Percolation, weeds and Bayesian inference - Assessing seed bank influence on plant metapopulation dynamics

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Apolline Louvet

Unité BioSP, Département SPE, INRAE Avignon

Joint work with Nathalie Machon (CESCO, MNHN), Clément Mantoux (INRIA Paris), Jean-Baptiste Mihoub (CESCO, MNHN), Alexandre Robert (CESCO, MNHN) et Amandine Véber (MAP5, Univ. Paris-Cité)

Motivations

Biological system of interest: spontaneous flora ("weeds") at the base of trees in streets

Motivations

Relevance in ecology:

- Potential ecological corridors between larger urban green spaces.
- Highly fragmented environment.
- Very frequent extinction events.

  Ex: Population wiped out once a year by gardeners.

[Maurel, 2010]: Urban tree bases contain fewer invasive species than natural environments

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Relevance for mathematicians:

- Equidistant patches along a line $\Longrightarrow$ Real-life stepping-stone model.
- Action of the gardeners $\Longrightarrow$ Non-overlapping generations.

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Relevance for researchers interested in dormancy:

? What is dormancy ?

What is dormancy ?

Dormancy is defined as a reversible state of reduced metabolic activity [Lennon et al., 2021]

- For bacteria: quiescence
- For insects: diapause
- For plants: seed-banking

⊖: No reproduction when in a dormant stage

⊕: Protection from adverse conditions affecting only active individuals

Example: Gardeners removing weeds from tree bases

$\Longrightarrow$ Possible bet-hedging strategy in disturbed environments

⚠Different possible types of seed banks

- Transient seed bank: < 1 generation (*e.g.*, during winter) $\Longrightarrow$ Not the focus of this talk
- "Actual" seed bank: ≥ 1 generations

Seed bank detection

? How to detect whether a seed bank is present ?

- Direct observation [Baskin and Baskin, 2000]
  - Sort seeds in soil sample
  - Place them in germination chambers

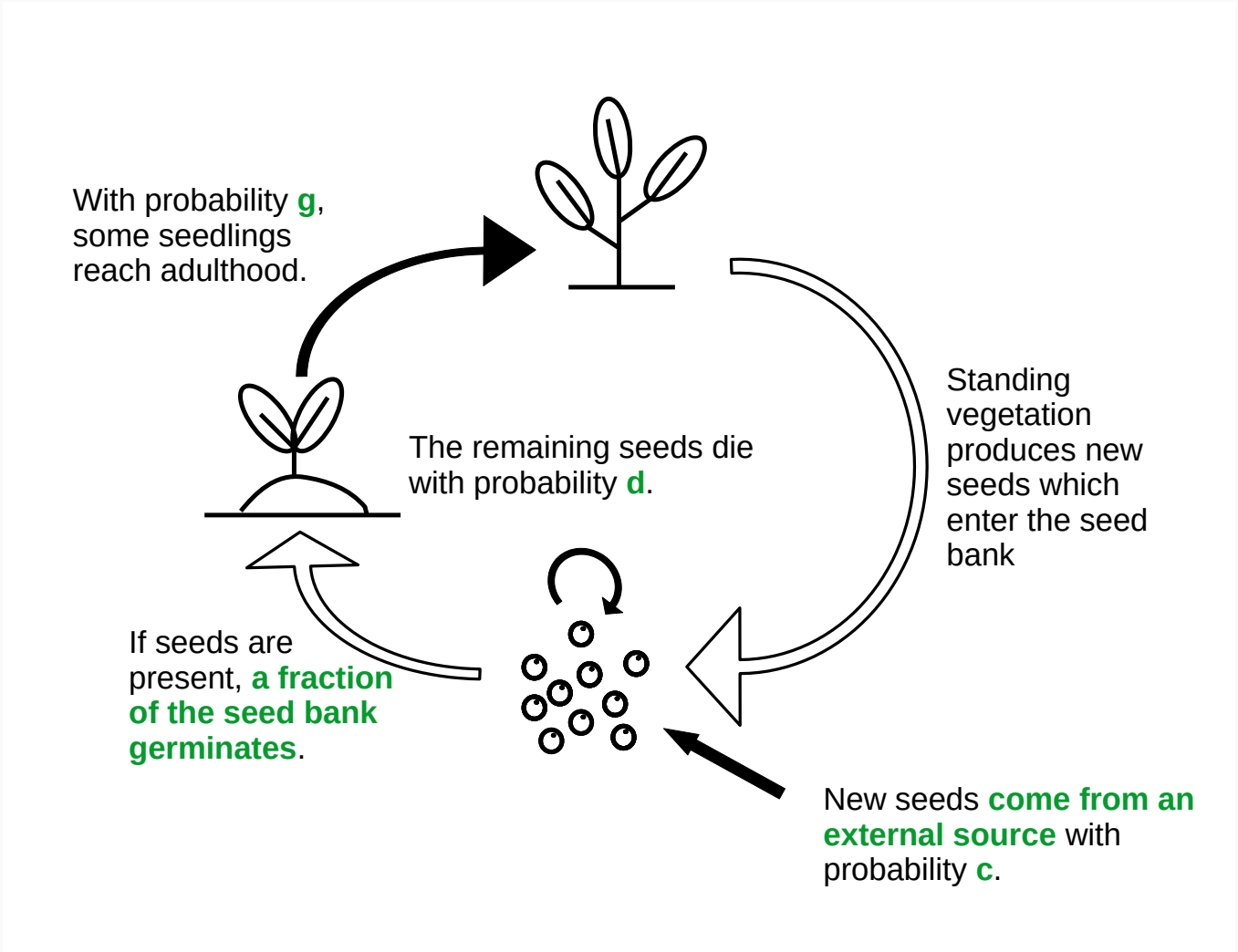
⚠ Very costly and time-intensive

⚠ What seeds would have actually germinated in tree bases ?

- Indirect observation via its effect on easier to observe variables
  - [Le Coz et al., 2019]: abundance data
  - [Blath et al., 2020]: genetic diversity
  - [Pluntz et al., 2018]: presence/absence data

Modelling framework: The PRM with seed bank

[Pluntz et al., 2018]: Introduces a variant of the Propagule Rain Model (PRM, [Gotelli, 1991]) with a seed bank component



Seed bank detection with the PRM-SB

$d = 1$: No seed bank

VS

$d < 1$: Presence of a seed bank

$\Longrightarrow$ Seed bank detection possible by **estimating the parameters** of the underlying PRM-SB model

Presence/absence of plants: Observed

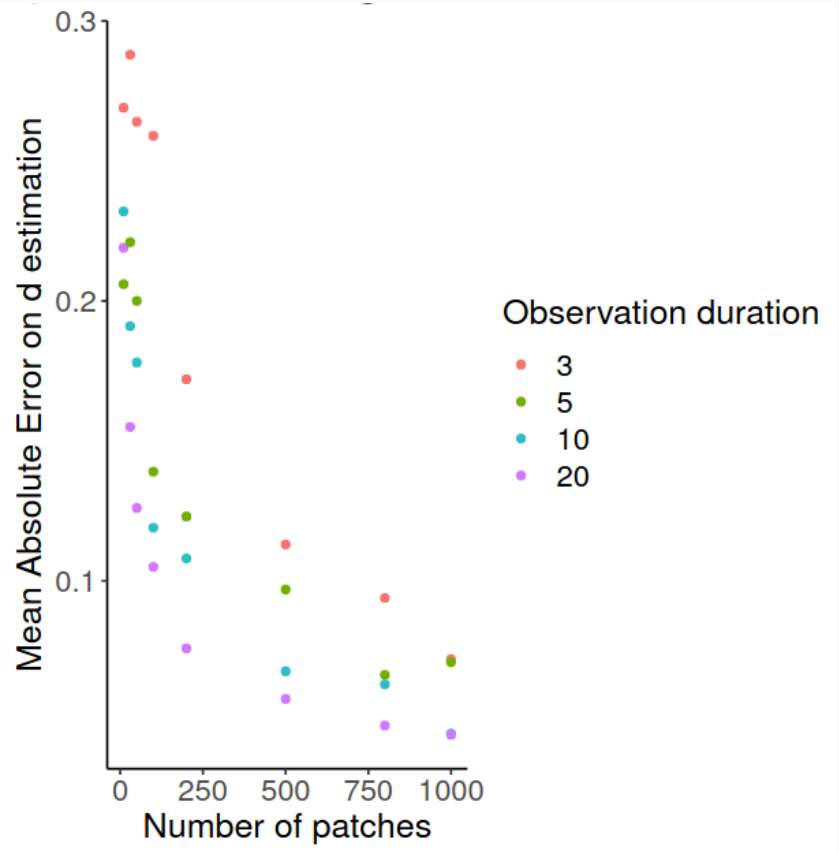
Presence/absence of seeds: Hidden, but **influences the observed state**

$\Longrightarrow$ **Hidden Markov Model**, possible to use classical estimation methods for such models

⚠With this estimation method,

estimation of g > estimation of c > estimation of d

Why is d ill-estimated ?



Whenever colonisation/non-extinction occurs, new seeds enter the seed bank, and its **previous state is erased**

$\Longrightarrow$ For some parameter sets, the seed bank is "masked"

$\ominus$ Hard to estimate dormancy parameters

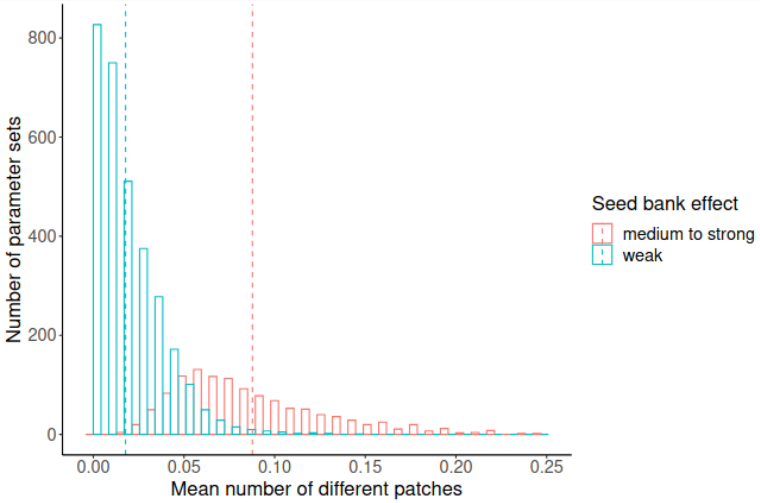
$\oplus$ The seed bank has a **limited effect on the observed dynamics**

The SBCE probability

SBCE probability: [Louvet et al., 2021] Measure **how "visible" is the seed bank in plant observations**

$$\mathbb{P}_{SBCE} = g \times \frac{(1-g)(1-c)(1-d)}{1-(1-g)(1-c)(1-d)}$$

"probability of delayed germination, without colonisation events occurring in the meantime"



$\approx$ error rate made when approximating a PRM-SB with parameters (g, c, d) by one with parameters $(g, c, 1)$

Application - The *Paris 12* dataset

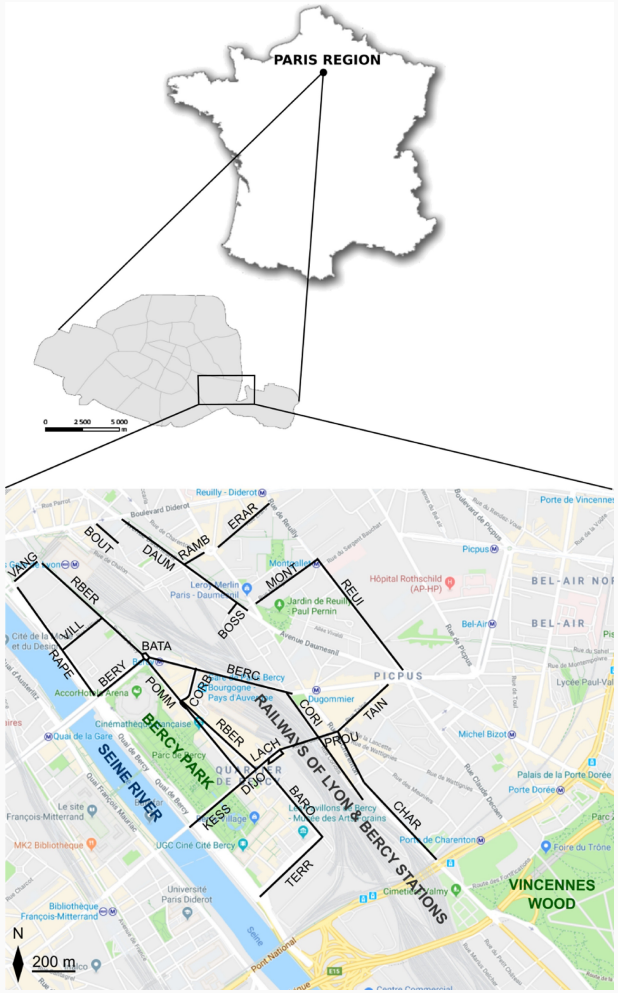
- > 1300 tree bases in 14 streets in Paris
- **Floristic inventories** carried out annually from 2009 to 2018
  - All years except 2013: All species inventoried
  - 2013: Only ~ 10 species inventoried

$\Longrightarrow$ **Presence/absence data**

1 **pair (species, street)**

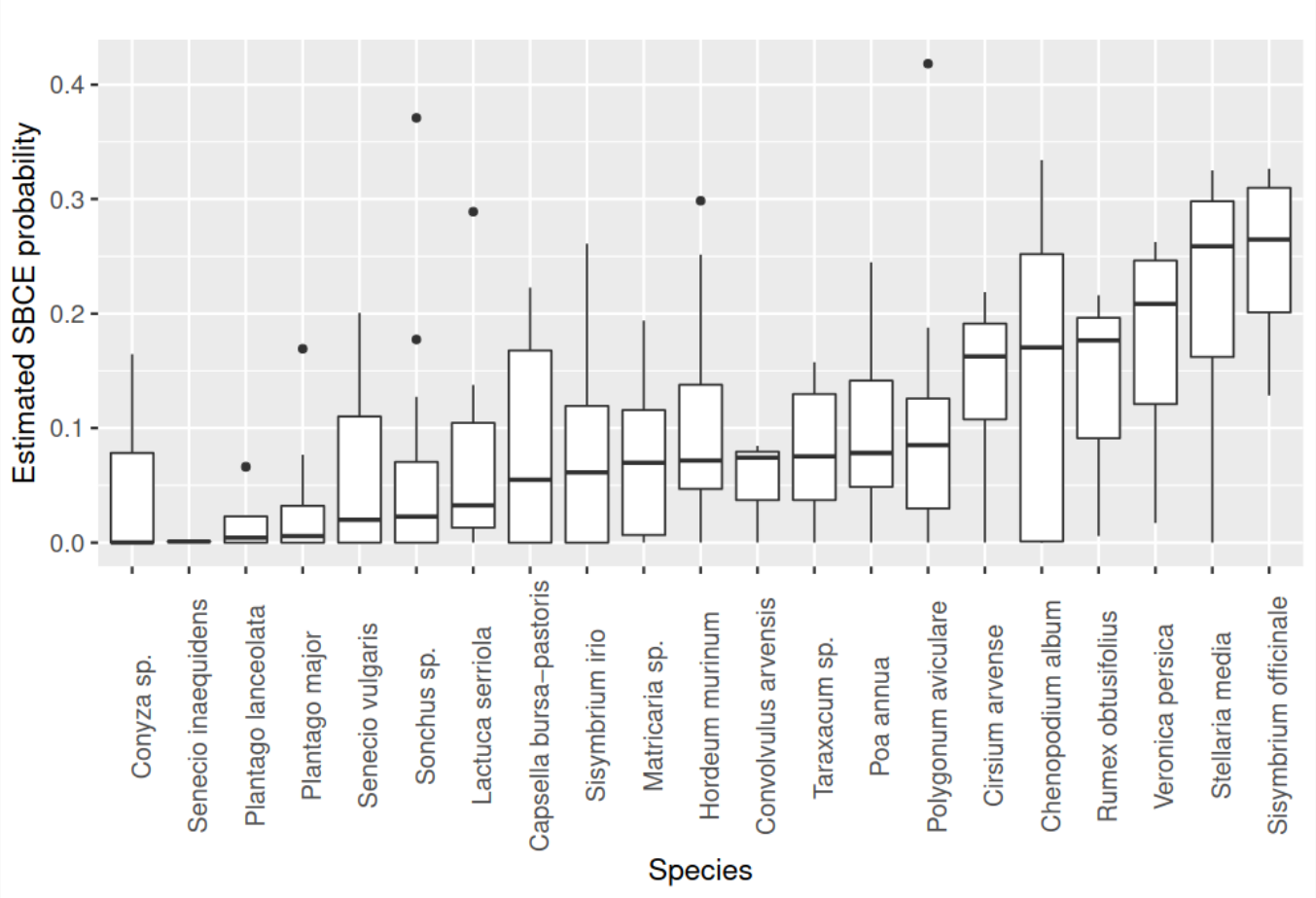
=

1 **metapopulation**



Application - The *Paris 12* dataset

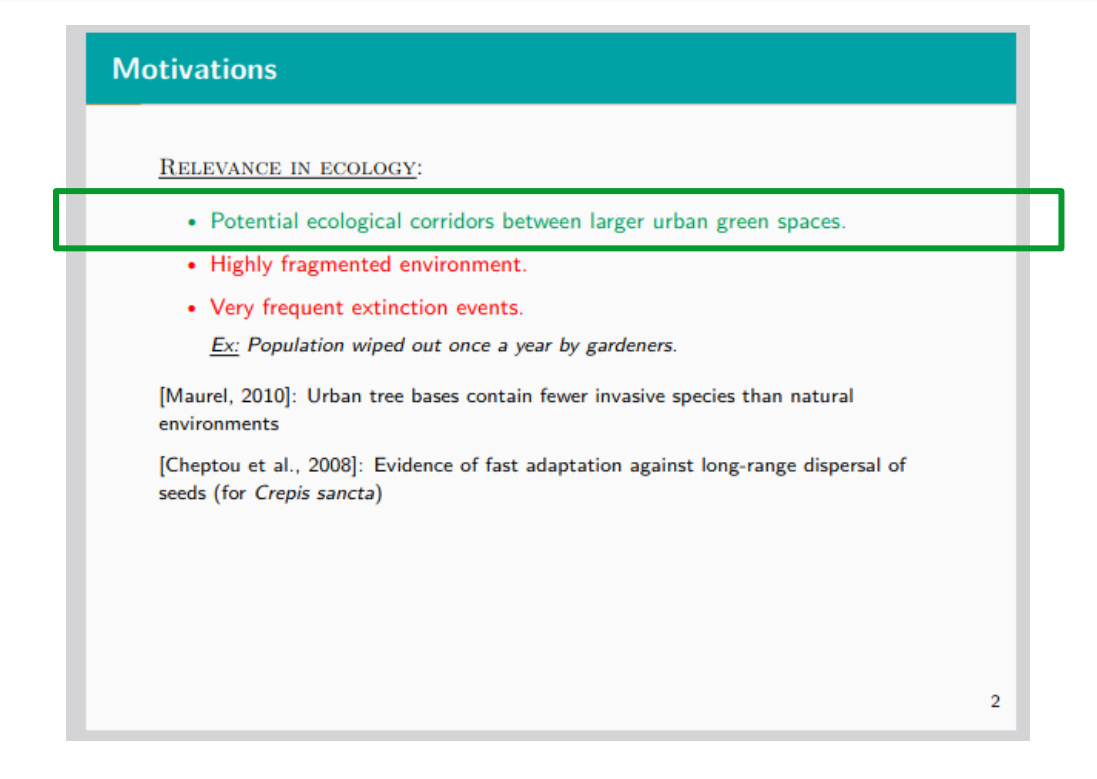
Results: Distribution of estimated $\mathbb{P}_{SBCE}$ across streets for each species



$\Longrightarrow$ For some species, dormancy has a **significant effect** on the **observed plant metapopulation dynamics**

⚠ *No explicit spatial structure/inter-patch colonisation dynamics in the PRM-SB*

Identification of ecological corridors



Motivations

RELEVANCE IN ECOLOGY:

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2

? **Are urban tree bases used as ecological corridors by weeds ?**

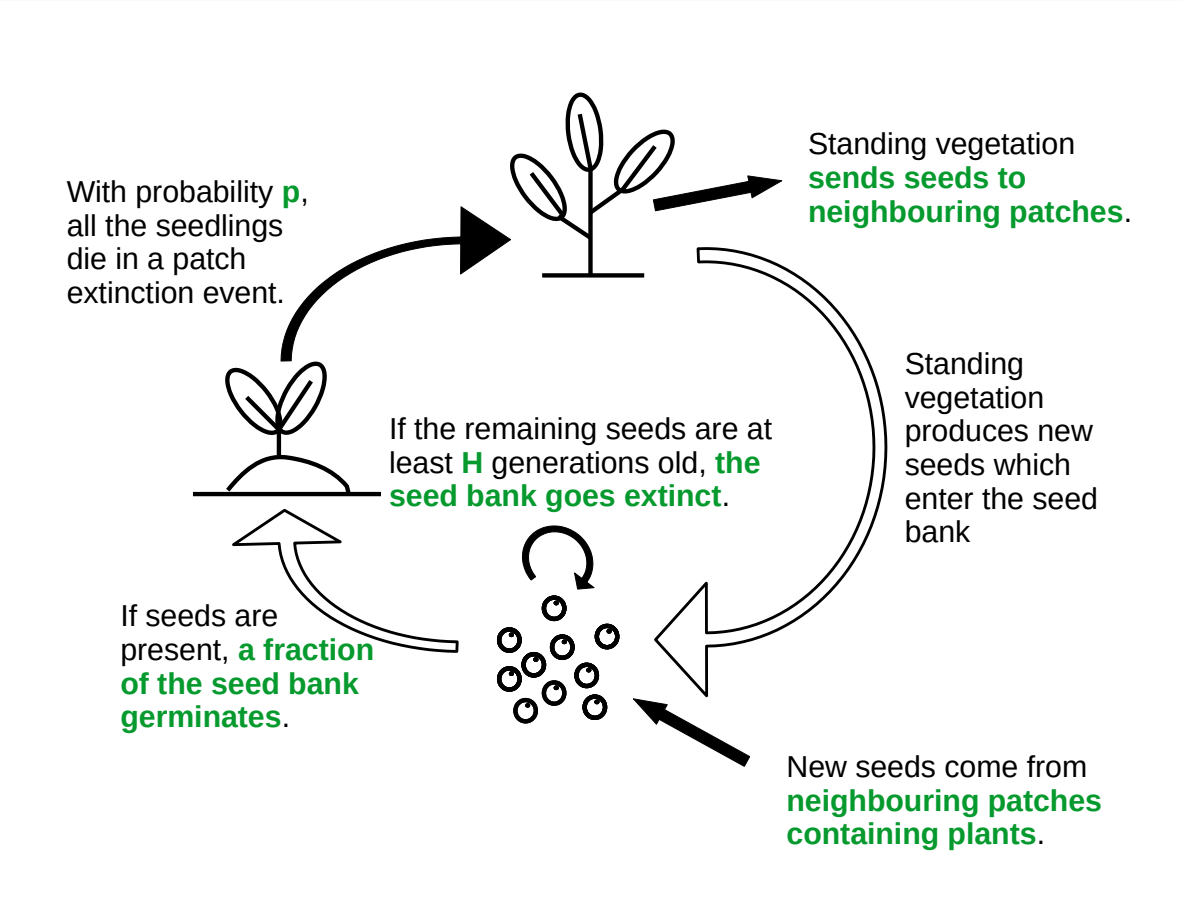
[Dornier et al., 2011, Omar et al., 2019]: Results obtained using a **Levins model** [Levins, 1969]

⚠ No seed bank, and by [Louvet et al., 2021], dormancy has to be taken into account for at least some species

$\Longrightarrow$ Introduction of a **variant of the Levins model with a seed bank component**

The BOA process

The **BOA** (or *Best Occupancy Achievable*) process is a variant of the **Levins model** [Levins, 1969] with simplified inter-patch colonisation dynamics and a **seed bank component**.



Introduced in [Louvet, 2022] as the large population limit of a (meta)population genetics process with intra-patch dynamics given by a Wright-Fisher model with a seed bank component and recurrent patch extinction events.

BOA process and identification of ecological corridors

? How to use the BOA process to identify ecological corridors ?

Idea:

Ecological corridor

$\Longleftrightarrow$

The BOA process survives forever
with non-zero probability

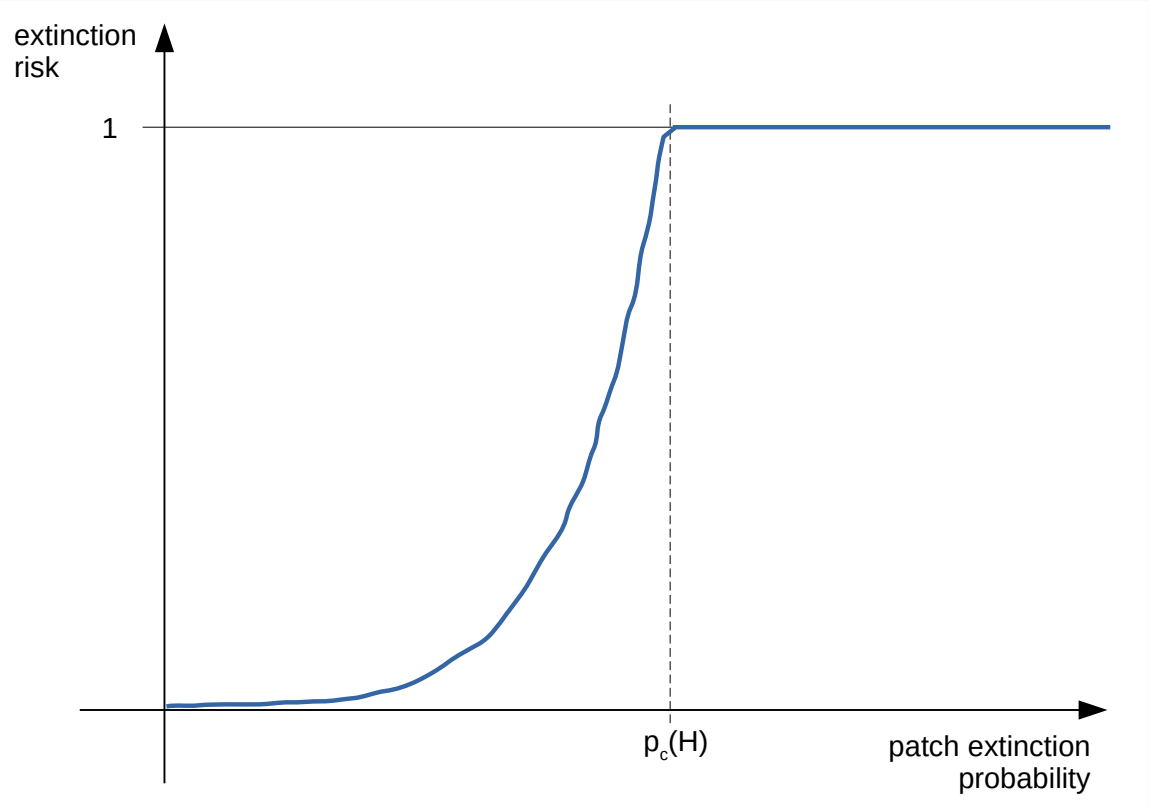
⚠Survival probability of the BOA process given estimates of model parameters?

- "Brute-force" approach: Do a lot of simulations.
- Percolation approach: Introduce a **metric of the extinction risk** based on a result from percolation theory.

Percolation approach for the assessment the extinction risk

Theorem [Louvet, 2022]

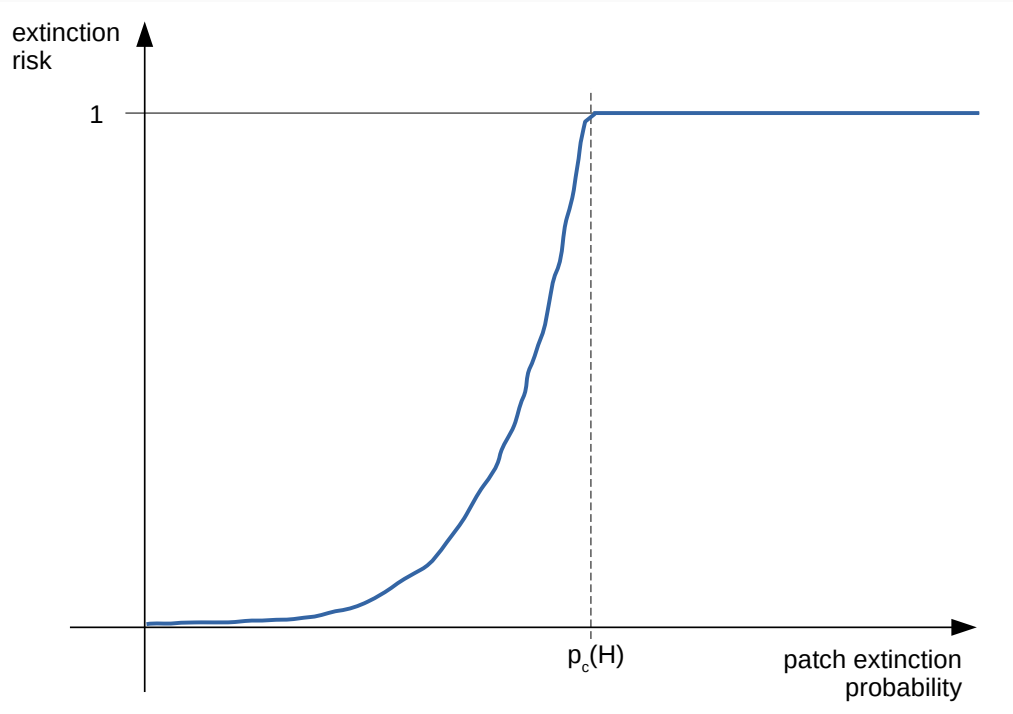
For all $H \geq 0$, there exists $p_c(H) \in (0,1)$ such that:
- If $p > p_c(H)$, the BOA process goes extinct in finite time a.s.
- If $p < p_c(H)$, the BOA process survives with a non-zero probability that increases with $|p - p_c(H)|$



Percolation approach for the assessment the extinction risk

⚠**Qualitative result**: No explicit expression for the extinction probability at the metapopulation scale

⚠**Threshold effect**: Need to account for the uncertainty on the estimates of p and H



Additional issues with the estimation of H:

- Unless p is very low, the cases $H = 0$ and $H \neq 0$ can easily be differentiated
- However, long dormancy durations only have a limited impact on the observed dynamics

Percolation approach for the assessment the extinction risk

⚠**Qualitative result**: No explicit expression for the extinction probability at the metapopulation scale

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Solution: The MaxGER metric

$\Longrightarrow$ The MaxGER metric is defined as

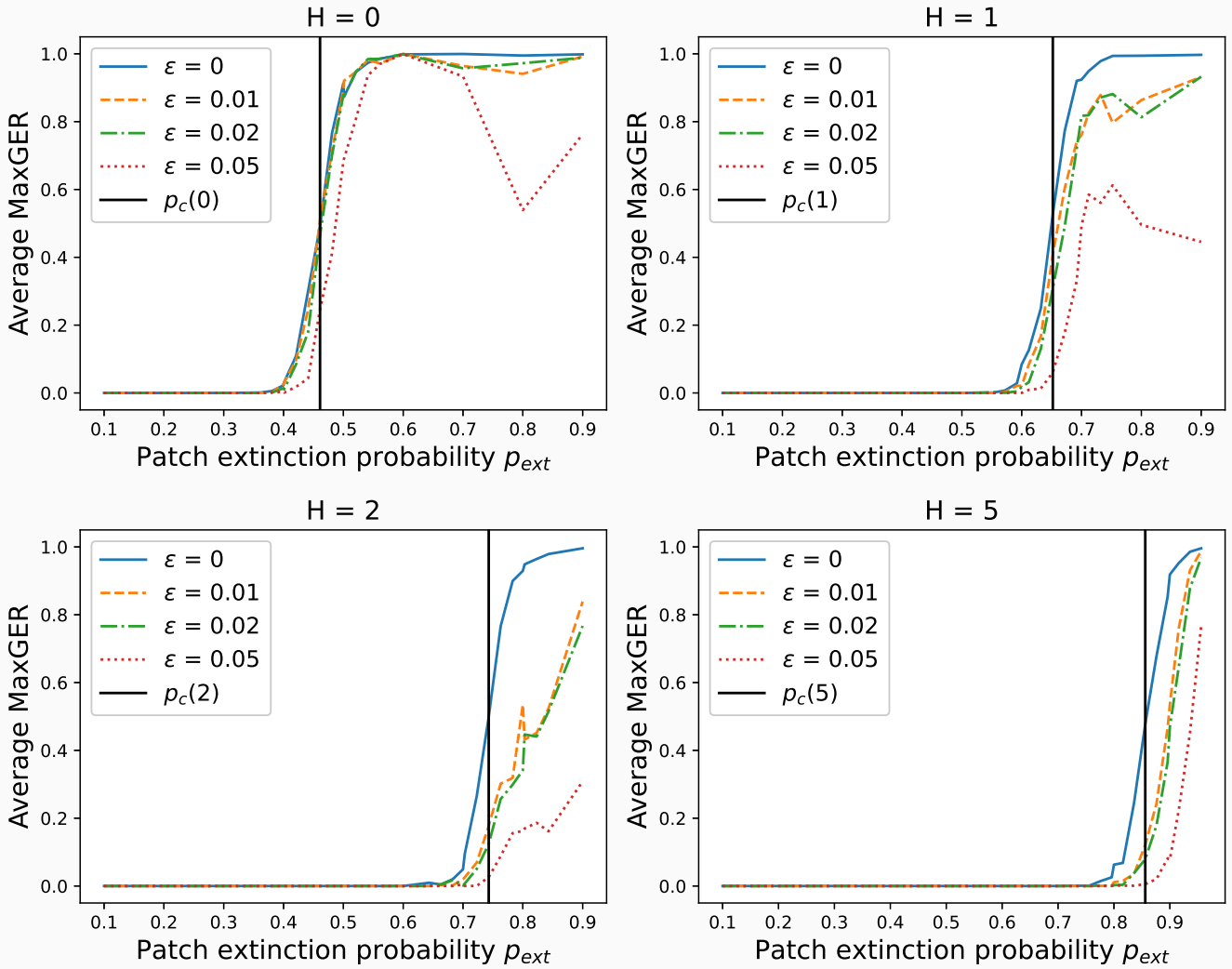
$$\text{MaxGER} := \mathbb{P}_{post}\left(p > p_c(H) \middle| H = H_{inf}\right),$$

where

$$H_{inf} := \min\left\{\widehat{H} \geq 0 : \mathbb{P}_{post}\left(H \leq \widehat{H}\right) \geq 0.05\right\}.$$

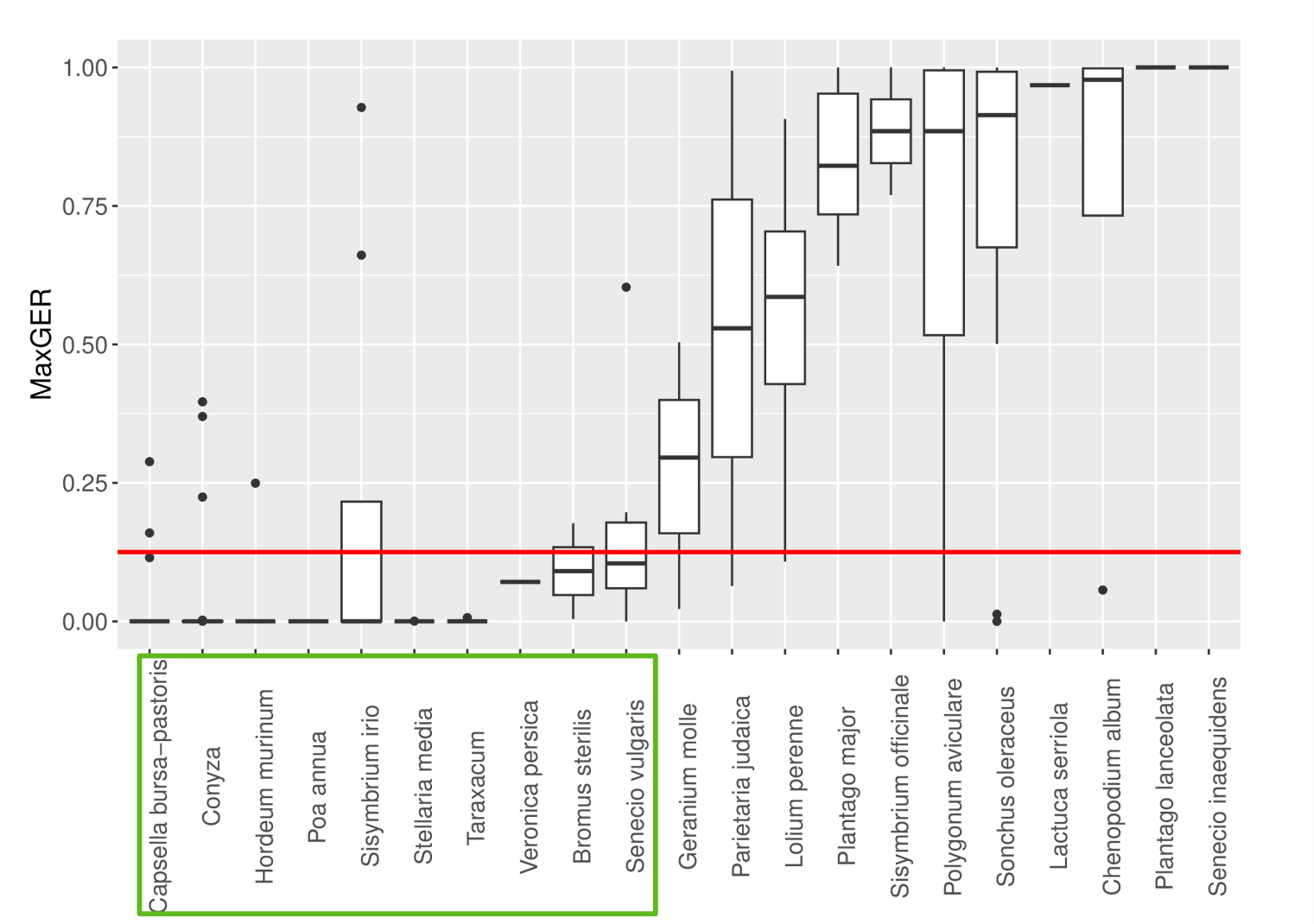
Assessment of the performance of the MaxGER metric

Assessment of the performance of the MaxGER metric on simulated datasets, generated using a BOA process ($\epsilon = 0$) and including an error rate when recording data ($\epsilon =$ 0.01, 0.02, 0.05).



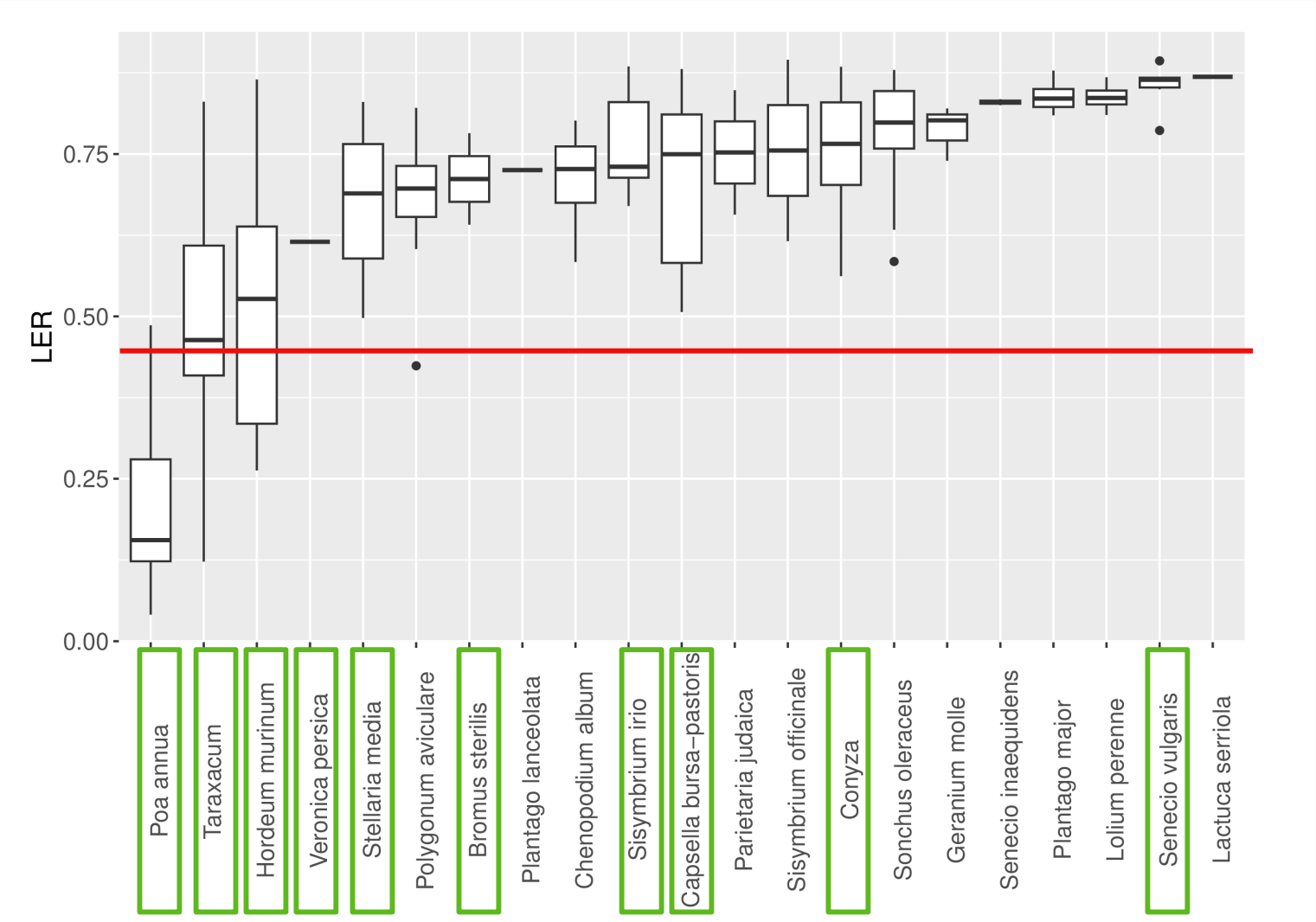
Results

① Some species **are able** to use tree bases as ecological corridors



Results

② Dormancy **is important** for survival in tree bases



LER: Local Extinction Risk, i.e., estimated patch extinction probability

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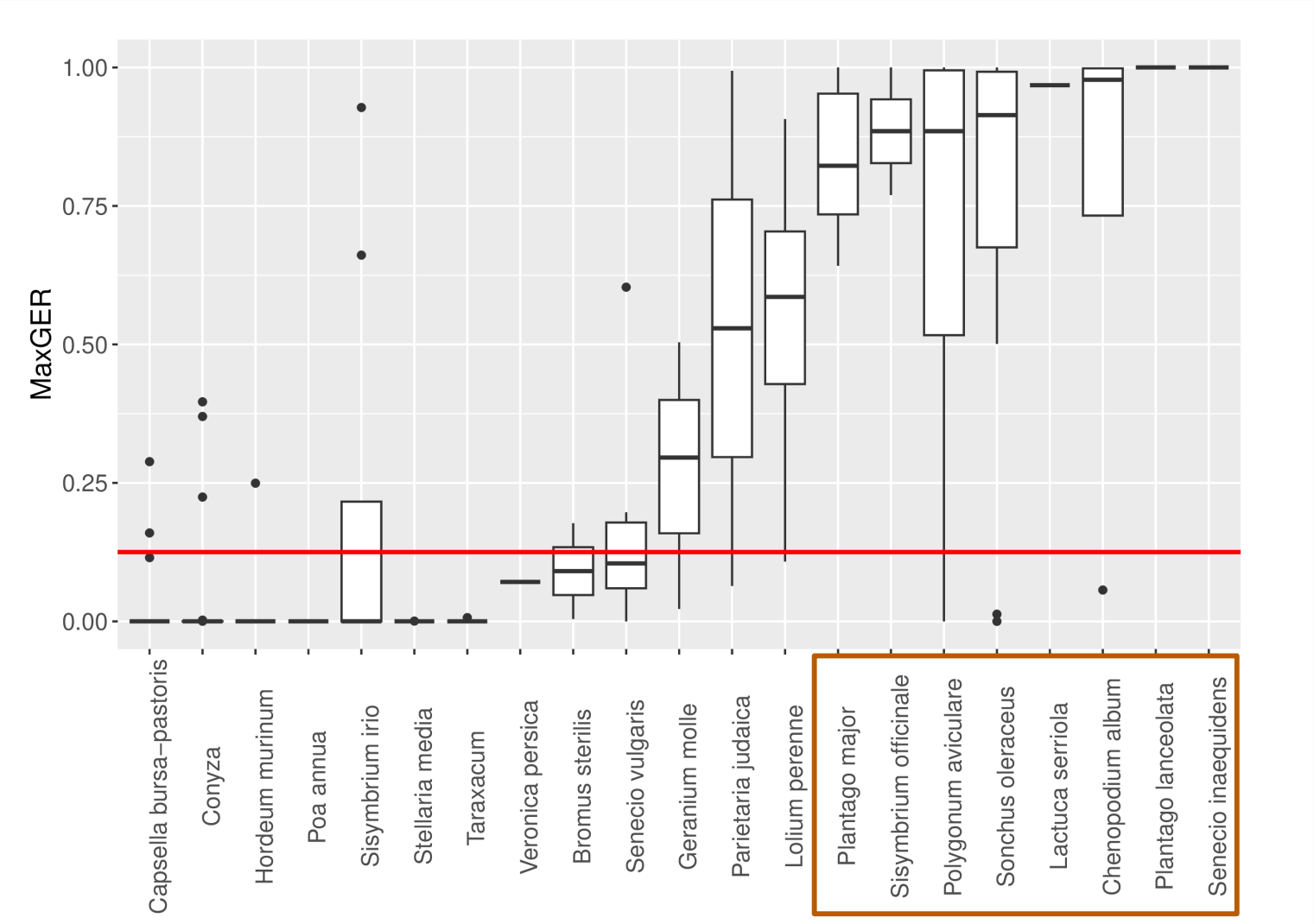

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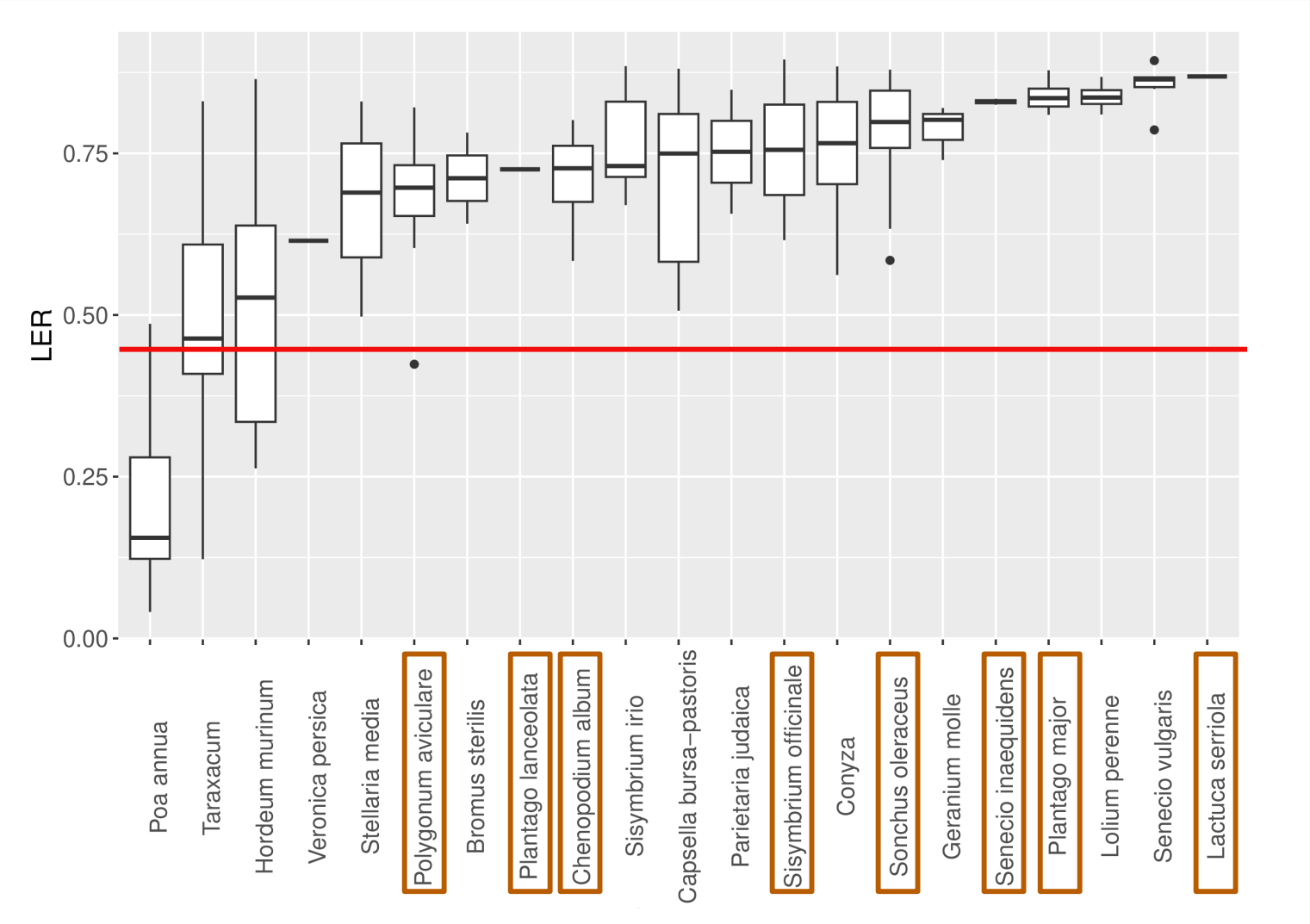
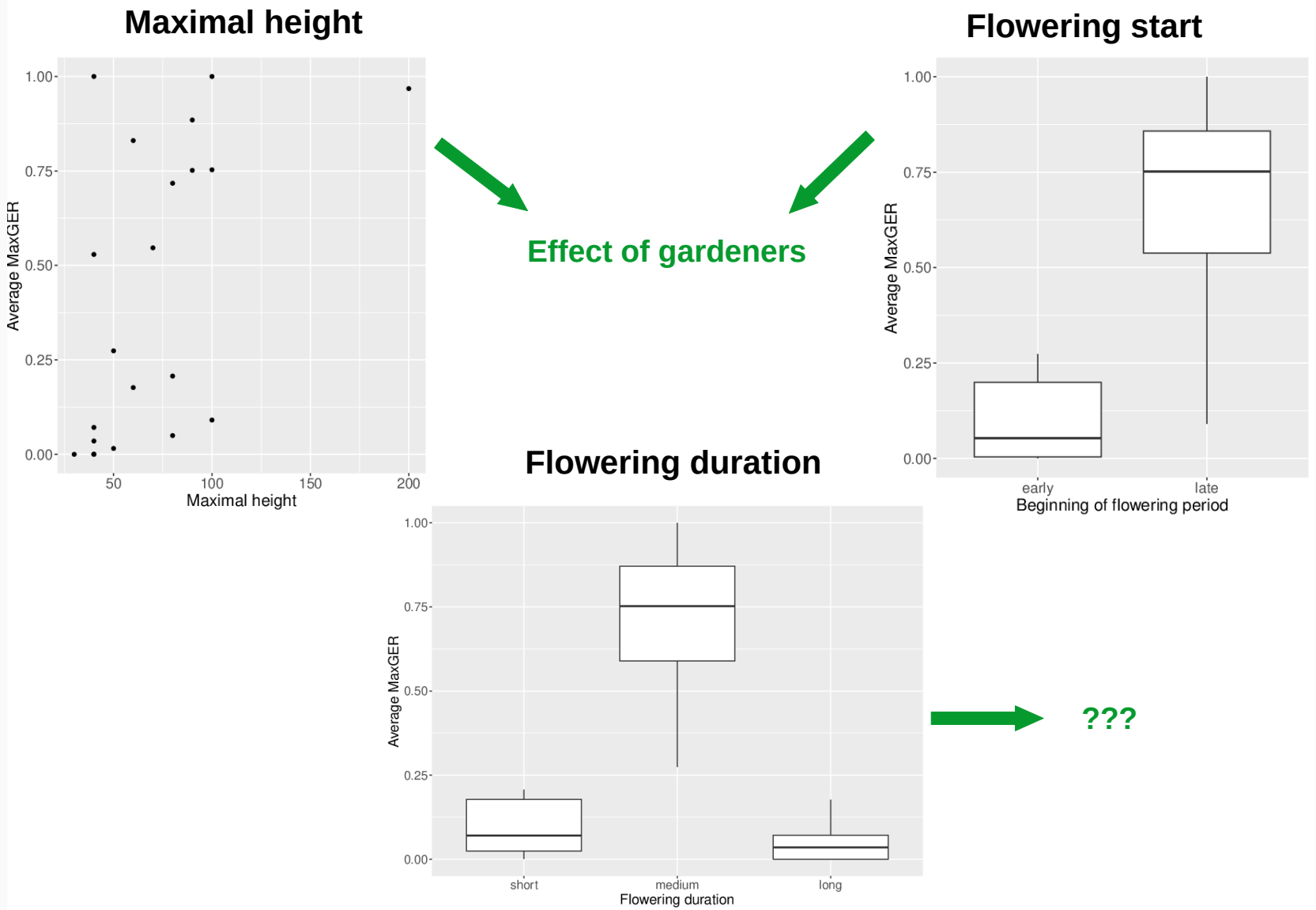


Influence of other biological traits

Plant trait	Values taken
Dispersal mechanism	Anemochorous (by wind) Barochorous (by gravity) Epizoochorous (by animals, without ingestion) Autochorous (by the plant)
Flowering duration	Short (≤ 3 months) Medium (≥ 4 and ≤ 6 months) Long (≥ 7 months)
Seed mass	Quantitative variable (in grams)
Heat preference	Sensitive (Ellenberg value ≤ 6) Resistance (Ellenberg value ≥ 7)
Pollination vector	Insect Wind Selfed
Maximal height	Quantitative variable (in centimeters)
Beginning of flowering period	Early (in April or earlier) Late (in May or later)

Results

③ Three other correlations identified



Results - Summary

① **Are urban tree bases used as ecological corridors ?**

$\Longrightarrow$ **Yes** (for some species)

② **Is dormancy important ?**

$\Longrightarrow$ **Even more than expected**

③ **Are other traits important ?**

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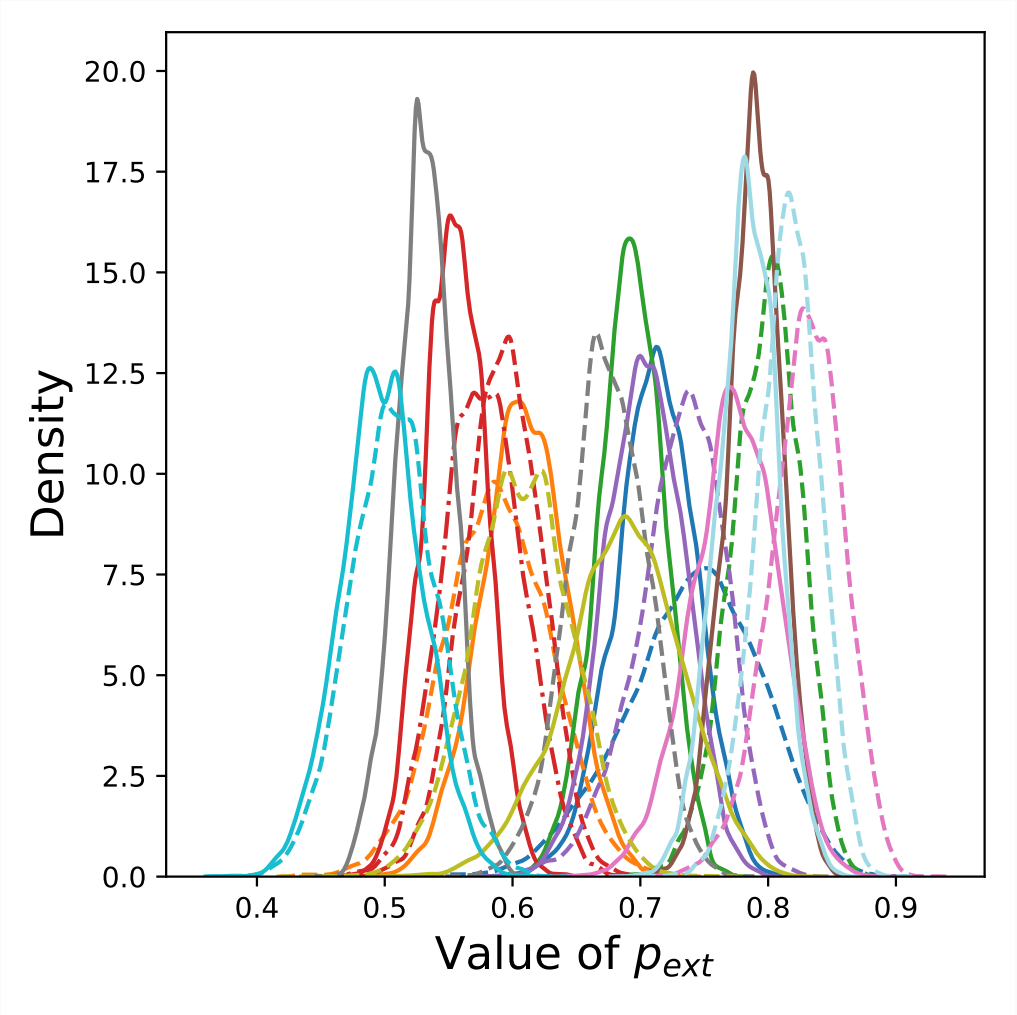
⚠**Is the model valid ?**

Validity of the model

Ex: Posterior distributions of patch extinction probabilities for *Stellaria media*. The colour indicates the street.



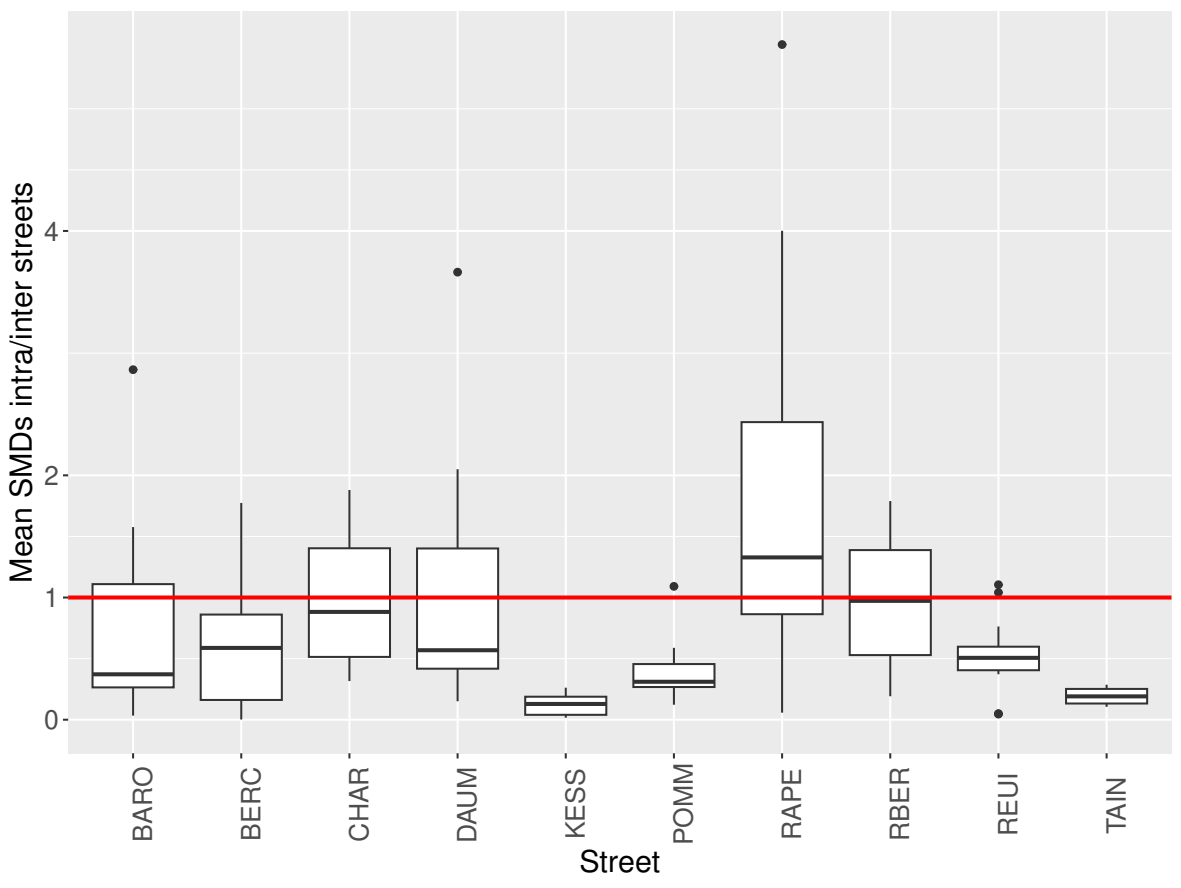
Validity of the model

$\Longrightarrow$ Comparison of posterior patch extinction probabilities between portions:

→ of the same street → of different streets

SMD < 1: probabilities closer for portions of a same street

SMD > 1: probabilities closer for portions of different steets



Thank you for your attention !

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Biostatistique BIOSP & Processus Spatiaux

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