Understanding the emergence of organisational properties in ecological systems

Individual-based models as tools for ecological theory and application

Broder Breckling
Hauke Reuter and Ulrike Middelhoff

Let us start slowly

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To a guided tour through the
application range of Individual-based models

Let us start slowly

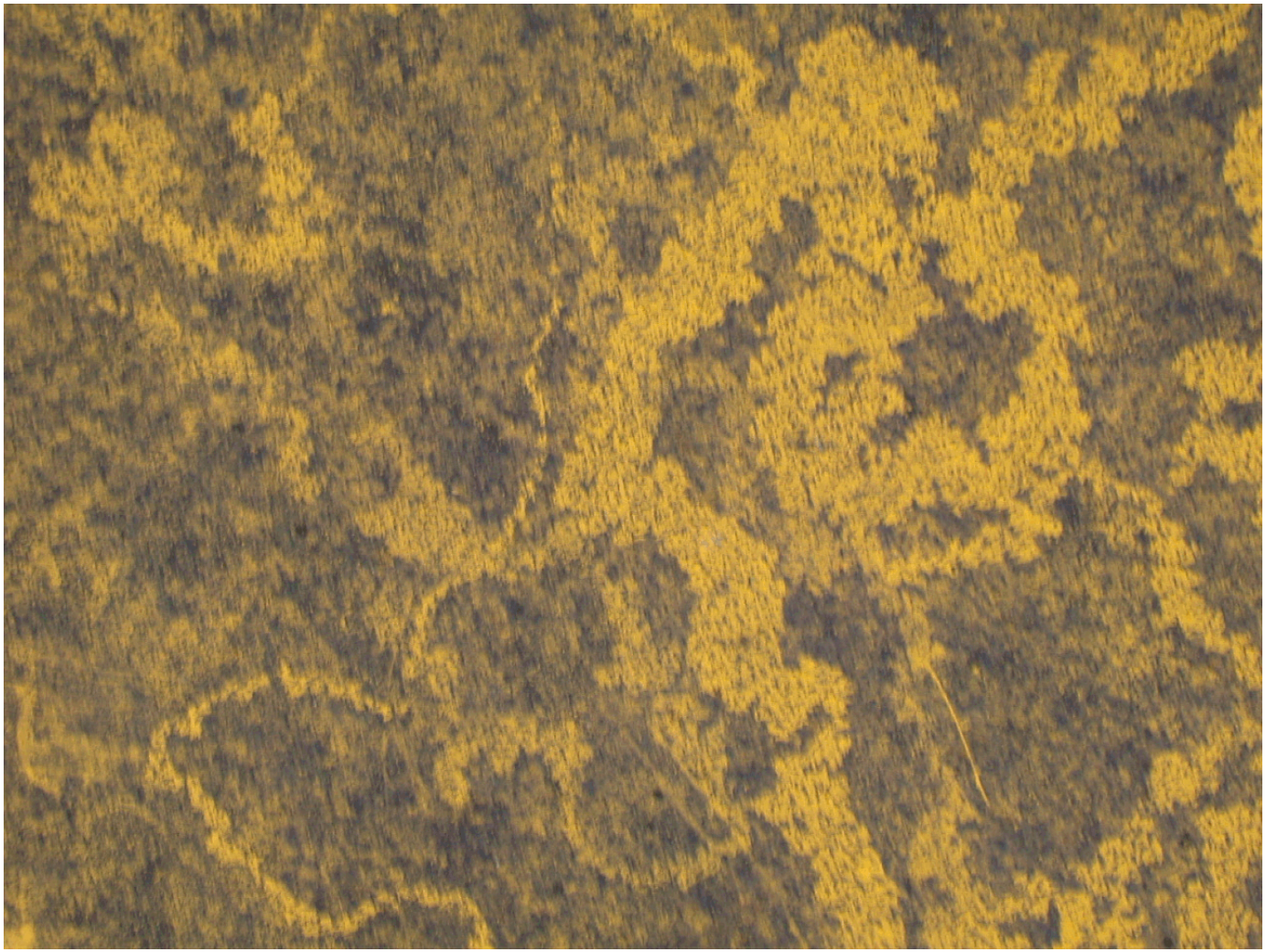
Cepaea hortensis http://www.graficimages.com/snail.JPG

Snail Trail

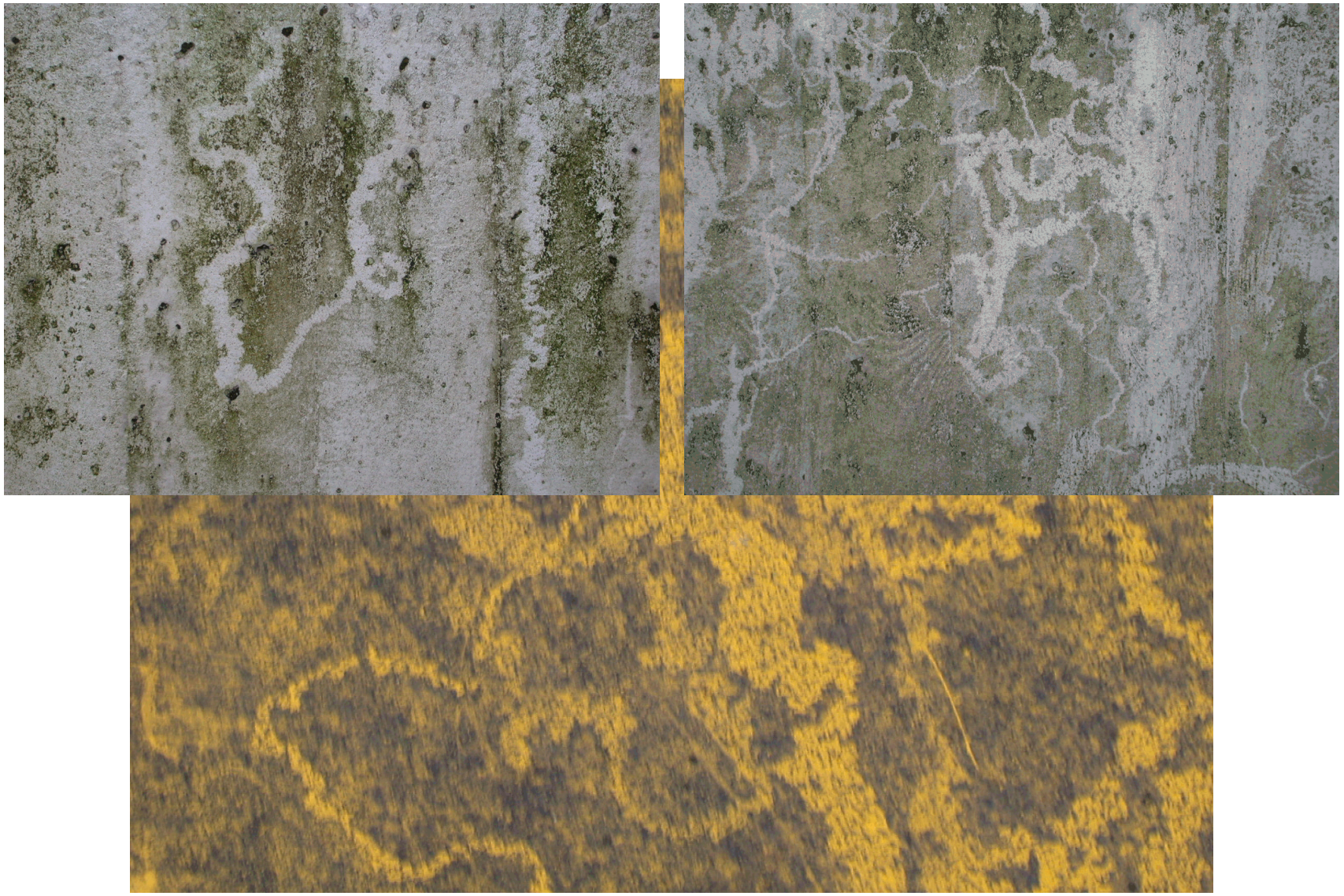
Cepaea hortensis

Cepaea hortensis http://www.graficimages.com/snail.JPG

Snail Trail



Snail Trail



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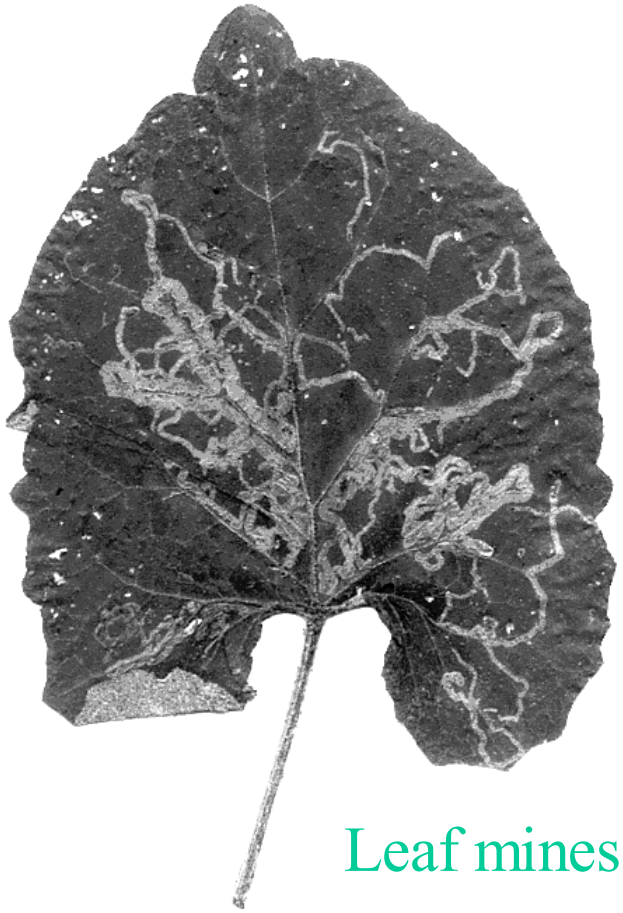
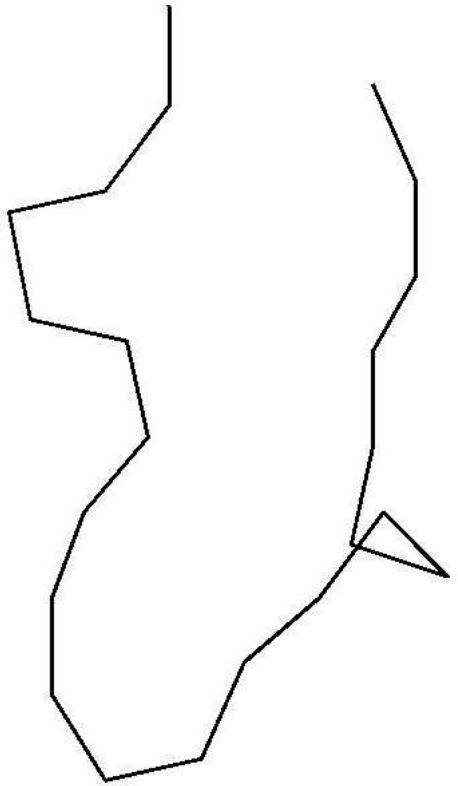


Leaf mines

Snail Trail

Starting point
for movement modelling



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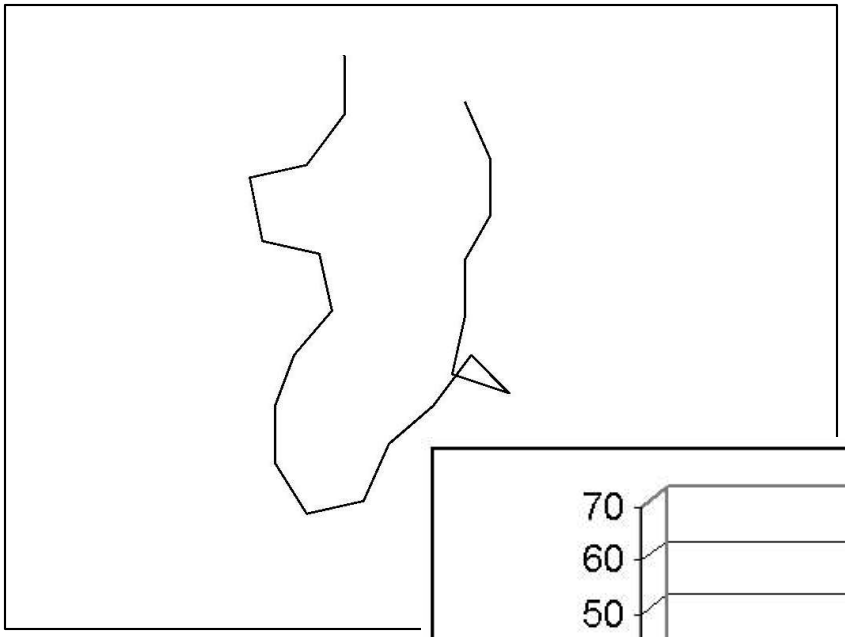

Starting point
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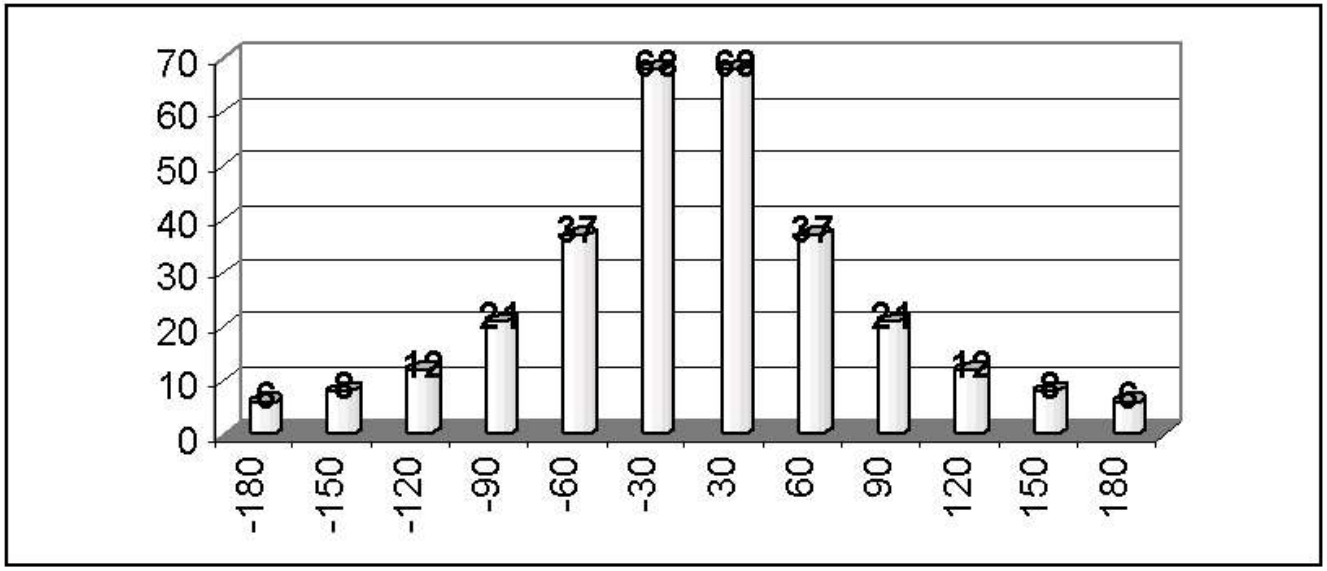
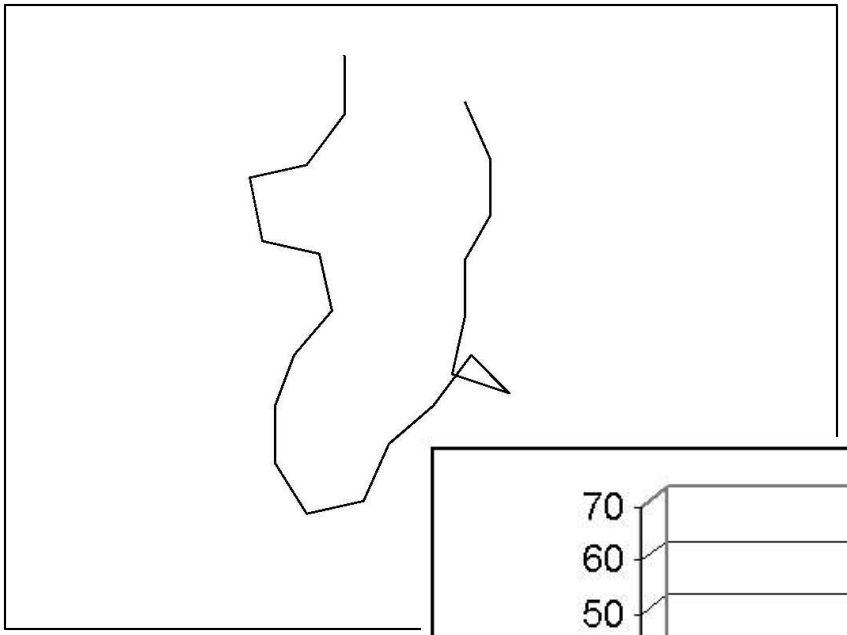
Frequency of turning angles



ECEM '04, Breckling et al.

Snail Trail



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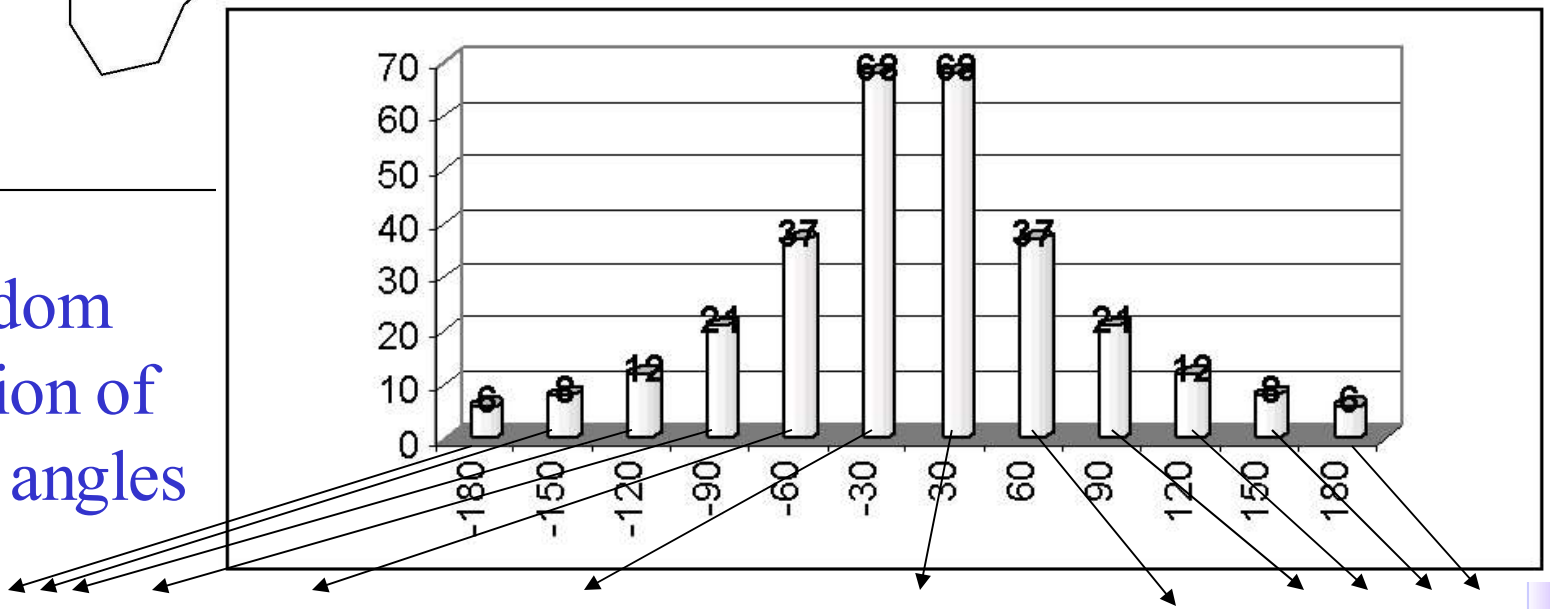

Random
selection of
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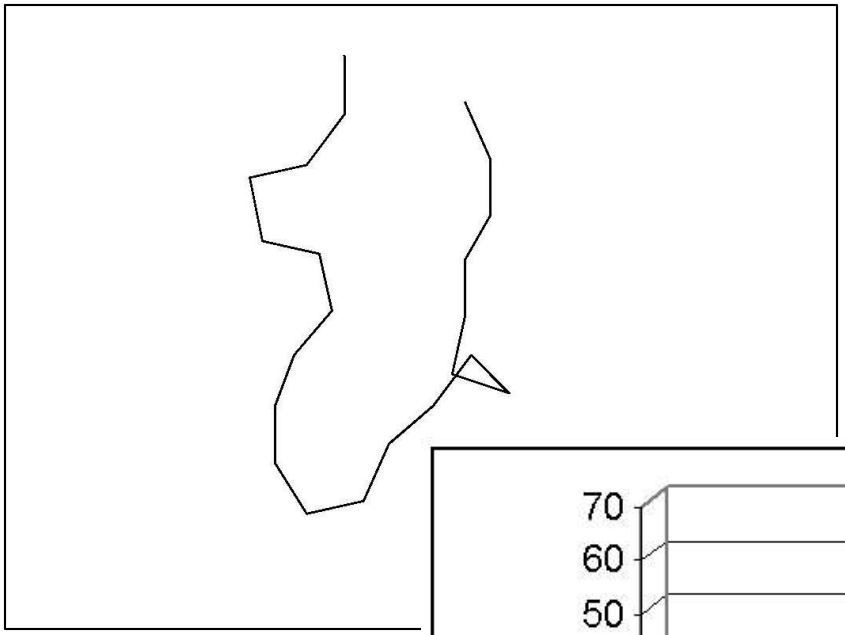

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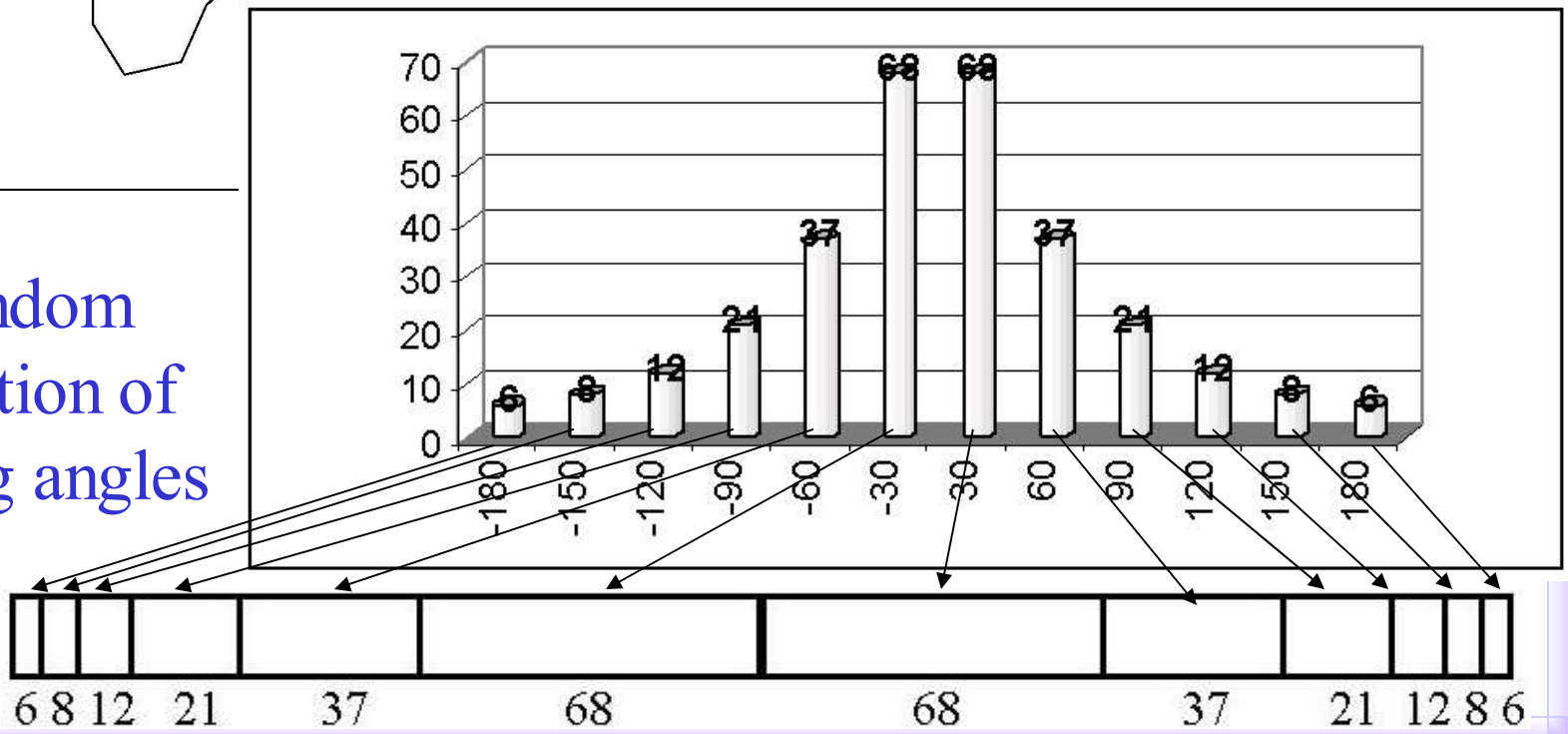
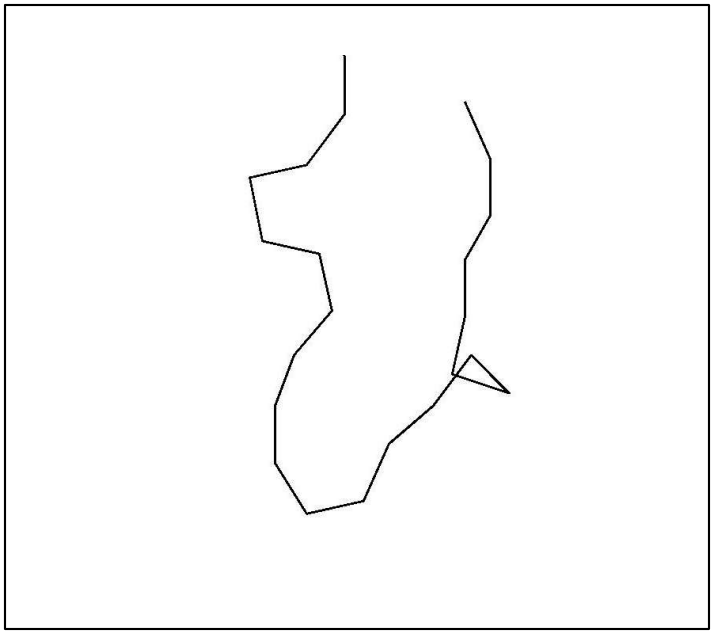


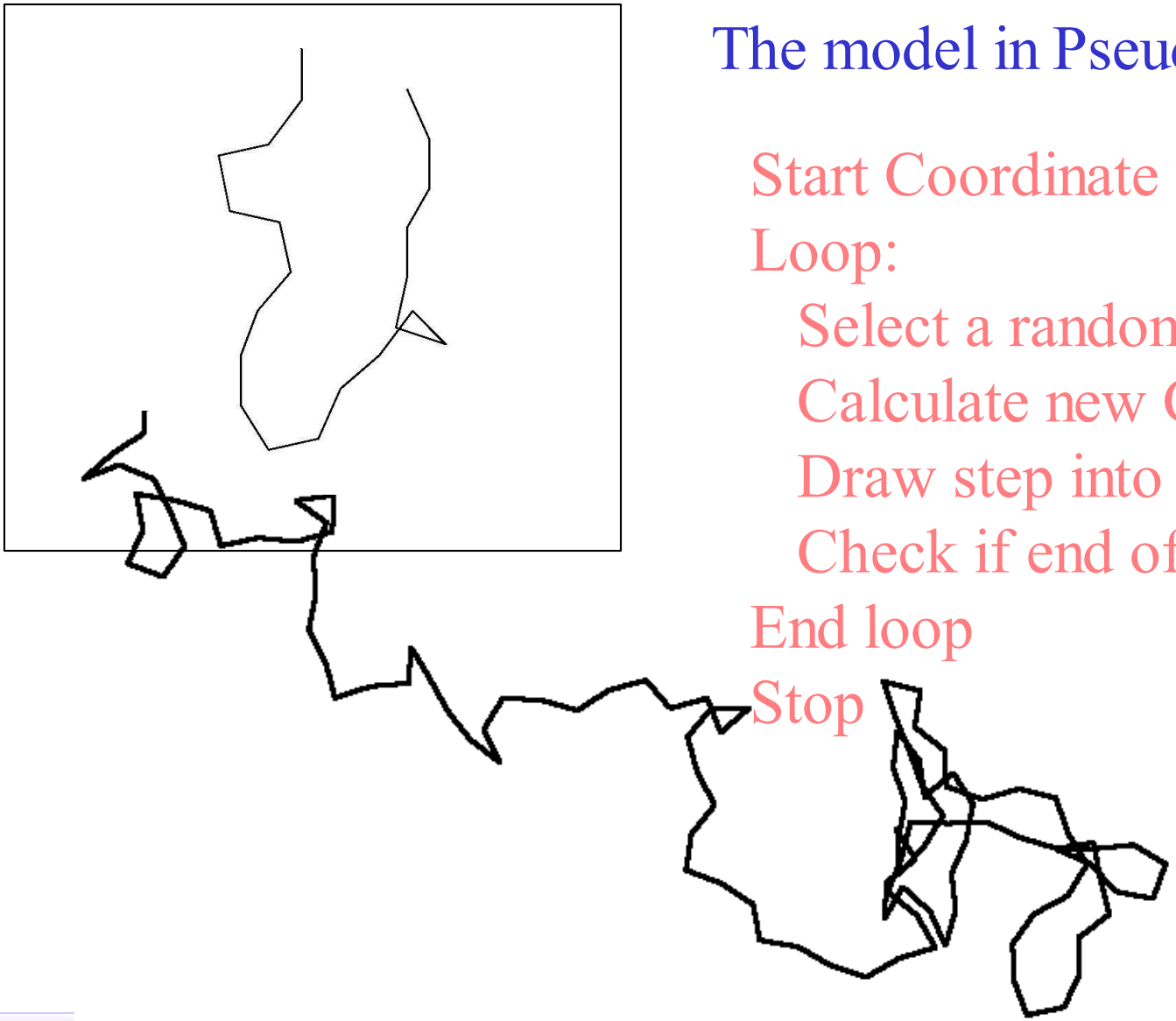
Snail Trail



The model in Pseudo-Code

Start Coordinate
Loop:
  Select a random angle
  Calculate new Coordinate
  Draw step into that direction
  Check if end of iteration
End loop
Stop

Snail Trail



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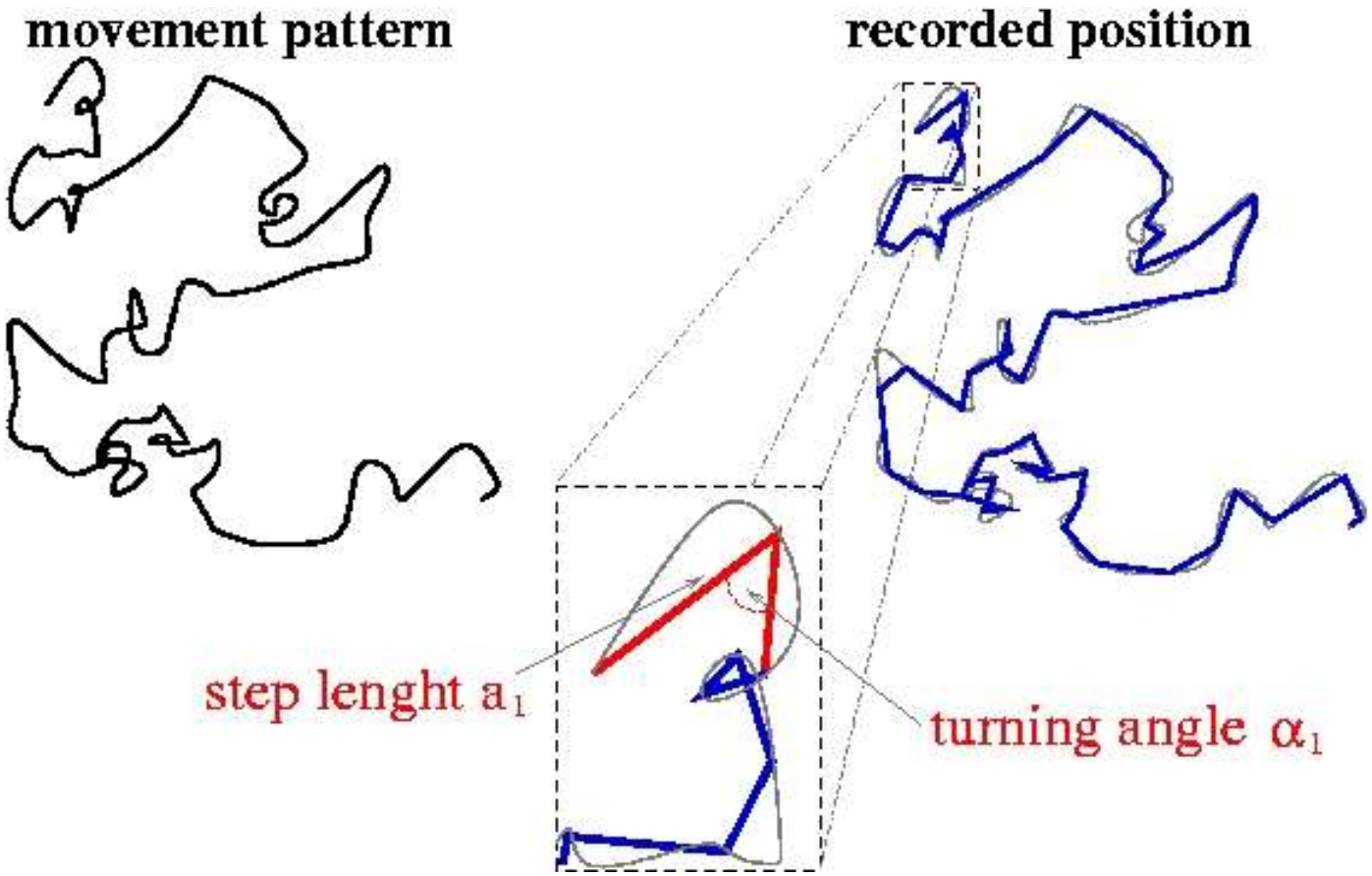


Rules to chose length and angle
are a general task for movement modelling

Theoretical aspects

Simple activities of single individuals can be modelled with conventional programming approaches using loop structures.

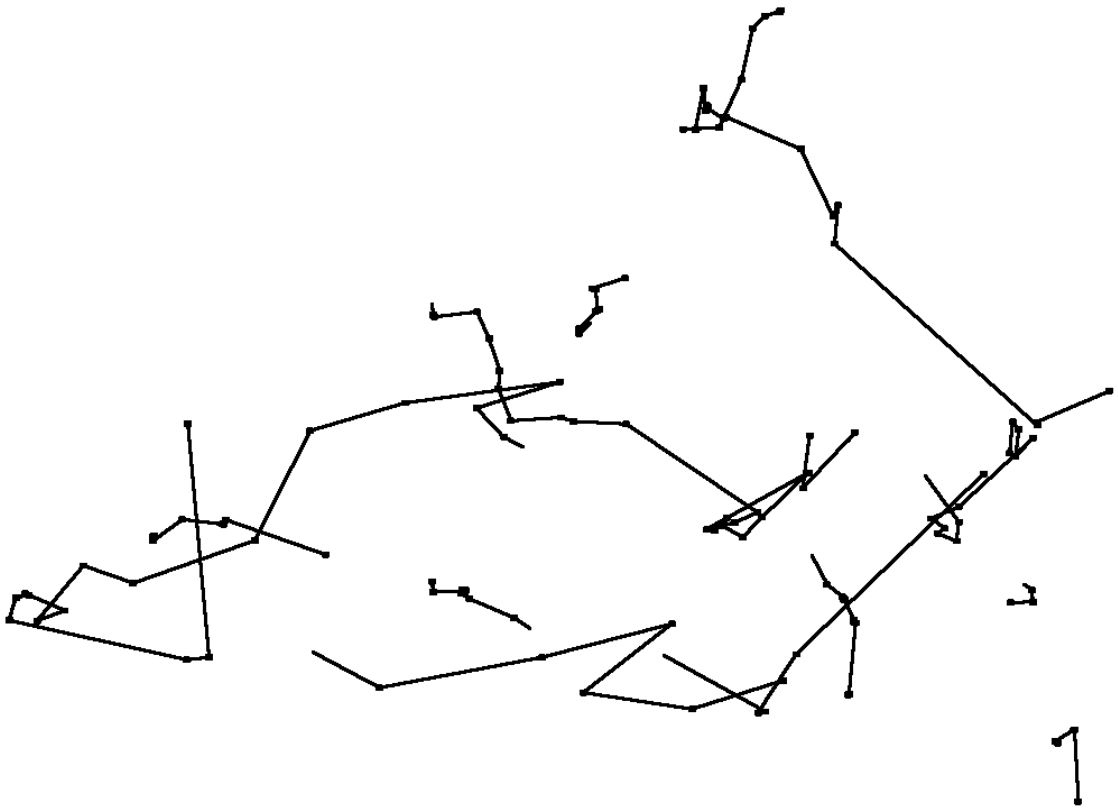
(Inter-)action of different individuals requires a quasi-parallel approach using object orientation.

Carabid Beetles

Carabus coriaceus

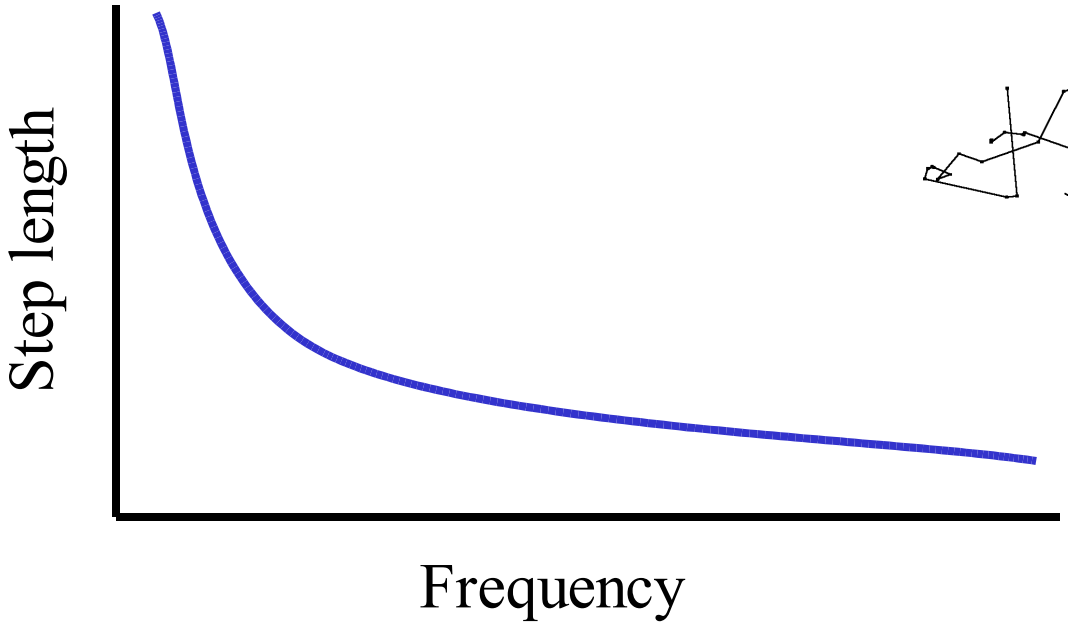
Carabus coriaceus http://www.berze-nagy.sulinet.hu/tanos/allatok/borfut.jpg

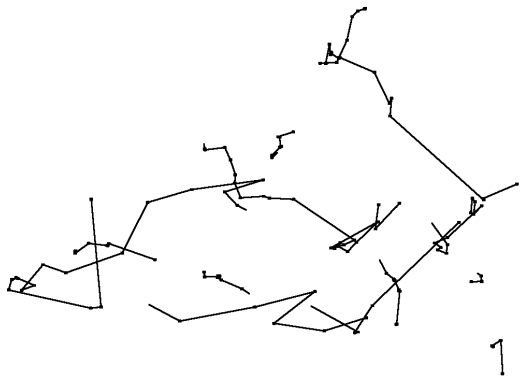
Carabid Beetles



Telemetrically recorded positions of different individuals

Carabid Beetles

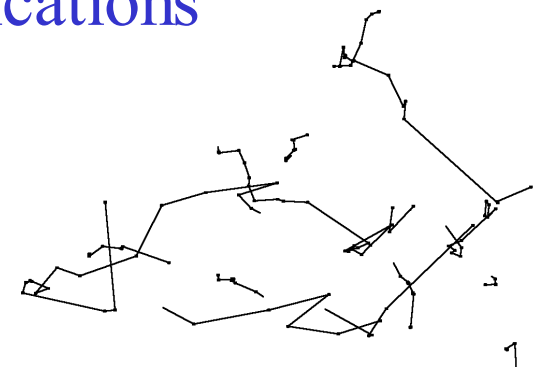


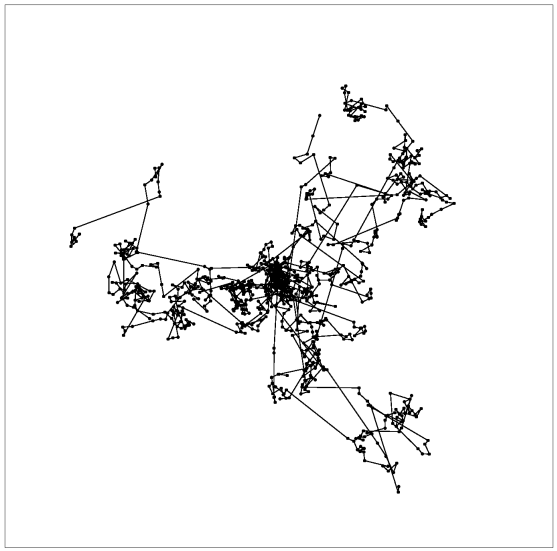


Angles: Random

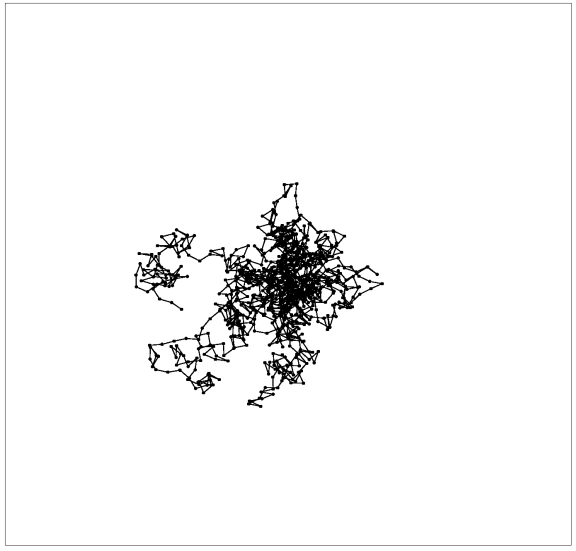
Step-length: Hyperbolic (Length and frequency are inversly related: large steps are rare, short steps are frequent)

Carabid Beetles
Estimating dispersal implications

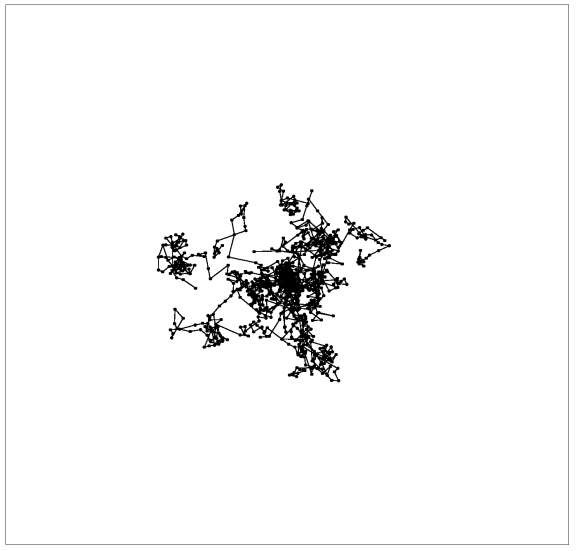




Standard hyperbolic model

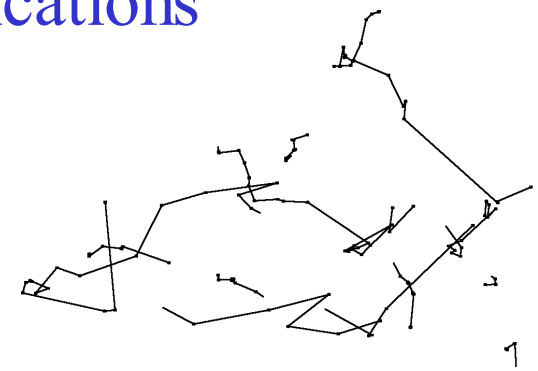


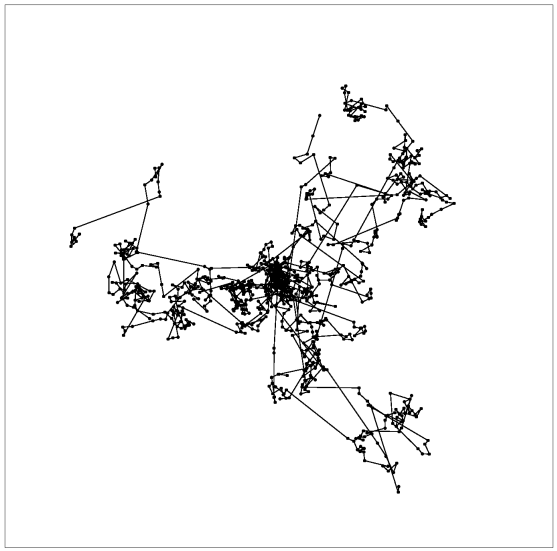
Average step length every day

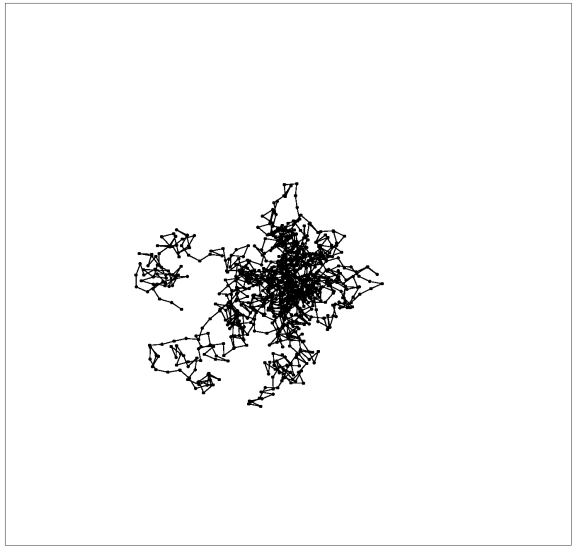


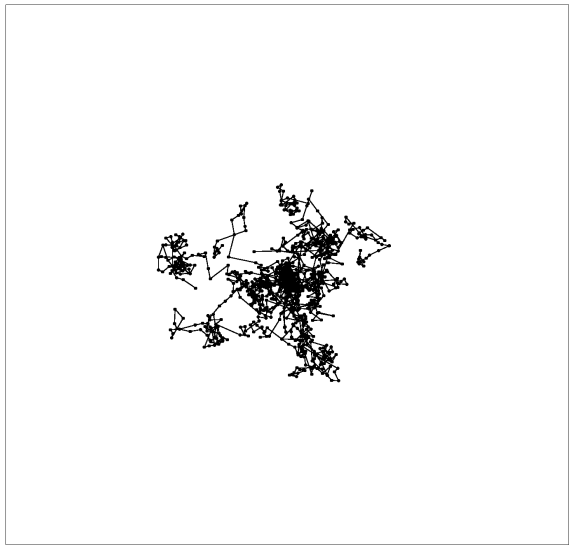
Omission of the largest 5% of steps

Carabid Beetles
Estimating dispersal implications



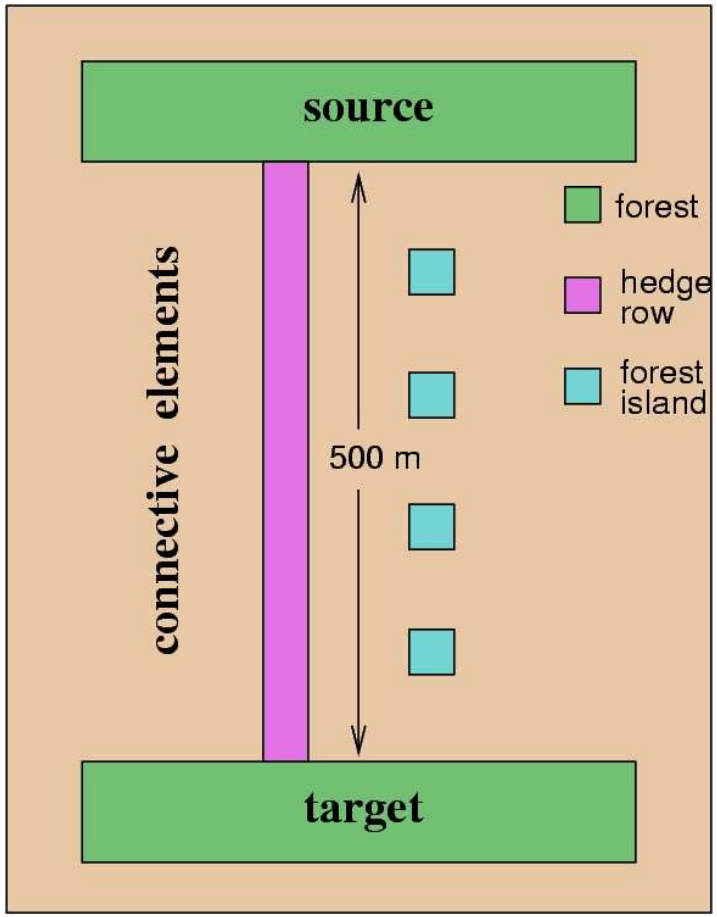






Conclusion: Rare events (large steps)
are important to explain dispersal distances

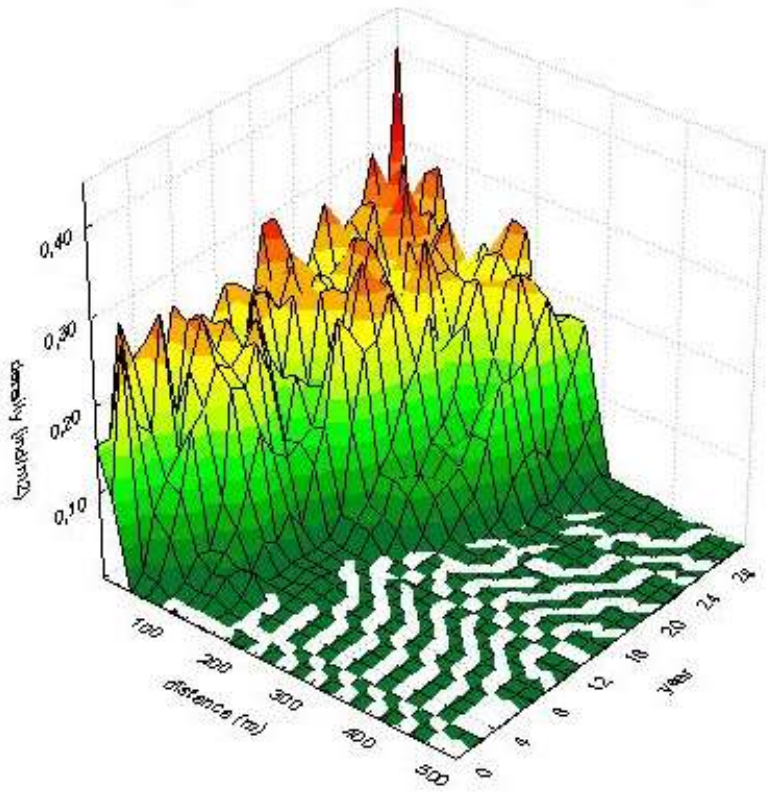
Dispersal of Carabids



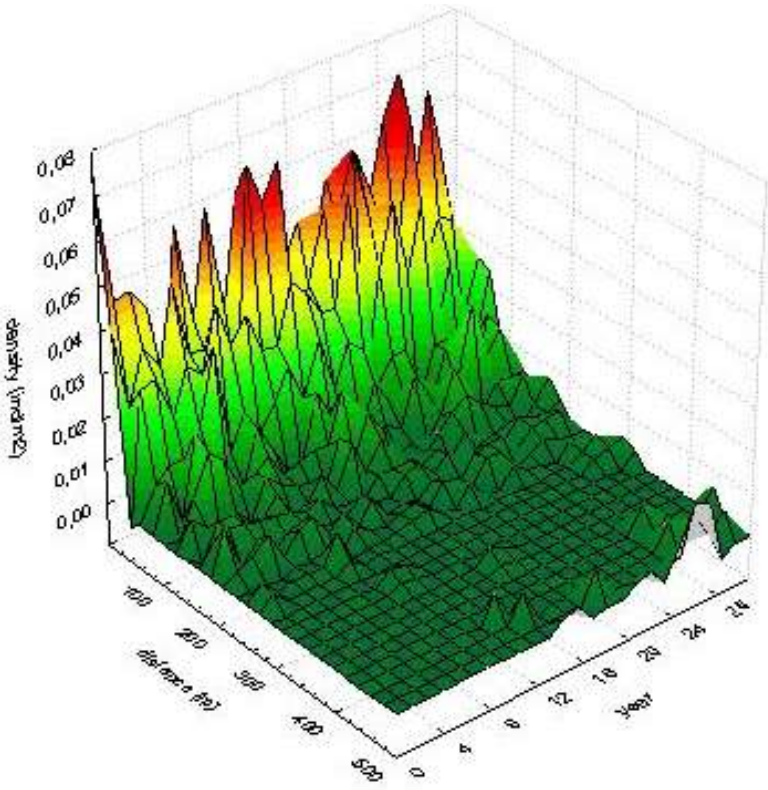
ECEM`04, Breckling et al.

Dispersal of Carabids

a) *Abax parallelepipedus*



b) *Carabus hortensis*

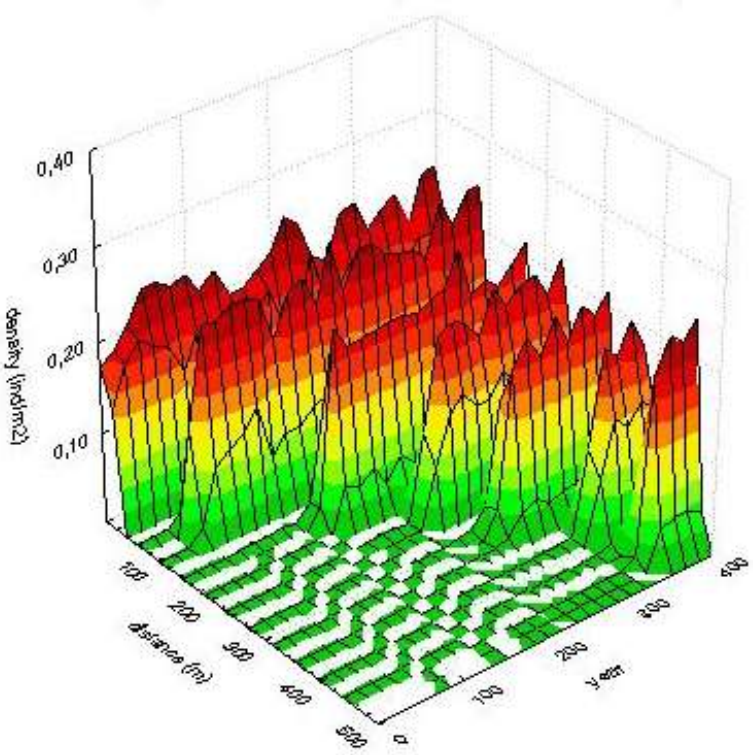


Dispersal in hedgerows

ECEM`04, Breckling et al.

Dispersal of Carabids

a) *Abax parallelepipedus*



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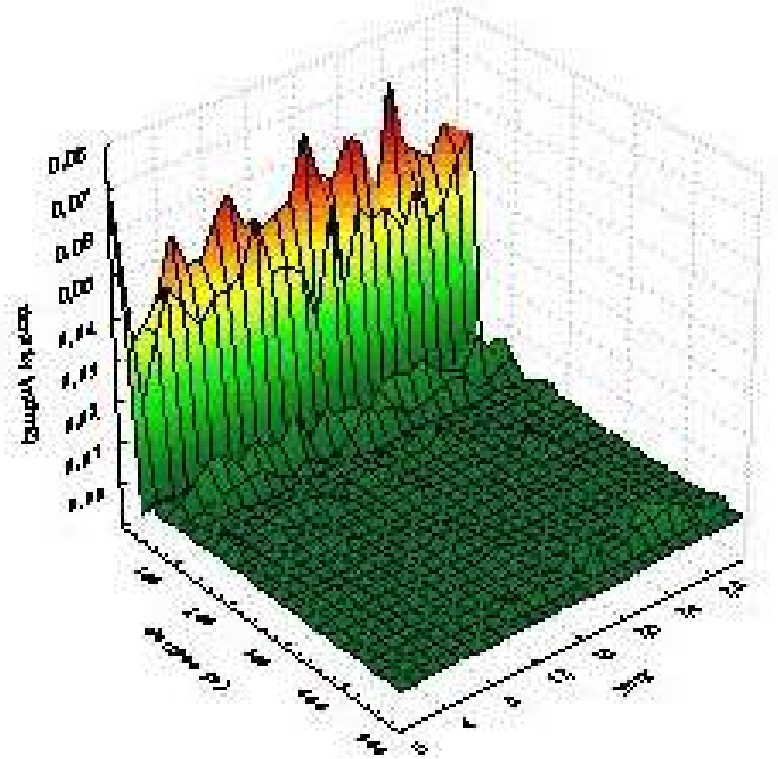
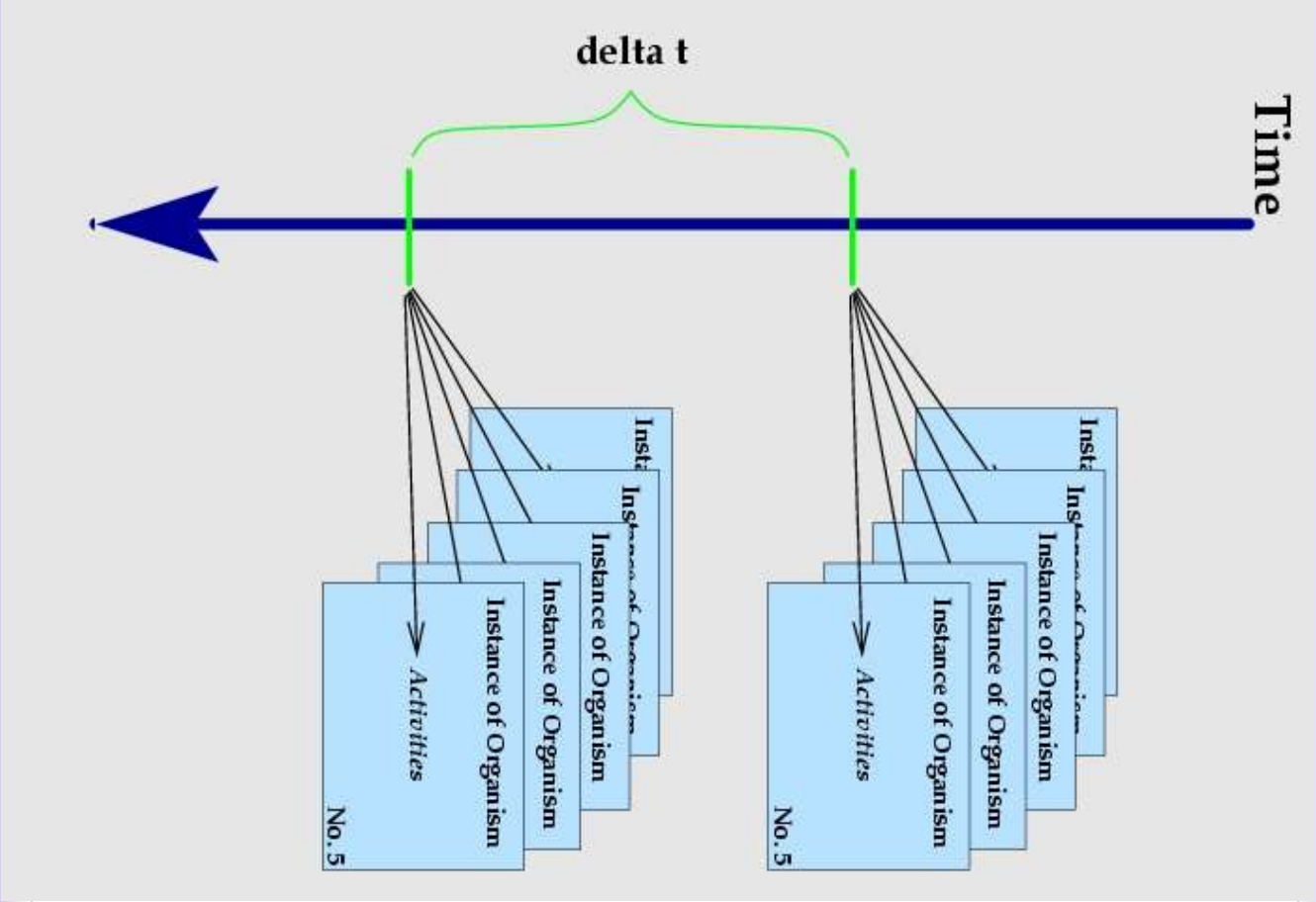


Dispersal on stepping stones

ECEM`04, Breckling et al.

Theoretical aspects



Periodic Event Scheduling:
Exogene organisation (top down)

More complex pattern:
Interactive movement: Schooling

Herring

Interactive movement: Schooling

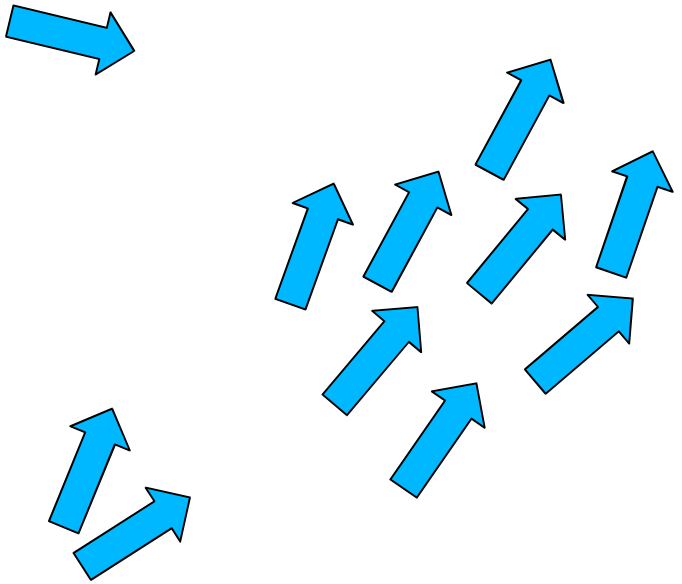
Clupea harengus

Clupea harengus http://www.aquarium-kiel.de/rundgang/heri2.jpg

Herring

Rules for schooling behaviour

- No leaders
- Attraction within visible range
- Parallel orientation within preferred swimming distance
- Repellence when too close



- Integrating all visible neighbours according to their distance

Adequate parametrisation leads to realistic school simulations.

Herring

We imagine a clumped dispersal of food particles
where individuals either slow down
or occasionally swith to random directions

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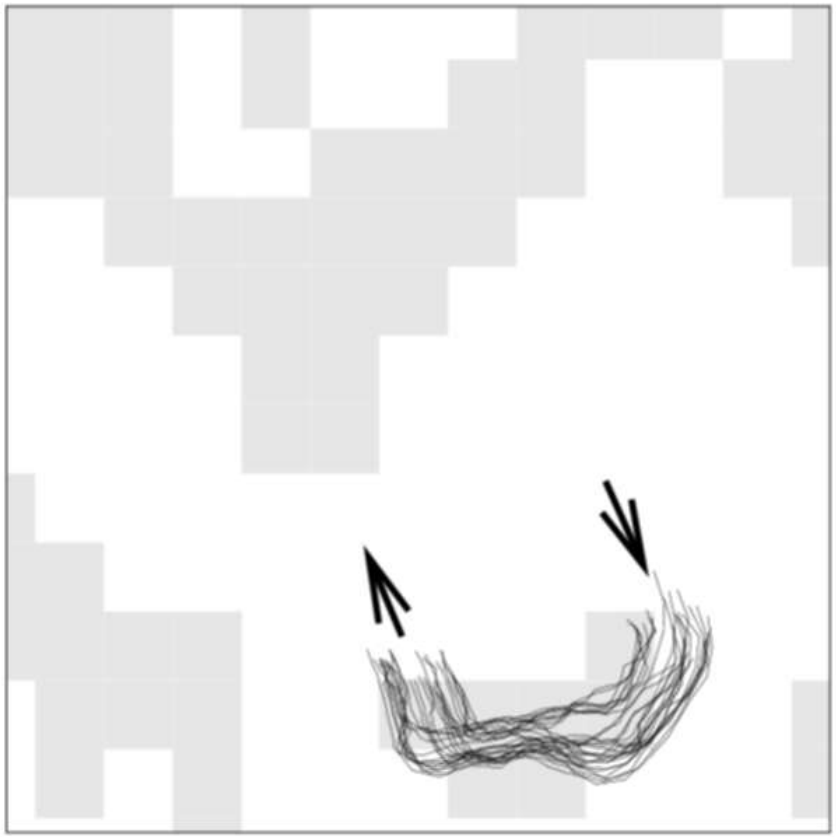

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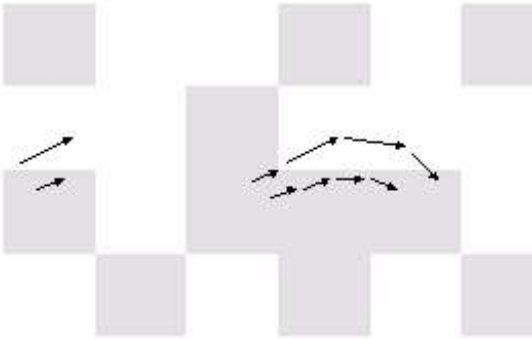
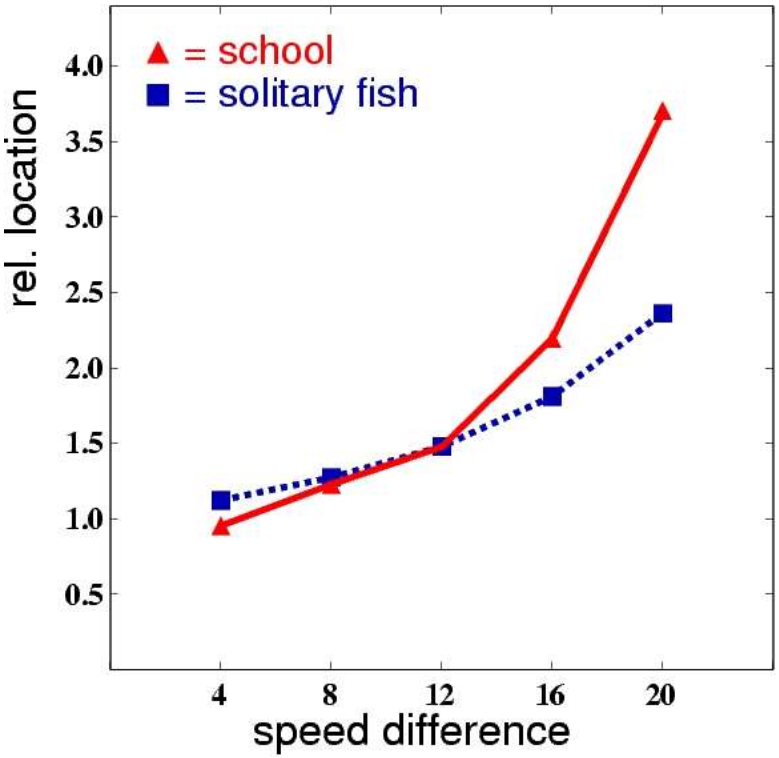
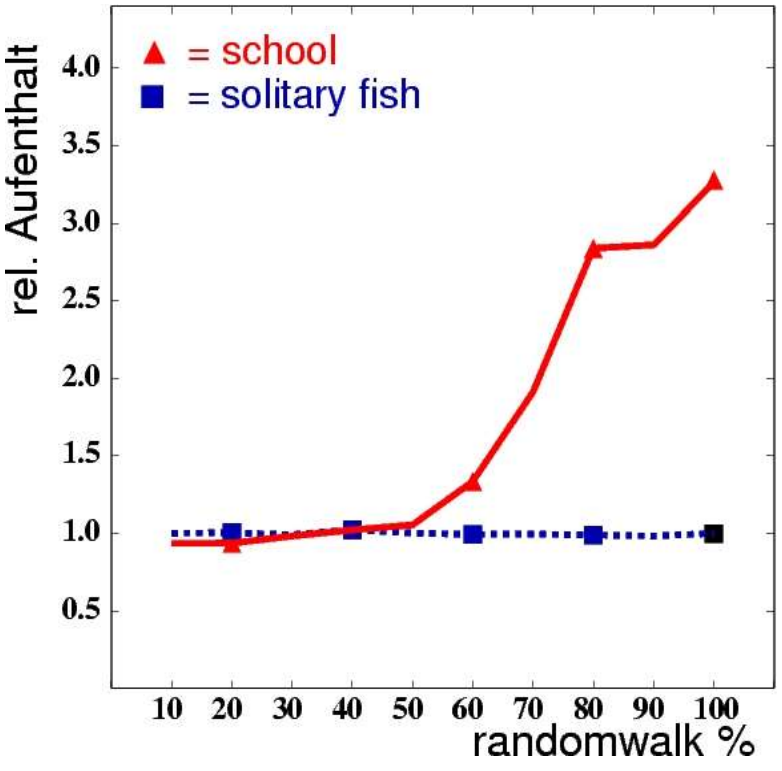


Herring

Quantitative evaluation of schooling search compared to solitary search





Herring

Emergent property:

In a food gradient the school orients towards increased food densities

The school as a higher level entity acquires a propery that each single individual does not have.

Roach

A more detailed fish model

Rutilus rutilus

Rutilus rutilus http://www. agrino.org/fishing/ photos/freshfish/roach.jpg

Roach

A more detailed fish model

ROACH -
Scientific name: *Rutilus rutilus*
Common size: 15-22 cm, weight: 100-250 gr
Fishing season: Any time of the year
Bait: Corn, flour, boiled potato etc
Hook size: No. 14-12 Line: 0.12-0.15 mm
Prefers shallow water with rocky or sandy bed.

One of the most frequent fish in smaller freshwater lakes in Germany

Rutilus rutilus http://www. agrino.org/fishing/ photos/freshfish/roach.jpg

Roach

A more realistic fish model

Empirical model basis:

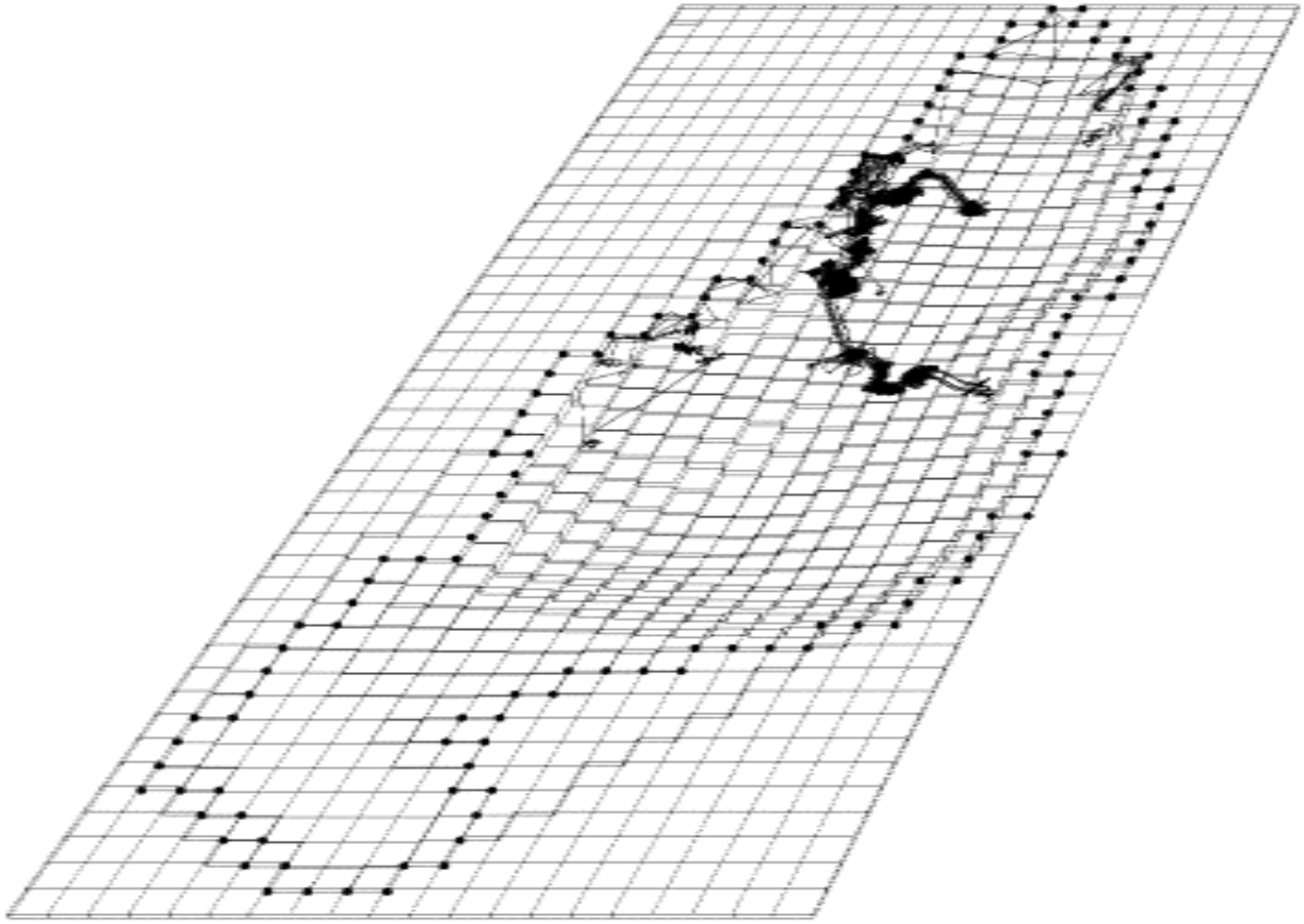
- Laboratory studies on energy assimilation
- Distribution studies in the lake
- Growth curves
- food density
- temperature and other limnic parameter

One of the most frequent fish in smaller freshwater lakes in Germany

Rutilus rutilus http://www. agrino.org/fishing/ photos/freshfish/roach.jpg

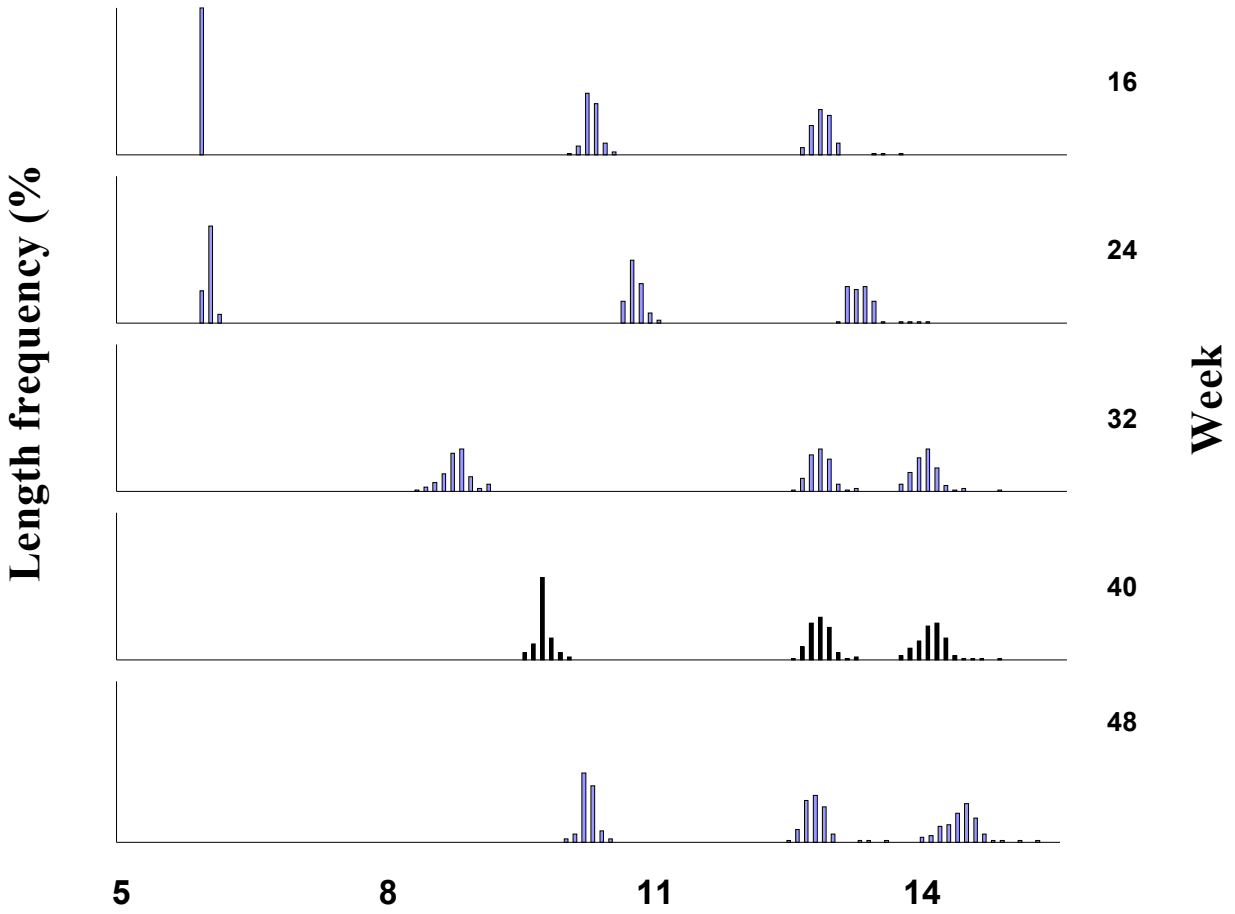
Roach

In Lake Belau (Schleswig Holstein)



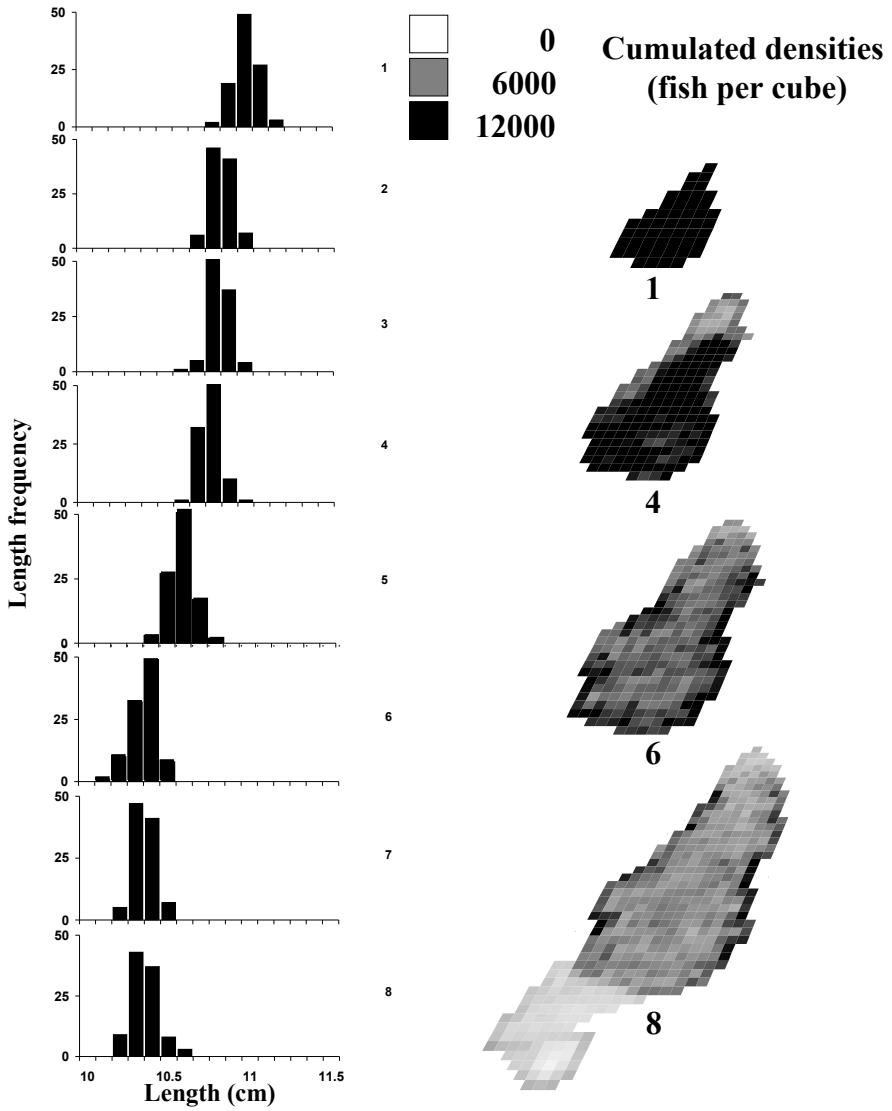
Traces of 30 individuals

Roach



Simulated cohort development over 3 years

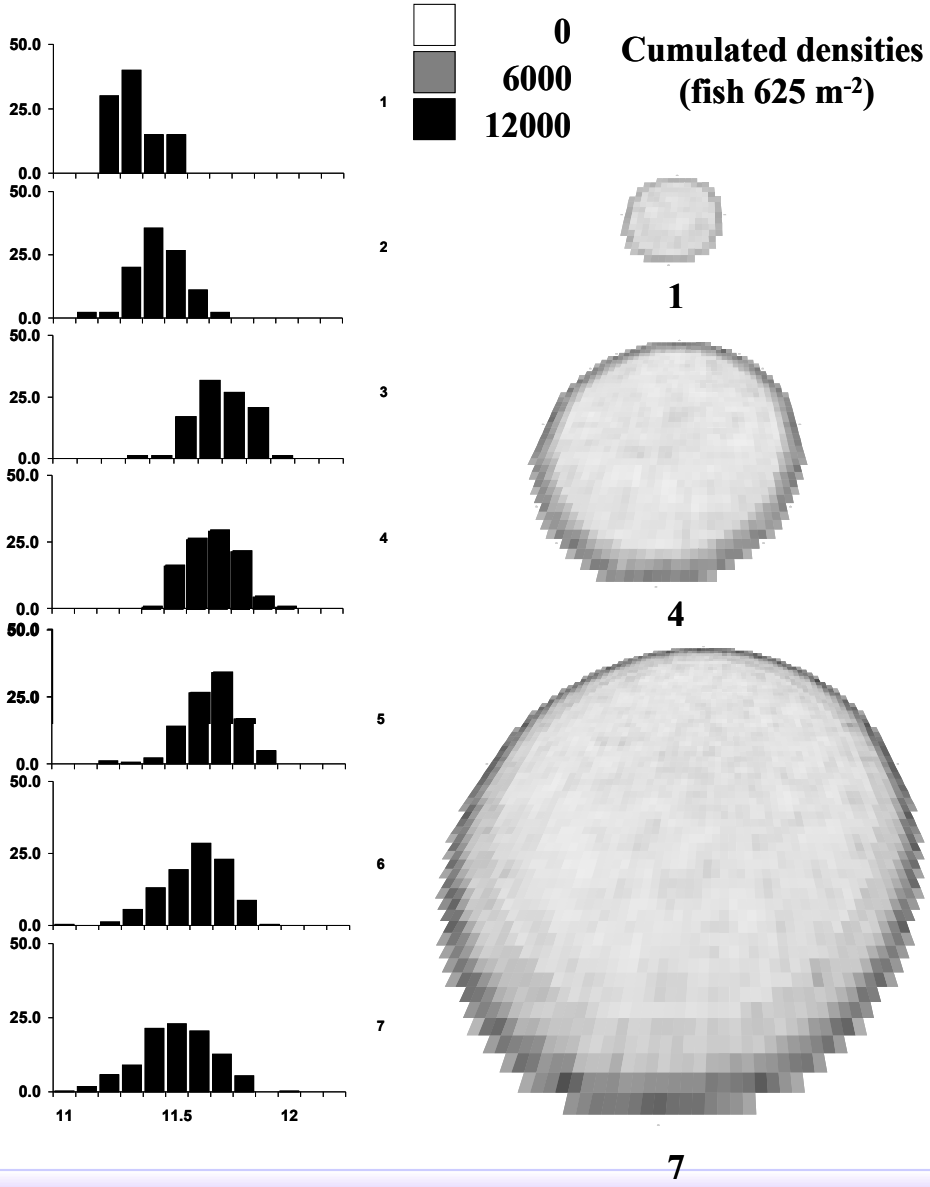
Roach



If-Then relationships in imaginary lakes

ECEM'04, Breckling et al.

Roach

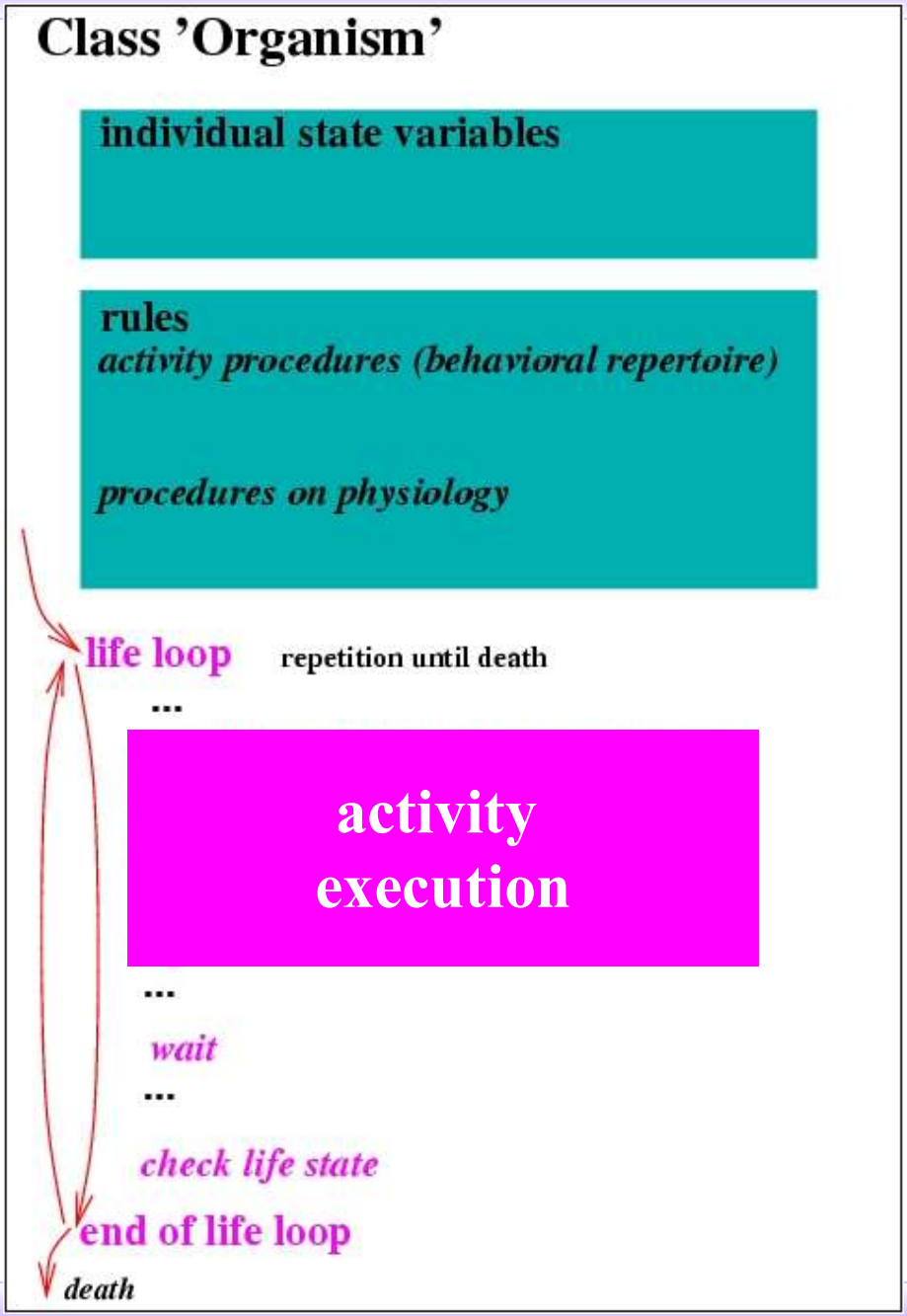


If-Then relationships in imaginary lakes

(constant proportion of 30 % littoral)

ECEM'04, Breckling et al.

Elements of the Class 'Organism'



Rodents

Complex population dynamics

Microtus agrestis

Clethrionomys glareolus
(Bank vole)

Microtus agrestis http://www.biologie.uni-osnabrueck.de/Ethologie/bilder/small_mam/arvicolidae/microtus_agrestis1.jpg

Clethrionomys glareolus (Bank vole) http://212.187.155.84/pass_06june/Subdirectories_for_Search/SpeciesKingdoms/0Families_ACrM_Rodentia/Muridae/Clethrionomys/Clethrionomys_glareolus/Images/Clethrionomys_glareolus_DT.jpg

Rodents
Complex population dynamics

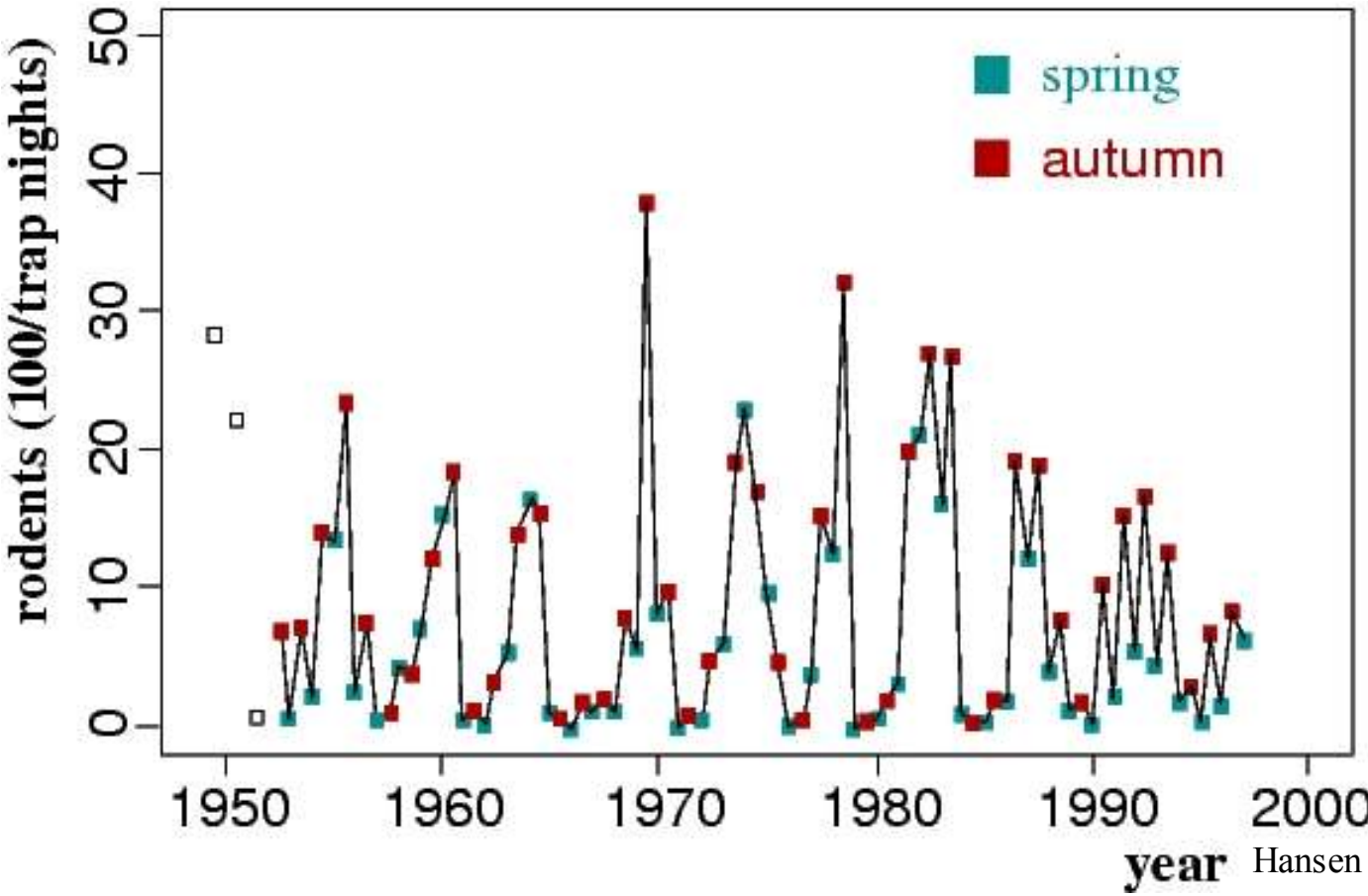
Cyclic Population outbreaks
depending on

- Environmental structure
- Food availibility
- Physiological properties
- Predators
- ...

Top down or bottom up control
of cycles?

Rodents

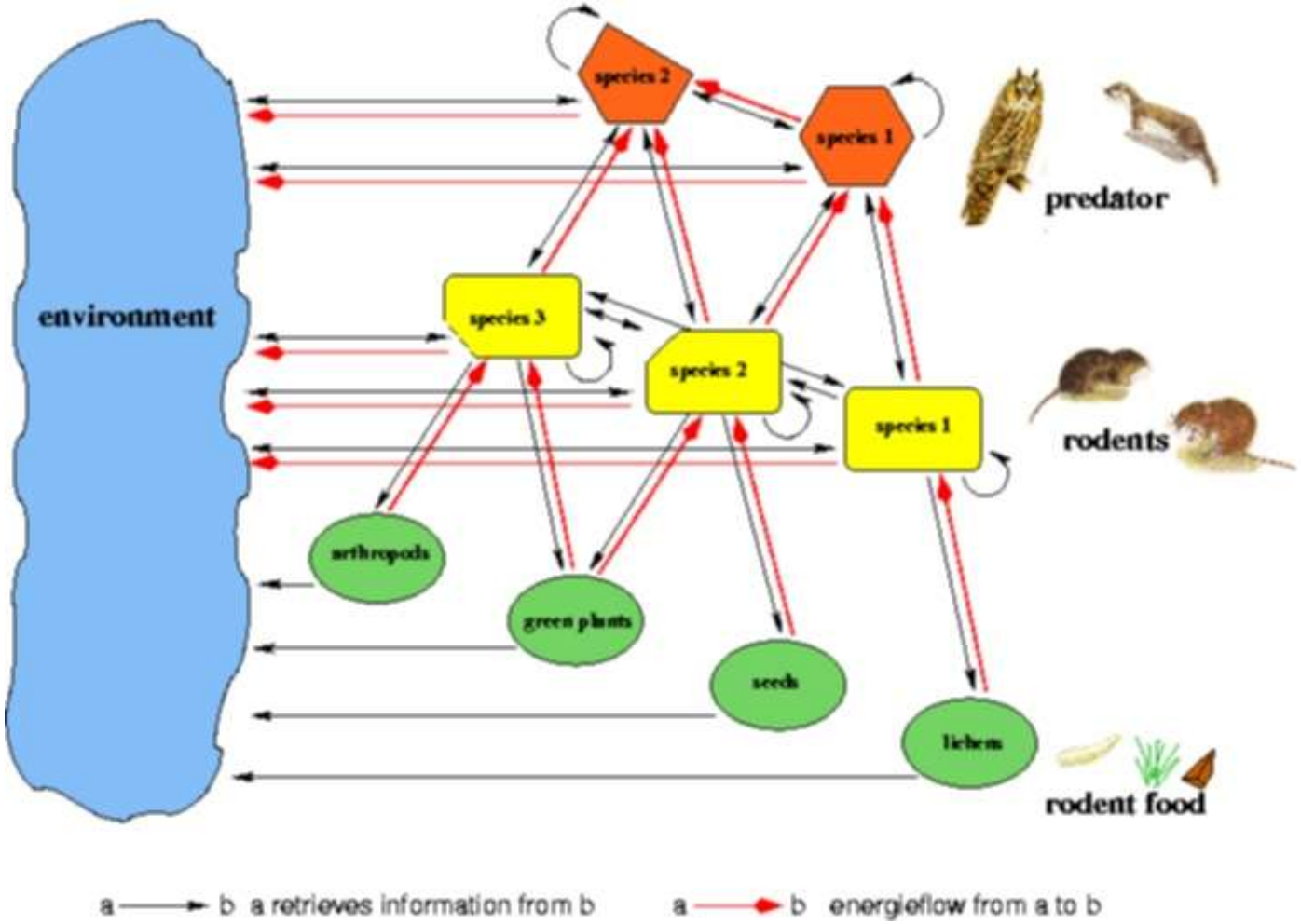
Measured population densities



Hansen et al. 1999

Oscillations of rodent abundances in Scandinavia

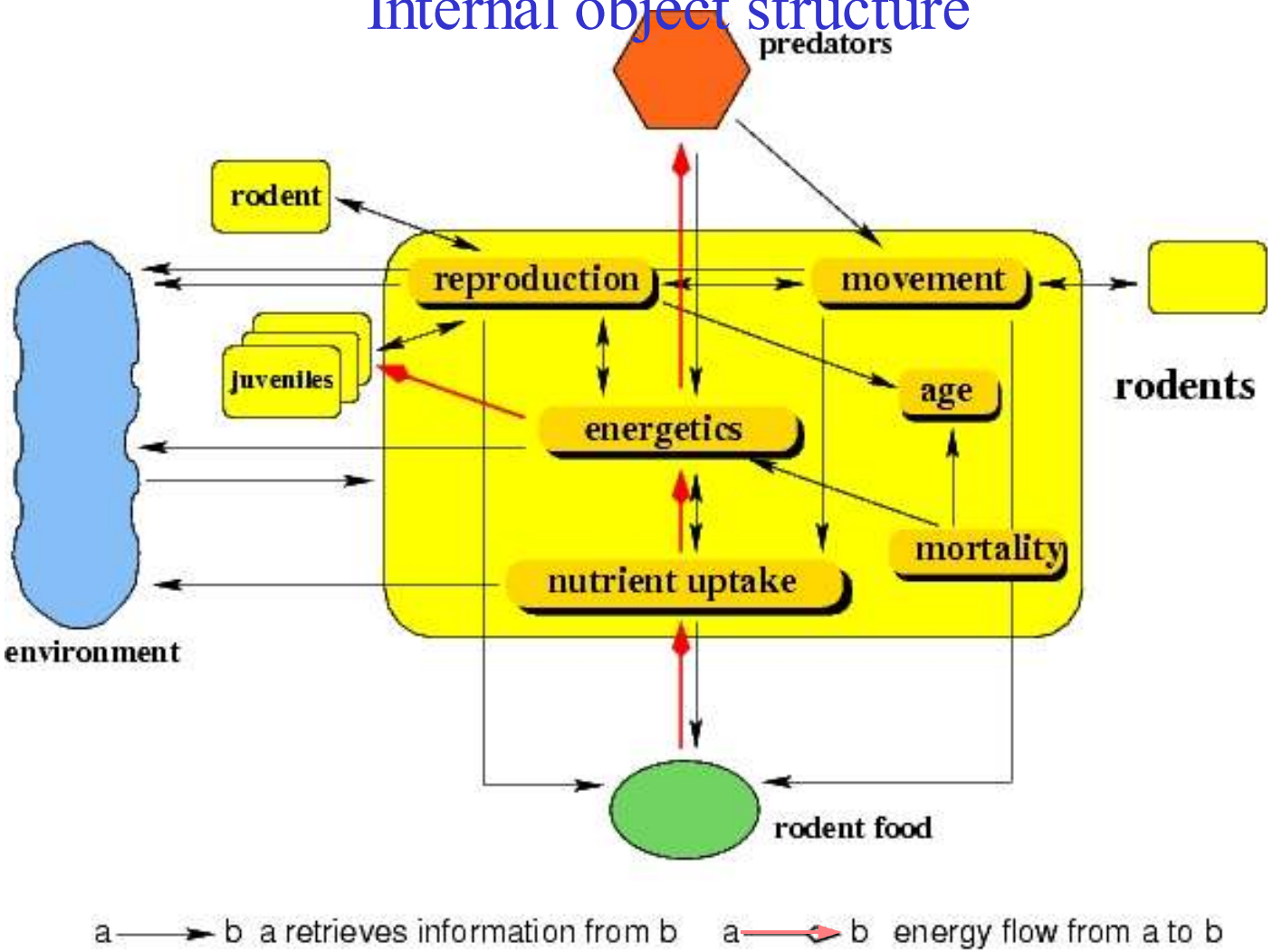
Rodents
Food web



Main Components of the rodent community model

Rodents

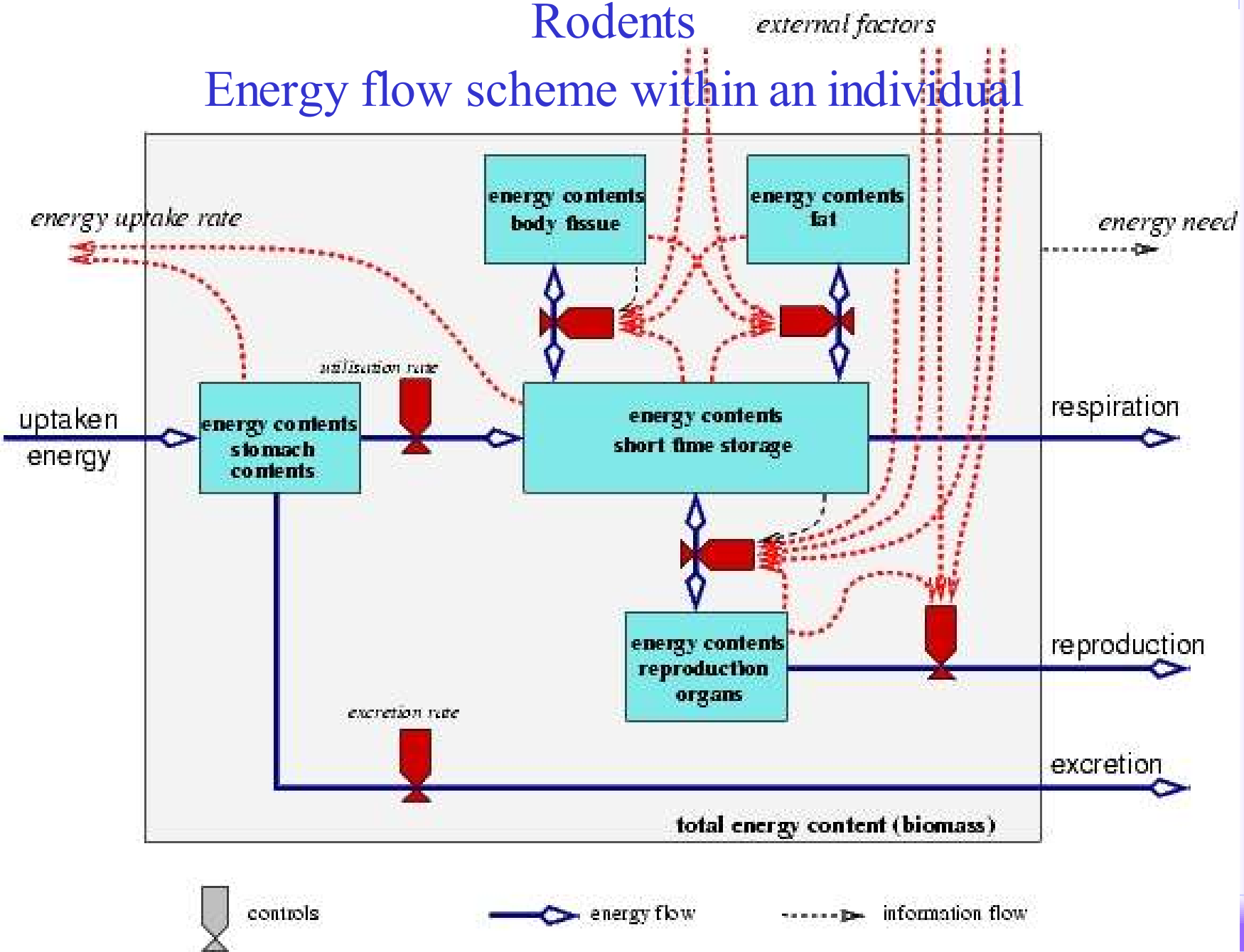
Internal object structure



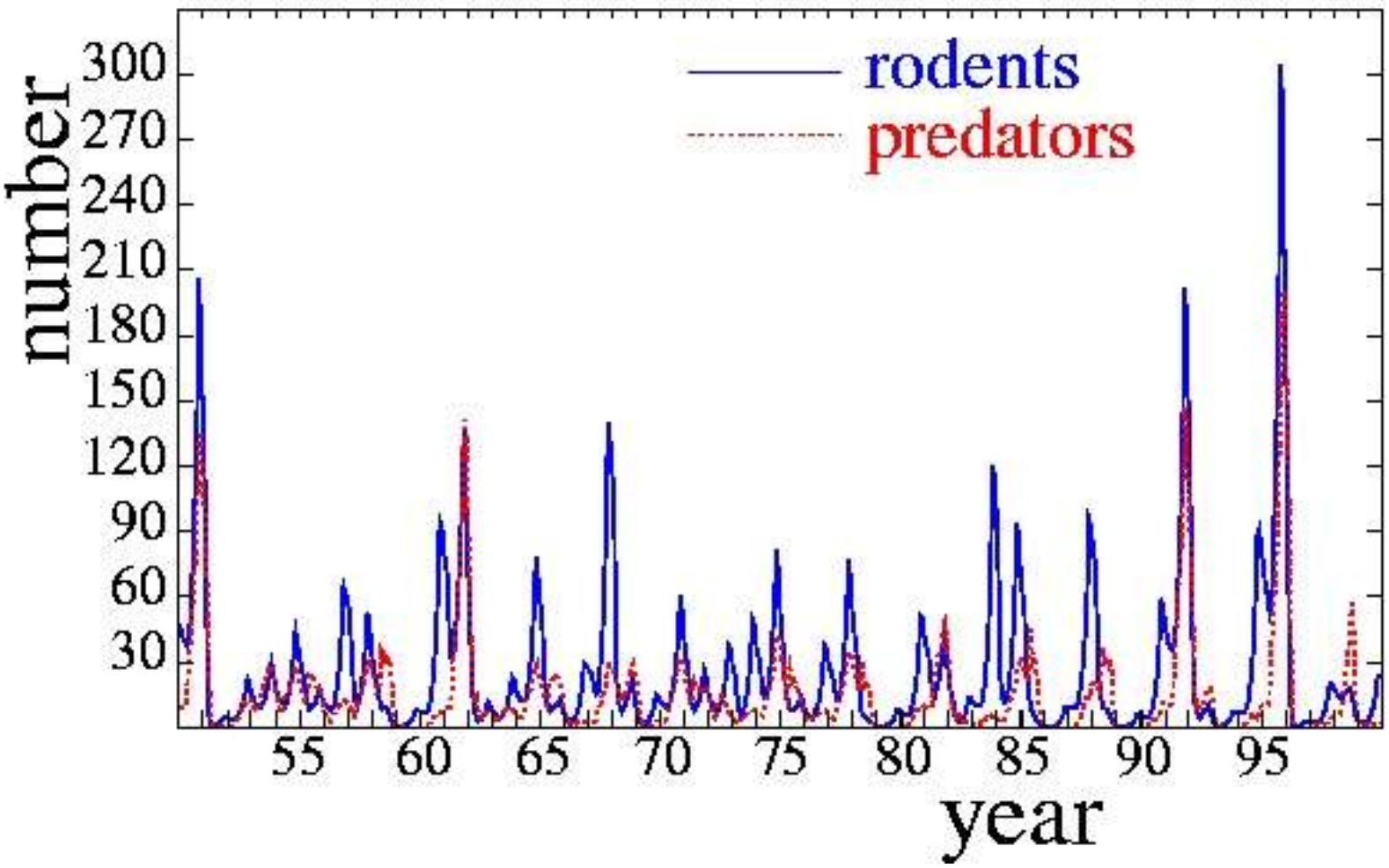
Main Components and interactions of the rodents

Rodents

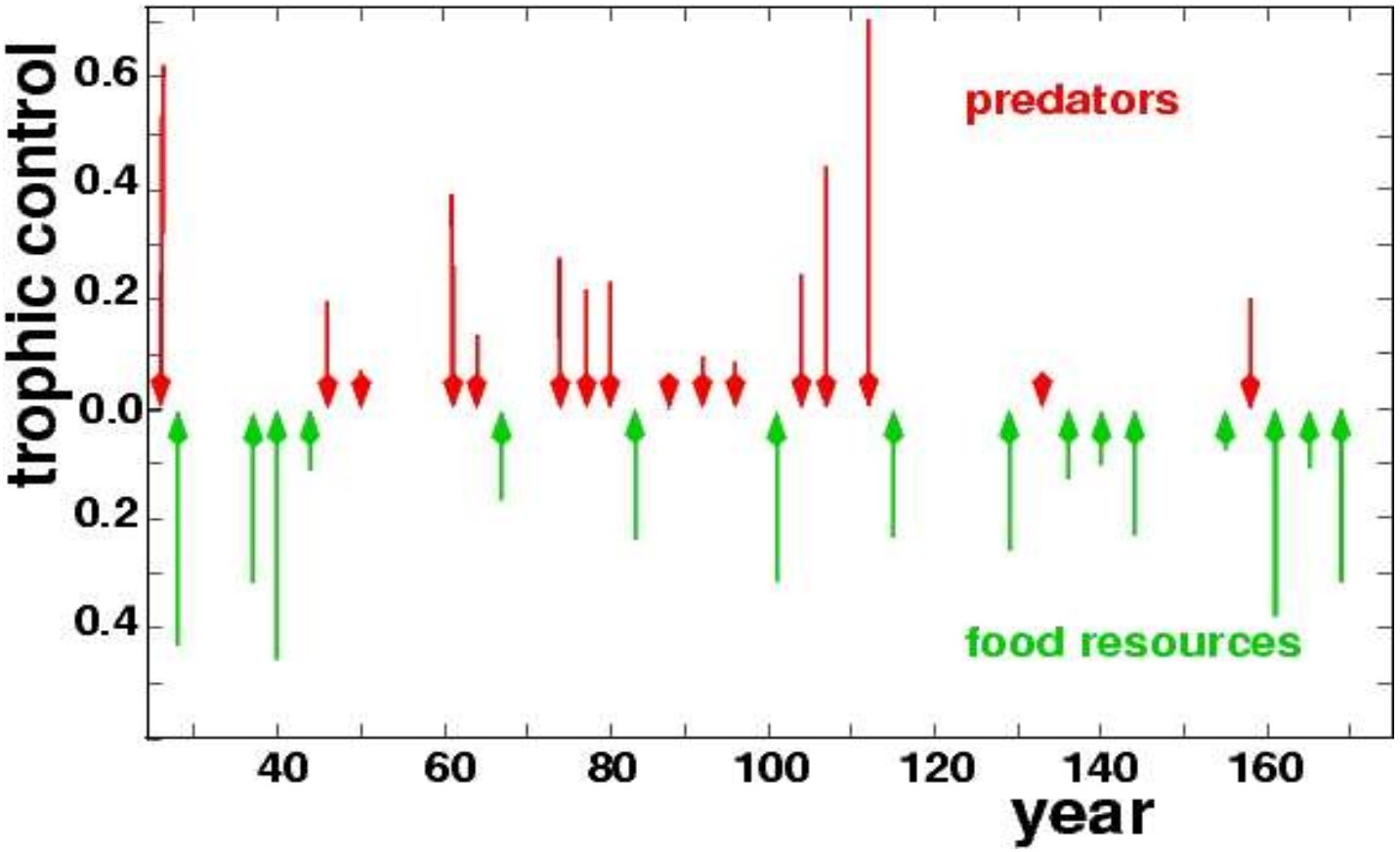
Energy flow scheme within an individual



Rodents
Simulated Population dynamics



Rodents
Trophic Control

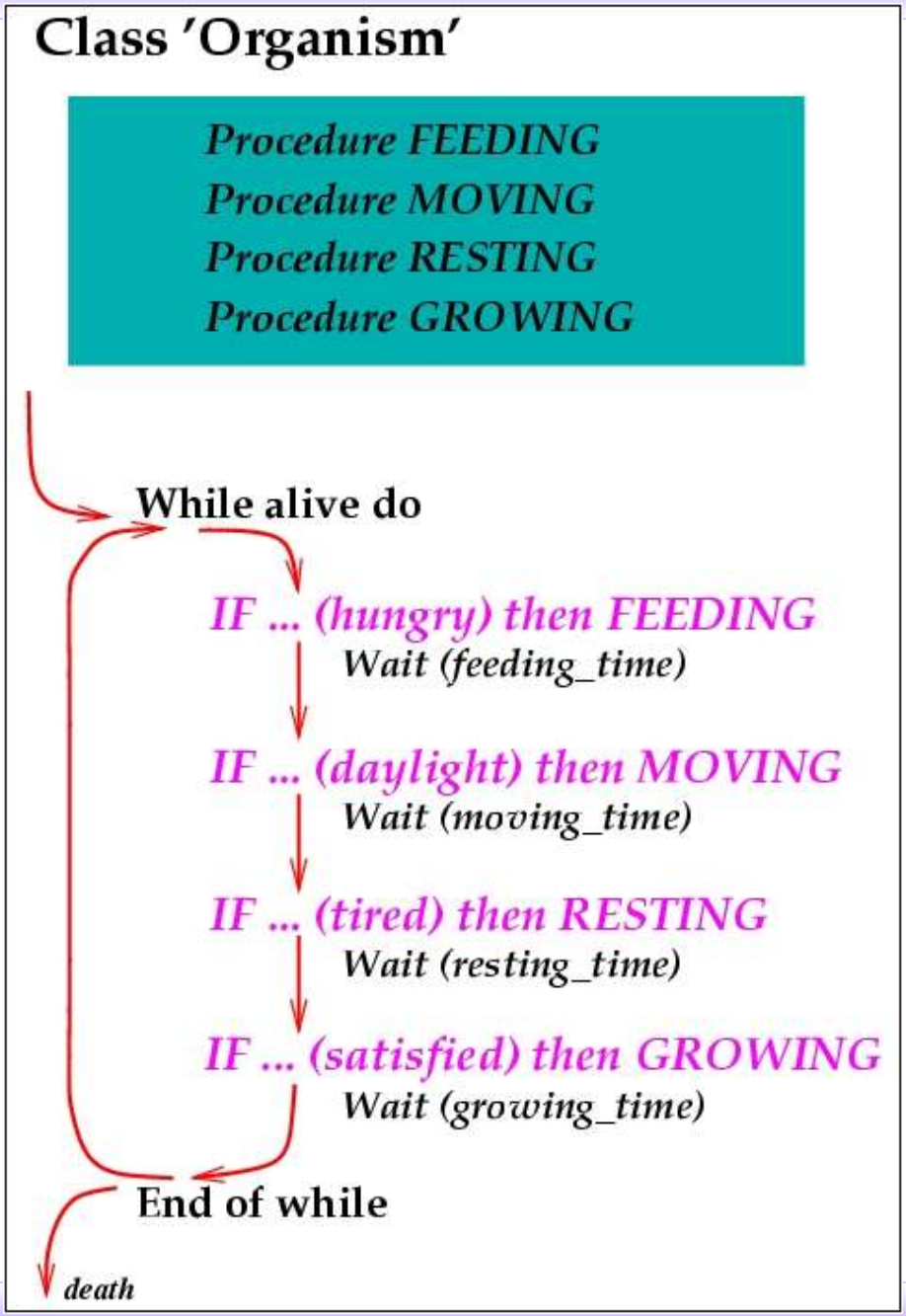


Top down

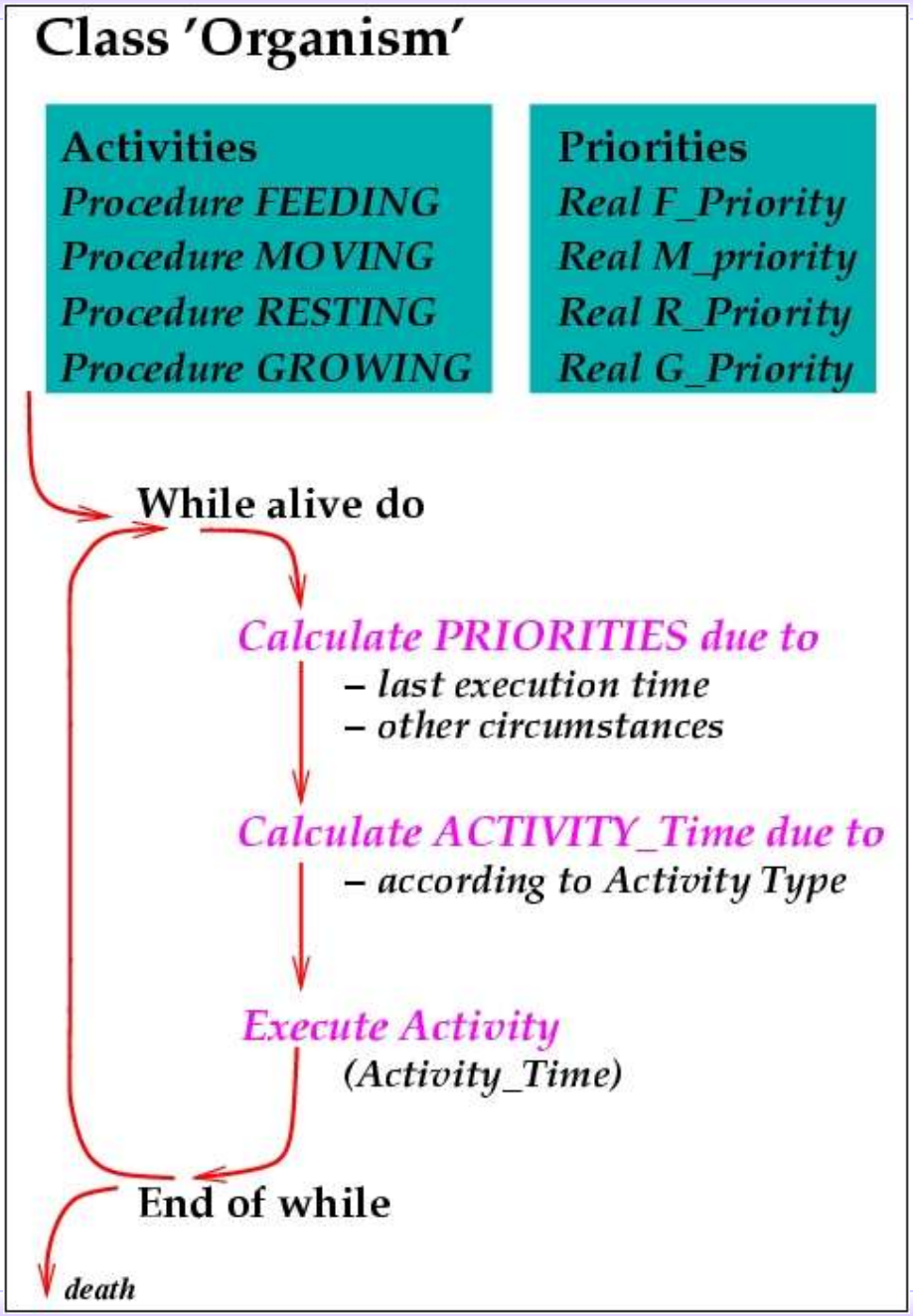
Bottom up

ECEM'04, Breckling et al.

Cyclic Activity Control



Priority Driven Activity Control



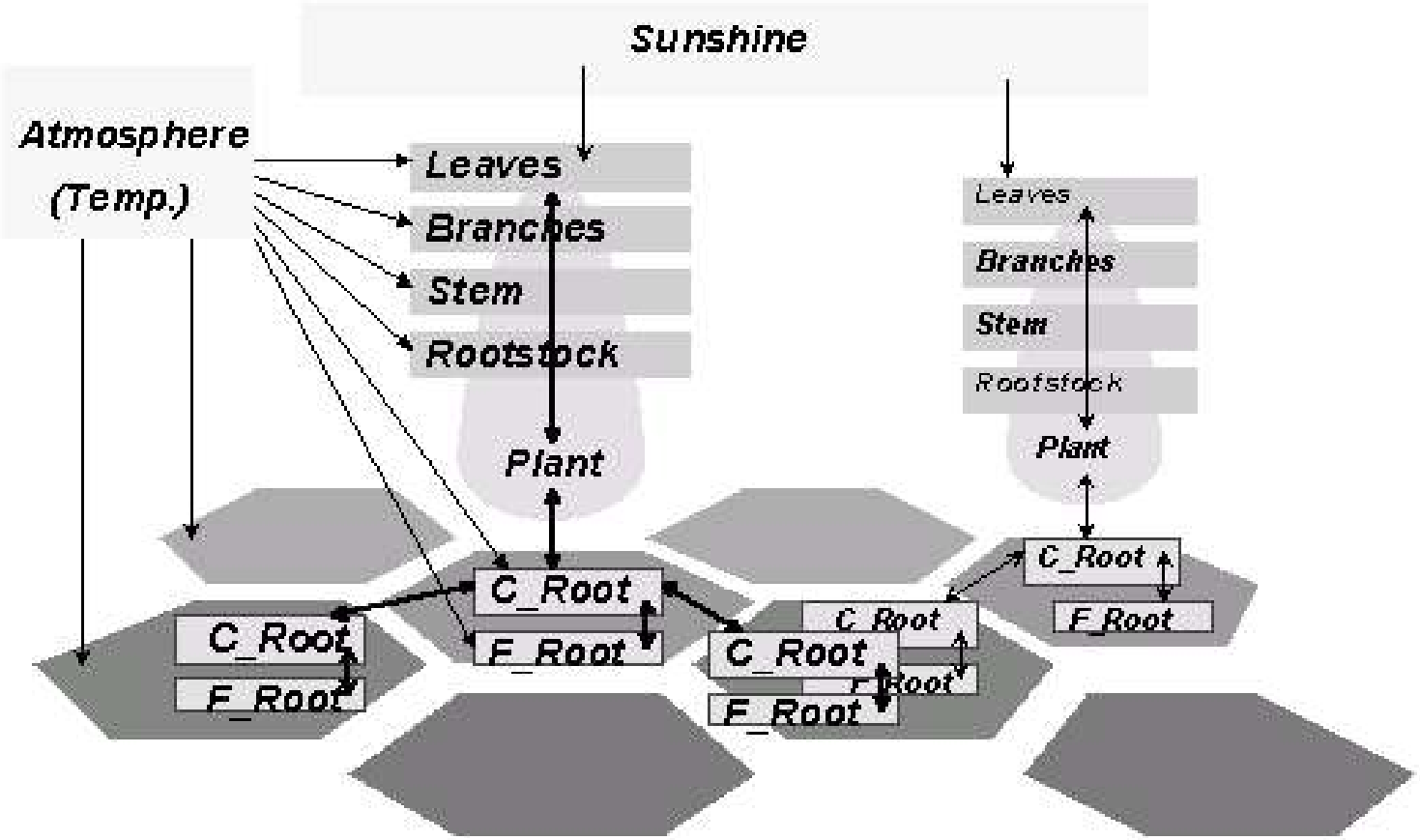
Alder

Combined Functional - Architectural Plant modelling

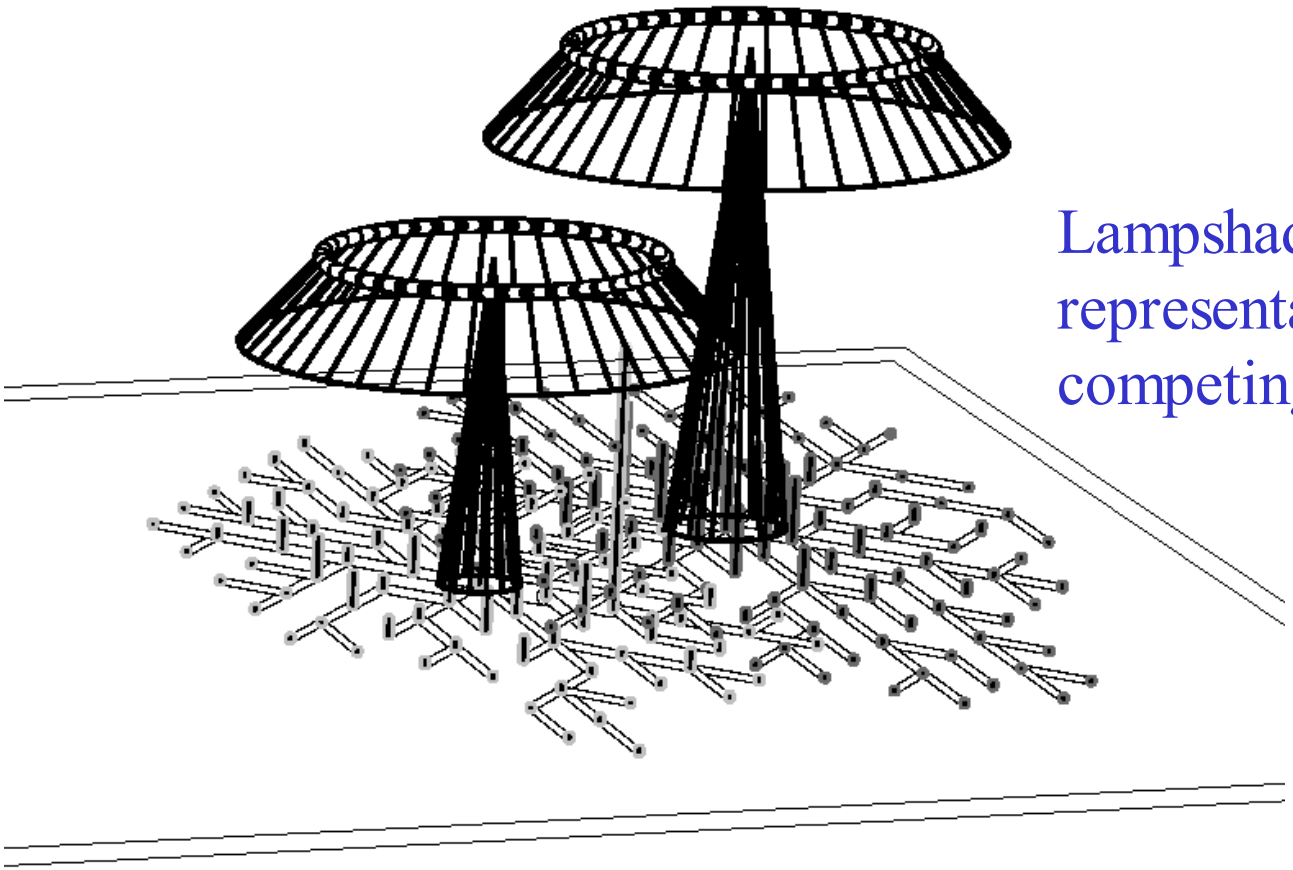
Alnus glutinosa

Alnus glutinosa http://www.shee-eire.com/Herbs,Trees&Fungi/Trees/Alder/Photos/alder-002.jpg

Alder Roots

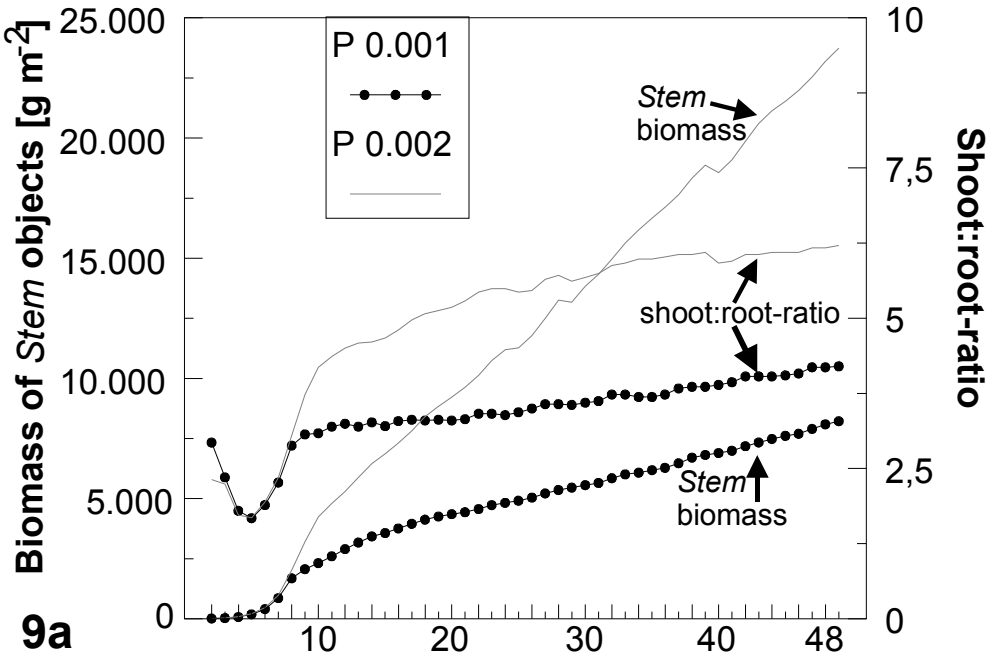

Sunshine
Atmosphere
(Temp.)
Leaves
Branches
Stem
Rootstock
Plant
Leaves
Branches
Stem
Rootstock
Plant
C_Root
F_Root
C_Root
F_Root
C_Root
F_Root
C_Root
F_Root
C_Root
F_Root

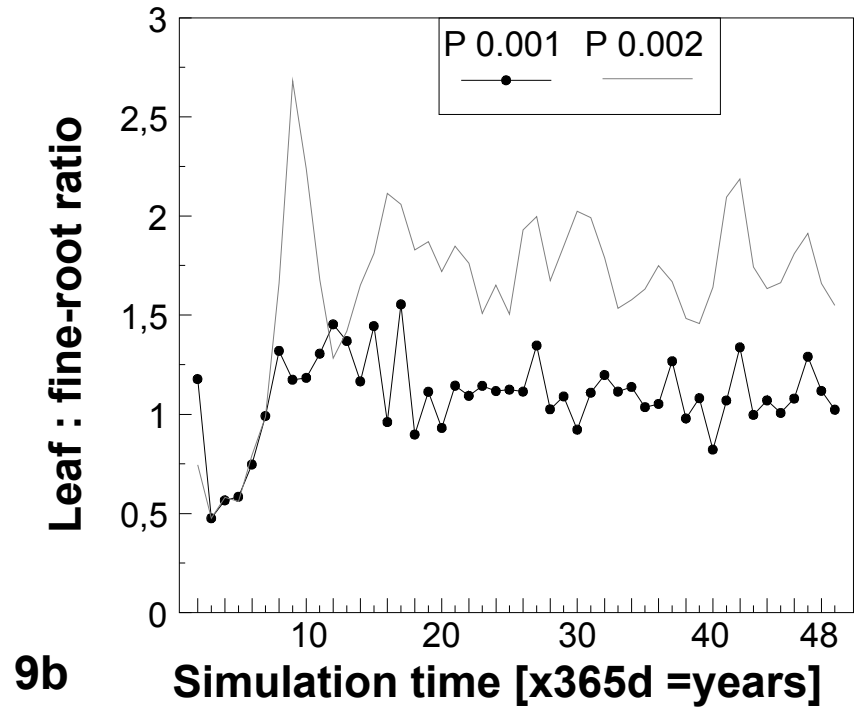
Alder Roots

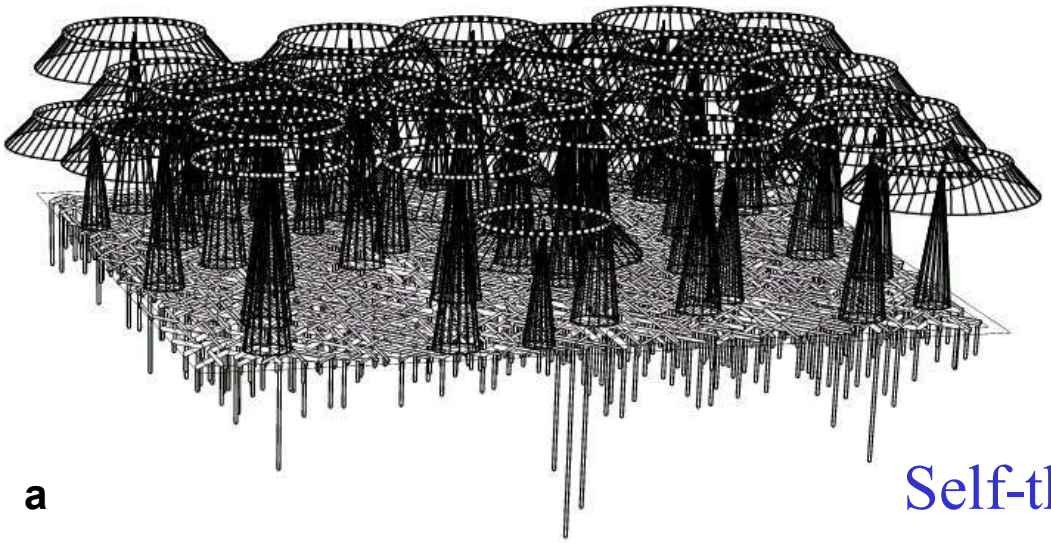


Lampshade representation of competing trees

Development of tree compartments

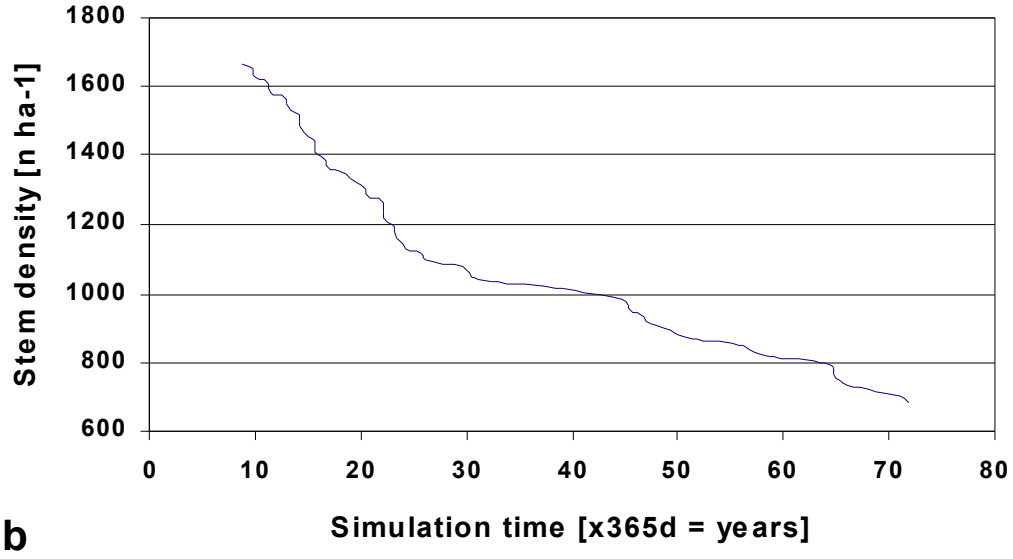






a

Self-thinning



b

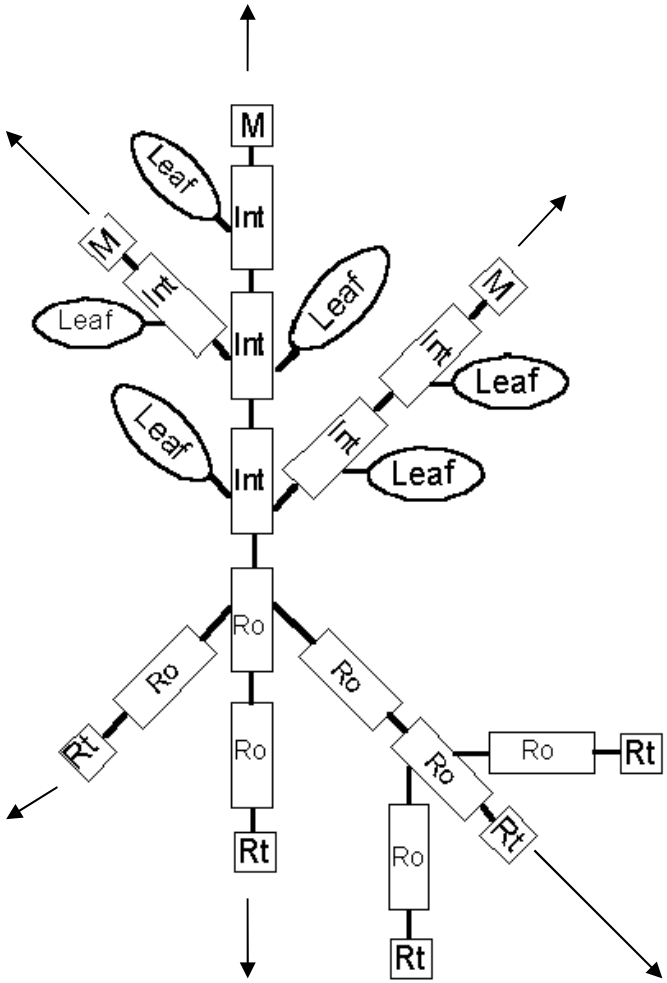
Alder

Combined Functional - Architectural Plant modelling

Alnus glutinosa

http://www.shee-eire.com/Herbs,Trees&Fungi/Trees/Alder/Photos/alder-001.jpg

Model Example: Object Oriented Plant Simulation

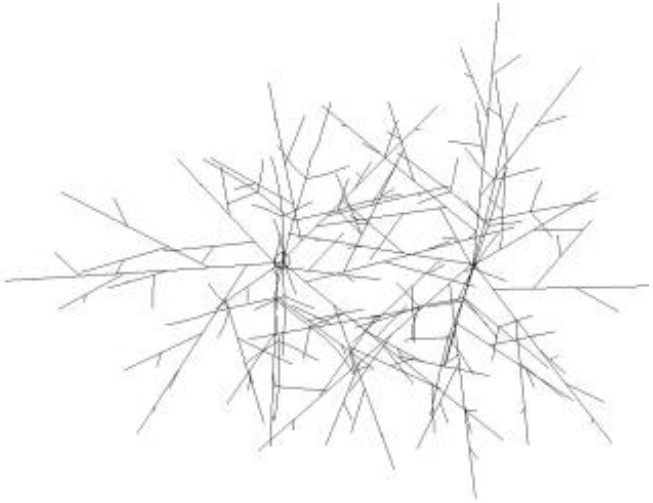


- Each of the object carries its co-ordinates and can access its (local) environment
- Each object performs its specific actions according to the local conditions
- Each object is updated independently
- The structure of the plant emerges as a result of the local interactions

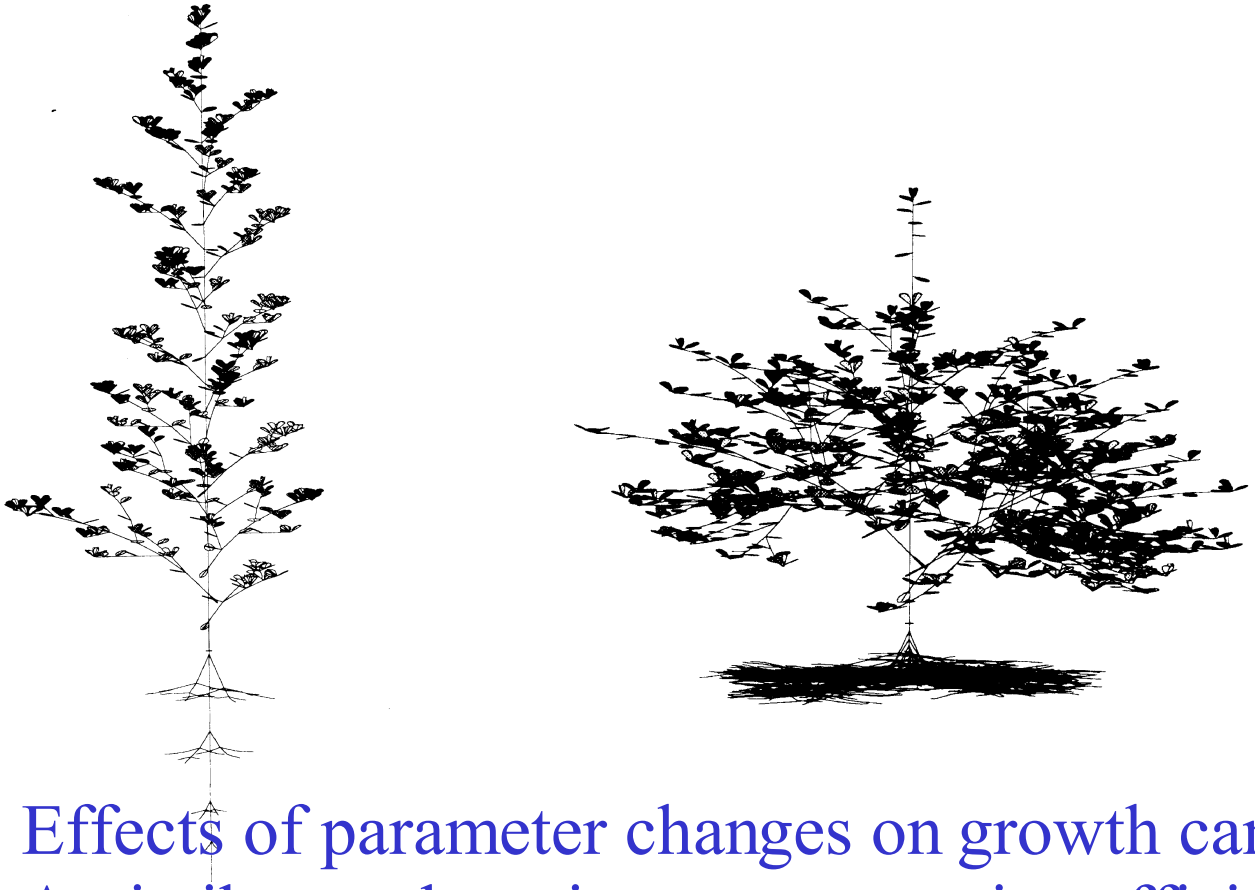
Alder Shoot

- Parametrisation was done according to short-term measurements
- Plant competition and stand interaction can be modelled

Alder Shoot

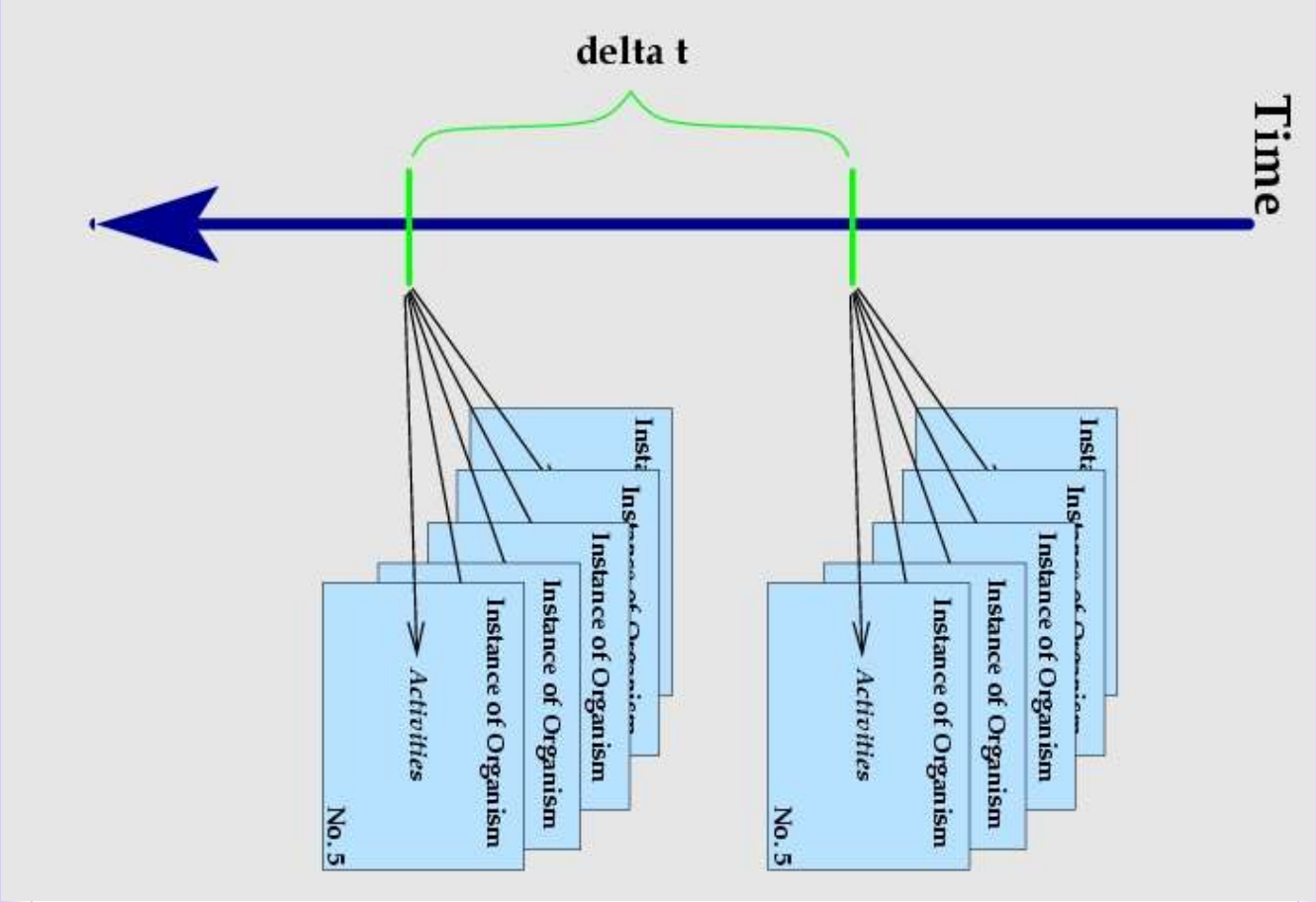


Alder Shoot

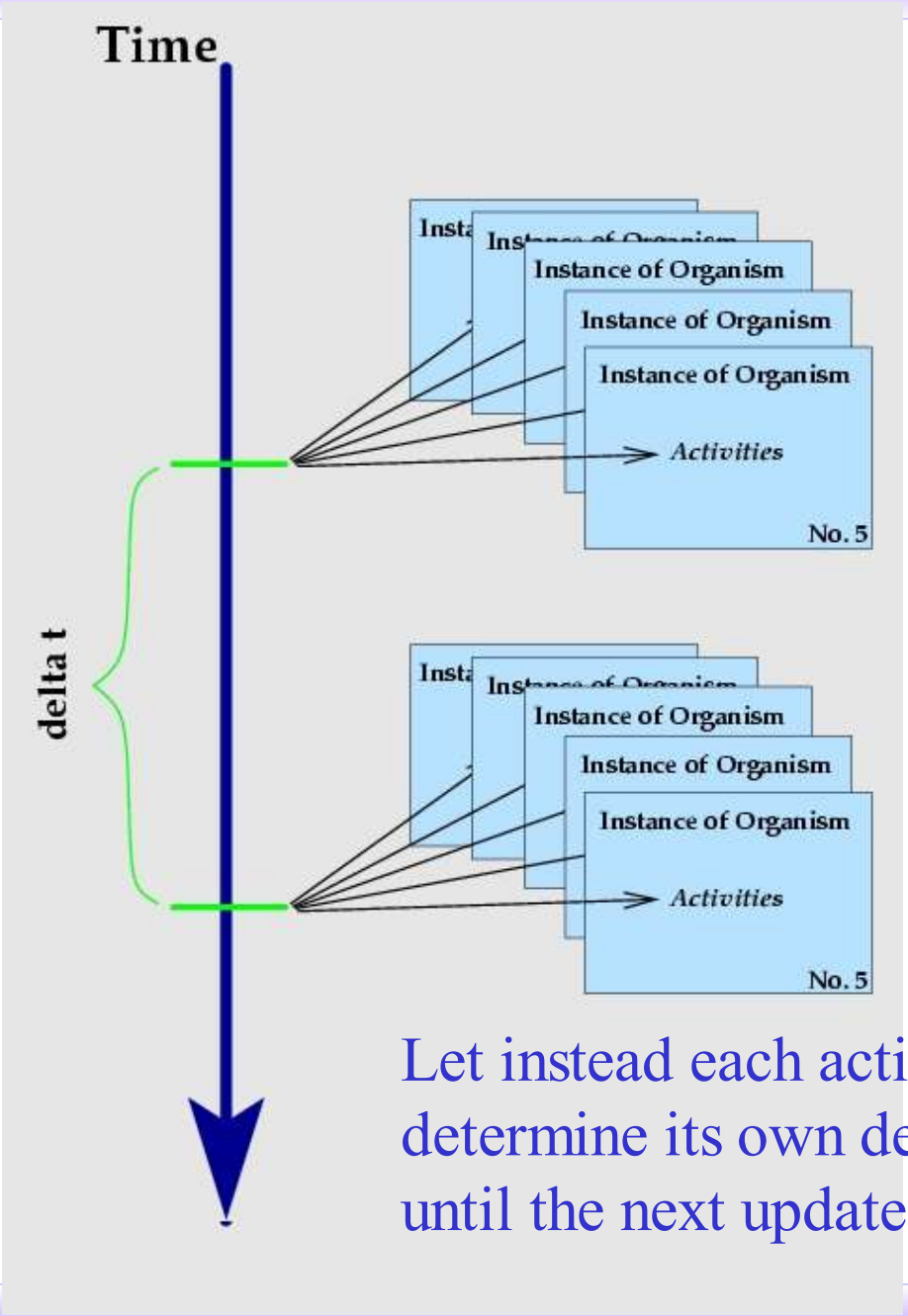


Effects of parameter changes on growth can be tested: Assimilate and nutrient transportation efficiency and its long term effect for the plant architecture

Theoretical aspects



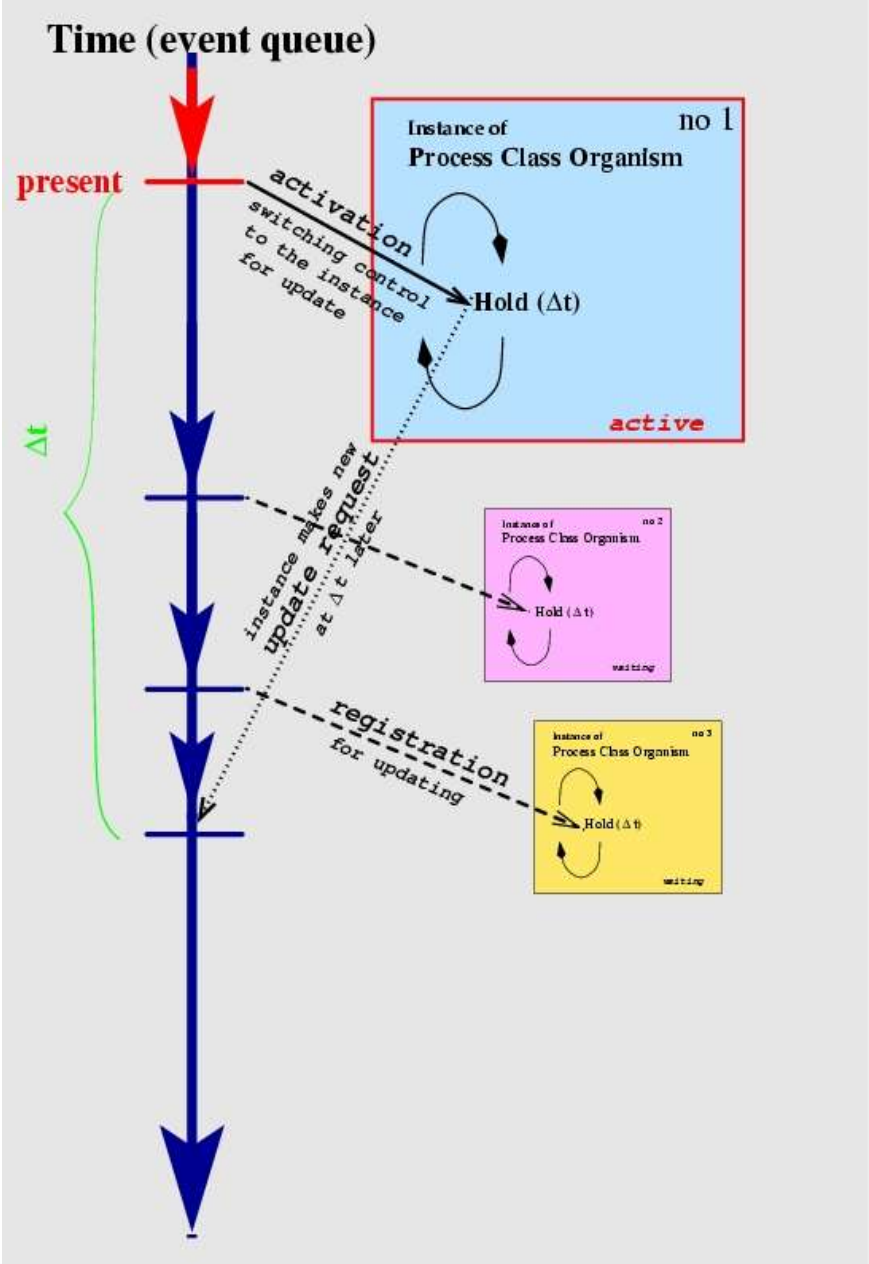
Periodic Event Scheduling:
Exogene organisation (top down)



Let instead each active object determine its own delta t until the next update

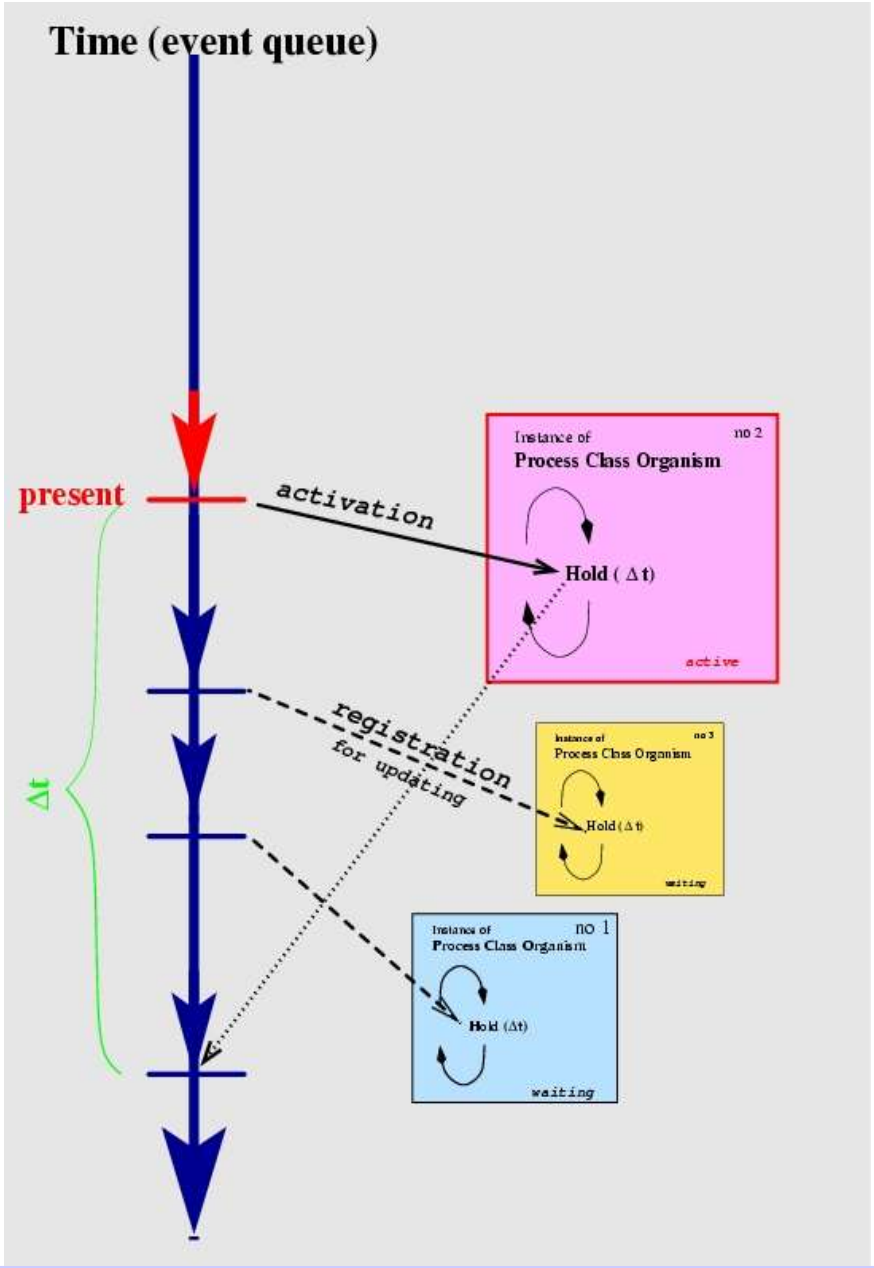
Periodic Event Scheduling: Exogene organisation

Autonomous (Quasi Parallel) Event Scheduling (bottom up)

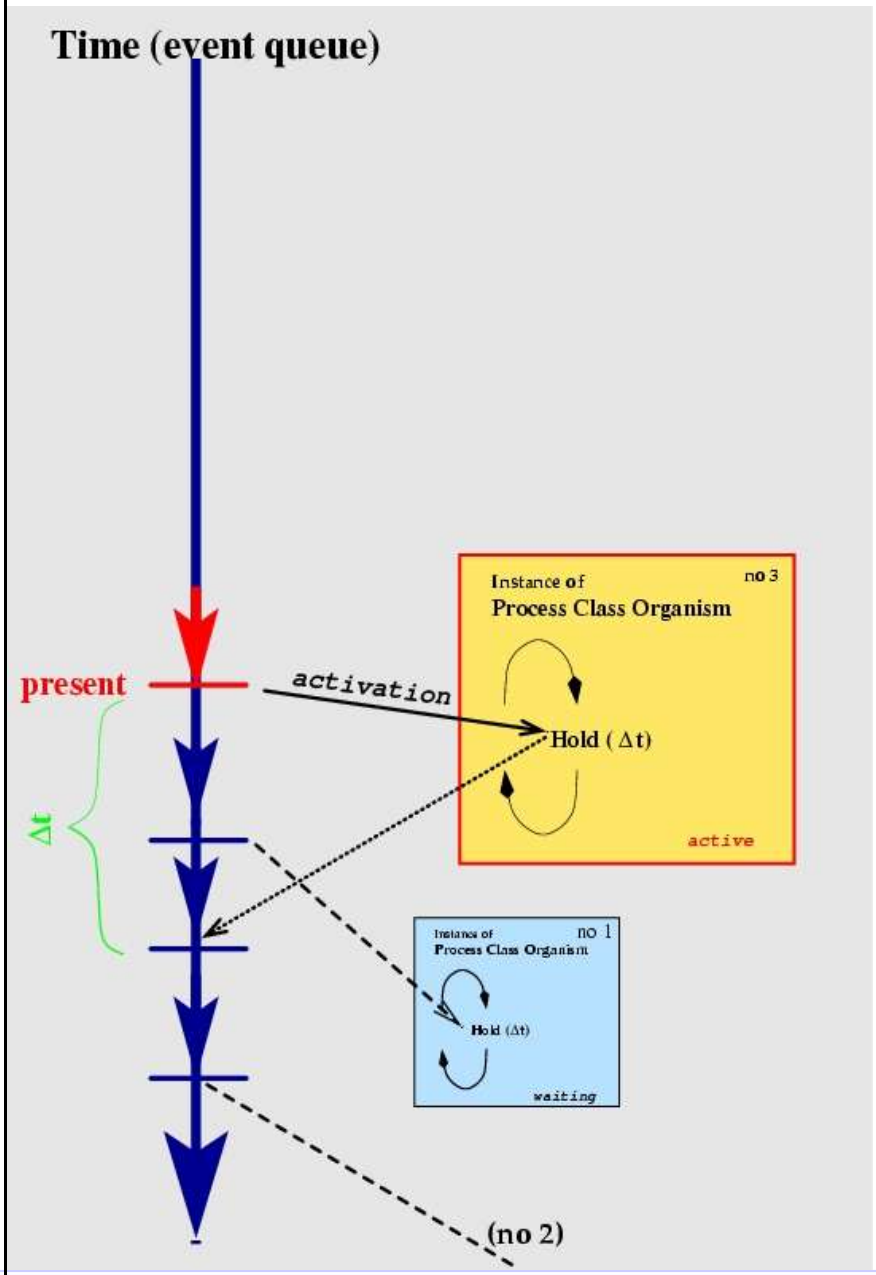


Theoretical aspects

Autonomous (Quasi Parallel) Event Scheduling



Autonomous (Quasi Parallel) Event Scheduling



Regional Context

Rodents

Carabid beetles

Roach

Alder

Research Site Lake Belau
Ecology Centre Kiel
Schleswig Holstein, Northern Germany

Project GenEERA

Generic Detection and extrapolation of oilseed rape dispersal

Analysis of dispersal potential of
genetically modified oilseed rape on different scales...

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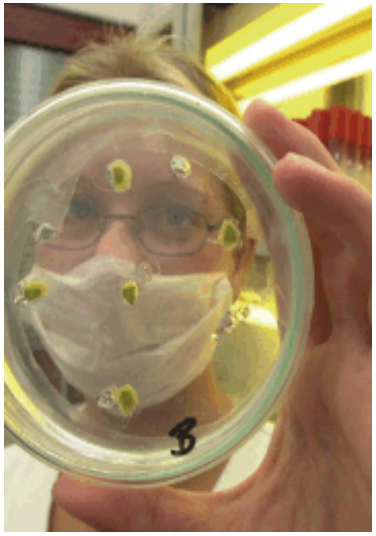
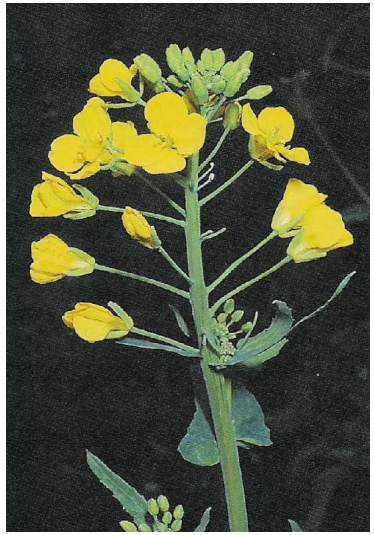


Background:
Transgenic oilseed rape is under admission for commercial release

Project GenEERA

For biosafety research
different scales have to be investigated

Brassica  *napus*

Micro-Scale:
Physiological properties, Hybridisation with related species

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Farm-Scale:
Cultivation measures, pollen transfer, seed dispersal

Project GenEERA

Landscape Scale:
Dispersal frequencies depending on habitat type

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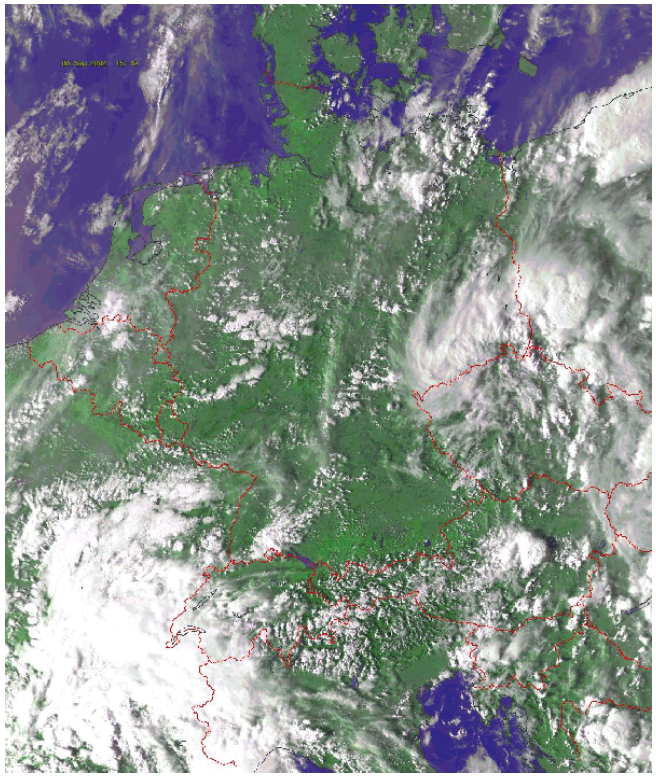


Regional Scale:
Cultivation pattern, regional pollen transfer, coexistence implications, regionalisation

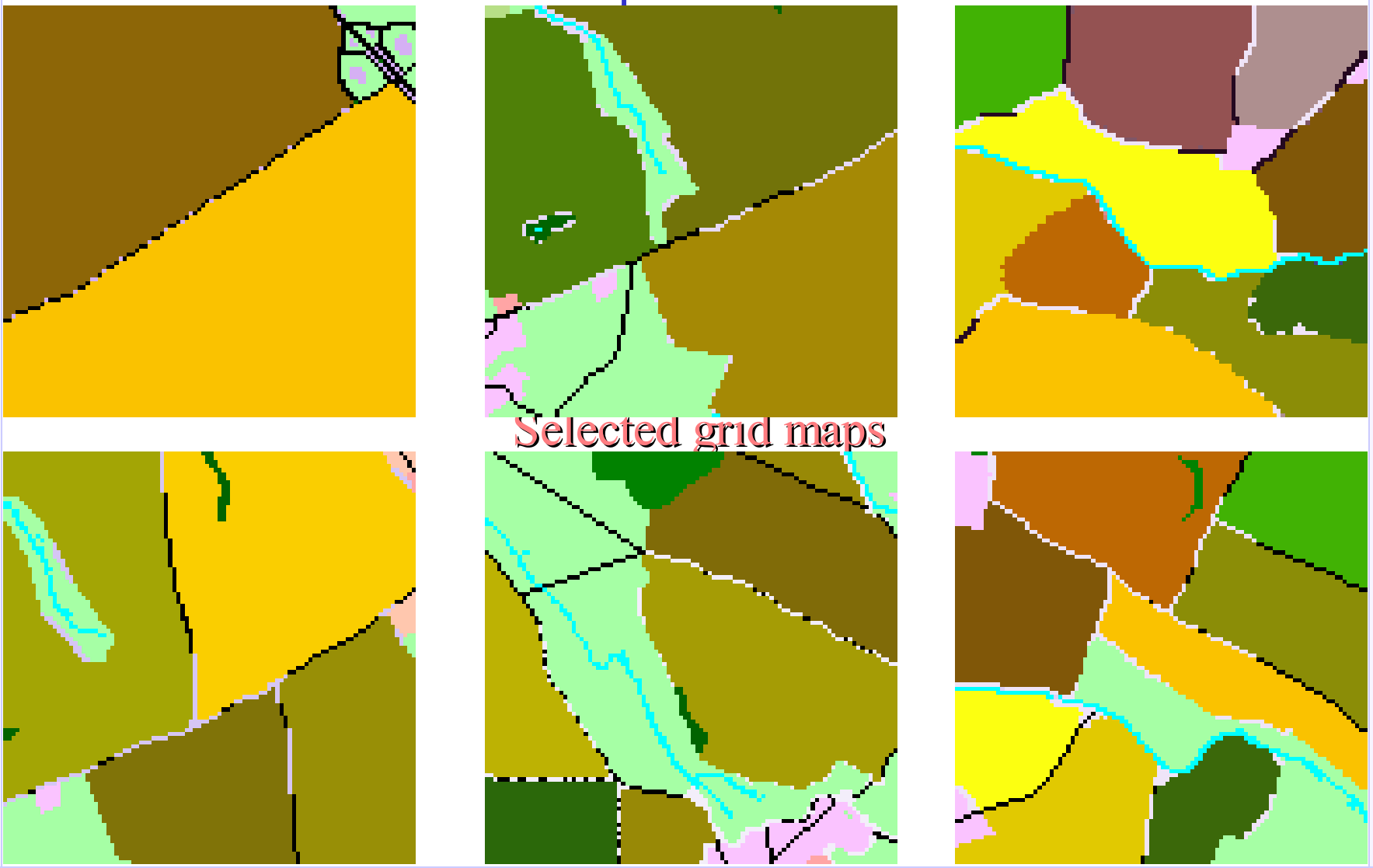
Biosafety research
Some results

Oilseed rape hybridises with more than 10 related species as rare events.

Seeds can survive up to ten years or more in the soil seed bank.

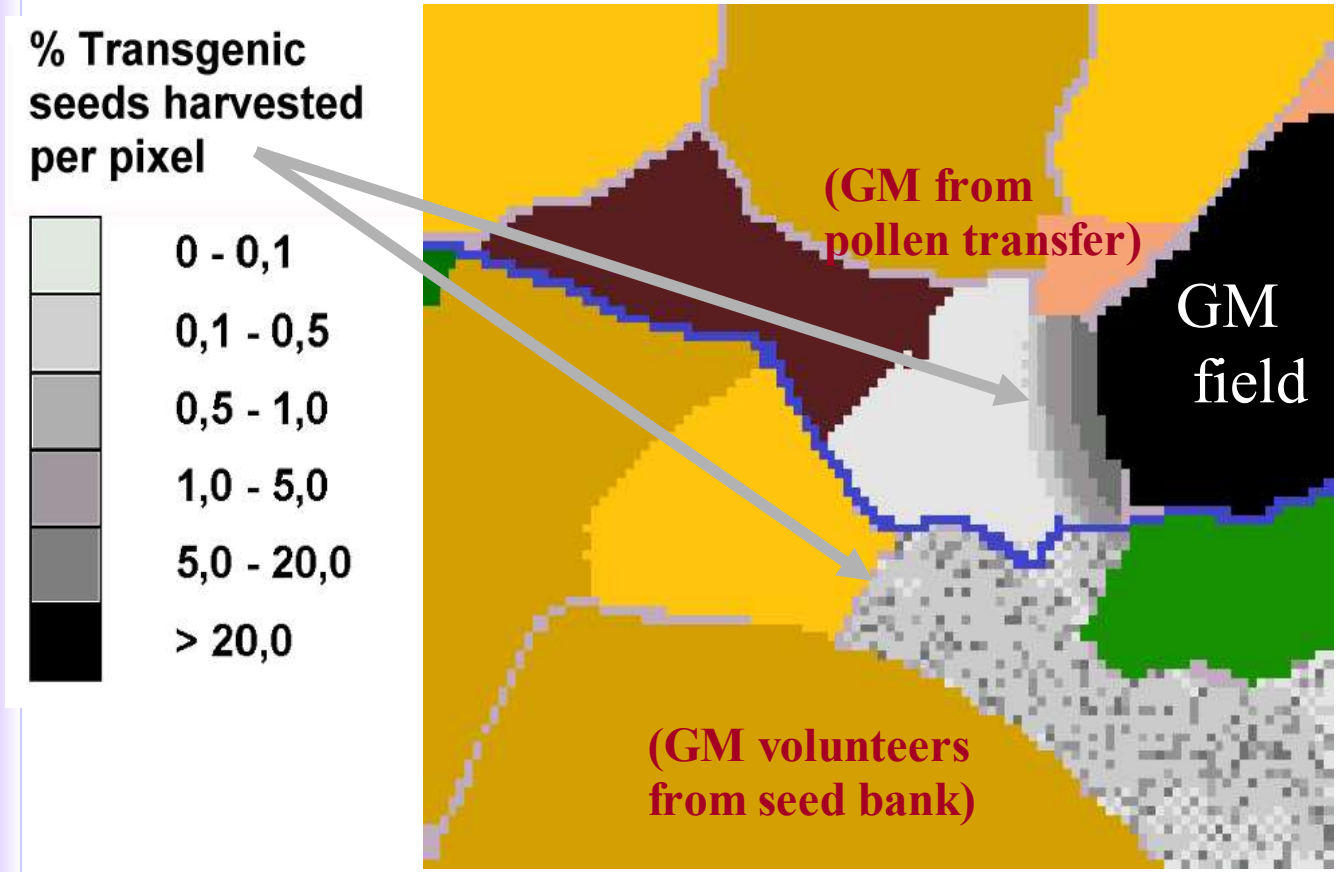
Old varieties, more than 10 years out of cultivation have been detected in the wild

GenEERA
Input data



Selected grid maps

Project GenEERA
Some results



- 1km² grid map
- Climate impact
- Phenology
- Cultivation practice
- Pollination
- Seedbank
- Genetic Markers

Simulation of cultivation...
Scenarios for typical situations for larger areas

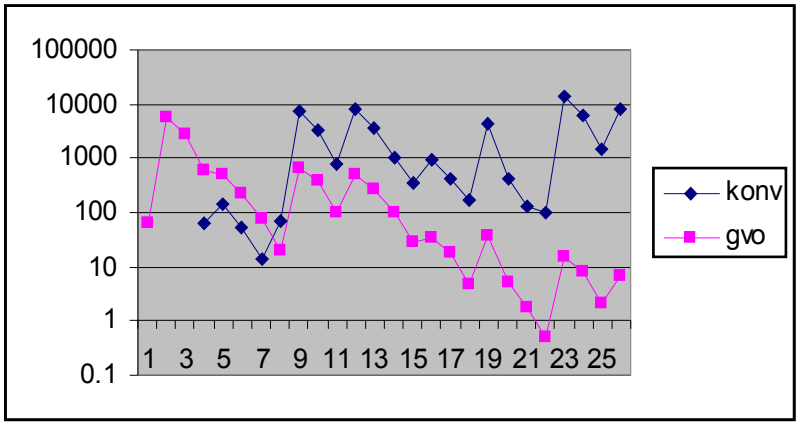
ECEM'04, Breckling et al.

Project GenEERA
Some results

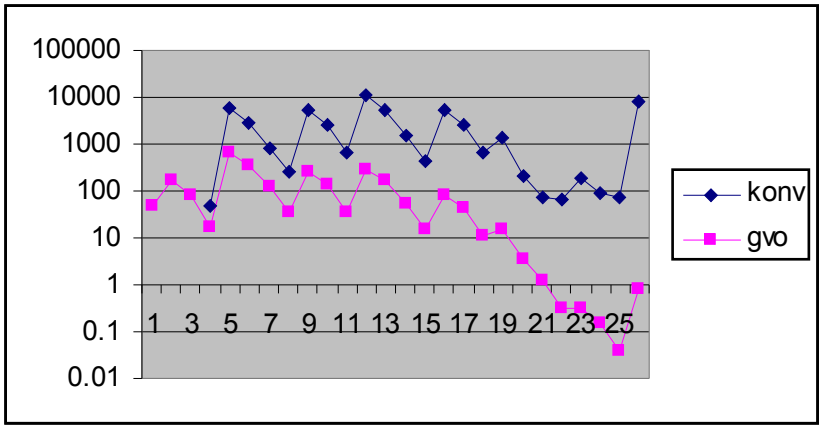
Variant 1:

- stubble breaking immediately
- ploughing after 1 week
- rigid tine after 7 weeks

Scenario with medium level of seed loss during GMO-harvest: ***18 %***

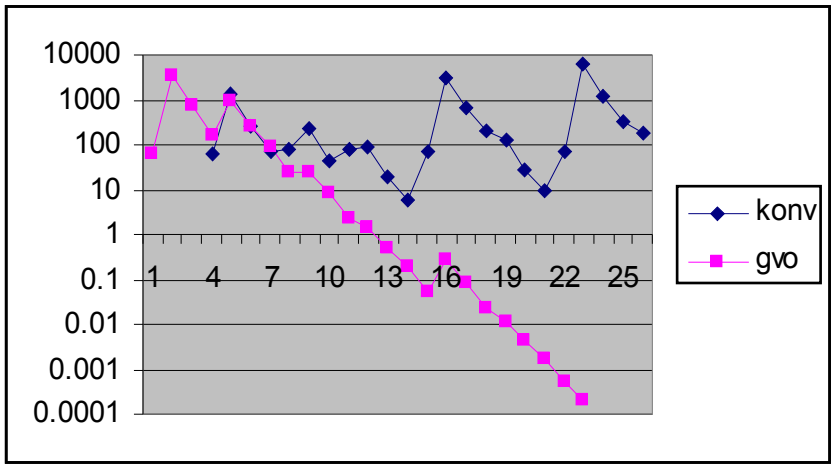


Scenario with very low level of seed loss during GMO harvest: ***1 %***

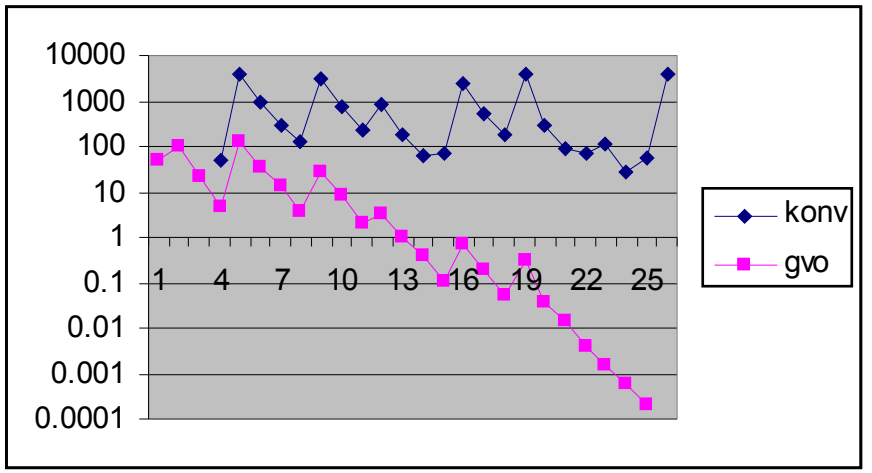


Simulation of soil seed bank after
one year cultivation of genetically modified oilseed rape

Project GenEERA
Some results



Scenario with medium level of seed loss during GMO-harvest: ***18 %***



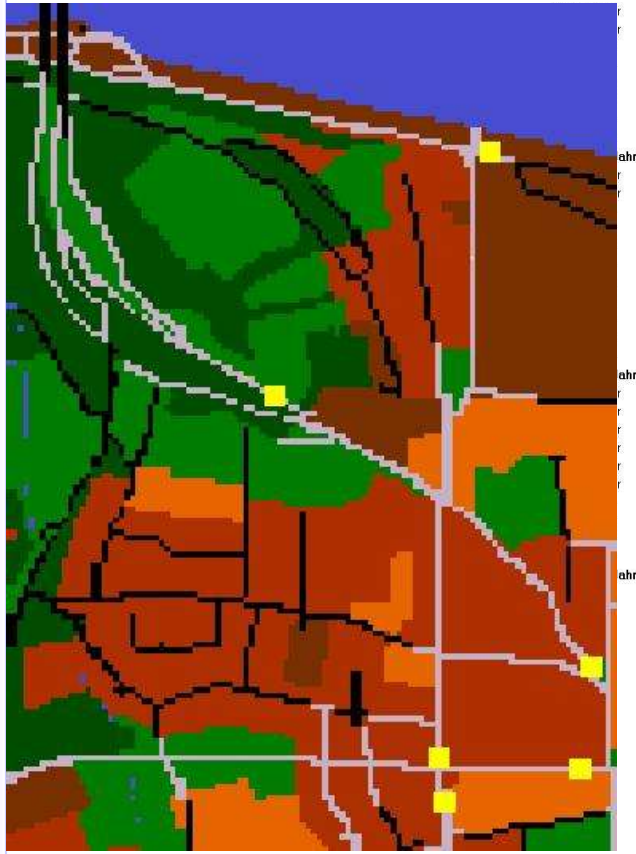
Scenario with very low level of seed loss during GMO harvest: ***1 %***

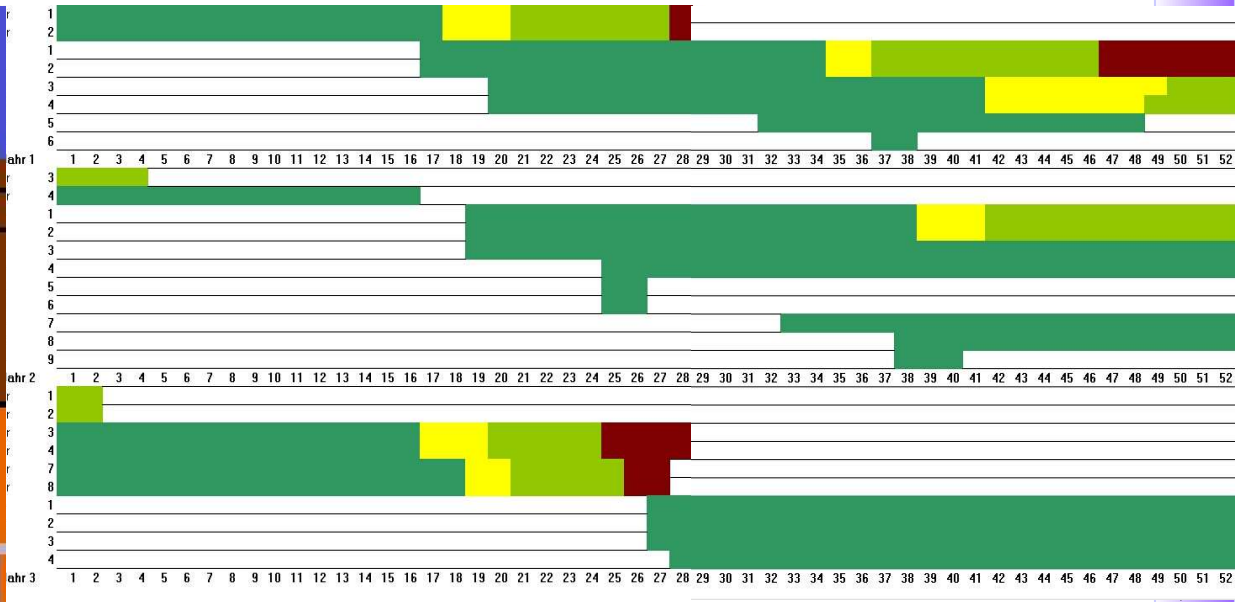
Variant 2:

- stubble breaking after 1 week
- ploughing after 4 weeks
- rigid tine after 7 weeks

Simulation of soil seed bank after one year cultivation of genetically modified oilseed rape

Project GenEERA
Some results



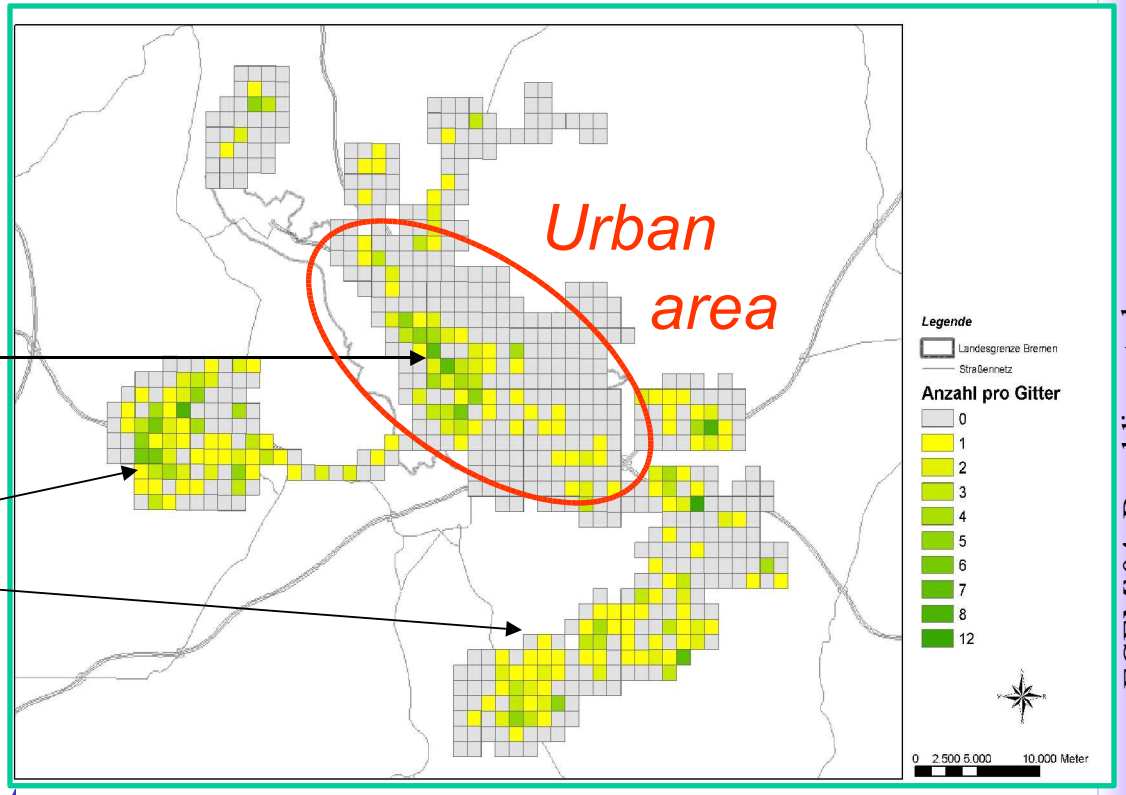


Rosette Flower Seed Growth Maturation

Horizontally: Weeks of the year.
Each line represents the phenology of an individual.

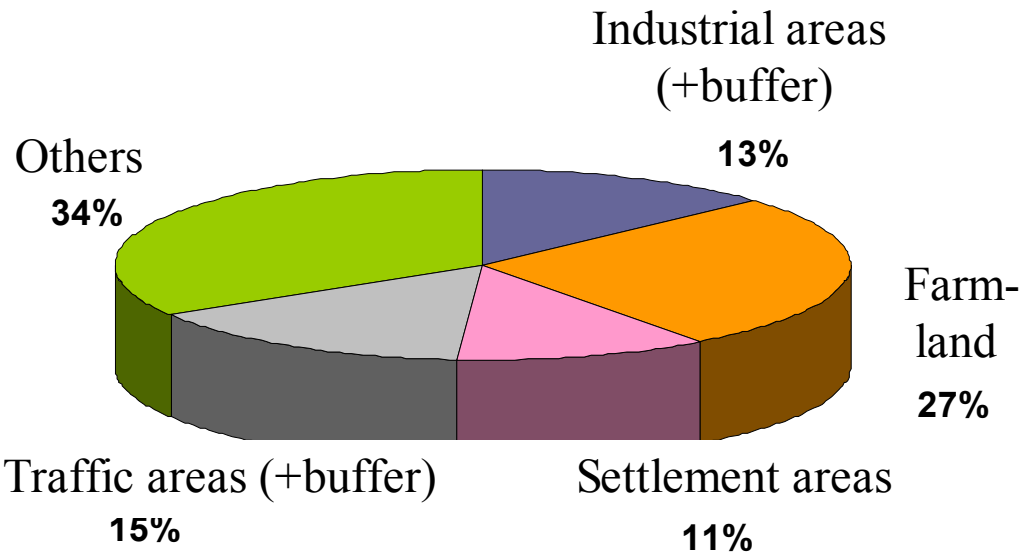
Simulated development of feral plants

Project GenEERA
Some results



Observed dispersal pattern:
Feral oilseed rape in Bremen and surroundig

Project GenEERA
Some results



Observed dispersal pattern in the landscape:
Feral oilseed rape. Around one location each km²

Project GenEERA
Some results
The regional centre of diversity: the Bremen harbour area

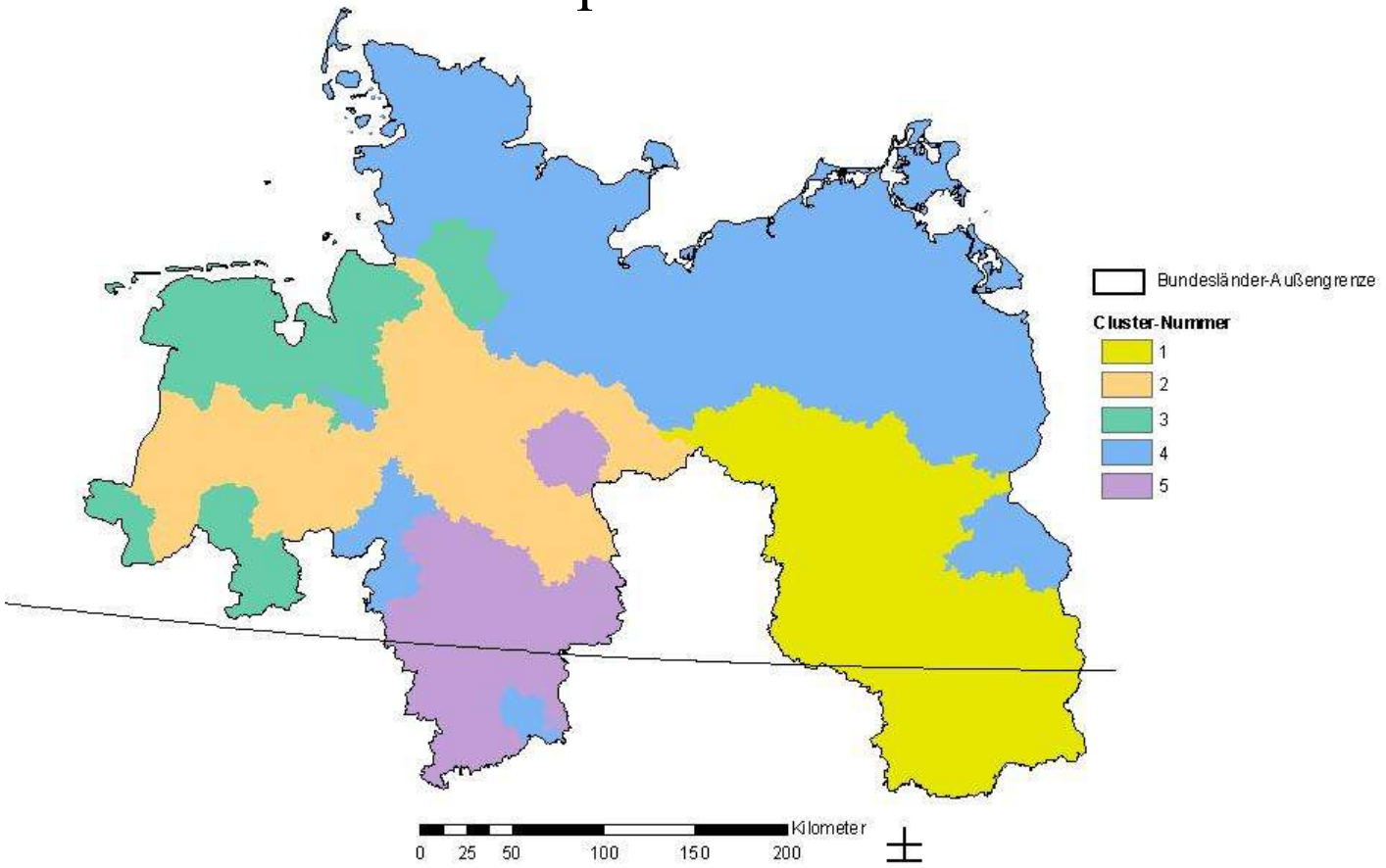
Legende

- Raphanus raphanistrum
- Diplotaxis tenuifolia
- Kulturraps
- Ruderalraps
- Straße
- Autobahn
- Bundesstraße
- Landesstraße
- Kreisstraße
- Gemeindestraße
- Straße im Bau
- Weg

0 500 1.000 Meter

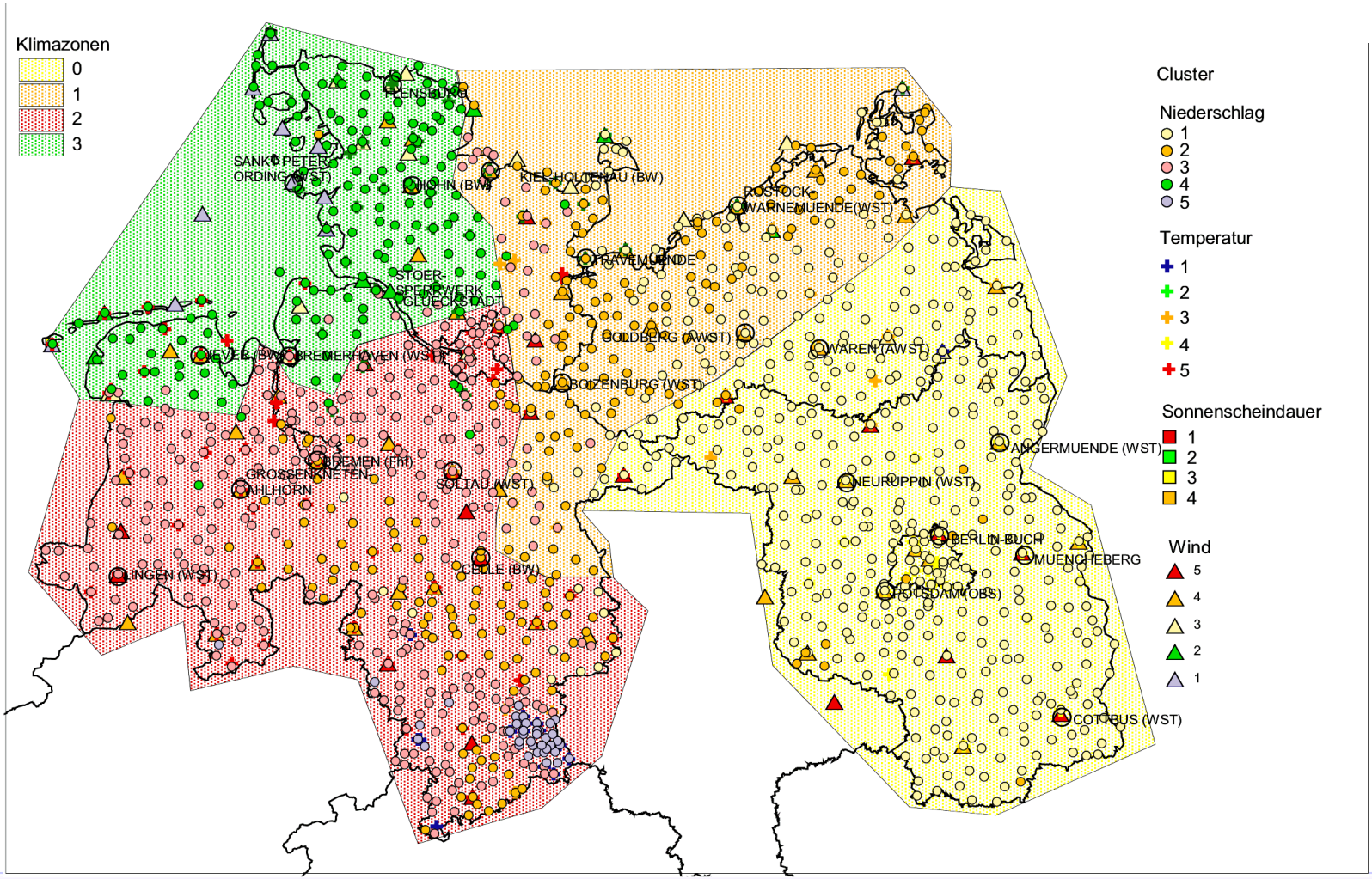
GenEERA
Input data

Crop rotation clusters



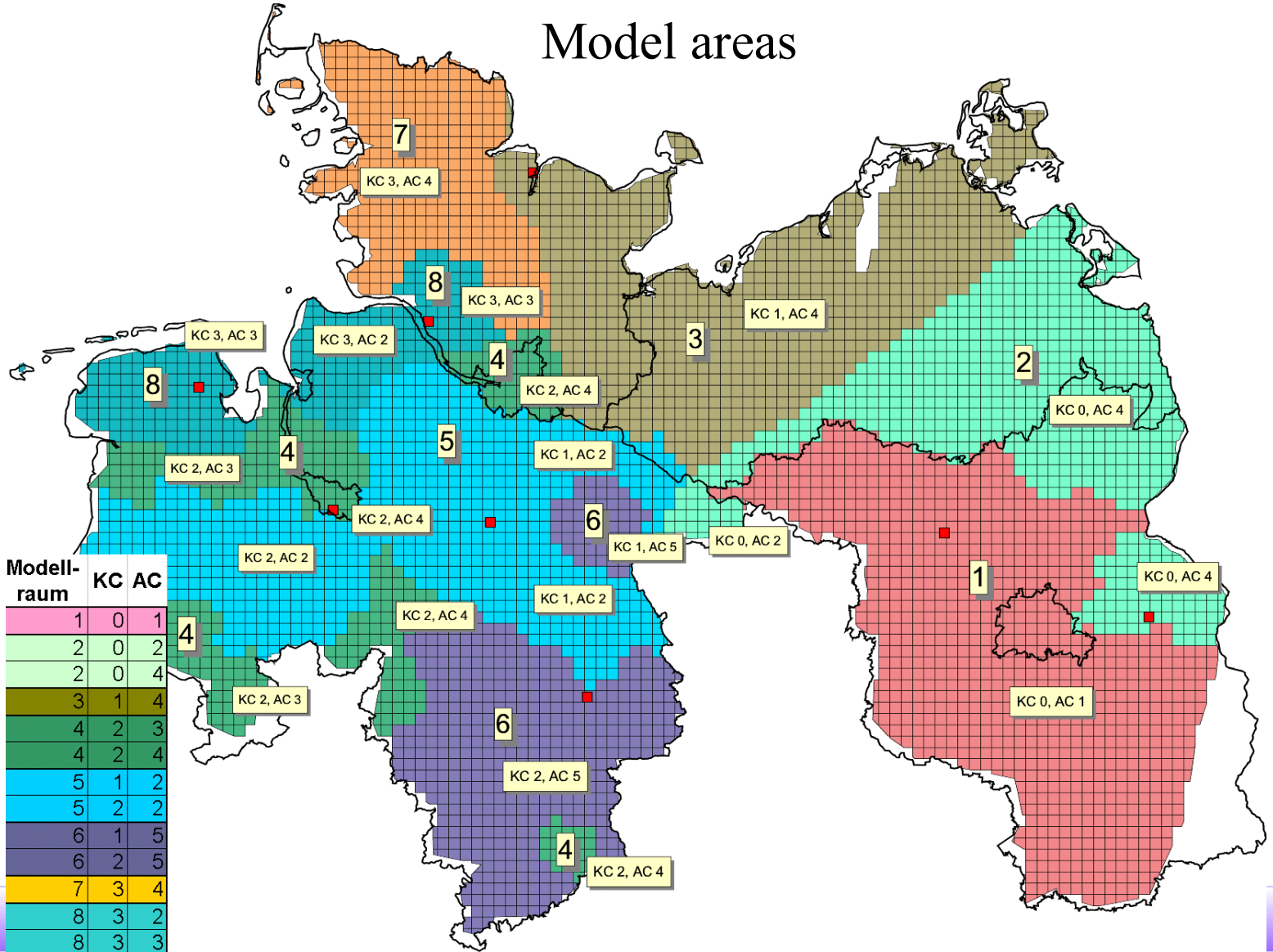
GenEERA
Input data

Climate clusters



GenEERA
Input data

Model areas



Modell-raum	KC	AC
1	0	1
2	0	2
2	0	4
3	1	4
4	2	3
4	2	4
5	1	2
5	2	2
6	1	5
6	2	5
7	3	4
8	3	2
8	3	3

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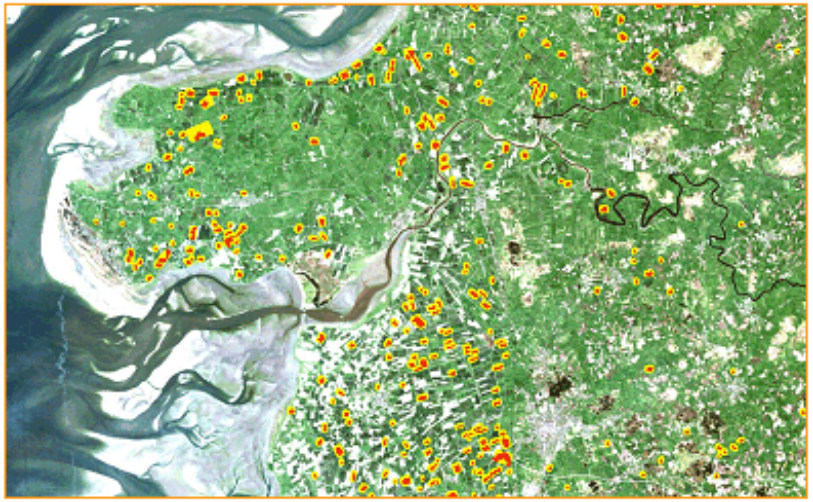
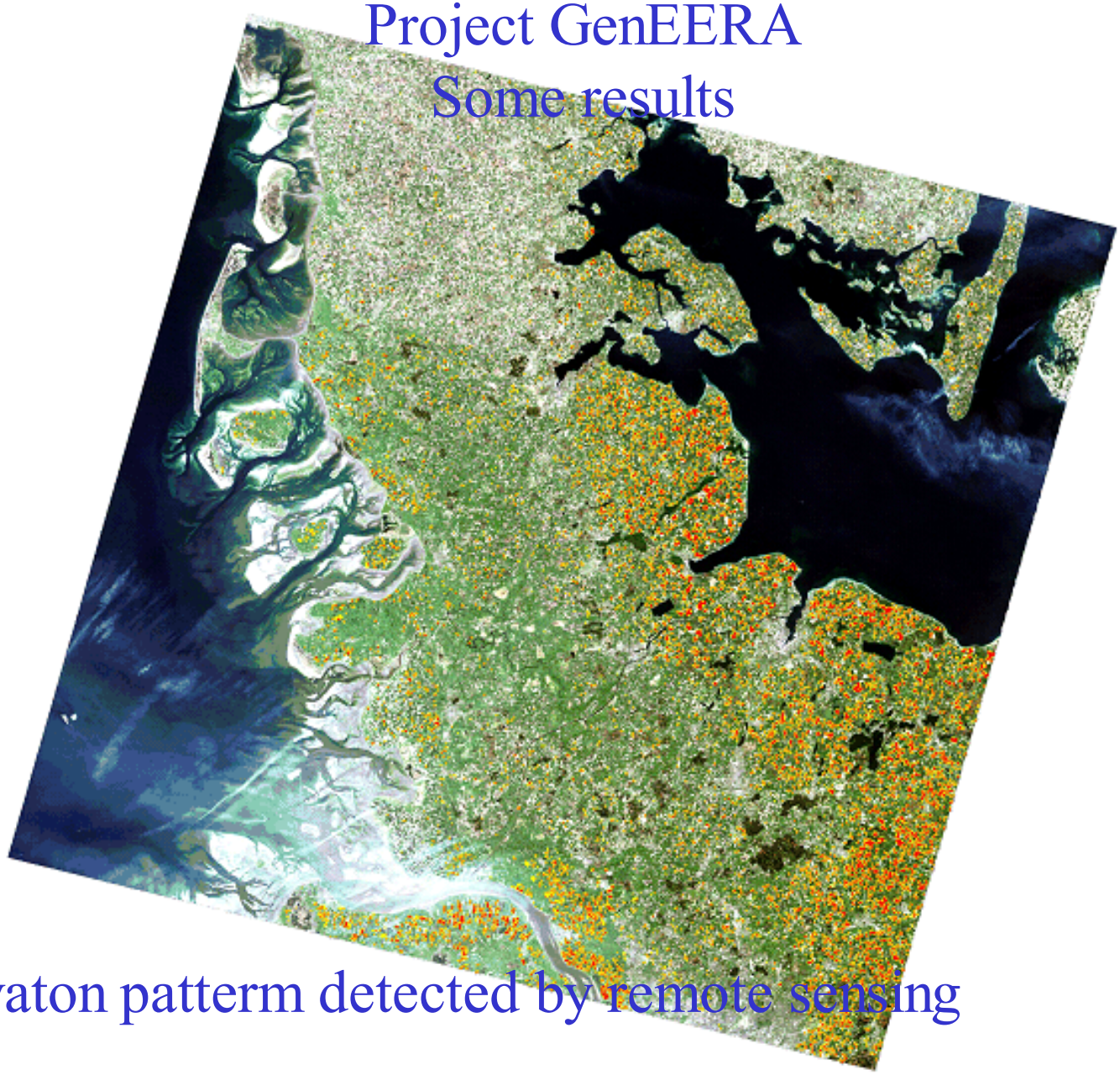
Some results



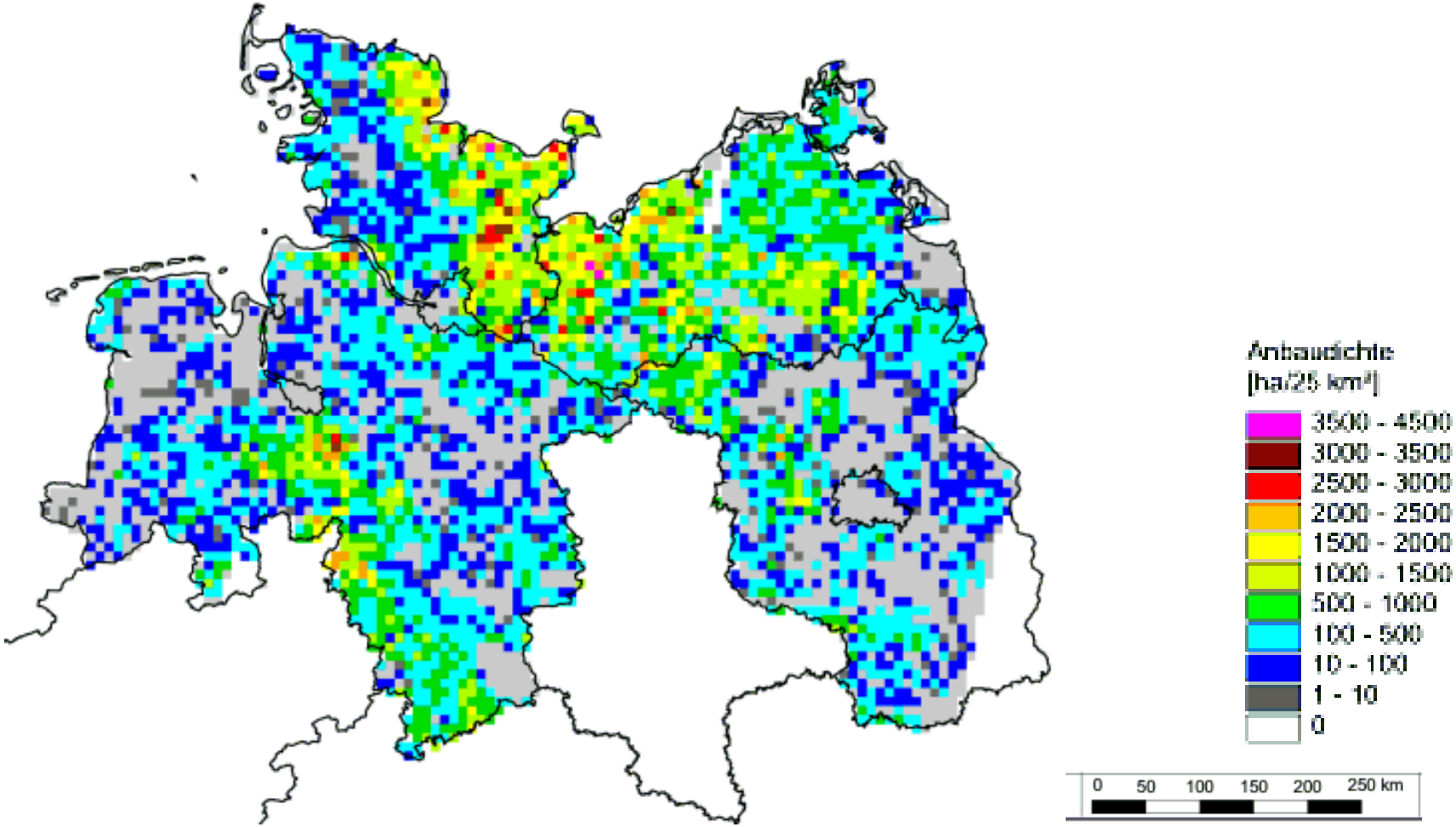
Cultivaton patterm detected by remote sensing

Project GenEERA
Some results



Cultivaton patterm detected by remote sensing

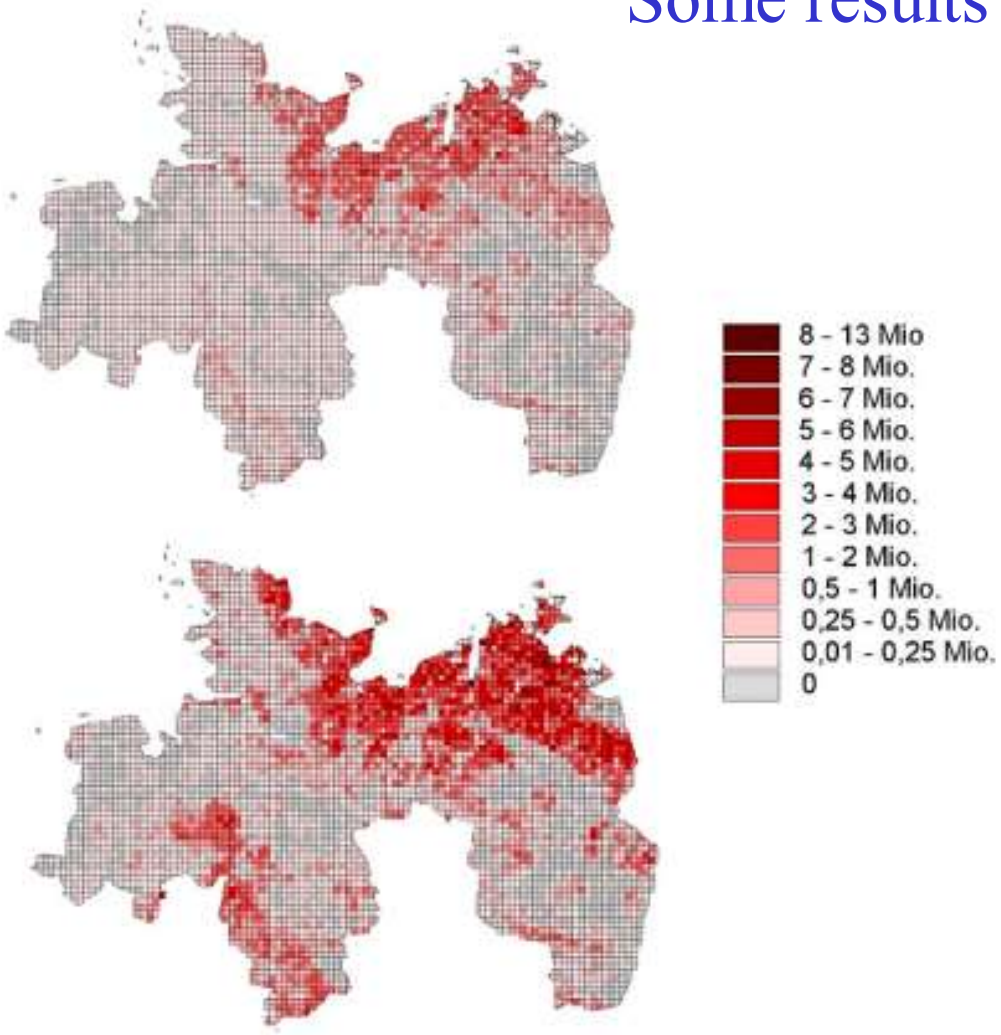
Project GenEERA
Some results



Oilseed Cultivaton density for Northern Germany (grid: 5 x 5 km)

ECEM`04, Breckling et al.

Project GenEERA
Some results



Model extrapolation:

Frequency of transgenic seeds in farmland soil seed bank after 5 years of 10 % transgenic oilseed market share..

...and after another 5 years with 50 % market share

ECEM`04, Breckling et al.

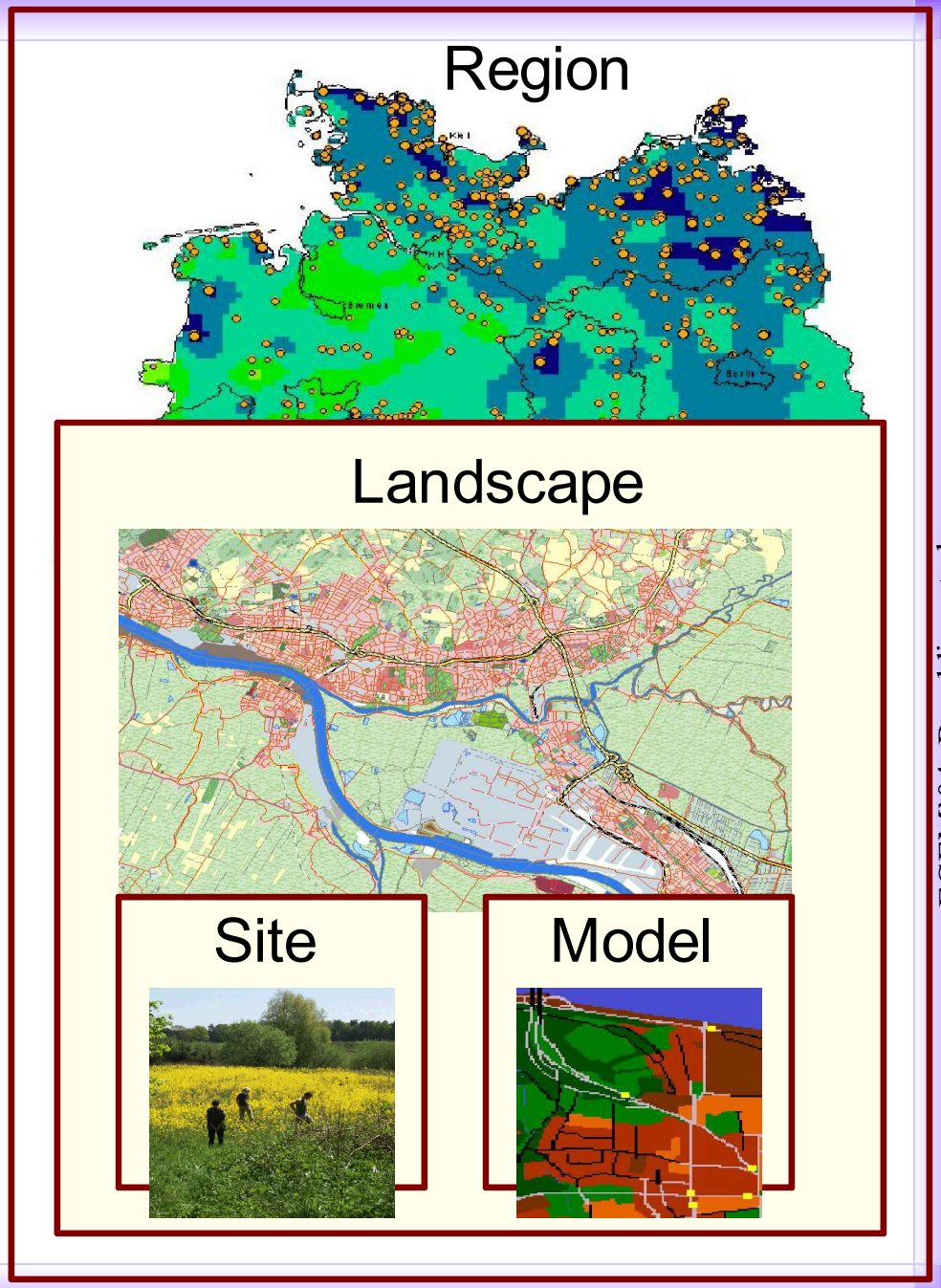
Individual-based modelling contributes to understand large scale ecological dynamics

in this example combined with

- Geography,
- Remote sensing,
- Climatology,
- Agronomy,

and

- Geostatistics



ECEM'04, Breckling et al.

Some main points about Individual-based models:

The approach is simple.

Everybody can start with it

However, it can become as complex as our understanding of life is

The same basic structure can be applied throughout ecology

Major progress is made combining individual-based models and other techniques.

Epistemological implications:

In advanced applications differential equations are frequently used as sub-units.

In addition, the approach allows to simulate structural changes of the system

This shifts the focus of systems analysis from quantitative to an integration of qualitative aspects

Thank you for your attention and ...

Thanks to

Individual-based Modelling Group
Hauke Reuter, Ulrike Middelhoff, Franz Hölker,
Fred Jopp, Christiane Eschenbach

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Cepaea hortensis http://www.graficimages.com/snail.JPG