Individual-based modelling in RangeShiftR

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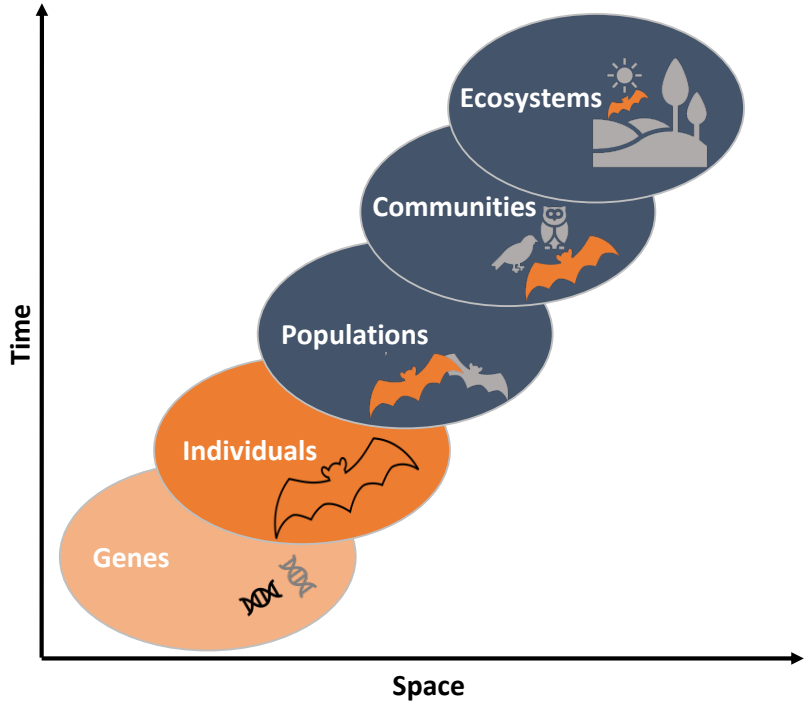
Pictures from www.undekade-biologischevielfalt.de

Ecology is hierarchical

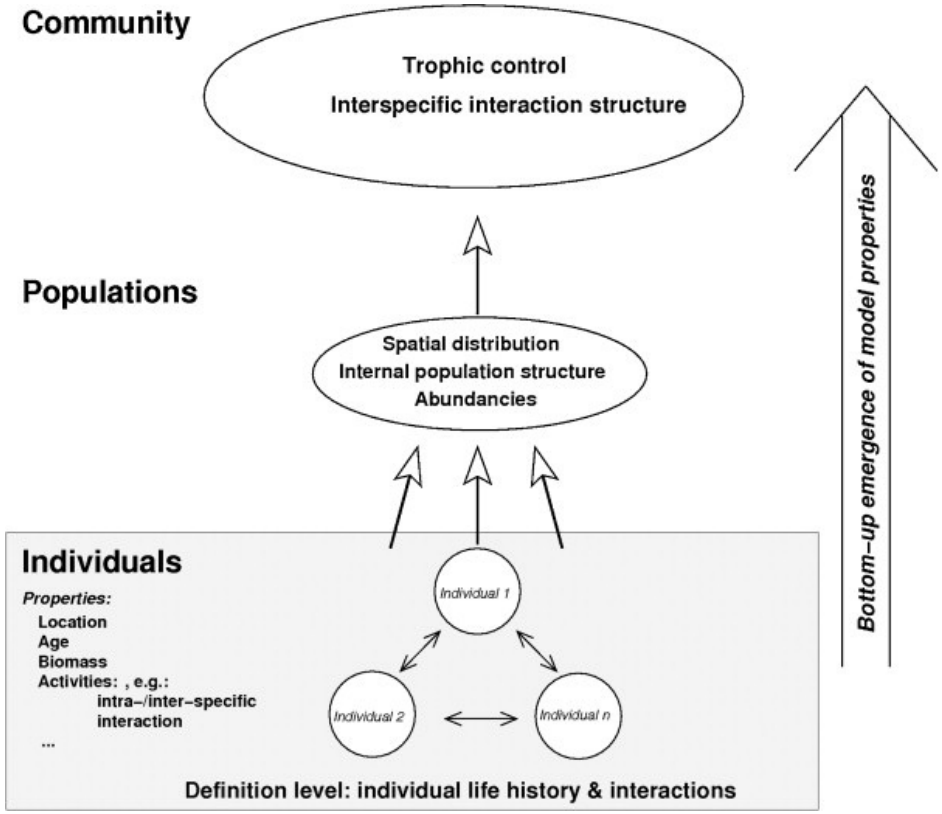
- Hierarchy of organisational levels from genes to ecosystems
- Each level operates and evolves on a characteristic spatial and temporal scale

➢ It is crucial to find the the appropriate modelling level for the given ecological problem or application



Emerging population dynamics

- "The whole is more than the sum of its parts." – Aristotle
- **Bottom-up approach**: use knowledge about behavior of single individuals to infer properties of the larger population or community

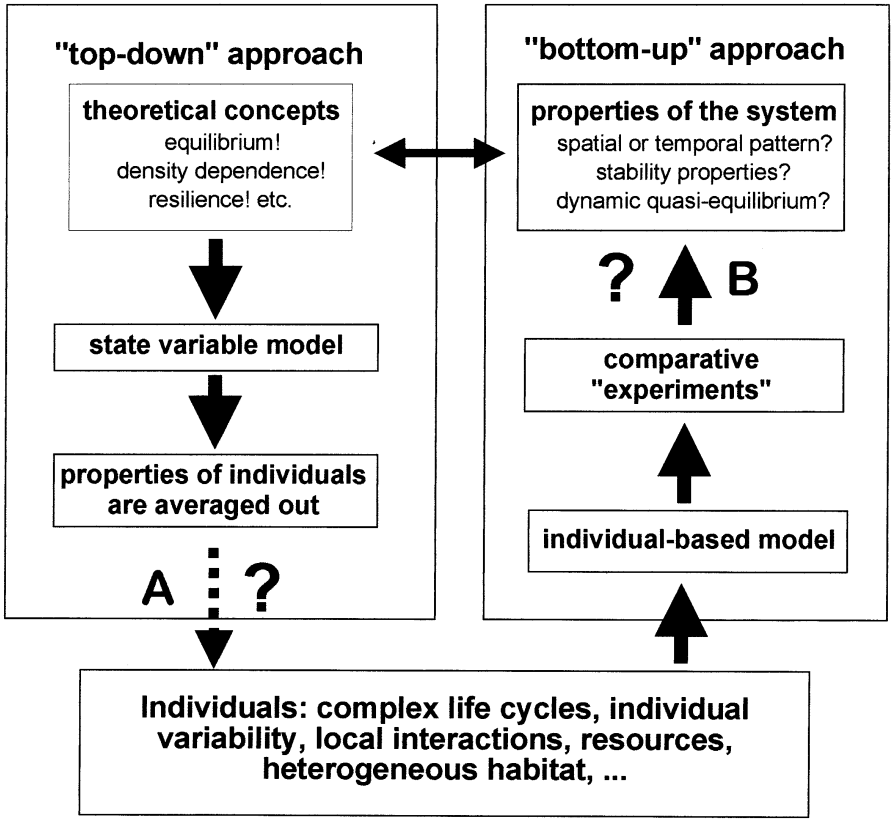


Reuter, et al. (2010) Basic Appl Ecol 11: 572-581.

Individual-based models (IBM)

- Individuals/agents as unique discrete entity
  - Characterised by at least one state/property (additional to age) that changes through time

- Allow to account for individual variability, local interactions, individual space use, behaviour …



Grimm (1999) Ecol Mod 115: 128-149.

IBM state variables and processes

Population

Growth rate, demographic structure, range dynamics, ...

Environment

Space is represented as a regular 2D grid, where each cell is characterised by:

- Habitat suitability index / Carrying capacity
- Land cover proportions
- Strength of abiotic drivers

Density-dependence

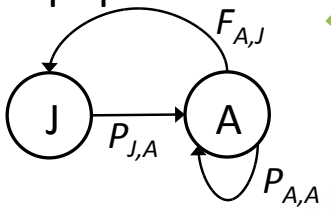
Individual

- **State**: sex, age/stage, position, traits, genes, etc.
  - ➢ can vary among individuals and/or across time
- **Behaviour/Processes**: reproduction, aging, maturing/developing, dispersal, mortality
  - ➢ can be dependent on current state and environment

RangeShiftR

- Simulating local population dynamics and dispersal

Local population dynamics described by population model, e.g. logistic growth or matrix population model



Dispersal described by dispersal kernel or movement simulator

Landscape can be described as patch-matrix landscapes, patch types of different quality, of grid cells of different quality

RangeShiftR – local population dynamics

- Option 1: Non-overlapping generations and no stage structure
  - Discrete generations
  - In each generation life cycle: reproduction, death of adults, offspring dispersal
  - Described by discrete form of logistic growth

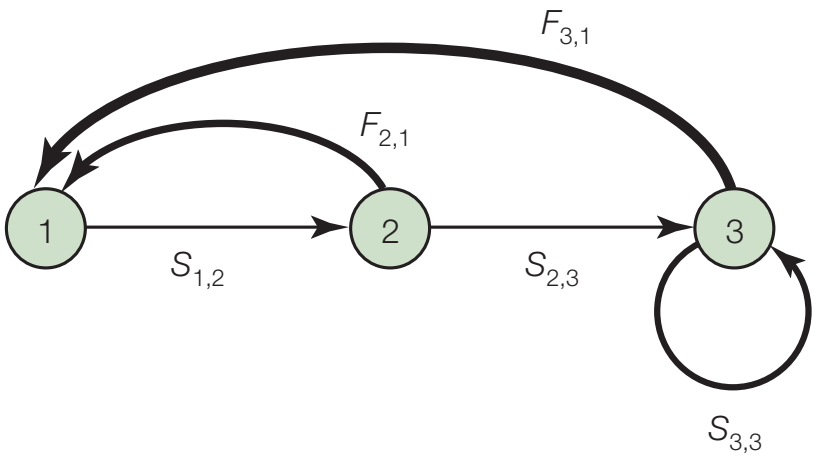
$$Poisson\left(\frac{R_{i,t}}{1+\left|R_{i,t}-1\right|*\left(\frac{N_{i,t}}{K_{i,t}}\right)^{bc}}\right)$$

  - Important: individual-based formulation, meaning the number of offspring produced by adult is drawn from random distribution

RangeShiftR – local population dynamics

- Option 2: overlapping generations and stage structure
  - Parameters provided through classical transition matrices (but applied stochastically)
  - Transition matrices can be age-structured (Leslie matrix) or stage-structured (Lefkovitch matrix)

Life-cycle graph:



Stages:

1. Juveniles / first-year birds do not breed
2. Second-year birds are inexperienced breeders
3. Mature adults are experience breeders

Transition rates:

- $F_{i,1}$ Fecundity
- $S_{i,j}$ Development rate (transition to next stage)
- $S_{i,i}$ Survival probability

With (2019) Oxford Univ. Press.

RangeShiftR – local population dynamics

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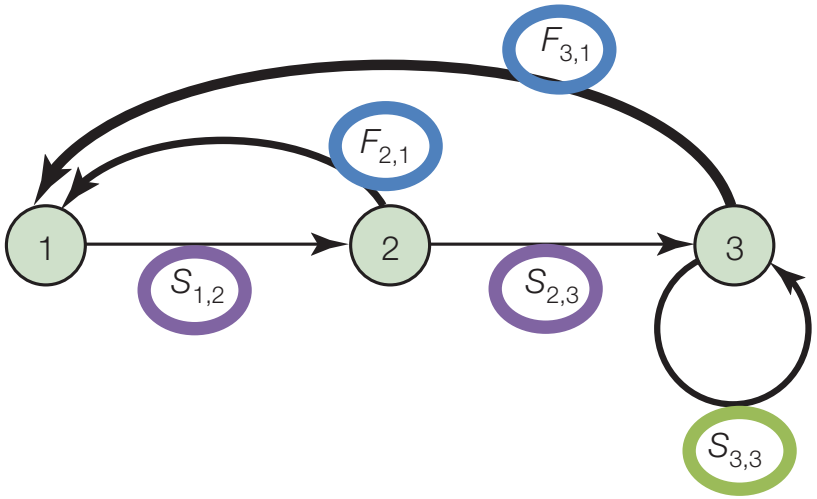
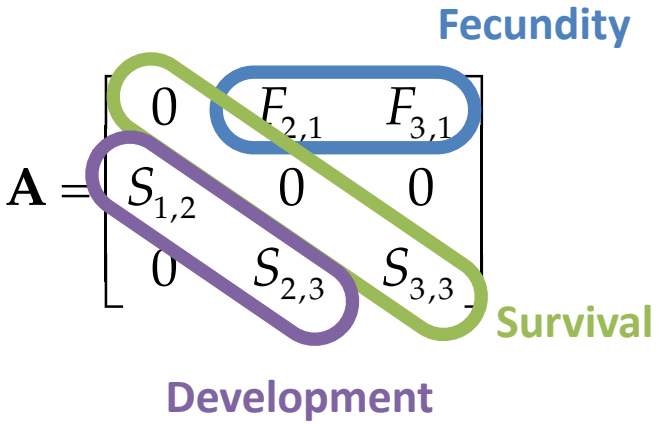


(Lefkovitch) Transition matrix:



With (2019) Oxford Univ. Press.

Dispersal

- Natal/juvenile dispersal: spatial process by which individuals move away from birth location
  - avoid kin competition, exploit new resources

- Critical for range expansion and spatial gene flow

- Associated with various costs and trade-offs that determine the eventual displacement distance
  - has impacts on both population dynamics and genetics

Dispersal

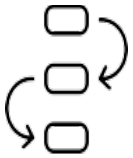
Fig. 1. Dispersing individuals are a nonrandom subset of the population.

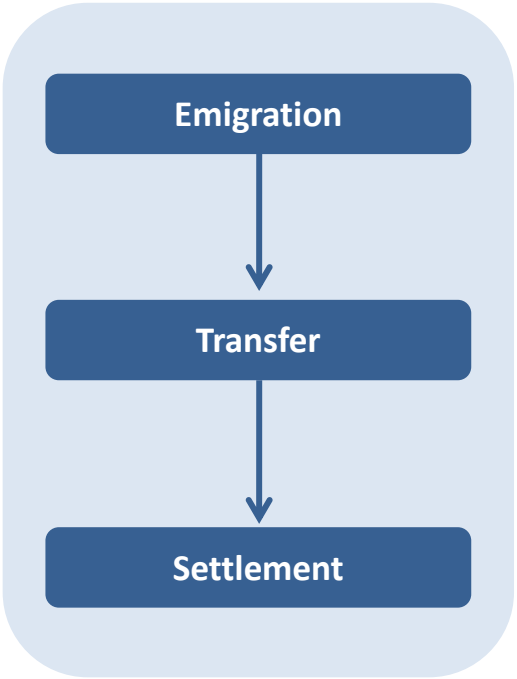
(**Left**) Dispersing females of the Glanville fritillary, Melitaea cinxia, have a higher flight metabolic rate and are more fecund than sedentary ones.

(**Right**) In Siberian jays, Perisoreus infaustus, the subordinate individuals disperse, whereas the heavier and more dominant remain in their natal territories.

Kokko & López-Sepulcre (2006) Science 313: 789-791.

RangeShiftR: three phases of dispersal



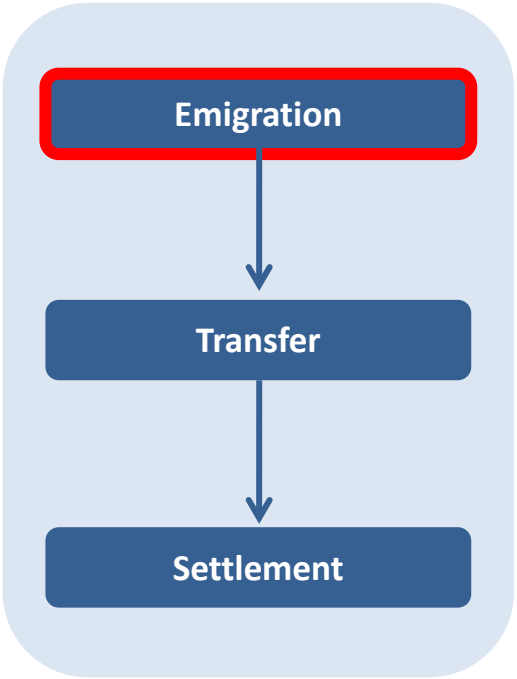


Leaving the natal site (area where born)

Movement through the landscape

Establish in a new habitat site /area

RangeShiftR: three phases of dispersal



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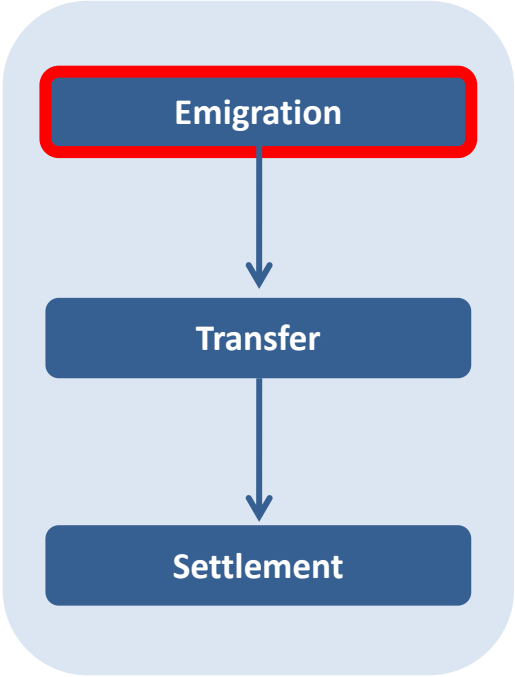
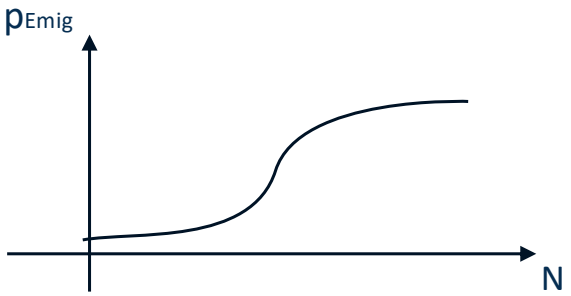
RangeShiftR: three phases of dispersal



Emigration probability:

- the probability that an individual will leave its natal patch during the present year
- can be density-dependent



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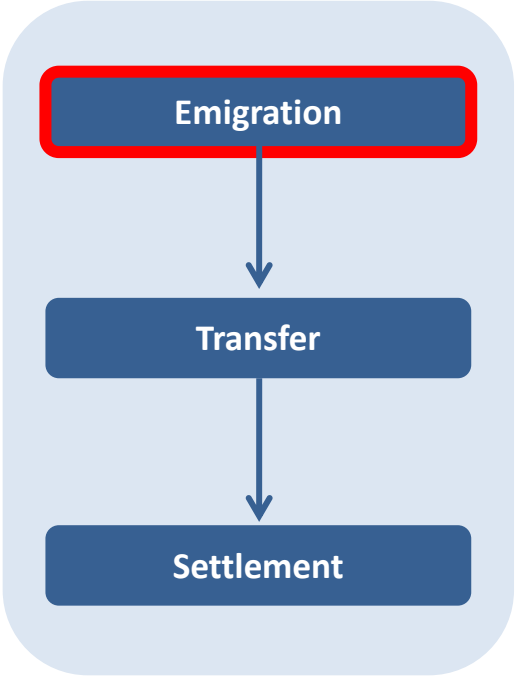

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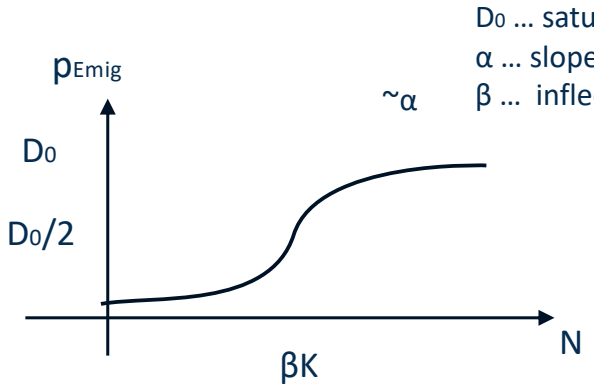
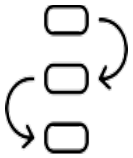
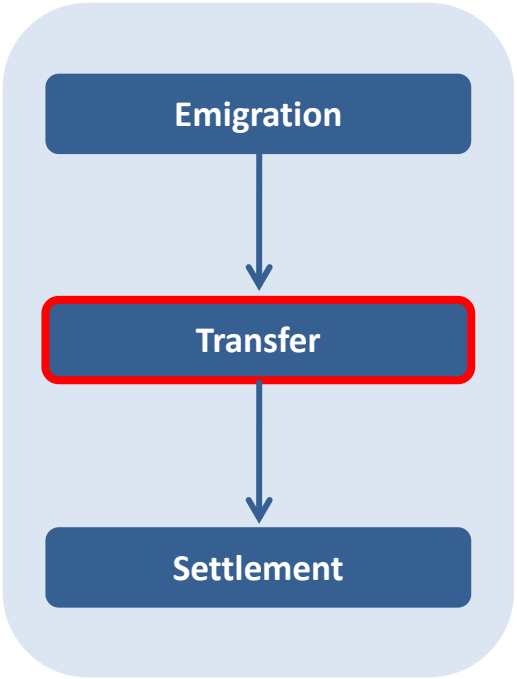


stage	sex	D0	α	β
0	0	0.4	10	1
0	1	0.9	10	1
…	…	…	…	…

sex = 0 … female
sex = 1 … male

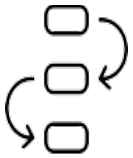
RangeShiftR: three phases of dispersal

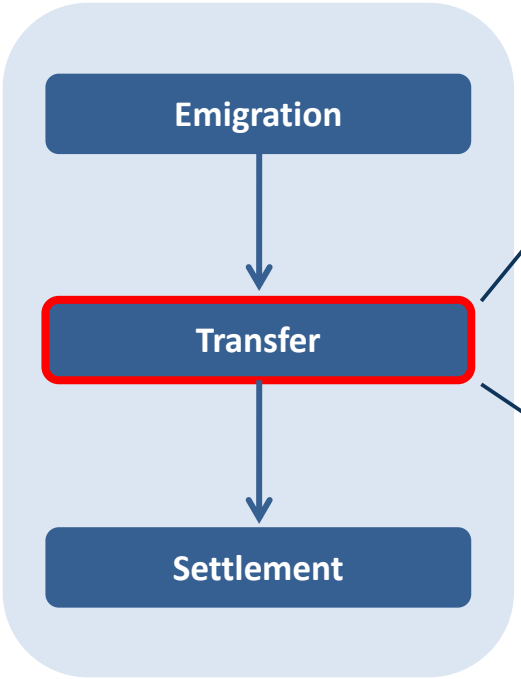




Movement through the landscape

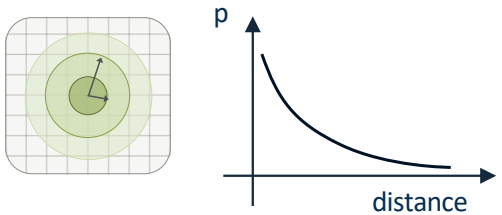
RangeShiftR: three phases of dispersal





Phenomenological models

e.g. Dispersal Kernel



Mechanistic models

e.g. Movement models:

step-wise processes that take perception and movement costs into account

RangeShiftR: mechanistic movement models

1.) Stochastic Movement Simulator

- step-wise process

Movement costs

3	4	1	0	0
1	1	3	3	5
2	3	1	1	4
1	1	0	0	0
5	4	1	0	0

Habitat cell

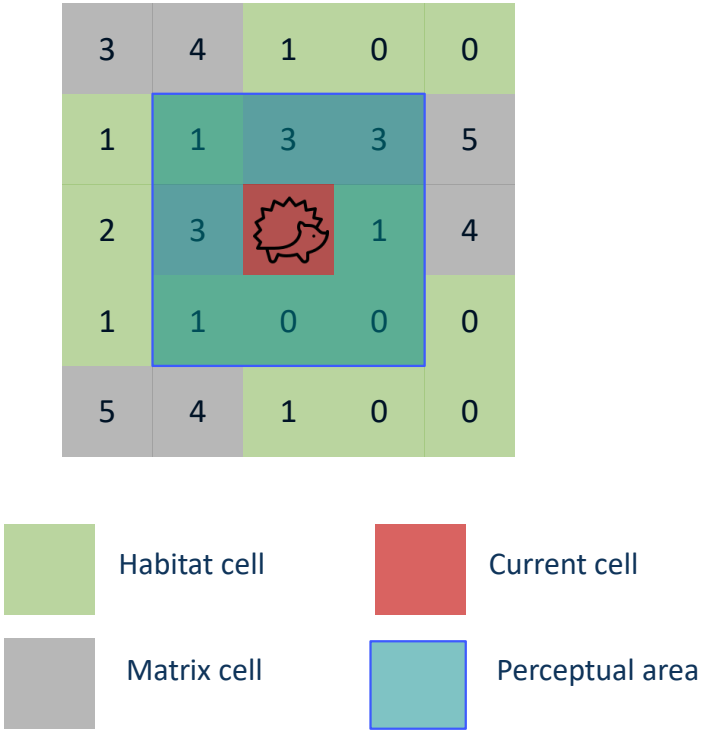
Matrix cell

RangeShiftR: mechanistic movement models

1.) Stochastic Movement Simulator

- step-wise process
- takes perception into account
  - perceptual range (e.g. 1 cell)

Movement costs

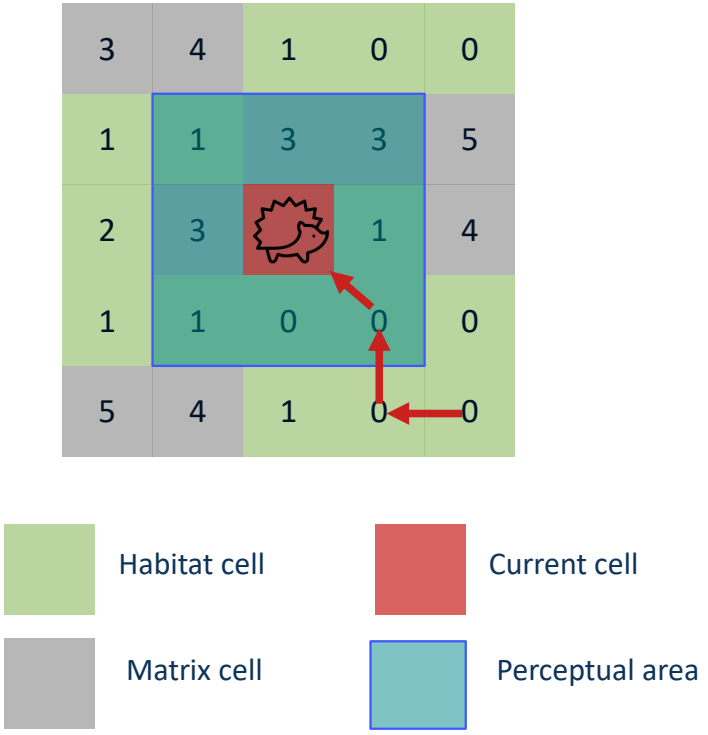


RangeShiftR: mechanistic movement models

1.) Stochastic Movement Simulator

- step-wise process
- takes perception into account
  - perceptual range (e.g. 1 cell)
- decision of next direction based on:
  - lowest average cost
  - preceeding steps in memory (e.g. 3 steps)
  - directional persistence

Movement costs



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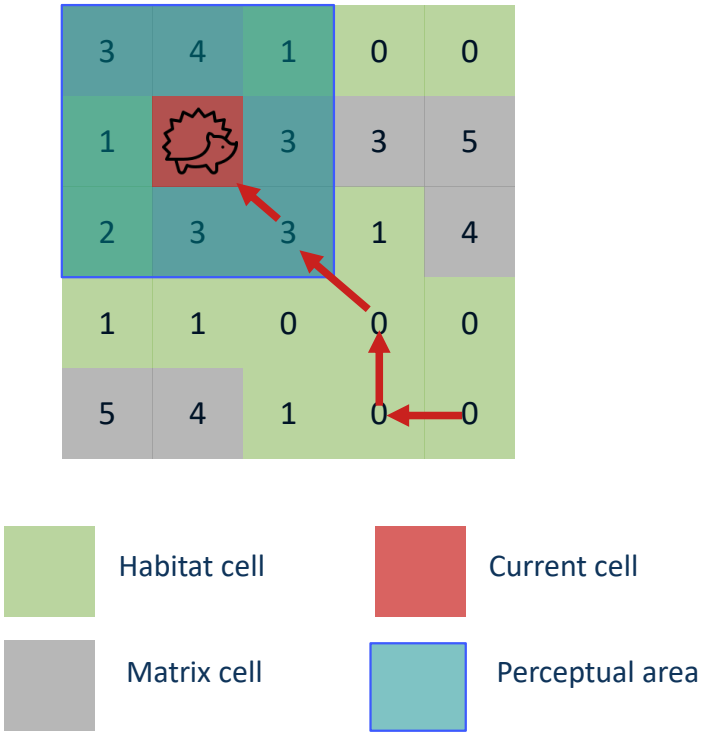
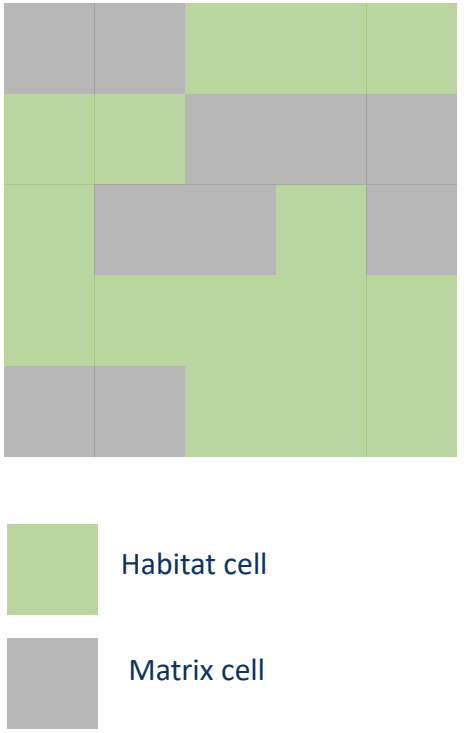


RangeShiftR: mechanistic movement models

2.) Correlated Random Walk

- step-wise process
- considers continuous space, not grid cells

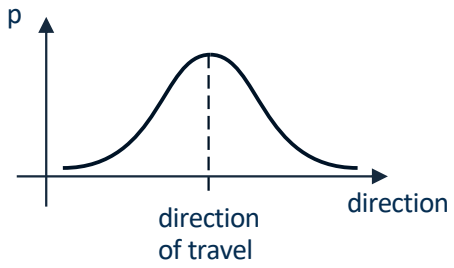
no consideration of costs



RangeShiftR: mechanistic movement models

2.) Correlated Random Walk

- step-wise process
- considers continuous space, not grid cells
- draws direction from a distribution:



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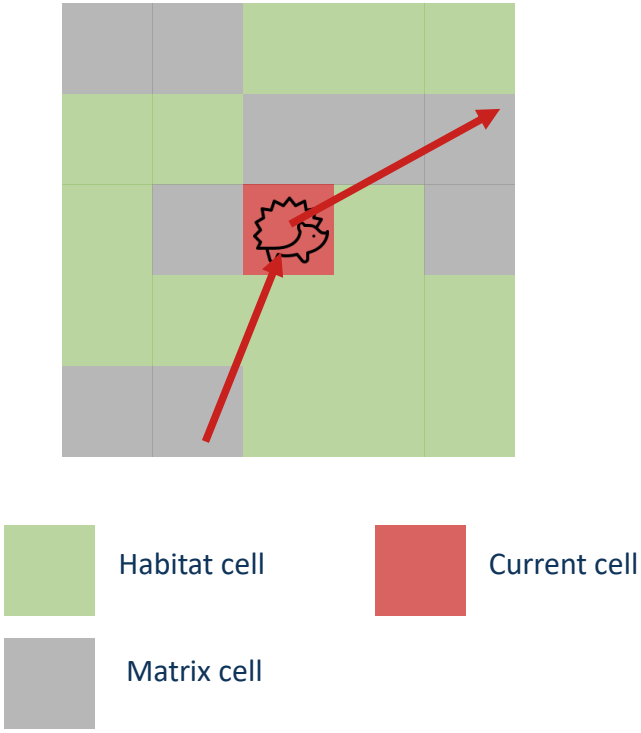
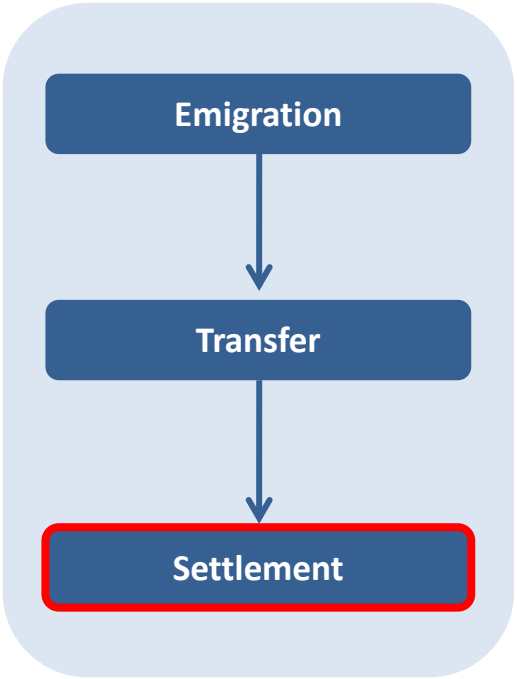
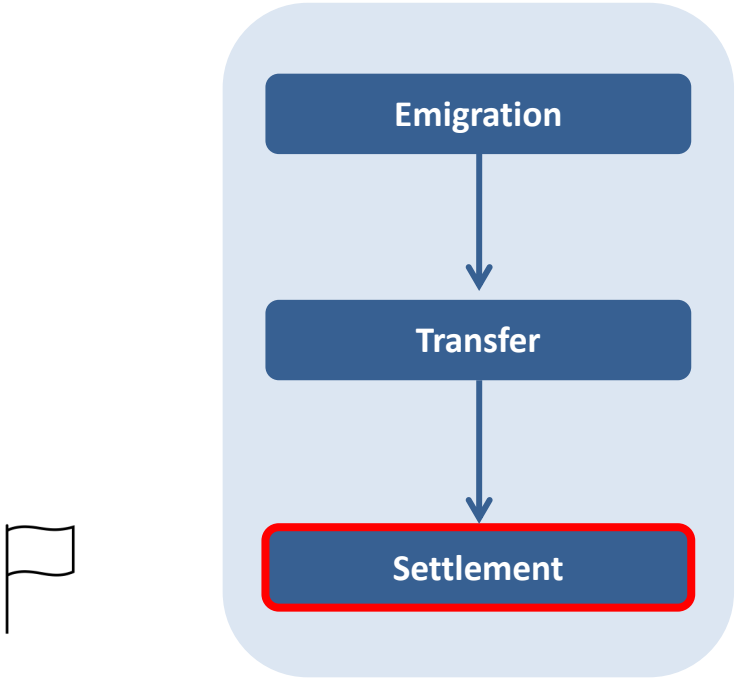


RangeShiftR: three phases of dispersal



Establish in a new habitat site /area

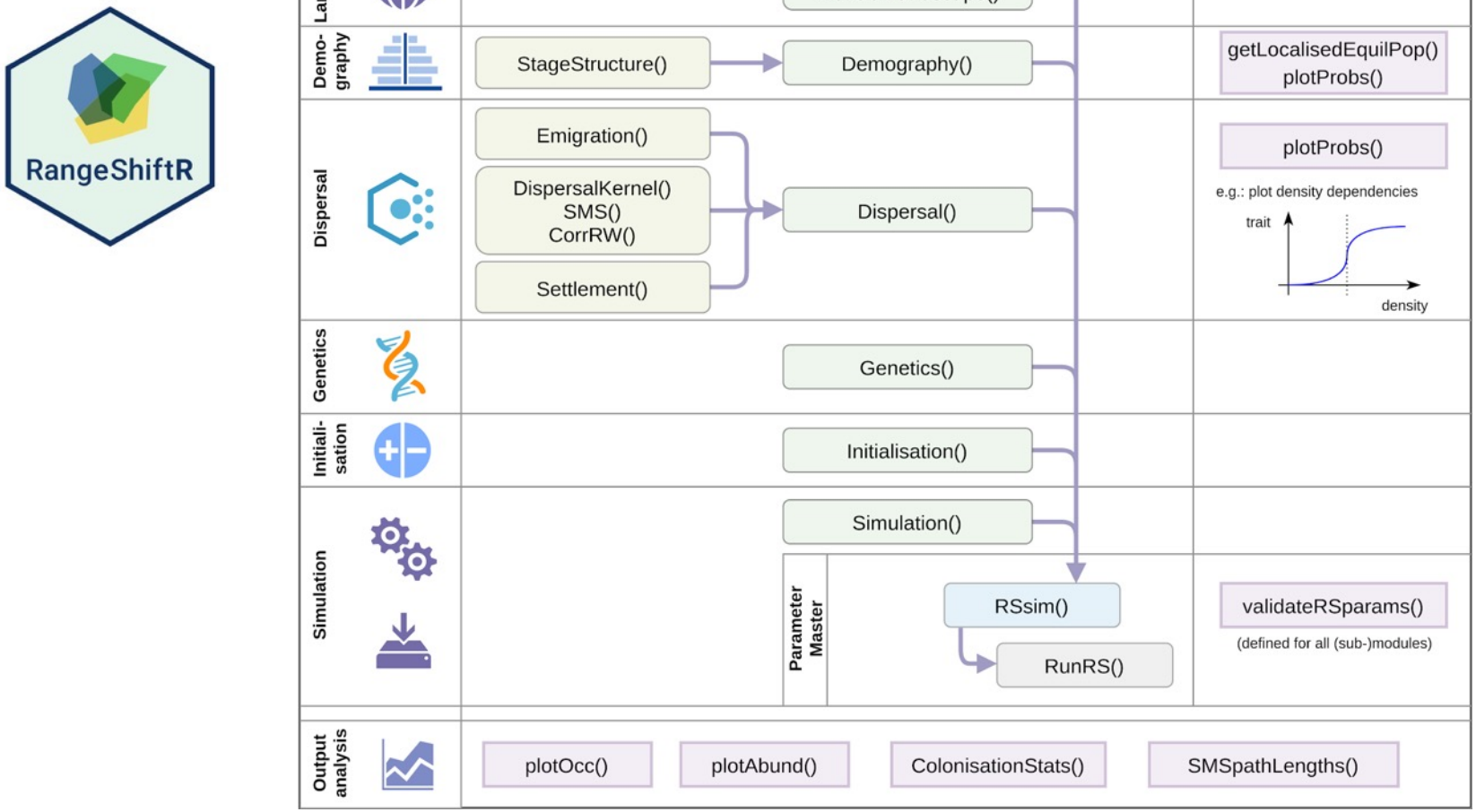
RangeShiftR: three phases of dispersal



Settlement probability:

- the probability that an individual will stay in a new habitat patch
- can be density-dependent (analogous to emigration probability)

RangeShiftR overview

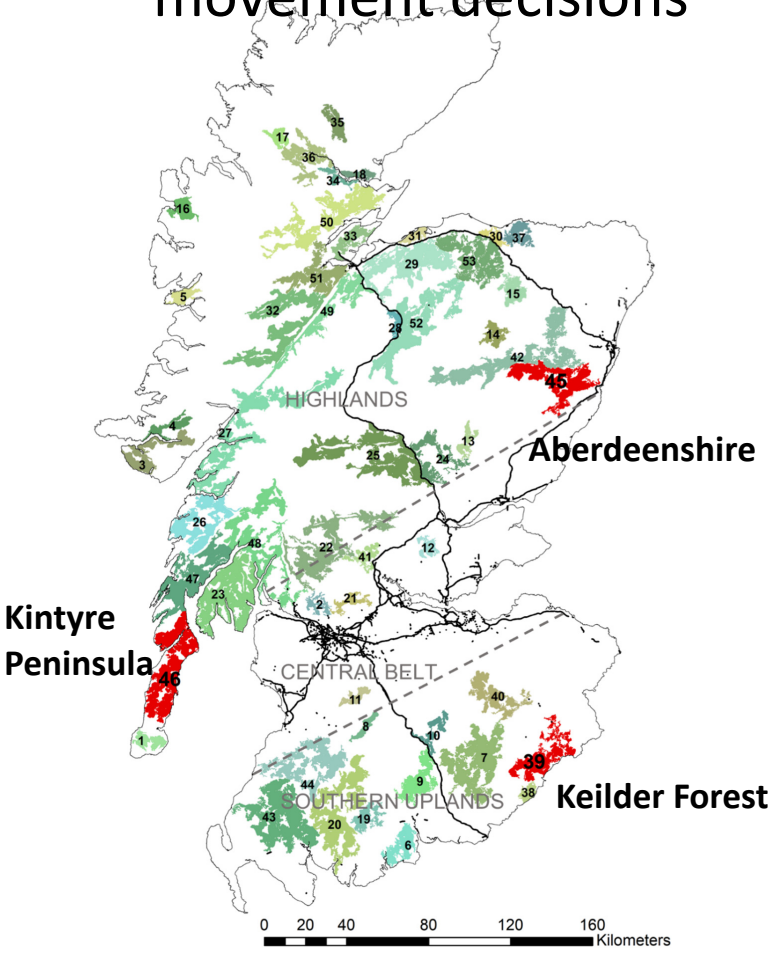


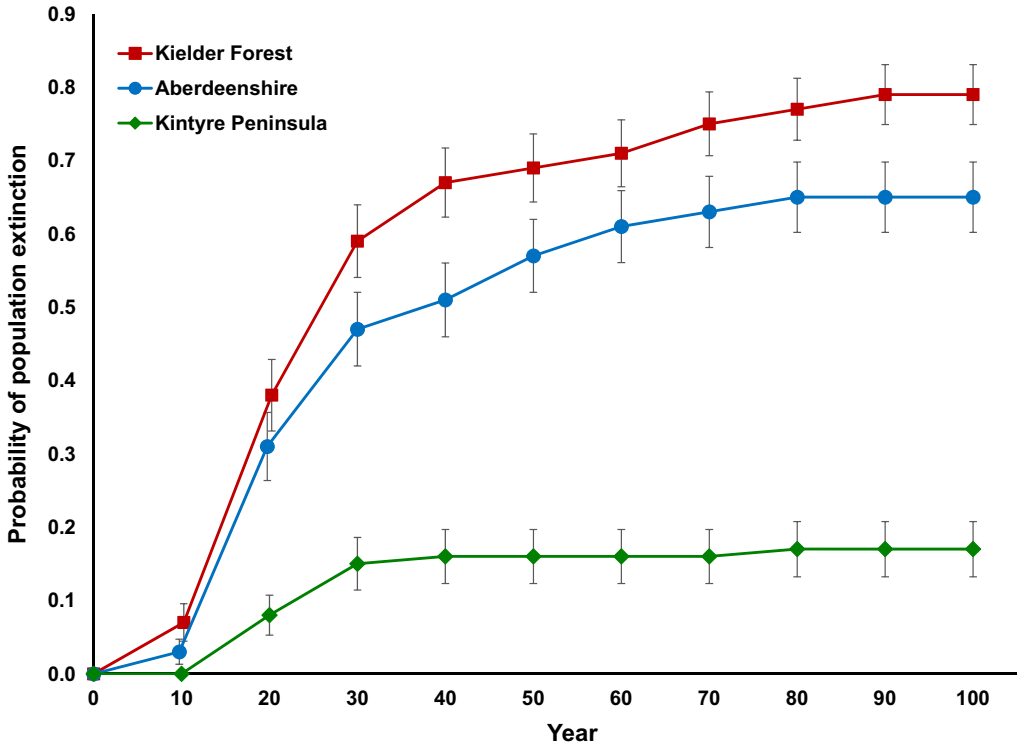
Malchow et al. (2021) Ecography. DOI: 10.1111/ecog.05689 .
Building on Bocedi et al. (2014) Methods Ecol Evol 5: 388-396. & Bocedi et al. (2021) Ecography. DOI: 10.1111/ecog.05687.

RangeShiftR case study

Example: Eurasian lynx, reintroduction Scotland

- Stage-structured model, individual-based movement decisions





Ovenden et al. (2019) Biol Cons 234: 140-153.

Thank you for your interest

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