Some contributions to mathematical modelling of fisheries

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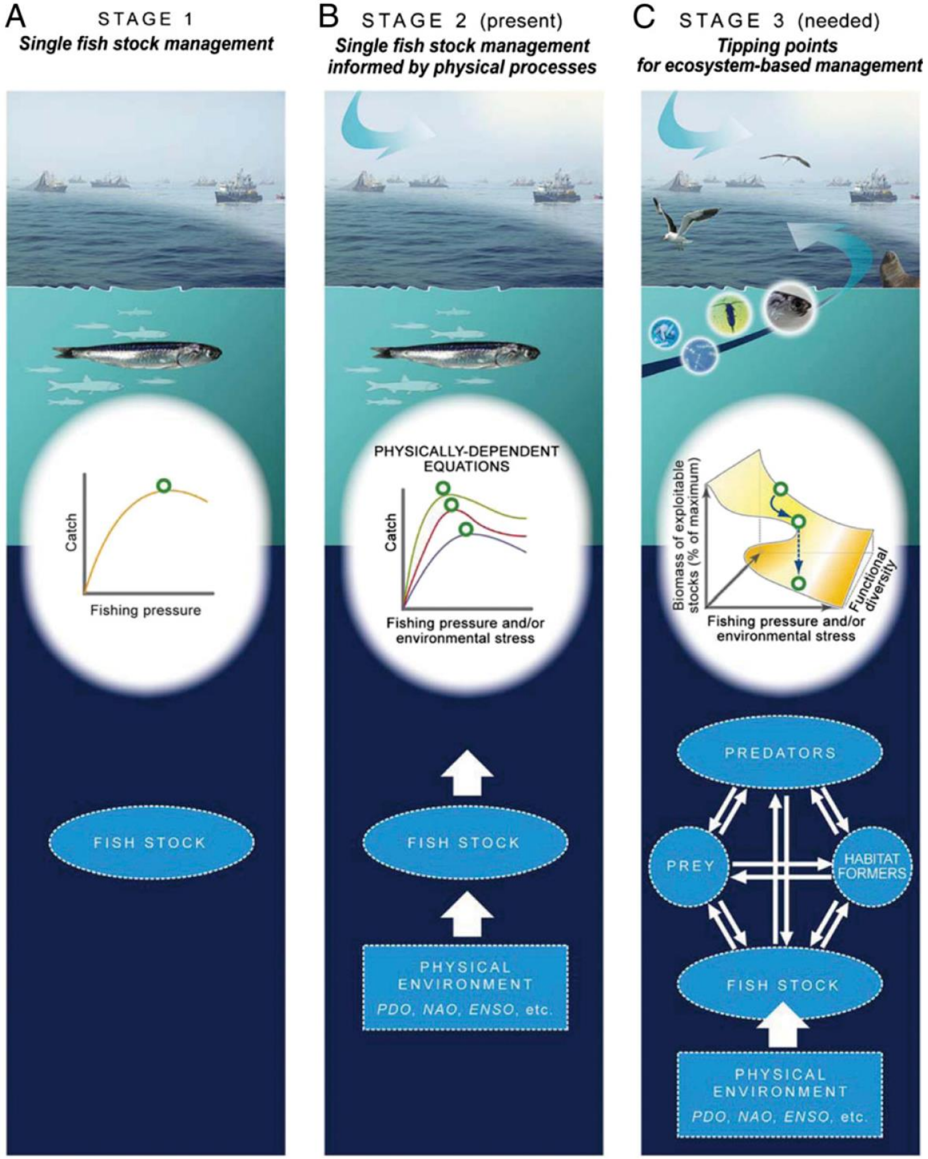
Introduction – Ecosystem based management and complexity



- Unexpected consequences of pressures on marine systems (overfishing, global warming, …)
- Important changes in community structure and ecosystem functioning
- Consequences on fisheries productivity
- Response to pressures involves complex dynamics with management issues
- Need to understand the consequences of the complexity of the natural networks in which harvested populations live

Travis et al., PNAS | **January 14, 2014** | vol. 111 | no. 2 | **581–584**

Modeling of fisheries : from simple to complex

Schaefer Model (1954)

- Isolated population (monospecific model)
- Maximum Sustainable Yield (MSY) concept

Community models based on population level

- ECOPATH – ECOSIM – ECOSPACE
- ISIS Fish

Community models including individuals properties

- Hartvig M. and Andersen K.
- Maury O.
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- Population density at equilibrium
- Population dynamics
- Spatial structure
- Stage structure
- Size structure
- Community structure and dynamics
- Effects of human pressures and response of the system :
  - ✓ Realistic response
  - ✓ Understandable

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Ecosystem based management of fisheries needs a complex system approach

- Stock belongs to a species network with lots of non linear interactions
- Adaptive strategies of species and adaptive strategies of fishermen

Dealing with complexity

From individuals to communities

Robustness of mathematical results : structural sensitivity

Aggregation of variables : basic ideas

$$\frac{d\mathbf{n}}{d\tau} = F(\mathbf{n})$$

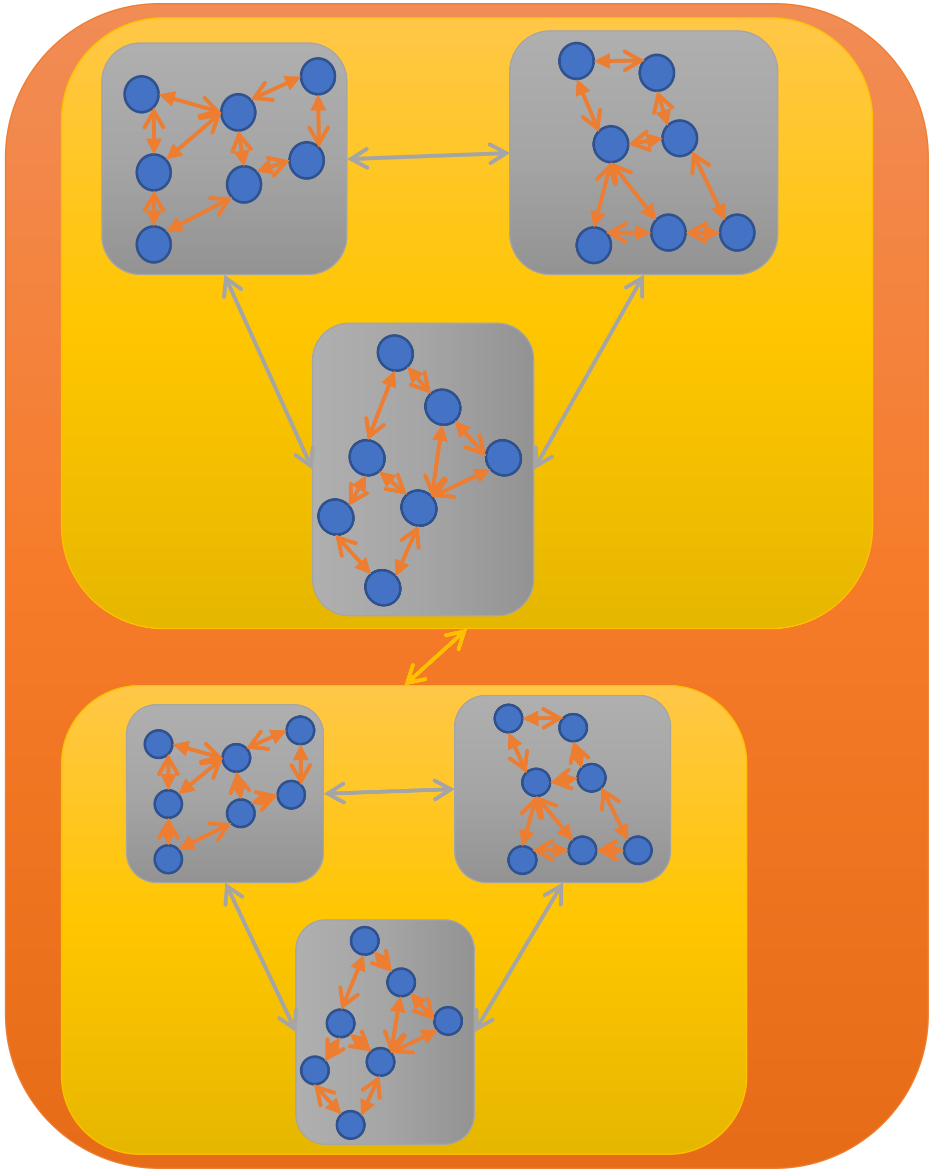
$$Y_j = \Phi_j(\mathbf{n})$$

dim(**Y**)<<dim(**n**)

n = micro – variables
Y = macro - variables

Colour	Organization level
	individuals
	sub-population (*e.g.* same trait)
	population
	community

Hierarchical system



Aggregation of variables : basic ideas

$$\frac{dn_i}{dt} = F_i\left(n_1,\ldots,n_N\right); N >> 1$$

$$Y_j = Y_j\left(X_1,\ldots,X_M\right); j = 1,..,M; M < N$$

$$\frac{dY_j}{dt} = \sum_{i=1}^{N} \frac{\partial Y_j}{\partial n_i}\frac{dn_i}{dt} = \sum_{i=1}^{N} \frac{\partial Y_j}{\partial n_i} F_i\left(n\right) \underset{?}{=} G_j\left(Y\right)$$

Luckyanov *et al.*, 1983

Iwasa Y, Andreasen V, Levin S. Aggregation in model ecosystems I: Perfect aggregation. Ecological Modeling 1987;37:287–302.

Iwasa Y, Levin S, Andreasen V. Aggregation in model ecosystems II: Approximate aggregation. Journal of Mathematics Applied in Medicine and Biology 1989;6:1–23.

Systems involving several time scales

In a system, each process takes place on its own caracteristic time scale and interact with other ones.

If a state variable is governed ***only by slow processes***, it is a ***slow variable***.

If a ***fast process*** is involved in the dynamics of a state variable, it is a ***fast variable***.

Remark : a fast variable can be at equilibrium, in which case it is fixed.

Systems involving several time scales

$$\frac{dx}{d\tau} = \boxed{F(x,y)} + \boxed{\varepsilon f(x,y)} \qquad \textbf{FAST}$$

$$\frac{dy}{d\tau} = \boxed{\varepsilon G(x,y)} \qquad \textbf{SLOW}$$

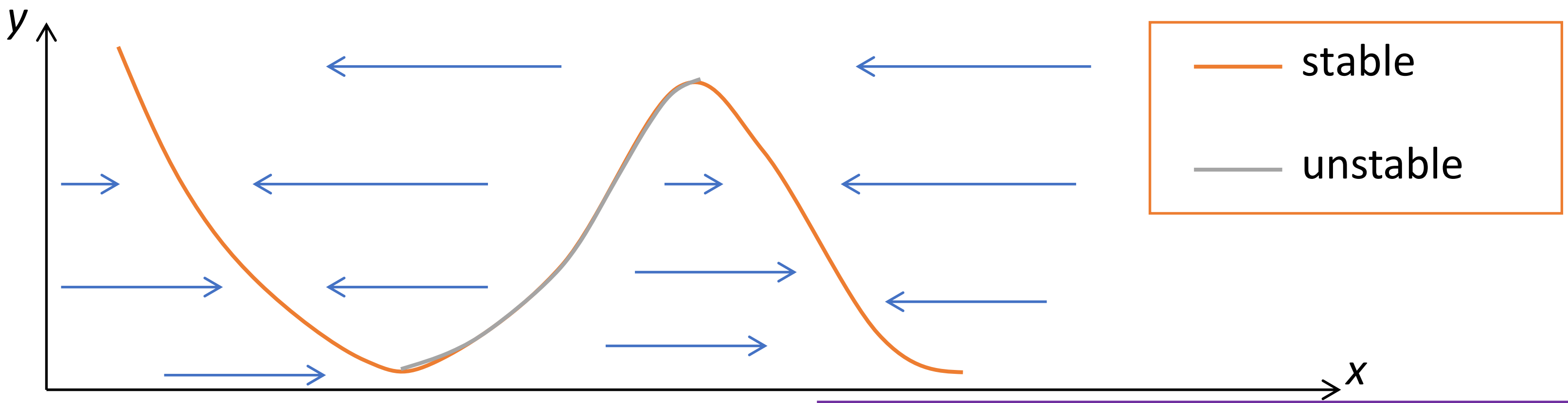
I - $\varepsilon = 0$

$$\frac{dx}{d\tau} = F(x,y)$$

$$\frac{dy}{d\tau} = 0$$

y is constant (does not depend on time)

ASSUMPTION : We assume that for all *y*, *x* reaches an equilibrium denoted by *x*(y).*



First example

$$\frac{\mathrm{d}x_1}{\mathrm{d}\tau} = m_2x_2 - m_1x_1 + \varepsilon x_1(r_1 - ay)$$
$$\frac{\mathrm{d}x_2}{\mathrm{d}\tau} = m_1x_1 - m_2x_2 + \varepsilon x_2r_2$$
$$\frac{\mathrm{d}y}{\mathrm{d}\tau} = \varepsilon y(bx_1 - d)$$

$$u_1^* = \frac{m_2}{m_1 + m_2} \quad \text{and} \quad u_2^* = \frac{m_1}{m_1 + m_2}$$

$$\frac{\mathrm{d}x}{\mathrm{d}t} = x(r - a_1y)$$
$$\frac{\mathrm{d}y}{\mathrm{d}t} = y(b_1x - d)$$

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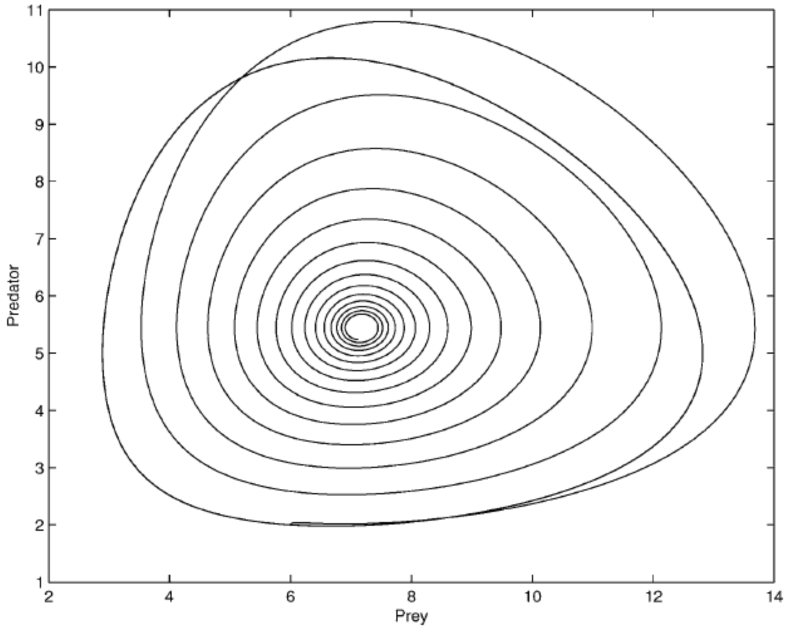

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$$\frac{\mathrm{d}x}{\mathrm{d}t} = x(r - ay) + \varepsilon x w_1(y)(r_1 - r_2 - a_1 y)$$
$$\frac{\mathrm{d}y}{\mathrm{d}t} = y(bx - d) + \varepsilon y b_1 w_1(y) x$$

where $w_1(y) = \frac{u_1^*(1 - u_1^*)}{m_2 + m_1}(r_1 - r_2 - a_1 y)$

First example

$$\frac{dx_1}{d\tau} = m_2 x_2 - m_1 x_1 + \varepsilon x_1 (r_1 - a y)$$
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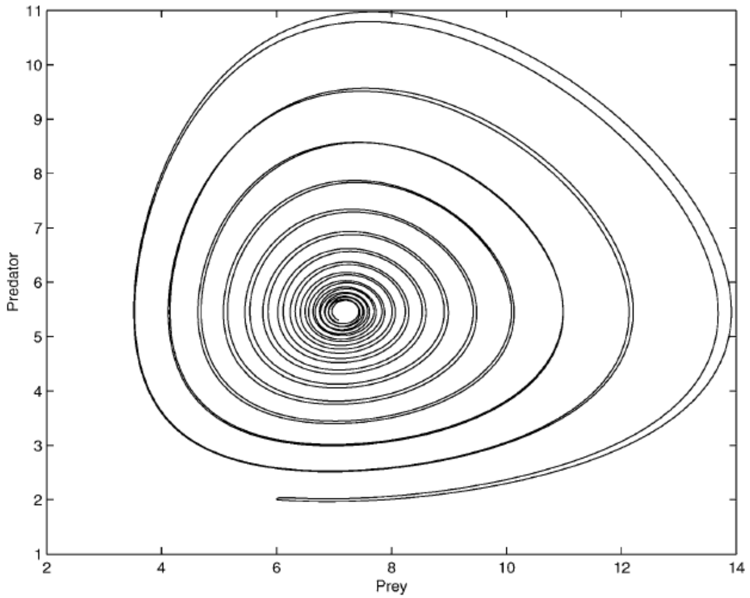

Stabilizing effect of the refuge (spatial heterogeneity) – (see Scheffer and de Boer, 1995)

J.-C. Poggiale and P. Auger, *Impact of spatial heterogeneity on a predator-prey system dynamics* C. R. Biol., 327, (2004), 1058–1063

Optimal number of sites in artificial pelagic multisite fisheries

Pierre Auger, Christophe Lett, Ali Moussaoui, and Sylvain Pioch

Can. J. Fish. Aquat. Sci. **67**: 296–303 (2010)

Ecological Complexity 7 (2010) 13–20

Contents lists available at ScienceDirect

Ecological Complexity

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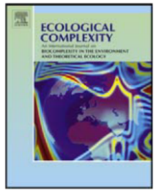


Effects of market price on the dynamics of a spatial fishery model: Over-exploited fishery/traditional fishery

Pierre Auger [a], Rachid Mchich [b,*], Nadia Raïssi [c], Bob W. Kooi [d]

Bravo R., Auger P., Poggiale J.-C., (2023), **The effect of connecting sites in the environment of a harvested population**, Mathematical Modelling of Nonlinear Phenomen, *in press*.

- shows the importance of maintaining corridors allowing individuals to move from one site to another in a network of sites,
- shows that the heterogeneity between the different sites is a favorable factor for the increase in the total optimal catch in the multisite fishery
- makes it possible to specify the conditions favorable to this increase in the capture at the MSY.

Spatial structure and physiology structure: how do they interact?

Chiara Accolla

What is the effect of schooling/swarming of populations on the functional response at large scales?

Schooling/swarming are phenomena based on **individual properties** (behavior, physiology) depending on **population densities**.

The **functional response** is a process based on **individual properties** (physiology, behavior), affected by **population densities**, and governing the **population dynamics**, the **flows in food webs** and thus **ecosystem functioning**.

Models :

1 – Individual-based models: a good level for data based knwoledge
2 – Population and community dynamics : a good level for ecosytem models

Spatial structure and physiology structure: how do they interact?

1 – Individual-based models: a good level for data based knowledge

Displacement of the individuals related to the relatively close other individuals : attraction/repulsion processes

a – for each individuals, define a position and a speed vector at time t=0

b – at time t+dt, for each individuals, consider the neighbors and determine the new speed vector according to defined rules and the state at time t.

Resource consumption:

a – catch prey in a close vicinity

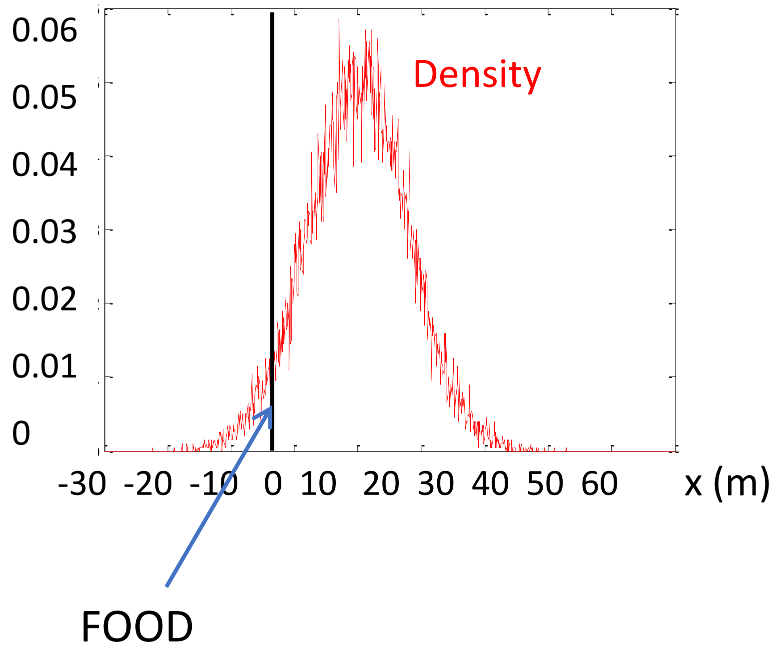
b – determine the new physiological state (DEB theory)

Reproduction and population growth:

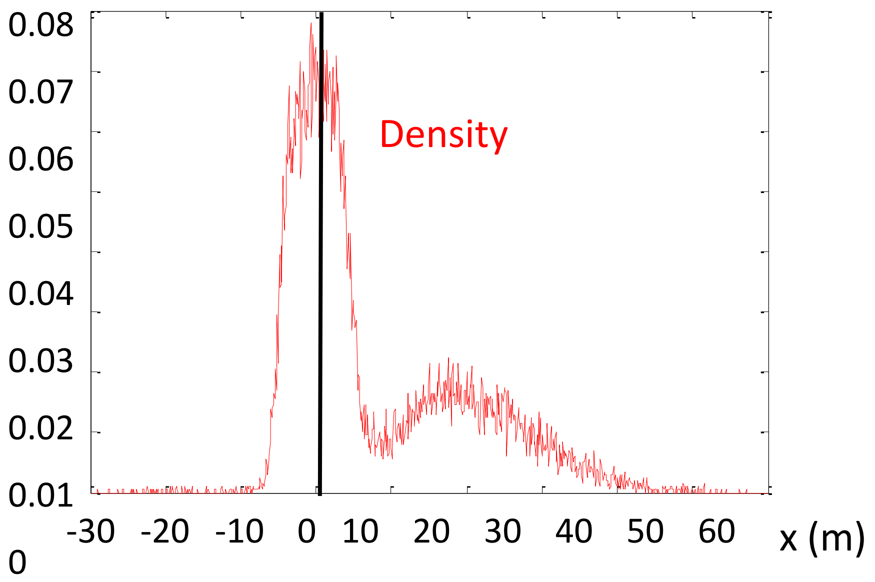
Defined by DEB at this scale

Spatial structure and physiology structure: how do they interact?

Initiale Conditions (t = 0)



Final distribution (t=tmax)



Spatial structure and physiology structure: how do they interact?

$$\boxed{x_k(t+\Delta t) = x_k(t) + a\nabla h(x)\Delta t + \sigma(|\nabla h(x)|)\Delta W_k}$$

IBM model

$$\boxed{dx_k = a\nabla h(x)dt + \sigma(|\nabla h(x)|)dW_k}$$

SDE's model

Assume a high number of individuals:

$$\boxed{\frac{\partial \rho(x,t)}{\partial t} = \frac{1}{2}\frac{\partial^2}{\partial x^2}(B^2\rho(x,t)) - \frac{\partial}{\partial x}(A\rho(x,t))}$$

PDE's model

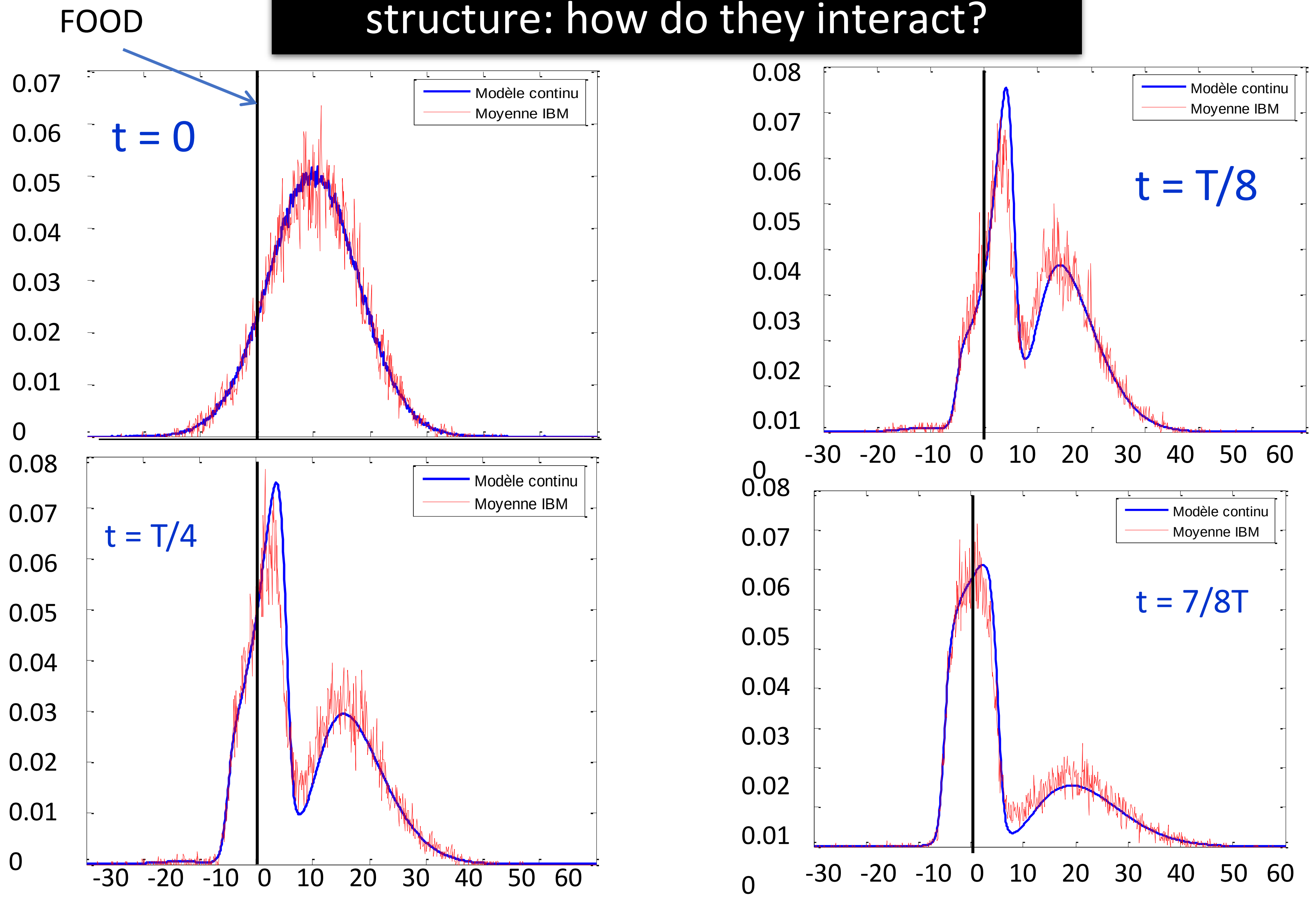
where $\rho(x,t)$ is the population density, and population parameters are linked to individual properties:

$$B = \sigma(|\nabla h(x)|)$$

$$A = a\nabla h(x)$$

Individual - Population relationship

Spatial structure and physiology structure: how do they interact?

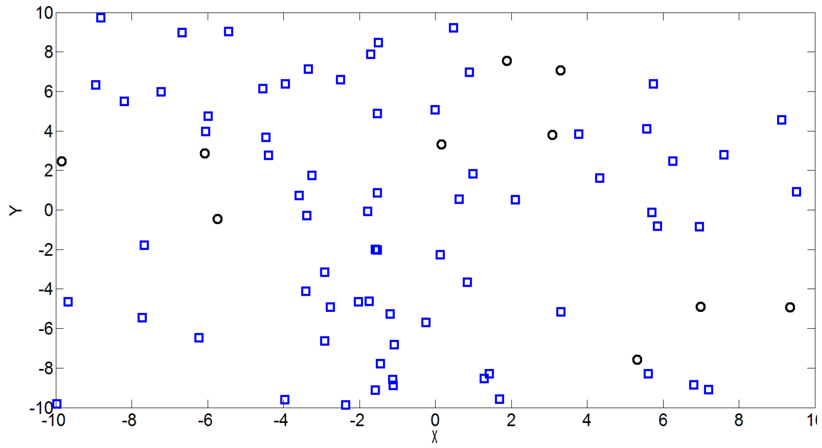


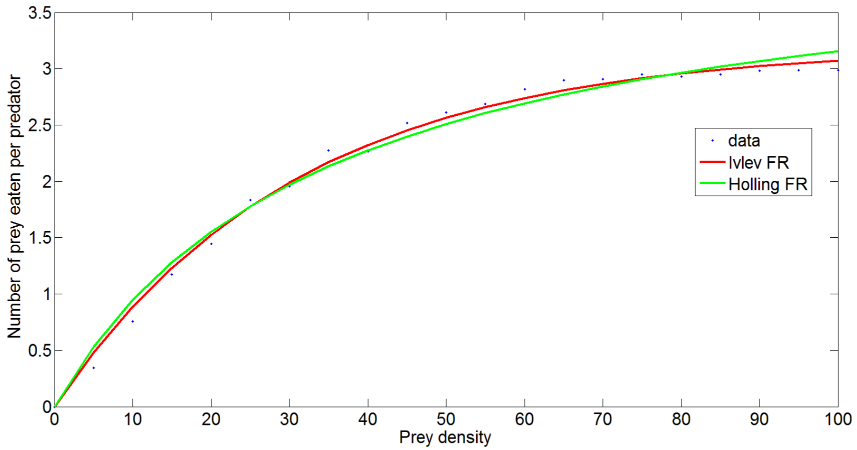
Spatial structure and physiology structure: how do they interact?

Analyze how behavioral displacements and metabolic properties interact;

Analyze the relationship between the number/biomass of prey eaten per unit (number/biomass) of predator per unit of time and the individual properties (metabolism, displacements)

Build a functional response at large scale, taking account for DEB theory and individual behavior;





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D. Morale, V. Capasso, K. Oelschläger, 2005, An interacting particle system modelling aggregation behavior: from individuals to populations, J. Math. Biol., 50: 49-66

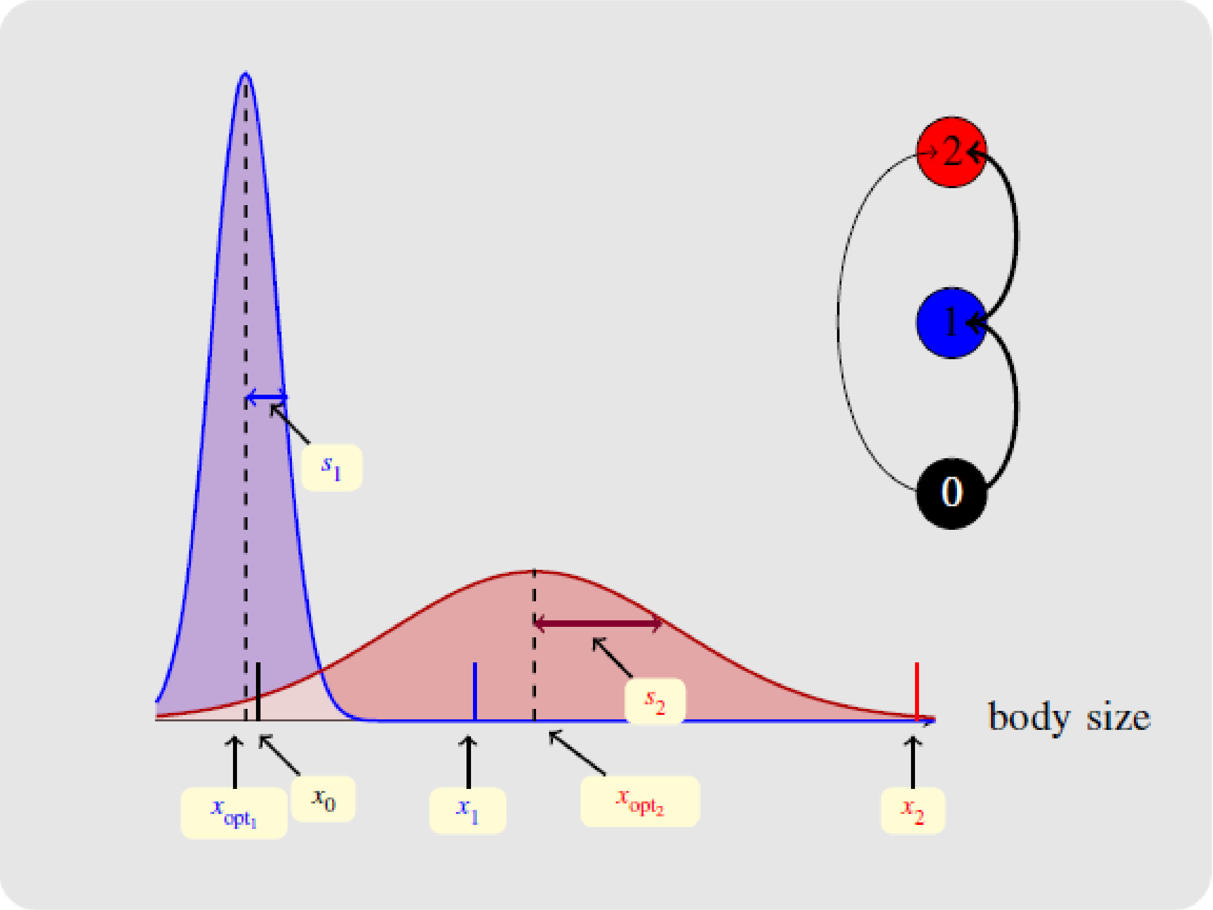
B. Faugeras and O. Maury, (2007), Modeling fish population movements: from an individual-based representation to an advection-diffusion equation. Journal of Theoretical Biology, 247(4):837-48

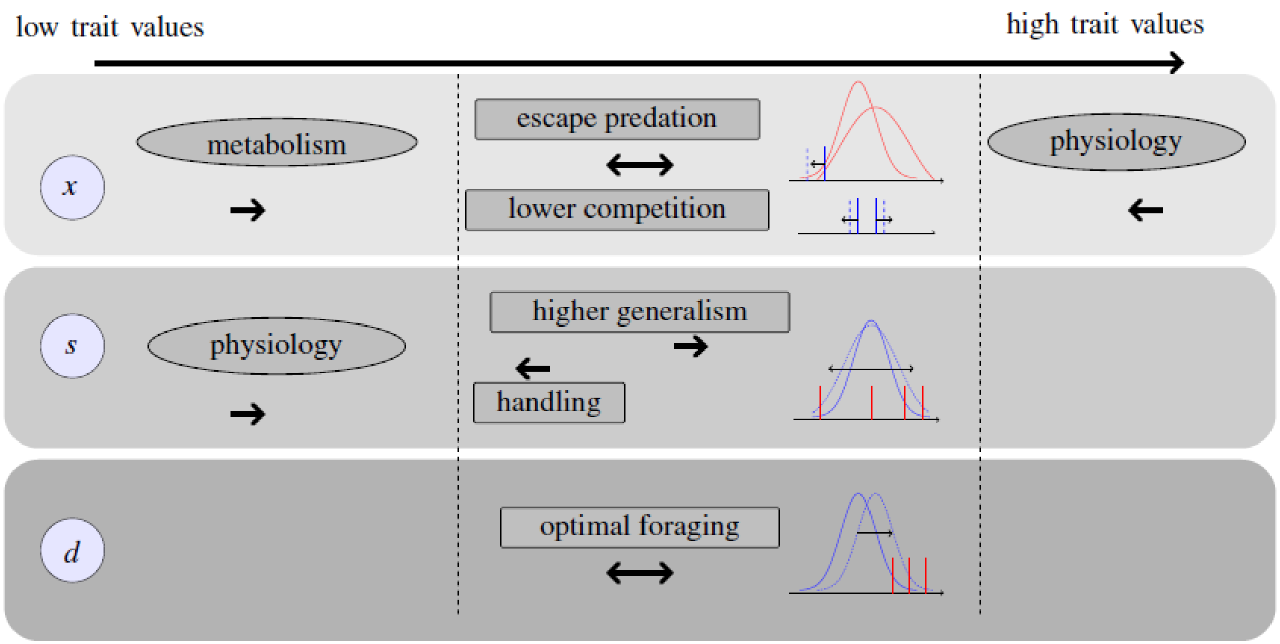
Does evolution design robust food webs?

B. Girardot, M. Gauduchon, F. Ménard and J. C. Poggiale

http://dx.doi.org/10.1098/rspb.2020.0747

PROCEEDINGS B





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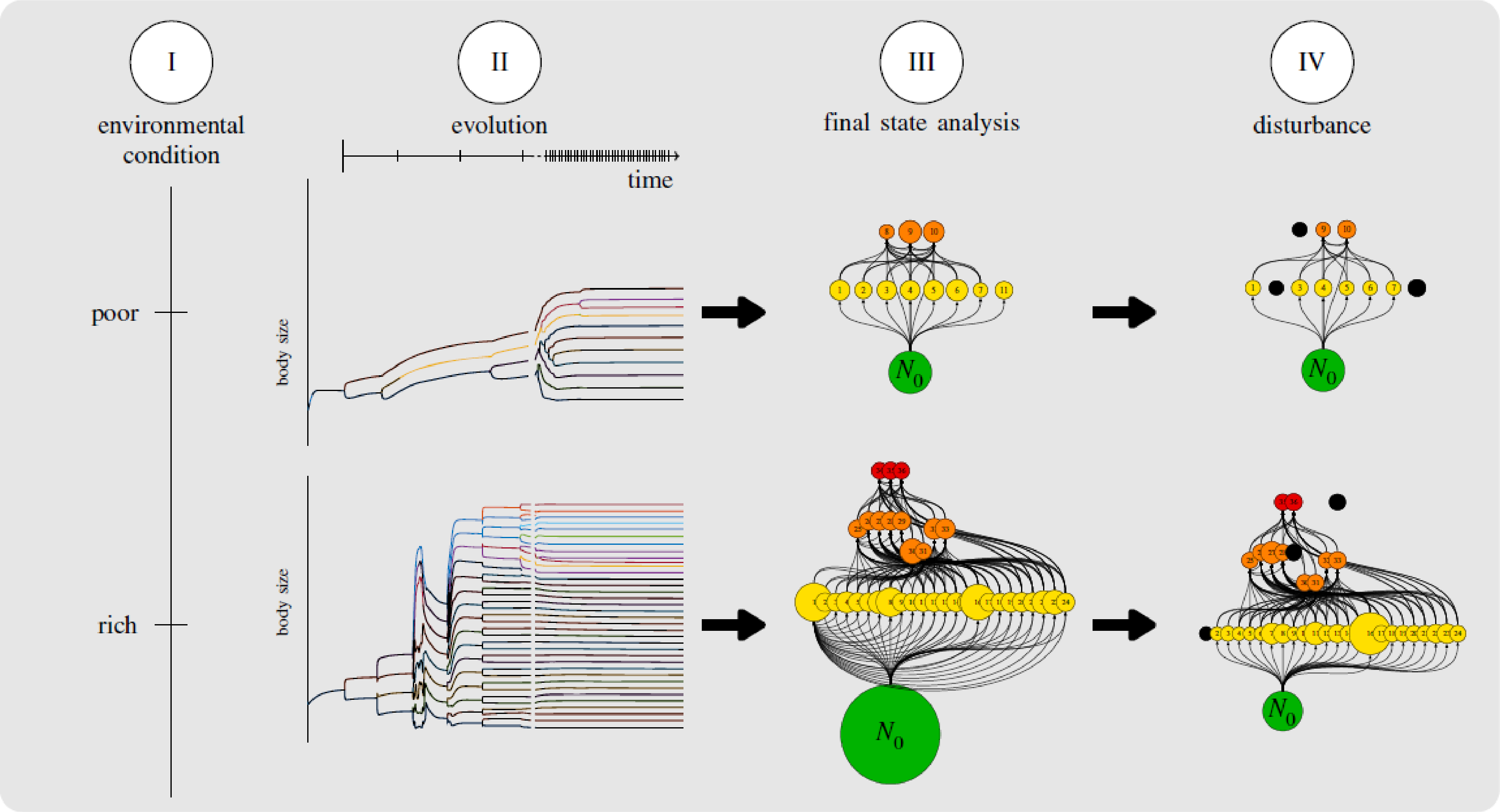
PROCEEDINGS B

B. Girardot, M. Gauduchon, F. Ménard and J. C. Poggiale



Thanks for your attention … and

… thanks to my collaborators:

Chiara Accolla
Clément Aldebert
Roger Arditi
Pierre Auger
Rafael Bravo de la Parra
Flora Cordoleani
Mathias Gauduchon
Benjamin Girardot
Bob Kooi
Bas Kooijman
Nicolas Loeuille
Olivier Maury
Frédéric Ménard
David Nérini
Robert Roussarie

MESSH– January 2023

Ecosystem-based and evolutionary approach to the exploitation of species

Théo Villain

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Jean-Christophe Poggiale (MIO, Marseille)
Eric Tromeur (Ministère de la transition écologique)

Institute of Ecology and Environmental Sciences of Paris
(lab)

Academic background

2016	Baccalauréat S	Physique-Chimie
2018	Classe préparatoire BCPST	ENS Paris-Saclay
2019	Licence 3	Health Biology ENS-PS
2020	Master 1	Health Biology ENS-PS
2021	Césure M2 FeSUP	Agrégation SV-STU courses
2021-2022	Master 2	BEE Theoretical Ecology

Ecosystem-based and evolutionary approach to the exploitation of species

for a sustainable management of fished socio-ecosystems

Fisheries Management

Current tools for fisheries management

- **Quotas** policy based on fish abundances and minimal size allowed to fish (MSY or MEY)

- Establishment of **Marine Protected Areas**

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Effects on ecosystems

- 30% of exploited stocks are **overexploited** *(FAO 2016)*

- 90% of big fishes have disappeared (over the last 50 years) *(Myers & Worm (2003))*

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Economic issues

- 100 millions of tons fished/y
- 263 billions of USD
- 10 % of global population directly relies on fisheries for food security and work

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- 263 billions of USD
- 10 % of global population directly relies on fisheries for food security and work

→ + 83 billions of USD with **sustainable fisheries** management (World Bank)

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FAO 2016, 2021

Fisheries Management

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Problems

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- No consideration of **interactions** inside food webs
- No consideration **evolutionary** effects

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Evolutionary effects

- Selective pressure on size forces fish **sizes to decrease** *(Olsen et al. 2004)*
- Reduction of **economic sustainability**

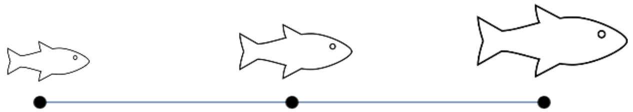
How resilience and sustainability of marine food webs respond to exploitation pressure?

Economic and ecological sustainability of fisheries ?

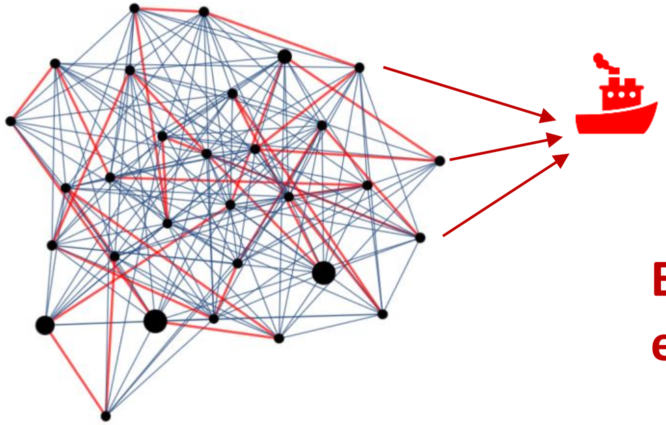
Effects of exploitation pressure on food web dynamics

$$\frac{dB_i}{dt} = \sum_{j=\text{ressource/prey}} e a_{ij} B_j B_i - \sum_{j=\text{predator}} a_{ji} B_j B_i - \sum_{j=\text{competitor}} c_{ij} B_j B_i - d_i B_i - E_i(z_i)$$

- **Allometric** models
- Evolution of size according to **adaptive dynamics**



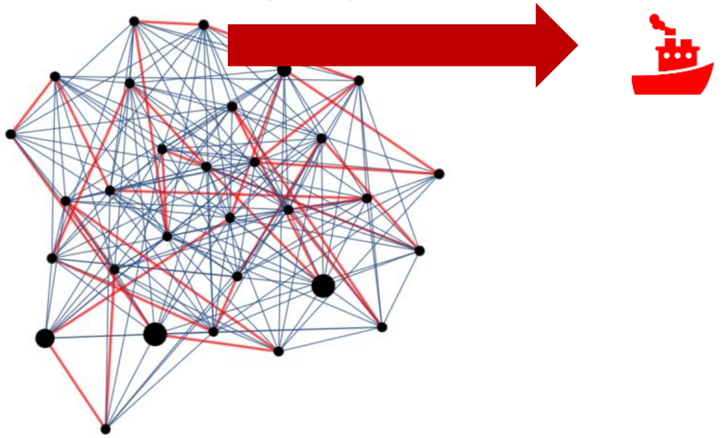
Establishment of food webs **highly structured by size** (eg. *Loeuille & Loreau 2005)*



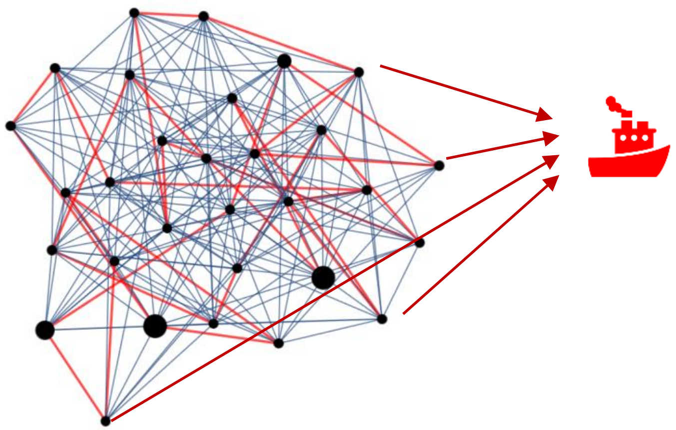
Effects of a given exploitation repartition on eco-evolutionary dynamics?

When Σ efforts constant

Unbalanced harvesting (eg. focused on apex predators)



Balanced harvesting



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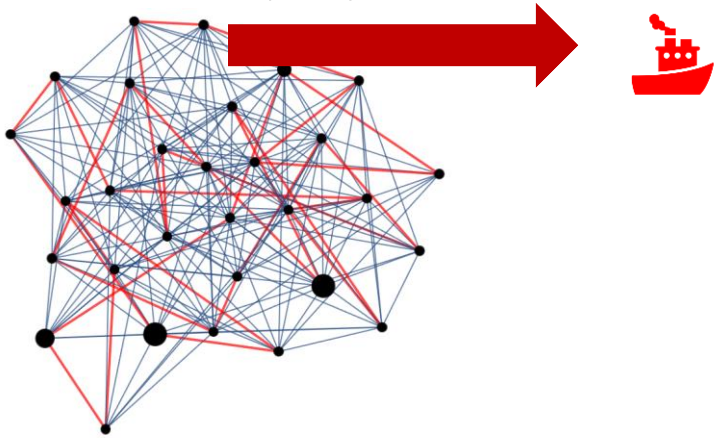

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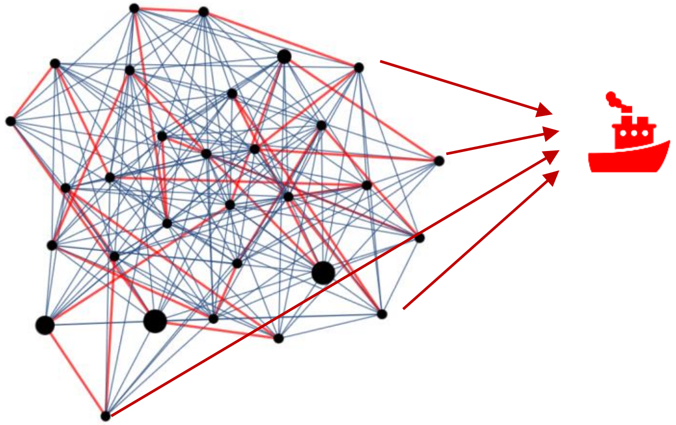


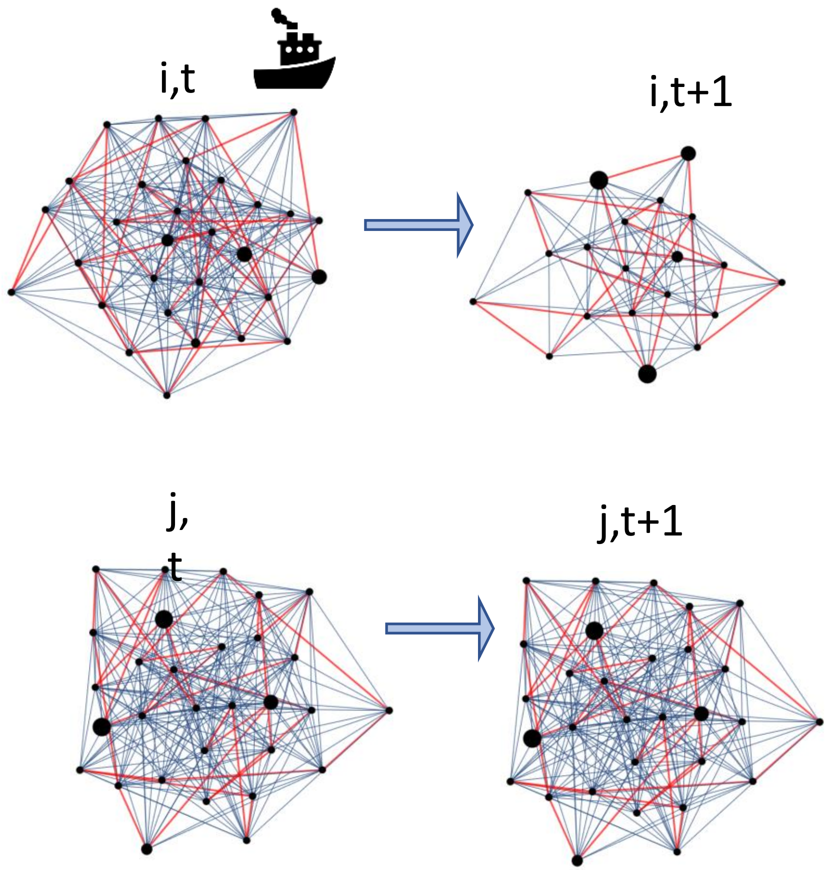
Predictions :

- Balanced harvesting : improves the socio-ecological sustainability (White *et al.* (2012), Zhou *et al.* (2019))

- Evolution towards small sizes : **evolutionary rescue** but decrease of future **fishing yields**

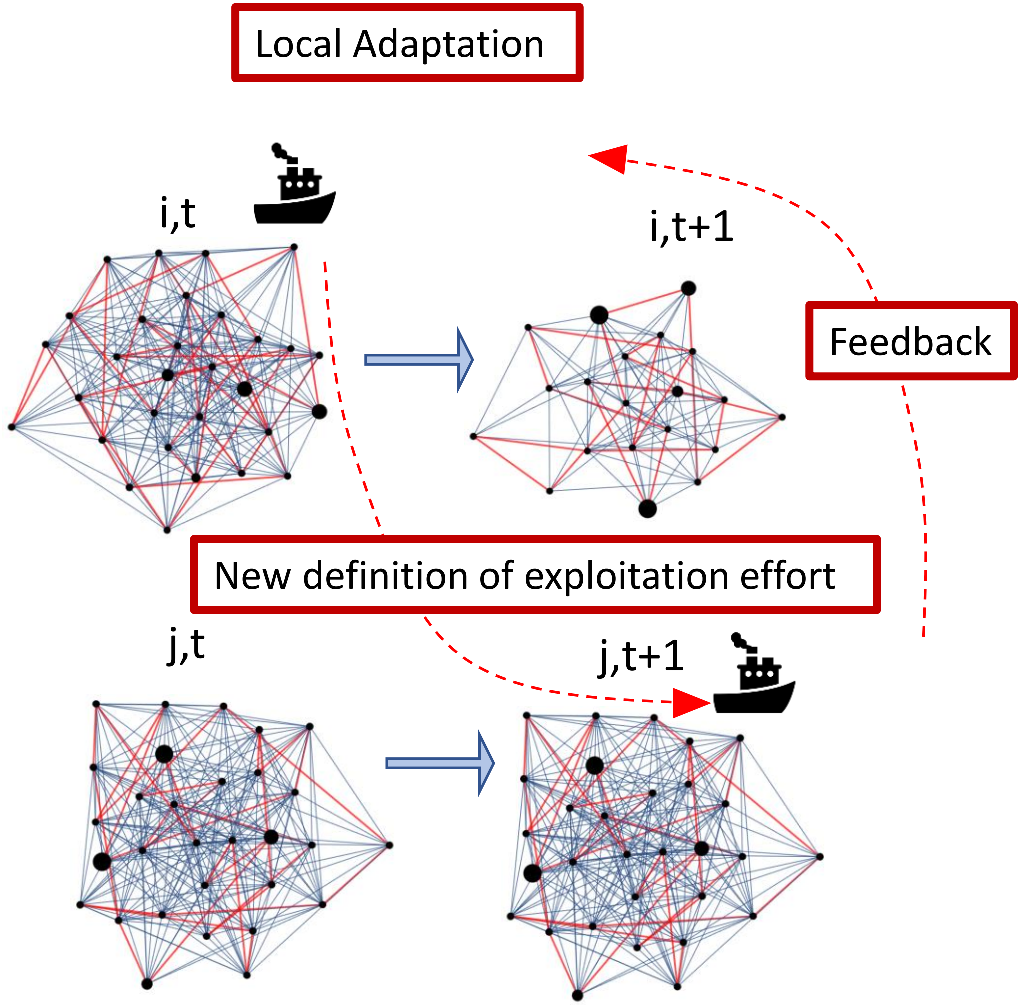
Adaptation of exploitation pressure and sustainability

Local adaptation



System sustainability with adaptive processes ?

Adaptation of exploitation pressure and sustainability



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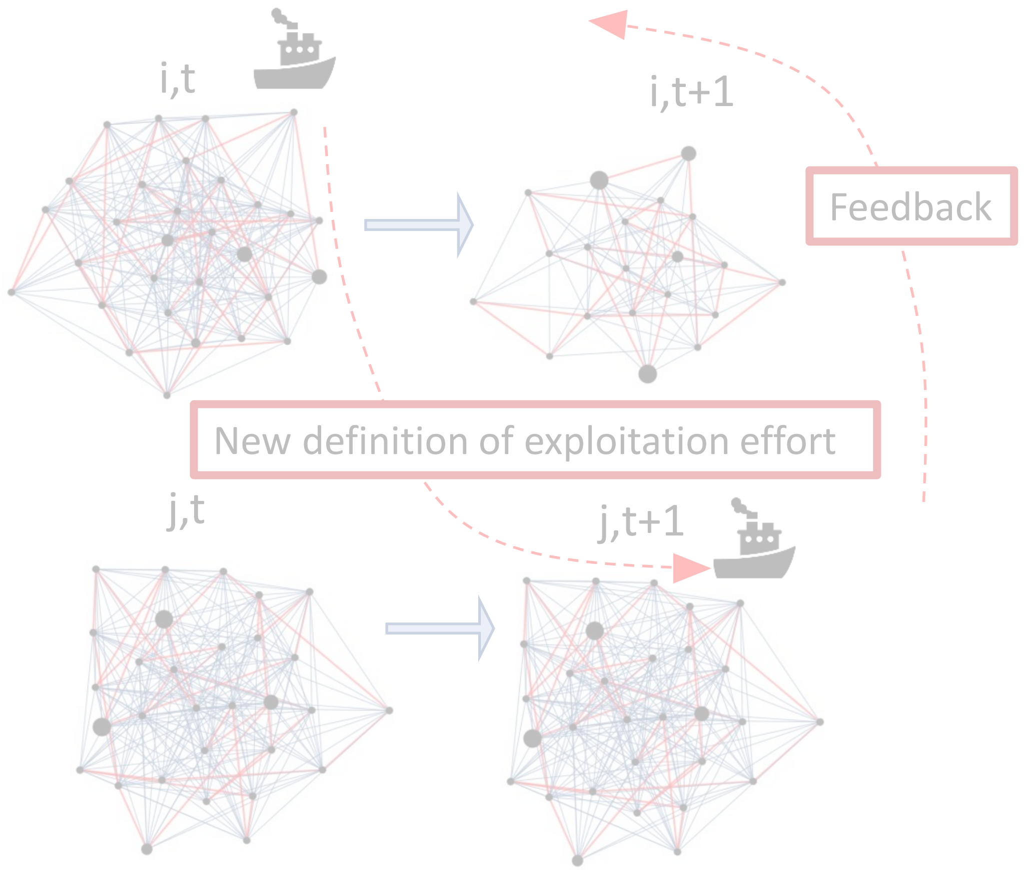


Global Scale

- Same processes at national scales vs economic communities

- Regional abundances variations -> redefining quotas and marine protected areas

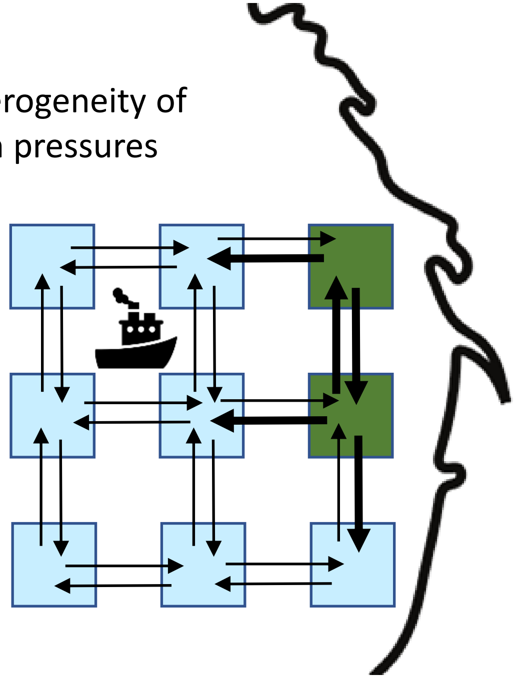
How to deal with fishermen behaviors ?

System sustainability with adaptive processes ?

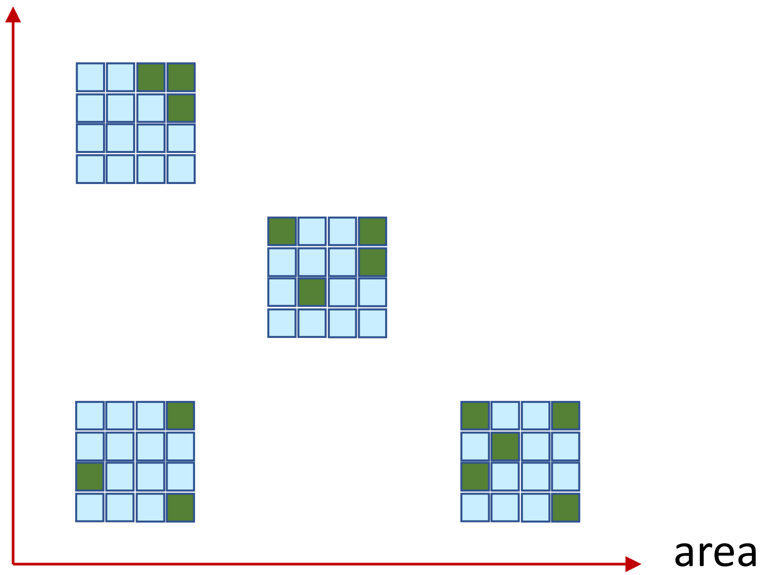
Spatial management of fisheries considering Marine Protected Areas

What is the optimal design for fisheries and networks sustainability ?

Spatial heterogeneity of exploitation pressures



Dispersion species *i*



« SLOSS : Single large or several small? »

Conciliate surface under protection, diversity, economic outputs and exploitation pressure

Gaines, S. D. et al. (2010)

Thank you !