Beyond administrative delimitations: uncovering patterns using complexity science

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Cities as complex systems: from interacting agents to generic properties, what are the key ingredients?

1. People! Cities have no meaning without people!
   → Understand the **demographic composition** and properly measure observed characteristics, e.g. inequality

2. Movement! Cities as spaces of connectivity: **NETWORKS**

3. *"If I live in zone A and need to work in zone B, can I afford it?"* Understand the interplay between the distribution of **land use**, **transport** and **rent**

4. *"This is a BIG city!"* Is population size a good parameter to predict certain characteristics? → **Increasing returns** (non-linear effects)

5. *"Why does a city look the way it looks?"* **Morphology,** can I measure it? Does it matter?

6. **Evolution and change**: are our cities the result of where we are, i.e. region, country; are we shaped by modernity, or are we intrinsically defined by our history?

Complex systems

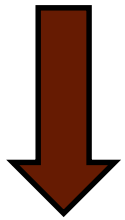
What is a complex system?

Complex systems

System = Interacting component 1 + Interacting component 2

+ Interacting component 3 + Interacting component 4

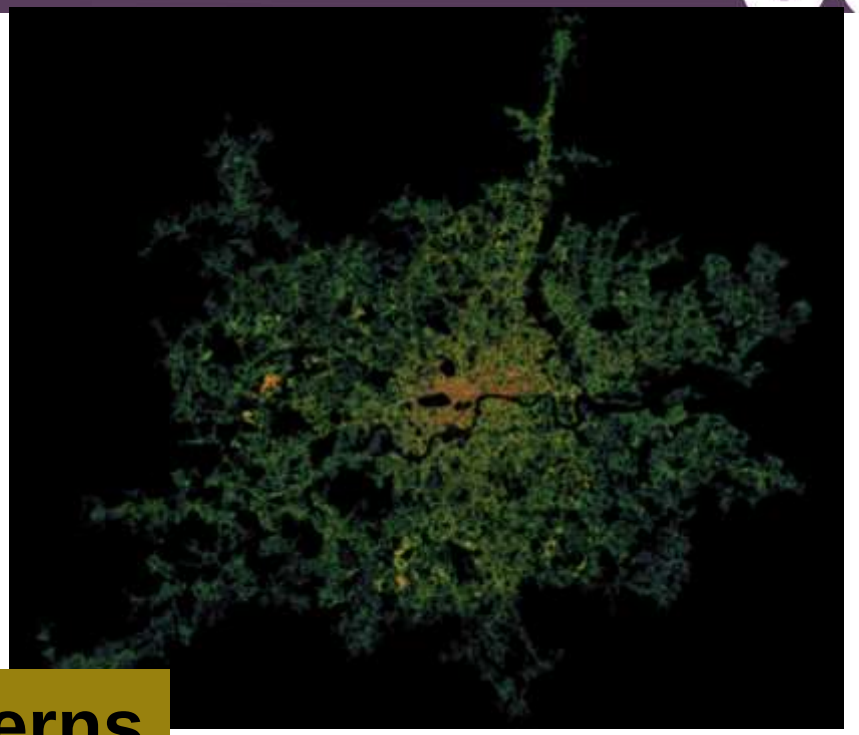
+ ... + Interacting component n



Emergent behaviour

collective behaviour not observed at the level of an individual component

Agricultural fields in Viet Nam



Street networks

Emergent patterns

Stock market

Traffic jams

Driving complex systems

Local interactions give rise to emergent properties

Need to understand local behaviours to drive the system to a desirable solution

Big picture shouldn’t be missed!!!

Are there any generic patterns observed in all countries? In all cities?

Some of these are:

- Distribution of city sizes
  → *Zipf's law*

- Growth of cities (law of proportionate growth independent of city size)
  → *Gibrat's law*

- Economies of scale/Increasing returns
  → *Scaling laws*

- Morphological structure of cities
  → *Fractal properties*

- Hierarchical structure
  → *Regions*

What was the initial cohesive force for settlements to form into communities?

- Was it interactions?
- Could trade capture this?
- If data non-available could we use distance as a proxy?

Are the emergent cities defined in terms of:

→ people?

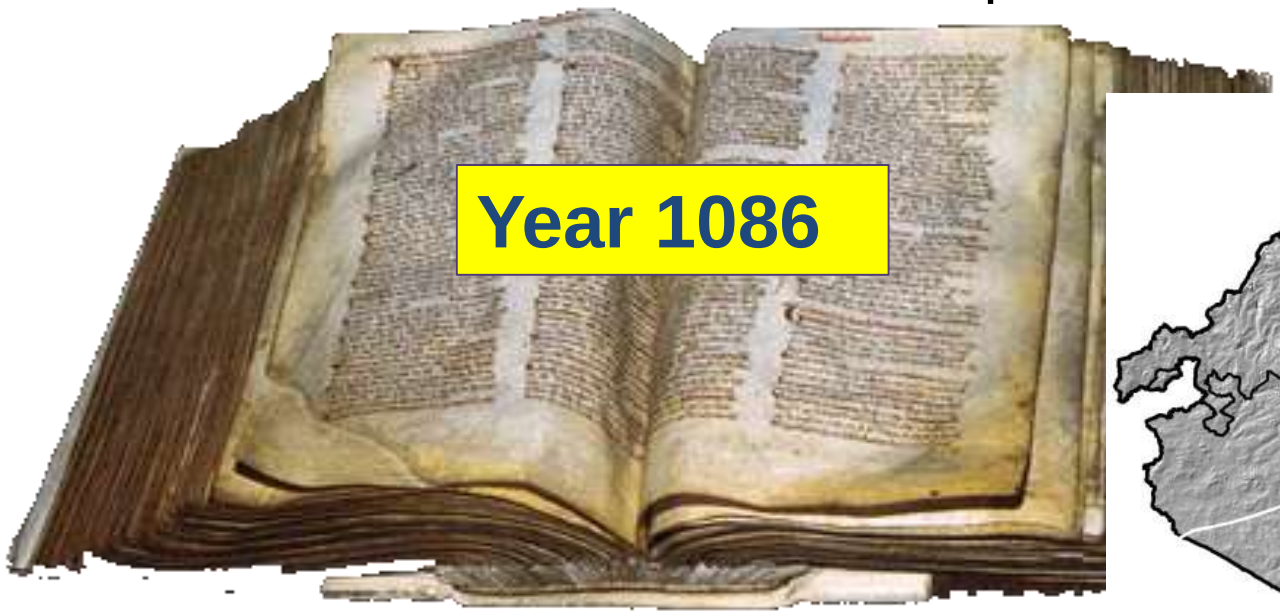
→ Infrastructure?

Let us look back almost 1000 years, and try to make sense of hierarchical structures from partial data.

Domesday Book: Great Survey of much of England and parts of Wales completed in 1086

Work done in collaboration with Stuart Brookes and Andrew Reynolds from the Archaeology Department, UCL.

Domesday Book: Great Survey of much of England and parts of Wales completed in 1086



Courtesy Stuart Brookes

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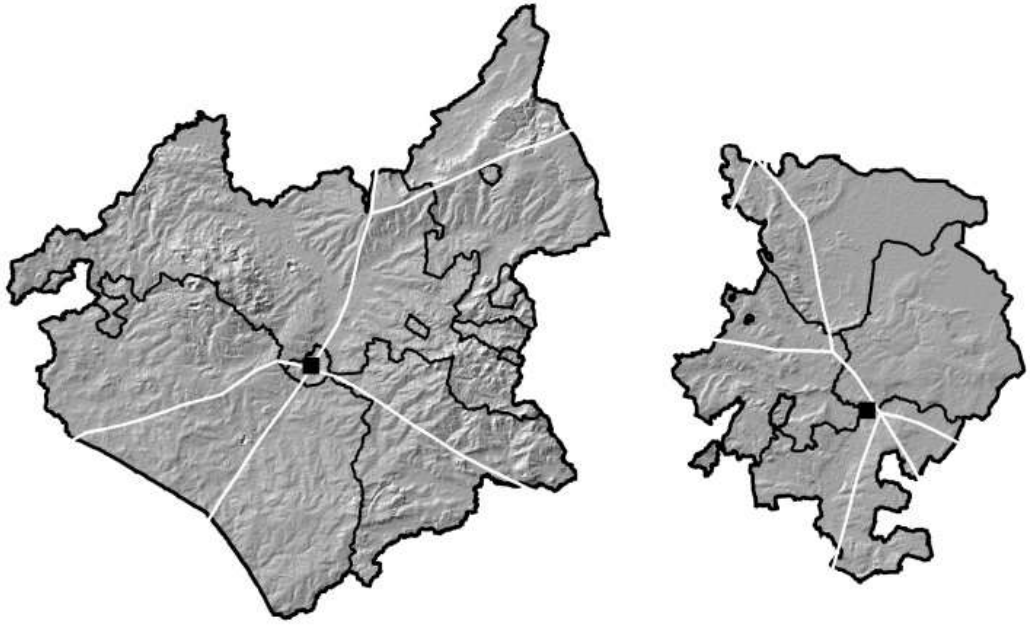
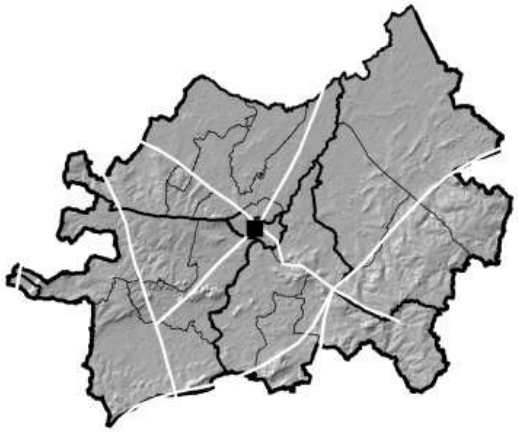
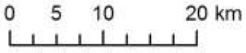


‘In Kiftsg

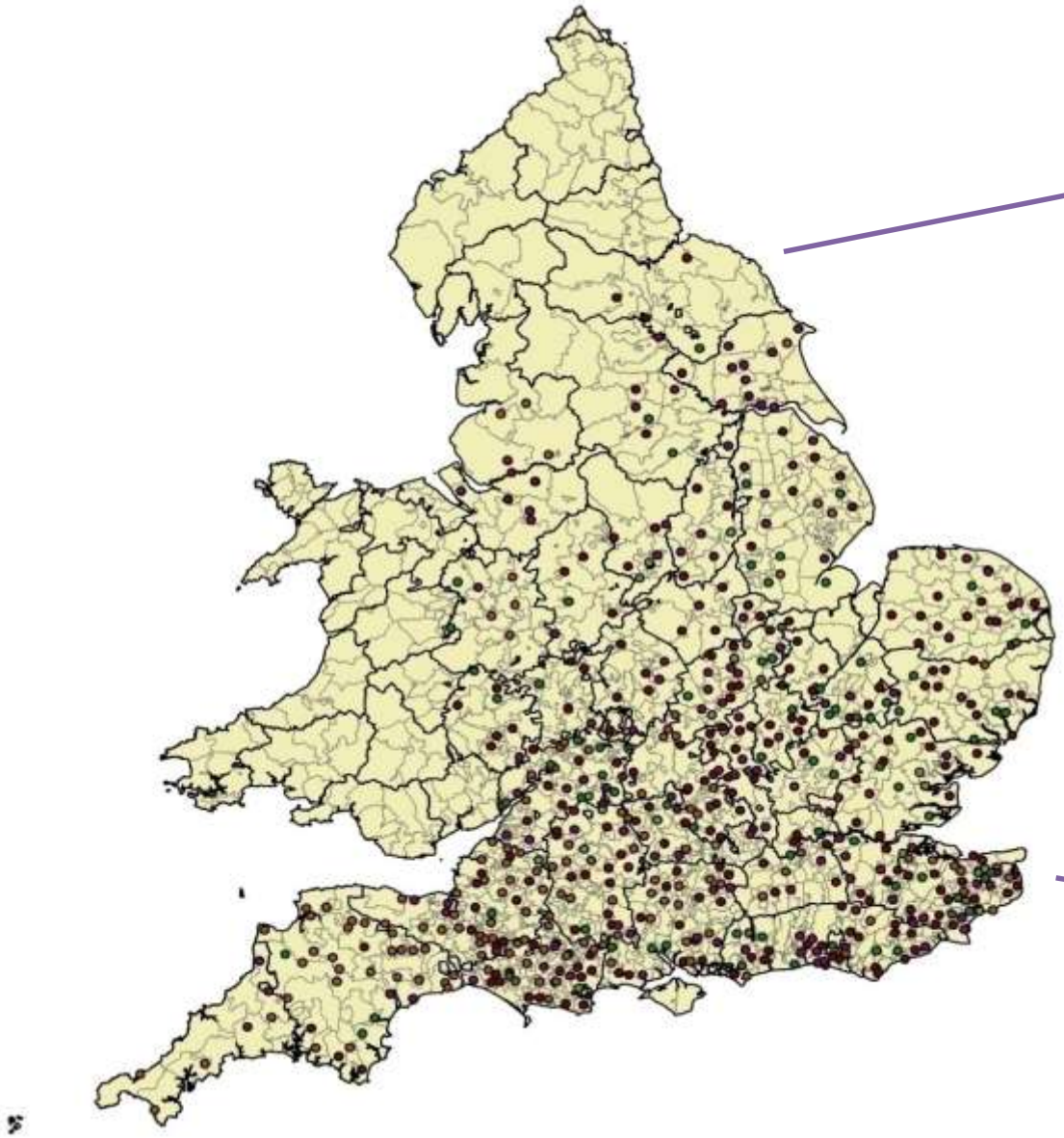
Hundred or **Wapentake** – administrative districts (usually named after their **meeting-place**)

Value of the holding



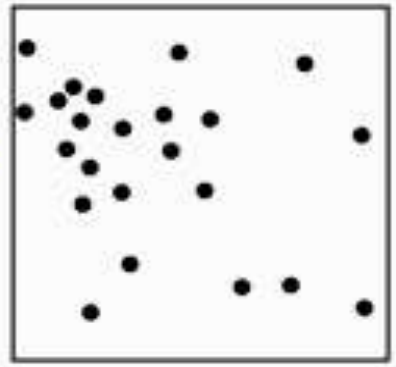


Domesday Book as a Cartographic resource



Administrative territories:
hundreds, wapentakes, shires, etc

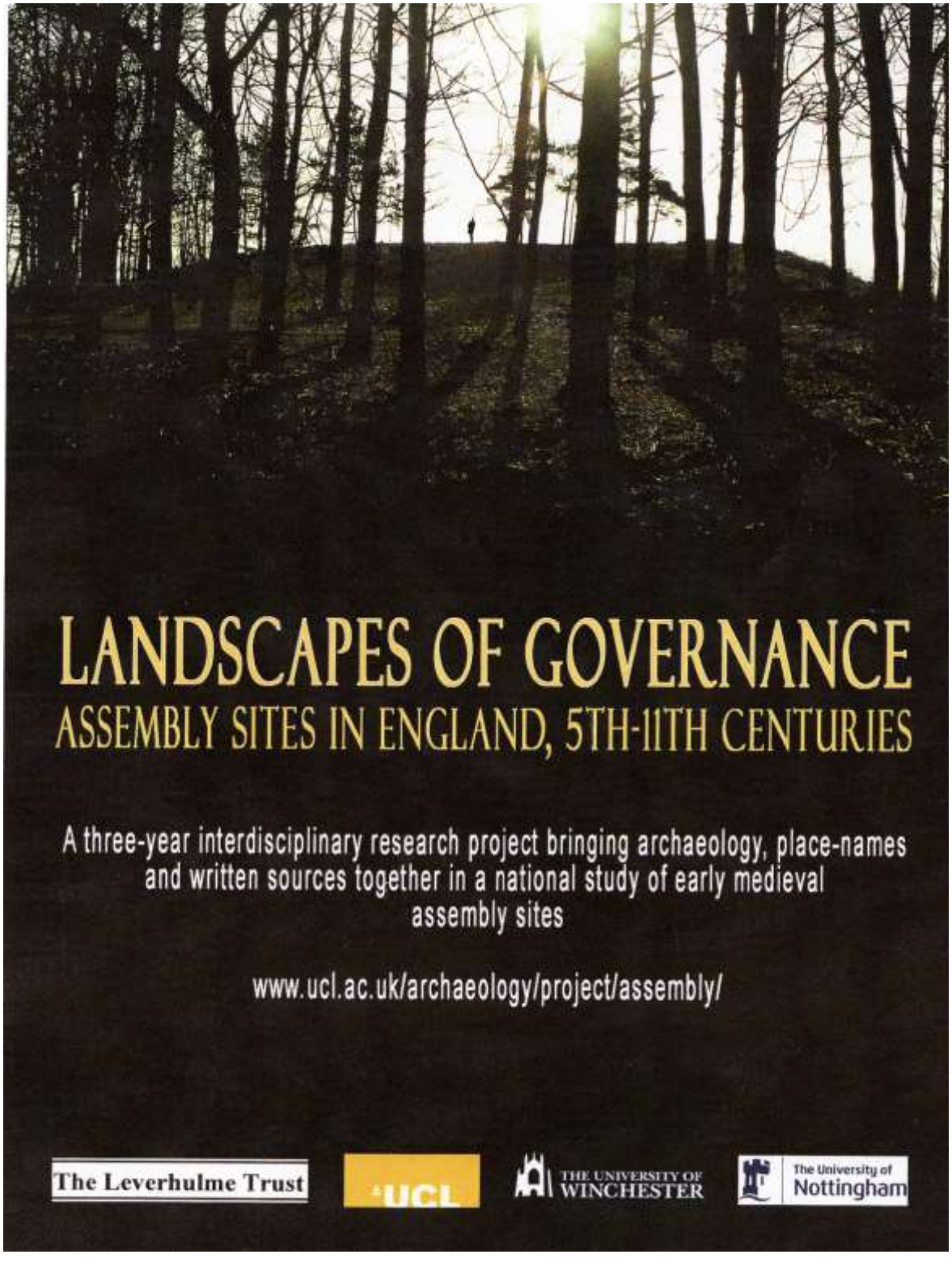
Places: Vills, meeting-places



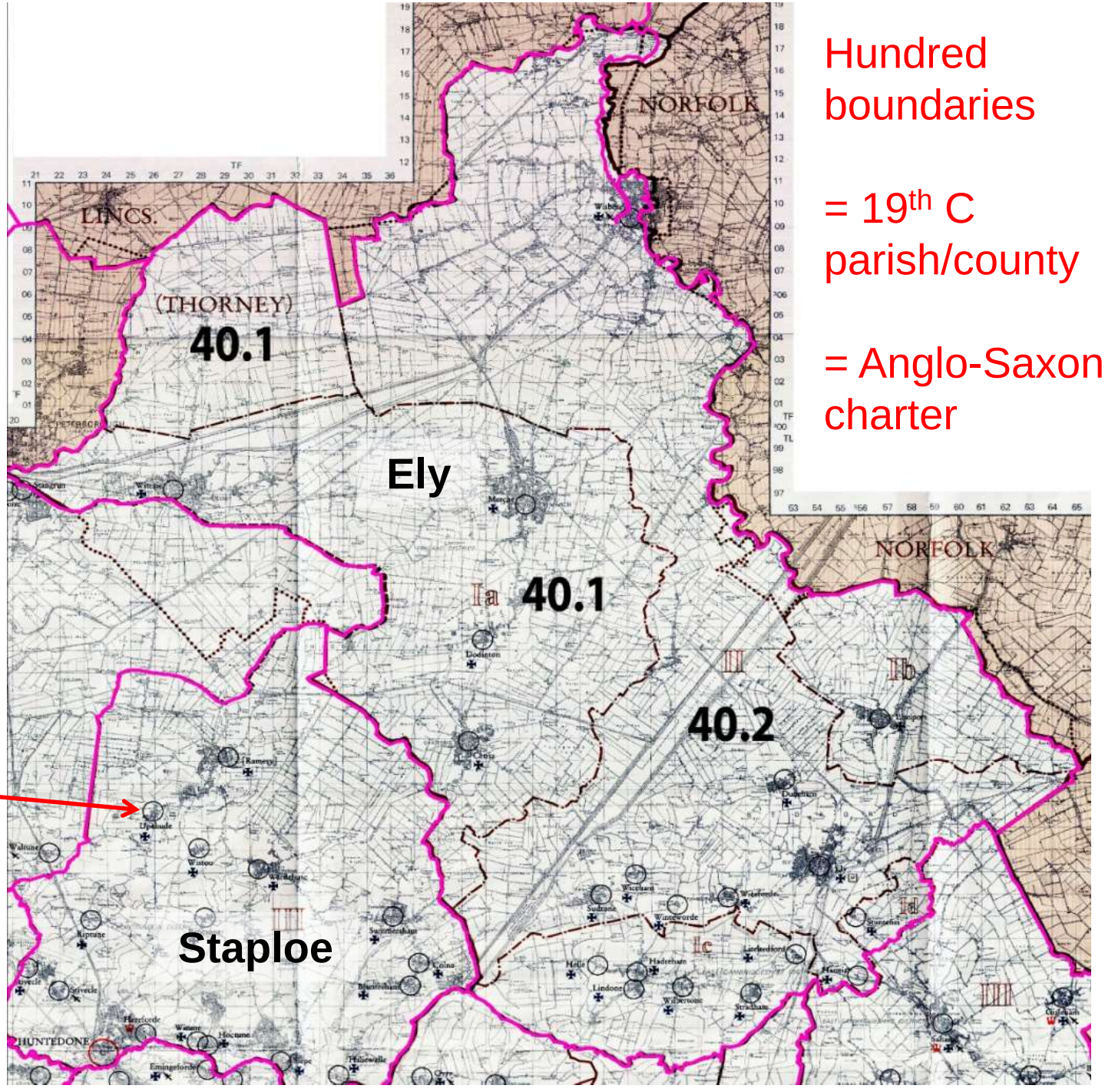
Courtesy Stuart Brookes

Landscapes of Governance: Anglo-Saxon Assemblies

Andrew Reynolds
John Baker
Stuart Brookes
Barbara Yorke
Jayne Carroll



Landscapes of Governance mapping



Hundred boundaries

= 19th C parish/county

= Anglo-Saxon charter

vills

Structure of administrative districts:

→ By the 11th century several phases of administrative reorganisation

→ **Palimpsest** - very different chronologies and histories lay behind local territories both within and between historically defined regions and polities.

→ Have the spatial patterns of the Vills left any clues with respect to the historical trajectories of Domesday administrative organisation?

Physical process leading to communities

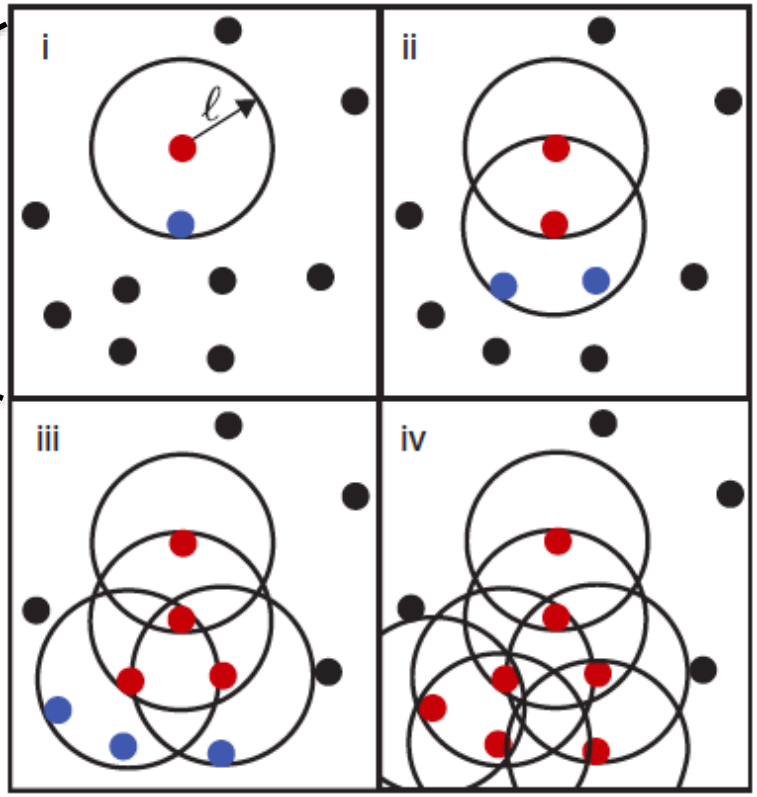
→ Connectivity given by proximity: distance a good proxy for interactions

Trade, illness, messages, etc. can spread in the urban system in the same way as a fire in a forest: model connectivity as a **percolation process**

Domesday Book as a Cartographic resource

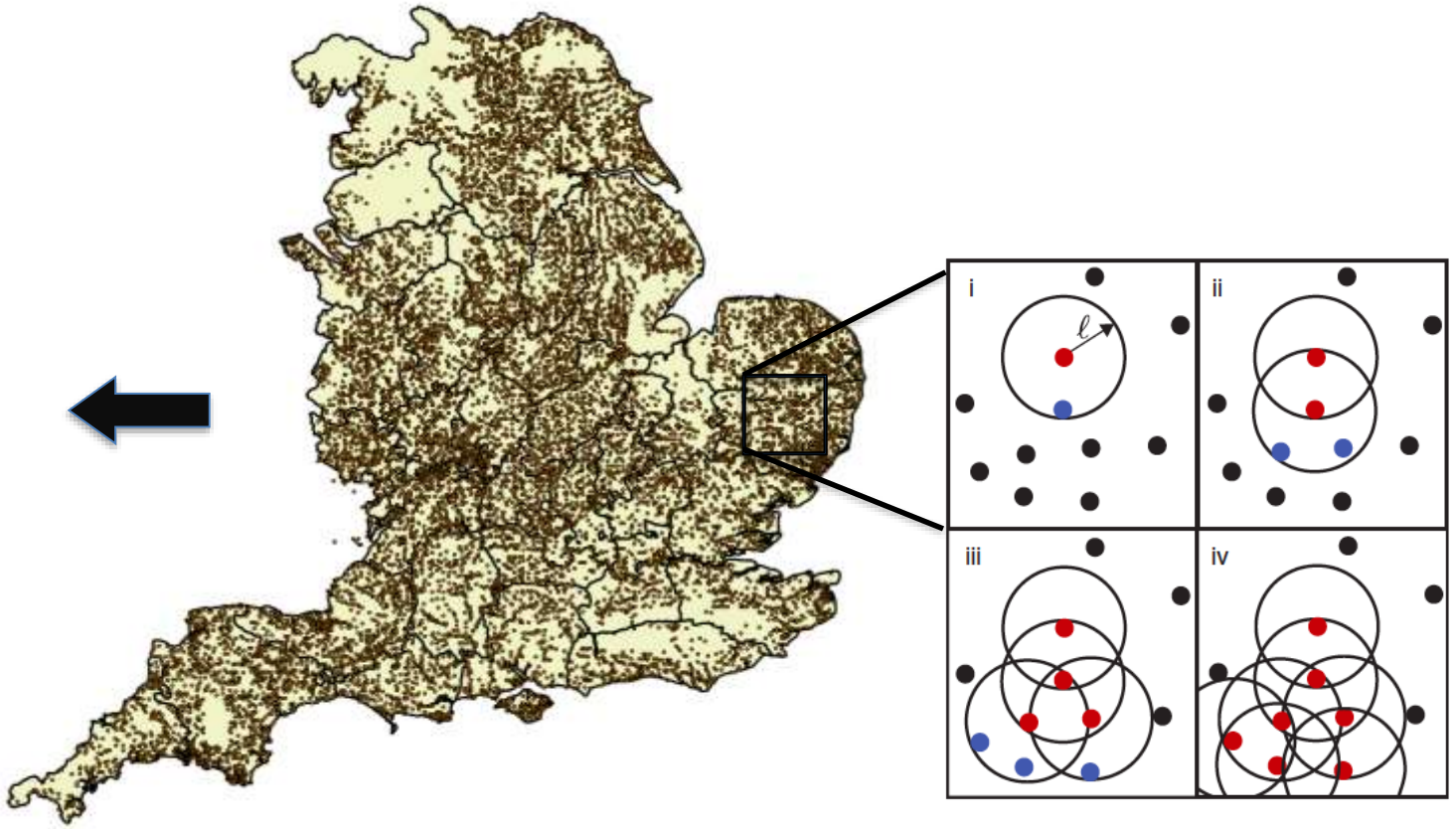
Vills in Domesday book

Points in the space



Imagine a disease spreading in vills as fire in a forest (percolation)

Vills: points in space



Imagine a fully connected network that we start disconnecting according to weakest links, in this case the largest distances.

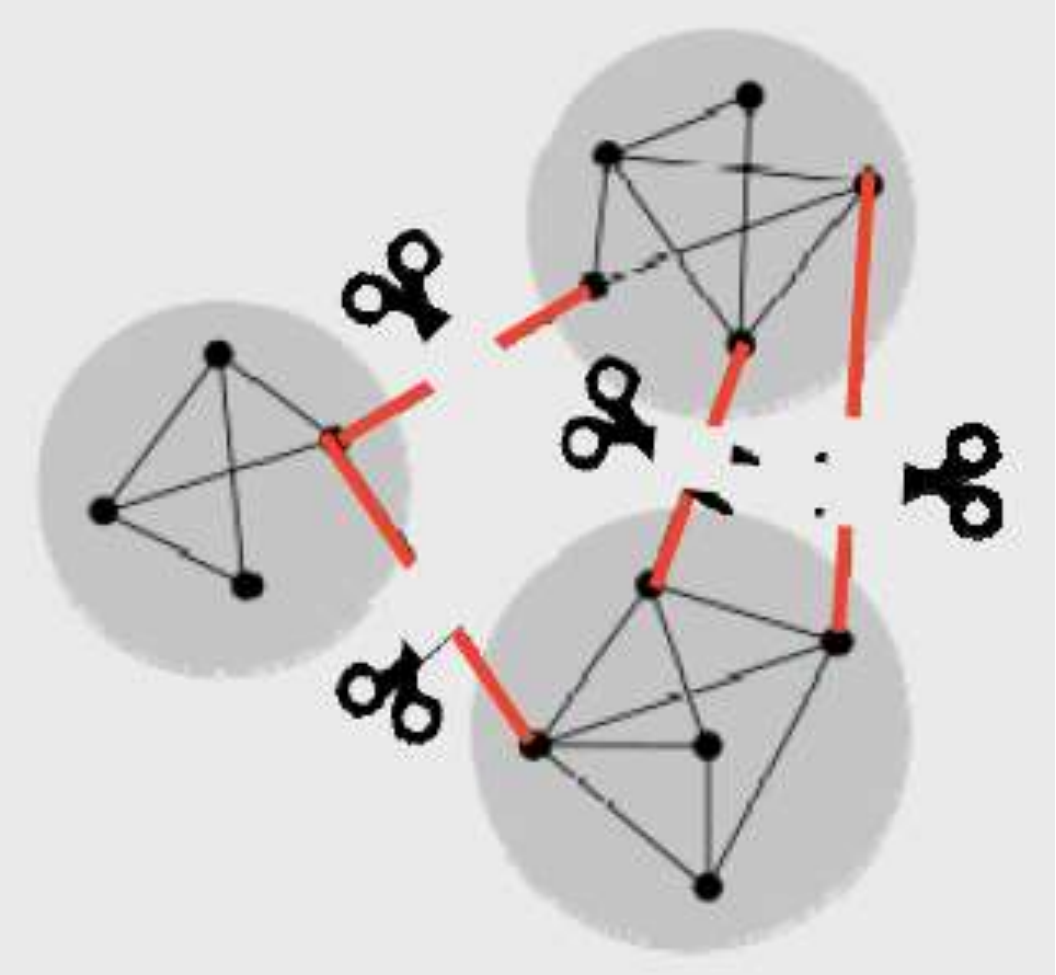
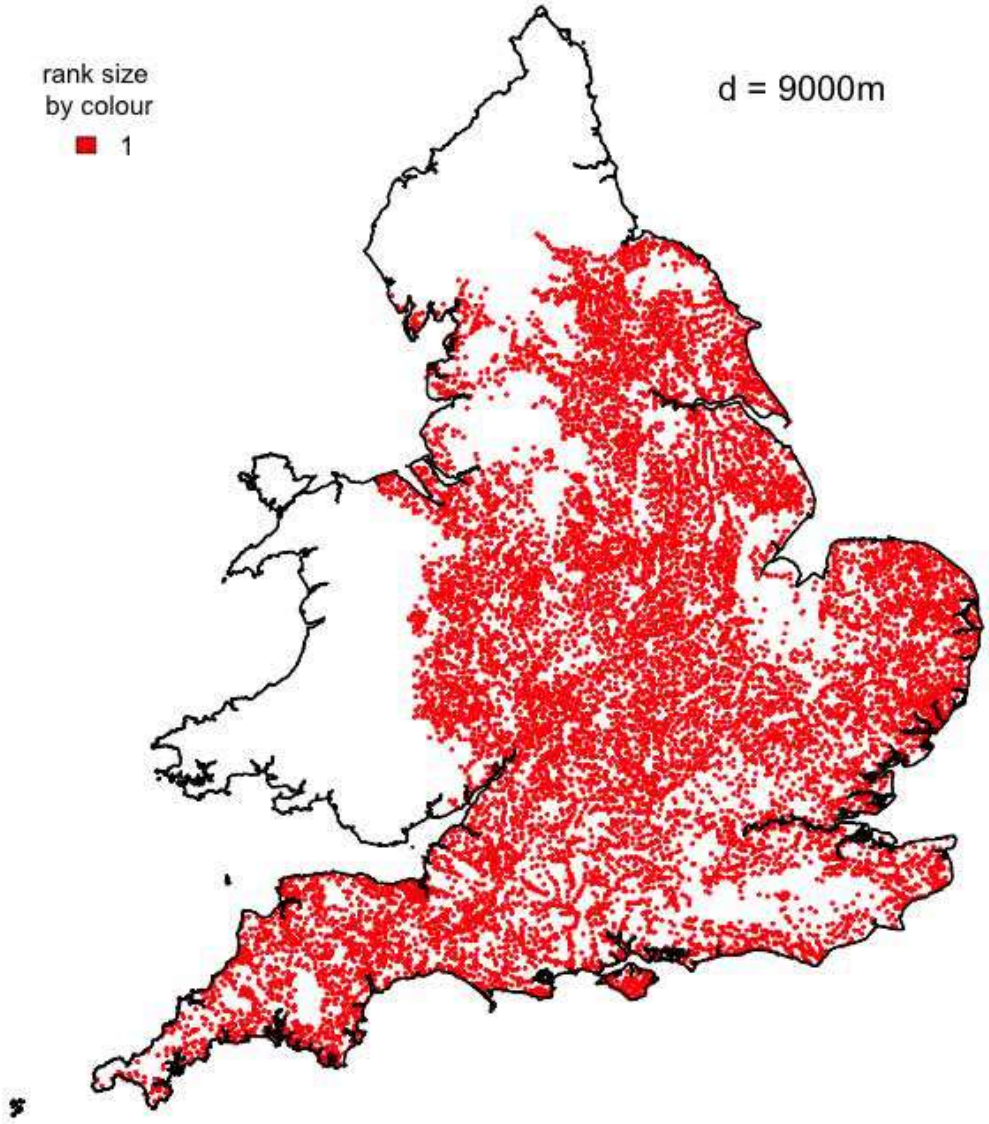
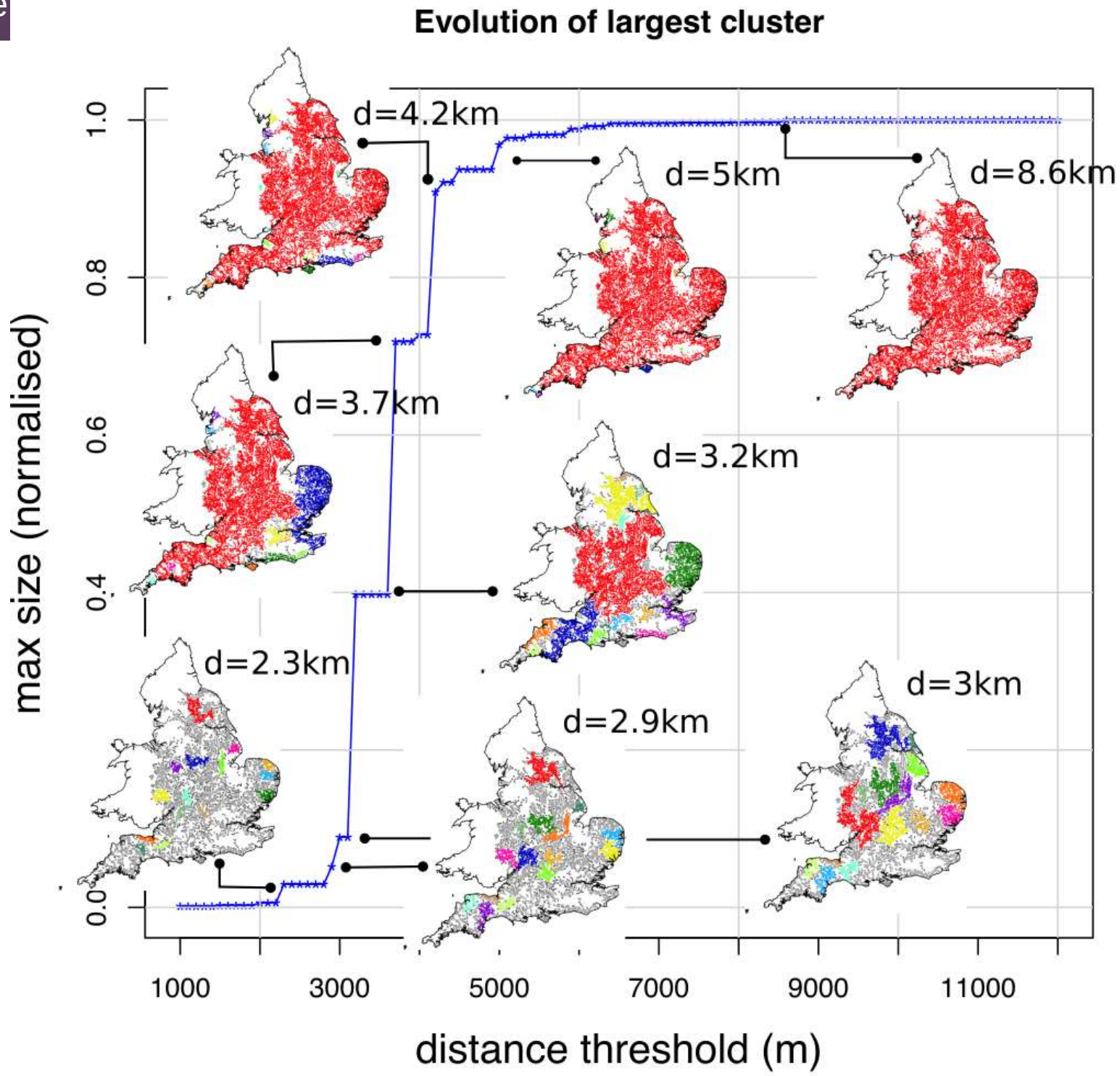


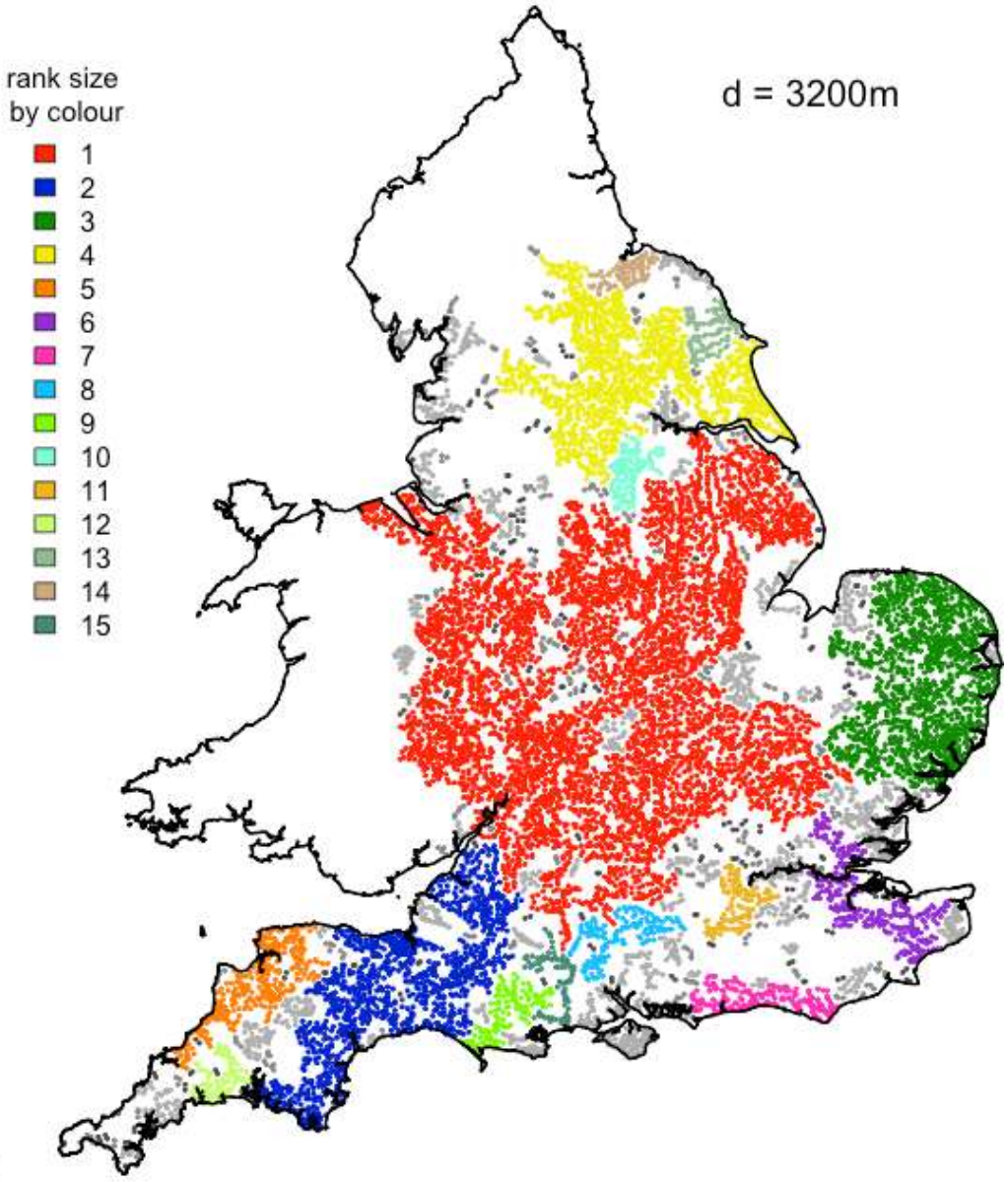
Image Mike Batty

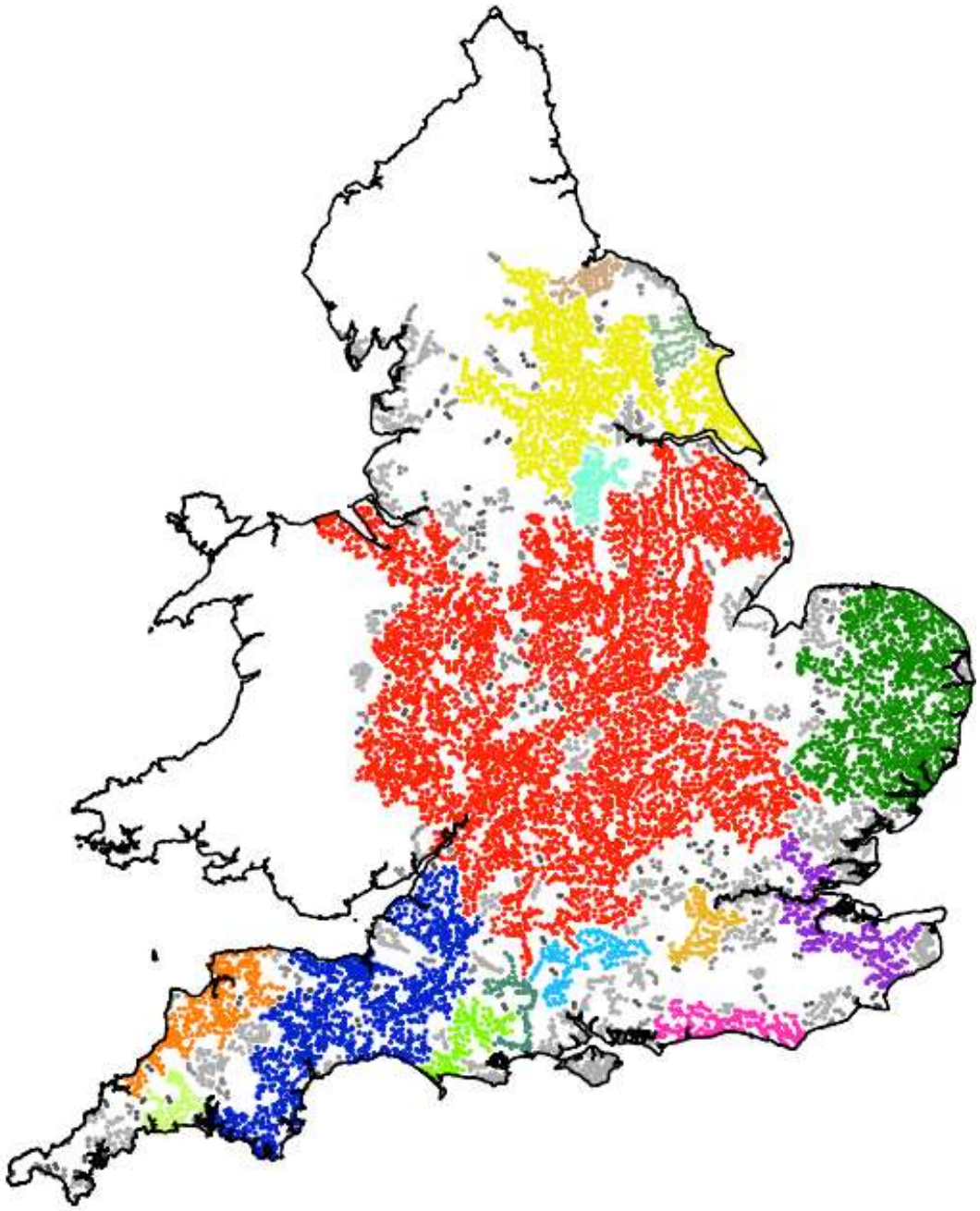
Places in Domesday Book

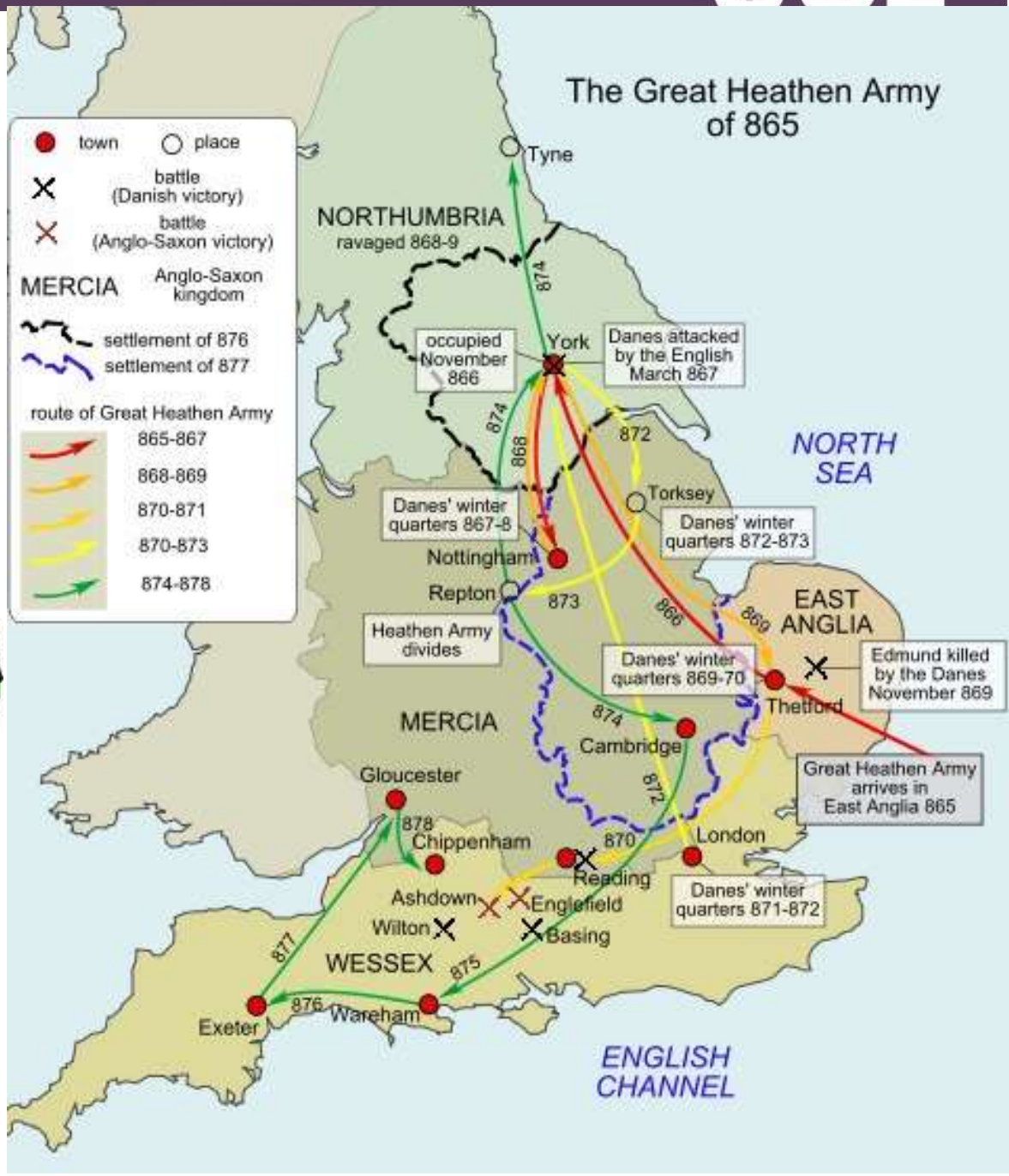


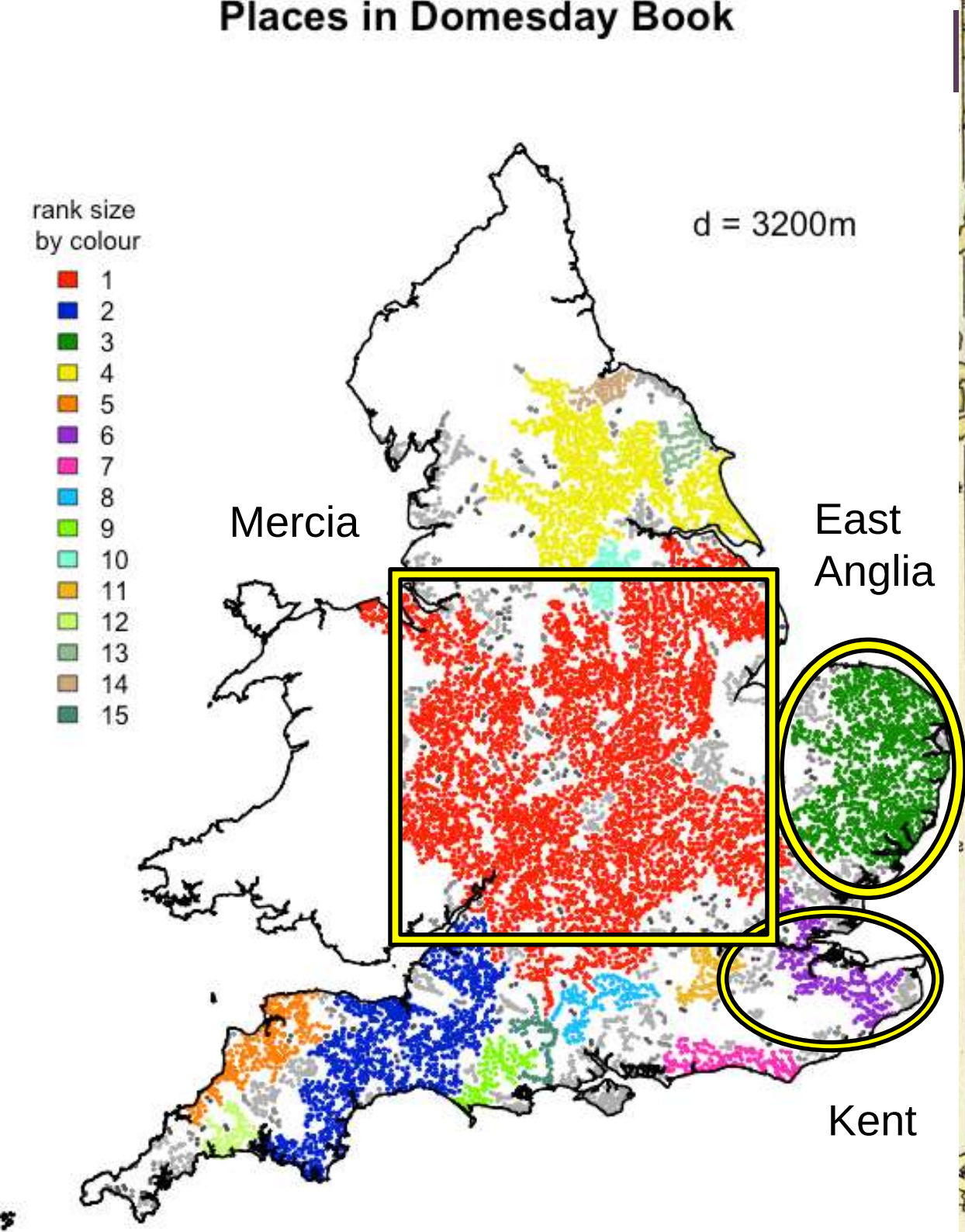

Evolution of largest cluster
d=4.2km
d=5km
d=8.6km
d=3.7km
d=3.2km
d=2.3km
d=2.9km
d=3km
max size (normalised)
0.0
0.4
0.6
0.8
1.0
1000
3000
5000
7000
9000
11000
distance threshold (m)

Settlement clusters = political geography of 8th to 9th centuries ‘the Mid-Saxon shuffle’

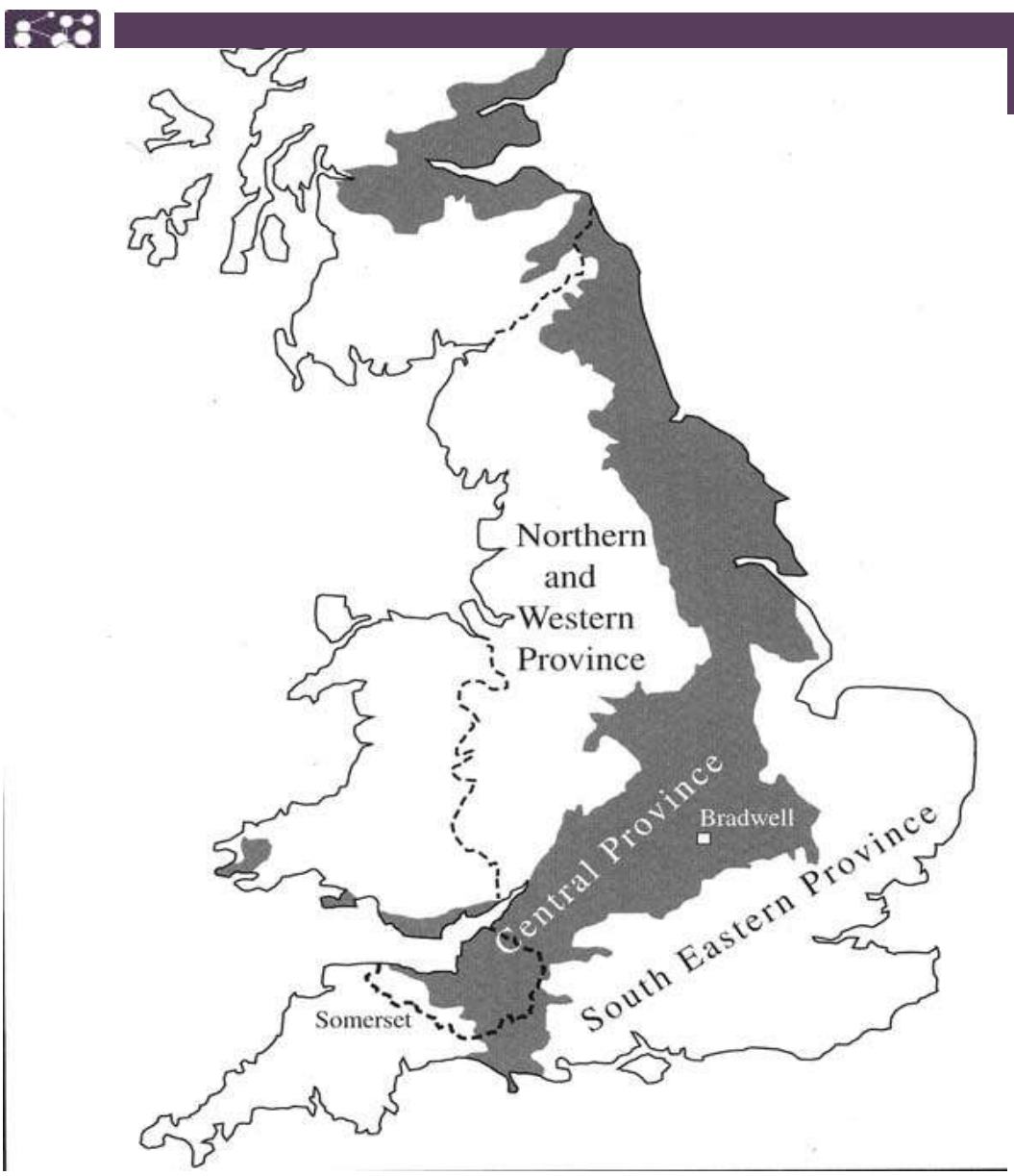





The Great Heathen Army of 865
town
place
battle (Danish victory)
battle (Anglo-Saxon victory)
MERCIA
Anglo-Saxon kingdom
settlement of 876
settlement of 877
route of Great Heathen Army
865-867
868-869
870-871
870-873
874-878
NORTHUMBRIA
ravaged 868-9
Tyne
874
occupied November 866
York
Danes attacked by the English March 867
872
868
874
NORTH SEA
Torksey
Danes' winter quarters 867-8
Danes' winter quarters 872-873
Nottingham
Repton
873
Heathen Army divides
868
869
EAST ANGLIA
Danes' winter quarters 869-70
Edmund killed by the Danes November 869
Thetford
MERCIA
874
Cambridge
Great Heathen Army arrives in East Anglia 865
Gloucester
872
878
Chippenham
870
London
Reading
Ashdown
Englefield
Wilton
Basing
Danes' winter quarters 871-872
877
WESSEX
875
876
Wareham
Exeter
ENGLISH CHANNEL


Places in Domesday Book
rank size by colour
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
d = 3200m
Mercia
East Anglia
Kent

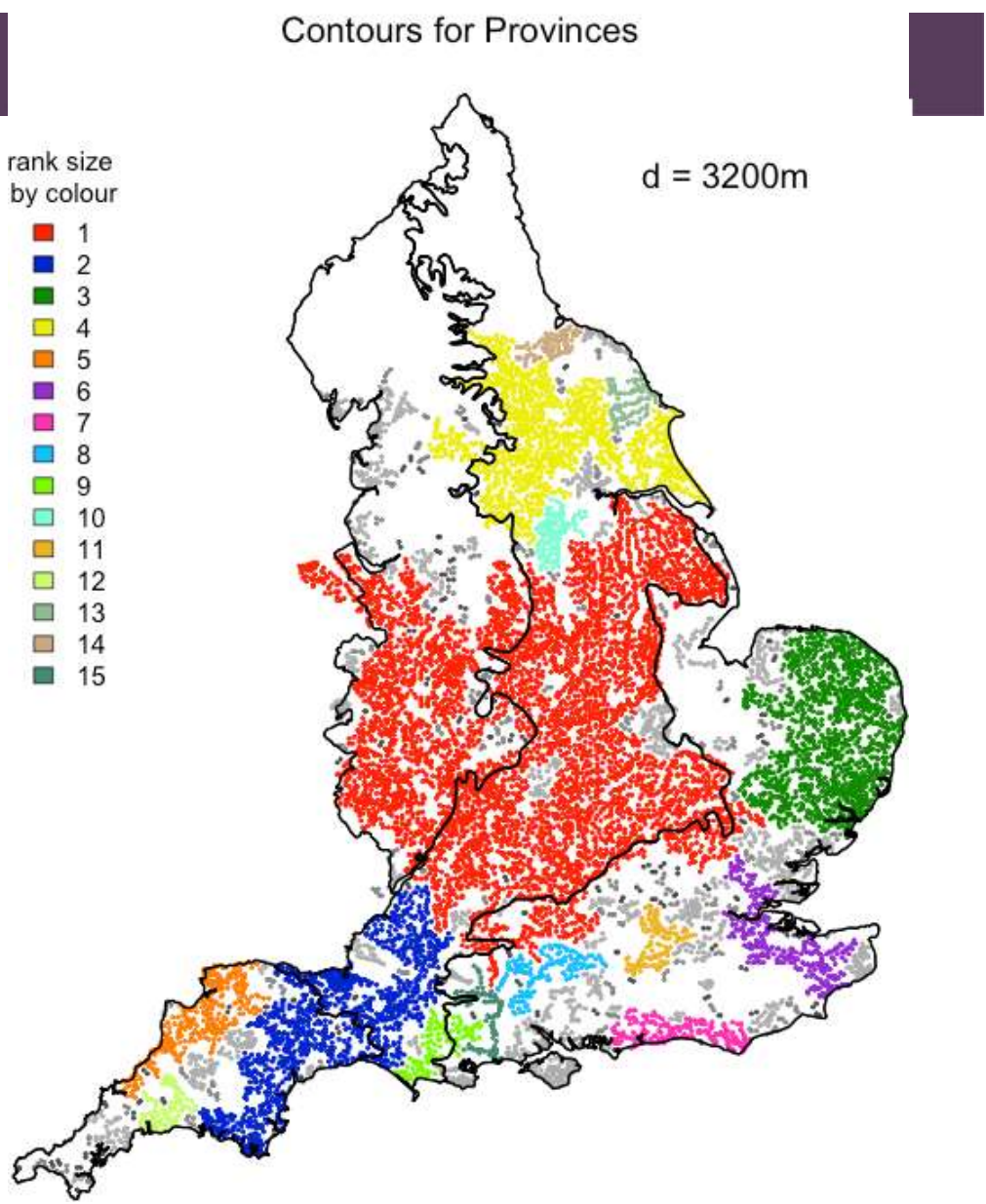

ANGLO-SAXON BRITAIN
"THE HEPTARCHY."
English Miles
0 10 20 40 60 80
PICTS
STRATHCLYDE
BERNICIA
NORTHUMBRIA
GALLOWAY
Man
DEIRA
LINDSEY
NORTH MIDDLE ANGLES
MERCIA (MIERCE)
SOUTH GYRWE
EAST ANGLES
WALES
SOUTH ANGLES
EAST SAXONS
MIDDLE SAXONS
SUSSEX
KENT
SOUTH SAXONS
Wight
WEST WALES
FRISIA



Roberts & Wrathmell 2000

An Atlas of Rural Settlement in England

BUT: is based on 19th century settlement patterns



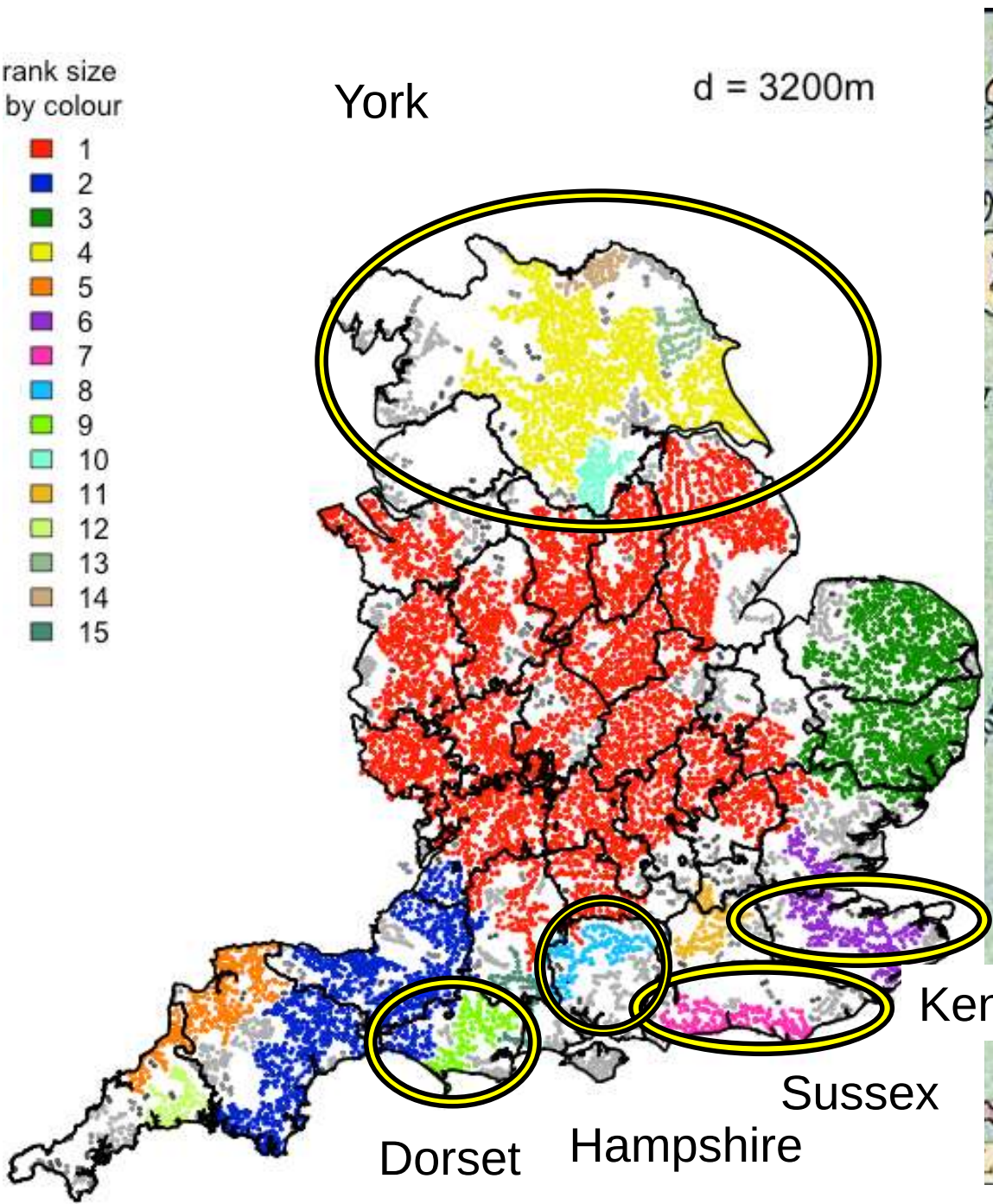
11th century settlements partly support the general pattern in the east

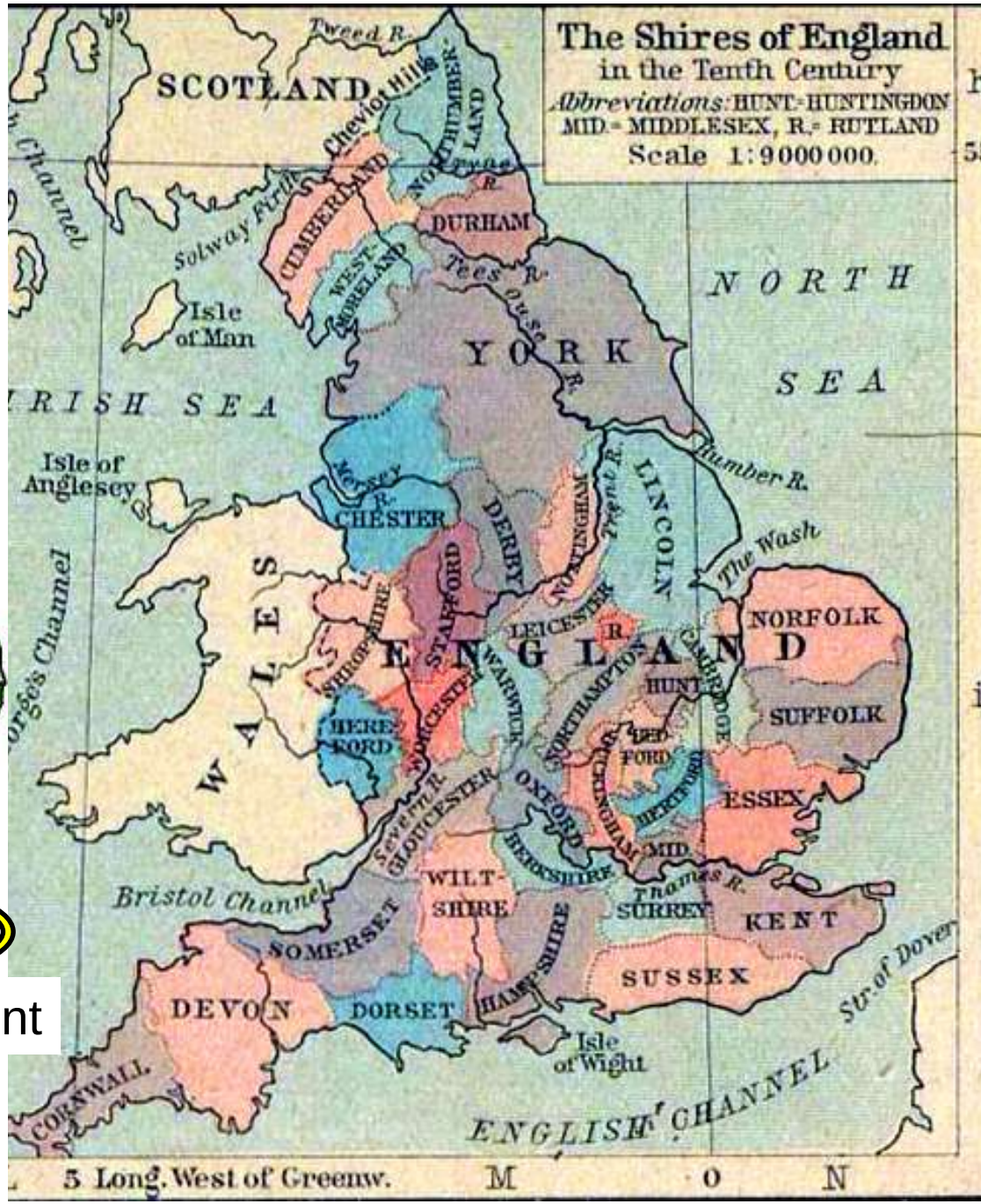
Much more complicated in the west

And if you read **The Hobbit** (if you haven't you should), you will also know that urban systems can be described in terms of "**Shires**".

Places in Domesday Book

Contours for English shires





Places in Domesday Book

Contours for English shires

rank size
by colour

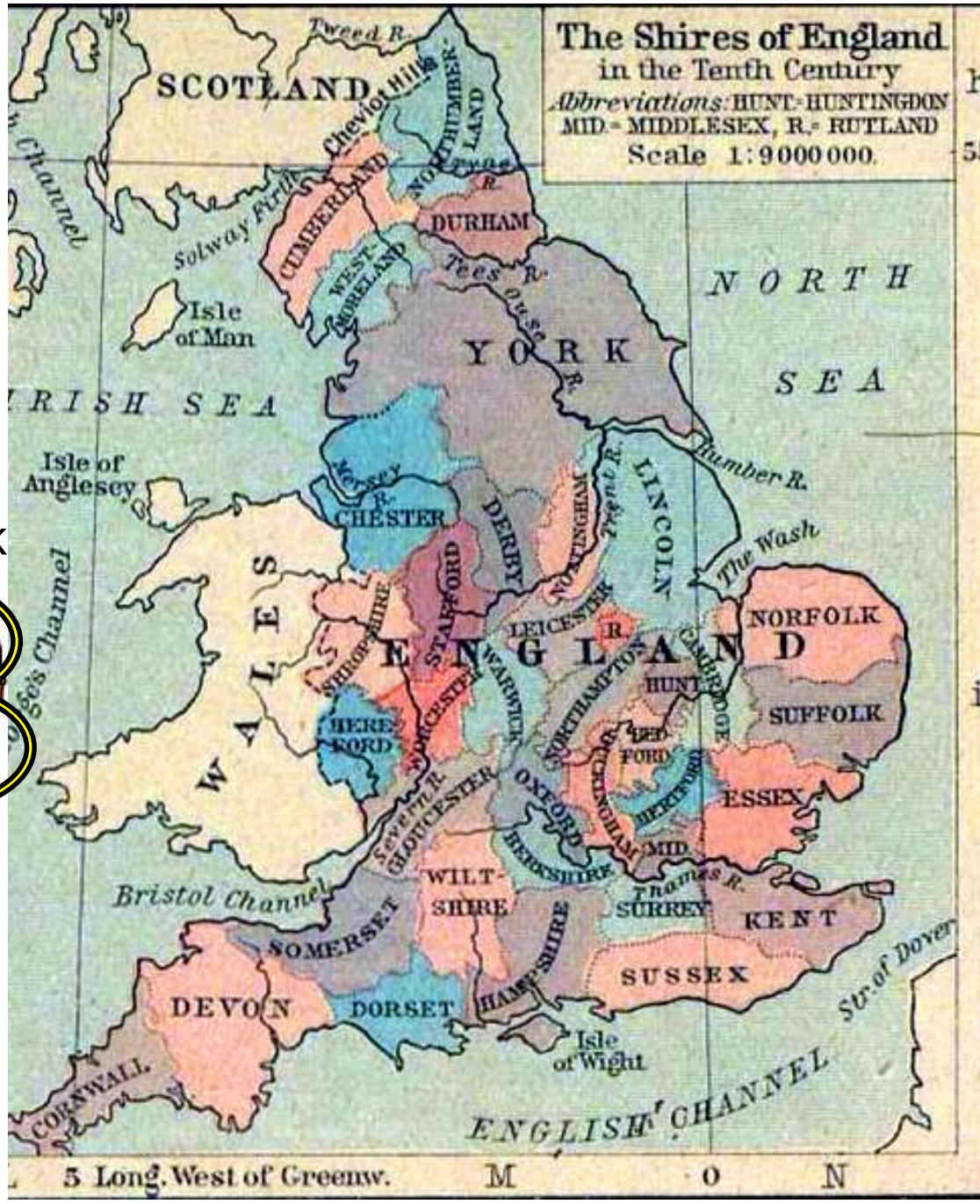
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

d = 3000m

Lincoln

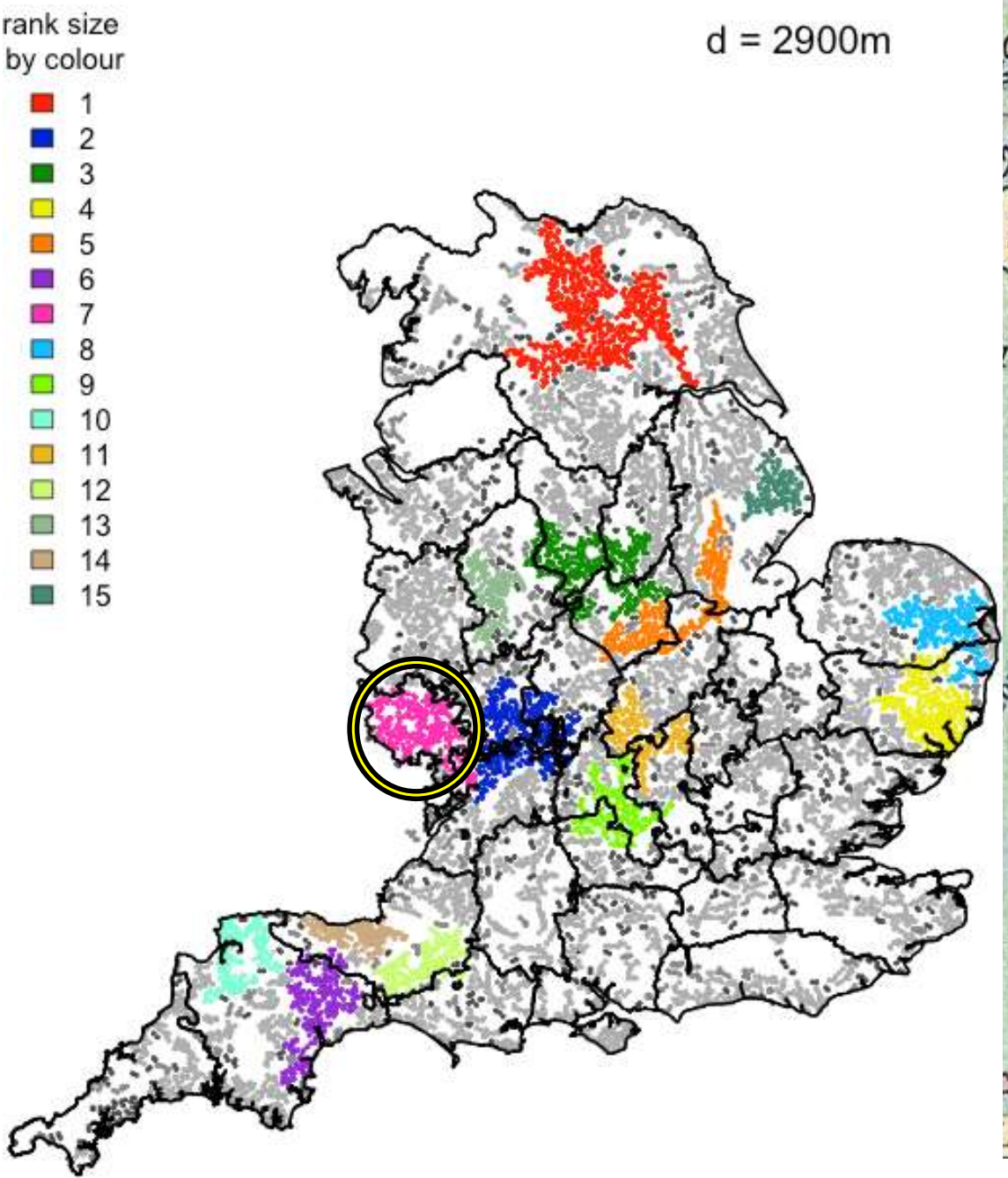
Norfolk

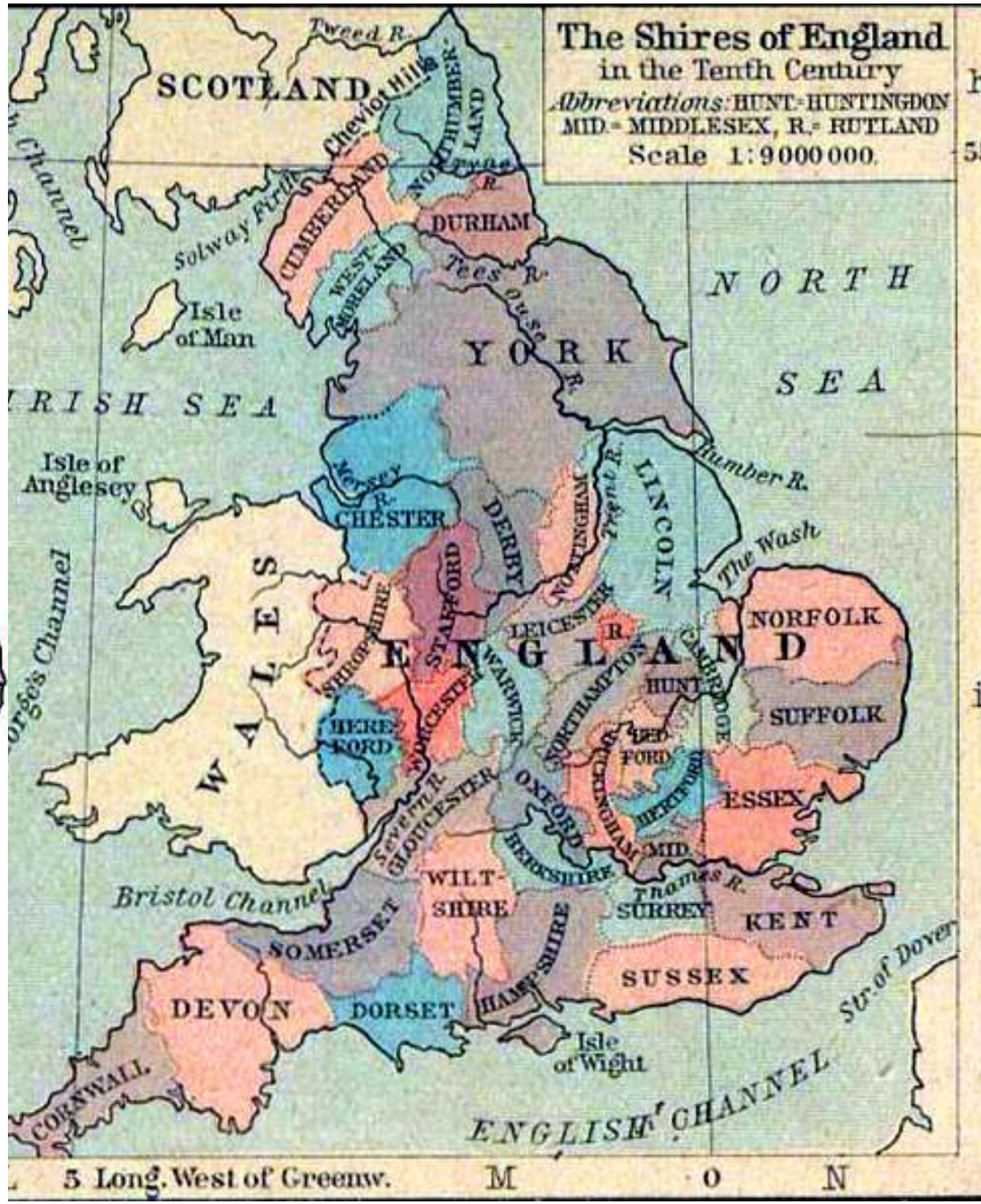
Suffolk



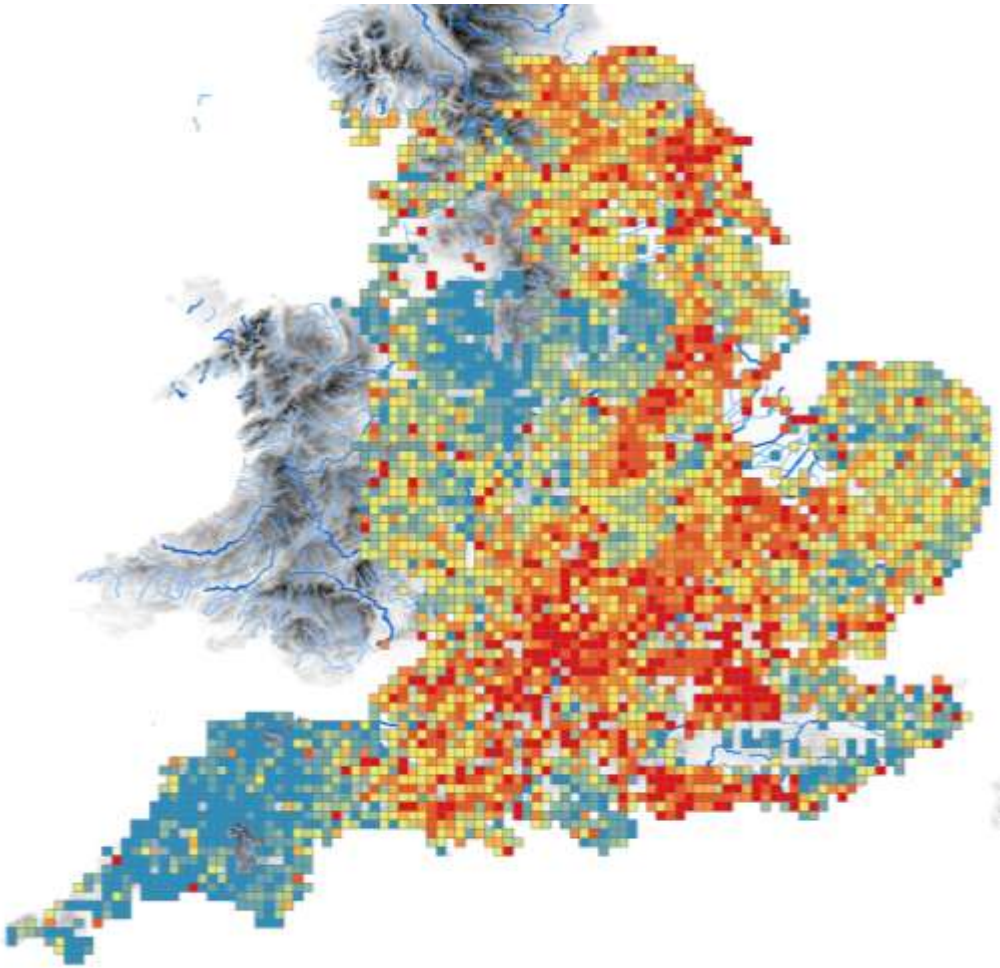
Places in Domesday Book

Contours for English shires

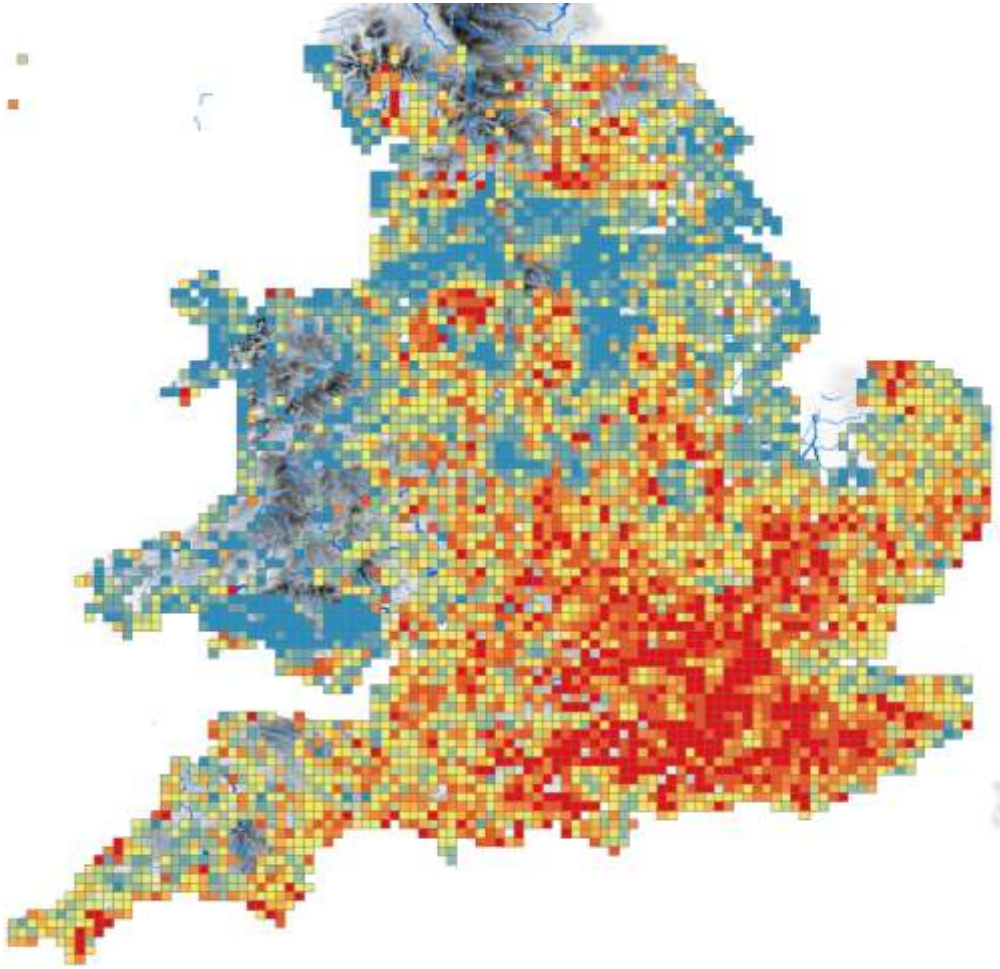




Average sum of holdings over 5km grid (1086 data)



Average house price over 5km grid (2013 data)



What about the 21st century?

→ In this globalised world can we still think that proximity in terms of distance bears any meaning to look at communities?

→ What can we take as a proxy for urbanisation?

Let us explore the oldest structure for trade and communication:

Street networks

Imagine a message spreading in a city as fire in a forest (percolation)

Intersection points

Let us look at Europe: Open Street Map

✧ Work by master student Thomas Russell

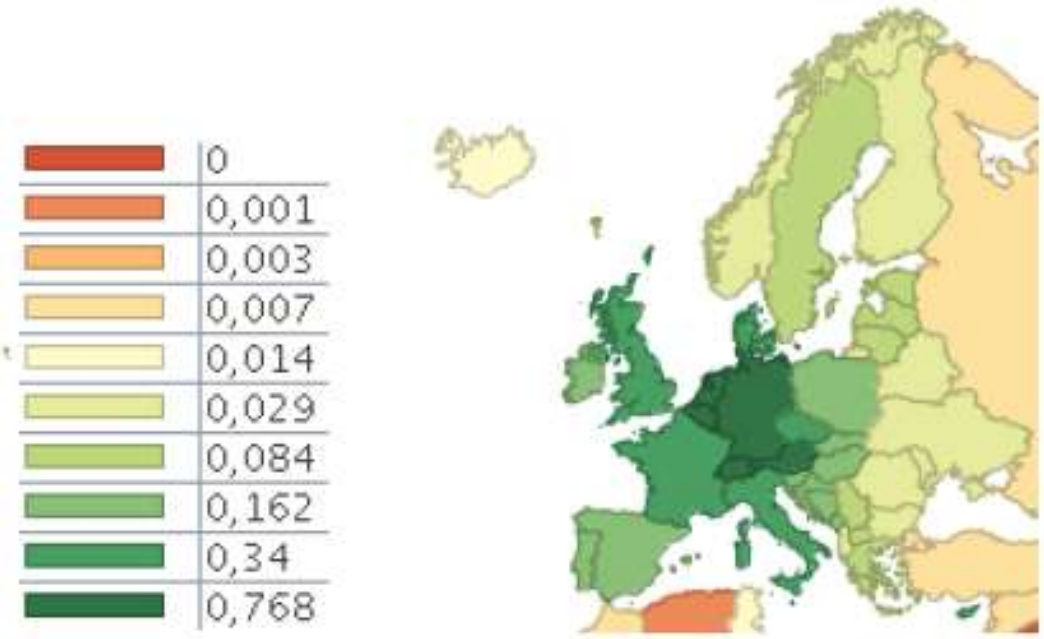


Figure 2: OSM users/day/1,000km², from Neis (2012)

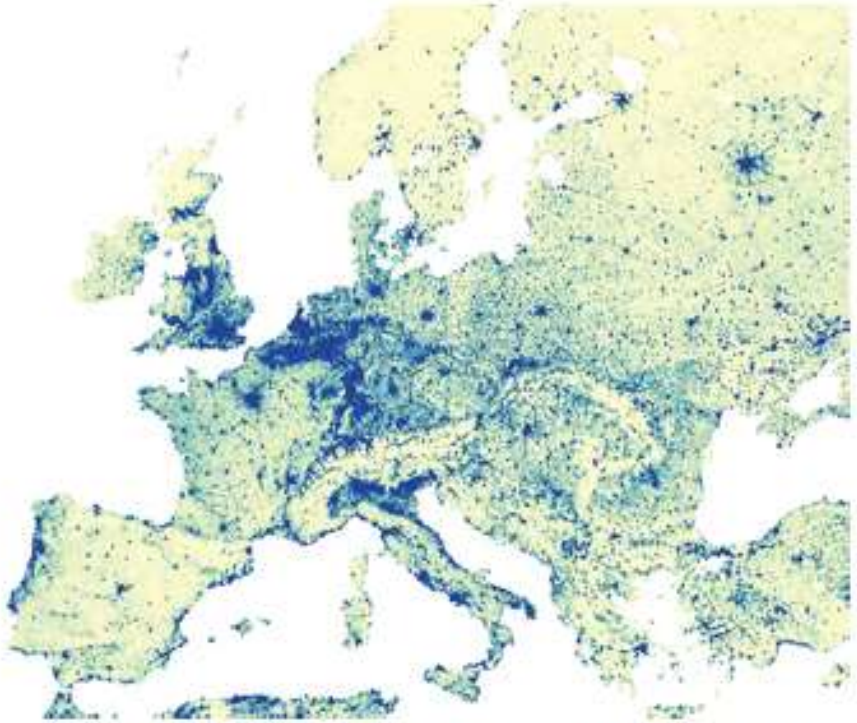


Figure 3: Population density in 2000, from Hyde 3.1

Higher population density → more potential contributors to the dataset

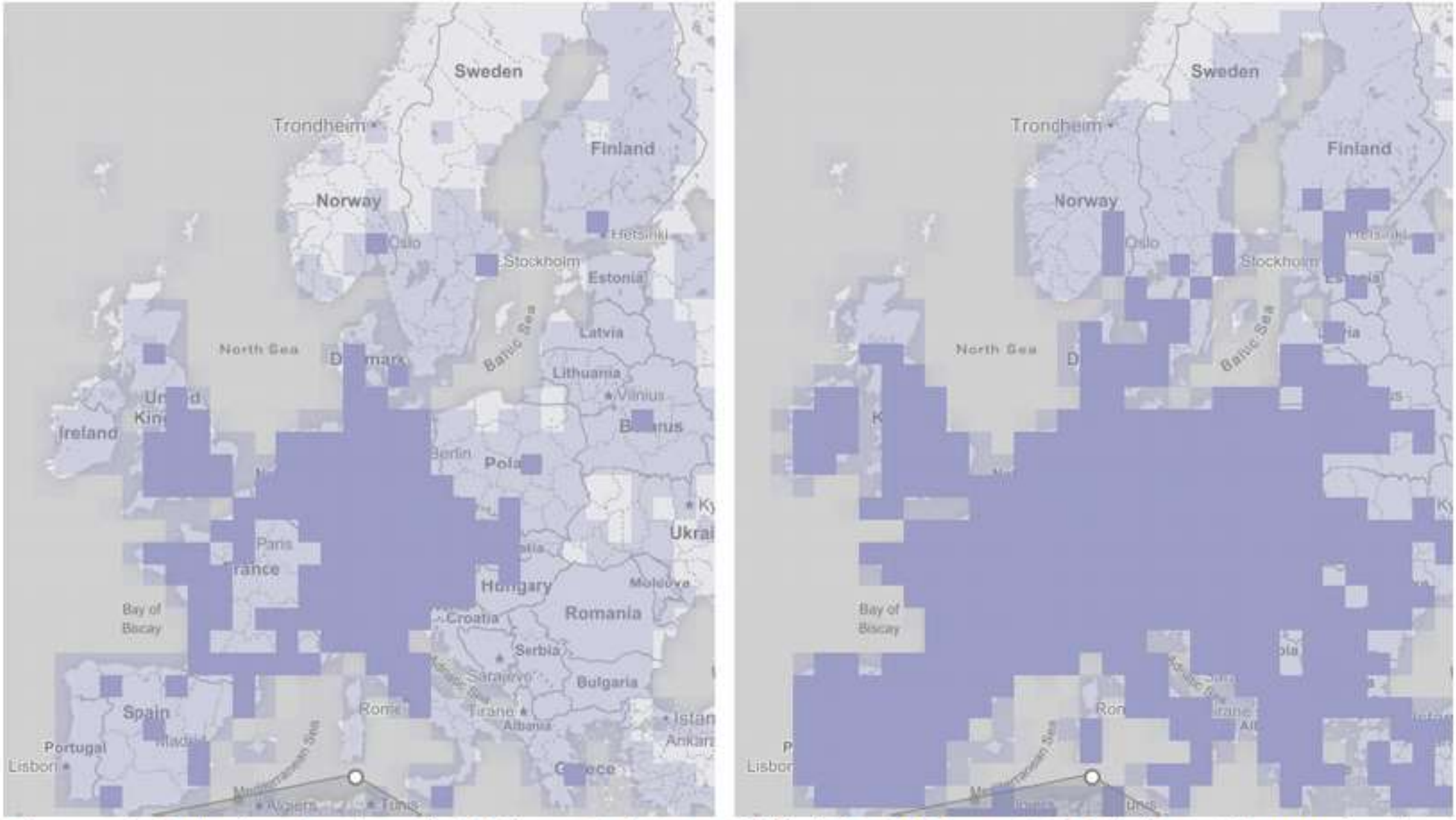


Figure 4: Relative density of OSM roads last modified in 2011 and 2016, from Humanitarian OpenStreetMap Team (2016)

Is this pattern the outcome of population densification?

→ let us look at a thousand years of population density evolution

Global Ecology and Biogeography
A Journal of Macroecology
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The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years

Kees Klein Goldewijk, Arthur Beusen, Gerard van Drecht, Martine de Vos

First published: 10 September 2010 Full publication history

DOI: 10.1111/j.1466-8238.2010.00587.x View/save citation

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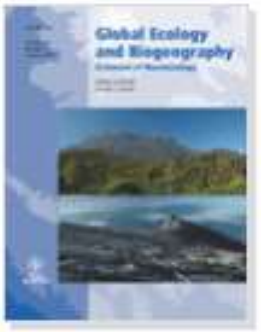
Am score 14



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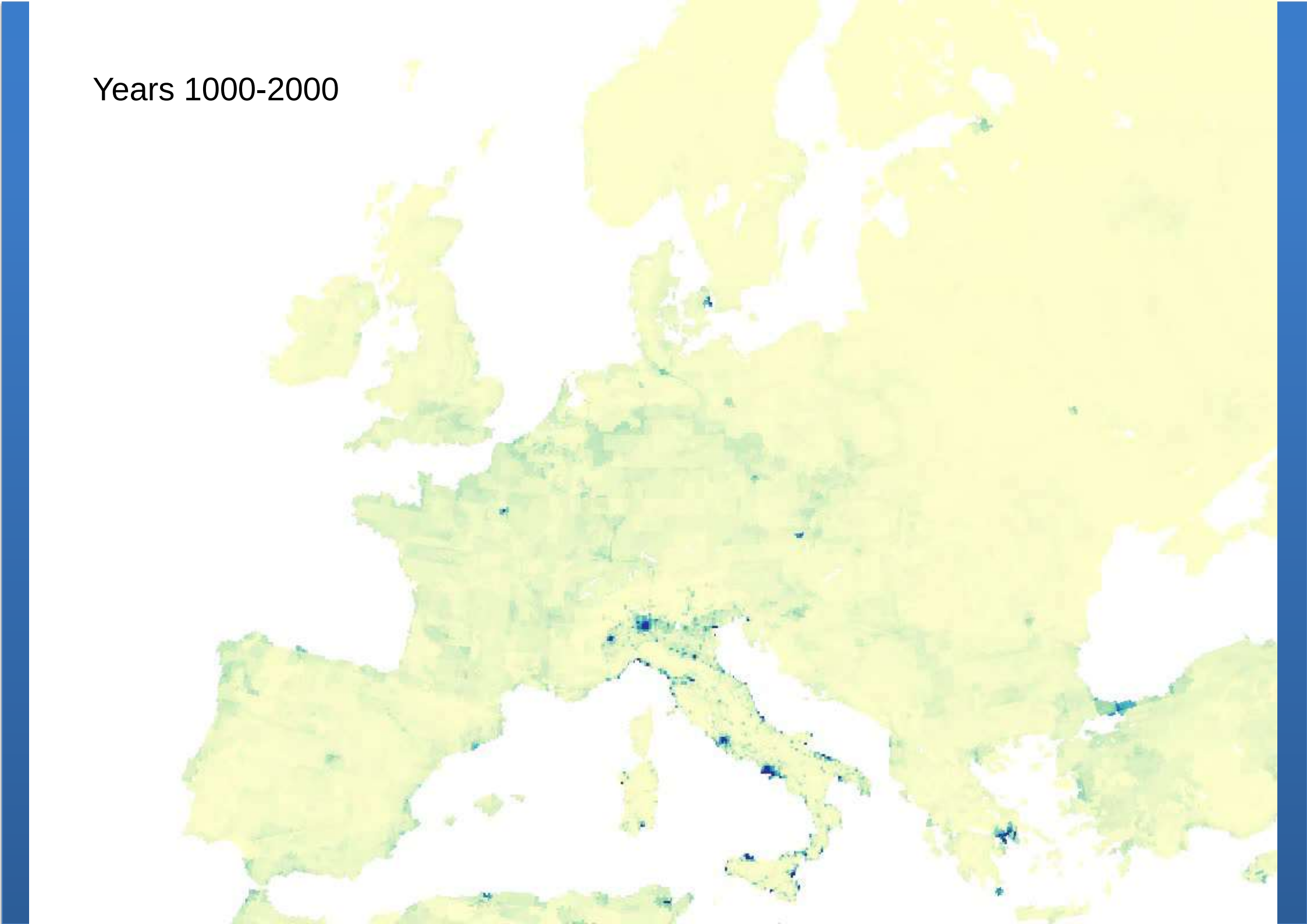
E-mail: kees.kleingoldewijk@pbl.nl

ABSTRACT

Aim This paper presents a tool for long-term global change studies; it is an update of the History Database of the Global Environment (HYDE) with estimates of some of the underlying demographic and agricultural driving factors.

Methods Historical population, cropland and pasture statistics are combined with satellite information and specific allocation algorithms (which change over time) to create spatially explicit maps, which are fully consistent on a 5' longitude/latitude grid resolution, and cover the period 10,000 BC to AD 2000.

Years 1000-2000

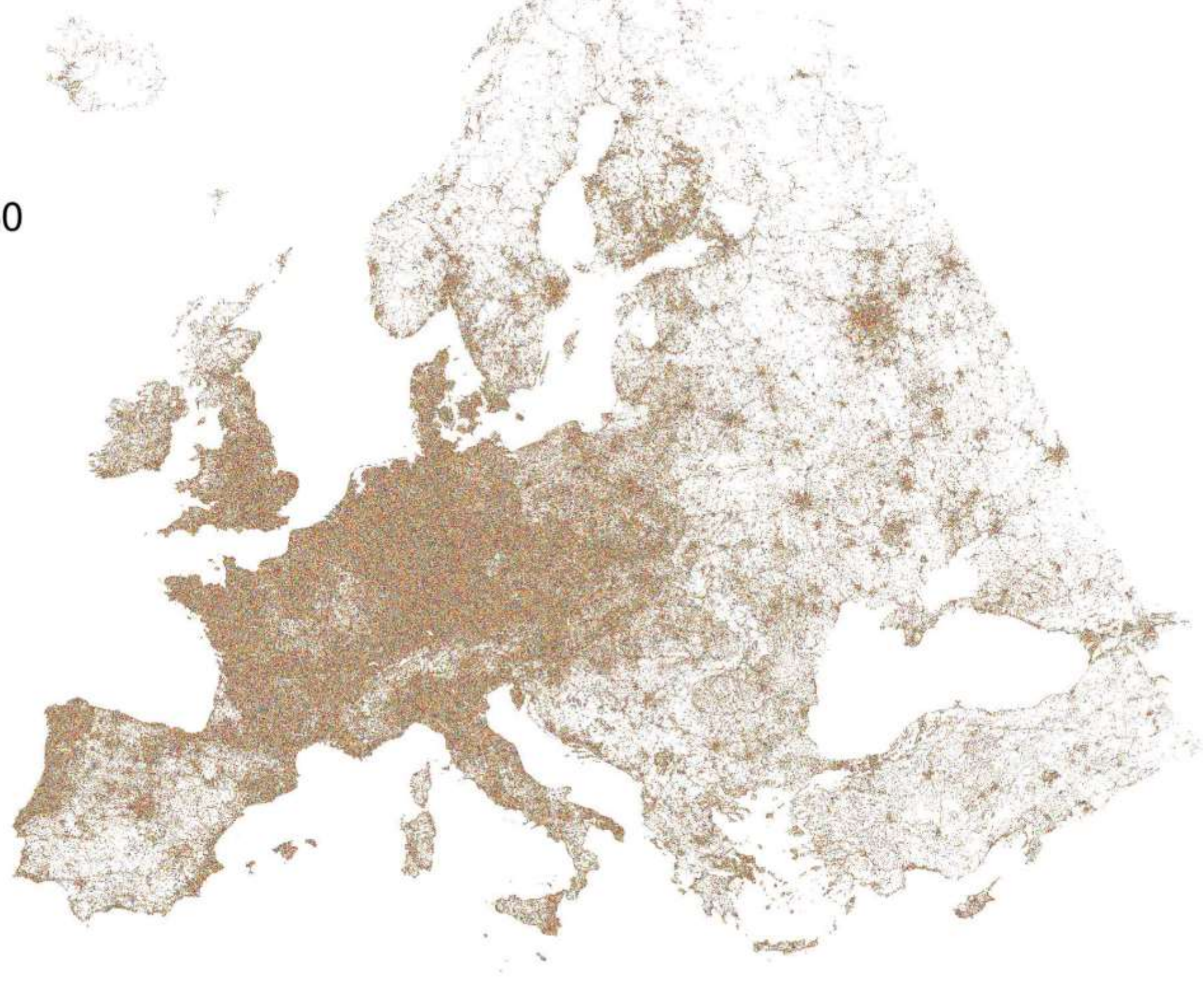


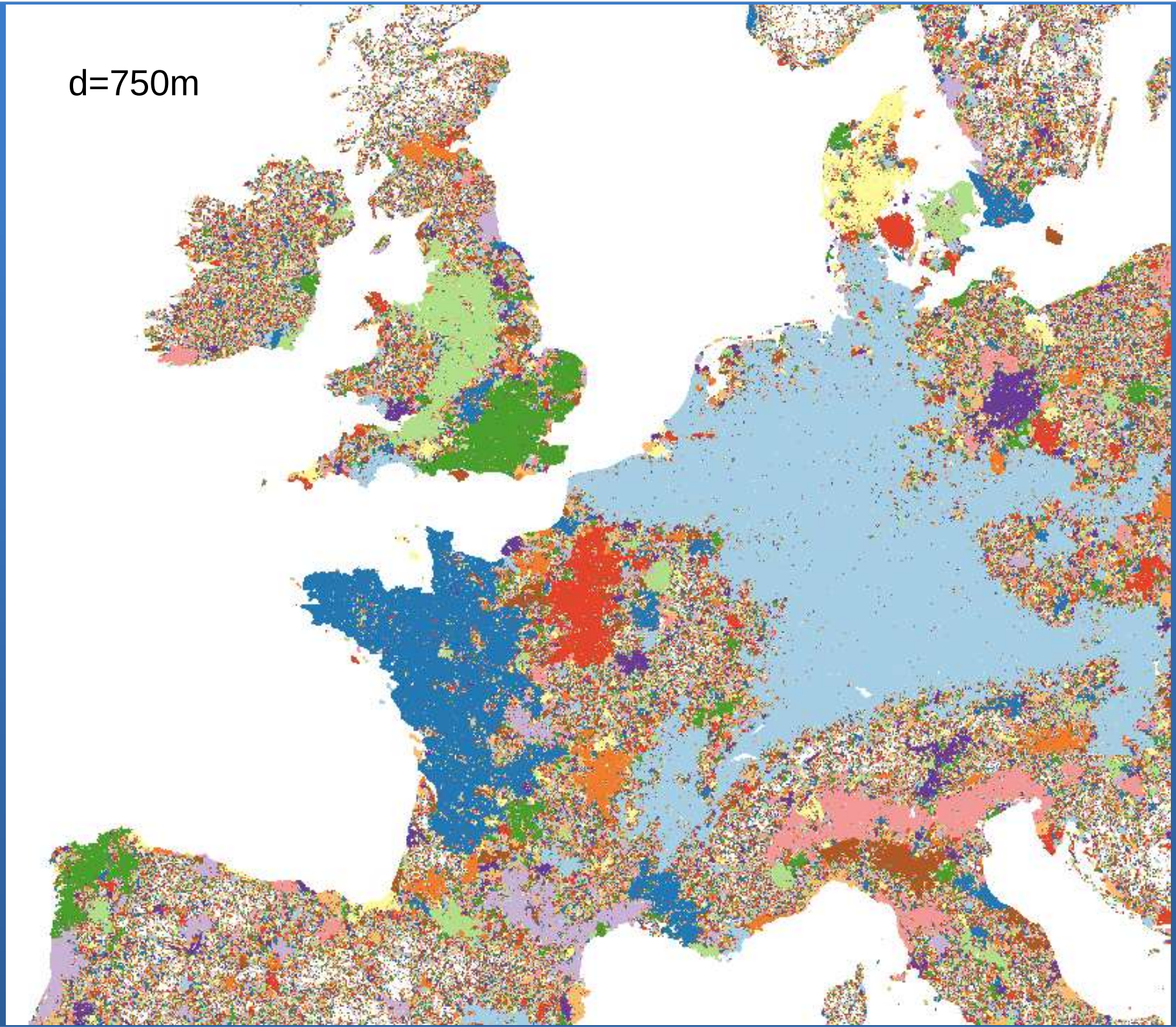
Higher road density represented via giant cluster advancing.

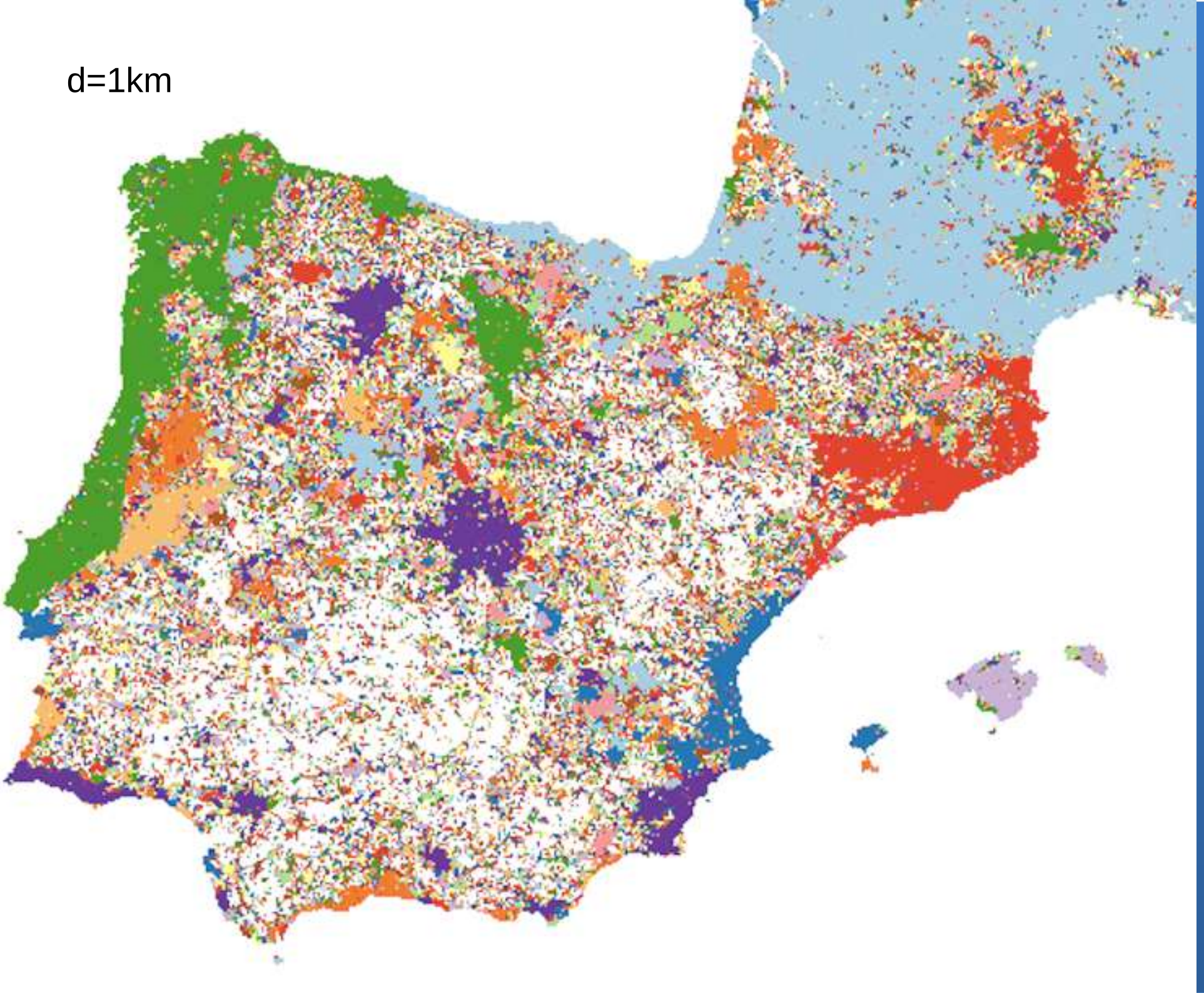
What about regions?

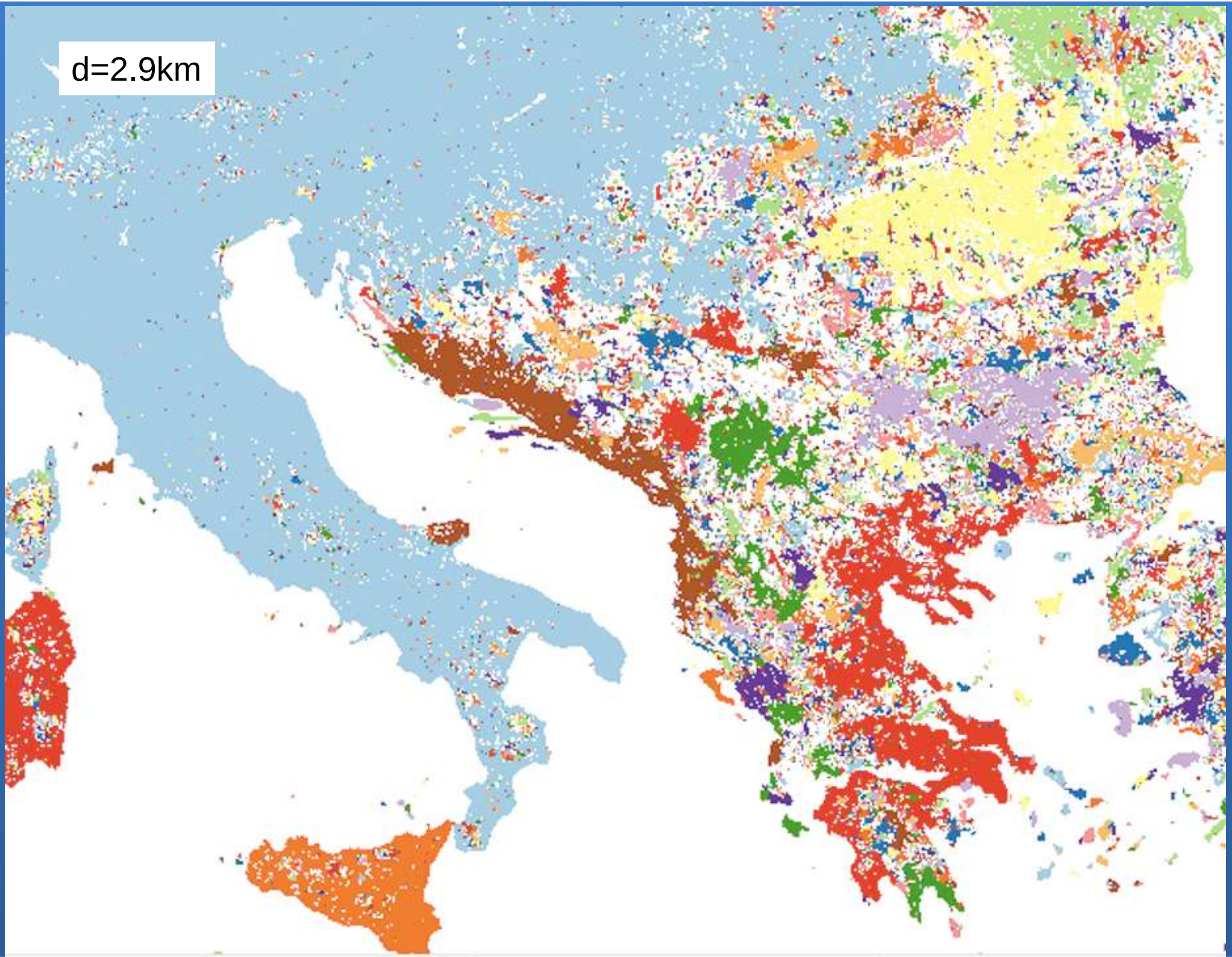
→ rank clusters

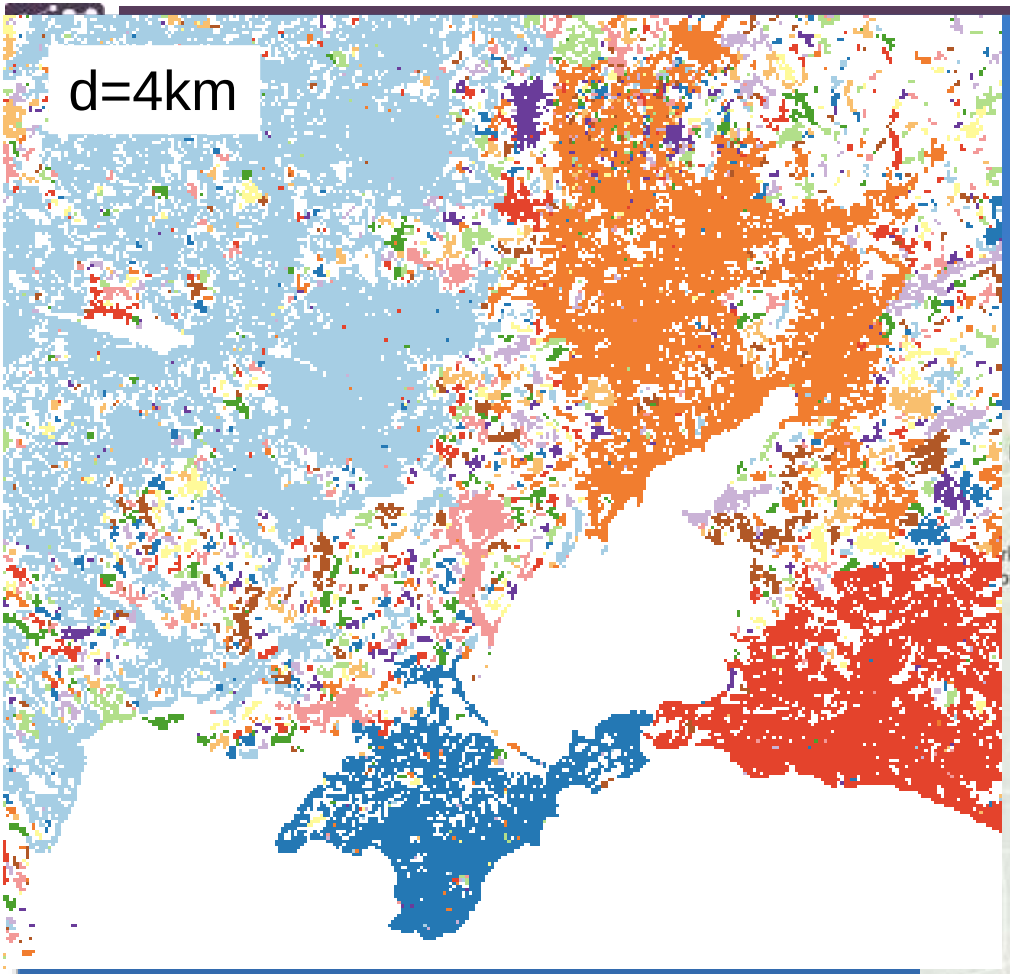
50




d=750m


d=1km


d=2.9km



Ukraine conflict: Battles rage in Donetsk and Luhansk

19 January 2015 | Europe

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Ukraine crisis: 'Russians' occupy Crimea airports

28 February 2014 | Europe

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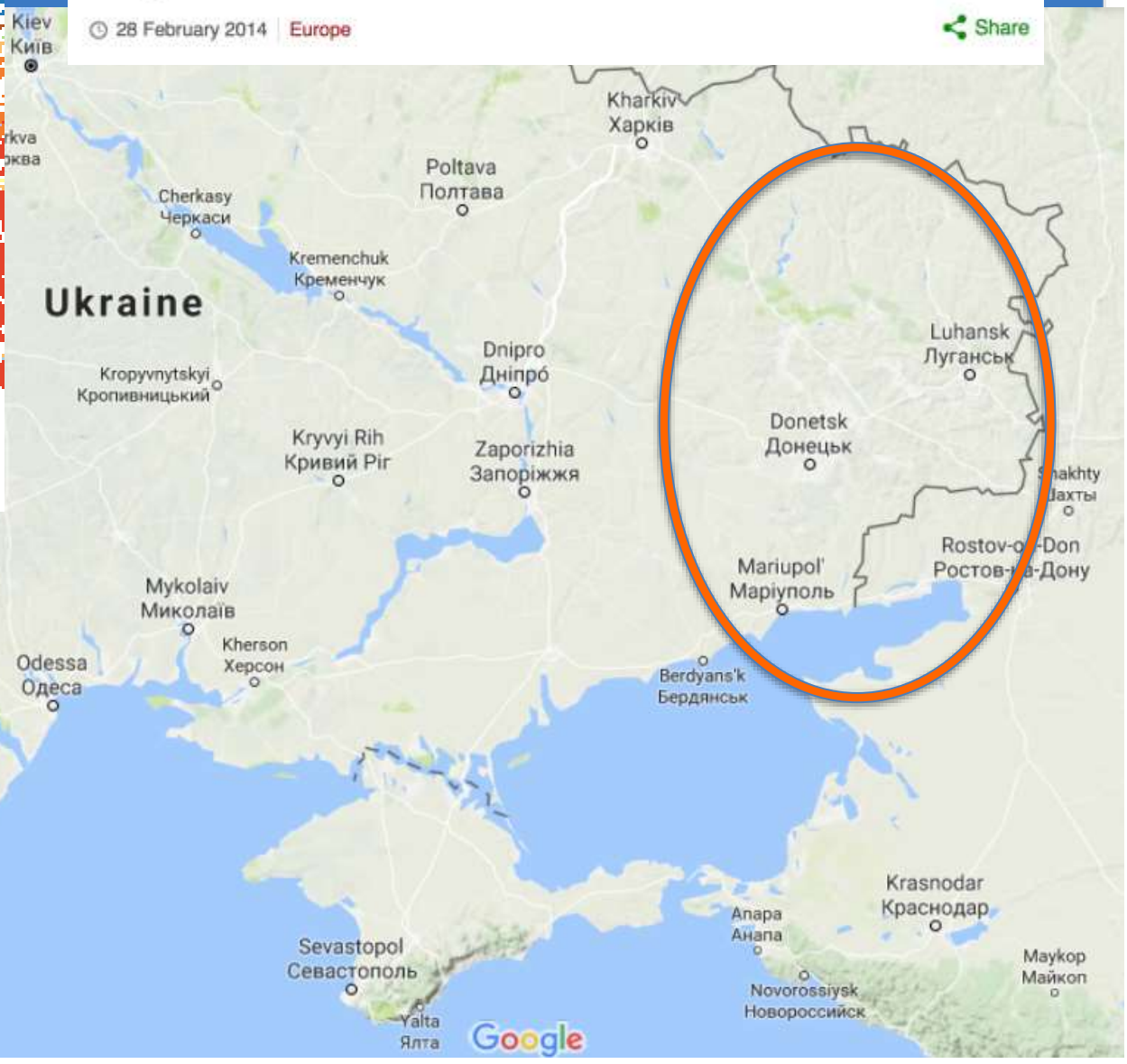
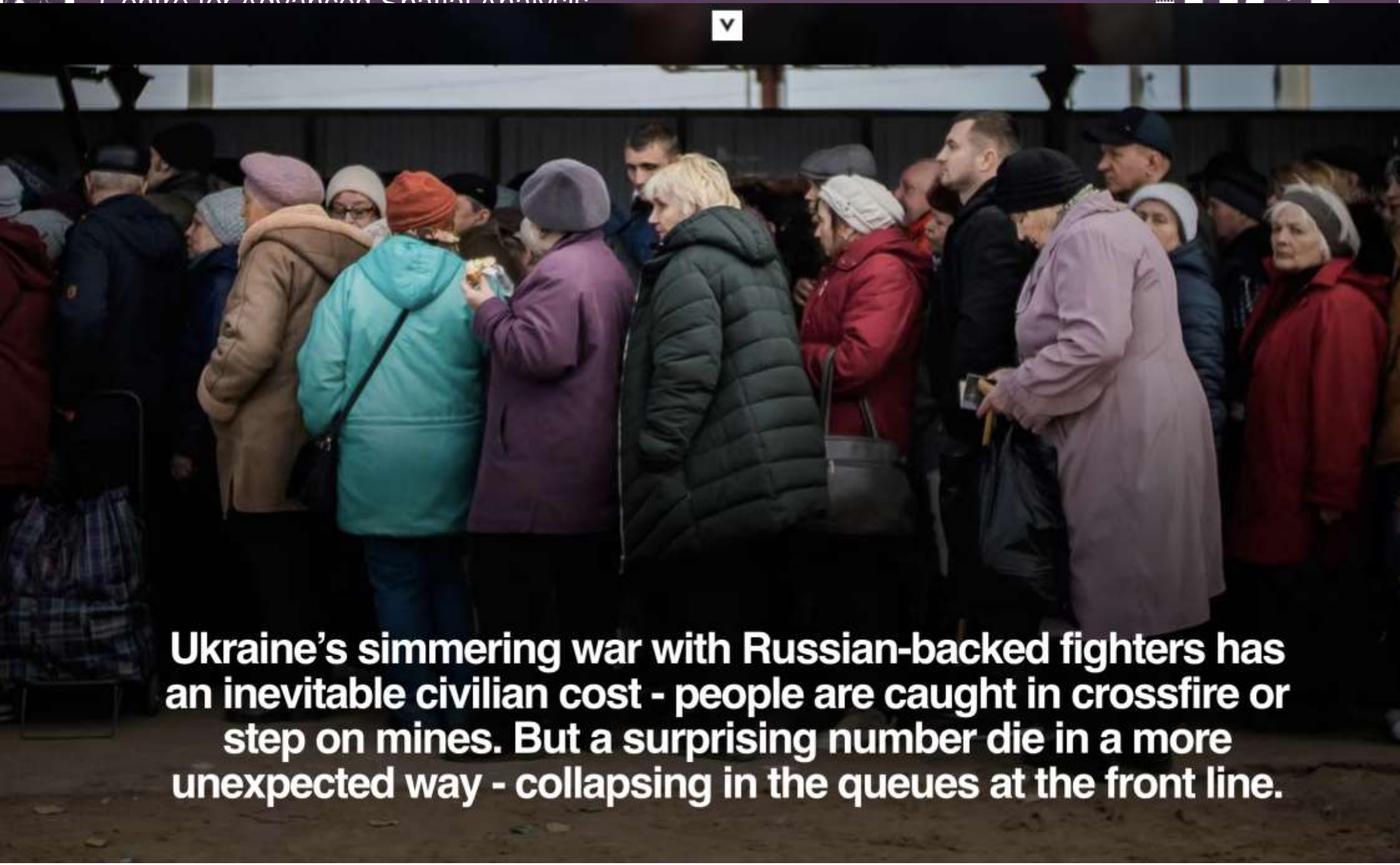



Kiev
UKRAINE
LUHANSK
Stanytsia Luhanska
Mayorsk
DONETSK
Marinka
UKRAINE
Novotroitske
RUSSIA
Hnutove
Crossing points
Russian-backed separatist-controlled area
BBC

The killer queues of Ukraine


Ukraine’s simmering war with Russian-backed fighters has an inevitable civilian cost - people are caught in crossfire or step on mines. But a surprising number die in a more unexpected way - collapsing in the queues at the front line.

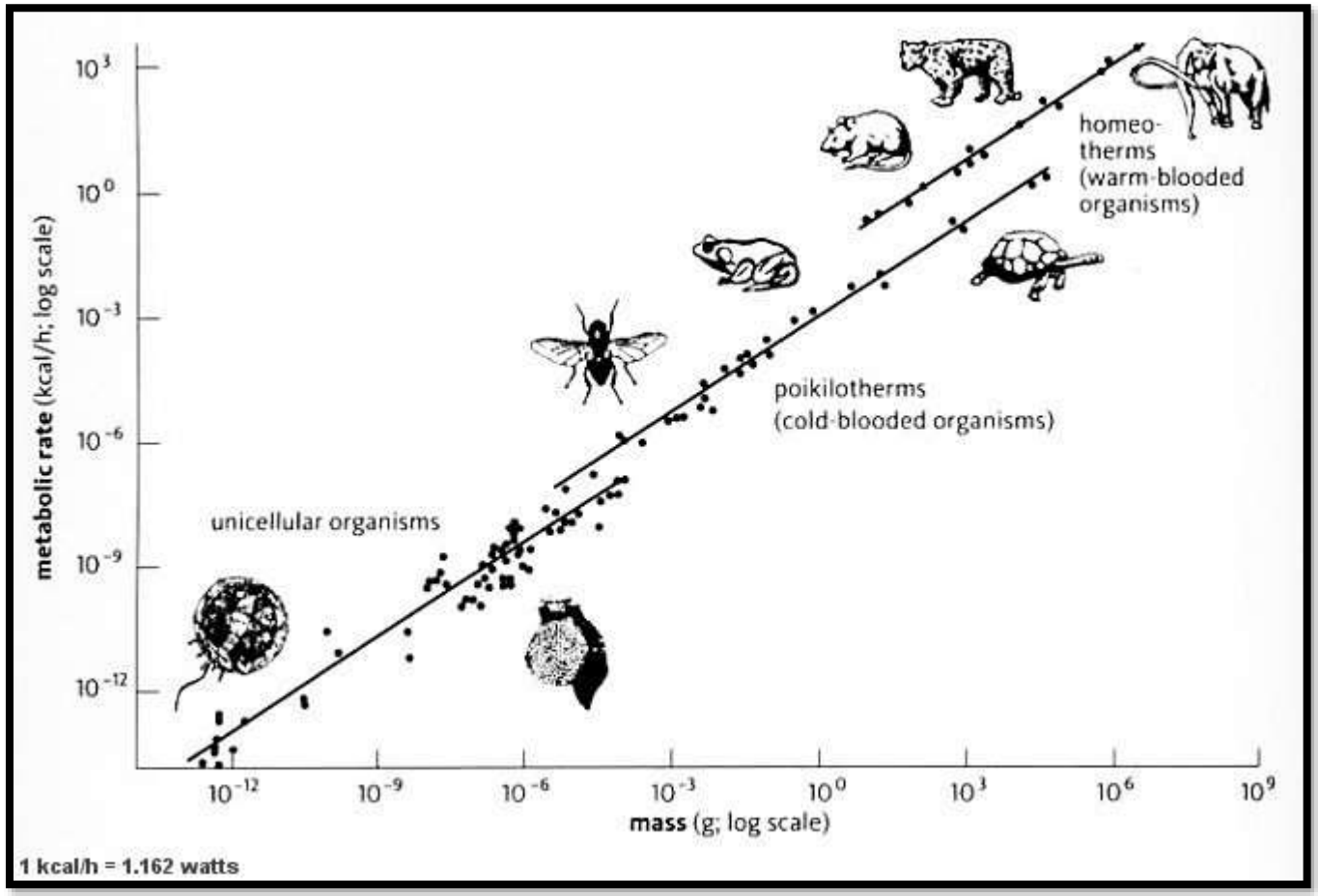
Boundaries and measurements

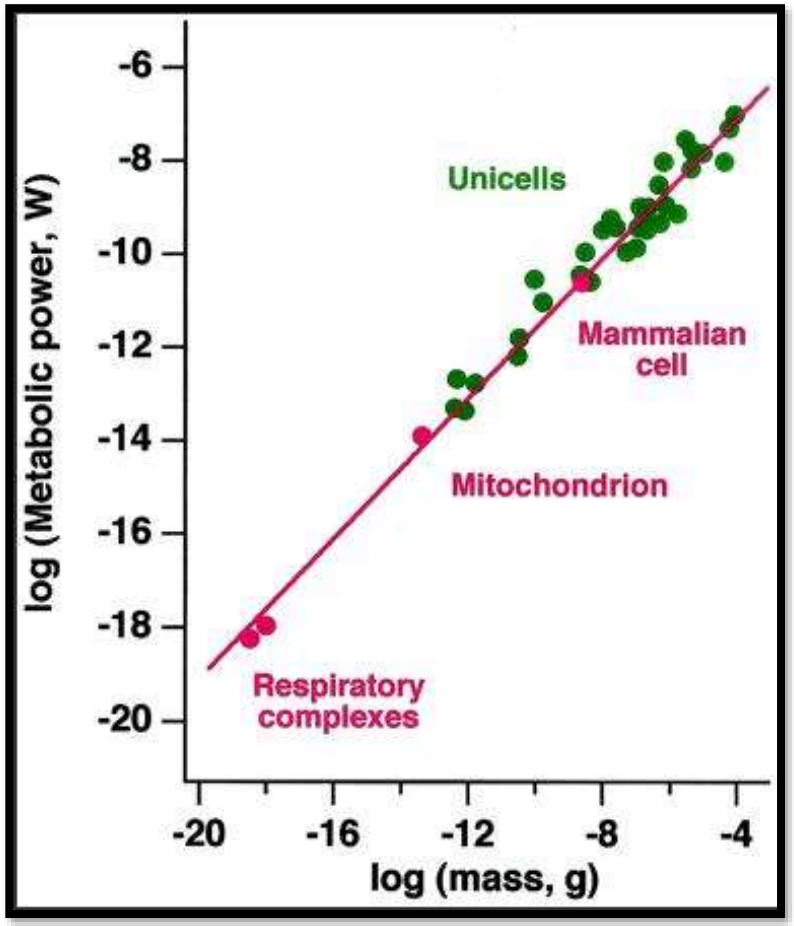
- In addition to putting cities into their right context/region, the next question that arises, is what is to be considered the extent of a city.
- Does it matter whether we consider cities or metropolitan areas?
- Is there a minimum size for a city to be considered as part of the systems of cities in a country?

→ Urban scaling laws

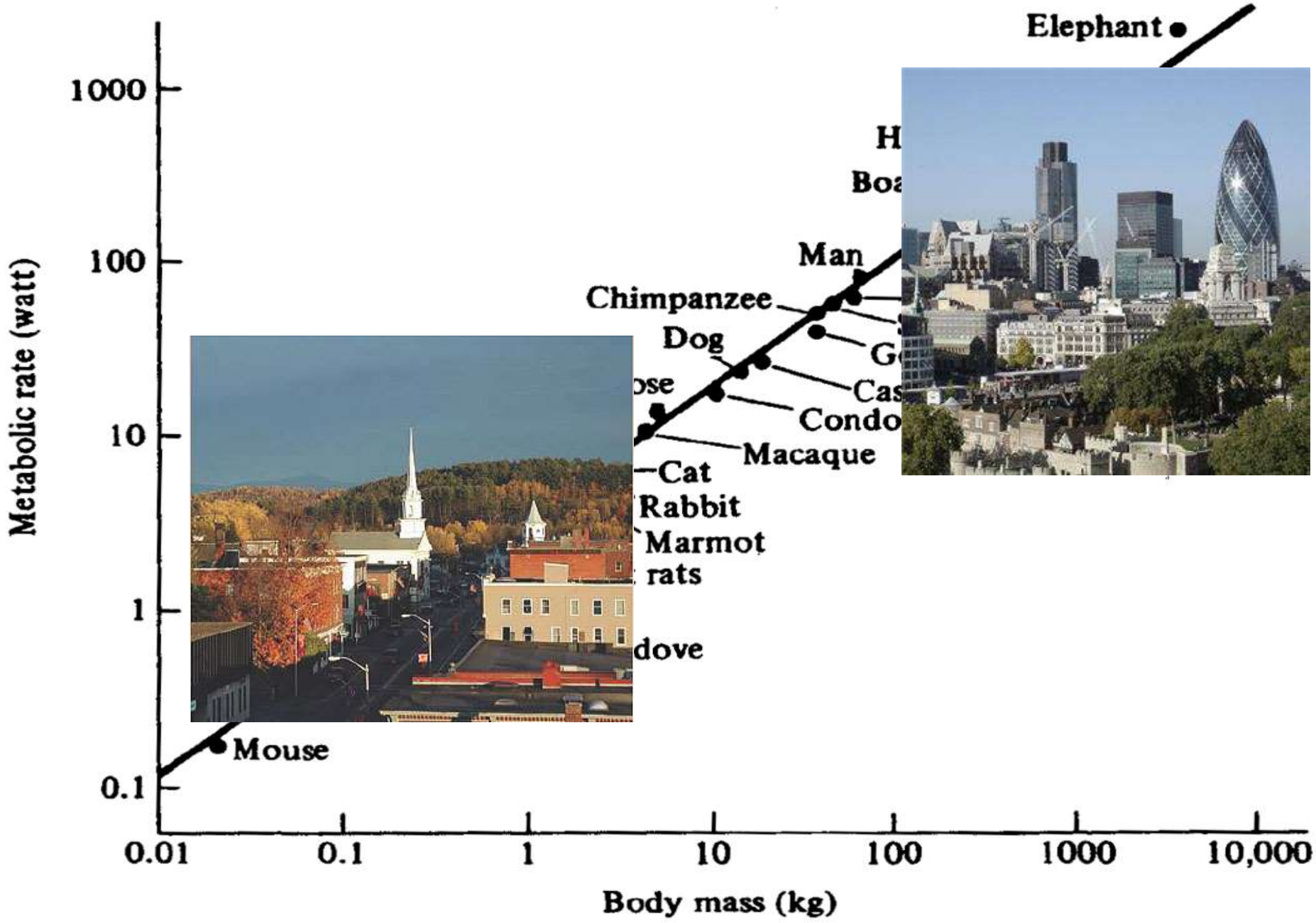
Examples

Kleiber's law: $R \sim M^{3/4}$ metabolic efficiency



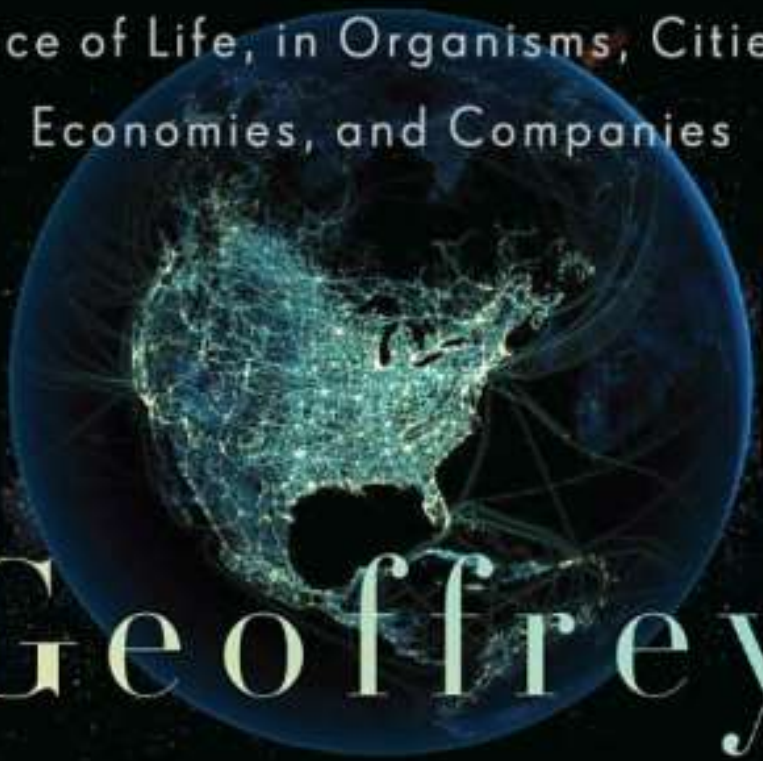


Original results published in:
Kleiber M.(1947), "Body size and metabolic rate". *Phys. Rev.* **27** (4): 511–541.


Elephant
1000
100
10
1
0.1
Metabolic rate (watt)
Man
Chimpanzee
Dog
Macaque
Cat
Rabbit
Marmot
rats
dove
Mouse
0.01
0.1
1
10
100
1000
10,000
Body mass (kg)

SCALE

The Universal Laws of Growth, Innovation, Sustainability, and the Pace of Life, in Organisms, Cities, Economies, and Companies



Geoffrey West

PNAS | April 24, 2007 | vol. 104 | no. 17 | 7301–7306

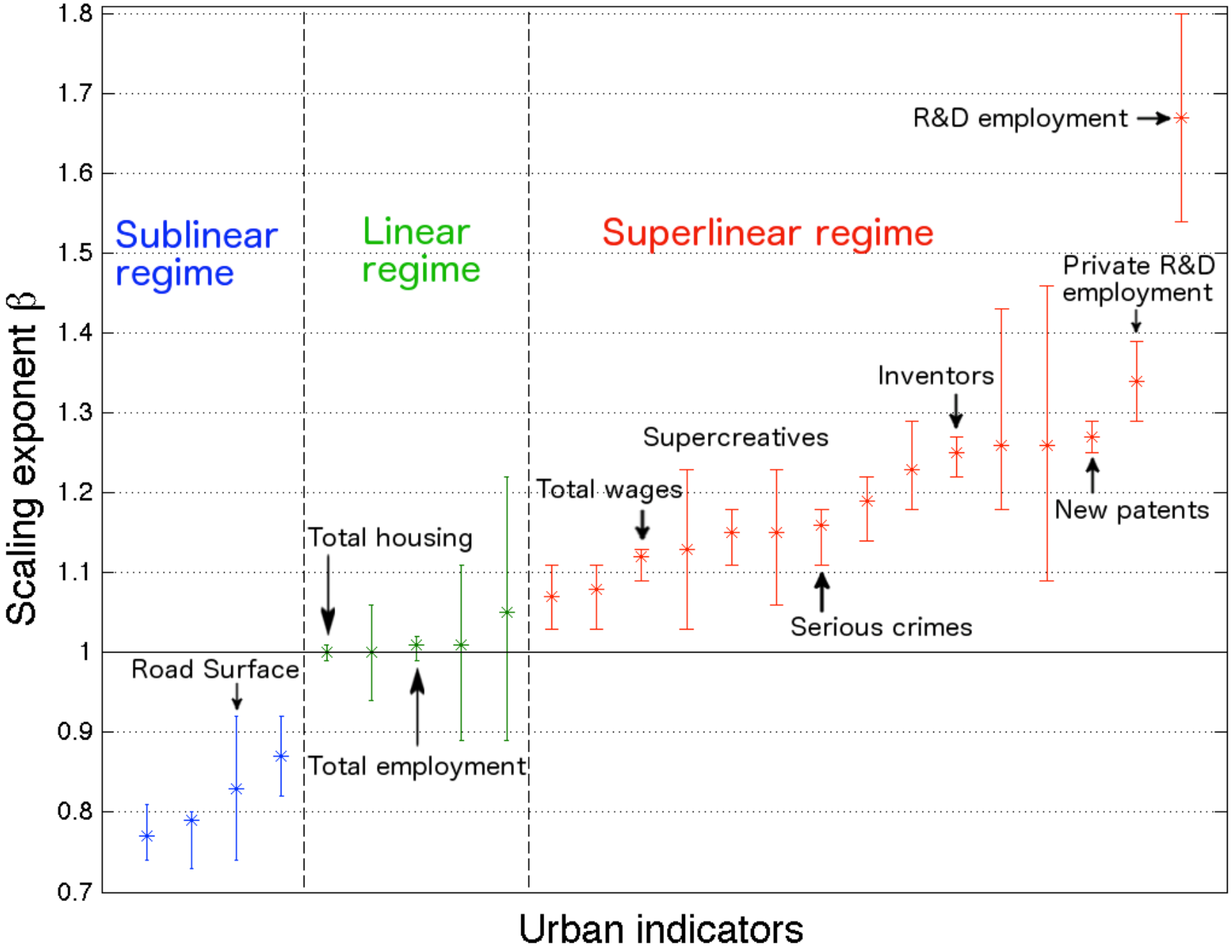
Growth, innovation, scaling, and the pace of life in cities

Luís M. A. Bettencourt*†, José Lobo‡, Dirk Helbing§, Christian Kühnert§, and Geoffrey B. West*¶

Scaling laws for urban indicators: $A \sim N^{\beta}$

- $\beta > 1$: superlinear regime (increasing returns)
  - interactions between individuals: e.g. wealth, crime, innovation, etc.
- $\beta \approx 1$: linear regime (proportional to population)
  - basic individual needs: e.g. electricity consumption, number of households, etc.
- $\beta < 1$: sublinear regime (economies of scale)
  - services and infrastructure: e.g. length of roads, number of gas stations, etc.

Results from Bettencourt et al. PNAS 2007



Scaling Laws and Urban Systems

Denise Pumain

- Scaling
- Sensitivity of measure to different boundary delimitations
- Speed of transportation
- Fractals

SFI WORKING PAPER: 2004-02-002

Testing scaling laws

- Look at scaling laws for a specific configuration of well-defined cities (consistent with the urbanised space)
- Look at scaling laws for metropolitan areas
- Explore the sensitivity of the exponent to the boundaries and distribution of cities

We need to use census data to measure the urban indicators
→ Aggregate unit census areas instead of taking the urban cores obtained through the percolation

Proposal: *Construct city boundaries in terms of the most basic parameter:*

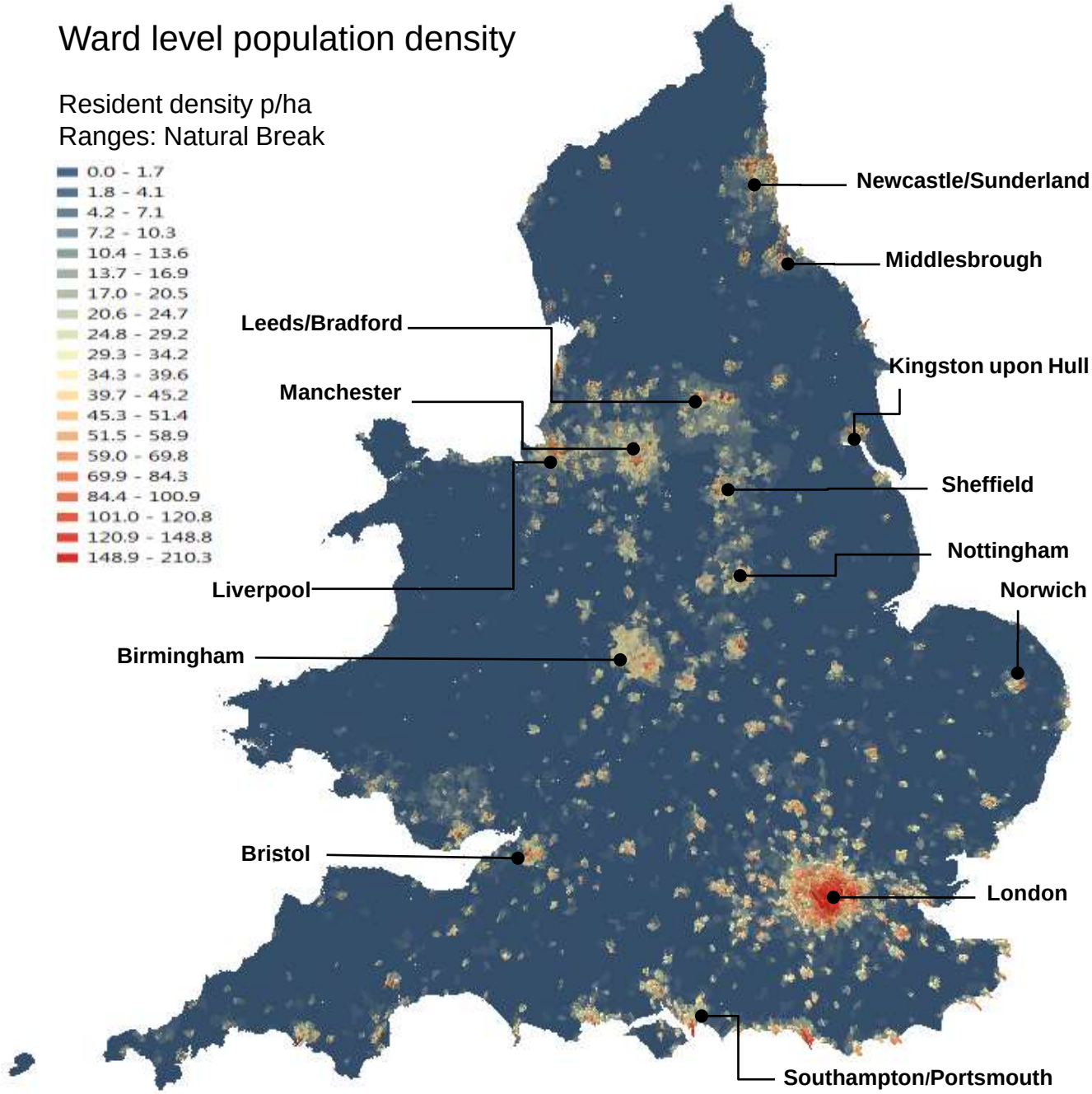
Population Density

1) Start from small units used in the census: WARDS

2) Cluster wards of density above a specific threshold

→ obtain a density cutoff for system of cities such that:

- Greater London Area recovered from cluster
- Liverpool and Manchester are two different clusters

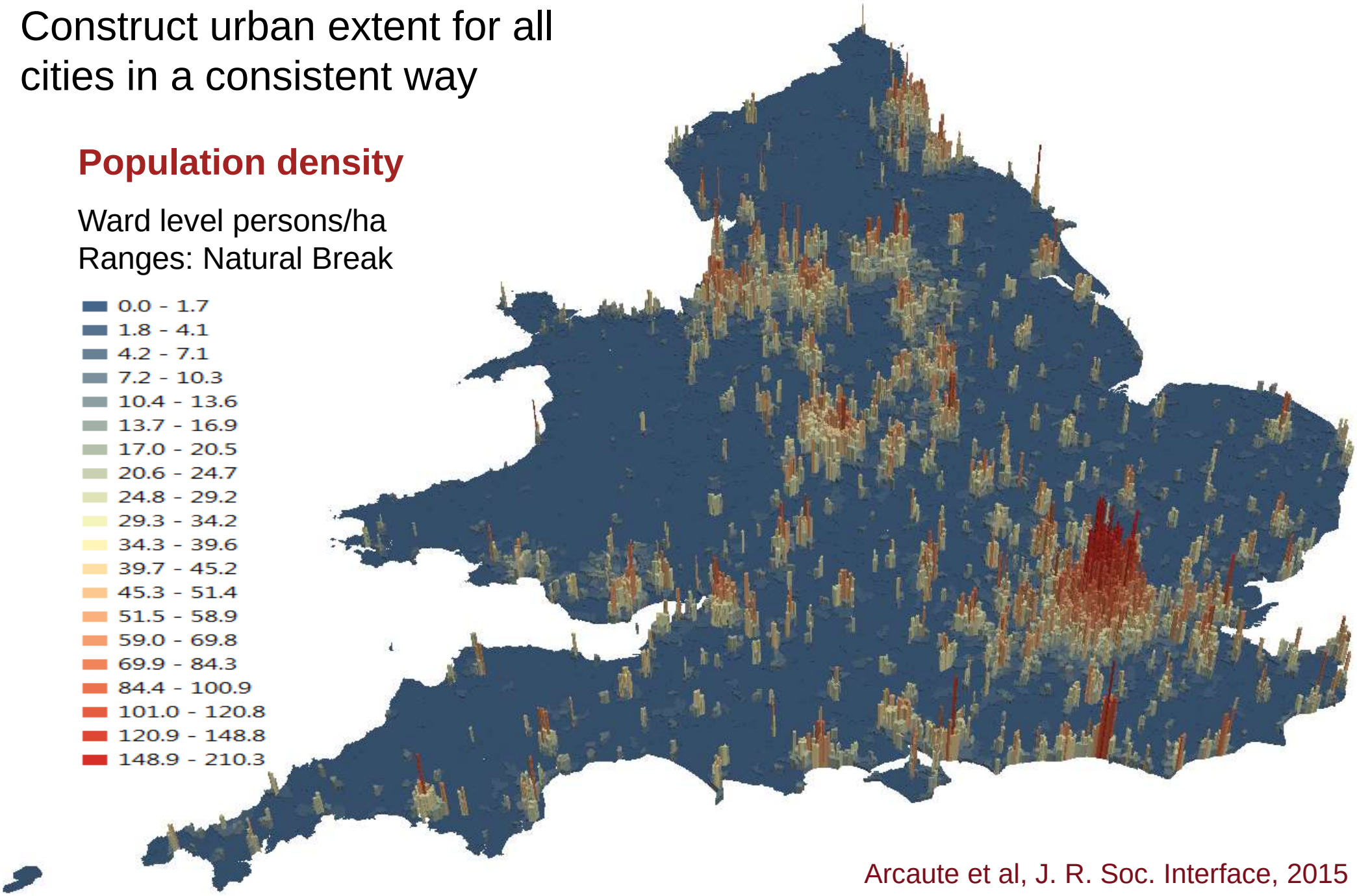


Arcaute et al, J. R. Soc. Interface, 2015

Construct urban extent for all cities in a consistent way

Population density

Ward level persons/ha
Ranges: Natural Break



Arcaute et al, J. R. Soc. Interface, 2015

Redefining cities using different density cutoffs: ρ = 40..1 persons/ha

Start at the core of cities: ρ=40 prs/ha

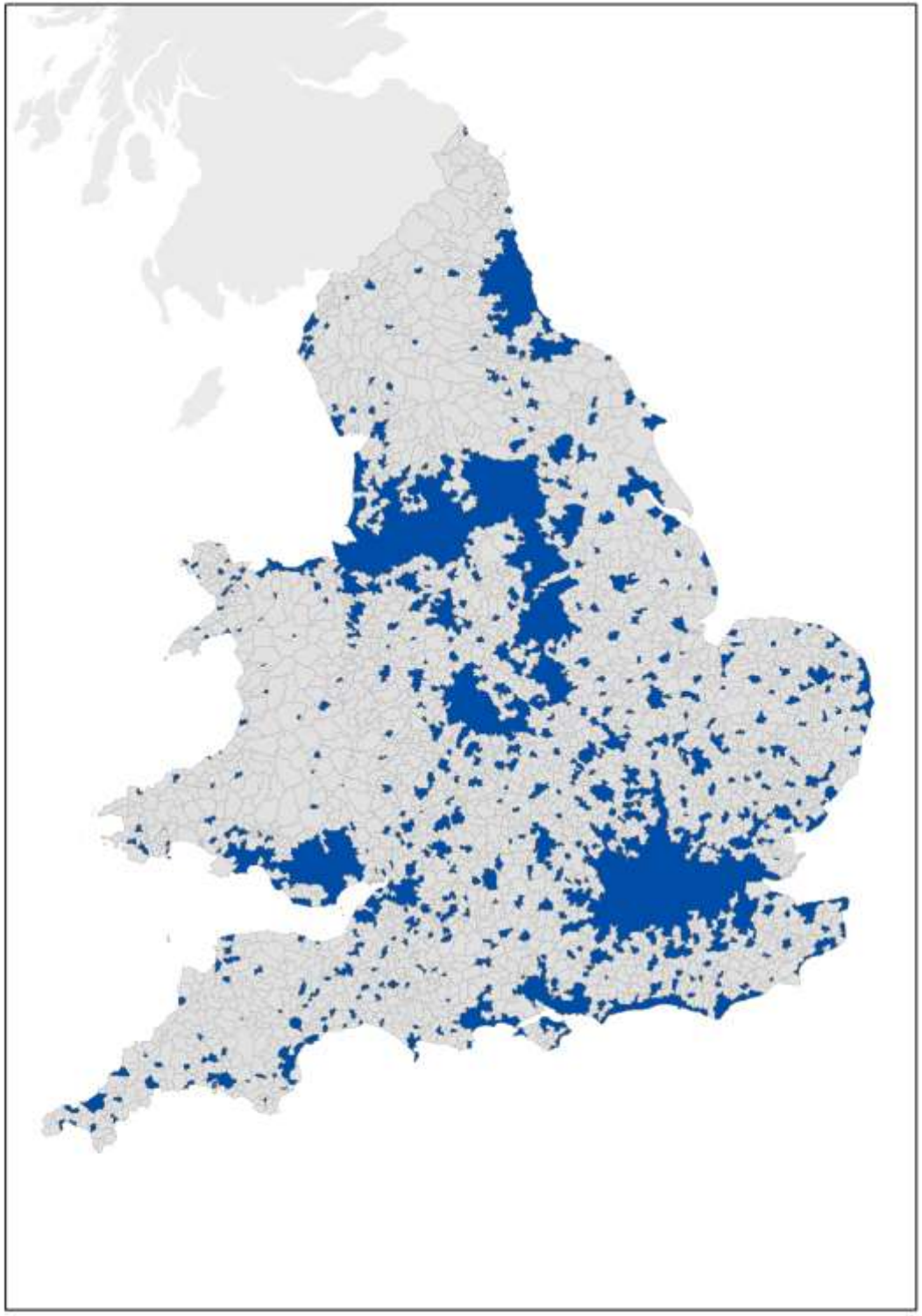
↓

decrease density

↓

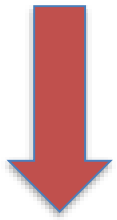
Obtain big clusters: cities have merged

Use census data (2001) for population density at the geographical unit of a *ward*.



Arcaute et al, J. R. Soc. Interface, 2015

Extend boundaries towards a functional definition of cities in terms of economic activity



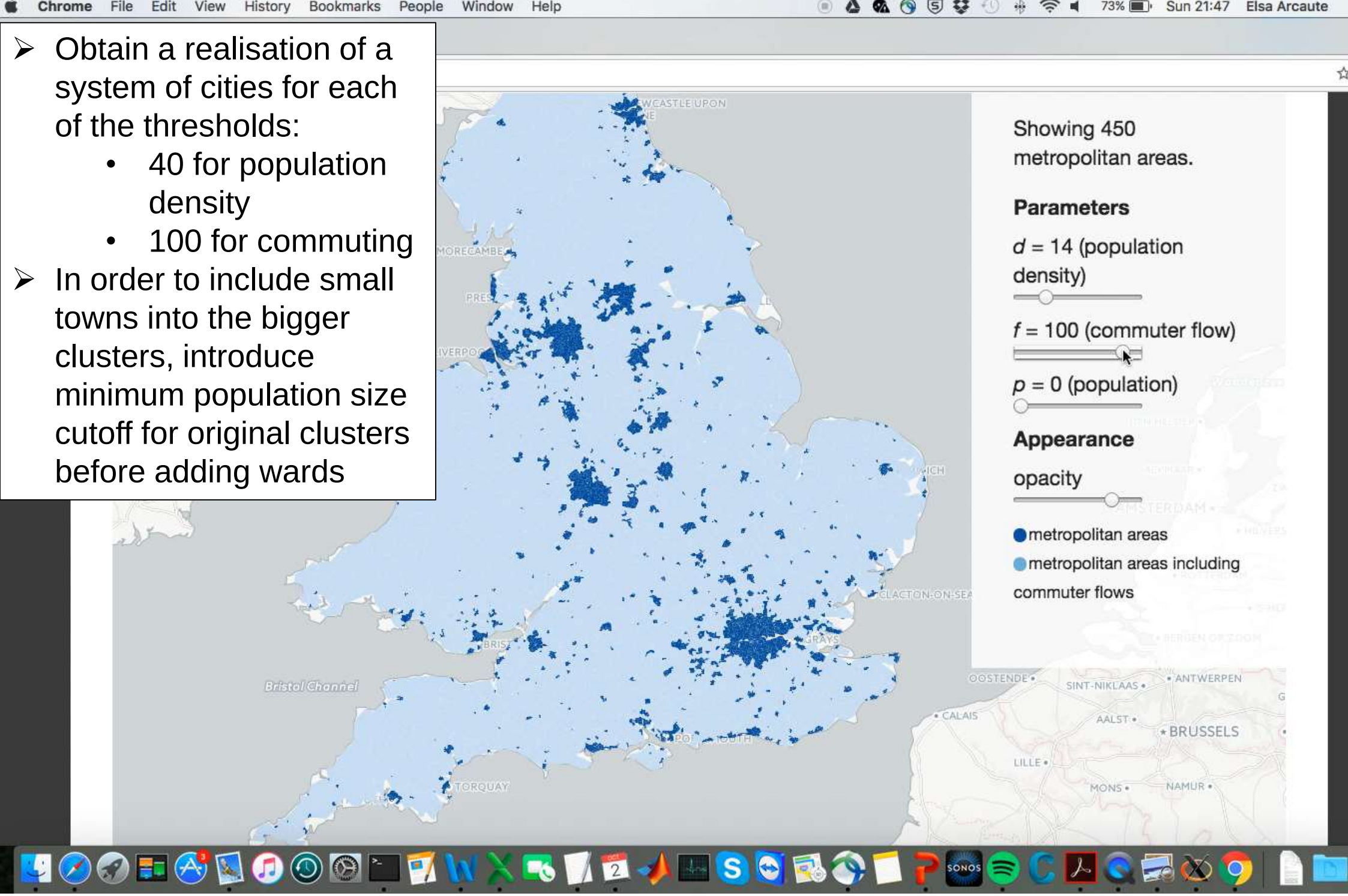
Add to predefined clusters (for all the different density cutoffs) wards from which people commute to work if:

% commuters ≥ threshold: τ

Traditionally, metropolitan areas are defined for τ=30% commuters

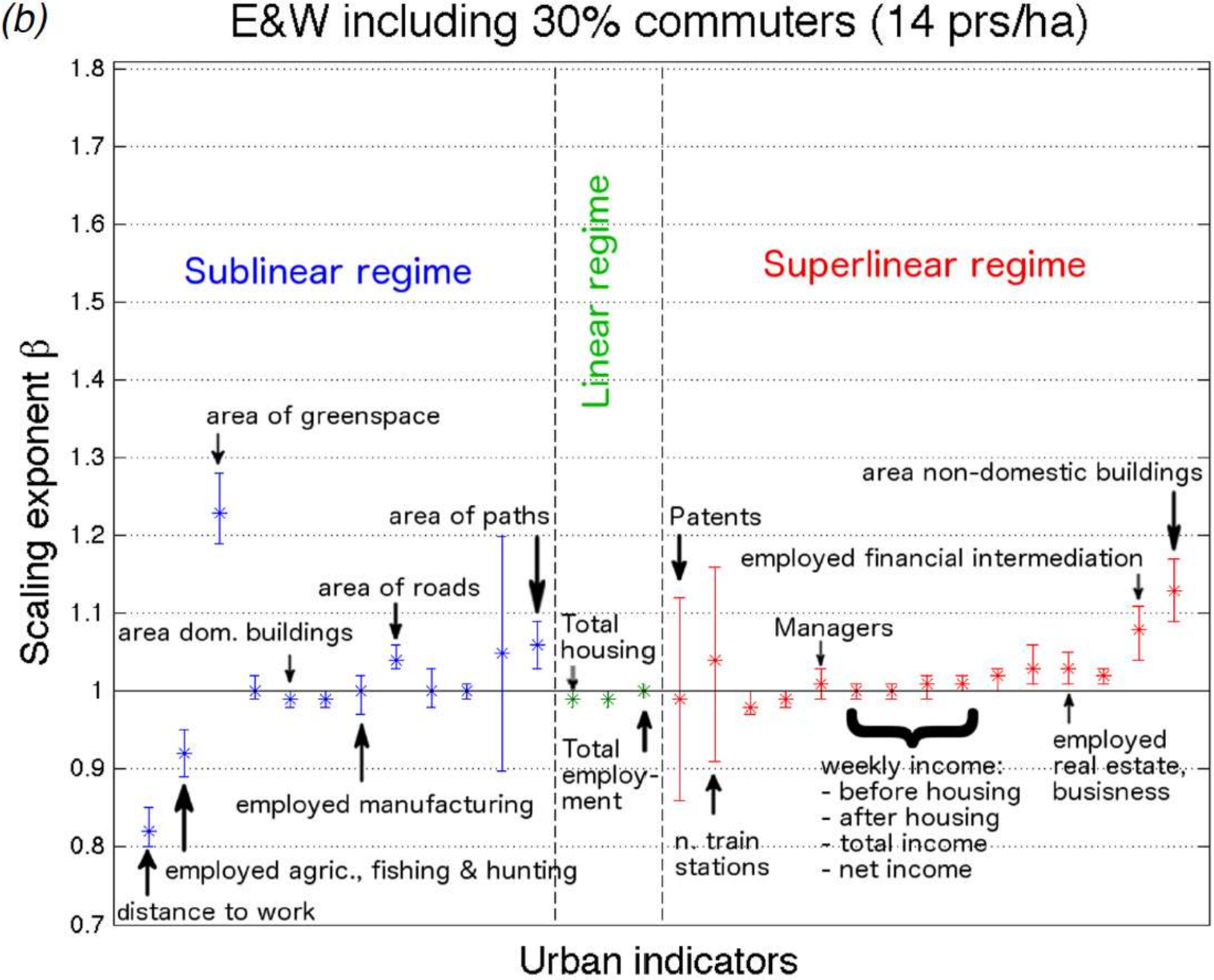
Arcaute et al, J. R. Soc. Interface, 2015

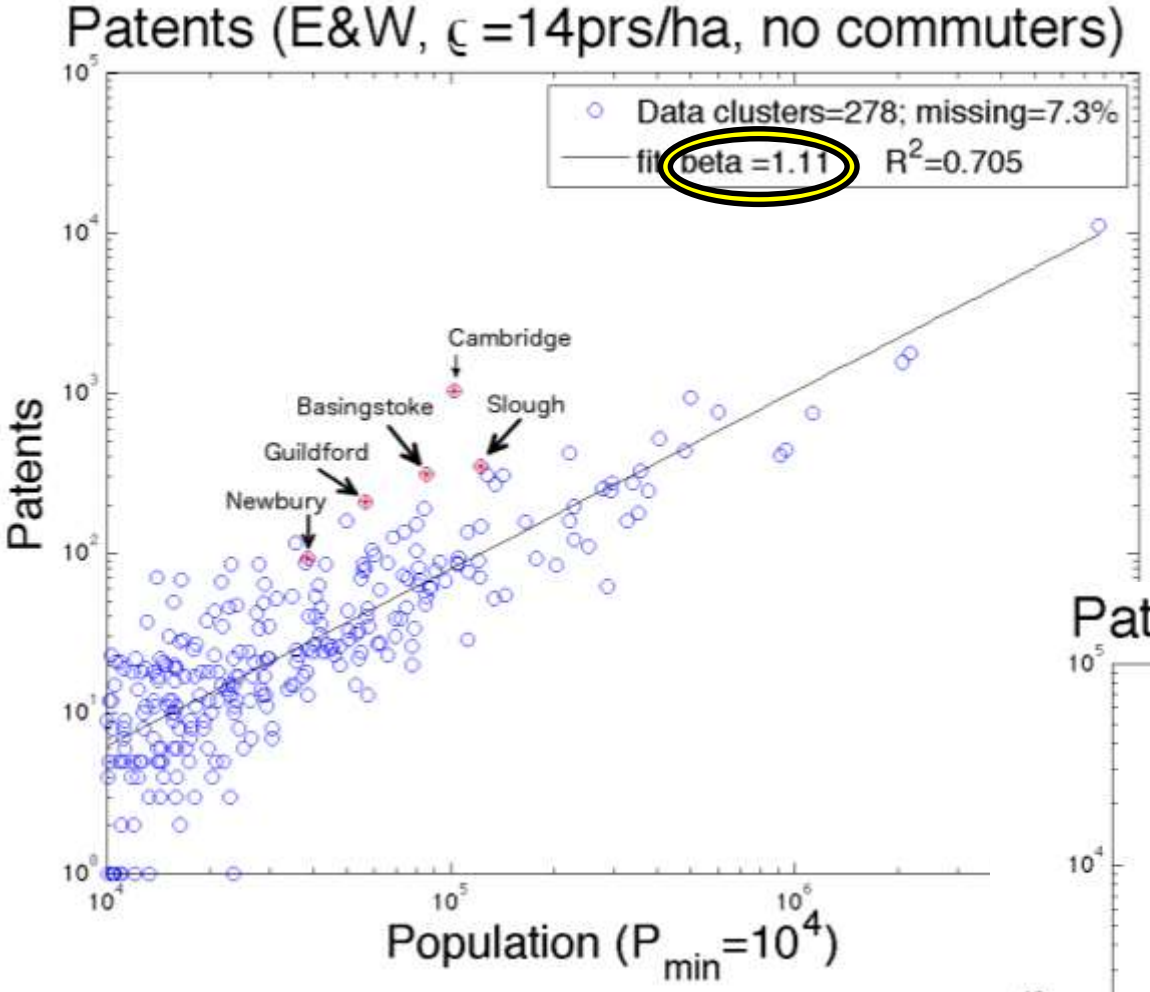
- Obtain a realisation of a system of cities for each of the thresholds:
  - 40 for population density
  - 100 for commuting
- In order to include small towns into the bigger clusters, introduce minimum population size cutoff for original clusters before adding wards

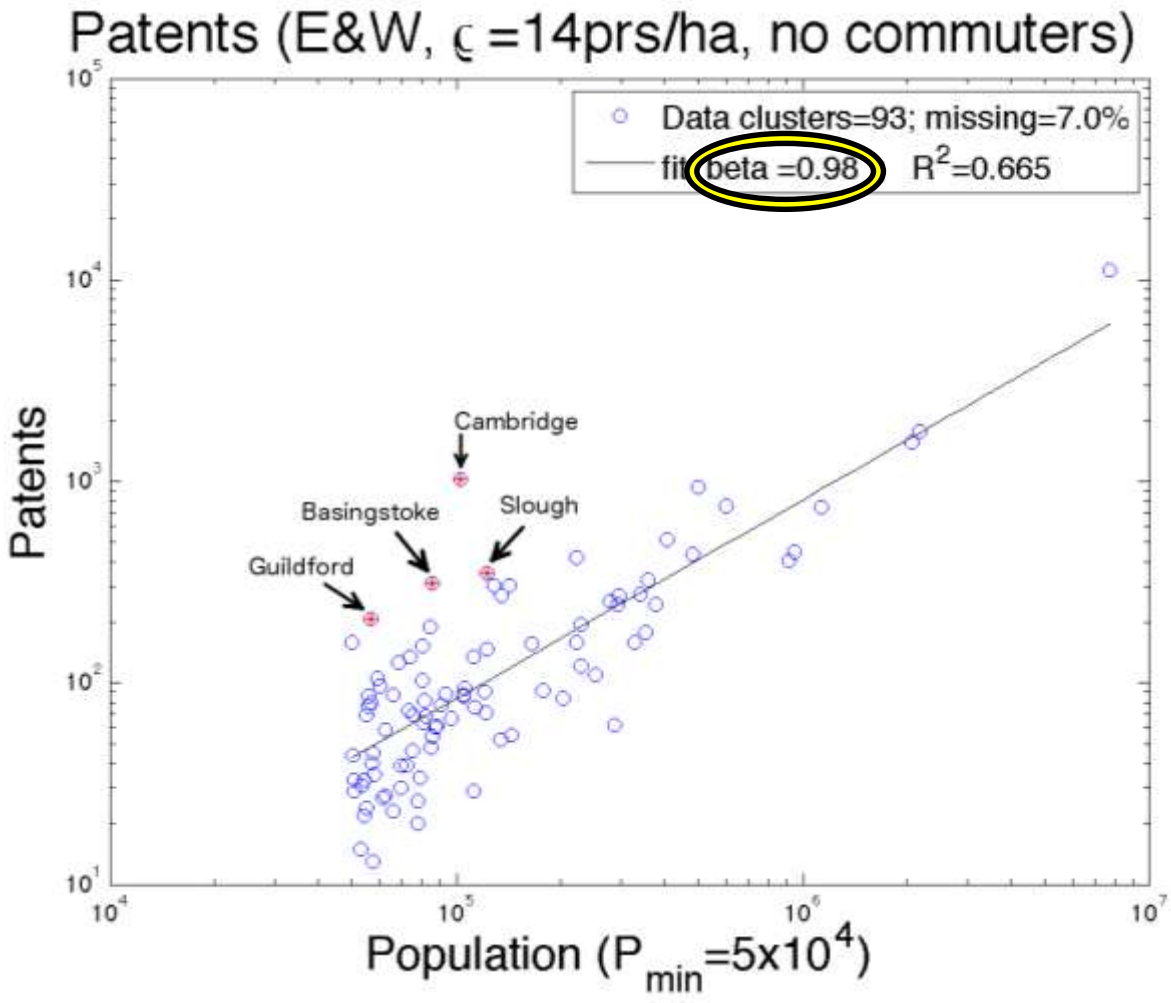


Arcaute et al, J. R. Soc. Interface, 2015

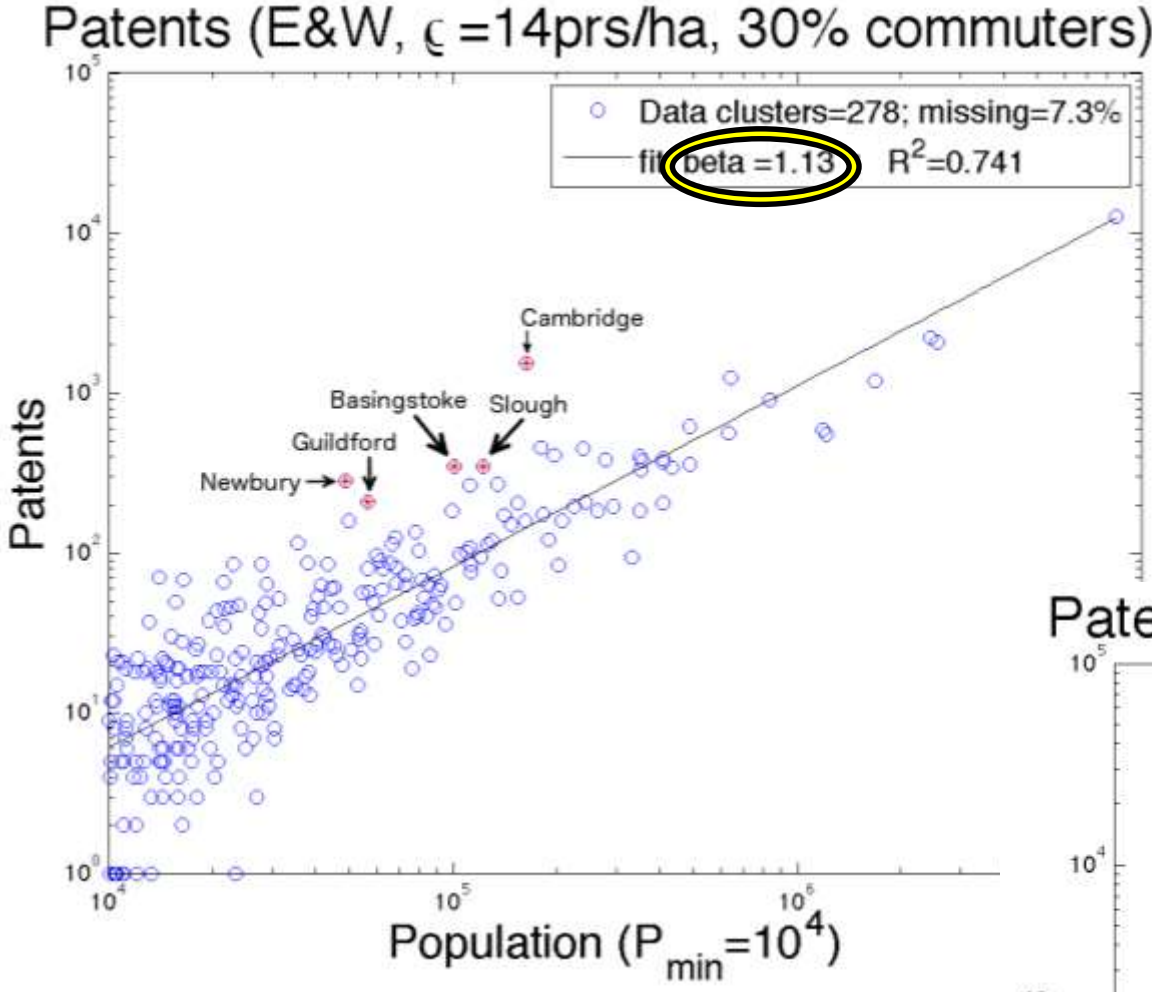
(b)


E&W including 30% commuters (14 prs/ha)
Scaling exponent β
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
Sublinear regime
Linear regime
Superlinear regime
area of greenspace
area of paths
area non-domestic buildings
Patents
employed financial intermediation
area of roads
area dom. buildings
Total housing
Managers
Total employ-ment
employed manufacturing
employed real estate, busisness
weekly income:
- before housing
- after housing
- total income
- net income
n. train stations
employed agric., fishing & hunting
distance to work
Urban indicators

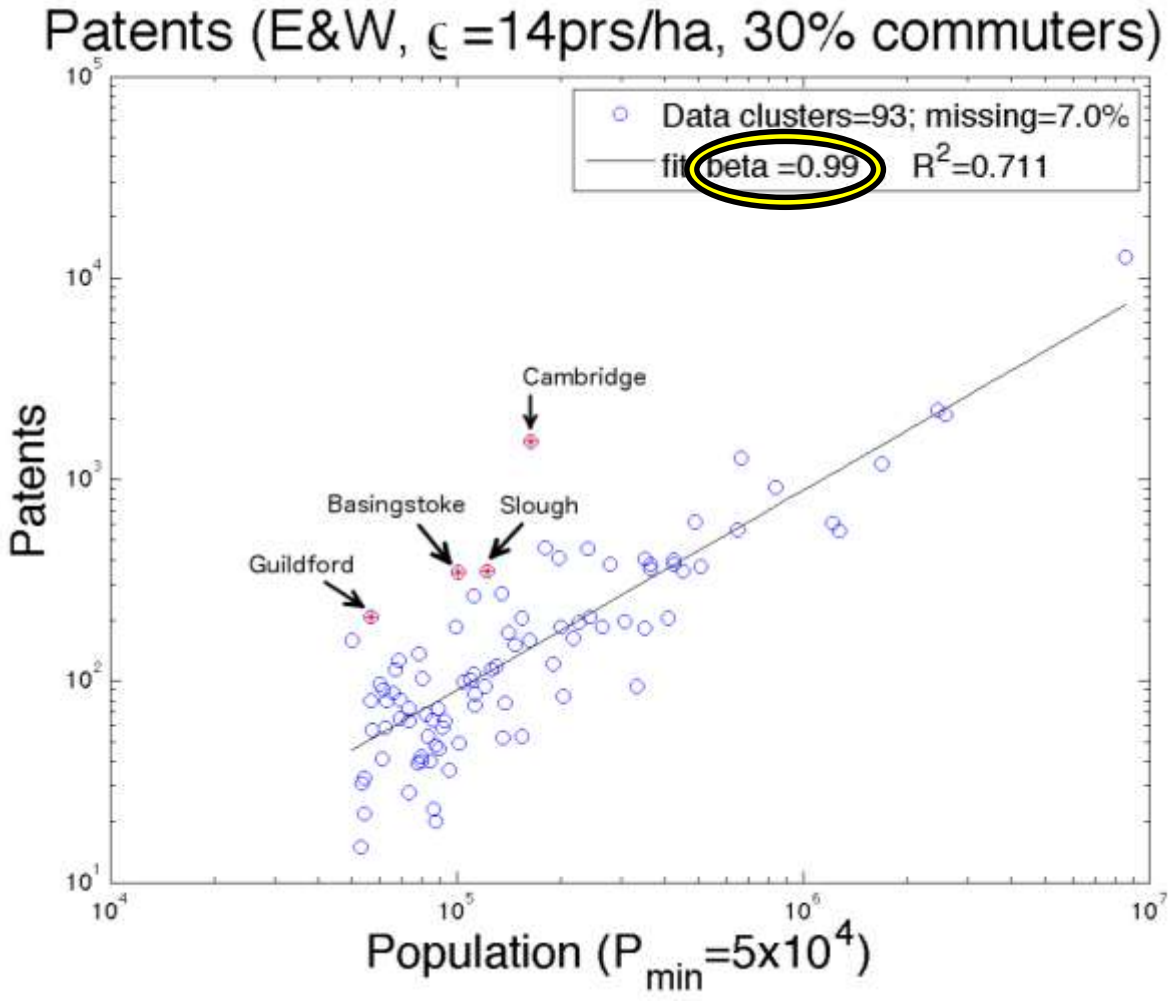




- **Higher residuals given by small cities!!!**
- **Some important ones disappear for high cutoffs on population size**



- **For this variable path dependencies more important than size**



- **The shift from urban form to metropolitan area SHOULD be visible for this variable according to theory: not the case, population cutoff more important**

Scaling laws do not give rise to consistent results

Exponent for scaling laws varies a lot depending on:

1) The definition for cities: urban cores and metropolitan areas give rise to different results

2) The number of cities under consideration: results are mainly valid for the large cities only!

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Is this scaling nonlinear?

J. C. Leitão, J. M. Miotto, M. Gerlach and E. G. Altmann

Max Planck Institute for the Physics of Complex Systems, Dresden, Germany

Essential paper if scaling laws are to be considered!!

Conclusions

- Connectivity between individuals and settlements leave footprints in the form of spatial patterns that can be traced back.

- These set the path for a hierarchical organisation of the urban system.

- The street network is an excellent proxy for urbanisation
  → memory of urbanisation process: A peak into history!
  → Observed in the hierarchical structure of the system (historical outcome)

- Can we recover this history through the different scales and layers of patterns left by ancestors?

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Thank you!!

Bibliography

- Christaller, W. 1966. *Central Places in Southern Germany*. Englewood Cliffs, NJ: Prentice-Hall. Original work published in German 1933.
- Zipf, G. K. 1949. *Human Behaviour and the Principle of Least Effort*. Cambridge, MA: Addison-Wesley.
- Alonso, W. 1964. *Location and Land Use*. Cambridge, MA: Harvard University Press.

Cities as complex systems:

- Berry, B. J. L. 1964. Cities as Systems within Systems of Cities. Papers of the Regional Science Association, 13:147-164.
- Jacobs, J. (see book)
- Batty, M. 2009. Cities as Complex Systems: Scaling, Interactions, Networks, Dynamics and Urban Morphologies. In *Encyclopedia of Complexity and Systems Science*. Vol. 1. ed. R. Meyers, 1041-1071. Berlin, DE: Springer.
- Batty, M., Axhausen, K., Fosca, G., Pozdnoukhov, A., Bazzani, A. 2012. Smart cities of the future. *Eur. Phys. J. Special Topics* **214**, 481-518.

Bibliography

- Batty, M. 2013. *The new science of cities*. The MIT Press, Cambridge, MA: London, England.
- Mike Batty has an excellent range of lectures online, with very relevant historical accounts and current research in this area

http://www.spatialcomplexity.info

Complex systems

- Weaver, W. 2004. Science and Complexity. *Classical Papers-Science and complexity, E:CO* Vol. 6, 3:65-74. Originally published as Weaver, W. (1948). “Science and complexity,” in *American Scientist* , 36: 536-544.
- Newman, M. E. J. 2011. Resource Letter CS-1: Complex Systems. *Am. J. Phys.* 78, 800.
- Santa Fe Institute has a free online course on complexity:

http://www.complexityexplorer.org