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## Functional Network of the City

Maxime Lenormand

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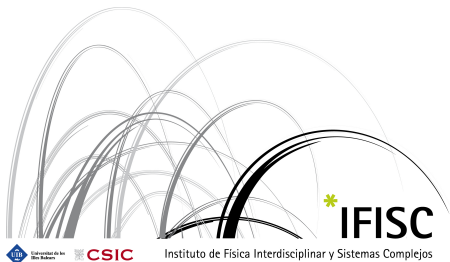
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# Functional Network of the City

Maxime Lenormand

CitiNet'14, Lucca, Italy

September 25, 2014



# Motivation

## Comparison of land use patterns across cities

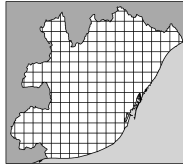
- ▶ Network approach to detect land use using mobile phone data
- ▶ Spatial organization (entropy, Ripley's K...)
- ▶ Land use model
- ▶ Mixing of land use



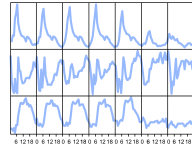
# Method used to extract the network



**Metropolitan Area**

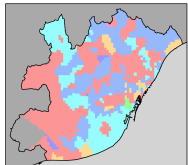


**Recordings sites**

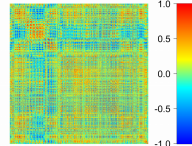
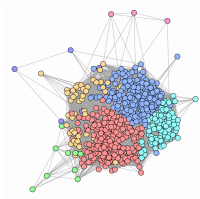


Time of Day

**Signals**



**Functional Network**

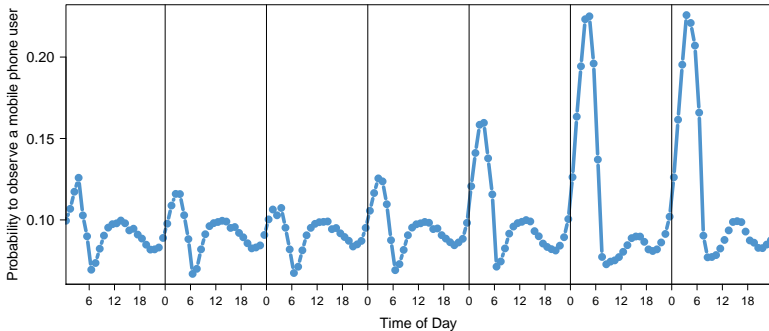


**Correlation Matrix**



# Method used to extract the network

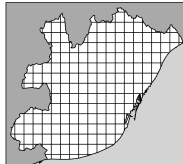
Probability to observe a mobile phone user in a given cell at a given time



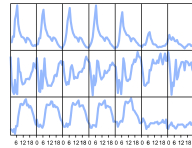
# Method used to extract the network



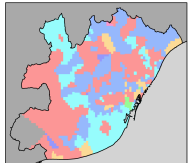
**Metropolitan Area**



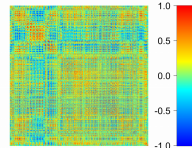
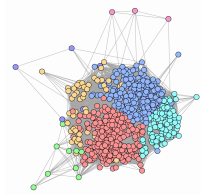
**Recordings sites**



Time of Day  
**Signals**



**Functional Network**

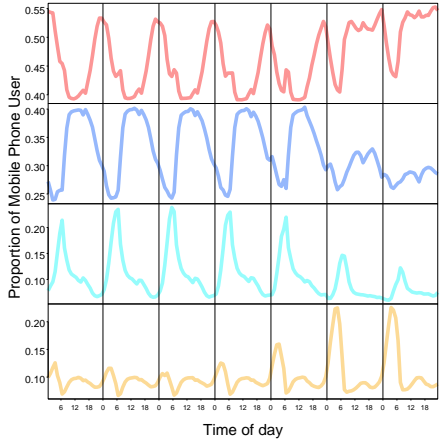
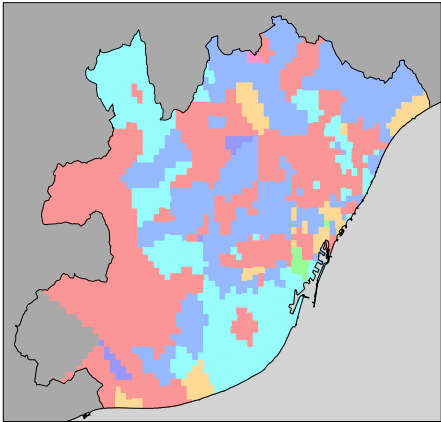


**Correlation Matrix**



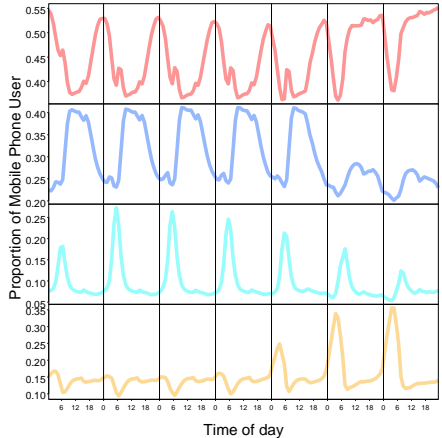
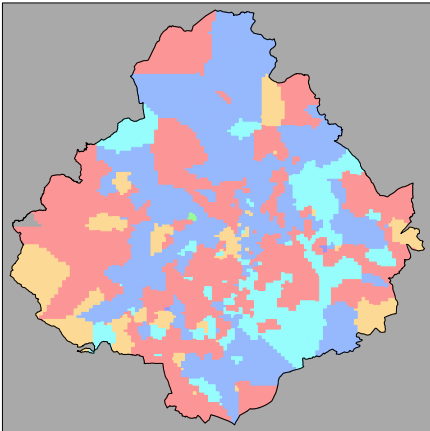
# Land use patterns

Barcelona (PGP = 60%)

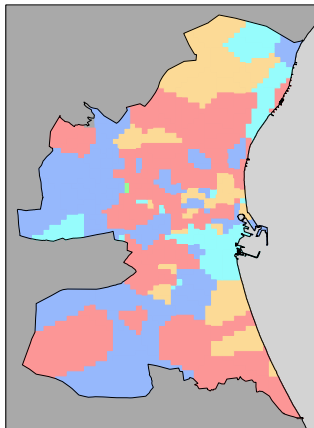


# Land use patterns

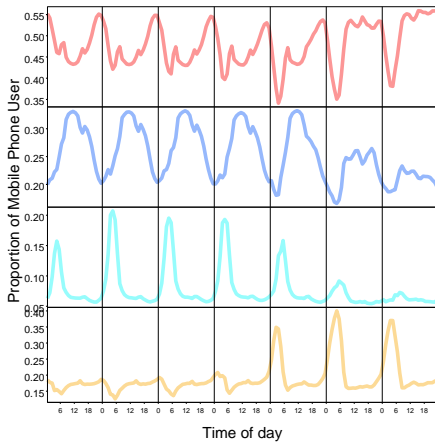
Madrid (PGP = 65%)



# Land use patterns

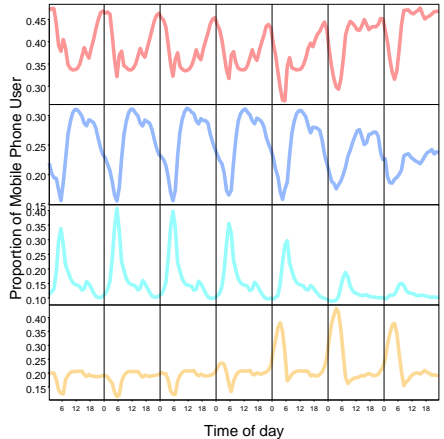
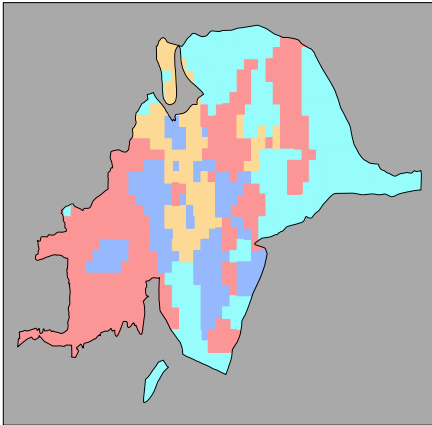


## Valencia



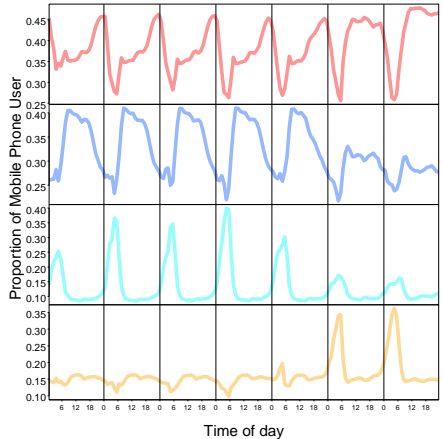
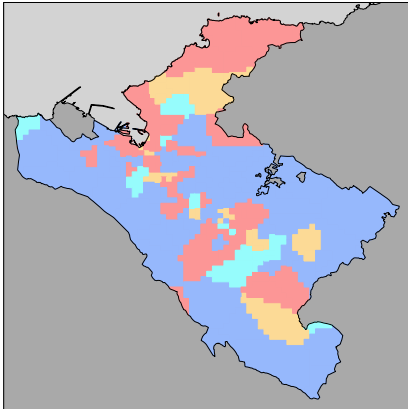
# Land use patterns

## Sevilla



# Land use patterns

## Bilbao



# Spatial organization of land use

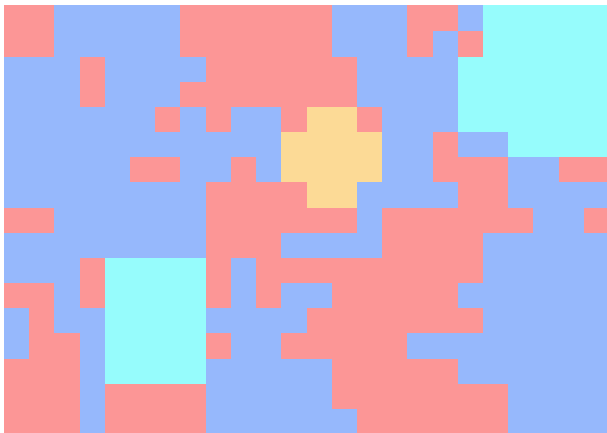
## Three measures of spatial heterogeneity

- ▶ Distribution of the distance between the cells and the city center
- ▶ Ripley's K
- ▶ Entropy index



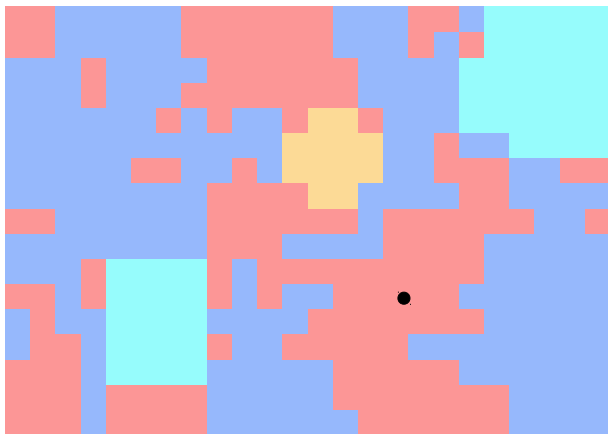
# Spatial organization of land use

## Distance to the city center



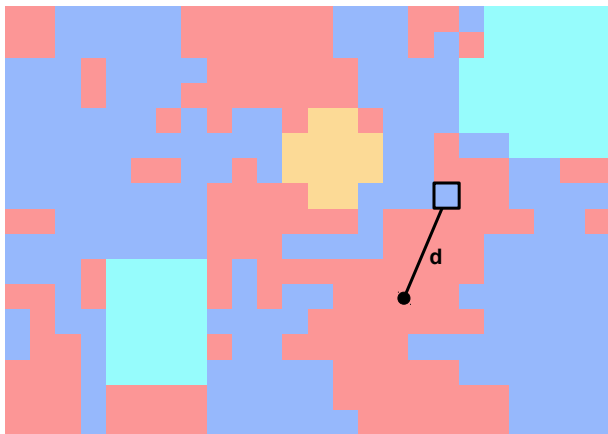
# Spatial organization of land use

## Distance to the city center



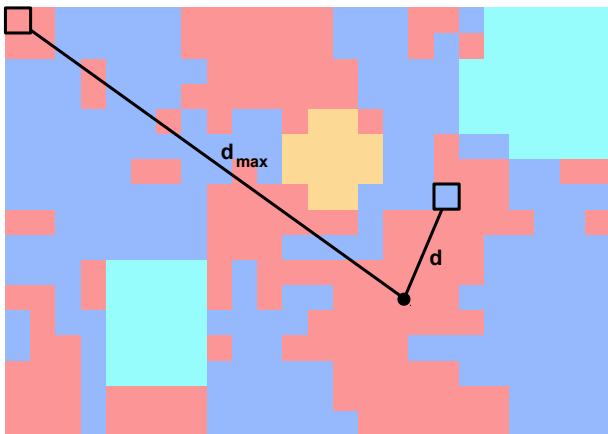
# Spatial organization of land use

## Distance to the city center



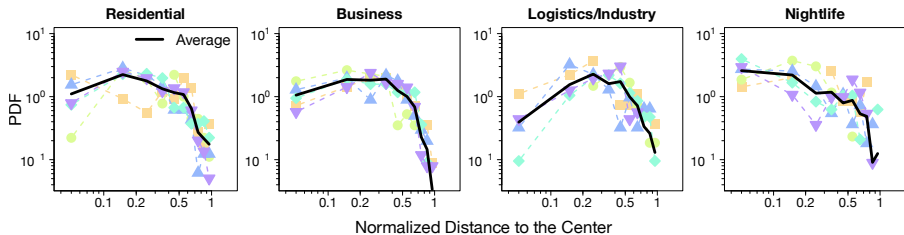
# Spatial organization of land use

## Distance to the city center



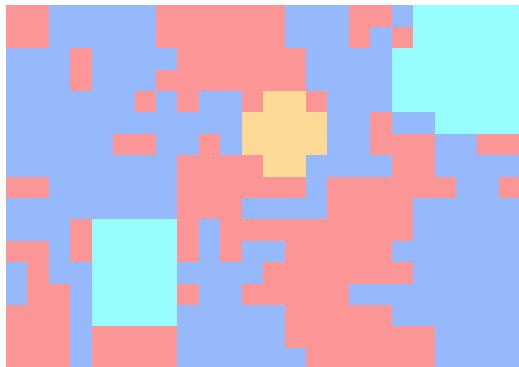
# Spatial organization of land use

## Distance to the city center



# Spatial organization of land use

## Ripley's K

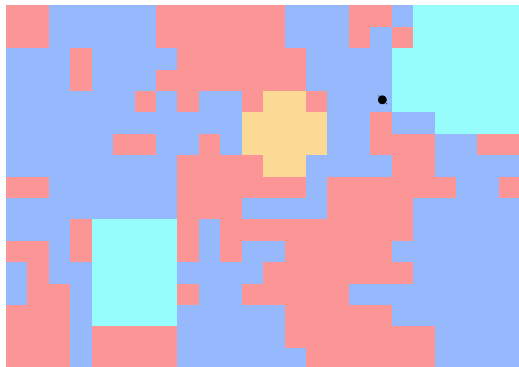


$$K(r) = \frac{A}{n^2} \sum_{i=1}^n N_i(r)$$

$$\hat{K}(r) = K(r)/K(1)$$

# Spatial organization of land use

## Ripley's K

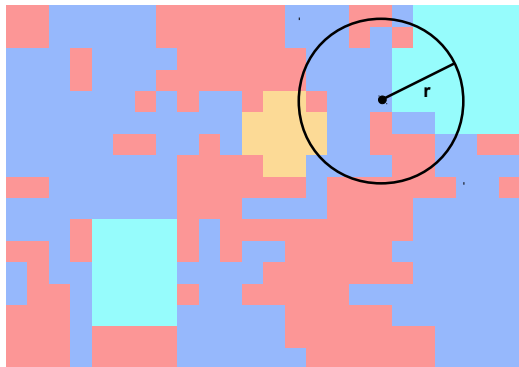


$$K(r) = \frac{A}{n^2} \sum_{i=1}^n N_i(r)$$

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# Spatial organization of land use

## Ripley's K



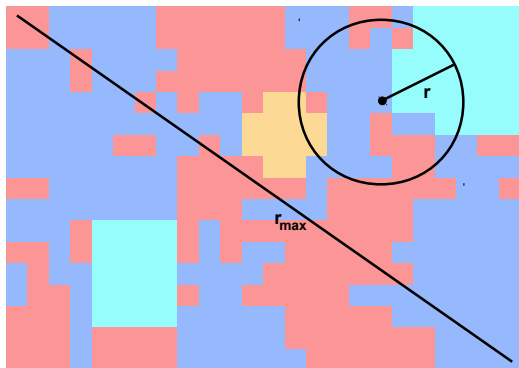
$$K(r) = \frac{A}{n^2} \sum_{i=1}^n N_i(r)$$

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# Spatial organization of land use

## Ripley's K

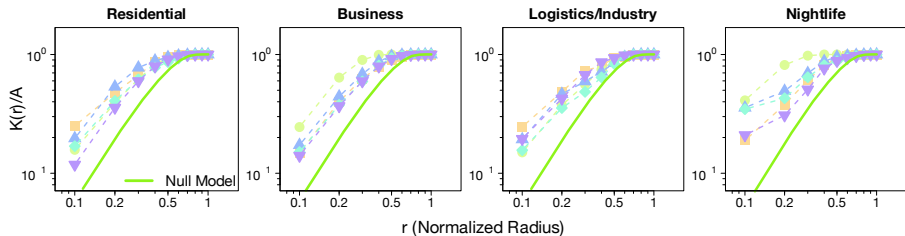


$$K(r) = \frac{A}{n^2} \sum_{i=1}^n N_i(r)$$

$$\hat{K}(r) = K(r)/K(1)$$

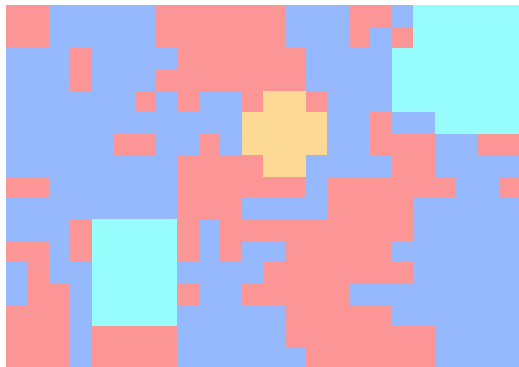
# Spatial organization of land use

## Ripley's K



# Spatial organization of land use

## Entropy index

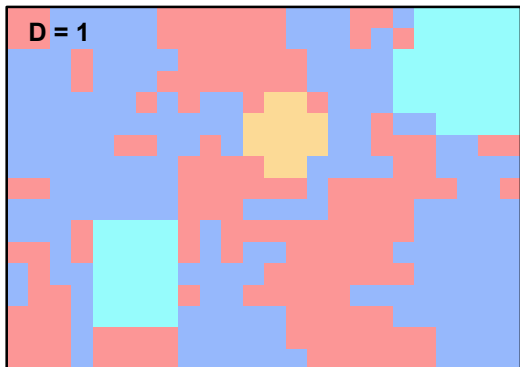


$$E_i = - \sum_{k=1}^4 f_i^k \ln f_i^k$$

$$E(D) = \frac{1}{D^2} \sum_{i=1}^{D^2} E_i$$

# Spatial organization of land use

## Entropy index

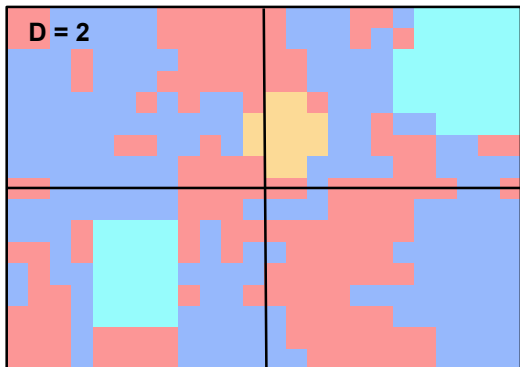


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# Spatial organization of land use

## Entropy index

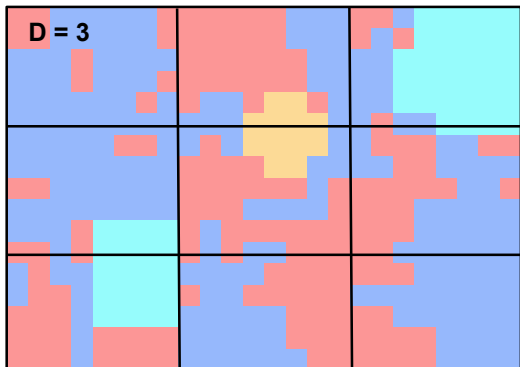


$$E_i = - \sum_{k=1}^4 f_i^k \ln f_i^k$$

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# Spatial organization of land use

## Entropy index

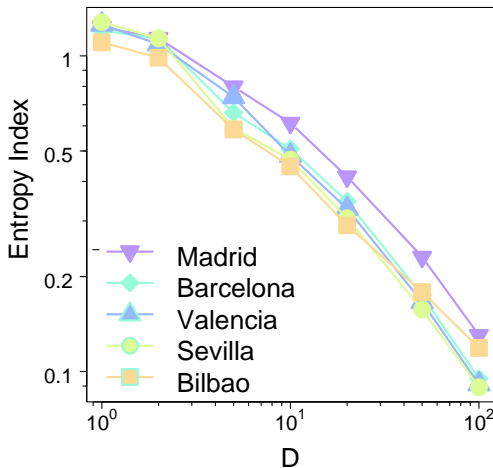


$$E_i = - \sum_{k=1}^4 f_i^k \ln f_i^k$$

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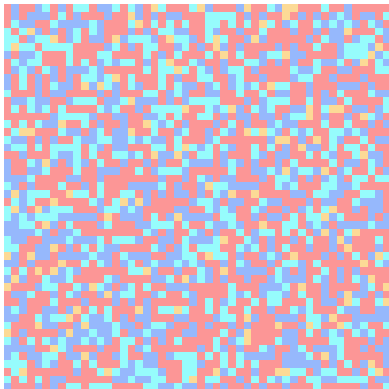
# Spatial organization of land use

## Entropy index



# Land use model

## Initial state



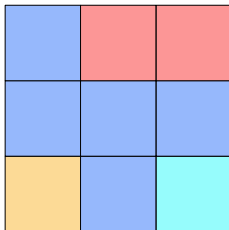


# Land use model

## Satisfaction index

Satisfaction index  $S_{ij}$  of a cell is based on the fraction of land use type among its neighbors

$$p = (p_1, p_2, p_3, p_4)$$

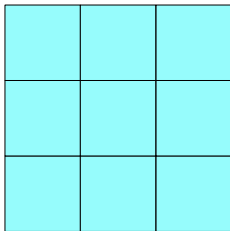


# Land use model

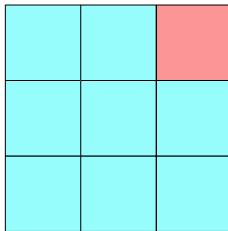
## Satisfaction index

### Logistics/Industry

$$S_{ij} = p_3$$



$$S_{ij} = 0$$

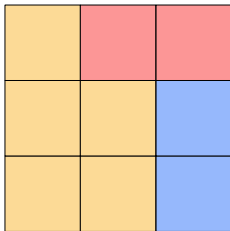


# Land use model

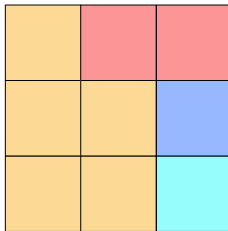
## Satisfaction index

### Nightlife

$$S_{ij} = p_4$$



$$S_{ij} = 0$$



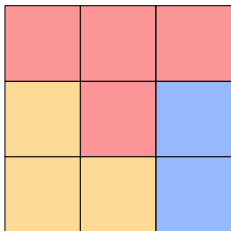
# Land use model

## Satisfaction index

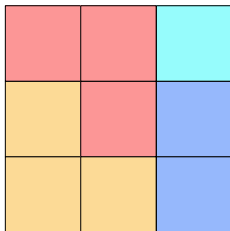
### Residential

$$\text{rand}() \geq \gamma$$

$$S_{ij} = p_1$$



$$S_{ij} = 0$$



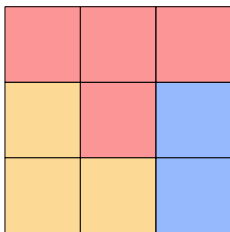
# Land use model

## Satisfaction index

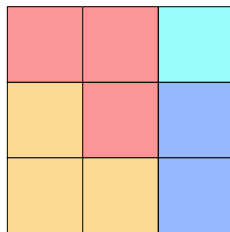
### Residential

$$\text{rand}() < \gamma$$

$$S_{ij} = 1$$



$$S_{ij} = 0$$



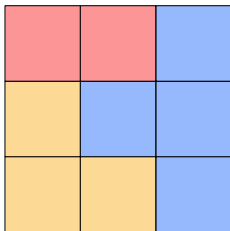
# Land use model

## Satisfaction index

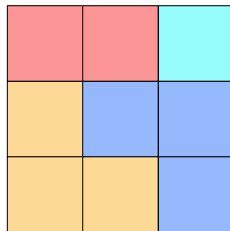
### Business

$$rand() \geq \gamma$$

$$S_{ij} = p_2$$



$$S_{ij} = 0$$



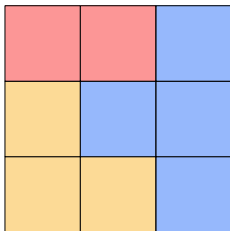
# Land use model

## Satisfaction index

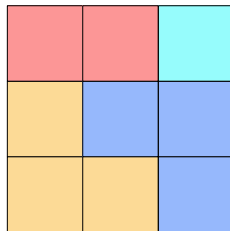
### Business

$$\text{rand}() < \gamma$$

$$S_{ij} = 1$$

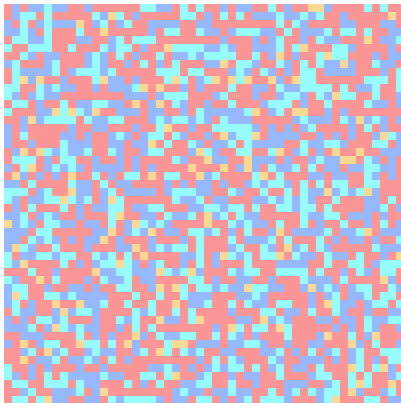


$$S_{ij} = 0$$



# Land use model Algorithm

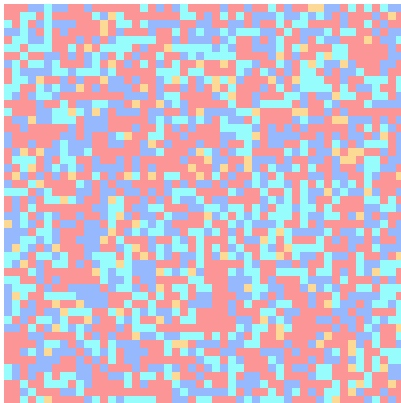
$t = 1$





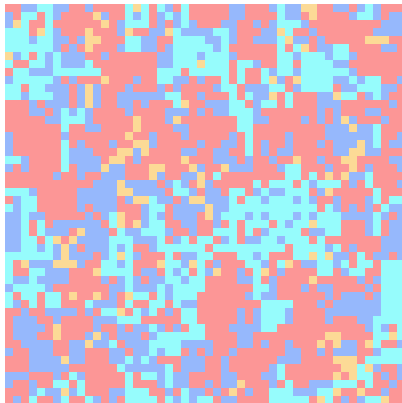
# Land use model Algorithm

**t = 1,000**



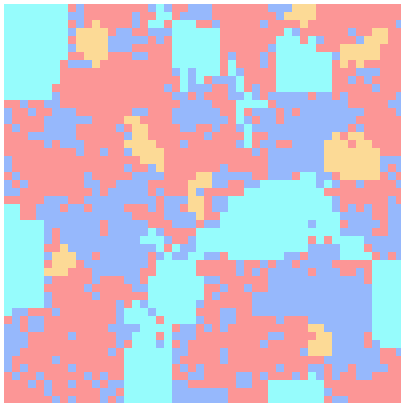
# Land use model Algorithm

**t = 10,000**



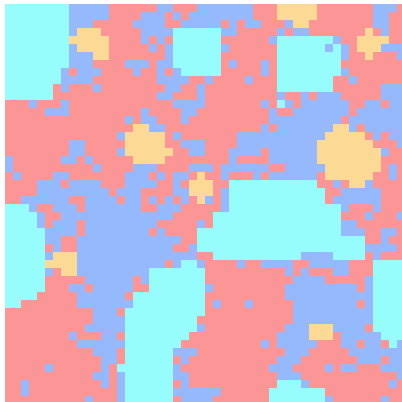
# Land use model Algorithm

**t = 100,000**



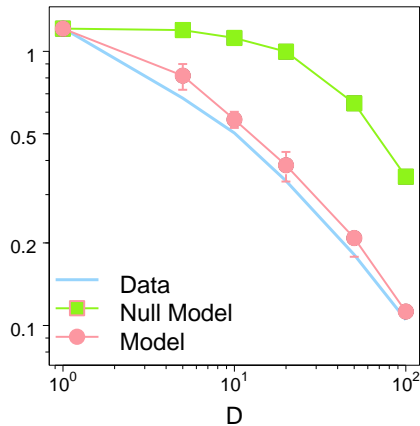
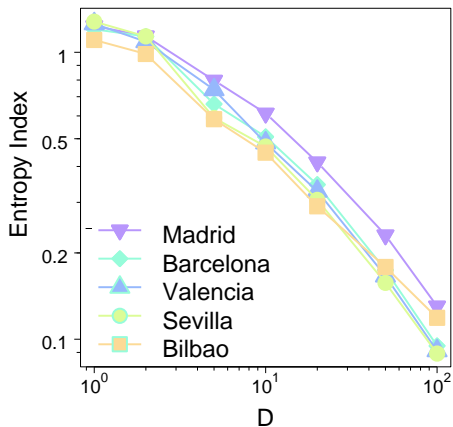
# Land use model Algorithm

**t = 300,000**



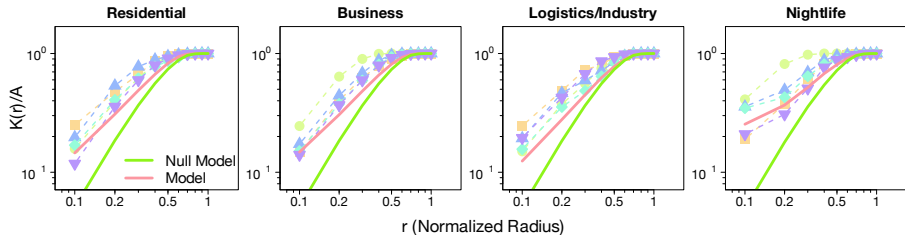
# Land use model

## Calibration of $\gamma$

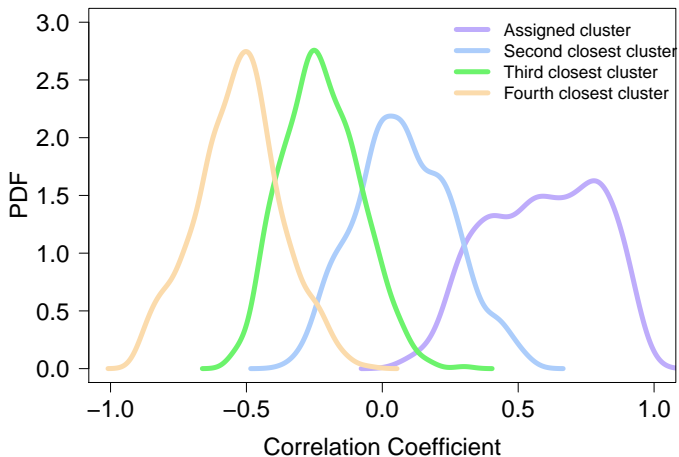


# Land use model

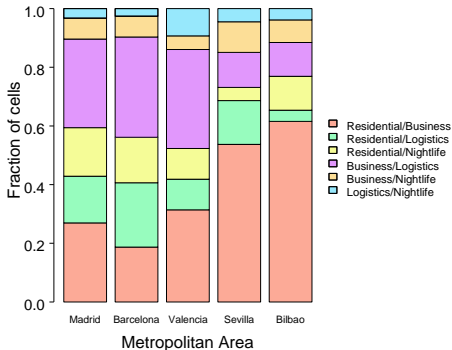
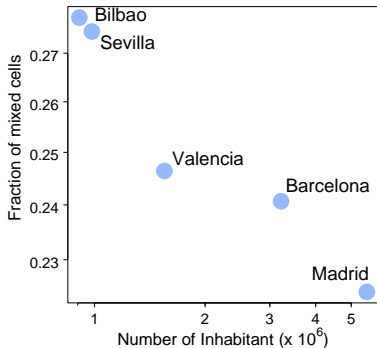
## Ripley's K



# Mixing of land use



# Mixing of land use





# Conclusions

- ▶ Network approach to detect land use using mobile phone data
- ▶ Four land use types (Residential, Business, Logistics, Nightlife)
- ▶ Similarities in the spatial organization of land use across cities
- ▶ Land use model based on attraction-repulsion rules between land use
- ▶ Mixing of land use



Miguel  
Picornell



Oliva  
Garcia Cantu



Thomas  
Louail



Ricardo  
Herranz



Marc  
Barthelemy



Enrique  
Frías-Martínez



Maxi  
San Miguel



José Javier  
Ramasco

**Lenormand *et al.*** Comparing and modeling land use organization in cities.