Lecture 4: Spatial Models in Ecology

Part I: From spatial patterns and processes

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Outline

1. Why explicitly consider space?
2. Classification of spatial models in ecology
3. Five ways to spacialize an ecological model
4. Quiz

1. Why explicitly consider space?

Heterogeneity in
- time → stochastic models
- space → spatial models
- individual traits → individual-based model

How can heterogeneity in space arise and when does it matter?

- Abiotic spatial heterogeneity
  - spatial heterogeneity/structure of habitat or landscape
  - influences relevant ecological processes

- Biotic spatial heterogeneity
  - Individuals create heterogeneity through their interaction,
  - relevant ecological processes act on a certain spatial scale,
  - self-organized spatial heterogeneity
1. Why explicitly consider space?

Abiotic spatial heterogeneity
- habitat quality
- resource availability
- predation risk
- dispersal barriers

Affects ecological processes
- dispersal probability
- mortality rate
- colonization probability
- behaviour

Biotic spatial heterogeneity
- territorial behaviour in animals
- local interaction between individuals
  - competition for space, nutrients or light in plants
  - competition for food, shelter etc. in animals
  - predation
  - disease transmission
- local dispersal

2. Classification of spatial models

1. Cause for heterogeneity: abiotic vs. biotic

2. Representation of space I: implicit vs. explicit

Spatially implicit models
incorporate assumptions about spatial structure of biotic interactions, but do not include geographical space

Spatially explicit models
represent a heterogeneous space which is continuous or discrete.
2. Classification of spatial models

1. Cause for heterogeneity: abiotic vs. biotic
2. Representation of space I: implicit vs. explicit
3. Representation of space II: discrete vs. continuous

Discrete
Space is divided into cells/patches/sites, neighbourhood relations, within patches/cells/sites homogeneous

Continuous
Space is referenced via a Cartesian coordinate system (x, y)

4. Basic unit: abundance-based vs. site-based vs. individual-based

abundance-based: basic unit = population (e.g. PDE)
site/grid/patch-based: basic unit = cell (e.g. CA)
individual-based: basic unit = individual (e.g. distance models)
2. Classification of spatial models

1. **Cause for heterogeneity:** abiotic vs. biotic
2. **Representation of space I:** implicit vs. explicit
3. **Representation of space II:** discrete vs. continuous
4. **Basic unit:** abundance-based vs. site-based vs. individual-based
5. **Number of dimensions:** 1, 2, 3

### Table: Spatial Models Classification

<table>
<thead>
<tr>
<th>Spatial Structure</th>
<th>Relevant Ecological Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual-based 'movement' models</td>
<td>patch-based 'movement' models, site-based models, individual- and grid-based models, individual-based models</td>
</tr>
<tr>
<td>Continuous/Discrete</td>
<td>Spatially implicit, discrete, discrete, discrete, continuous</td>
</tr>
<tr>
<td>Dispersal models</td>
<td>Metapopulation models, cellular automata, tessellation models, distance models</td>
</tr>
<tr>
<td>Dispersal and foraging in animals, dispersal in plants</td>
<td>Metapopulation dynamics, host-parasitoid dynamics, forest succession, wildfires, territory building, disease transmission in animals, competition, facilitation between plants</td>
</tr>
</tbody>
</table>

* Nadja Rüger; Lecture 4 „Spatial Models in Ecology“ (Part I, Day 4)
3. Five ways to spacialize an ecological model

3.1 Wildfires in boreal forests – Cellular Automaton
3.2 Plant competition and self-thinning – Distance models
3.3 Sustainable management of species-rich tropical forests –
   Individual- and grid-based ‘interaction’ model
3.4 Population dynamics of a territorial bird with social breeding –
   Individual- and grid-based ‘movement’ model
3.5 Metapopulation models and Meta-X (→ Part II)

3.1 Wildfires in boreal forests (Ratz 1995)

Spatial processes
fire spreads from one location to another depending on the
amount of flammable material

Non-spatial processes
aging of the forest; the amount of flammable material depends
on the age of the forest

Consequence
a complex mosaic of forest patches in different successional
stages is created (self-organized spatial heterogeneity)
3.1 Wildfires in boreal forests (Ratz 1995)

Questions

- Is there a general size distribution of wildfires?
- Is there a typical average fire size?
- Are there specific reasons for large fires?

- cell size = 5 ha (forest stand)
- cells age in steps of 10 years
- flashes at random locations
3.1 Wildfires in boreal forests (Ratz 1995)

flammability \( f = \text{ignition probability of stand} \)

\[
\text{flammability} = i + c \cdot (\text{age} / 10)^2
\]

\( c = 0 \): \( f \) constant

\( 0 < c < 1 \): \( f \) increases with stand age

size and shape of the fires emerge from simple model rules

3.1 Wildfires in boreal forests (Ratz 1995)

- size distribution is power law \( \rightarrow \) self organized criticality
- no typical average fire size
- no specific reasons for large fires

\[
\log(D(s)) = \log a + m \log(s)
\]

\[
D(s) = a \cdot s^m
\]
3.1 Cellular Automata

- discrete space, regular grid
- discrete time steps
- finite (small) set of states of cells
- neighbourhood size and shape
- site-based
- transition rules ('updating rules', 'next-state-function') describe neighbourhood interactions

Advantages
- within-site dynamics
- local interactions
- simple rules reflect ecological knowledge
- single species and community dynamics can be modelled
- computationally efficient

Disadvantages
- regular and equally-sized shape of sites

3.2 Plant competition (review Berger et al. 2008)

Ecological questions
How does inter- and intraspecific competition affect plant population dynamics (succession, self-thinning)?

Spatial processes
- competition
  - is a function of how space is divided or shared among individuals
  - interaction strength is a function of distance
- mortality
- seed dispersal

Non-spatial processes
I can't think of any, maybe you can?
3.2 Plant competition (review Berger et al. 2008)

### Fixed-radius neighbourhood (FRN)
- fixed radius of interaction for all individuals
- radius defined *ad hoc* or based on field data

*Advantage*
- conceptually simple

*Disadvantage*
- no size(or age)-dependency

### Zone-of-influence (ZOI)
- radius depends on size
- ZOI represents resource uptake, i.e. performance
- overlap of ZOIs represents competition → reduced performance
- used to understand size distributions of even-aged monocultures

*Advantages*
- conceptually simple

*Disadvantage*
- computationally non-trivial
- many studies ignore mortality
3.2 Plant competition (review Berger et al. 2008)

Field-of-neighbourhood (FON)

- Berger and Hildenbrandt (2000)
- radius depends on size
- competition strength depends on distance
- competition affecting focal plant = integral over the FONs of other plants in its area
- parameters defined *ad hoc* or based on field data
- mortality, growth and recruitment taken into account

\[ R = a \cdot \left( \frac{dbh}{2} \right)^b \]

Advantages
- represents interaction strength
- simple way to model effect of competition on seedling establishment

Disadvantage
- computationally 'expensive' and non-trivial

Example
Secondary mangrove succession
(Berger et al. 2006)
3.2 Distance models

- continuous space
- individual-based
- local competition, (dispersal)
- single or multiple species

Advantages
- variable (except FRN) scale of interaction

Disadvantages
- mechanisms of interaction are highly simplified = phenomenological description of competition
- computationally expensive

3.3 Sustainable management of tropical forests

(e.g. Köhler and Huth 1998, Köhler et al. 2001, 2003, Rüger et al. in press)

Question
How can species-rich rain forests be managed in a sustainable way?

Spatial processes
- competition for light
  - tree growth affects competition for light and vice versa (vertical)
  - harvesting affects competition for light (vertical)
- gap creation (horizontal)
- competition for space
  - (seed dispersal)
3.3 Sustainable management of tropical forests
(e.g. Köhler and Huth 1998, Köhler et al. 2001, 2003, Rüger et al. in press)

The model (FORMIND)
- plant functional types (PFT)
- individual-based
- process-based: regeneration, growth, mortality, competition for light and space, gap creation, logging
- tree growth modelled on a physiological basis
- horizontal space: 20 m × 20 m grids
- vertical space: 0.5 m height layers
- annual time steps

Competition for light

\[ I_t = I_0 \cdot e^{-k \cdot LAIC_t} \]

\[ PB = P_t(I_t) \cdot S \cdot CA \cdot codm \]

\[ B_{inc} = (1 - r_g)(PB - r_0B^t) \]

- \( I_0 \): Irradiance above forest
- \( k \): Light absorption coefficient
- \( PB \): Photosynthesis
- \( S \): Annual daylight time
- \( B_{inc} \): Annual biomass increment
- \( r_g \): Parameter of growth respiration
- \( I_t \): Irradiance at tree crown
- \( LAIC \): Cumulative leaf area index
- \( P_t \): Rate of photosynthesis
- \( CA \): Crown area
- \( B \): Biomass
- \( r_0 \): Parameter of maintenance respiration
- \( r_1 \): Parameter of maintenance respiration
3.3 Sustainable management of tropical forests
(e.g. Köhler and Huth 1998, Köhler et al. 2001, 2003, Rüger et al. in press)

Why so detailed?
- species-richness
- uneven age structure
- objectives: quantitative long-term information on detailed management strategies

however
- spatial heterogeneity within grid cells and height layers are ignored
3.3 Sustainable management of tropical forests
(e.g. Köhler and Huth 1998, Köhler et al. 2001, 2003, Rüger et al. in press)

Exemplary results

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Logged PFTs</th>
<th>Diameter range</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>4, 6</td>
<td>40 – 60 cm</td>
</tr>
<tr>
<td>S2</td>
<td>4, 6</td>
<td>40 – 100 cm</td>
</tr>
<tr>
<td>S3</td>
<td>4, 5, 6</td>
<td>40 – 60 cm</td>
</tr>
<tr>
<td>S4</td>
<td>4, 5, 6</td>
<td>40 – 100 cm</td>
</tr>
</tbody>
</table>

logging intensity: 5 – 100 m³/ha stem volume
logging cycle: 10 years
simulation time: 400 years
3.3 Sustainable management of tropical forests
(e.g. Köhler and Huth 1998, Köhler et al. 2001, 2003, Rüger et al. in press)

- Increase of small trees
- Drastic decrease of large old trees
- More homogeneous and younger forest structure

<table>
<thead>
<tr>
<th>Stem diameter</th>
<th>Stem number</th>
<th>Annual wood extraction (m³/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20–40 cm</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>40–60 cm</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>60–80 cm</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>80–100 cm</td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

Advantages of IBMs:
- Make testable predictions
- Can be parameterized with individual-level information
- Efficient way to represent spatial heterogeneity at relevant scale
- Single and multiple species
- Flexible

Disadvantages:
- Often complex = labour-intensive to parameterize and analyze
- Computationally expensive
Three models of forest dynamics

- How do they differ any why?
- What is the appropriate way to represent space?
- What is the appropriate spatial resolution?

3.4 Woodhoopoe population dynamics
(Neuret et al. 1995; Grimm and Railsback 2005)

- Green woodhoopoe (*Phoeniculus purpureus*)
- lives in riparian forests in Africa
- territorial
- social hierarchy
- social breeding: only alpha couple reproduces and helpers
- long-distance scouting forays

Spatial process
- long-distance scouting forays

Non-spatial processes
- reproduction, mortality
3.4 Woodhoopoe population dynamics
(Neuert et al. 1995; Grimm and Railsback 2005)

Ecological question:
How do long-distance scouting forays affect the spatial coherence and the persistence of the population?

The model
- 1 grid cell = 1 territory
- alpha couple reproduces
- helpers decide for scouting forays depending on their age and social rank
- the older individuals are and the lower their social rank the higher is the probability for long-distance forays
- time step = 1 month

→ long-distance scouting forays maintain the spatial coherence
→ if ≥ 15 territories are connected by scouting birds, the metapopulation persists
3.4 Individual- and grid-based ‘movement’ model

- individual-based
- discrete space, regular grid
- ‘movement’ model (dispersal model)
- no local interactions

Advantages
- of IBMs
  - make testable predictions
  - can be parameterized with individual-level information
- of grid-based models
  - efficient way to represent spatial heterogeneity at relevant scale
- single and multiple species
- flexible

Disadvantages
- often complex = labour-intensive to parameterize and analyze
- computationally expensive

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Literature:
Berger et al. 2006, 2008
Berger and Hildenbrandt 2000
Czárán 1998
Grimm and Railsback 2005
Köhler and Huth 1998
Köhler et al. 2001, 2003
Rüger et al. 2007
Neuert et al. 1995
Ratz 1995