Cellular Automata and Agent-Based Models for Earth Systems Research

Outline

- Introduction to Modelling and Simulation
- CA
    - theory and application
    - examples
- ABM
    - theory and application
    - examples

General Principles

- Natural systems can often be represented as continua
- These can be represented by continuous discrete fields or by equations describing rates of change
- Mathematically rates of change are expressed by differential equations.
- Sometimes precise analytical solutions exist but often they must be solved numerically.
- Advection and diffusion processes describe the rate of change of quantities in time and space.
- They are best represented by partial differential equations and frequently solved numerically using finite differences/ finite elements.

Modelling vs. Simulation

- Modelling:

  the act of abstracting from the real world and specifying it in some formalism

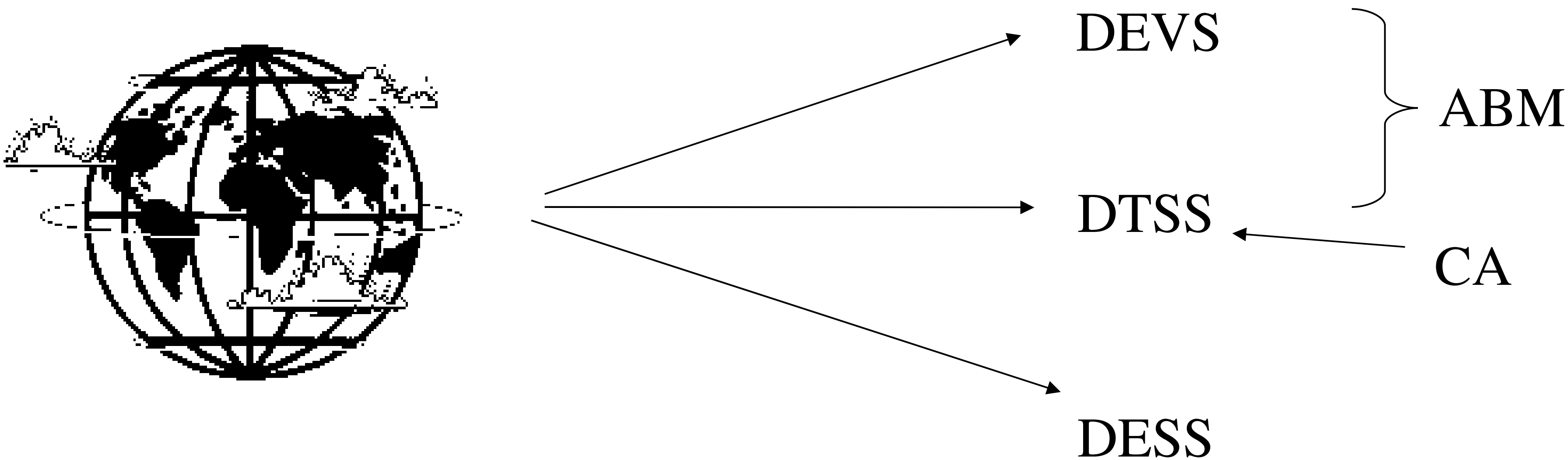
- Simulation:

  running the model

Discrete vs. Continuous

- Time, Space, & Attributes
- Discrete as approximation of continuous
- Not either/or

Modelling Framework



Discrete Event/Time/Equation Simulation System

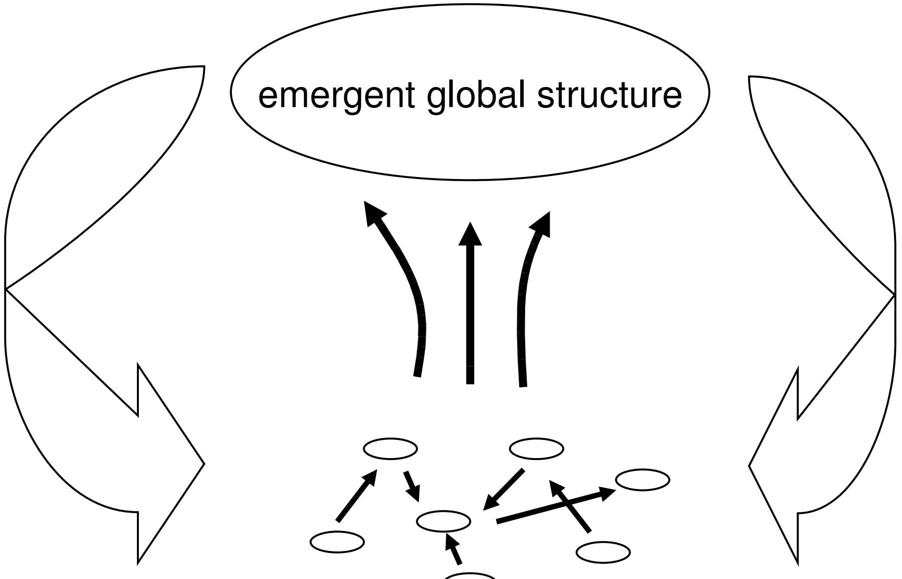
Following Zeigler *et al*. 2000

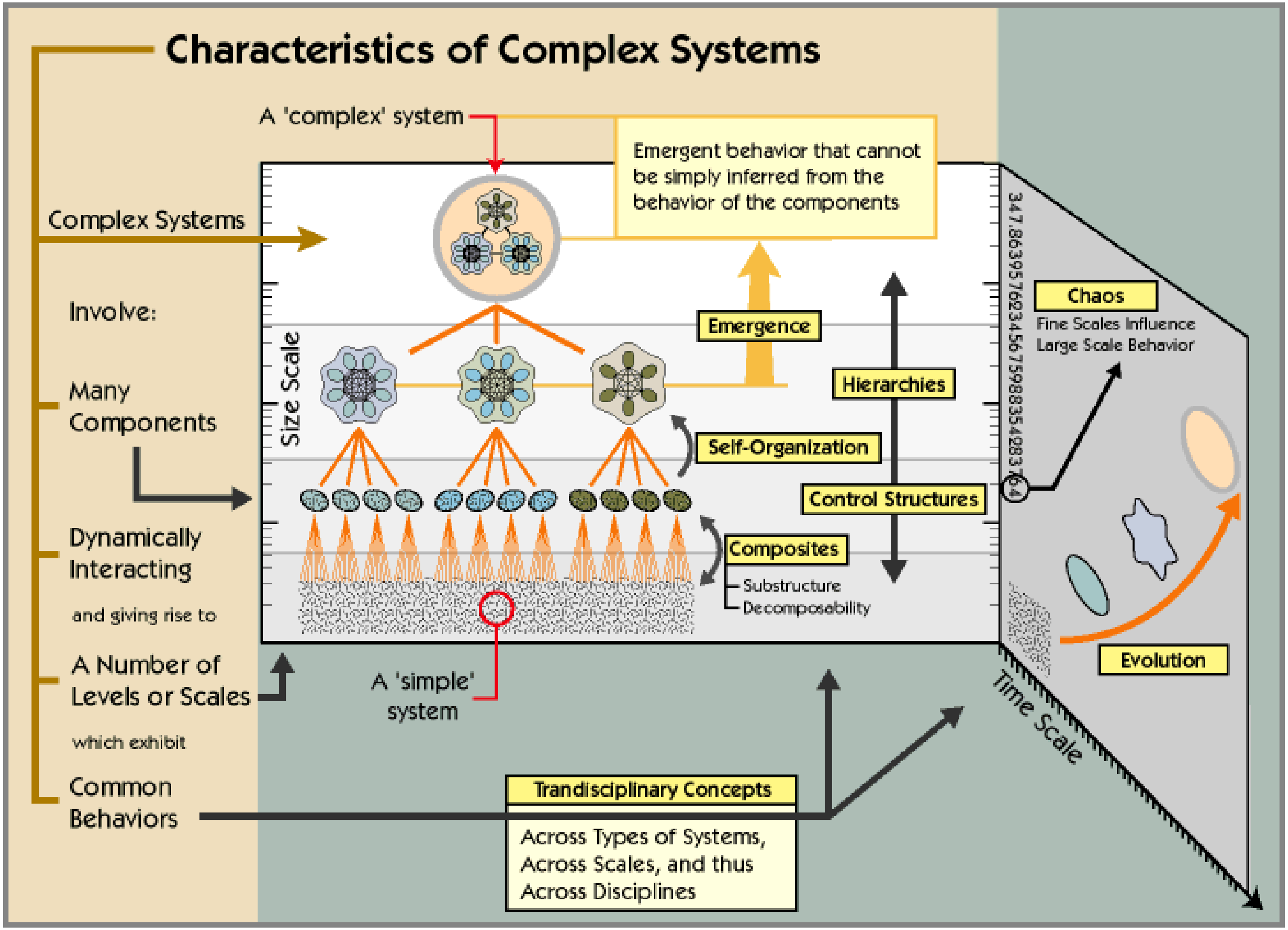
Complexity Theory

- Not a theory
- Chaos theory – Edward Lorenz
- Related to emergence

Emergence

- Complex behaviour emerges from simple interactions
- Inter-scale emergence vs. intra-scale emergence





Stolen from : http://necsi.org/projects/mclemens/cs_char.gif

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Cellular Automata (CA)

- Discrete dynamical systems

- Discrete = space, time, and properties have finite, countable states

- Complexity is bottom up

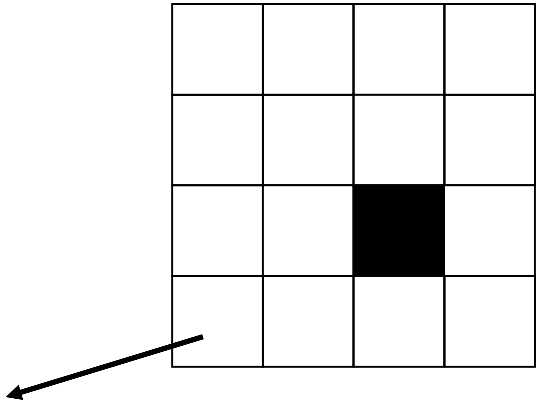
CA background

- Early research in the 40’s
- Popularised by The Game of Life
- Now used in modelling physical and human systems, e.g.
  - soil erosion
  - vegetation dynamics
  - urbanization/ land use change
  - sand piles

(And studied by a bunch of people obsessed with discovering all of the possible patterns that can be created by CA)

CA components

- Cellular Space or Lattice
- Cell States
- Neighbourhood
- Transition Rules
- Discrete Time

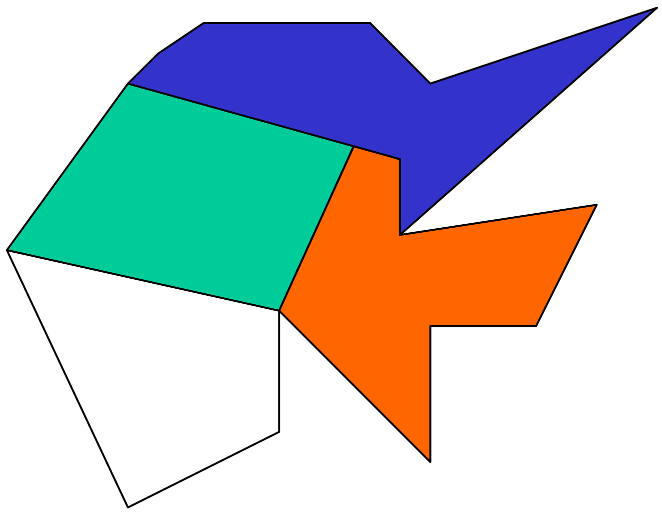


if (some condition holds)
do x

finite set of cell states

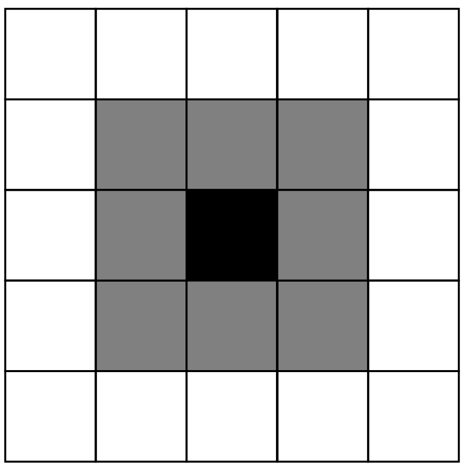
Spaces

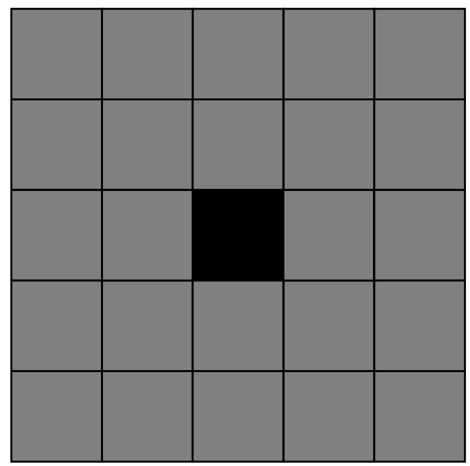
- Traditionally Raster
- Vector
- Graph
- Higher dimensional spaces?



CA Neighbourhoods

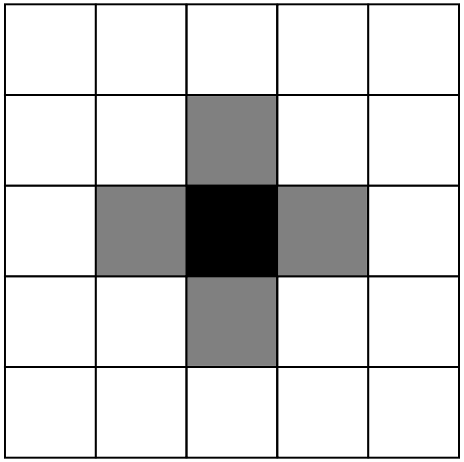
Moore:

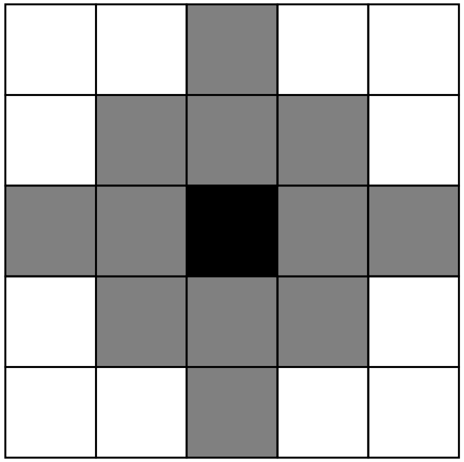




CA Neighbourhoods

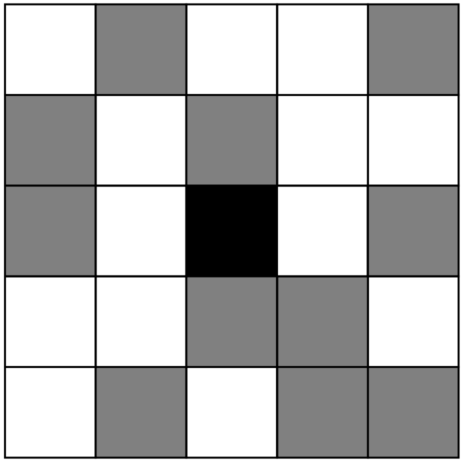
von Neumann:

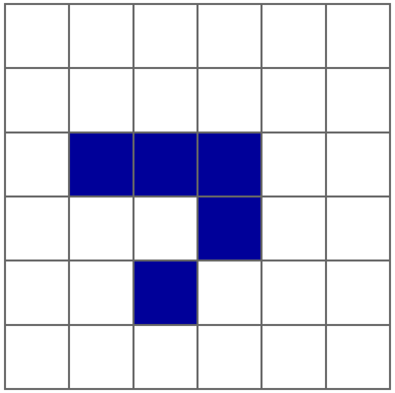




CA Neighbourhoods

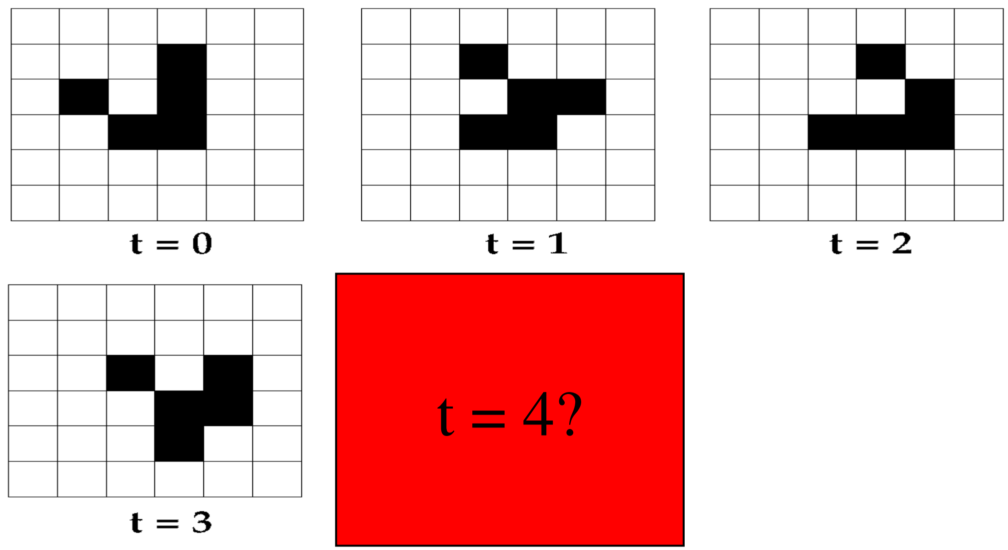
Arbitrary:





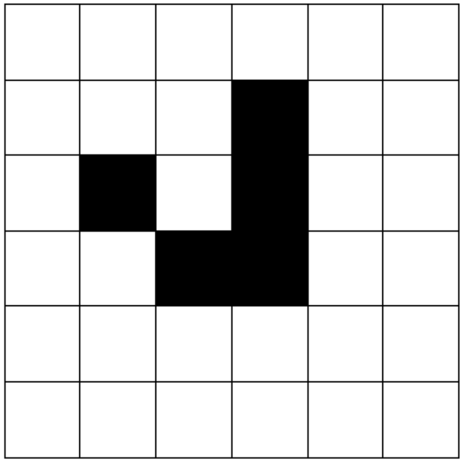
game of life glider

Game of Life Rules



1. A dead cell with exactly 3 live neighbours becomes alive

2. A live cell with 2 or 3 live neighbours stays alive; otherwise it dies.



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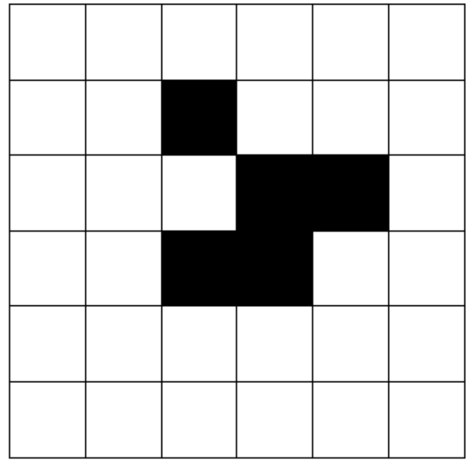

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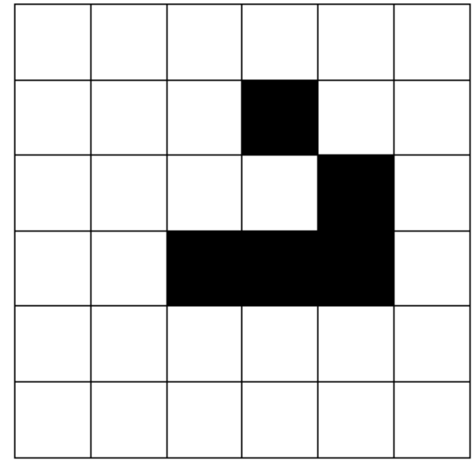
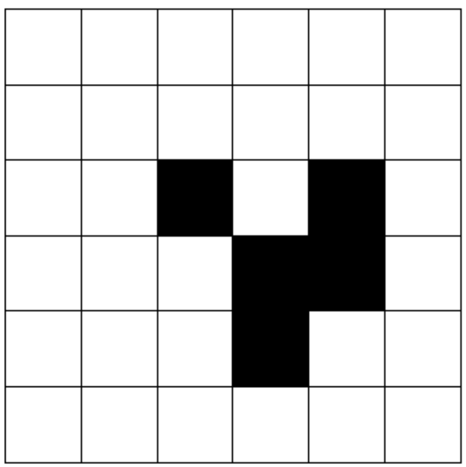


t = 2



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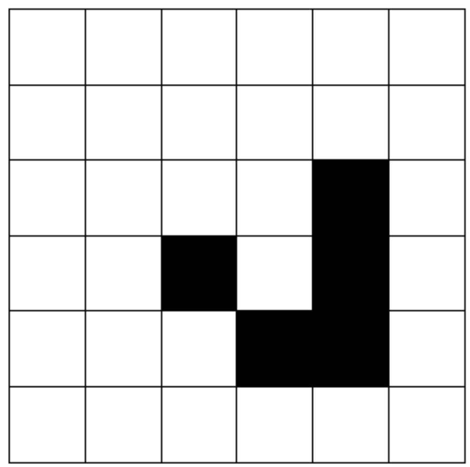
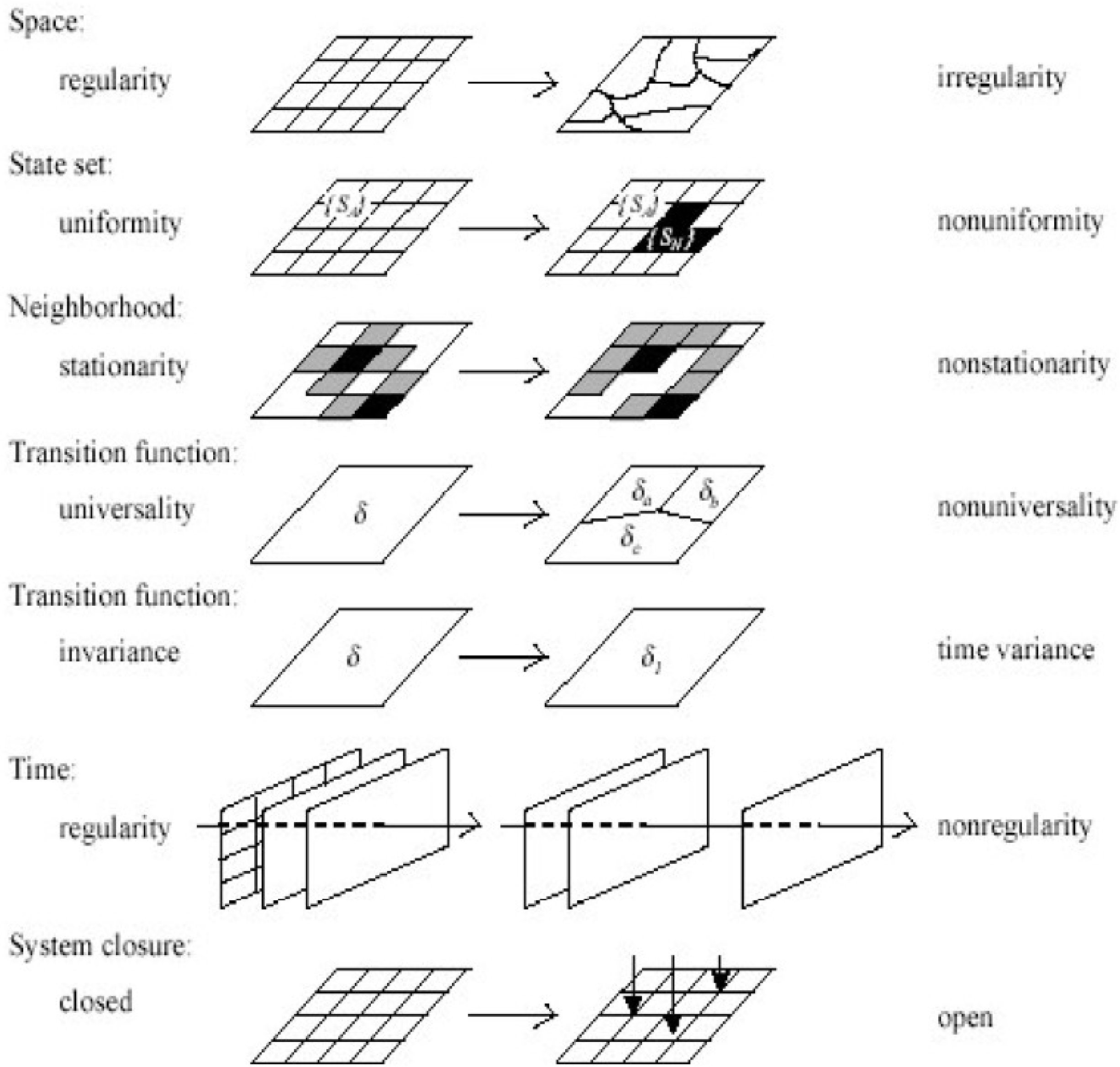
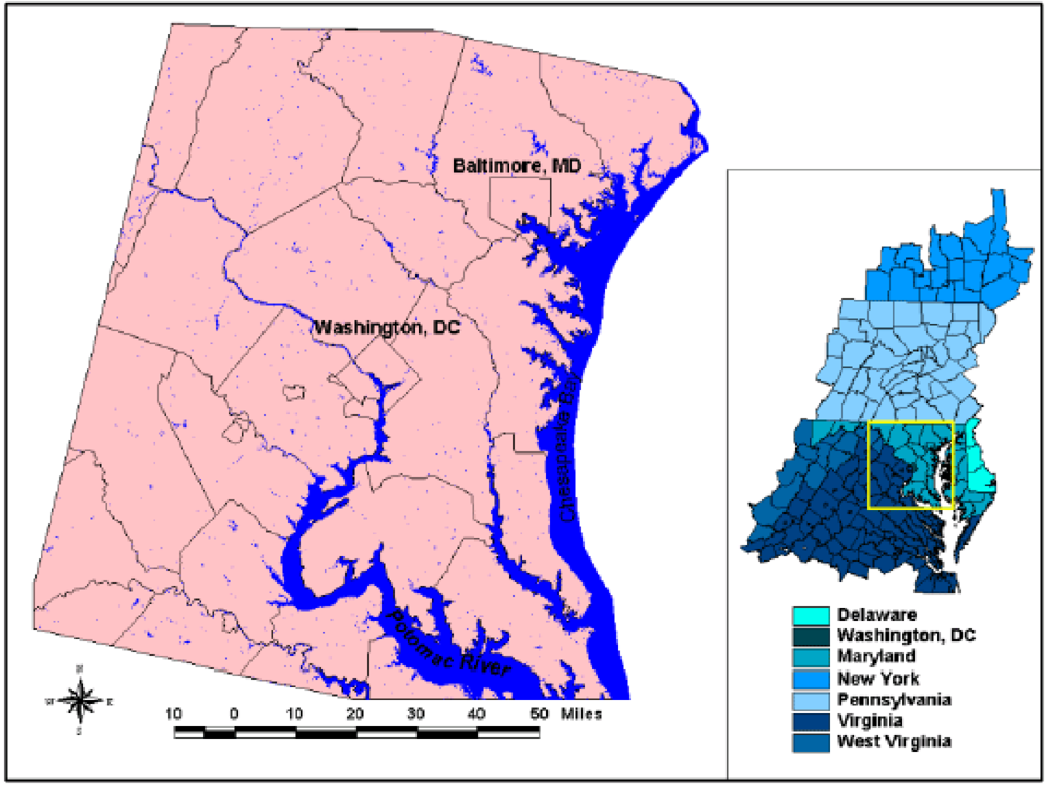


t = 4



Rinaldi E (1999)."The Multi-Cellular Automaton: a tool to build more sophisticated models. A theoretical foundation and a practical implementation" in Rizzi P. e Savino M. (eds) *On the edge of the Millennium. Proceedings of Computer in Urban Planning and Urban Management 6th International Conference* F. Angeli 1999 (in pubblicazione) e in *Proceedings ESIT Creta* (in pubblicazione)

CA Applications: urban growth

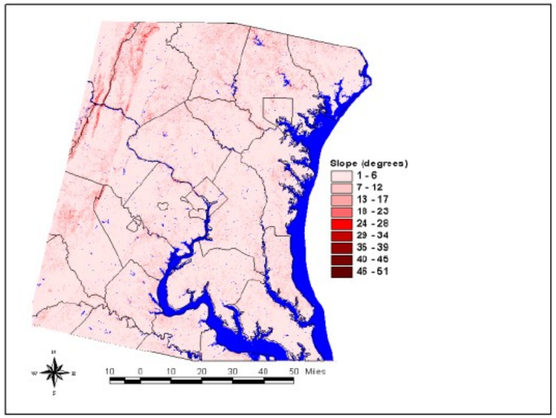


Model of Future Growth in the Washington, DC-Baltimore Region 1986-2030 using the SLEUTH model

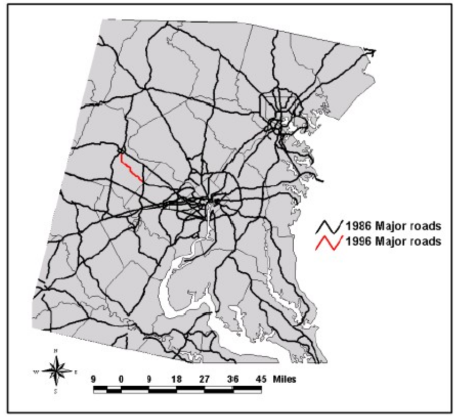
http://www.geog.umd.edu/resac/urban-modeling.htm

SLEUTH growth coefficients

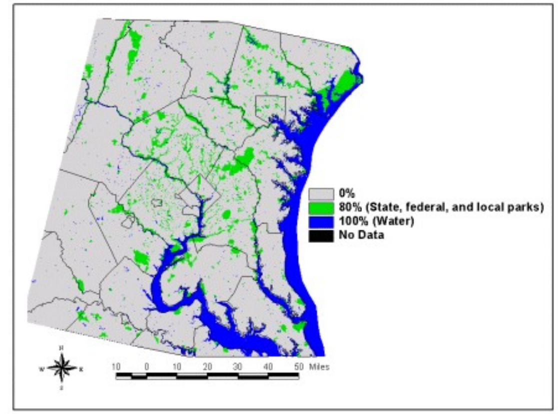
- dispersion coefficient
  - spontaneous or road influenced growth
- breed coefficient
  - new spreading centre or road influenced growth
- spread coefficient
  - edge growth from spreading centre
- slope coefficient
  - lower slopes are easier to build on
- road gravity coefficient
  - distance from road influences growth



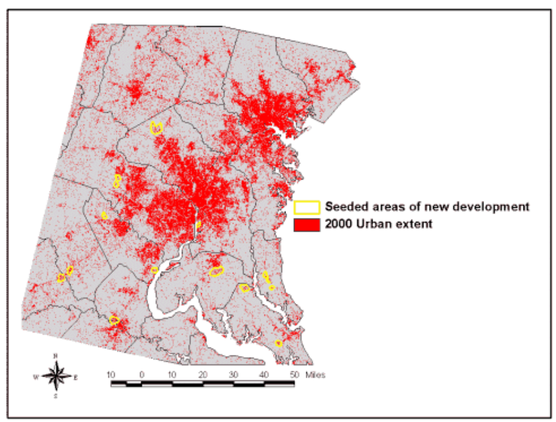
slope



roads



excluded areas

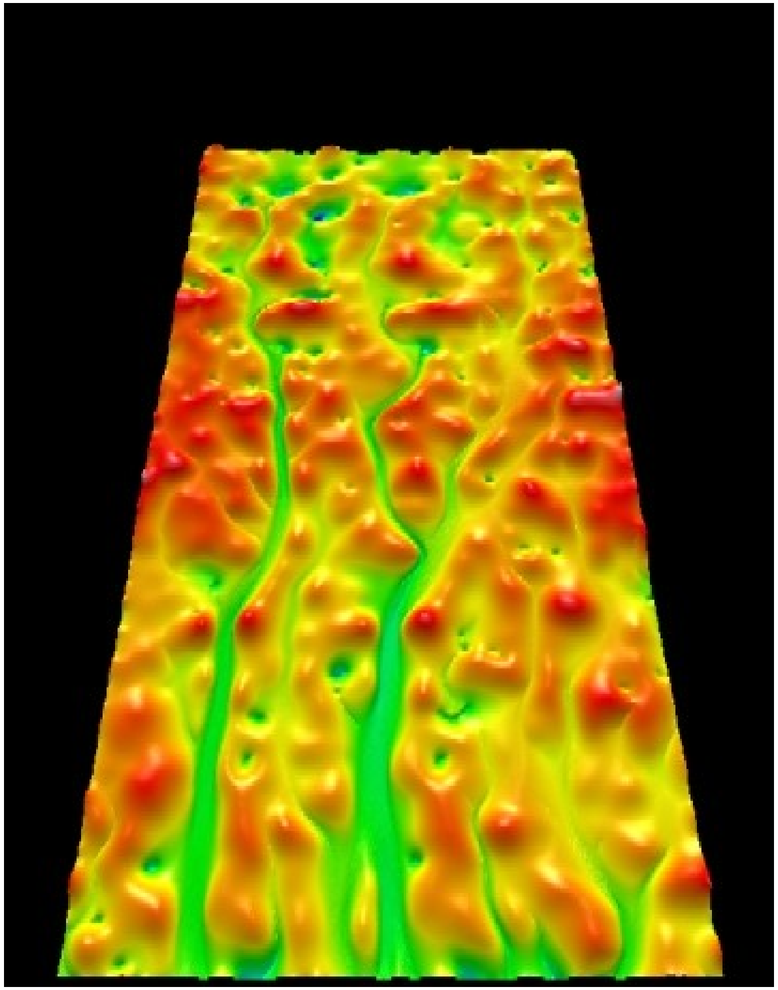


CA results

http://www.geog.umd.edu/resac/urban-modeling-animation1.htm

CA Applications: Soil Erosion

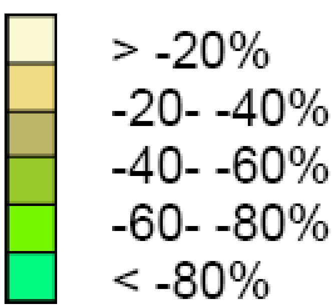
- RillGrow 2 by Favis-Mortlock

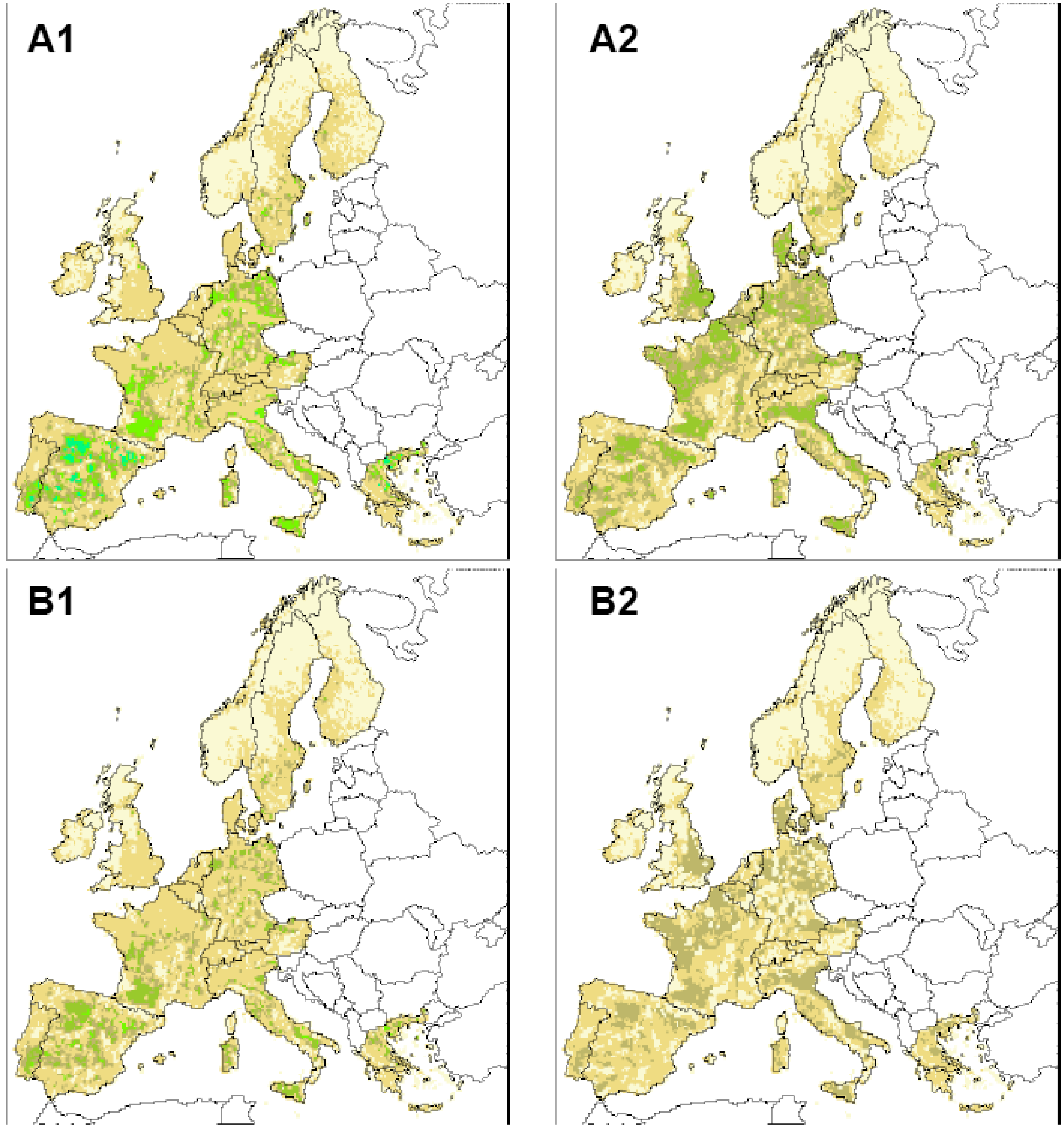


http://www.soilerosion.net/rillgrow/

CELLULAR AUTOMATA IN INTEGRATED MODELLING

Change in cropland area (for food production) by 2080 compared to baseline (%) for the 4 SRES storylines and HADCM3



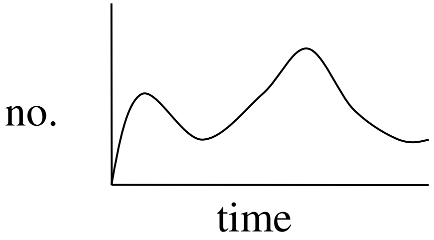


After: Schröter et al. (2005). Ecosystem service supply and vulnerability to global change in Europe. *Science*, **310** (5752), 1333-1337

Analysis of CA Output

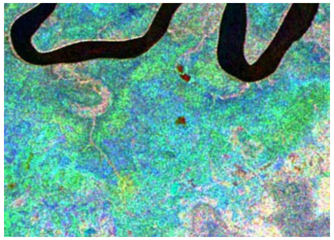
- Plot cell attributes

- Plot number of cells in certain state



- Use metrics for describing spatial pattern

e.g. patch size metrics



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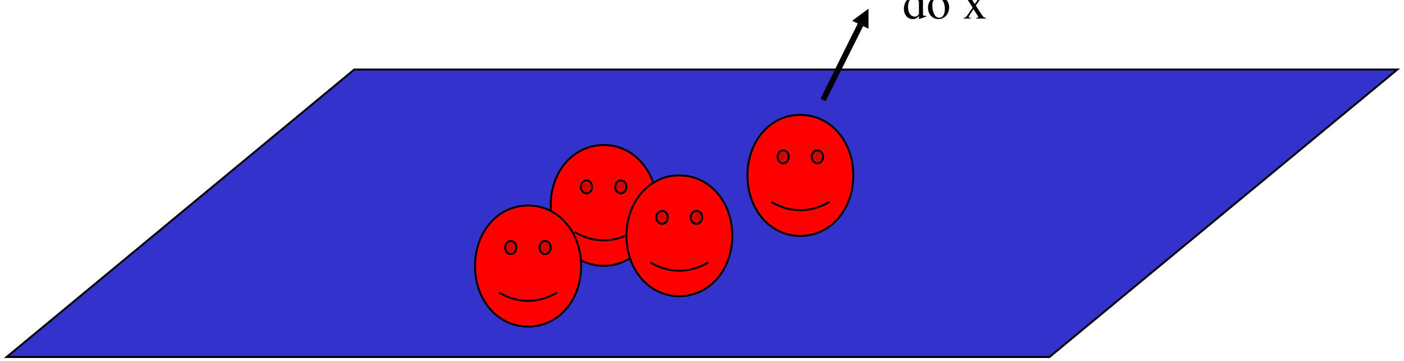
Agent Based Model (ABM)

A representation of a system in which *agents* interact with each other and their *environment* using a set of rules

- Also called multi-agent systems (MAS)

ABM Components

- Space (environment)
- Agent(s) – rules defining interaction and neighbourhoods
- Discrete Time



what is an agent?

Represents:

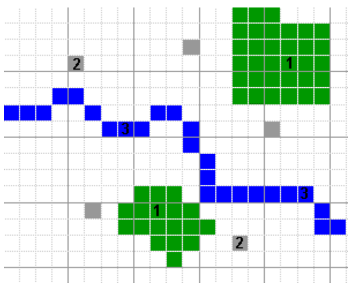
- some discrete thing in the world (usually a living thing)
- something with behaviour

Representation:

- Physically - Geometric object
- Programmed – an object with attributes and behaviour

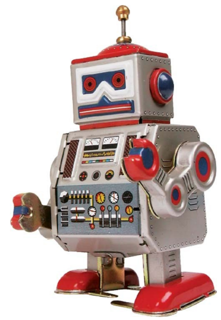
agent

- behaviour:
  - Rational – deterministic / Stochasti
  - e.g. BDI algorithm
- communication:
  - Stigmergic
  - Message passing



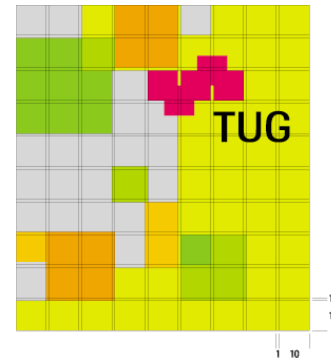
same initial conditions

+



deterministic
agents

=



same final state

+stochasticity

Environmental Examples

?

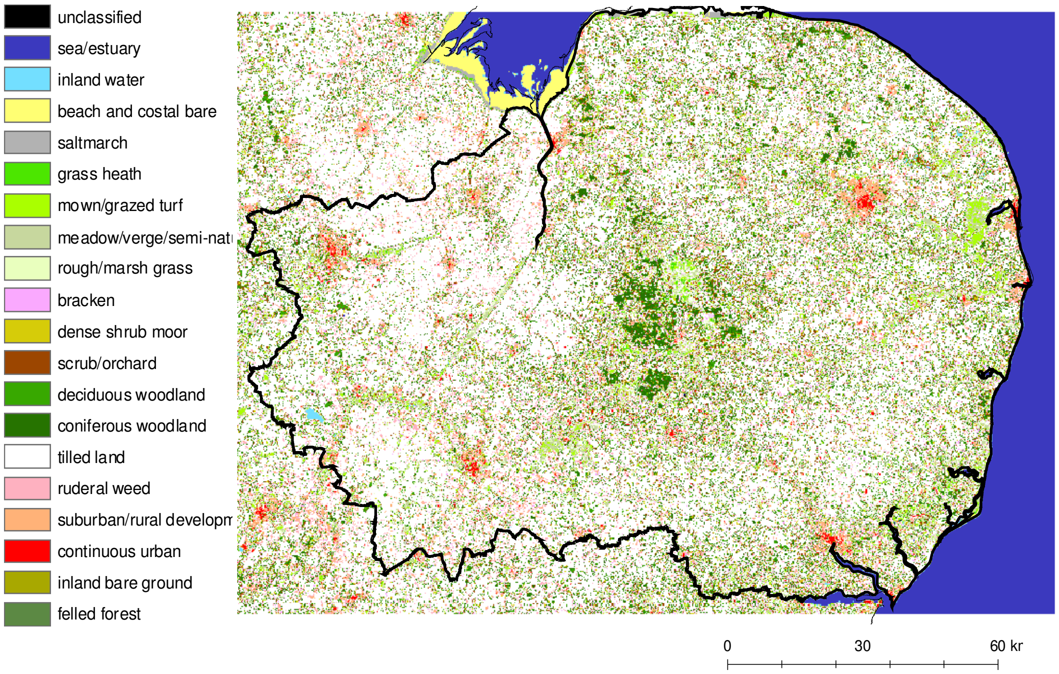
Types of ABM

- Fixed behaviour model vs. evolutionary model
  - e.g. genetic algorithms

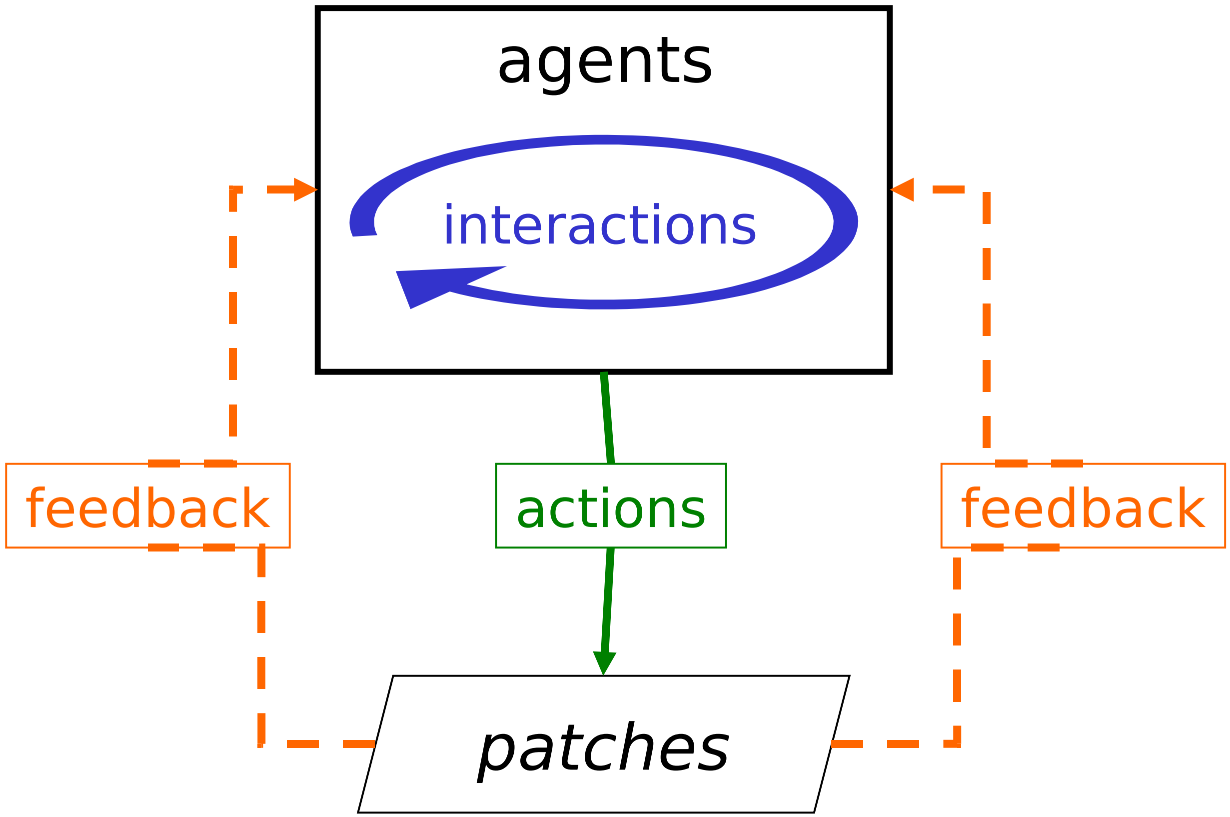
- Top down vs. or plus bottom up

Example – urban land use in East Anglia

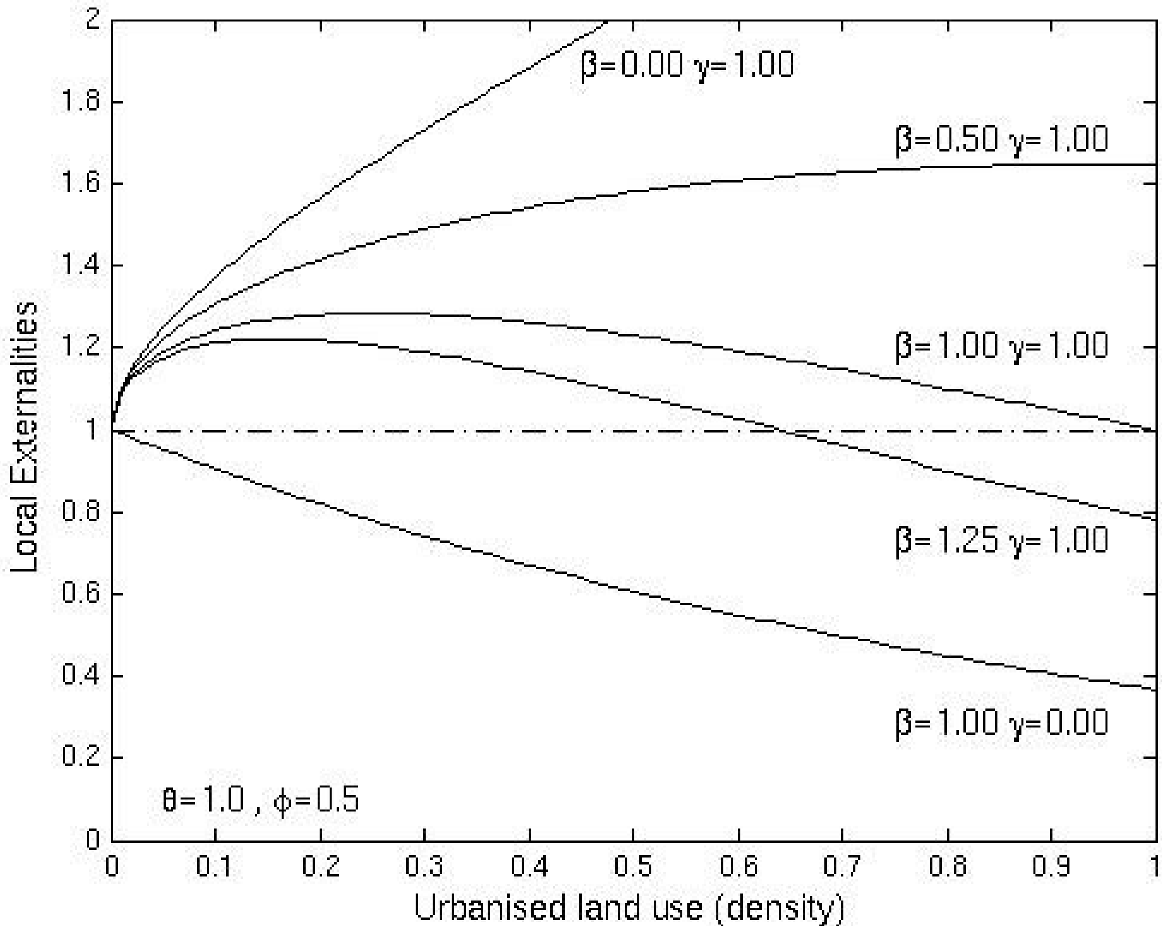
- Endogenising the planning process



Source: Lilibeth Acosta-Michlik and Corentin Fontaine; funded by the Tyndall Centre

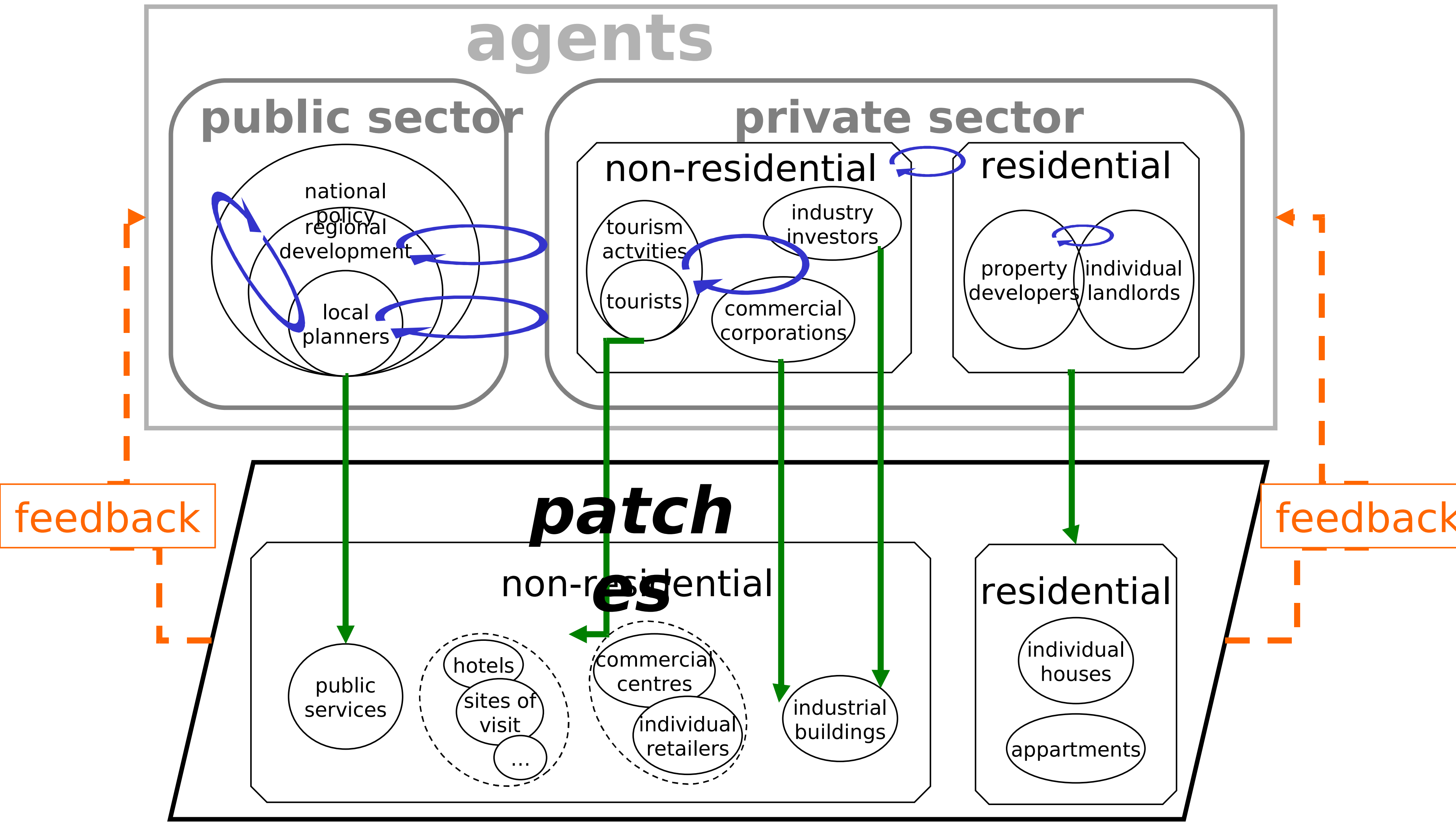

agents
interactions
feedback
actions
feedback
patches

Agent-environment interaction



β and γ are parameters affecting preferences for landscape and service amenities, respectively

After: Caruso, G., Peeters, D. and Cavailhès, J. and Rounsevell, M.D.A. (2007). 'Spatial configurations and cellular dynamics in a periurban city'. *Regional Science and Urban Economics*, **00**, 000-000 (in press)

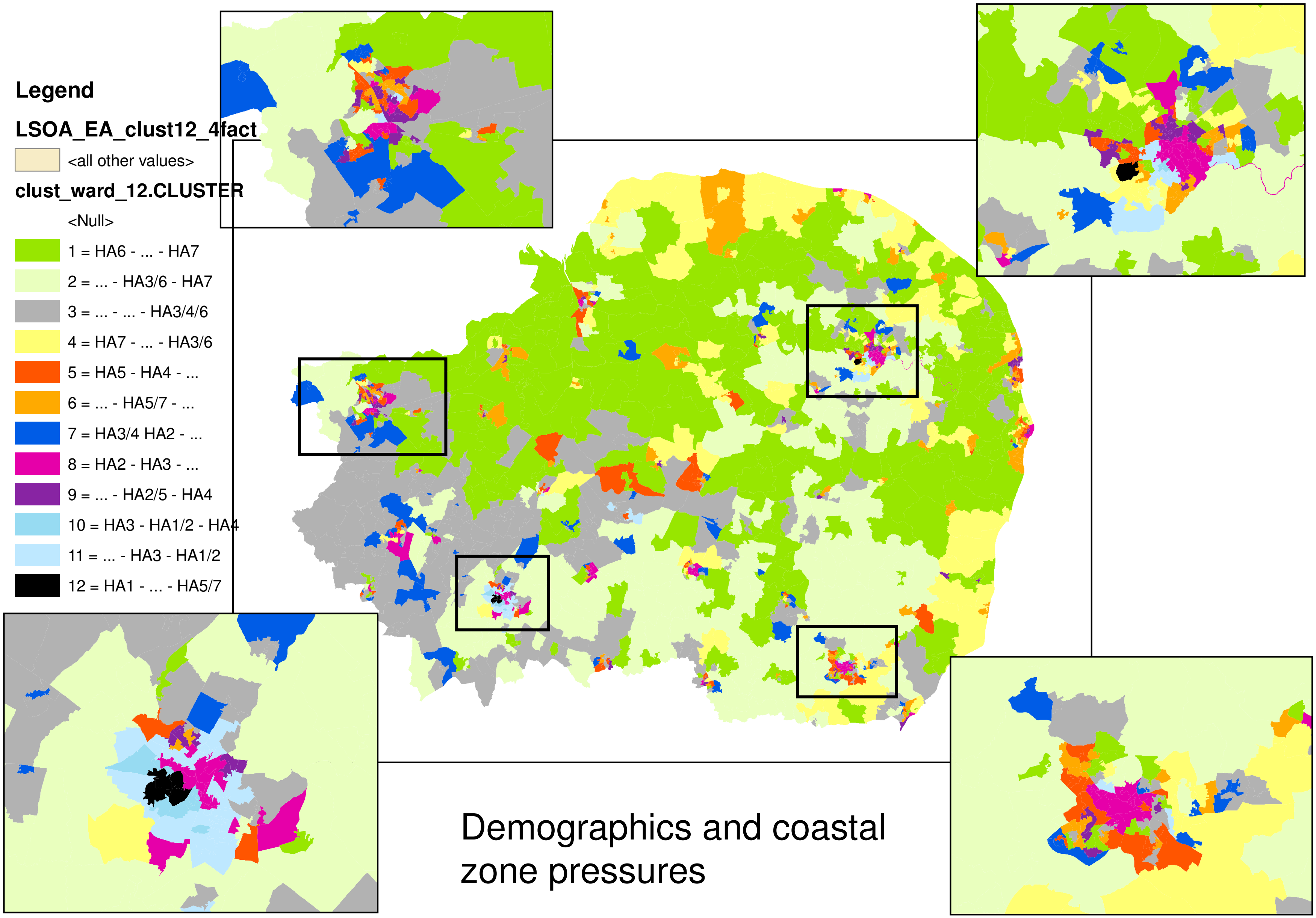

agents
public sector
national policy
regional development
local planners
private sector
non-residential
tourism actvities
tourists
industry investors
commercial corporations
residential
property developers
individual landlords
patches
non-residential
public services
hotels
sites of visit
...
commercial centres
individual retailers
industrial buildings
residential
individual houses
appartments
feedback
feedback

Residential agents

- Socio-economic data analysis
- Agent profiles (household types) & location trends

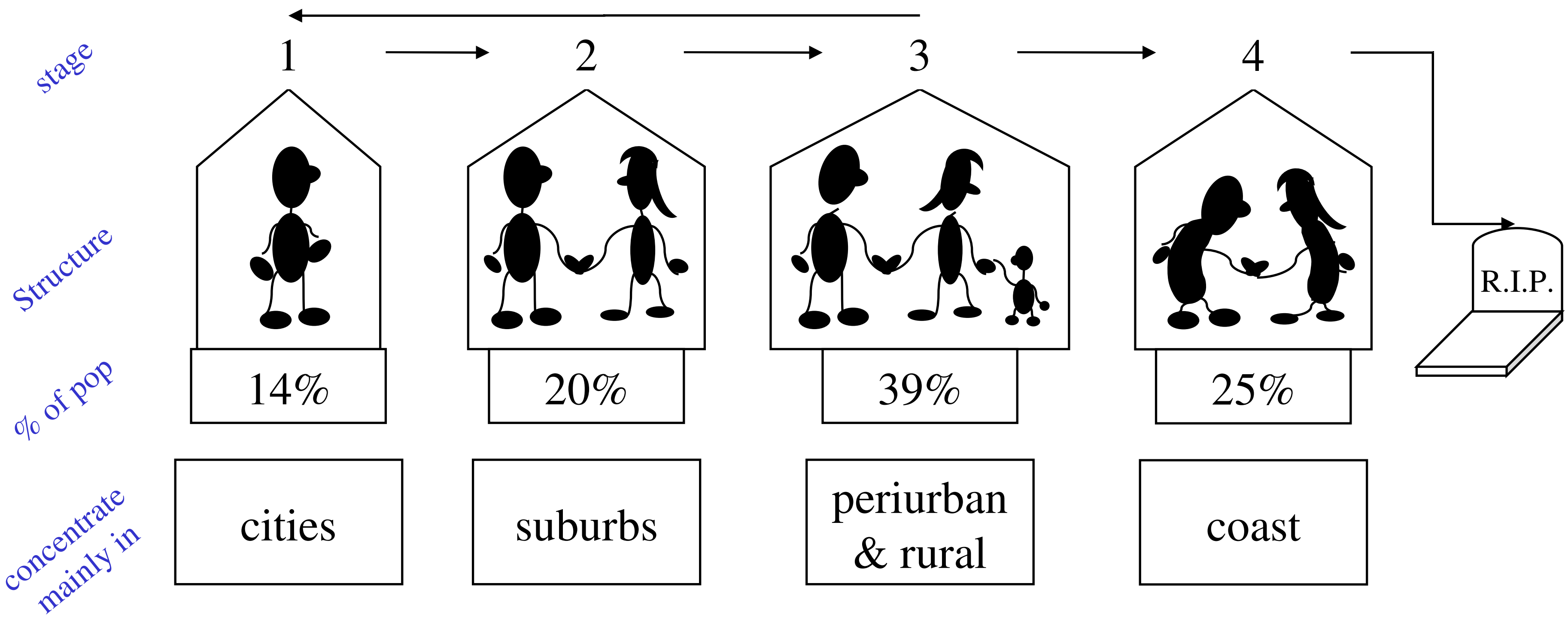
		CLUSTERS											
		1	2	3	4	5	6	7	8	9	10	11	12
isolated student	HA1										++	+	+++
single person	HA2							+	+++	++	++	+	
couple	HA3		++	+	+			+++	++		+++	++	
couple with dep. children	HA4			+		++		+++		+	+		
single-parent family	HA5					+++	++			++			+
couple with non-dep. children	HA6	+++	++	+	+								
all retired	HA7	+	+		+++		++						+

Household agent location preferences



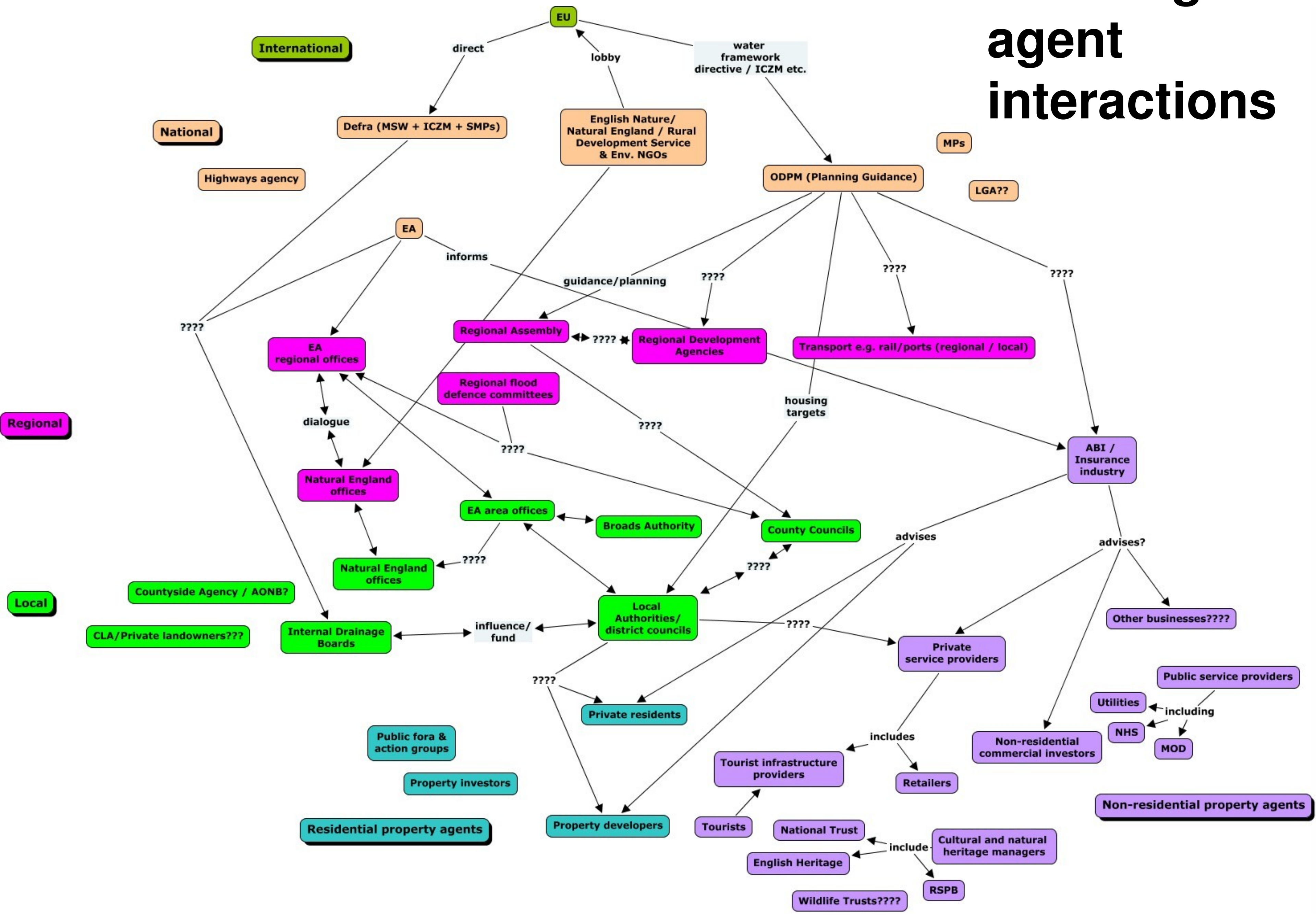
Demographics and coastal zone pressures

Residential model runs

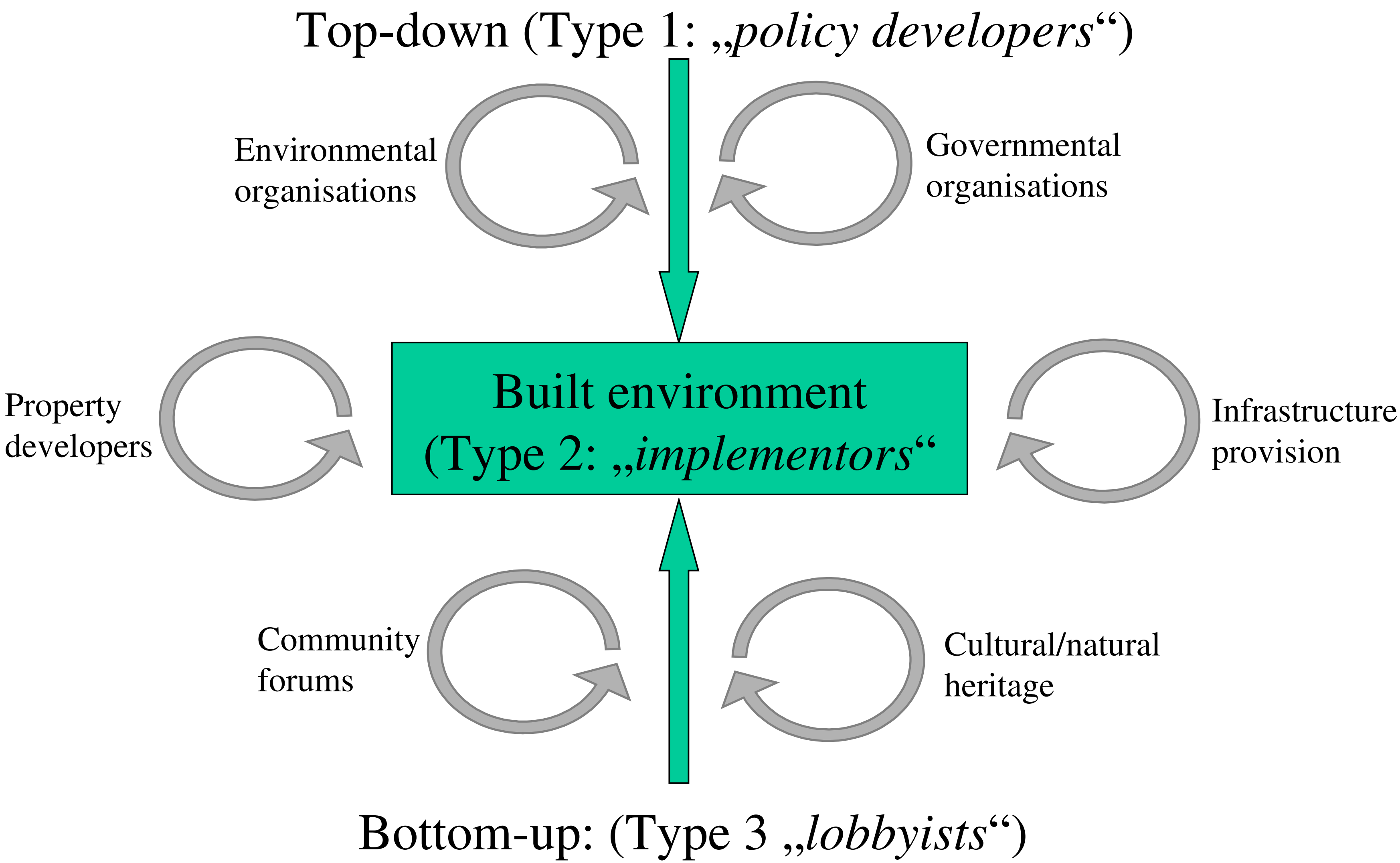


Model run animation

Planning agent interactions



Conceptual planning model



ABM as Computational Laboratory

- Testing hypotheses
- Testing methodologies
- Is your ABM deterministic or has it got a stochastic component?
- How many simulations is enough?
- How do we interpret model results?
- Statistical analysis of results

Analysis of ABM Output

- Plot agent attributes
- Plot number of agents of certain type
- Spatial pattern metrics

  - temporal considerations (at a time or over time)

Difference between CA and ABM

?

What is the goal of modelling?

- to predict the represented system?
- to understand and explain the represented system?

References

General Modelling:

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CA:

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- Papers on the RePast site: repast.sourceforge.net/papers