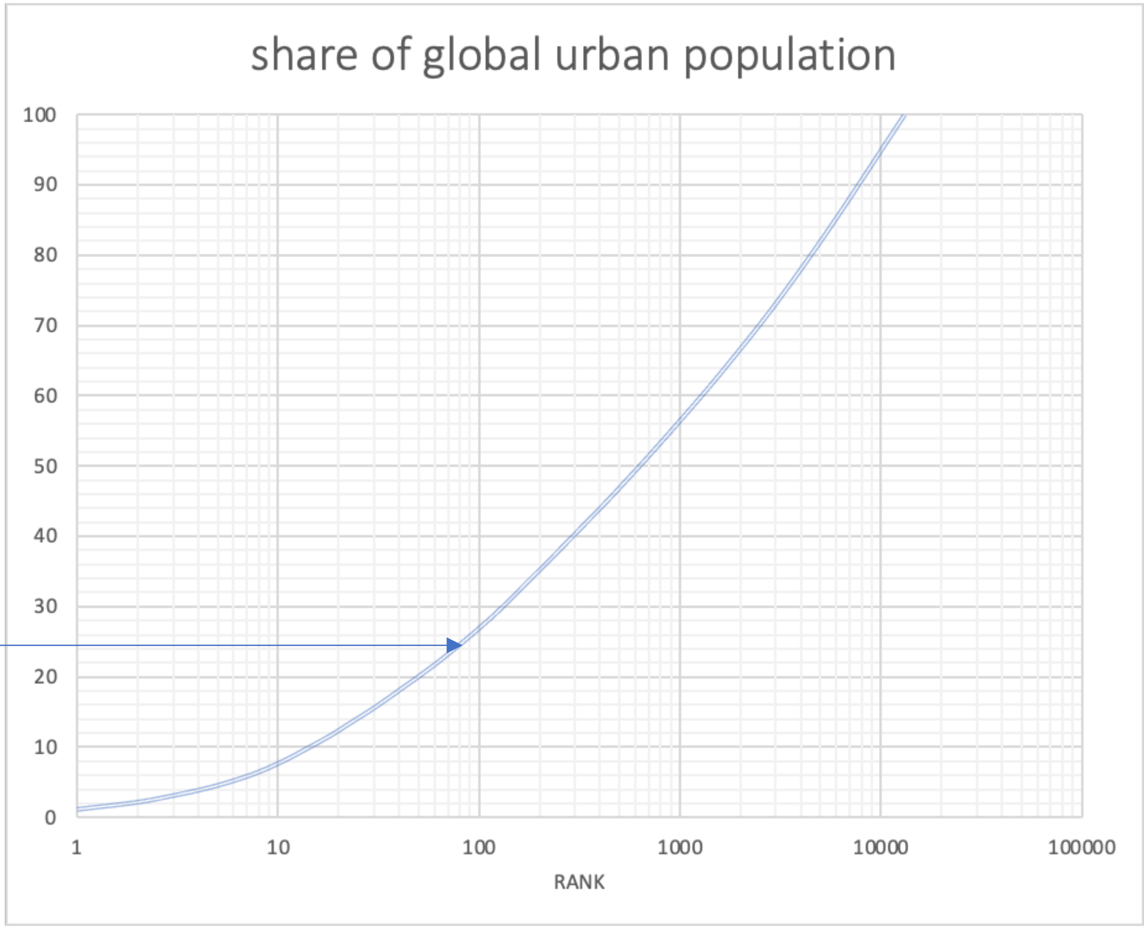
Abstract

We definitely live in an increasingly urban World for half of humanity now lives in cities. Cities provide wealth but also negatively impact the environment and the health of citizens. Arguably the benefits and costs of cities relate to both their size, in population terms, and their internal structure, in terms of the relative spatial arrangement of built-up and natural land. Much of urban research focusses on very large cities and urban cores. Yet 3 urban human out of 4 live in cities of less than 4 million inhabitants (according to the global GHSL dataset). Similarly, 3 out of 4 in a typical (European) city do not live in its core but beyond (using a 7-8km radius to define core for a city like London or Paris). To address urban sustainability issues and design adaptation policies, these 75% certainly count and, we can argue, also deserve specific attention because of the relative proximity between urban and non-urban (natural) use that smaller cities and suburban (non-core) areas may permit. In this respect, it is key to understand how the internal structure of cities, in particular the form and density of built-up areas and the interwoven green space emerge out of the core up until the fringe. It is also key to understand whether the form of cities, especially density gradients and the share of urbanised/non-urbanised land change with city size. In this talk we draw lessons from 2 research approaches to urban forms: one theoretical that uses spatial micro-economic simulations, and one empirical that uses spatially detailed land use datasets. Our theoretical simulations relate individual behaviour to urban forms while our empirics relate urban forms to city size. Both have in common a radial perspective to cities, i.e. explicitly or implicitly assuming that the accessibility trade-off to a given centre is a key determinant of locations and land uses. In both cases, we look at urbanisation and green space structures and at pollution exposure as an example of impact.

3 “urban human” out of 4 live in cities of less than 4 million inhabitants

25% -> Rank 84 ~ 4. 10^6 inhab.

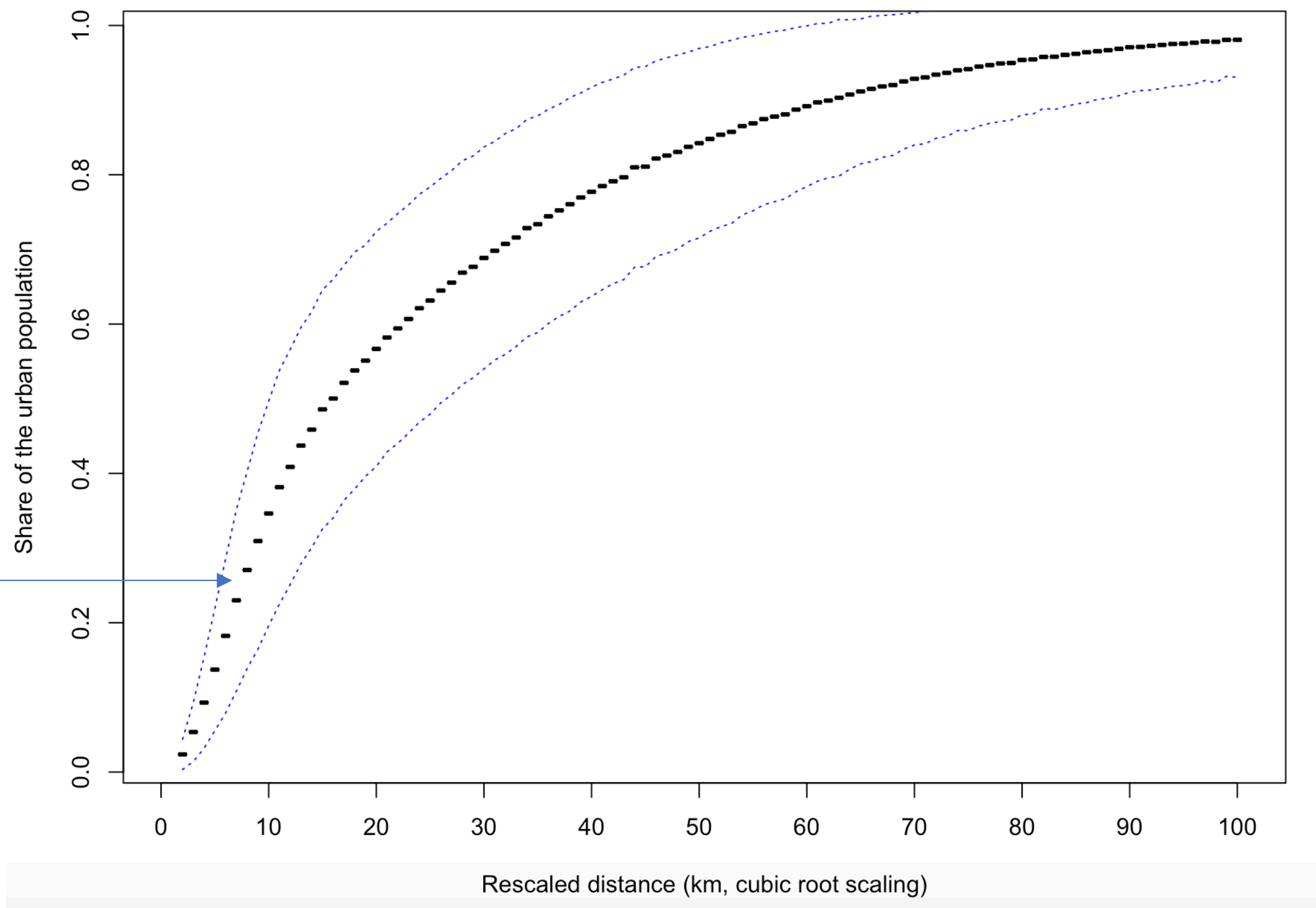
(cumulated: 0.88 billion inhab.)



Author computation from https://ghsl.jrc.ec.europa.eu/datasets.php aggregate urban centers population table

3 “European urban human” out of 4 live out of the central core

25% -> within 7 km equivalent of Paris CBD



75% urban population

> <

Strong focus on compactness and densification (urban planning) and agglomeration benefits over last 20 years

“Central city” and “Global city” focus in smart cities/urban governance/urban economics literature

Objectives: Understanding Radial Urban forms

- How urbanisation develops from centre to periphery ?
- Any general law and link with city size?
  - Route 1 : Empirical – statistical trends in land use profiles

- How can different urbanisation forms emerge from simple residential choice mechanisms?
  - Route 2: Theoretical – simulations from scratch

Motivating questions – 1/2 societal/scientific

- Are bigger cities better/greener?
  - *"as cities get bigger, they get greener in the sense of becoming more sustainable"* (Batty 2014, p.40) ?
  - *Triumph of the city* (Glaeser 2012)
- Alternative: What role for smaller cities and for suburbs?
  - Arguably built-up space more closely integrated with natural undeveloped land (maybe?) and source of social benefits/environmental effects mitigation?
  - *Suburban planet* (Keil 2017)
- Which internal structure for a better/greener city **given its size**?

Motivating questions – 2/2 epistemological

- A city is more than a single aggregate number as in urban systems theory / and geographical economics
- Liaise intra-urban forms/patterns with aggregate social/environmental outcomes, including size

- Question the definition of a city/urban region
  - E.g. Louf,Barthelemy 2014: whether bigger cities are more green depends on definition

- Long-run: Integrate dichotomous intra-urban and inter-urban research/theories

Plan

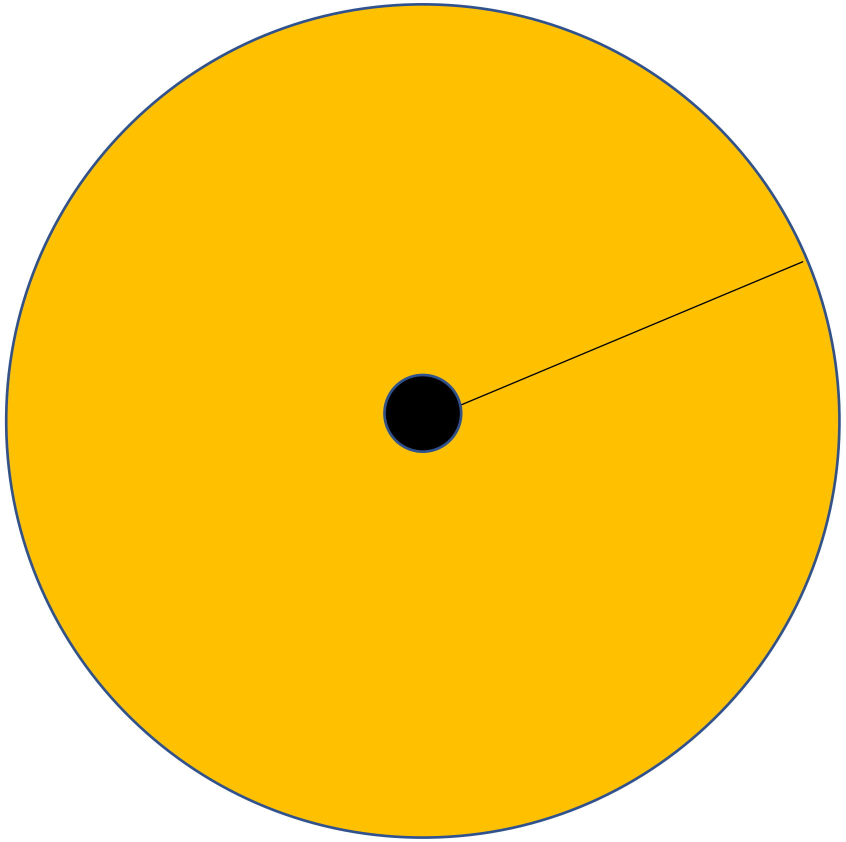
- Radial/monocentric bias

- Route 1: Empirical research
  - 1.1. Document urbanisation profiles in Europe and the World
  - 1.2. Green space gradient /integration and ecosystem services

- Route 2: Micro-economic theoretical simulations
  - 2.1. Urban patterns with endogeneous green space
  - 2.2. Urban patterns with endogeneous pollution

Radial perspective – reasonnable “bias”?

- Radial ~
  - One main centre
  - Centre-periphery distance lens



Radial assumption is **empirically acceptable**

- Polycentricity emerges when cities grow large (Barthelemy et al.) Monocentricity is valid for a very large set of cities. *(I am fine with a 90% relevance ;-))*
- Dominance of one center in polycentric systems
- Polycentricity depends on scale, i.e. delineation of cities (see later for a resolution):
- Center-periphery interactions are many and add to commuting for work/school

Radial assumption is **methodologically useful**

- **Fundamental trade-off between land/housing costs and transportation costs**

- Dialogue with urban economics where space is 1D
  - Complementarities, falsification tests of theories
  - Clark 1951 negative exp. density , now explored with large datasets

- 1D => Capacity to obtain analytical results mathematically that
  - Complement simulations in 2D space (ABM)
  - Constrain numerical explorations => facilitates exploration of multi-parameters space

- Many planning instruments are implicitly/explicitly radial:
  - green belts, congestion charge, parking policies, housing/land pricing systems,…

Plan

- Radial/monocentric bias
- Route 1: Empirical research
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Land use data

- Europe:
  - Urban Atlas 2006 and 2012 (+combined with CORINE Land cover)
  - N=305 functional urban regions (defined from density and commuting thresholds)
  - Authors: European Union
  - Source: https://land.copernicus.eu/
- World
  - Atlas of Urban Expansion 2016
  - N=200 select sample
  - Authors: Angel et al. New York Univ., UN-Habitat, & Lincoln Institute of Land Policy
  - Source: https://www.lincolninst.edu/publications/other/atlas-urban-expansion-2016-edition

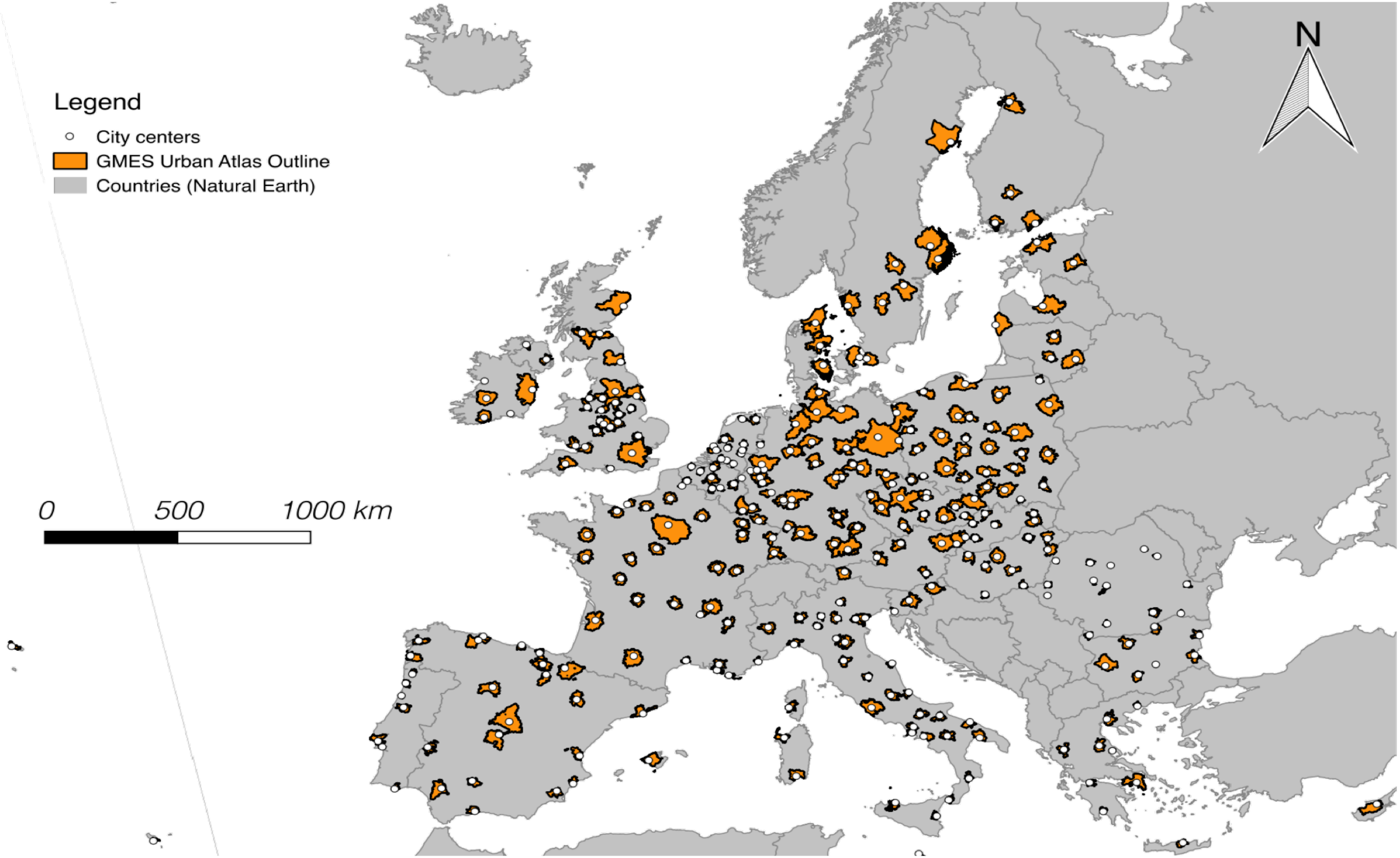
Europe : Methods- Europe

1. Radial computation of land use shares (and density) per distance bands
   - Vector buffers or Raster-based distances and cross-tabulation
   - + Geostats population downscaling for density
2. Stretching of axes as a f(total urban population) to optimize signal/noise ratio

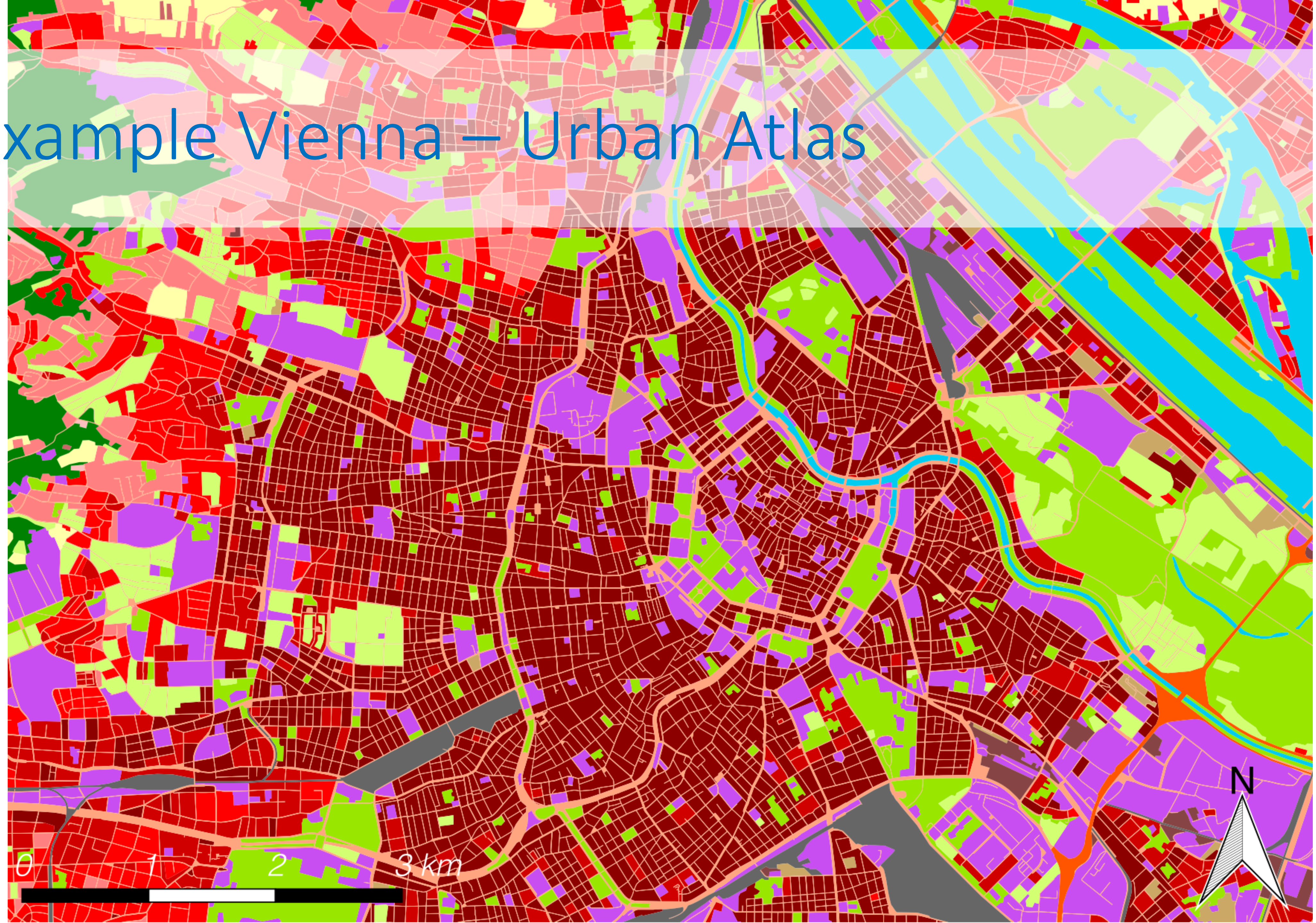
=> scaling law for internal urban profile !

Ongoing work for EU2012 (combined with CORINE land cover) with total population endogenized.

Methods details and results for EU 2006: Lemoy and Caruso, 2018. Evidence for the homothetic scaling of urban forms. *Env. And Planning B*.


Legend
City centers
GMES Urban Atlas Outline
Countries (Natural Earth)
0
500
1000 km
N

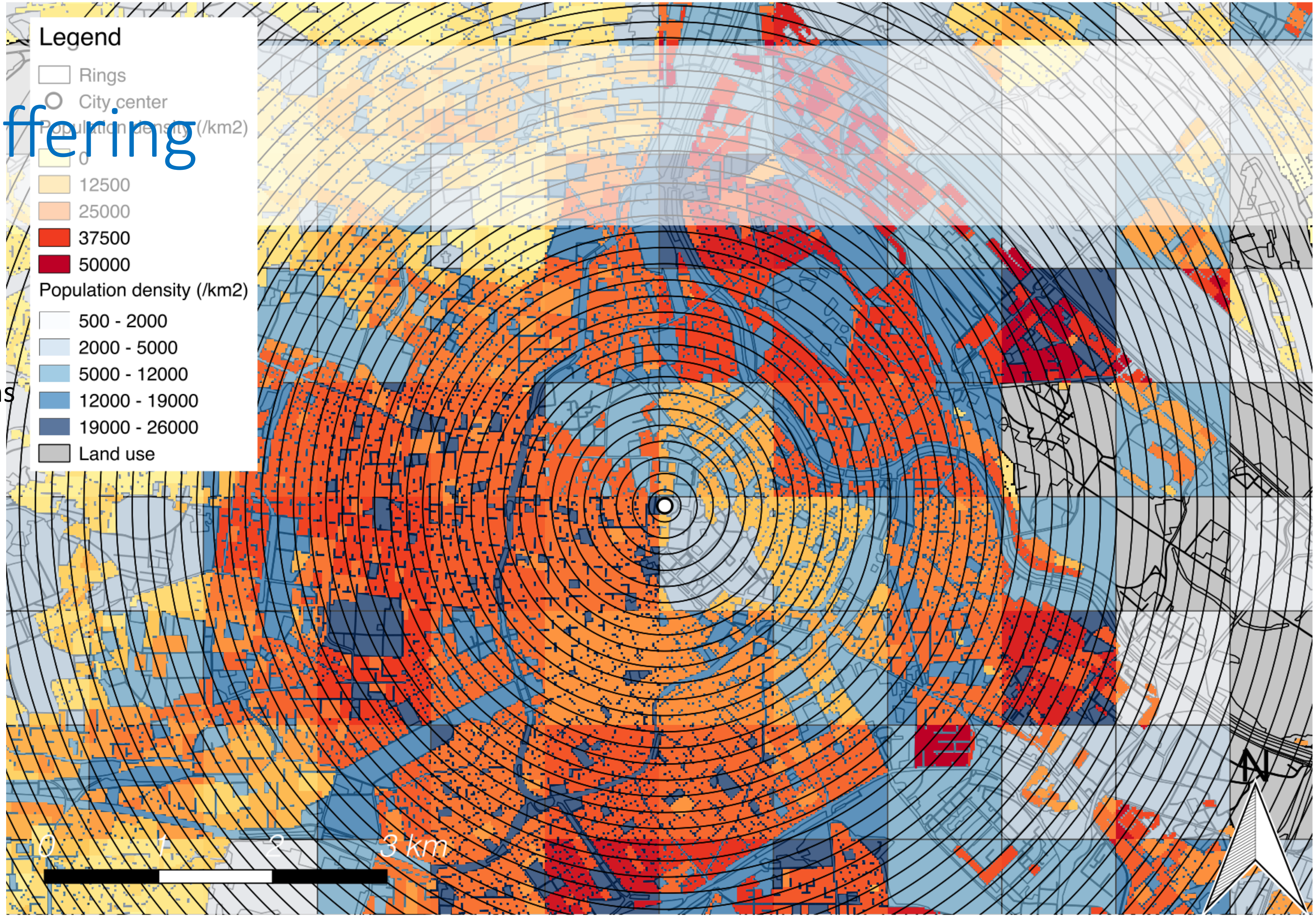
Example Vienna – Urban Atlas



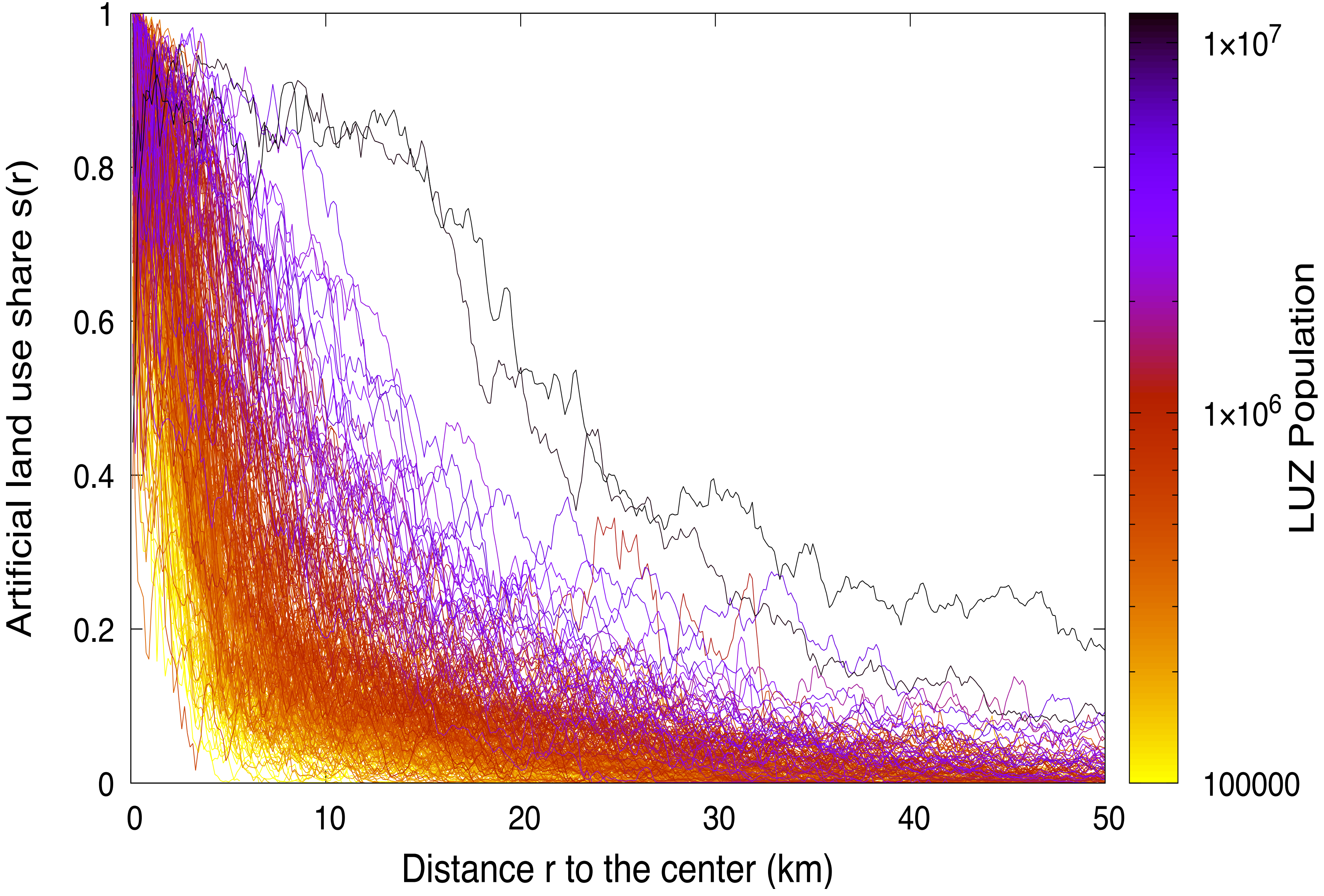
Buffering

CBD =
City halls +
Own corrections

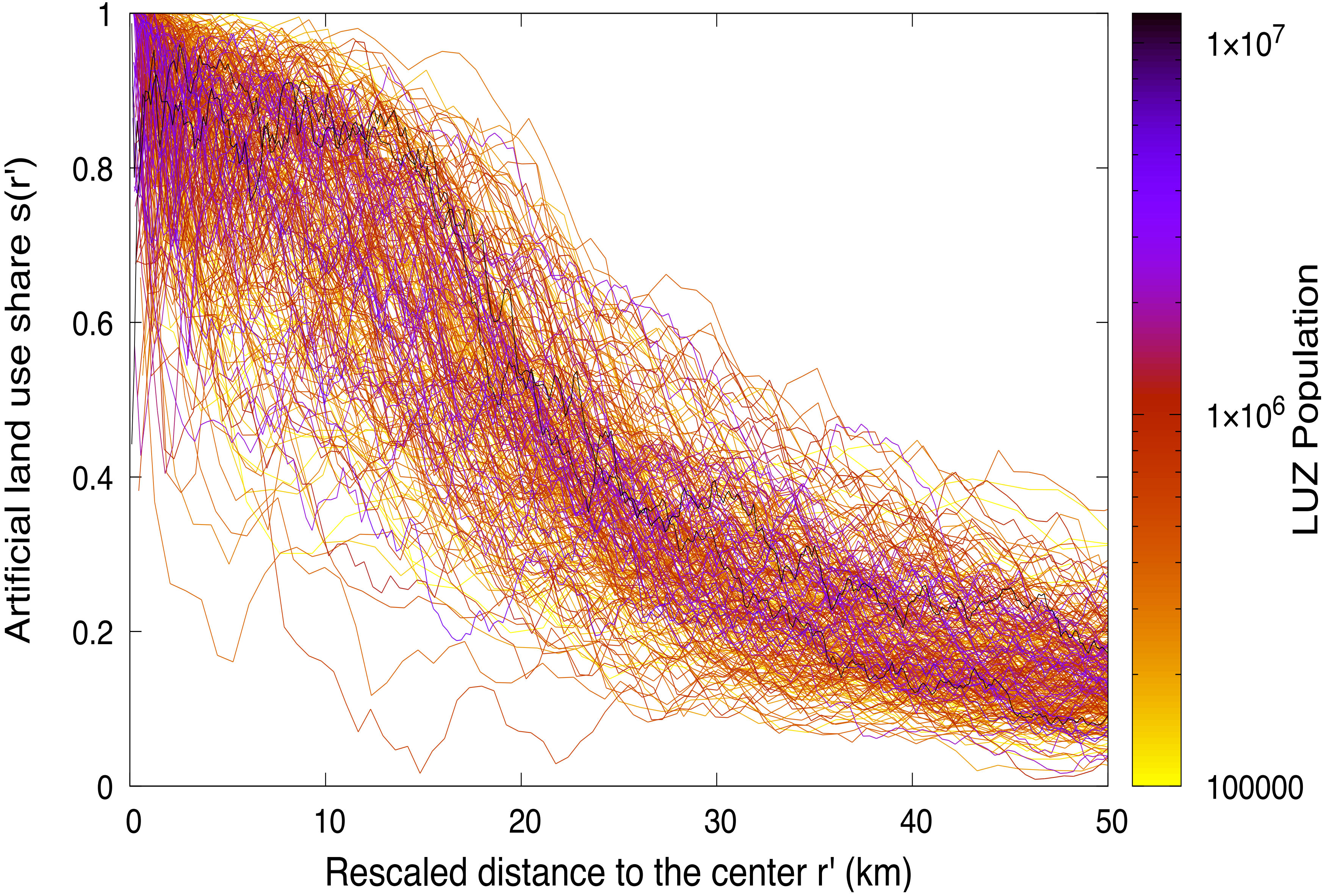
Geostats
Population
downscaling



Artificial Land use profile in Europe (2006)



Artificial Land profile in Europe - rescaled

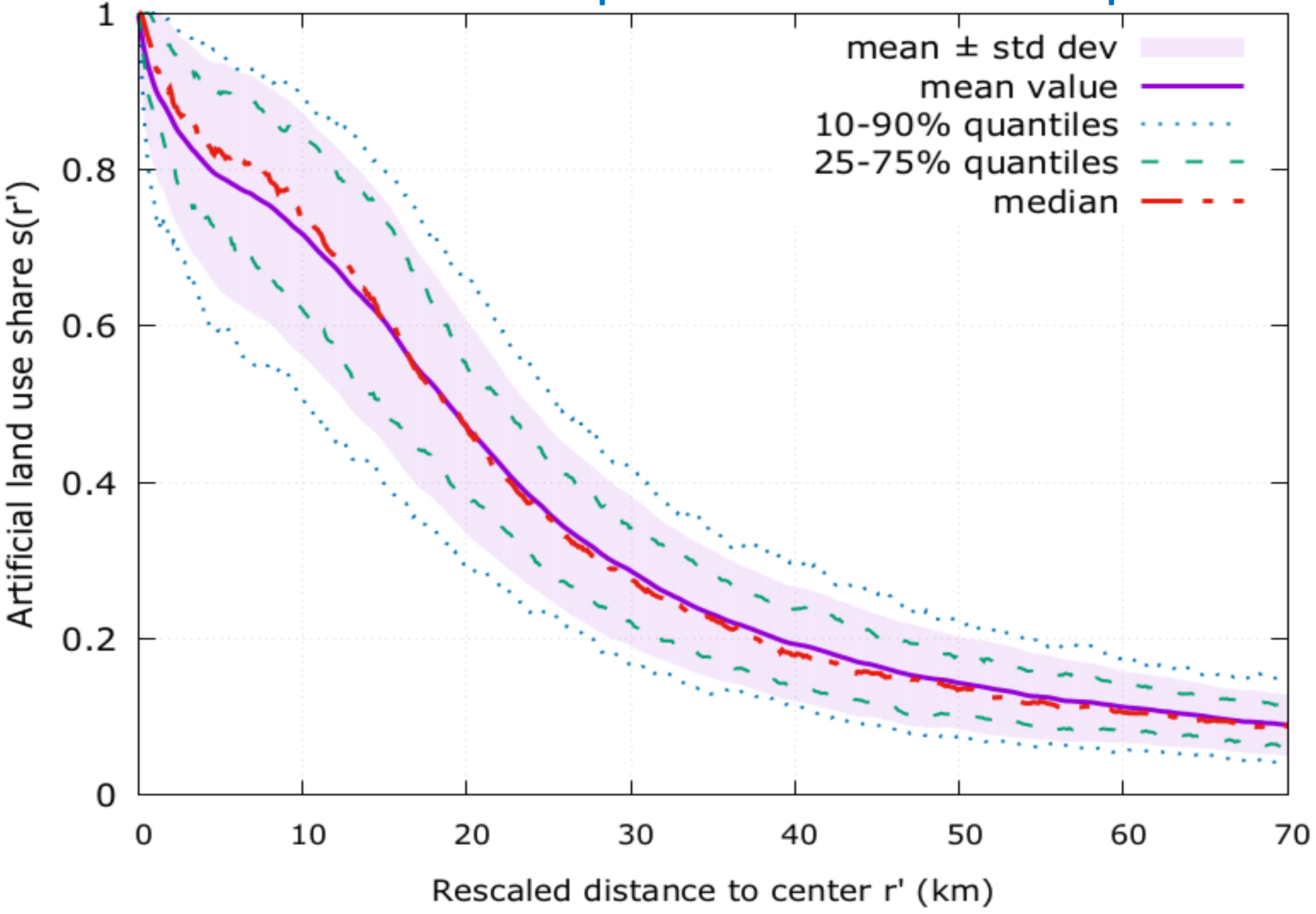


Rescaling the x-axis only, by the square root of population:

$r' = r/k,$

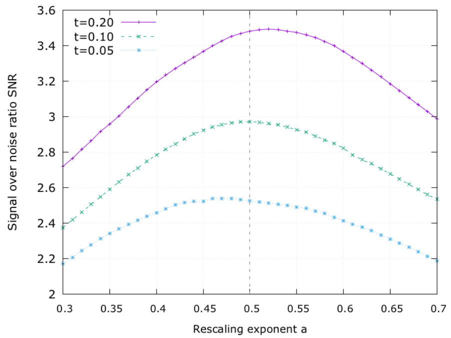
$k = \sqrt{N/N_{London}}$

Artificial Land profile in Europe - rescaled



Finding 1: Strong central trend (law)

Finding 2: Square root is optimal rescaling



'Signal'= $\int \langle s(r') \rangle 2\pi r' dr'$

'Noise'= $\int \sigma(s(r')) 2\pi r' dr'$

$r' = r/(N/N_{London})^a$

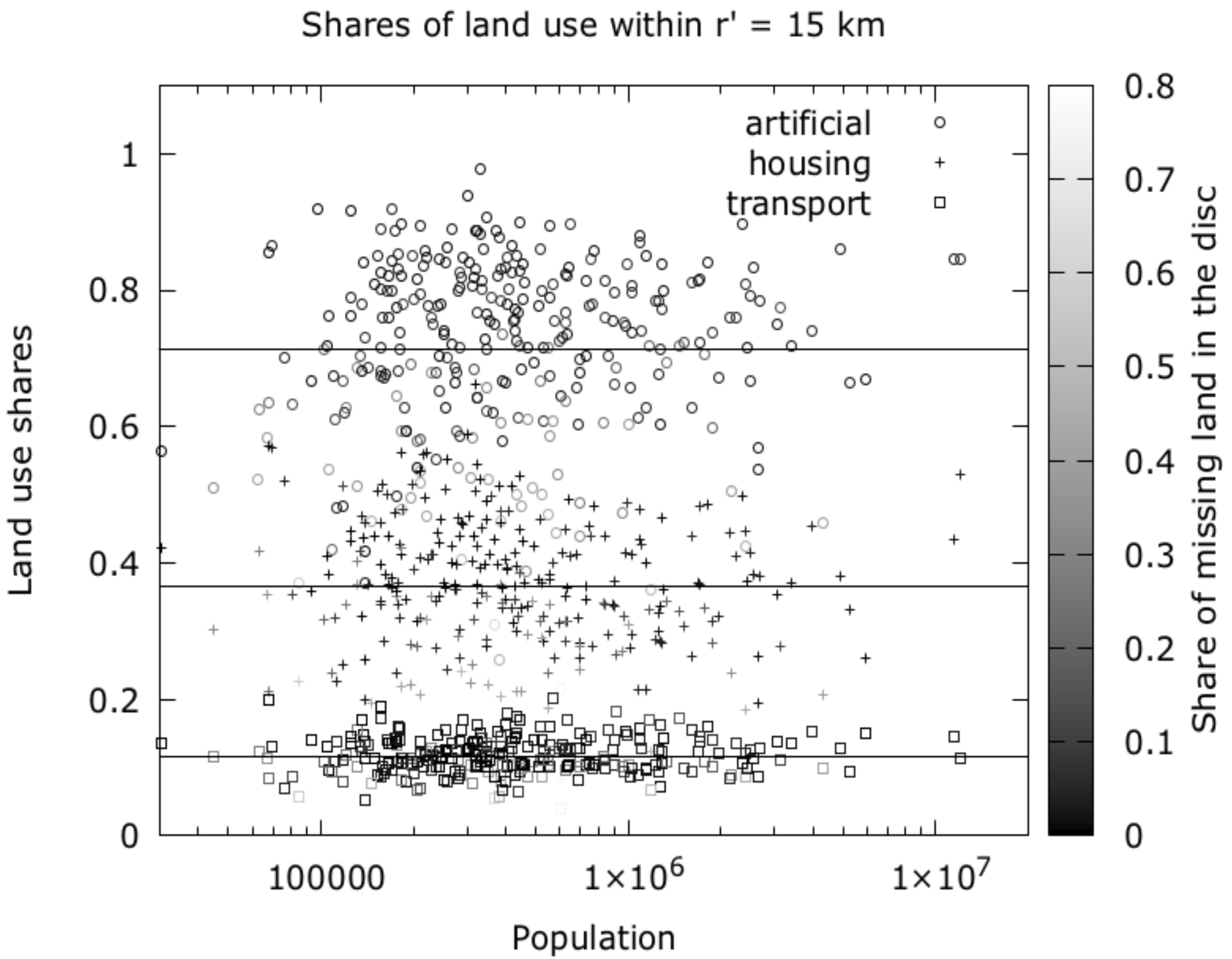
Artificial Land profile in Europe

Finding 3: constant share (no drift) at a given rescaled distance

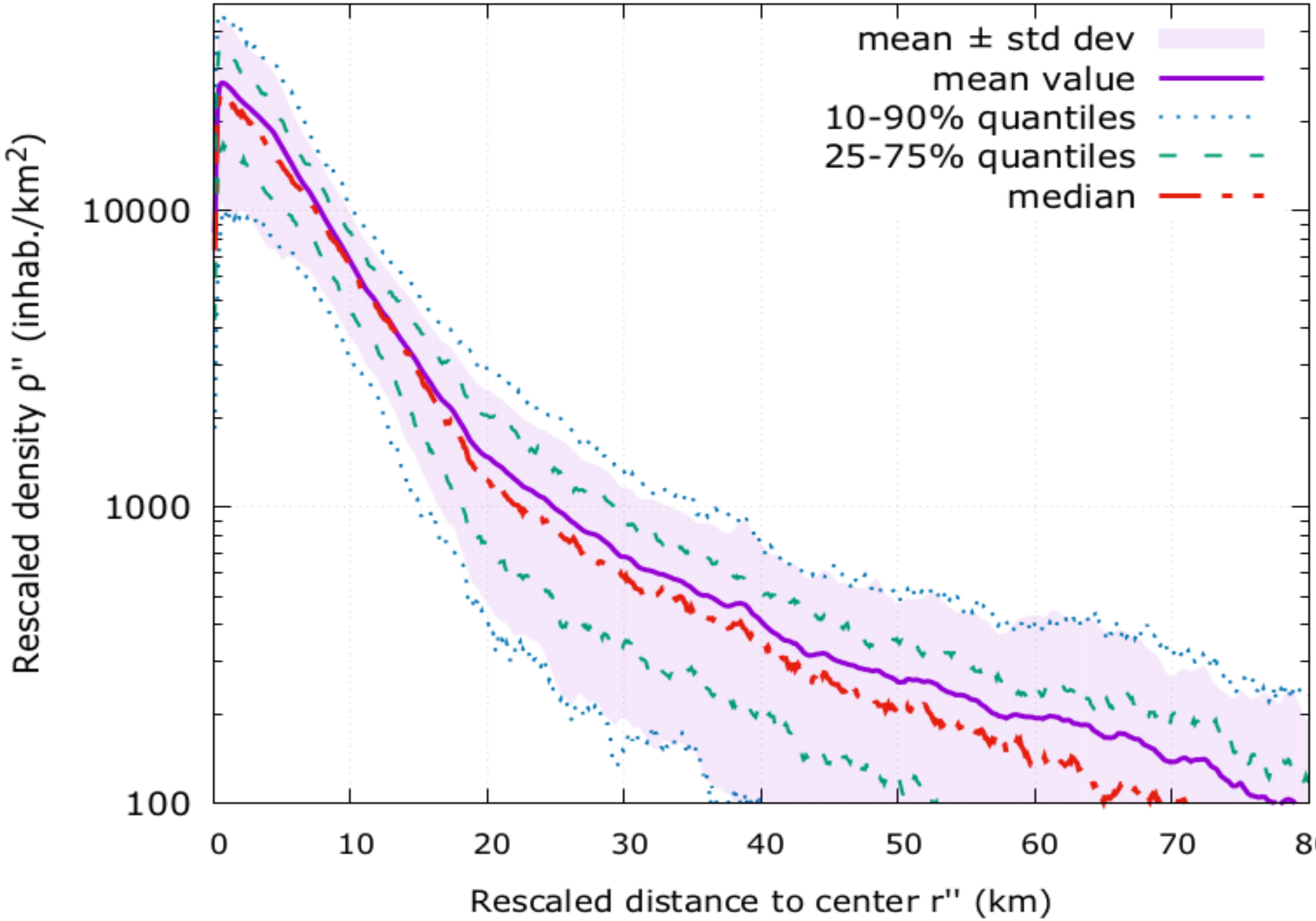
Great news for defining cities comparably on a morphological base!

Let's compare "**core cities**" e.g. defined as 70% of urbanised land at fringe

or "**cities with their sububurbs**" e.g. so that 40 % urbanised land at fringe



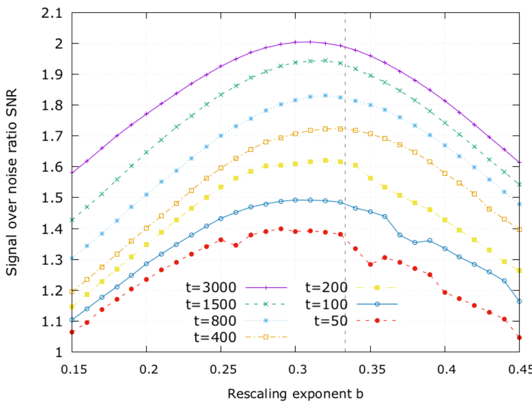
Population density profile in Europe- rescaled



Finding 1: Strong central trend (law)

(more dispersed at tail)

Finding 2: Cube root is near optimal rescaling of both axes



'Signal'= $\int \langle \rho''(r'') \rangle 2\pi r'' dr''$

'Noise'= $\int \sigma(\rho(r'')) 2\pi r'' dr''$

$r'' = r/(N/N_{London})^b$

$\rho'' = \rho/(N/N_{London})^b$

Empirical evidence to the intuition of Nordbeck 1971

It seems legitimate to claim that all urban areas have the same form and shape.

In the same way that a vulcano is a volume of dimension 3, so we may consider population of a tätort [urban area] as a volume with the same dimensionality. The area of a tätort has the dimension 2.

It follows then that the b-value in the allometric formula $A = -aP^b$ *ought to be* $2/3$

Nordbeck, S., 1971. Uban Allometric Growth. *Geografiska Annaler. Series B, Human Geography.* 53, 54–67.

Regression estimate of the urban land gradient for **any city given its population size**

Linear (L) $\log(s_N(r)) \sim \log(a_N) - r/l_N$

Non Linear (NL) $s_N(r) \sim a_N \exp(-r/l_N)$

with

$\log(l_N) \sim \log(l_1) + \alpha \log N$

$l_N \sim l_1 N^{\alpha}$

imposed to 1

	L	NL	SNL	NL20	SNL20
Scaling exponent α	0.310***	0.499***	0.512***	0.506***	0.512***
	(0.024)	(0.012)	(0.014)	(0.012)	(0.011)
Exp(constant): l_1 (m)	124.2***	7.64***	6.23***	7.06***	6.64***
	(45.4)	(1.32)	(1.24)	(1.15)	(1.03)
Observations	302	302	302	246	246
R^2	0.356	0.847	0.816	0.886	0.897

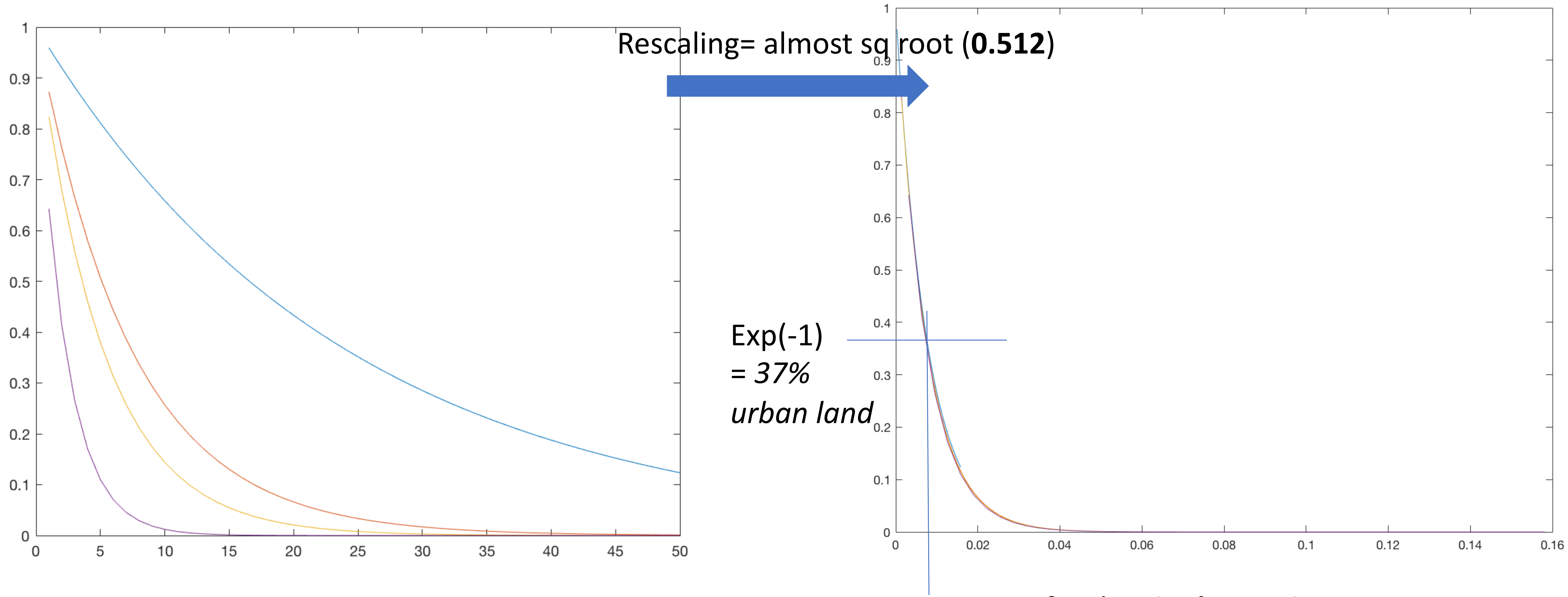
Note: ***p<0.01

Linear model on logs performs badly

Square root confirmed

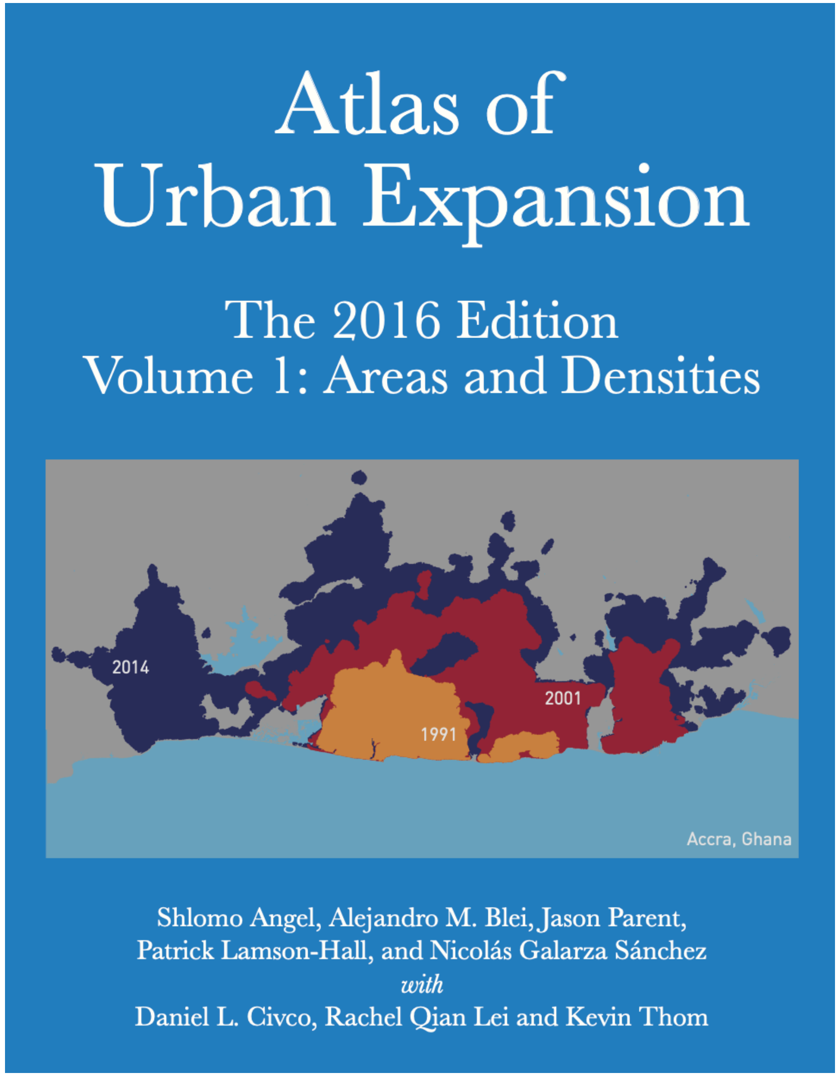
Coastal cities removed

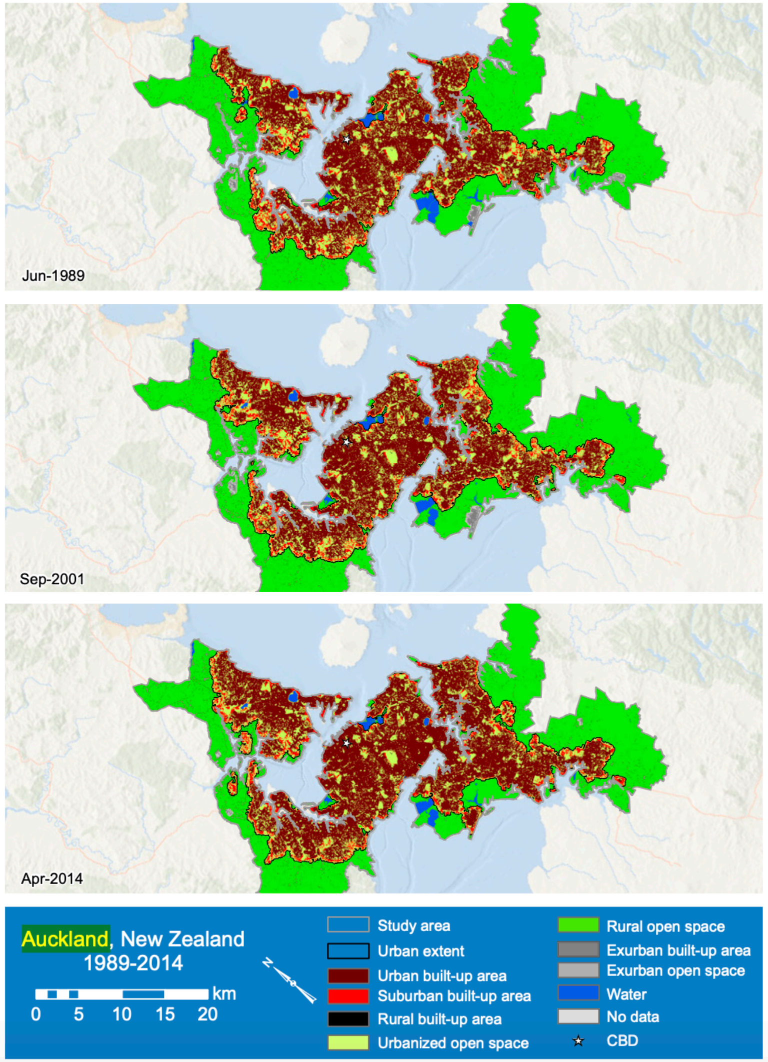
Half of the land is urbanised at 17 / 5 / 3.5 km from the center for a city of 10 / 1 / 1/2 million inhabitants



at **6.64 m** *for the* ***Singleton City***

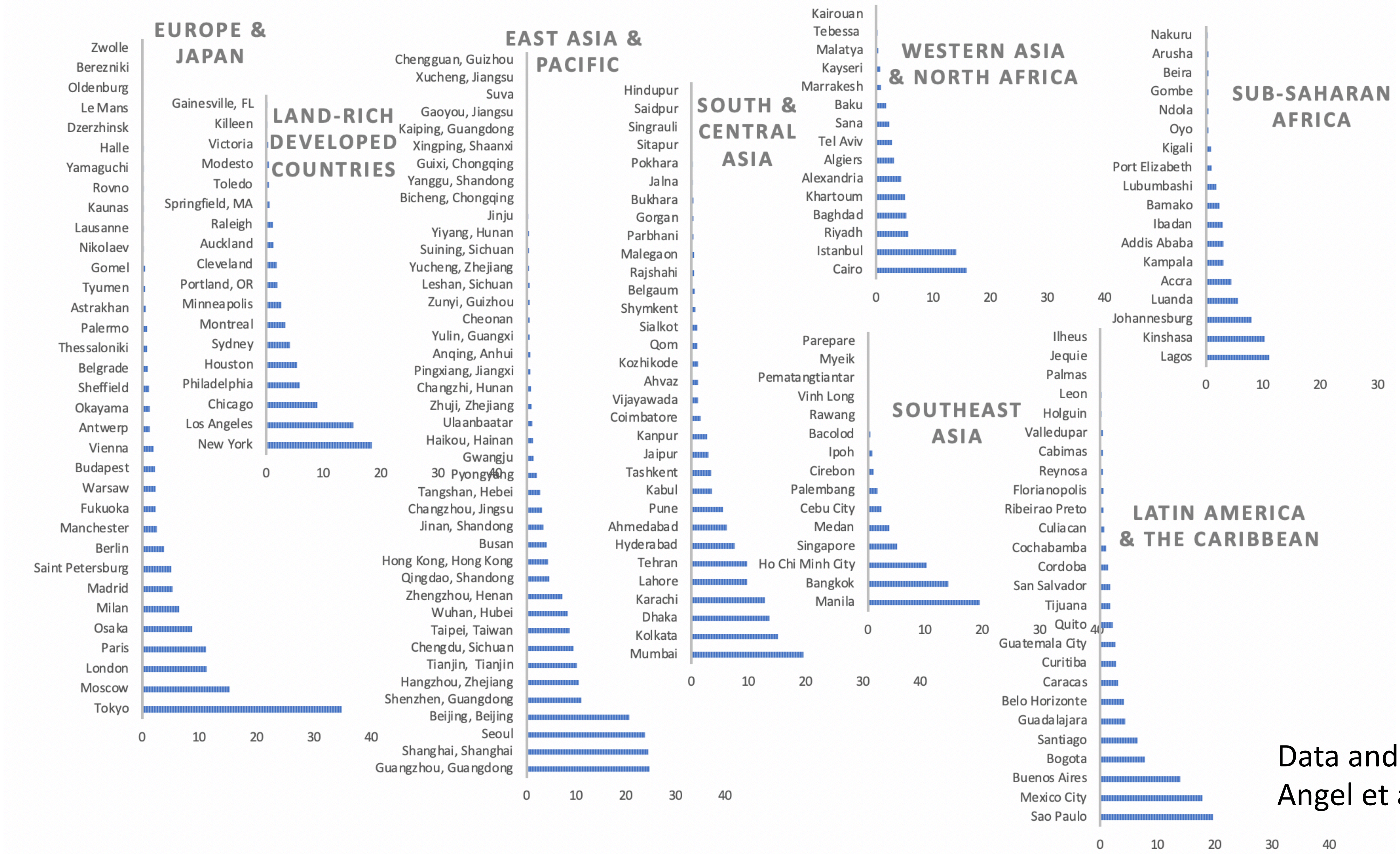
EU specific? How robust? -> worlwide sample





Angel et al, 2016

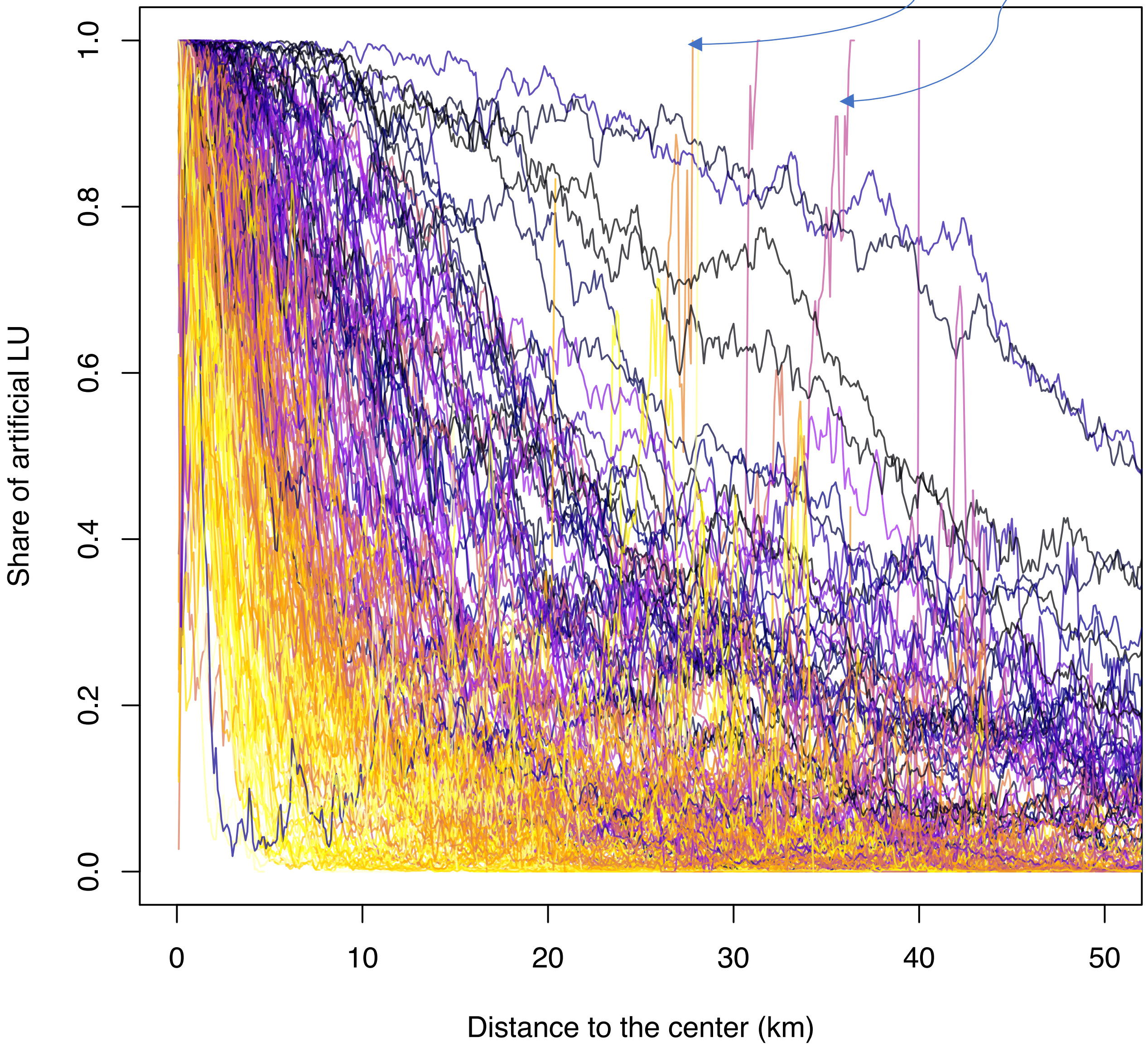
EU specific? How robust?-> worlwide sample



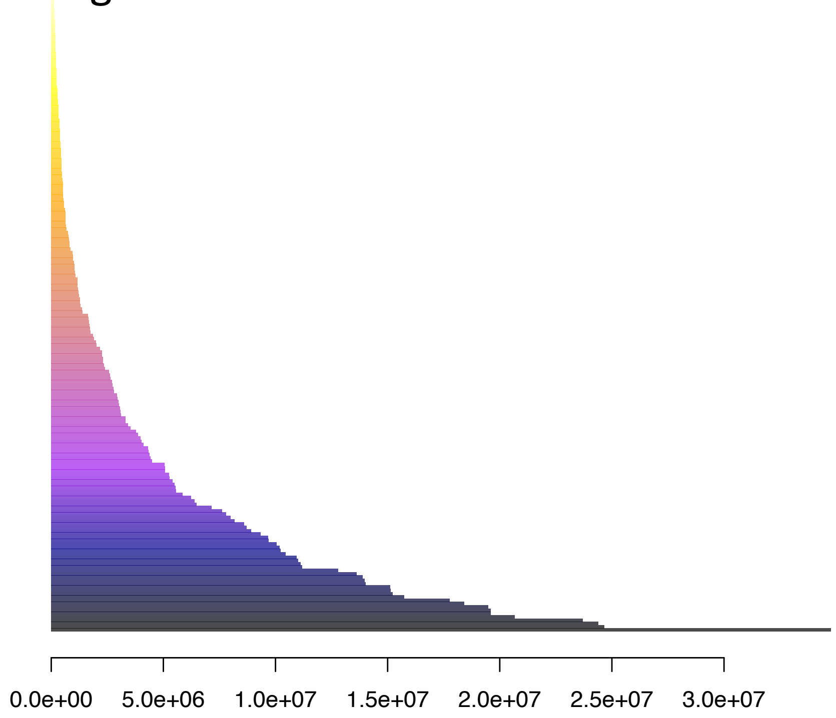
Data and categories from Angel et al, 2016

Artificial Land use profile - Atlas of Urban Expansion ~2014

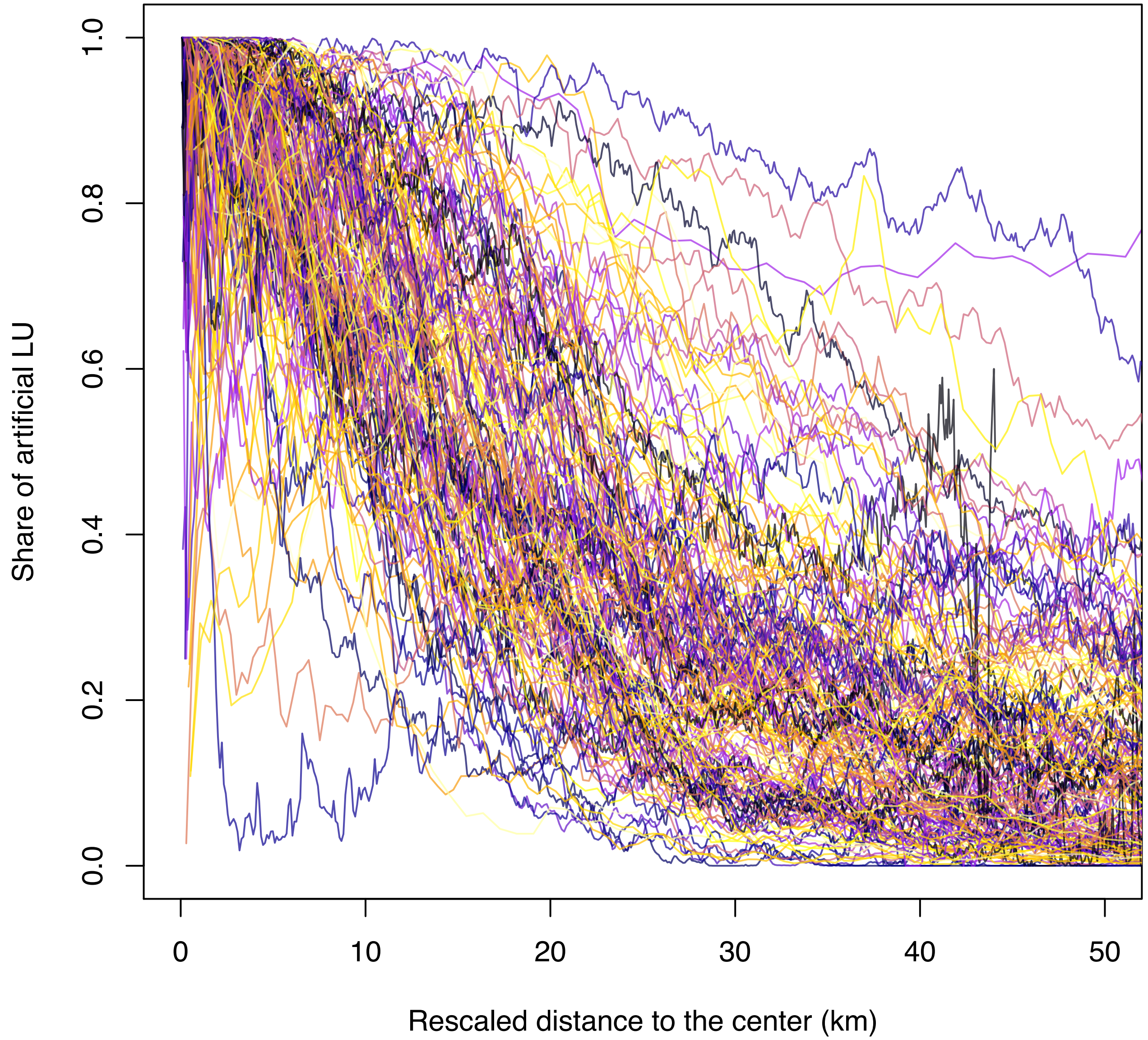
Only few conurbation polycentricity issues

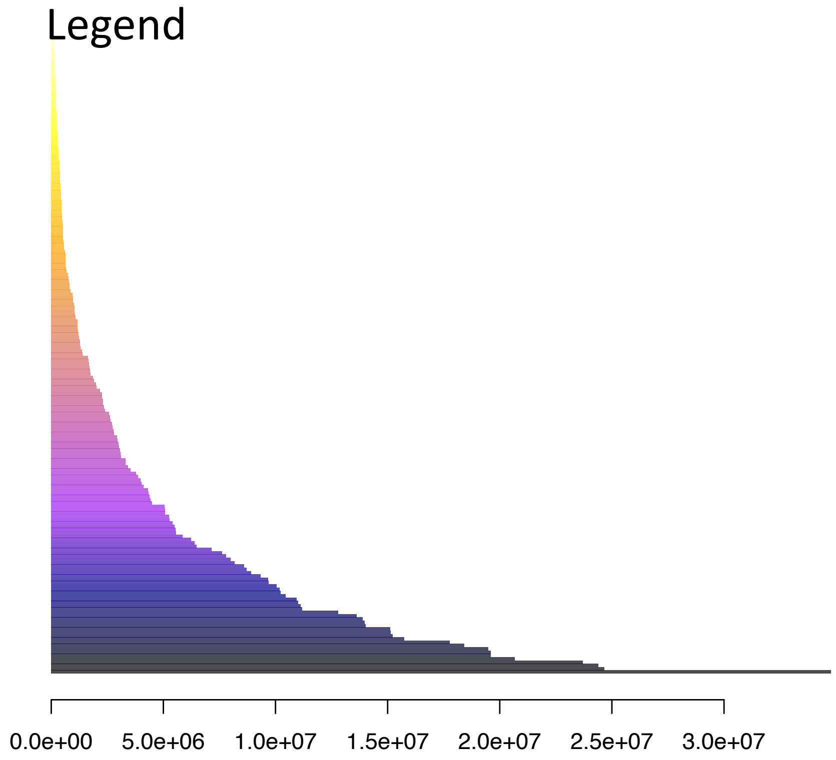


Legend

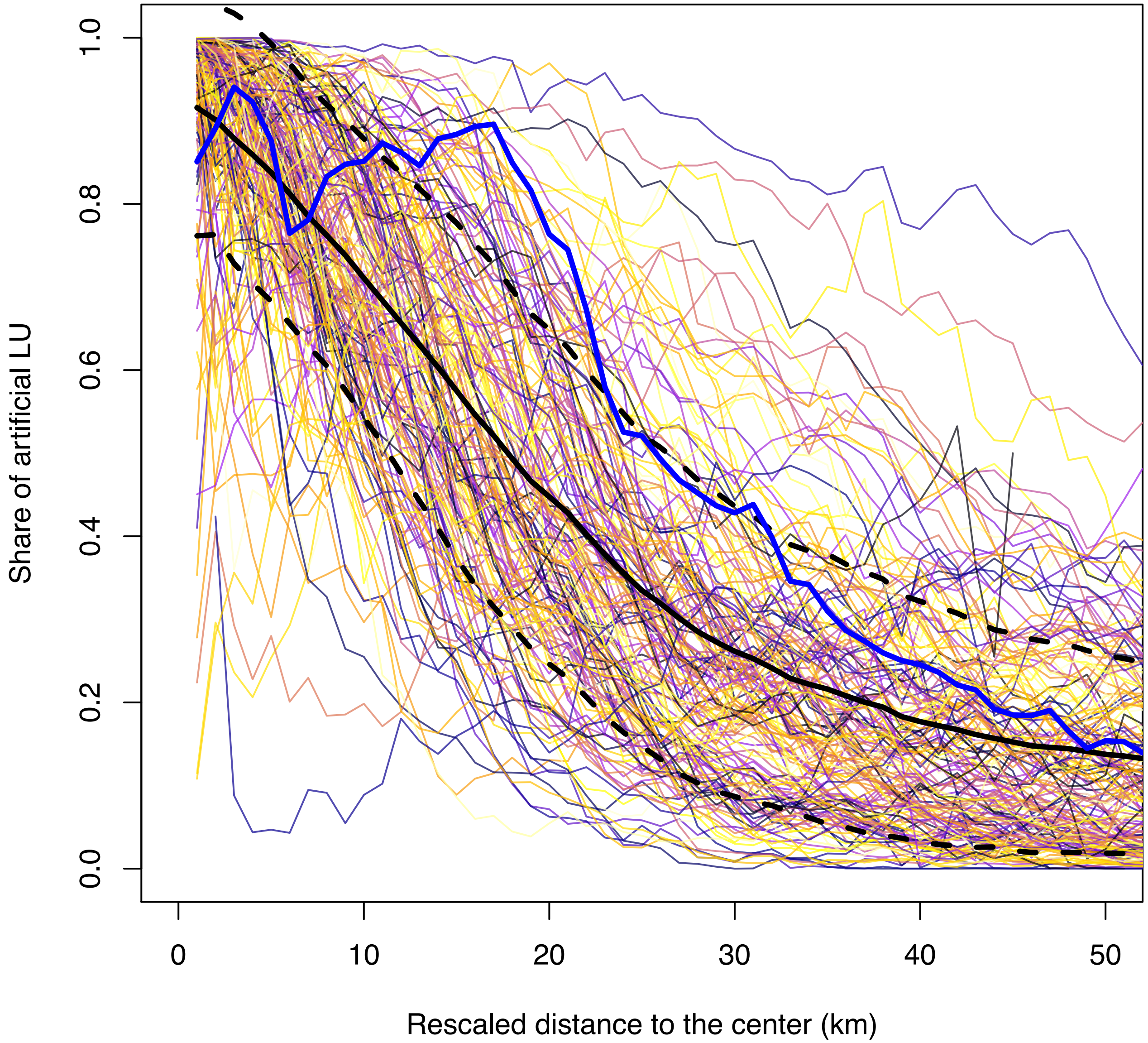


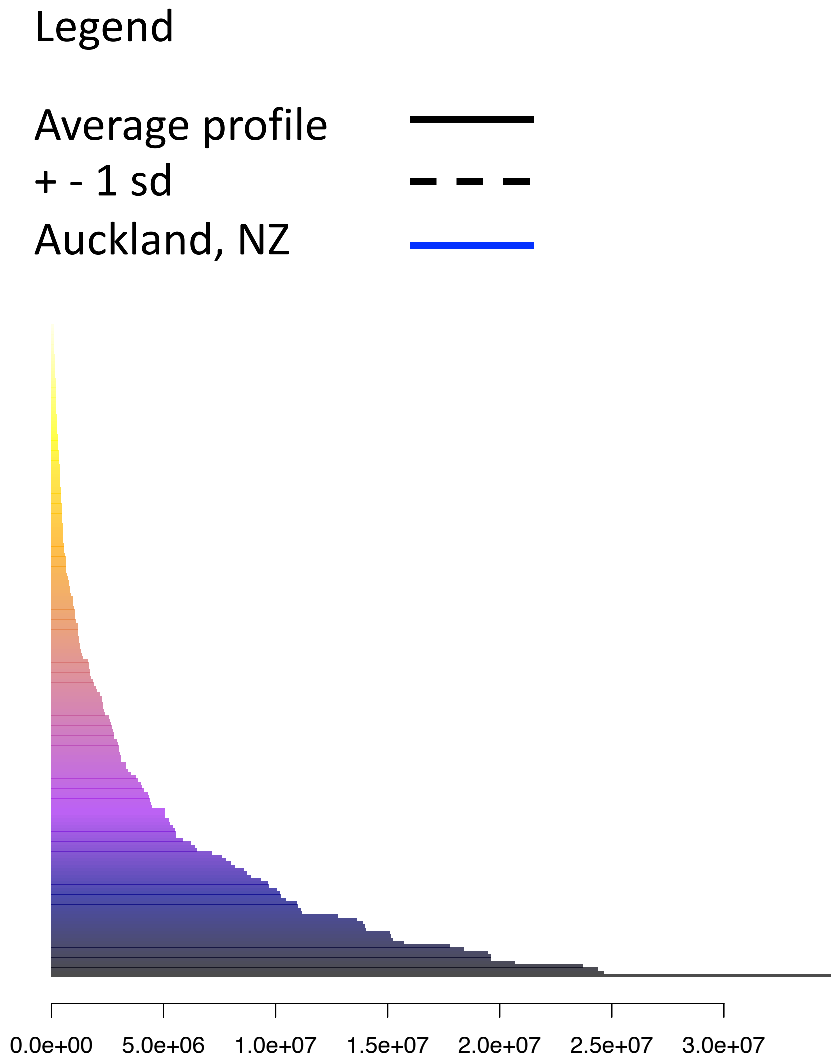
Artificial Land use profile - Atlas of Urban Expansion ~2014 - Rescaled





Artificial Land use profile- Atlas of Urban Expansion ~2014 – Rescaled (1km smooth) + AUCKLAND, NZ

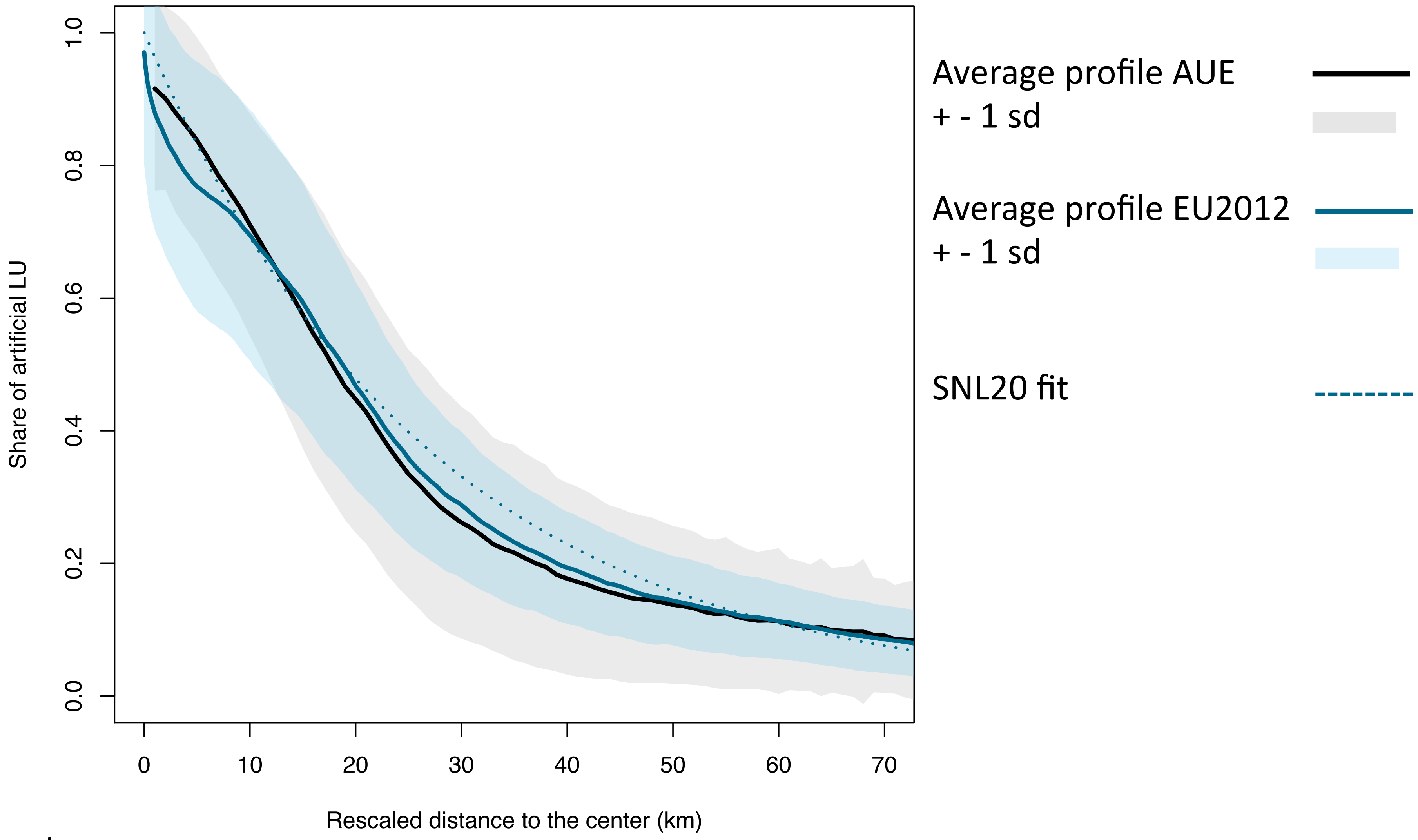




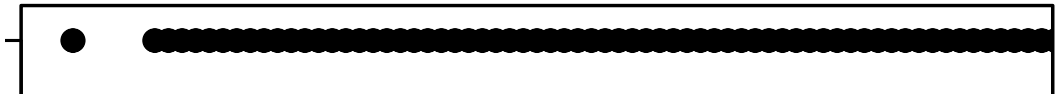
Artificial Land use profile - Atlas of Urban Expansion ~2014 and EU 2012 Urban Atlas **compared**

Finding: Same average profile despite very different samples and city sizes

(no significant difference except for smalldistances)

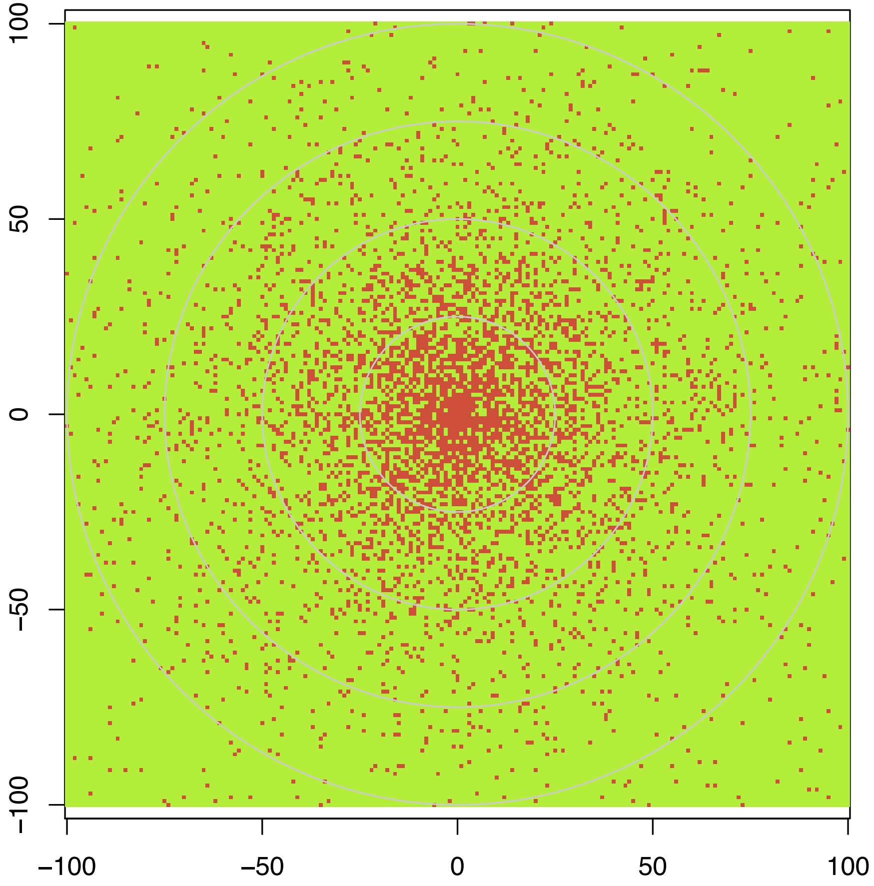


Mean comparison t-test p.value > 0.05

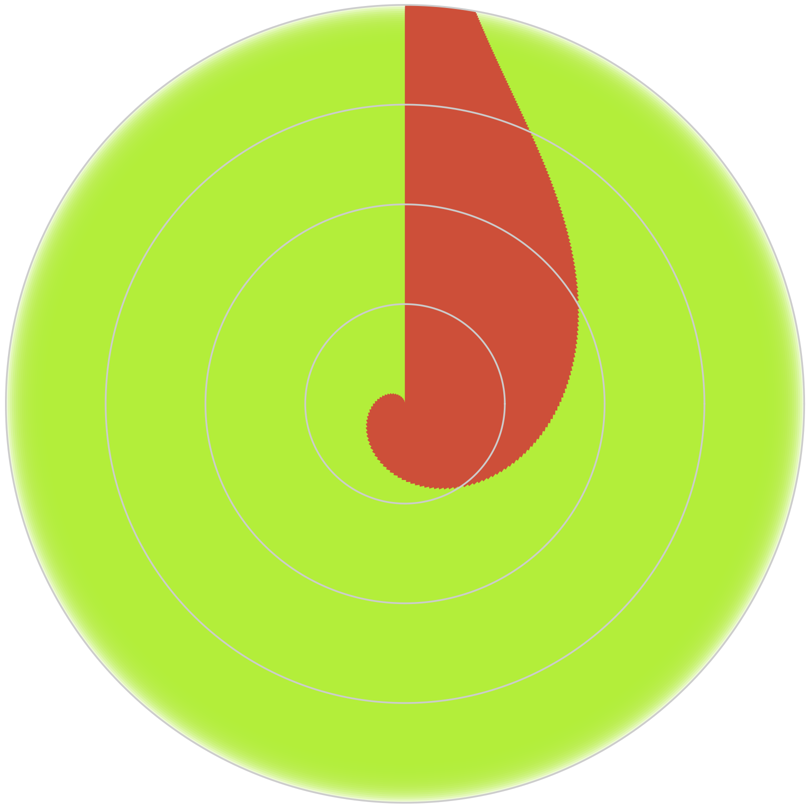


From 1D profiles to 2D patterns – An “average” city

Random draw from SNL20 fit



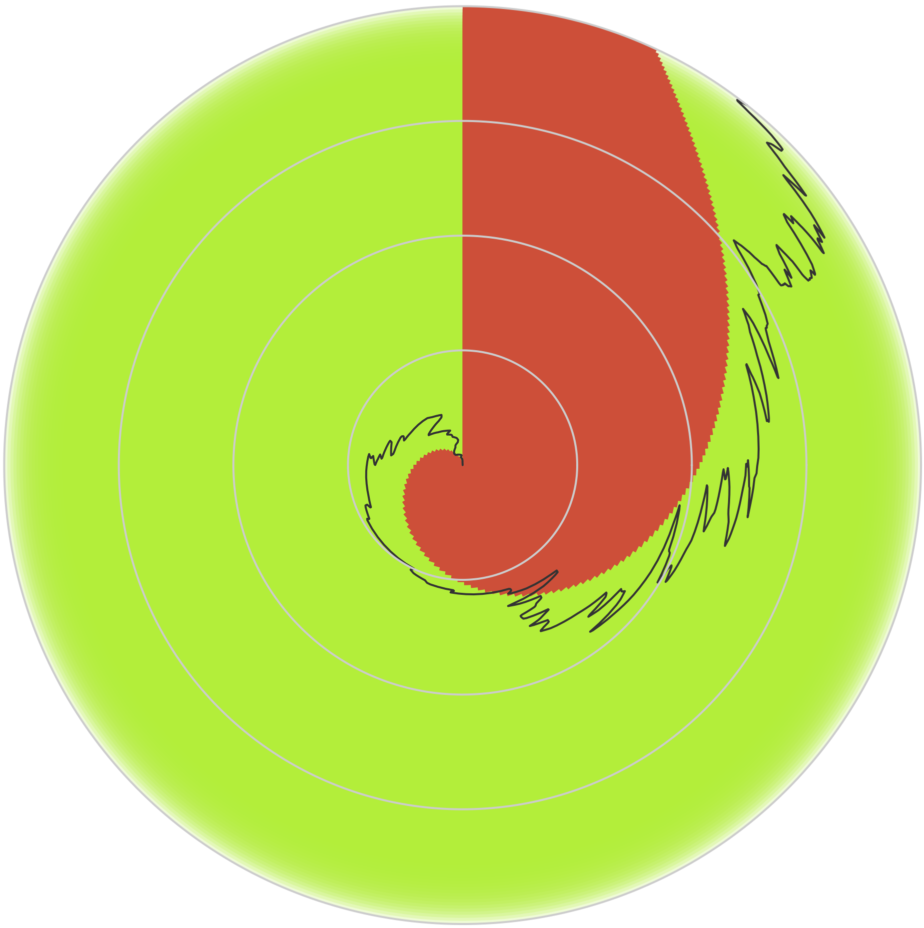
Stacking urban land clockwise



From 1D profiles to 2D patterns – An “average” city

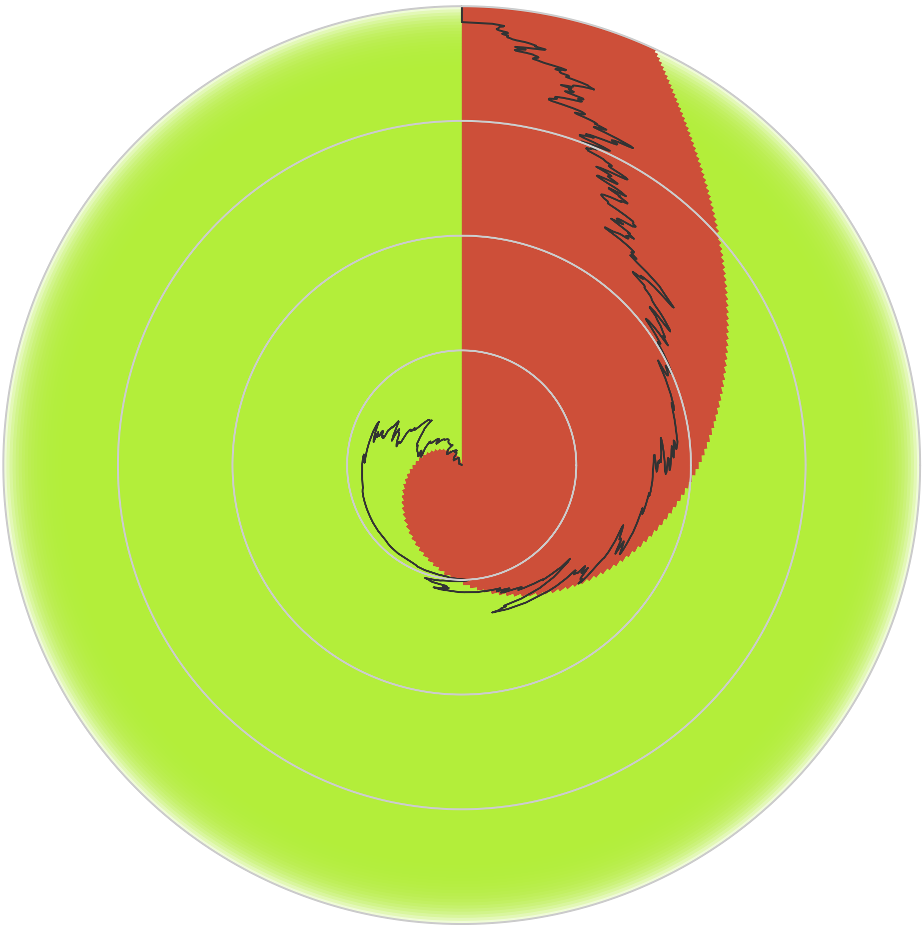
Stacking urban land clockwise

Brussels



Stacking urban land clockwise

Paris



Plan

- Radial/monocentric bias
- Route 1: Empirical research
  - 1.1. Urbanisation profiles in Europe and the World
  - 1.2. Green space profile /integration and ecosystem services
- Route 2: Micro-economic theoretical simulations
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Green urban space

- Local green space is a strong residential choice factor
  - Push towards periphery
  - Source of leapfrogging development (fragmented natural land in periphery)

    see models part 2
  - Source of urban gentrification

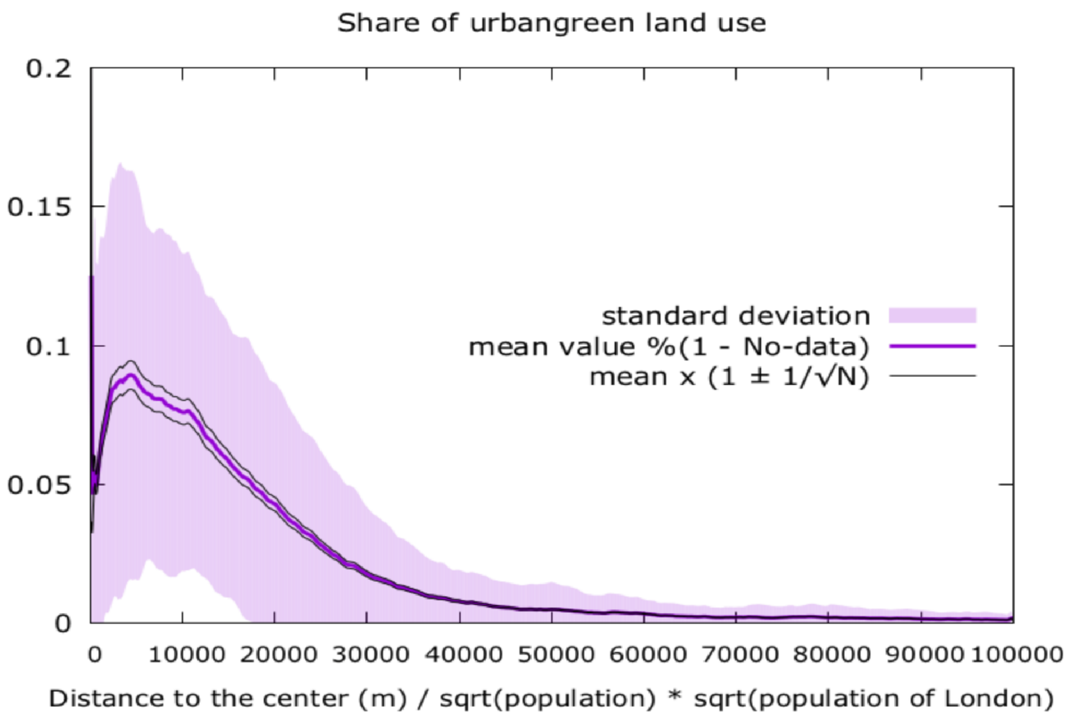
- Green space provide
  - leisure and health benefits
  - climate (heat island), pollution and runoff regulation

.... depending on how integrated within the urban fabric (landscape metrics)

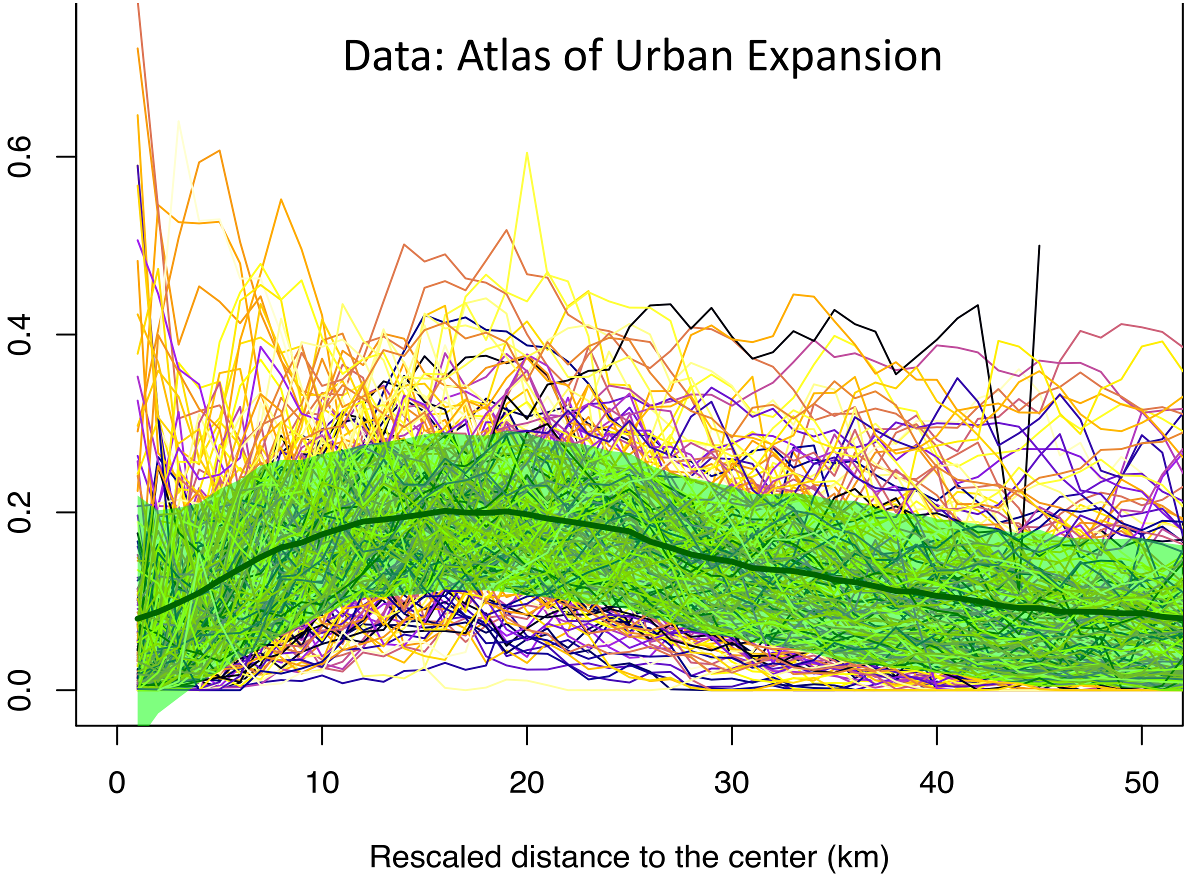
Green urban space – radial profile

- Theory (Tran and Picard, 2020): skewed inverted U shape of green space in equilibrium
- Empirically finding: in line with theory but robustness?… (definition problem?)

Data: EU Urban Atlas 2006



Data: Atlas of Urban Expansion



Green urban space: landscape typology and Ecosystem Services score

Step 1. Link Ecosystem Services with landscape metrics (expansion to Burkhard's land cover – ES matrix)

Step 2. Typology of EU cities

Step 3. Ecosystems Services score (weighted sum) per city

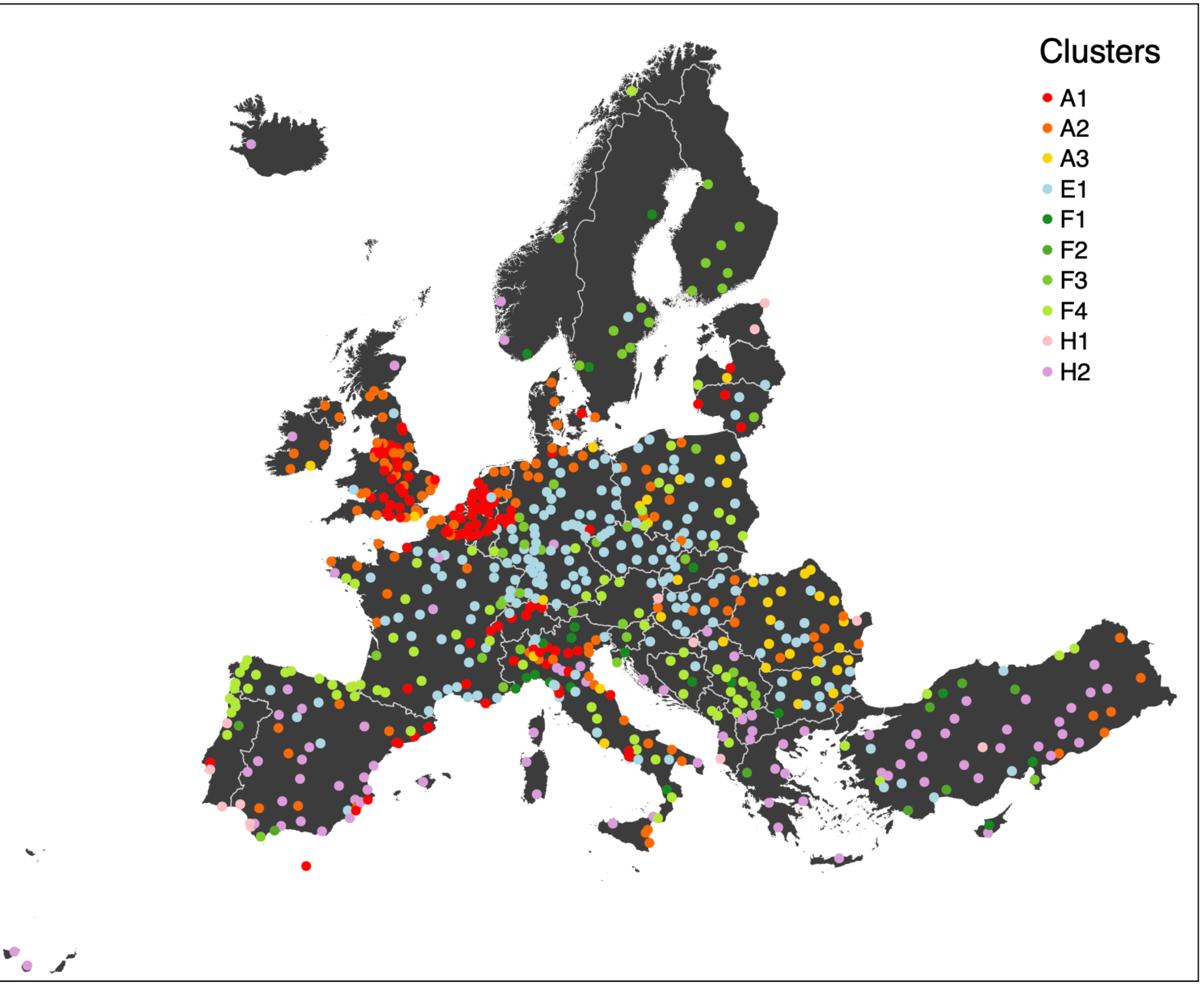
Ecosystem Services Provision weights

Metrics	Macro climate regulation	Micro climate regulation	Air quality regulation	Rainwater regulation	Mental and physical health
ForestsPct	4.00	5.00	5.00	3.00	4.00
Forests_area_cv	4.00	5.00	5.00	3.00	4.00
Forests_area_mean	4.00	5.00	5.00	3.00	4.00
Forests_cohesion	4.00	5.00	5.00	3.00	4.00
Forests_contig_mean	4.00	5.00	5.00	3.00	4.00
Forests_division	0.00	0.00	0.00	-3.00	3.00
Forests_edgeD	4.00	5.00	5.00	5.00	4.00
WetlandsPct	4.00	4.00	0.00	3.00	4.50
HerbaceousPct	1.33	2.00	0.67	1.00	2.33
ArtificialPct	1.50	-1.50	-1.00	-1.00	3.50
Artificial_cohesion	2.00	-2.00	-2.00	-1.00	3.50
Artificial_contig_mean	2.00	-2.50	-2.00	-1.00	4.00
Forests_UrbanFabric1500	4.00	5.00	5.00	5.00	4.00
Artificial_UrbanFabric1000	3.00	-2.00	-1.00	-1.00	5.00
Vegetation_Roads1500	4.00	5.00	5.00	4.00	4.00
Roads_cohesion	-4.00	-2.00	-4.00	-4.00	-2.00
Roads_contig_mean	-4.00	-2.00	-4.00	-4.00	-2.00
Roads_edgeD	-4.00	-2.00	-4.00	-4.00	-2.00
Indus_cohesion	-5.00	-2.00	-5.00	-4.50	-1.00
Indus_contig_mean	-5.00	-2.00	-5.00	-4.50	-1.00
UrbanFabric_cohesion	-3.50	-5.00	-5.00	-4.50	-4.00
UrbanFabric_contig_mnea	-3.50	-5.00	-5.00	-4.50	-4.00
ImperviousPct	-3.50	-5.00	-5.00	-4.50	-4.00

Table 2: Coefficients (β_{ij}) of UFES budget for each metric (i) and UFES (j)

Boura, Caruso 2020 working paper

Green urban space: landscape typology and Ecosystem Services score



Boura, Caruso 2020 working paper

Figure 3: Typology of the 689 FUAs (10 clusters from the HCA)

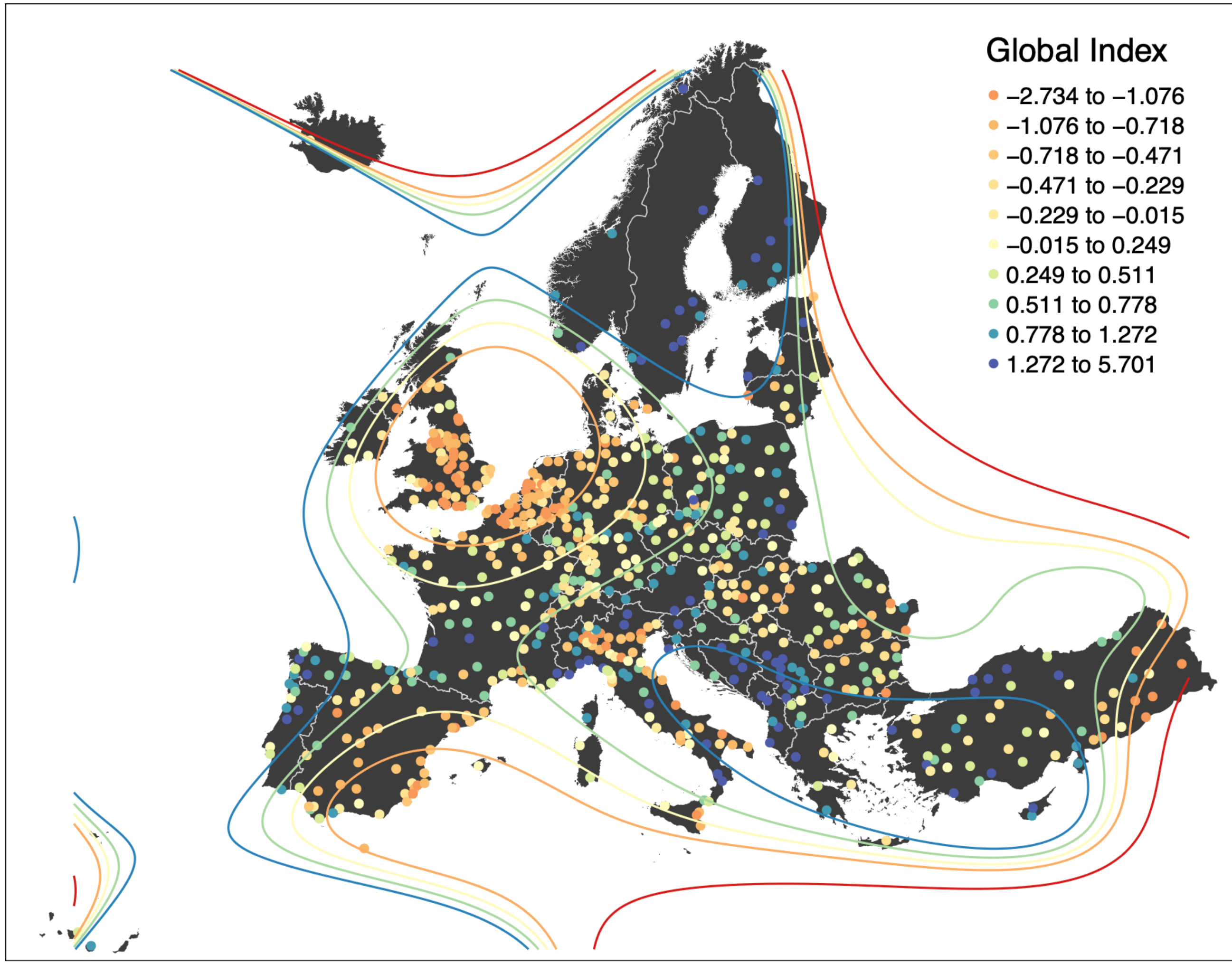
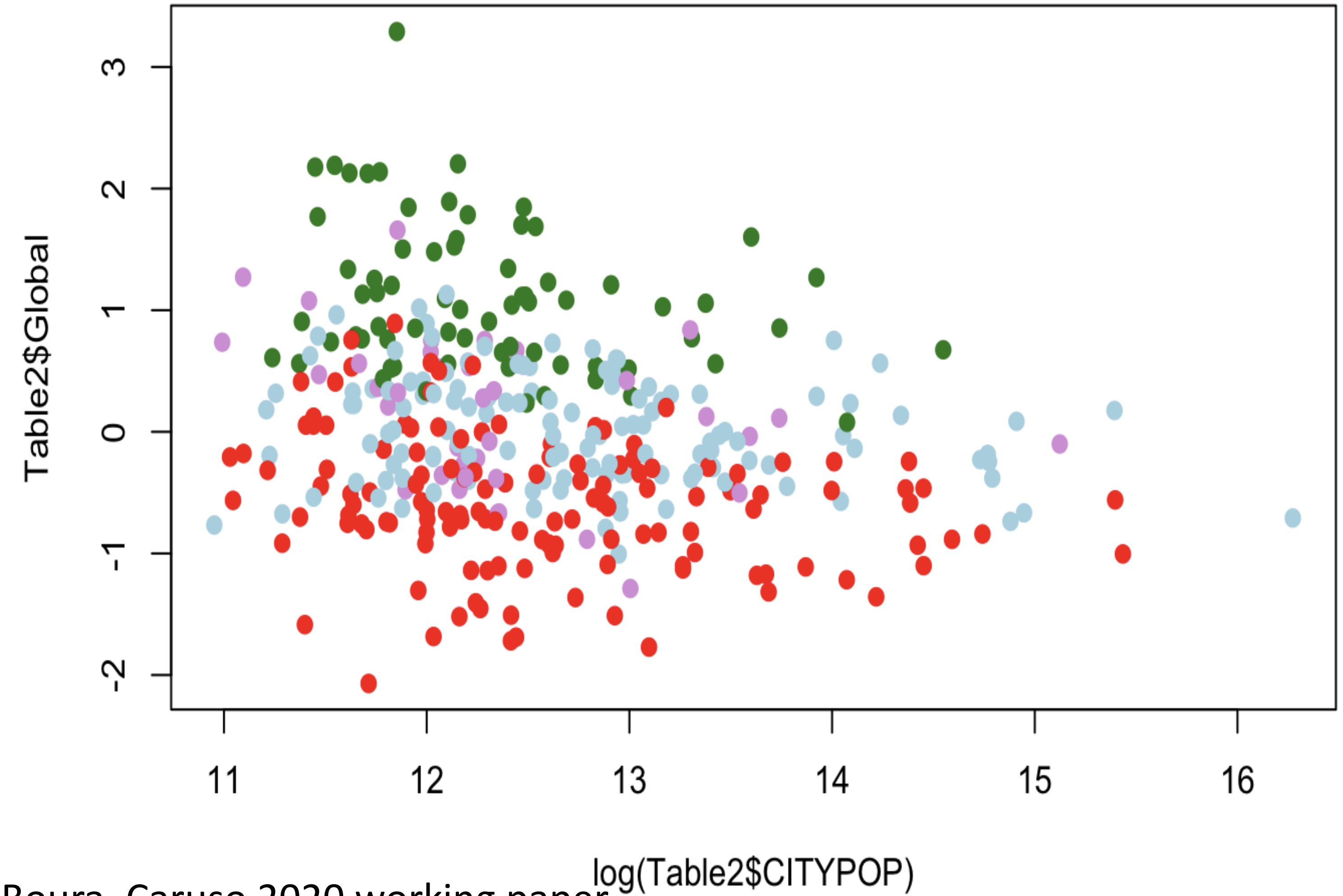


Figure 7: Map of global index distribution per deciles (with contour lines)

Green urban space: Ecosystem Services score and **city size**



Boura, Caruso 2020 working paper

Finding: Green space ES provision decrease with (log) city size (even after controlling for urban forest integration types

```
Call:
lm(formula = Table2$Global ~ log(Table2$CITYPOP) + Table2$Group)

Residuals:
     Min       1Q   Median       3Q      Max
-1.61109 -0.34474  0.01319  0.36290  2.12031

Coefficients:
                                 Estimate Std. Error t value Pr(>|t|)
(Intercept)                       1.87402    0.39377   4.759 2.81e-06 ***
log(Table2$CITYPOP)              -0.14597    0.03068  -4.758 2.83e-06 ***
Table2$GroupAnthropogenic Cities -0.62261    0.06468  -9.626  < 2e-16 ***
Table2$GroupForest Cities         1.02664    0.07863  13.056  < 2e-16 ***
Table2$GroupHerbaceous Cities     0.08608    0.09805   0.878    0.381
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.5219 on 364 degrees of freedom
Multiple R-squared:  0.5818,    Adjusted R-squared:  0.5772
F-statistic: 126.6 on 4 and 364 DF,  p-value: < 2.2e-16
```

Plan

- Radial/monocentric bias
- Route 1: Empirical research
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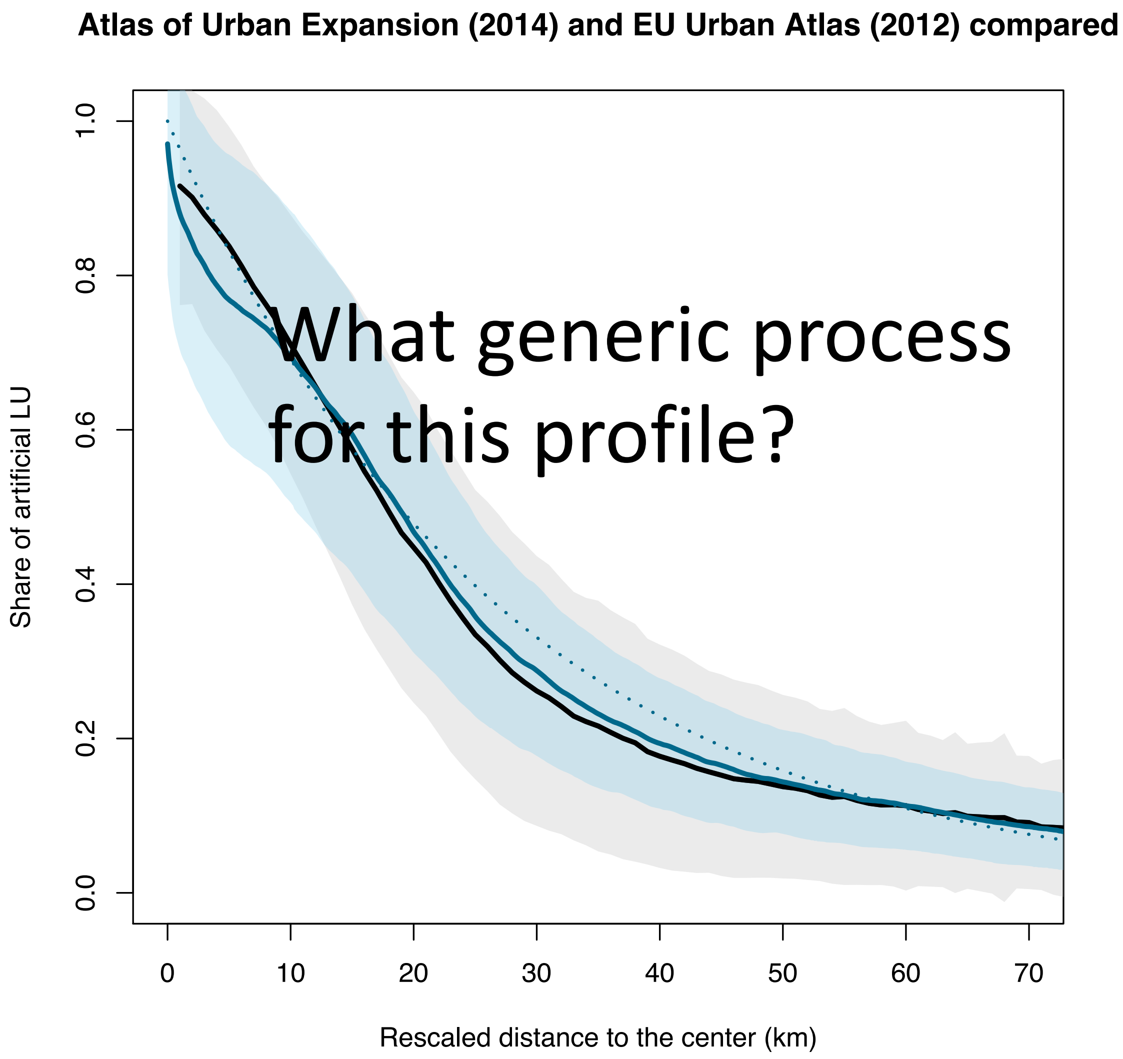
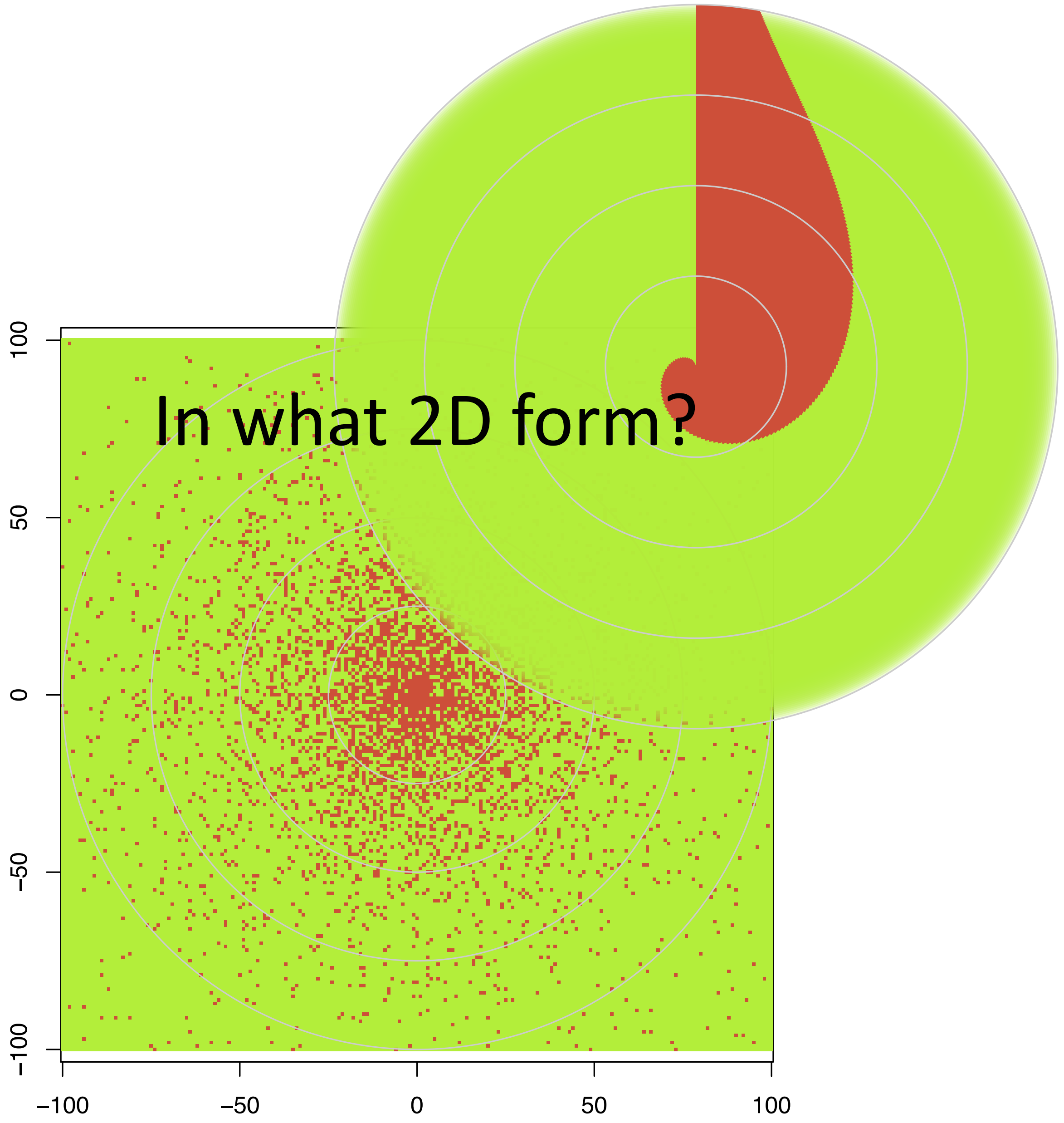
  - 2.2. Urban patterns with endogeneous pollution

How can such general urbanisation patterns emerge?





Micro-economic theory for urban land share profile?

- Urbanisation gradients almost completely ignored in urban economics
  - Cities are entirely built discs in theory! Only the fringe distance matters.
  - The co-existence of developed & undeveloped land at given distance is a puzzle
  - (… and how it scales with total population is not a question)

- >< Population density profiles,
  - i.e. Density = inverse of housing consumption, which results from agents trading-off housing and commuting costs (Alonso, 1964)
  - Observed scaling of population density profile with population fit theory when urban land share is controlled for (see Delloye, Caruso, Lemoy, 2019. Alonso and the scaling of urban profiles. *Geographical Analysis*)

4 “micro” sources for leapfrog/scattered developments

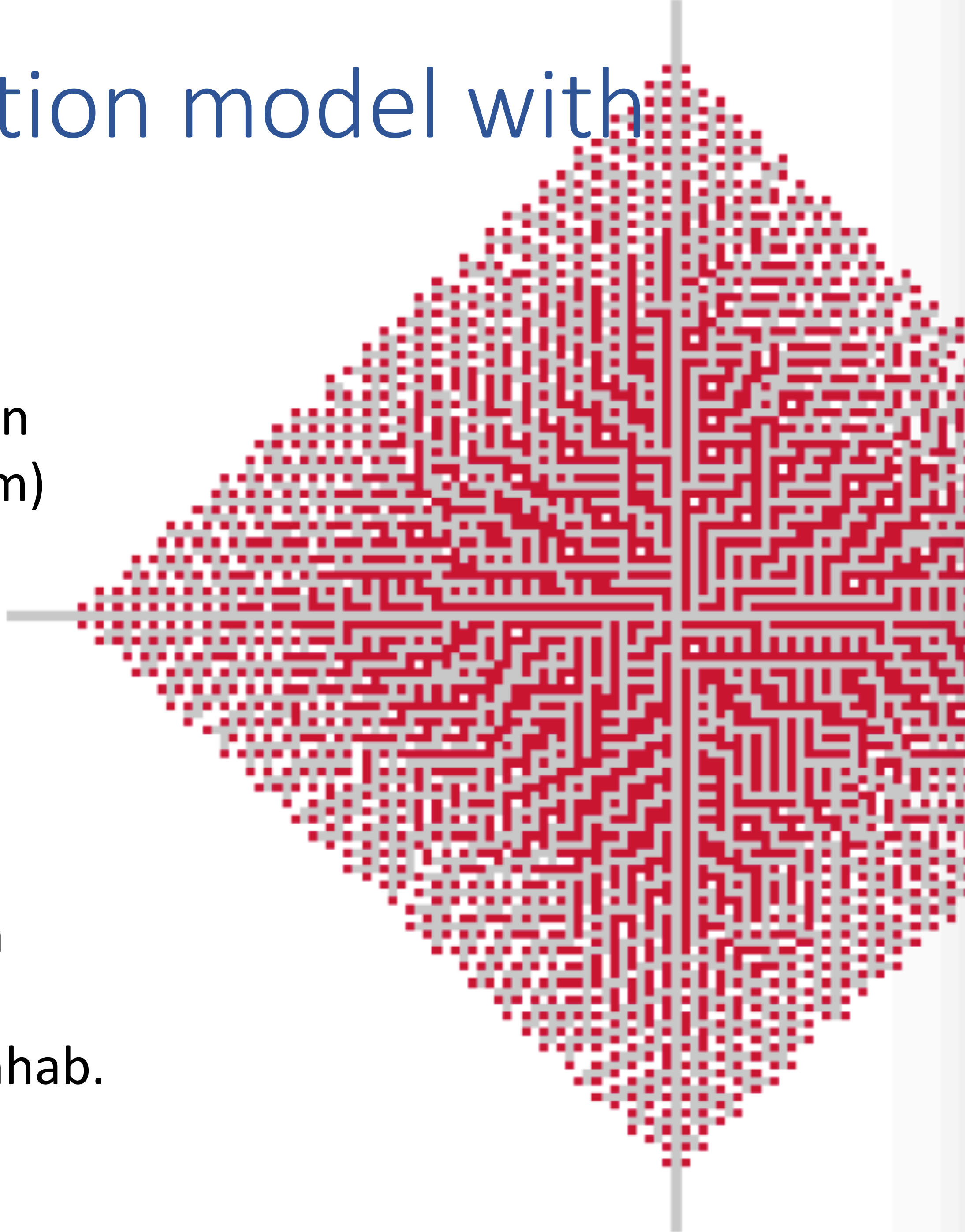
- Dynamic uncertainties Capozza and Helsley, 1990. The stochastic city. *J. of Urban Economics* 28(2): 187-203.
- Thin markets with income heterogeneity Chen, et al., 2017. Market thinness, income sorting and leapfrog development across the urban-rural gradient. *Regional Sc. & Urban Economics*, *66*, pp.213-223.
- Local externalities: positive effect of green space
  - in continuous space Cavailhès, et al., 2004. The Periurban City: Why to Live Between the Suburbs and the Countryside. *Regional Sc. & Urban Economics* 34, 681–703.
  - In 2D discrete space Caruso, et al., 2007. Spatial configurations in a periurban city. A cellular automata-based microeconomic model. *Regional Sc. & Urban Economics* , 37(5), pp.542-567; Caruso et al, 2015. Greener and larger neighbourhoods make cities more sustainable! *Computers, Env. & Urban Syst*, *54*, pp.82-94.)
- Local externalities: negative effect of local pollution Schindler and Caruso, 2020. Emerging urban form–Emerging pollution: Modelling endogenous health and environmental effects of traffic on residential choice. *Env. & Plan B* , *47*(3), pp.437-456.

Micro-economic 2D simulation model with green space preference

- CBD and cross-road given at center at t0
- Urbanisation develops from successive migration
- Endogeneous land market (short-run equilibrium)
- Long-run equilibrium: urbanisation stops when migration is no longer beneficial

Residential choice:
Radial push-pull (commuting *vs* housing costs)
Local push-pull (socialize vs green) focal function

Parameters calibrated to 3 French cities ~200 k. inhab.



Caruso et al, 2015

Residential choice

NO BLACK BOX MODEL

EXPLICIT BEHAVIOUR

Utility:

$$U(Z,H,E,S) = \kappa Z^{1-\alpha} H^{\alpha} E^{\gamma} S^{\delta}$$

Budget:

$$Z + RH = Y - \theta D$$

Z: non spatial good (numÈraire)
H: plot size
θ: unitary transport cost
D: commuting distance along road network
α: preference for housing ($0 < \alpha < 1$)
δ: preference for social ($\delta > 0$)
Y: income
E: local green space externalities ($E > 0$)
S: local social externalities ($S > 0$)
R: land rent
γ: preference for green ($\gamma > 0$)
$\kappa = \alpha^{-\alpha}(1-\alpha)^{\alpha-1}$

Neighbourhood: $\widehat{w}$ (window, viewshed, 'amenity-shed')

Local density: ρ

Open space amenities:

$$E = e^{-\rho}$$

Social amenities:

$$S = e^{\rho}$$

Net amenities:

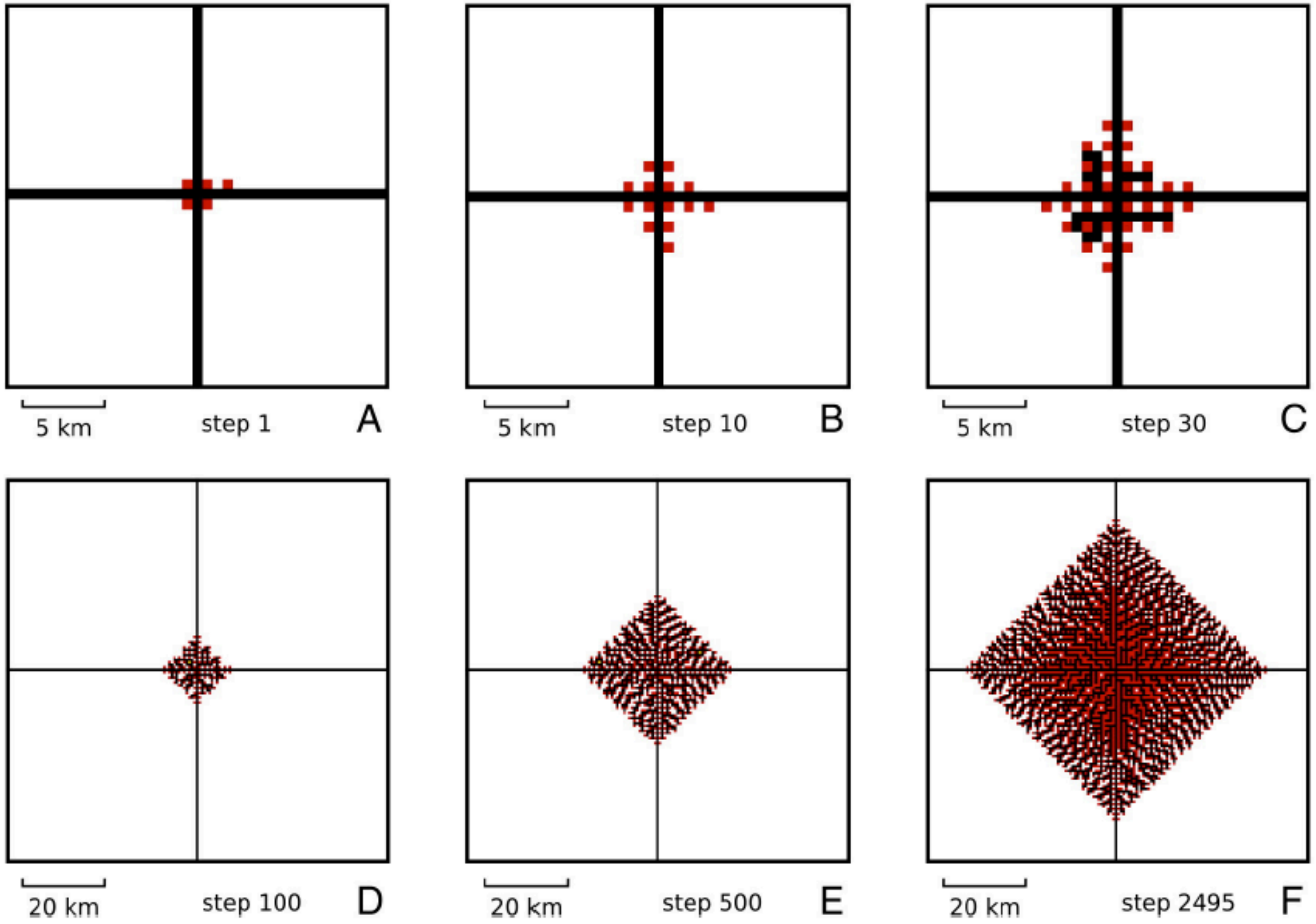
$$E^{\gamma} S^{\delta} = e^{-\gamma\rho} e^{\delta\rho} = e^{-\beta\rho}$$

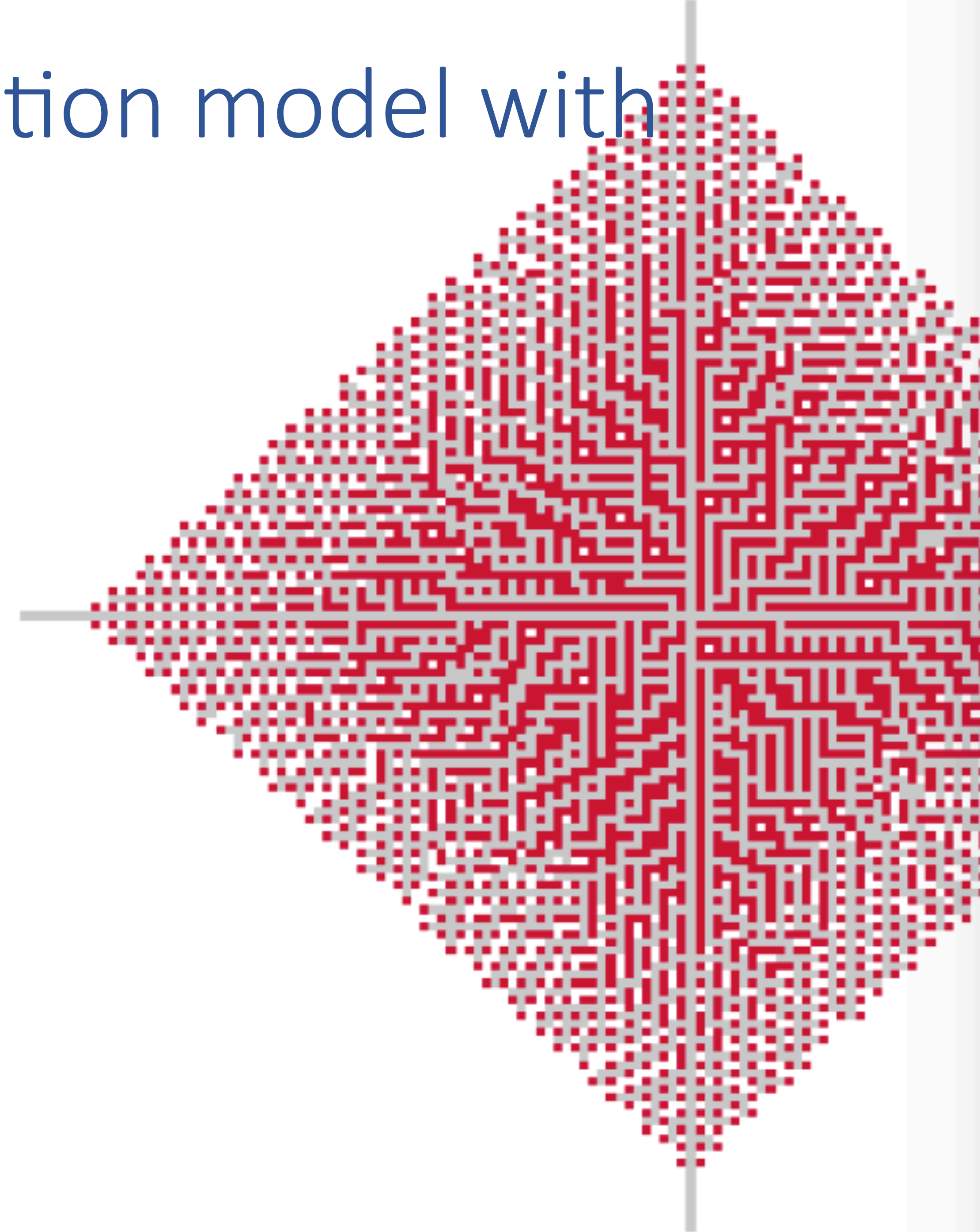
Endogeneous rents

$$R^t(x) = [Y - \theta D(x)]^{1/\alpha} (U^t)^{-1/\alpha} \exp\left[-\beta\rho^{t-1}(x)\right]$$

Caruso et al, 2015

Micro-economic 2D simulation model with green space preference





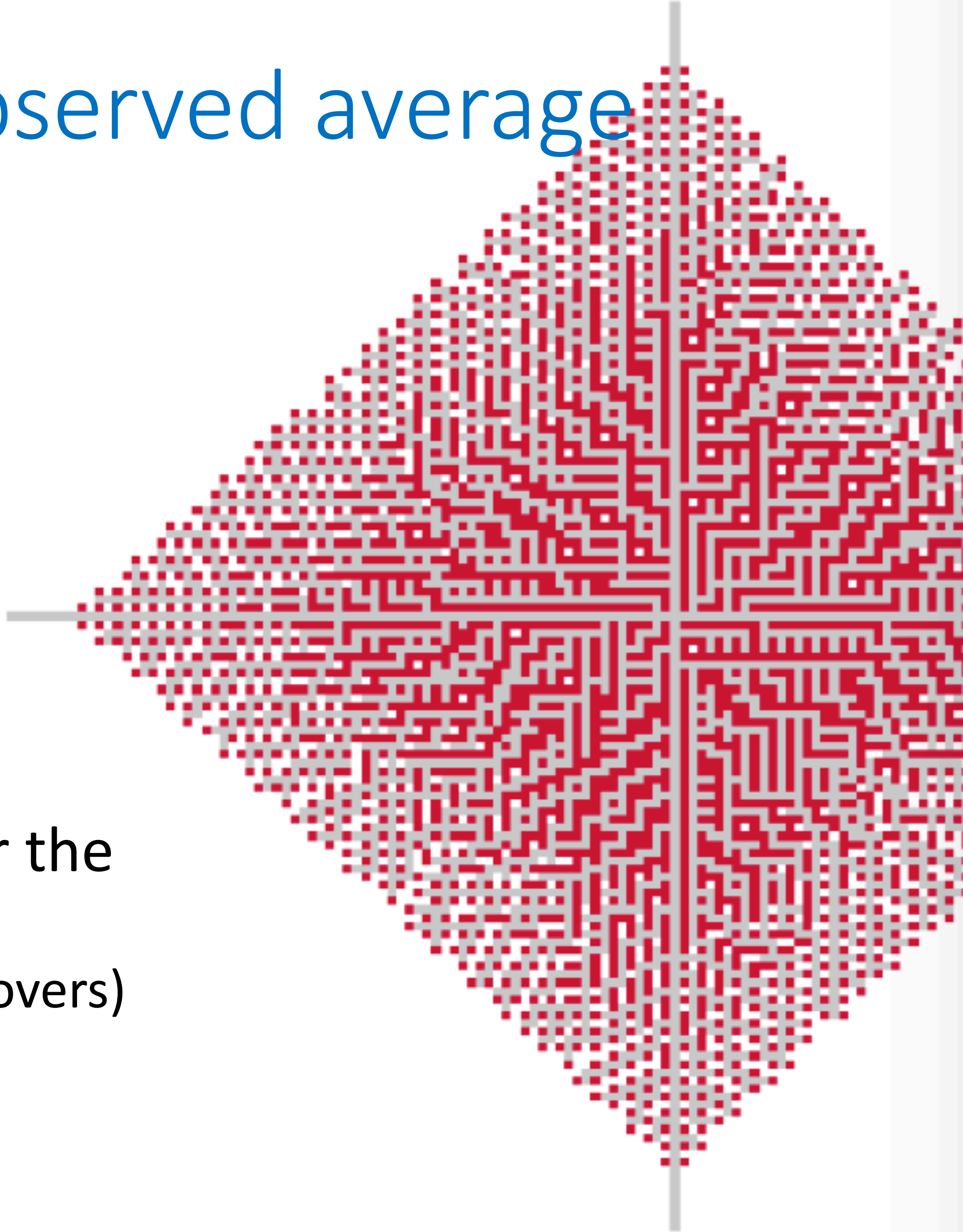
Caruso et al, 2015

Poor correspondence to observed average radial profile

- **Urbanisation gradient is too flat**

2 promising solutions:

- Non-linear transport costs
- Differentiated neighbourhood size for the local effects (green space valued at larger distance from home than local density spillovers)



Generic normative lessons from changing parameters/changing parameters

- Example: increasing neighbourhood size, i.e. facilitating trips at no cost to local green
- => different spatial arrangement of built and green space
- => **welfare and sustainability gains for a given population**

Aggregate characteristics of the city after varying neighbourhood size.

Neighbourhood size $\hat{w}$	$\hat{w} = 1$	$\hat{w} = 2$	$\hat{w} = 3$	$\hat{w} = 8$
	600 m	1200 m	1800 m	4800 m
Population	171,197	165,658	166,323	166,936
Utility	19,916	21,268	21,484	23,630
Density (inhab per sq.km within footprint)	66	76	79	125
Roads (m) per inhab	11.11	7.61	5.37	1.27
Maximum distance to CBD (km)	36	33	32	26
% Green space within footprint	17.94	34.48	41.79	63.28

Caruso et al, 2015

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Micro-economic 2D simulation model with traffic pollution

- No explicit preference for green space
- Avoidance of local traffic pollution
- Sprawl and scatteredness increase with
  - increasing pollution awareness
  - Increasing size of pollution perception neighbourhood
- Resulting radial profile of pollution

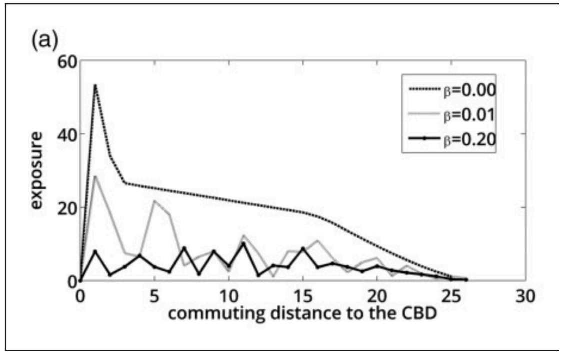

Figure 3. Households' exposure (a) and emission cor
an increasing aversion β (with $\gamma = \phi = 0$).

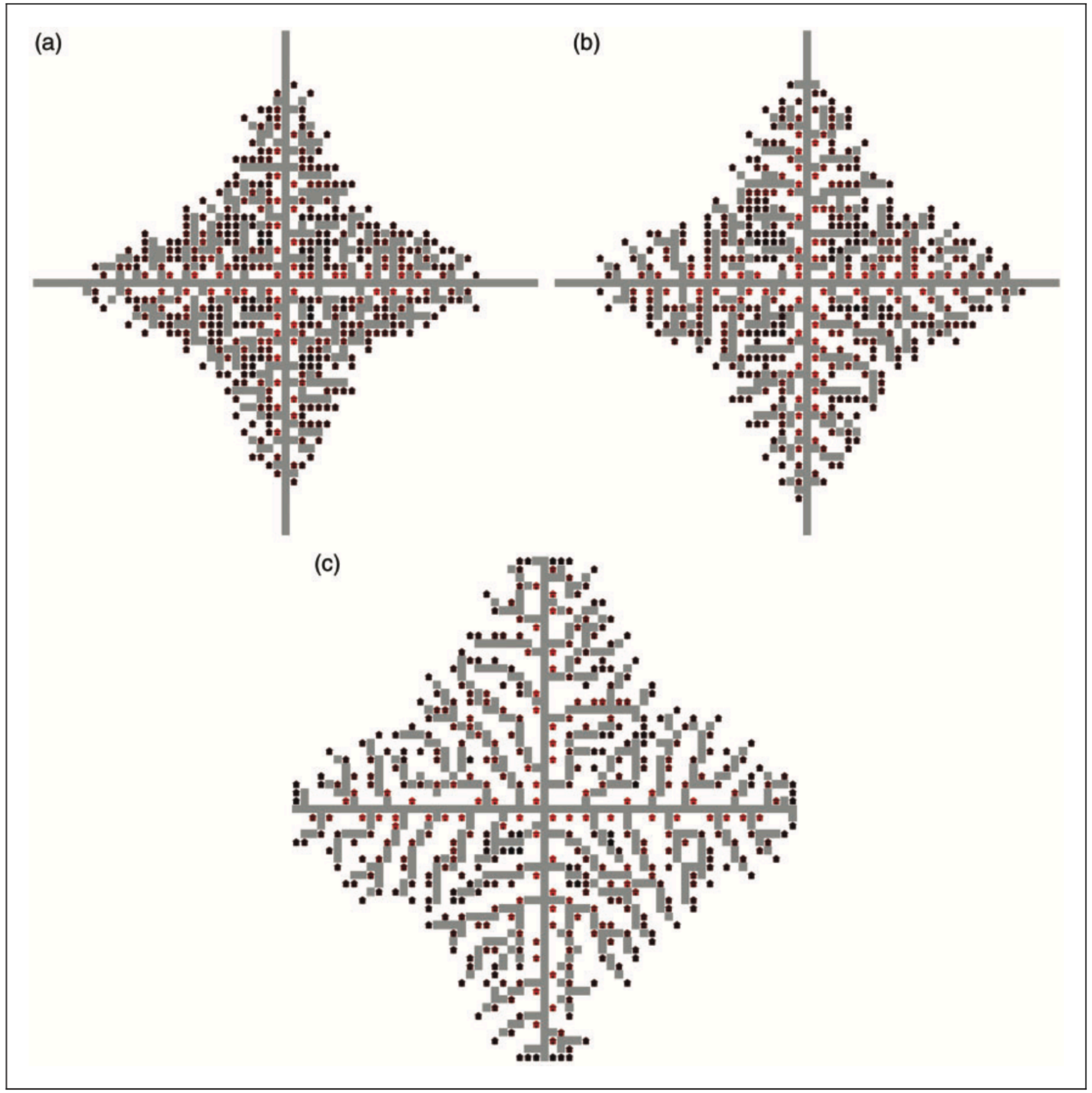

Figure 4. Urban structures as result of increases in households' perception neighbourhood $\tilde{n}$ ($\beta = 0.2, \gamma = \phi = 0$). (a) $x = 1.5$. (b) $x = 2$. (c) $x = 2.5$.

Schindler and Caruso, 2020

Concluding remarks

- Homothetic radial profiles: large cities are no exceptional urban forms but… larger objects

- Local environmental effects (impact not divisible per capita) worsen with city size
- But the spatial arrangement of built and non-built/green space seem to be key under the constraint of a given radial profile

- Suggestion/wish: shift away some urban research focus from large and core cities’ smartness to smaller cities and suburbs, which may be easier to ‘retrofit’ with nature

Thank you for your attention!

geoffrey.caruso@uni.lu