Sustainable spatial management strategies of agricultural areas

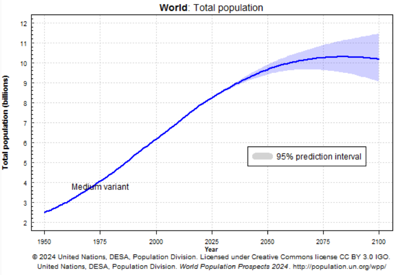
Madeleine Kubasch (iEES, École polytechnique)
Joint work with Manon Costa (IMT) and Nicolas Loeuille (iEES, SU)

Journée Workshop de la Chaire MMB, 21/11/2025

Introduction

Agricultural management strategies need to reconcile two key objectives:

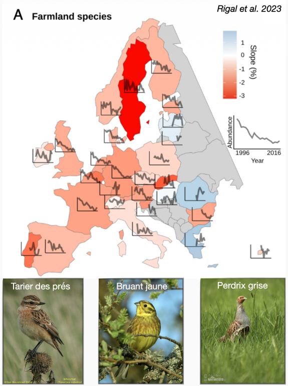
- **Yield goal**: feed a growing humanity (2024-2050: +1.5 billion people).



Introduction

Agricultural management strategies need to reconcile two key objectives:

- **Yield goal**: feed a growing humanity
- **Conservation goal**: biodiversity crisis.
    - Bird abundance decreased by 25% (1980-2016).
    - Main driver: agricultural intensification (Rigal et al., 2023).

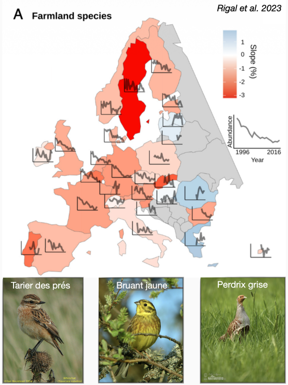


Introduction

Agricultural management strategies need to reconcile two key objectives:

- **Yield goal**: feed a growing humanity
- **Conservation goal**: biodiversity crisis.

⇒ Can we design agricultural landscapes that feed us without silencing nature?



Land sharing versus land sparing framework (Green et al., 2005)

Land sparing :

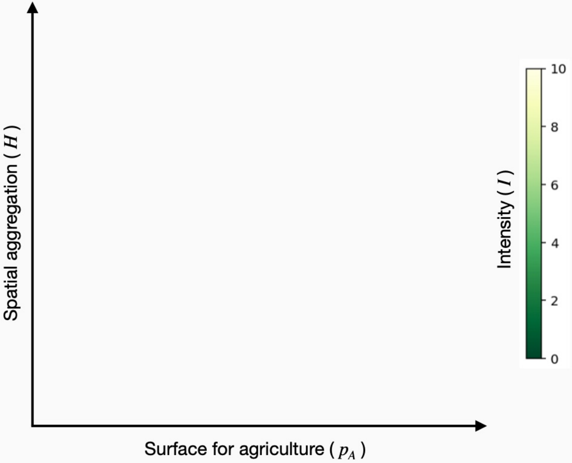
- Smaller surface used for agriculture.
- High spatial aggregation.
- Intensive agriculture.

Land sharing :

- Larger surface used for agriculture.
- Low spatial aggregation.
- Agroecological practices.

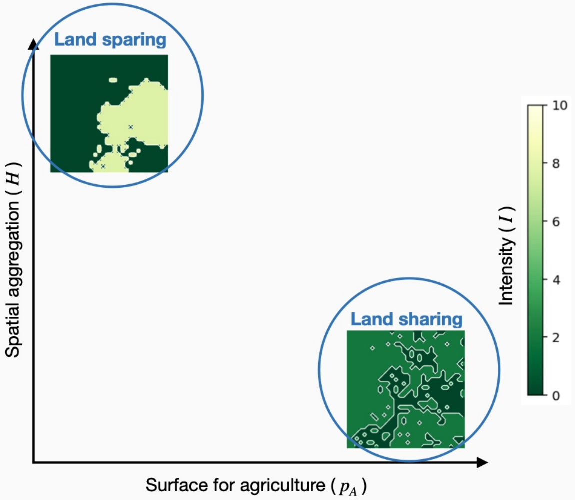
Introduction

Agricultural landscape $\rightarrow$ 3 parameters:

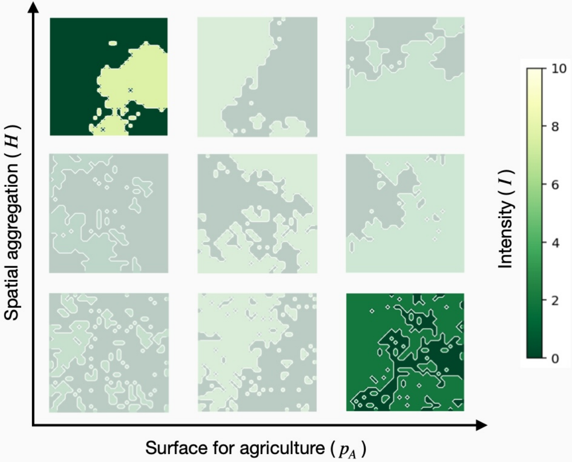


Introduction

Agricultural landscape → 3 parameters:



Agricultural landscape → 3 parameters:



Talk outline

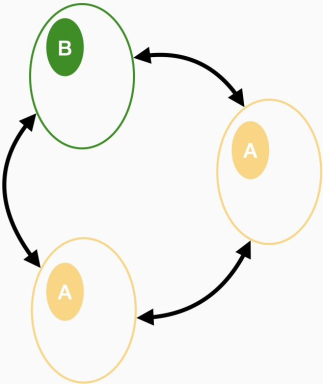
How does this spatial heterogeneity impact both conservation and yield goals?

1. **The metacommunity model:** how to model the ecological dynamics of several species in an agricultural landscape?
2. **Metacommunity persistence:** can we predict which species survive in the long run?
3. **Biodiversity-yield trade-off:** which spatial management strategies allow to reconcile conservation and yield goals?

The metacommunity model

What is a metacommunity?

Metacommunity: a set of local communities that are linked by dispersal of multiple interacting species (Leibold et al., 2004; Mouquet and Loreau, 2003).



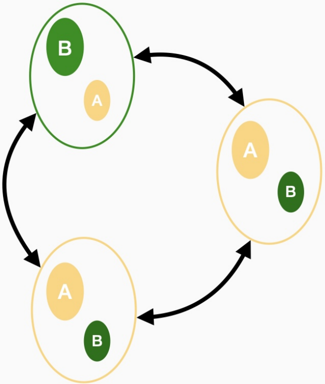
Ecological equilibirum:

- Species sorting.

Adapted from (Leibold et al., 2004).

What is a metacommunity?

Metacommunity: a set of local communities that are linked by dispersal of multiple interacting species (Leibold et al., 2004; Mouquet and Loreau, 2003).



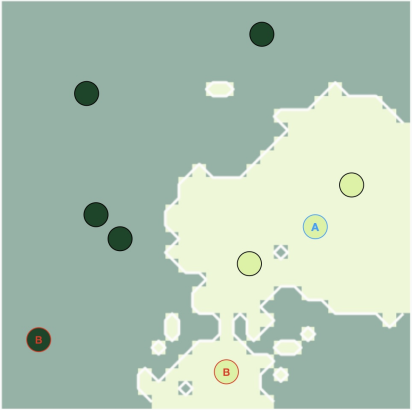
Ecological equilibirum:

- Species sorting.
- Mass effects (source-sink).

$\Rightarrow$ Biodiversity depends on heterogeneity between habitats and their spatial arrangement.

Adapted from (Leibold et al., 2004).

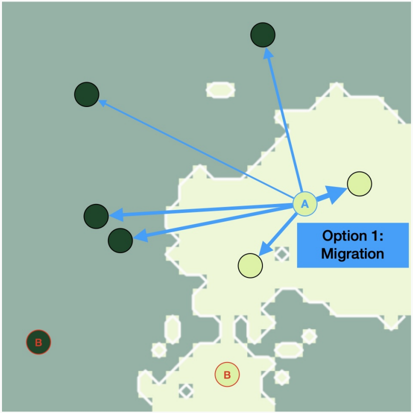
A spatial metacommunity model



Patch occupancy model:

- K patches uniformly distributed over the landscape.
- Pool of S species who differ in dispersal and local extinction rates.
- Absence/presence of each species in each patch.

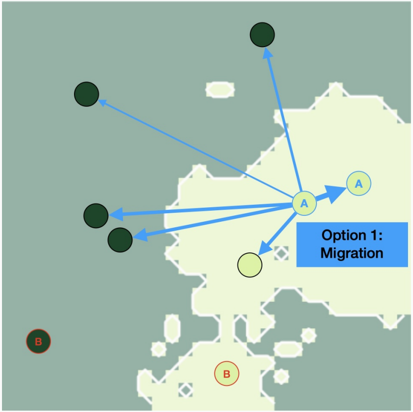
A spatial metacommunity model



Patch occupancy model: Species j inhabiting a patch at x may...

- Colonise an empty patch at $y \to$ rate $K^{-1}c_j(x, y)$ depends on distance.

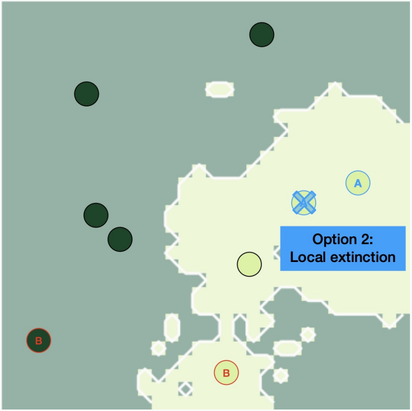
A spatial metacommunity model



Patch occupancy model: Species j inhabiting a patch at x may...

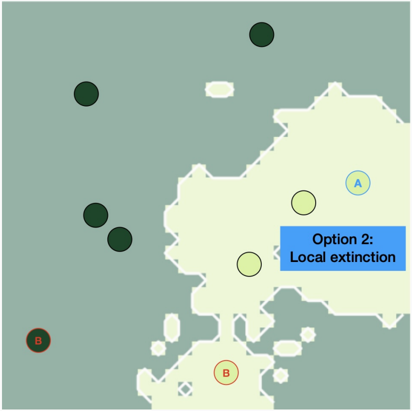
- Colonise an empty patch at $y \rightarrow$ rate $K^{-1}c_j(x,y)$ depends on distance.

A spatial metacommunity model



Patch occupancy model: Species j inhabiting a patch at x may...

- Colonise an empty patch at $y \to$ rate $K^{-1}c_j(x, y)$ depends on distance.
- Go locally extinct $\to$ rate $\tau_j(x)$ depends on patch type.



Patch occupancy model: Species j inhabiting a patch at x may...

- Colonise an empty patch at $y \rightarrow$ rate $K^{-1}c_j(x, y)$ depends on distance.
- Go locally extinct $\rightarrow$ rate $\tau_j(x)$ depends on patch type.

A spatial metacommunity model

Saturate the landscape with patches $\implies$ the model becomes continuous in space.

For $i \in \{1, \dots, S\}$, let $u_i(t, x) \in [0, 1]$ be the probability of observing species i at point $x \in \Omega$ at time $t \geq 0$.

In particular, $\sum_{i=1}^{S} u_i \leq 1$.

Remark: this corresponds to a graphon limit of a stochastic process, similar to (Delmas, Frasca, et al., 2024).

A spatial metacommunity model

Saturate the landscape with patches $\implies$ the model becomes continuous in space.

For $i \in \{1, \dots, S\}$, let $u_i(t, x) \in [0, 1]$ be the probability of observing species i at point $x \in \Omega$ at time $t \geq 0$.

In particular, $\sum_{i=1}^{S} u_i \leq 1$. Finally, for $i \in \{1, \dots, S\}$:

$$\partial_t u_i(t, x) = \underbrace{-\tau_i(x) u_i(t, x)}_{\text{Local extinction}} +$$

Remark: this corresponds to a graphon limit of a stochastic process, similar to (Delmas, Frasca, et al., 2024).

A spatial metacommunity model

Saturate the landscape with patches $\implies$ the model becomes continuous in space.

For $i \in \{1, \ldots, S\}$, let $u_i(t, x) \in [0, 1]$ be the probability of observing species i at point $x \in \Omega$ at time $t \geq 0$.

In particular, $\sum_{i=1}^{S} u_i \leq 1$. Finally, for $i \in \{1, \ldots, S\}$:

$$\partial_t u_i(t,x) = \underbrace{-\tau_i(x) u_i(t,x)}_{\text{Local extinction}} + \underbrace{\left(1 - \sum_{j=1}^{S} u_j(t,x)\right)}_{\text{Probability that } x \text{ is empty}} \underbrace{\int_\Omega u_i(t,y) c_i(x,y) dy.}_{\text{Colonization by dispersal}}$$

Remark: this corresponds to a graphon limit of a stochastic process, similar to (Delmas, Frasca, et al., 2024).

Persistence criterion

What is persistence?

Focus on the case $S = 2$:

$$\partial_t u(t,x) = -\tau u + (1-u-v)\int_\Omega u(t,y)c(x,y)dy,$$
$$\partial_t v(t,x) = -\sigma v + (1-u-v)\int_\Omega v(t,y)\gamma(x,y)dy,$$

with $c, \gamma \in \mathcal{C}(\Omega^2, \mathbb{R}_+^*)$ and $\tau, \sigma \in \mathcal{C}(\Omega, \mathbb{R}_+^*)$ for $\Omega \subset \mathbb{R}^2$ compact.

Persistence: species u persists (strongly, uniformly) if there exists $\varepsilon > 0$ such that, for any non trivial initial condition, for any $x \in \Omega$,

$$\liminf_{t \to +\infty} u(t,x) > \varepsilon.$$

$\Rightarrow$ Given a landscape, can we predict if neither, one or both species persist?

The mono-specific case (Delmas, Dronnier, et al., 2022)

For a single species,

$$\partial_t u(t,x) = -\tau u + (1-u)\int_\Omega u(t,y)c(x,y)dy.$$

The mono-specific case (Delmas, Dronnier, et al., 2022)

For a single species,

$$\partial_t u(t,x) = -\tau u + (1-u)\int_\Omega u(t,y)c(x,y)dy.$$

Intuition : if u is capable of invading the landscape when it is empty (i.e. the zero equilibrium), then u persists in the long run $\rightarrow$ invasion fitness?

The mono-specific case (Delmas, Dronnier, et al., 2022)

For a single species,

$$\partial_t u(t,x) = -\tau u + (1-u)\int_\Omega u(t,y)c(x,y)dy.$$

Intuition : if u is capable of invading the landscape when it is empty (i.e. the zero equilibrium), then u persists in the long run $\to$ invasion fitness? **reproduction number!**

The mono-specific case (Delmas, Dronnier, et al., 2022)

For a single species,

$$\partial_t u(t,x) = -\tau u + (1-u)\int_\Omega u(t,y)c(x,y)dy.$$

Define the following operator by its action on $g \in L^\infty(\Omega, \mathbb{R}_+)$:

$$\mathcal{T}_u(g)(x) = \int_\Omega \frac{c(x,y)}{\tau(y)} g(y)dy$$

For related work, see also (Lajmanovich and Yorke, 1976; Thieme, 2011).

The mono-specific case (Delmas, Dronnier, et al., 2022)

For a single species,

$$\partial_t u(t,x) = -\tau u + (1-u)\int_\Omega u(t,y)c(x,y)dy.$$

Define the following operator by its action on $g \in L^\infty(\Omega, \mathbb{R}_+)$:

$$\mathcal{T}_u(g)(x) = \int_\Omega \frac{c(x,y)}{\tau(y)} g(y)dy$$

If its spectral radius $r(\mathcal{T}_u) > 1$ ($\approx$ **positive invasion fitness**), then for any non trivial initial condition,

$$u(t,\cdot) \xrightarrow{t\to\infty} \bar{u} > 0 \text{ uniformly on } \Omega.$$

Else, u converges uniformly to zero.

For related work, see also (Lajmanovich and Yorke, 1976; Thieme, 2011).

The mono-specific case (Delmas, Dronnier, et al., 2022)

If further any spot x is unavailable with probability $p(x)$:

$$\partial_t u(t,x) = -\tau u + (1 - u - p) \int_\Omega u(t,y) c(x,y) dy.$$

The mono-specific case (Delmas, Dronnier, et al., 2022)

If further any spot x is unavailable with probability $p(x)$:

$$\partial_t u(t,x) = -\tau u + (1 - u - p) \int_\Omega u(t,y)c(x,y)dy.$$

Define the following operator by its action on $g \in L^\infty(\Omega, \mathbb{R}_+)$:

$$\mathcal{T}_u(g)(x) = \int_\Omega \frac{c(x,y)g(y)}{\tau(y)} dy \text{ and } \mathcal{S}_p(g)(x) = (1 - p(x))g(x).$$

If the spectral radius $r(\mathcal{T}_u \circ \mathcal{S}_p) > 1$ ($\approx$ positive invasion fitness), then for any non trivial initial condition,

$$u(t,\cdot) \xrightarrow{t\to\infty} \bar{u}_p > 0 \text{ uniformly on } \Omega.$$

Else, u converges uniformly to zero.

Back to $S = 2$

- Let $\mathcal{T}_u$ and $\mathcal{T}_v$ be the linear operators associated to the invasion of the trivial equilibrium by u and v alone.
- We let $\bar{u}$ and $\bar{v}$ designate the mono-specific equilibria of u and v, if they exist.
- **Intuition:** in the long run, coexistence of u and v is possible if and only if each species can invade the other's mono-specific equilibrium. (Chesson, 2000)

Persistence criterion

Theorem

The persistence of the bi-specific metacommunity system is characterized as follows.

1. *If* $r(\mathcal{T}_u) \leq 1$ *and* $r(\mathcal{T}_v) \leq 1$, *then* $(u, v) \to (0, 0)$ *uniformly.*
2. *If* $r(\mathcal{T}_u) \leq 1$ *and* $r(\mathcal{T}_v) > 1$ *then* $(u, v) \to (0, \bar{v})$ *uniformly, and conversely.*
3. *If* $r(\mathcal{T}_u \circ S_{\bar{v}}) > 1$ *and* $r(\mathcal{T}_v \circ S_{\bar{u}}) > 1$, *then both* u *and* v *persist.*
4. *(Conjecture) If* $r(\mathcal{T}_u \circ S_{\bar{v}}) \leq 1$ *and* $r(\mathcal{T}_v \circ S_{\bar{u}}) > 1$ *then* $(u, v) \to (0, \bar{v})$, *and conversely.*

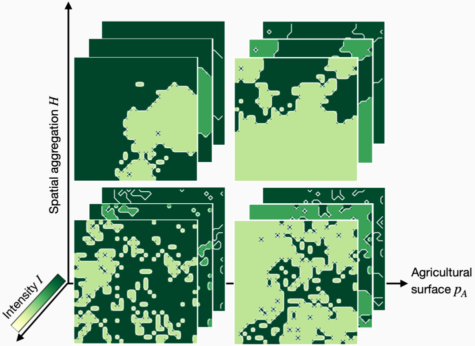
Persistence criterion

- The proof essentially relies on two ingredients:
  - If for any x, $p(x) \leq q(x)$, then $r(\mathcal{T}_u \circ \mathcal{S}_p) \geq r(\mathcal{T}_u \circ \mathcal{S}_q)$.
  - Control of u and v by comparing them to solutions of the mono-specific system with well-chosen values of p.
- Coexistence scenario: does the system converge to a coexistence equilibrium?

Exploring the biodiversity-yield trade-off

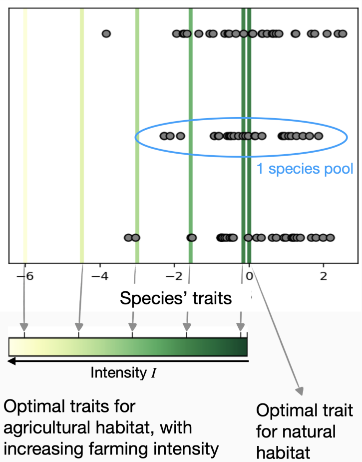
Management strategies of agricultural landscapes

Aim: evaluate the impact of a diverse family of management strategies on yield and biodiversity.



- Low to high values of agricultural surface and aggregation.
- Farming intensity ranges from hunter-gatherer to intensive agriculture.

Species pool



- Pools of 30 species who compete for space.
- Same dispersal kernel.
- Traits condition extinction rates in natural and agricultural patches (Kisdi, 2002).
- A species may colonize a patch occupied by a less adapted one.

Model outputs of interest

Yield: depends on farming intensity and local biodiversity, reflecting ecosystem services e.g. pollination (Burian et al., 2024).

At any point x, local yield is defined by

$$r(x) = \underbrace{i(x)}_{\text{Impact of farming intensity}} \times \underbrace{b(x)}_{\text{Ecosystem service}} .$$

Global yield:

$$Y = \int_A r(x)dx.$$

Model outputs of interest

Regional biodiversity: Many possible indicators may be considered (species richness, Shannon diversity...).

Here, we want to account for species' rareness, and the risk of spots being empty.

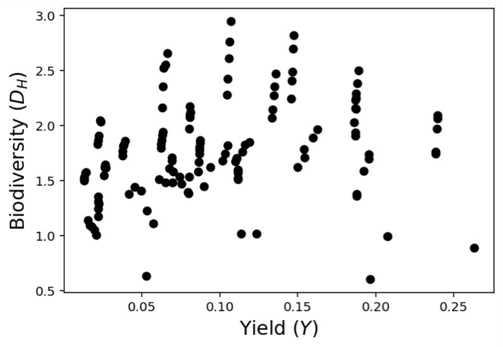
$\Rightarrow$ Hill diversity (Roswell et al., 2021):

$$D_H = \left(\sum_{i=0}^{S} \left(\int_\Omega u_i \right)^{1/2} \right)^2$$

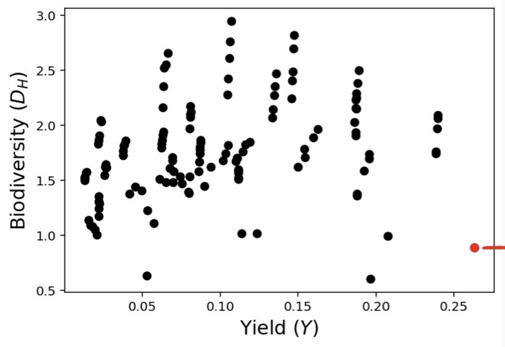
$\rightsquigarrow$ intermediate between species richness and Shannon diversity.

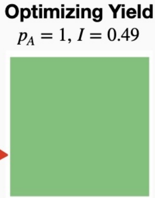
Optimal management strategies

- Average values of achieved yield and biodiversity for each management strategy (131 strategies total).
- **Trade-off**: overall, biodiversity tends to decrease with high yield.

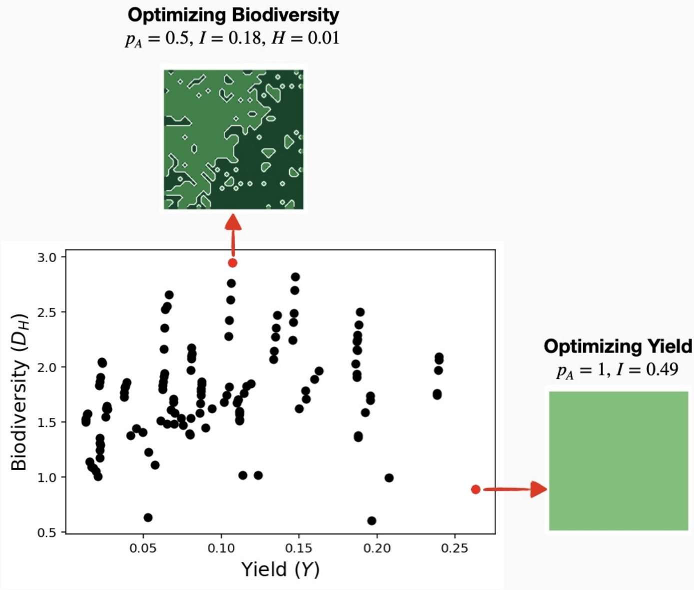


Optimal management strategies

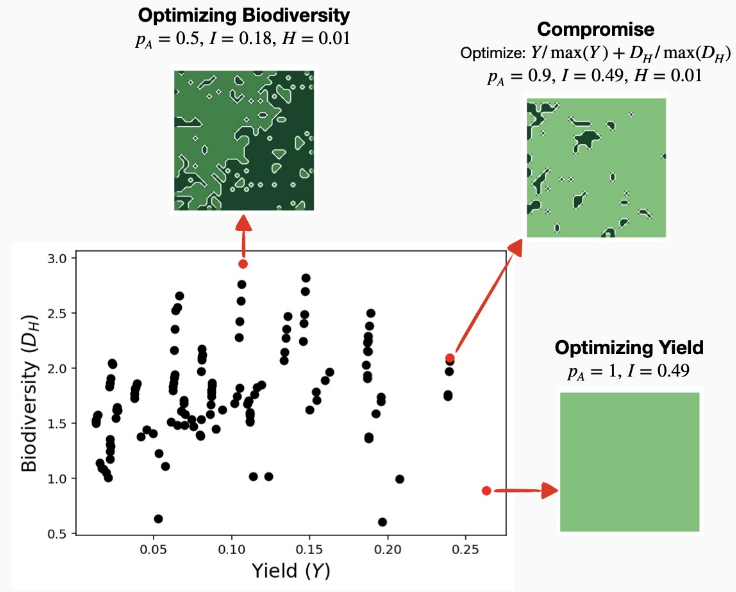




Optimal management strategies



Optimal management strategies



Conclusion and perspectives

Conclusion and perspectives

Ongoing work in progress:

- Persistence criterion: conjecture, numerical exploration.
- Further analysis of simulation results, e.g. **pretty good yield** (Hilborn, 2010): if we accept to reduce yield by 20-25%, does this allow for a significant gain in biodiversity?

Future directions:

- Impact of the agricultural landscape on the **evolution** of the specialization trait? $\rightarrow$ M2 internship of Lisa Paruit.
- Mutualistic or trophic **interaction networks**?

Thank you for your attention

Baron, Gemma L. et al. (Aug. 2017). **“Pesticide Reduces Bumblebee Colony Initiation and Increases Probability of Population Extinction”.** *Nature Ecology & Evolution* 1.9, pp. 1308–1316.

Burian, Alfred et al. (Mar. 2024). **“Biodiversity–Production Feedback Effects Lead to Intensification Traps in Agricultural Landscapes”.** *Nature Ecology & Evolution* 8.4, pp. 752–760.

Chesson, Peter (Nov. 2000). **“Mechanisms of Maintenance of Species Diversity”.** *Annual Review of Ecology and Systematics* 31.1, pp. 343–366.

Delmas, Jean-François, Dylan Dronnier, and Pierre-André Zitt (Mar. 2022). **“An Infinite-Dimensional Metapopulation SIS Model”.** *Journal of Differential Equations* 313, pp. 1–53.

Delmas, Jean-François, Paolo Frasca, et al. (2024). **“Individual-Based SIS Models on (Not so) Dense Large Random Networks”.** *Latin American Journal of Probability and Mathematical Statistics* 21.2, p. 1375.

References ii

Fournier, Nicolas and Sylvie Méléard (Nov. 2004). **"A Microscopic Probabilistic Description of a Locally Regulated Population and Macroscopic Approximations".** *The Annals of Applied Probability* 14.4, pp. 1880–1919.

Green, Rhys E. et al. (Jan. 2005). **"Farming and the Fate of Wild Nature".** *Science* 307.5709, pp. 550–555.

Habel, Jan Christian et al. (2019). **"Agricultural Intensification Drives Butterfly Decline".** *Insect Conservation and Diversity* 12.4, pp. 289–295.

Hilborn, Ray (Jan. 2010). **"Pretty Good Yield and Exploited Fishes".** *Marine Policy* 34.1, pp. 193–196.

Kisdi, Éva (June 2002). **"Dispersal: Risk Spreading versus Local Adaptation.".** *The American Naturalist* 159.6, pp. 579–596.

Lajmanovich, Ana and James A. Yorke (Jan. 1976). **"A Deterministic Model for Gonorrhea in a Nonhomogeneous Population".** *Mathematical Biosciences* 28.3, pp. 221–236.

References iii

Leibold, M. A. et al. (2004). **"The Metacommunity Concept: A Framework for Multi-Scale Community Ecology".** *Ecology Letters* 7.7, pp. 601–613.

Mouquet, Nicolas and Michel Loreau (Nov. 2003). **"Community Patterns in Source-Sink Metacommunities".** *The American Naturalist* 162.5, pp. 544–557.

Rigal, Stanislas et al. (May 2023). **"Farmland Practices Are Driving Bird Population Decline across Europe".** *Proceedings of the National Academy of Sciences* 120.21, e2216573120.

Roswell, Michael, Jonathan Dushoff, and Rachael Winfree (Mar. 2021). **"A Conceptual Guide to Measuring Species Diversity".** *Oikos* 130.3, pp. 321–338.

Thieme, Horst R. (May 2011). **"Global Stability of the Endemic Equilibrium in Infinite Dimension: Lyapunov Functions and Positive Operators".** *Journal of Differential Equations* 250.9, pp. 3772–3801.