Modelling spatial interactions for bivalve aquaculture

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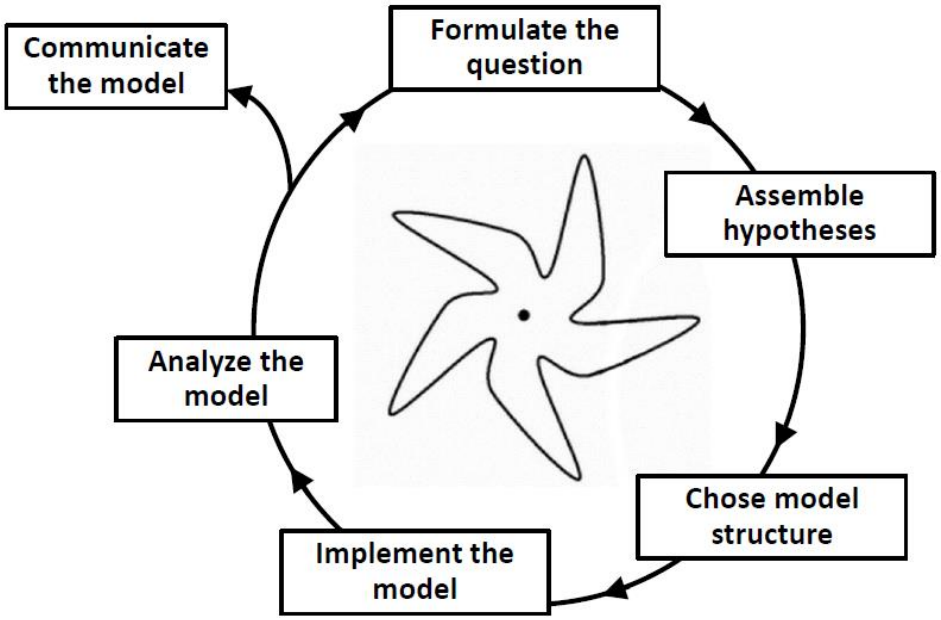
Mathematical Modelling

- **Definition**
  - Representation of a system = set of interactions between elements
  - Simplification
  - Designed to address a question
  - Mathematical formulation of rules

- **Modelling steps**



From Piou and Bommel

Scales, ecological questions, management applications

Examples

Spatial Scales

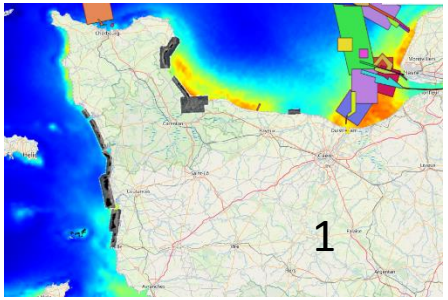
Individual performance

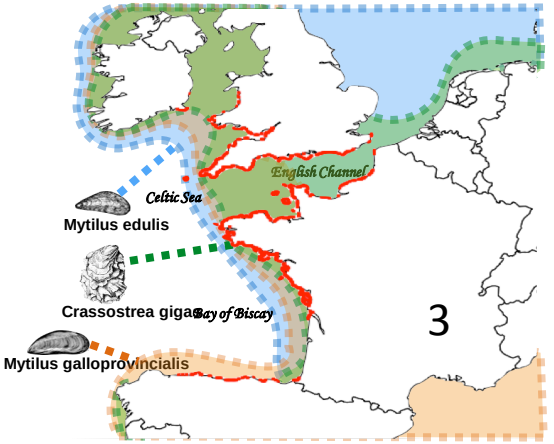
Ecosystem functionning

Aquaculture planning

Socio-ecosystem dynamics

Biogeography, macroecology



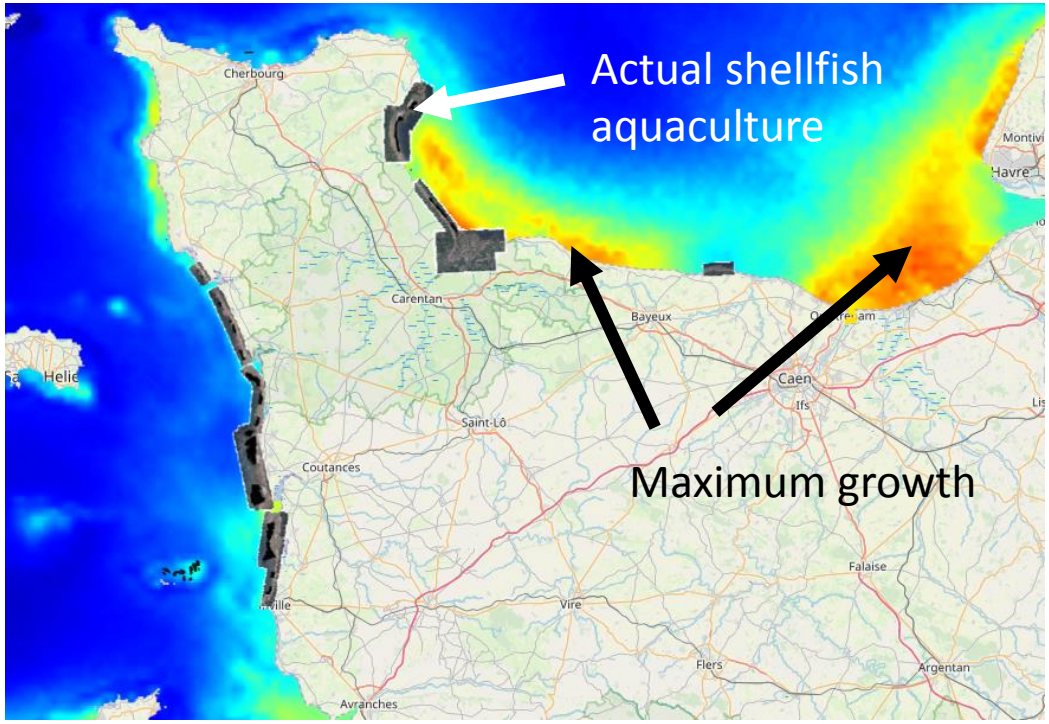


Marine Spatial Planning: spatial constraints

Scale	Drivers	Concepts	Modelling question	Issue
• Individual and farm • Time = year	• Temperature • Food • Density of cultivated species	• Dynamic Energy budget • Food Depletion	• Individual growth • Farm production	• Site selection for aquaculture • Optimisation of farm design • Marine spatial planning

Example = Marine Spatial Planning for oyster aquaculture in Normandy (Gangnery et al., in prep)

- ➢ **Simulation of oyster growth (DEB model)**



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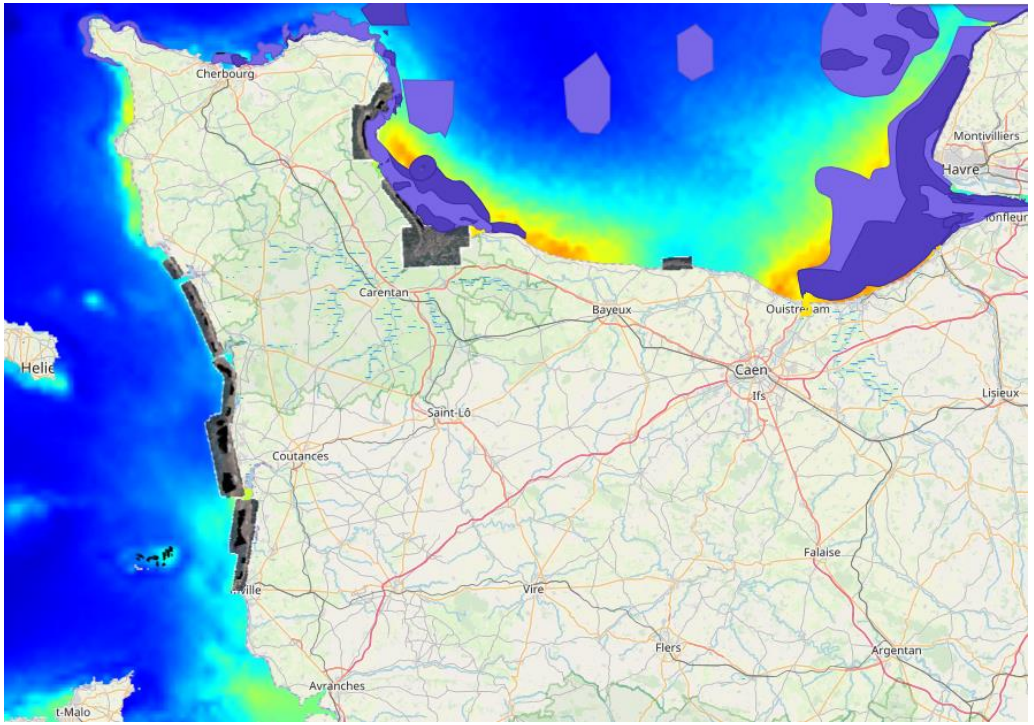
- **Spatial constraints: Protected areas**



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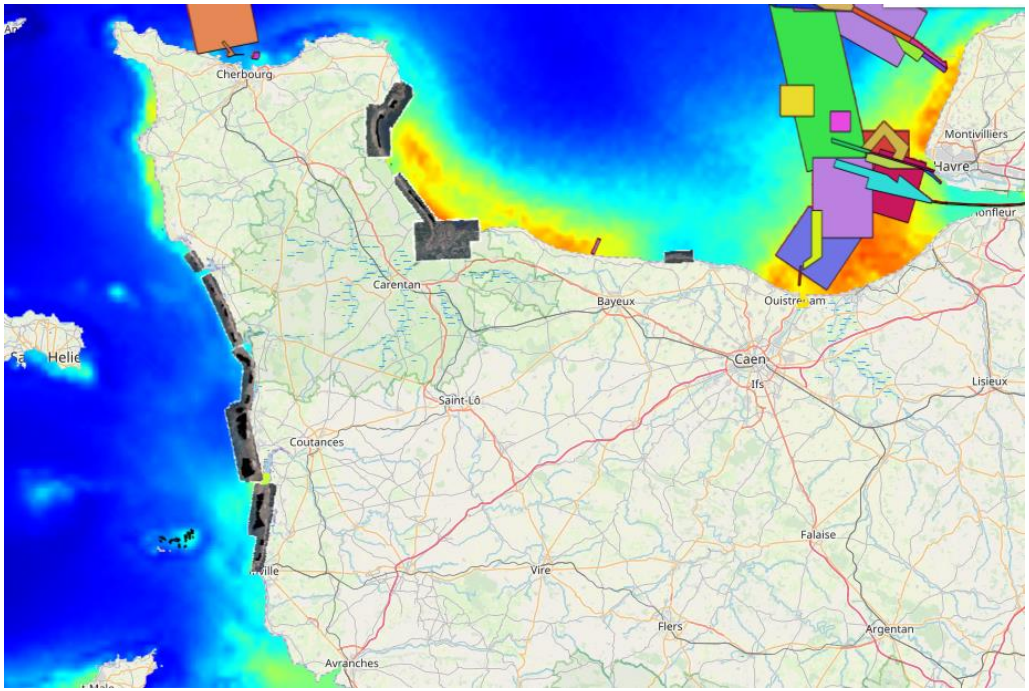
- **Simulation of oyster growth (DEB model)**
- **Spatial constraints: Protected areas**
- **Spatial constraints: Shipping zones**



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- **Simulation of oyster growth (DEB model)**
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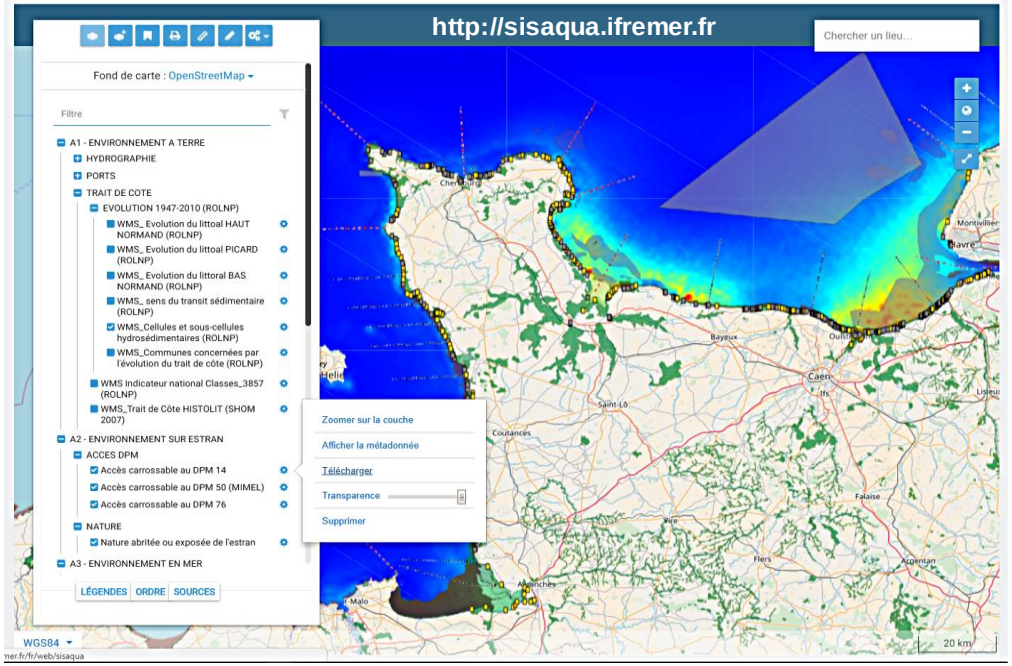
- **Spatial constraints: Shipping zones**
- **Product: Spatial Information System for Aquaculture**



SISAQUA visualization portal with offered options: metadata access and data downloading

Ecosystem functioning

Scale	Drivers	Concepts	Modelling question	Issue
• Space = farm within one management area • Time = year	• Temperature • Hydrodynamics • Density of cultivated species • Food concentration	• Epidemiological model • Hydrodynamic connectivity • Ecosystem functionning	• Factors controlling mass mortality • Competition fo food	• Zoning • Transfer of cultivated species • Effect of climate change • Carrying capacity

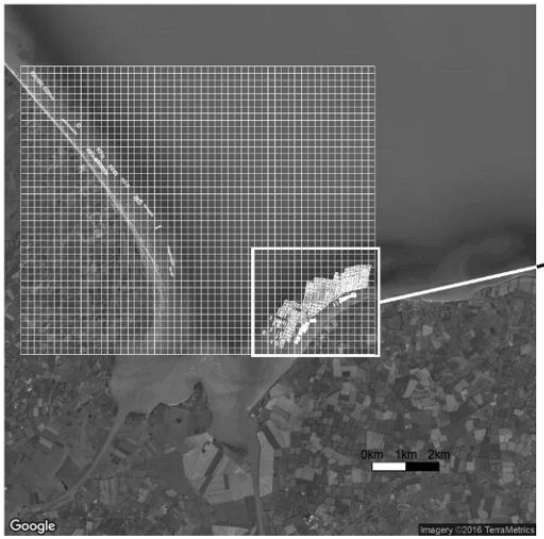
Example: role of connectivity to assess mortality of oysters (Lupo et al., in prep)

- Oyster farms
- Mortality due to Vibrio aestuarianus
- Epidemiology model
- Transport of pathogens

Mortality of oysters: role of connectivity

Connectivity between oyster farms (patches)

Hydrodynamical model to simulate transport of particles (pathogens) (200 m X 200 m)



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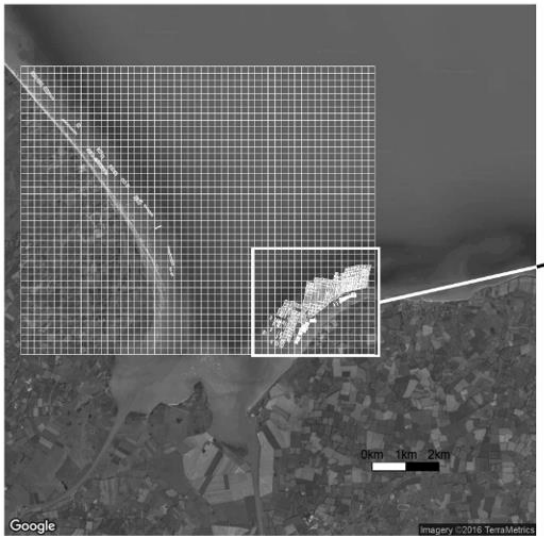

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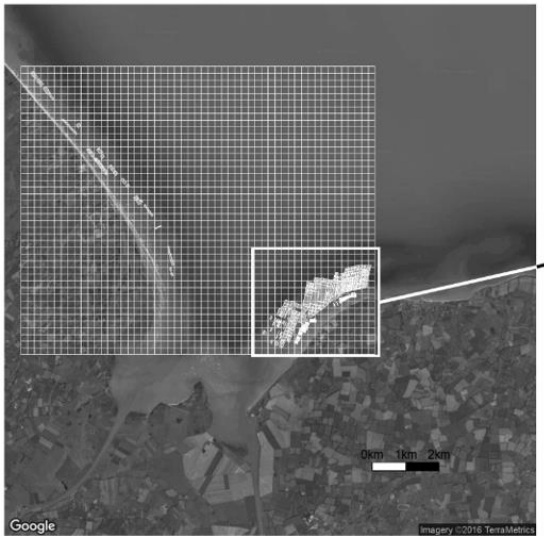

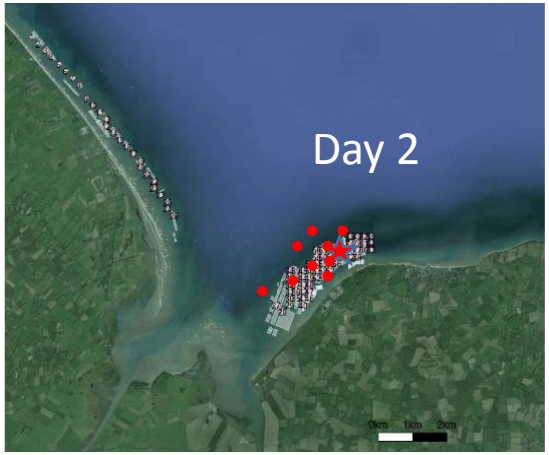

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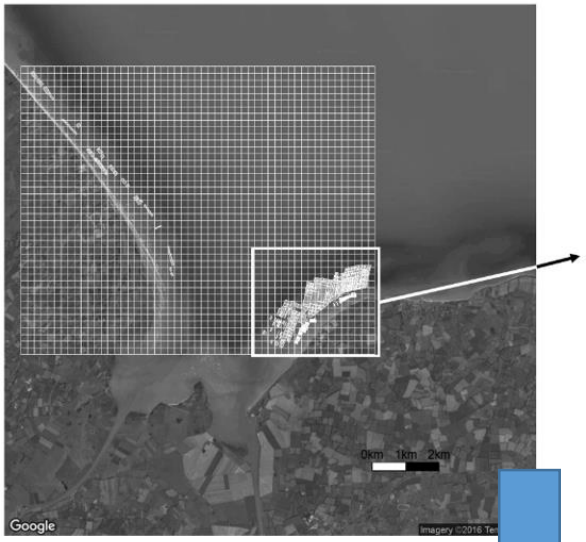
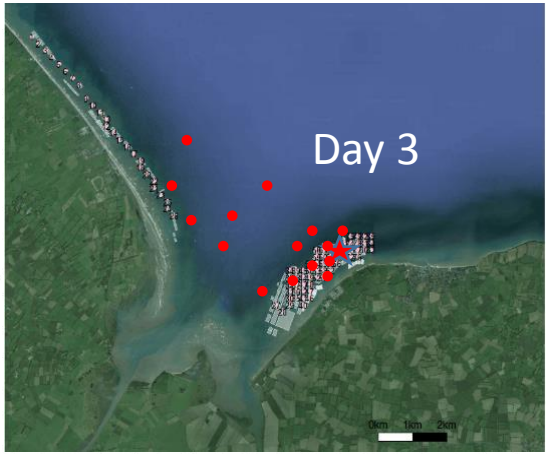
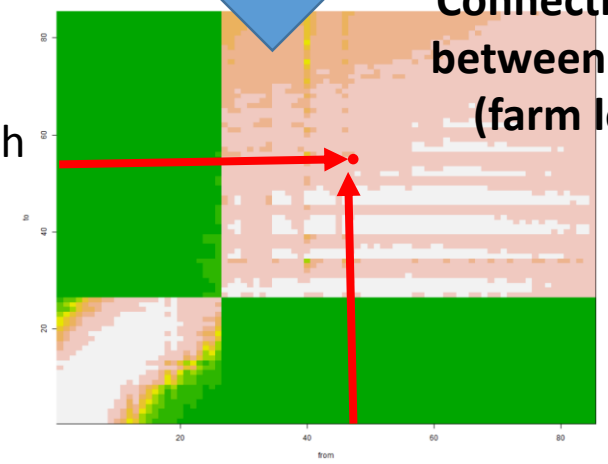




Connectivity matrix between 85 patches (farm locations)

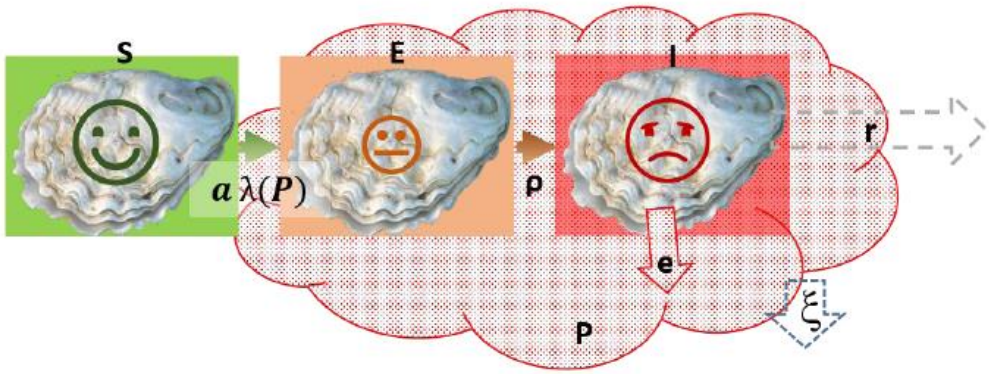
Target patch



Source patch

Mortality of oysters: role of connectivity

Epidemiological farm model

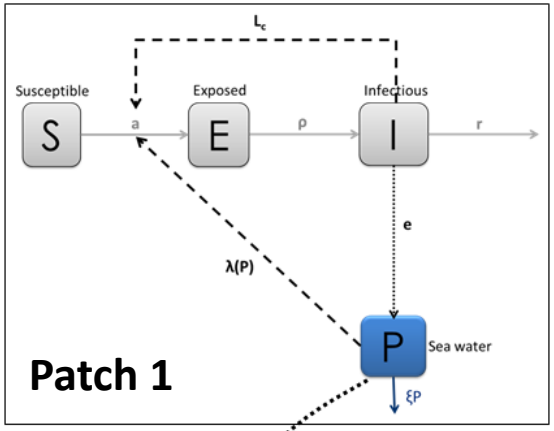


Model based experiments with controlled temperature conditions

Variable	Description
S	Susceptible individuals (number)
E	Exposed (Infected by not infectious) individuals (number)
I	Infectious individuals (number)
D	Oyster mortality

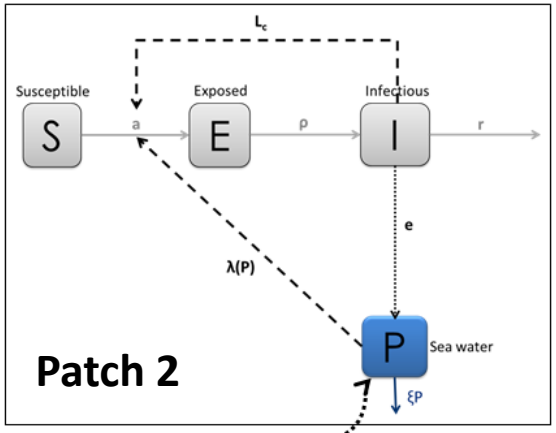
Mortality of oysters: role of connectivity

Integrated model



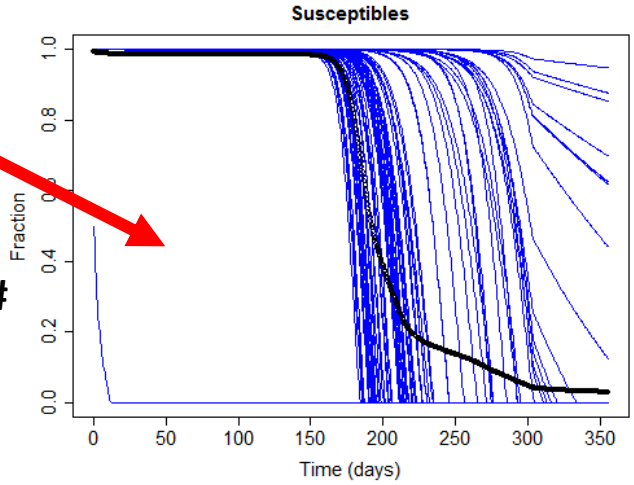
Environmental dependency of epidemiology

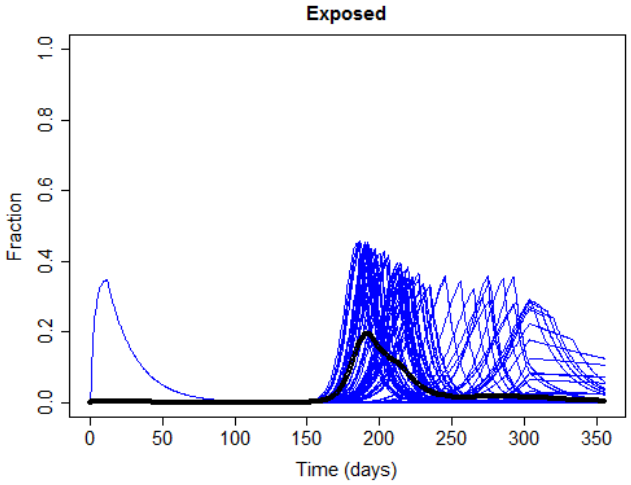
Hydrodynamic pathogen transportation/particle-tracking model

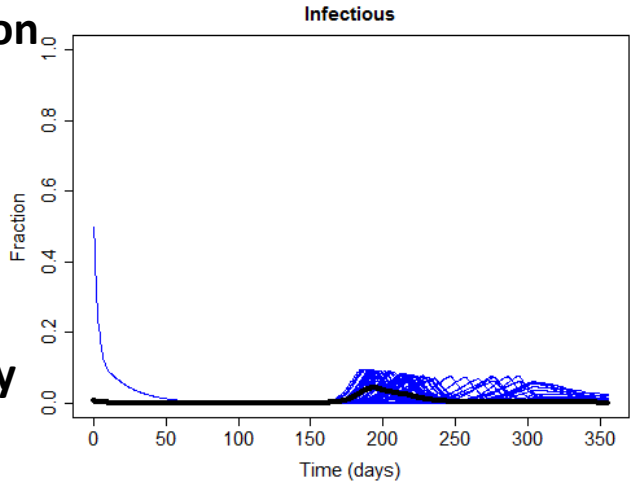


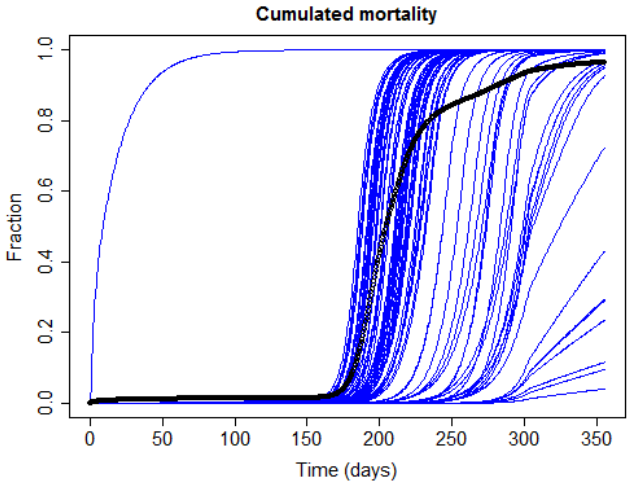
Mortality of oysters: role of connectivity

Infection trajectories





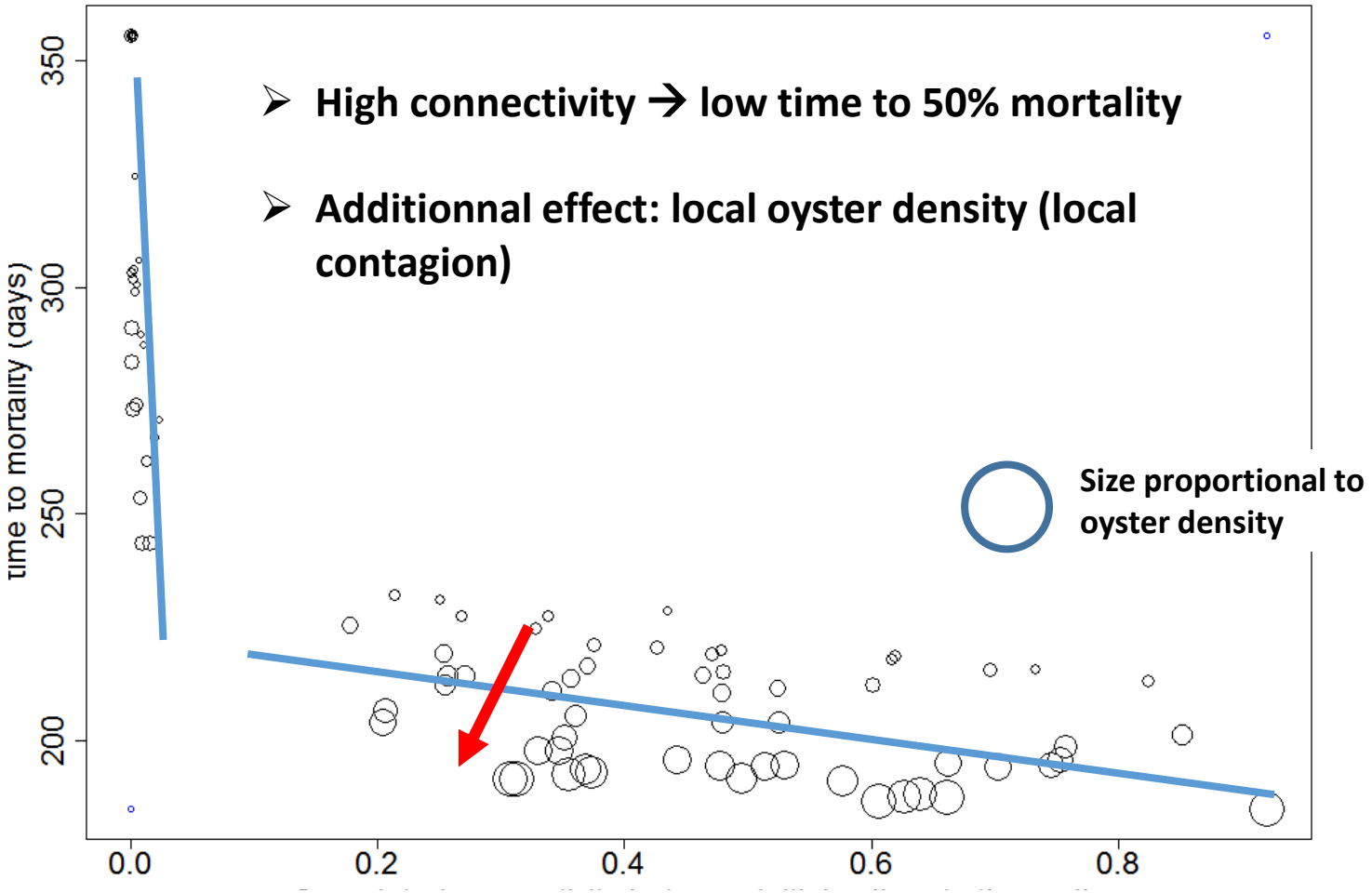




- Initial infection: patch # 78
- Delay depends on connectivity and location of the patch
- Total mortality reaches ca. 100% after 1 year
- Steep slope of mortality with temperature

Mortality of oysters: role of connectivity

Relation between time to reach 50% mortality and connectivity

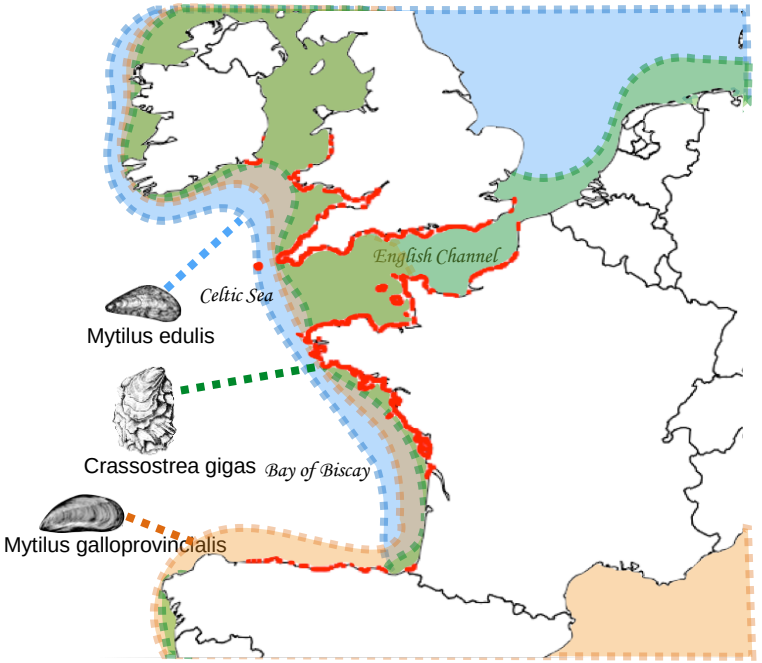


Macroecology

Scale	Drivers	Concepts	Modelling question	Issue
• Space = habitat • Time = century	• Temperature • Hydrodynamics • Food concentration	• Energy budget theory (full life cycle) • Hydrodynamic connectivity • Population dynamics	• Factors controlling colonisation • Response to climate change	• Rate of colonisation • Effect of climate change on recruitment

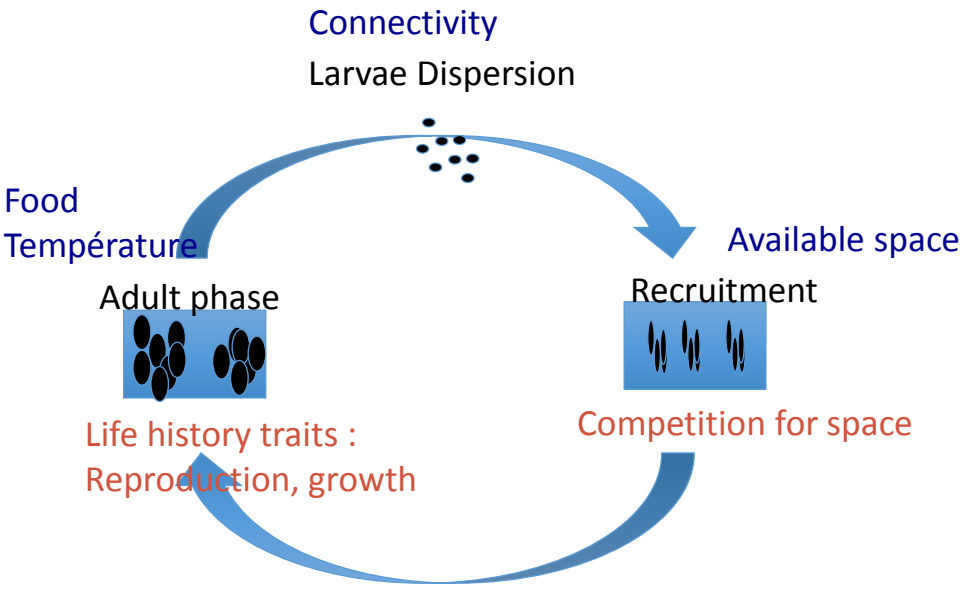
Example: response of colonisation rate of wild mussels to climate change (Thomas and Bacher, in prep):

- **Agent based population model (ABM)**
- **Climate scenarios (RPC)**



Response of colonisation rate to climate

Population dynamics

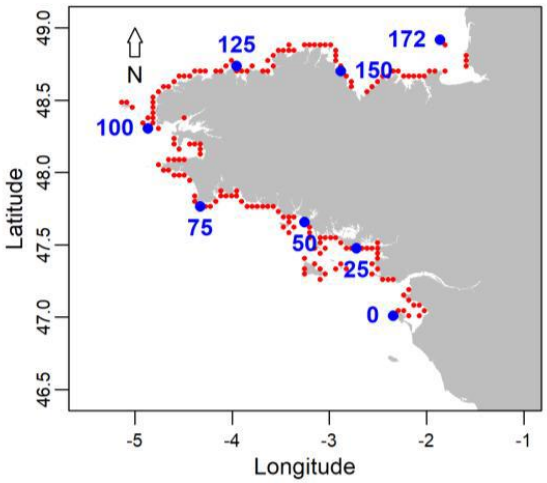


NETLOGO multi-agent simulation platform

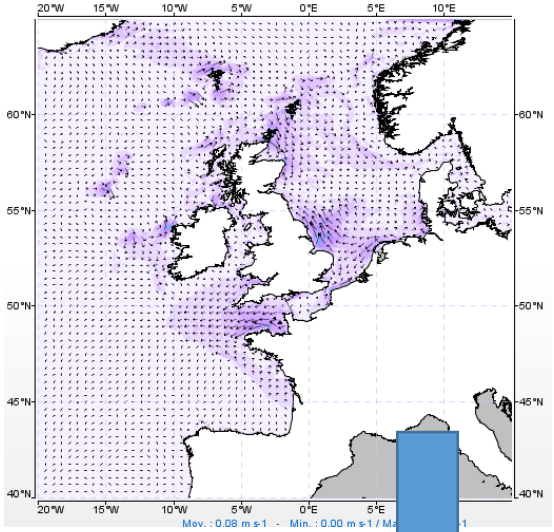
Response of colonisation rate to climate

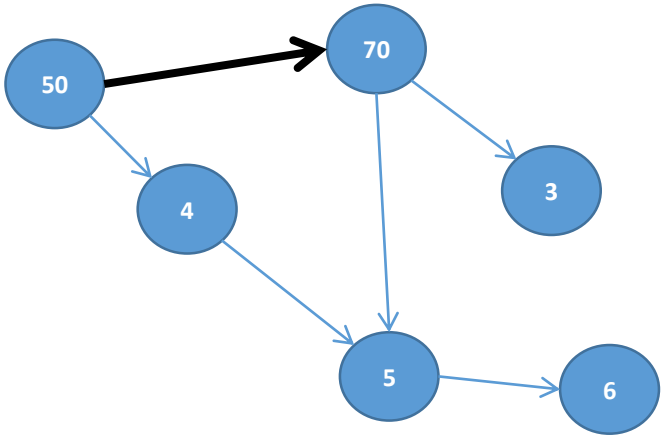
Connectivity between habitat patches

Habitat mapping (EUNIS)
Species preference (OBIS)



Hydrodynamic modelling



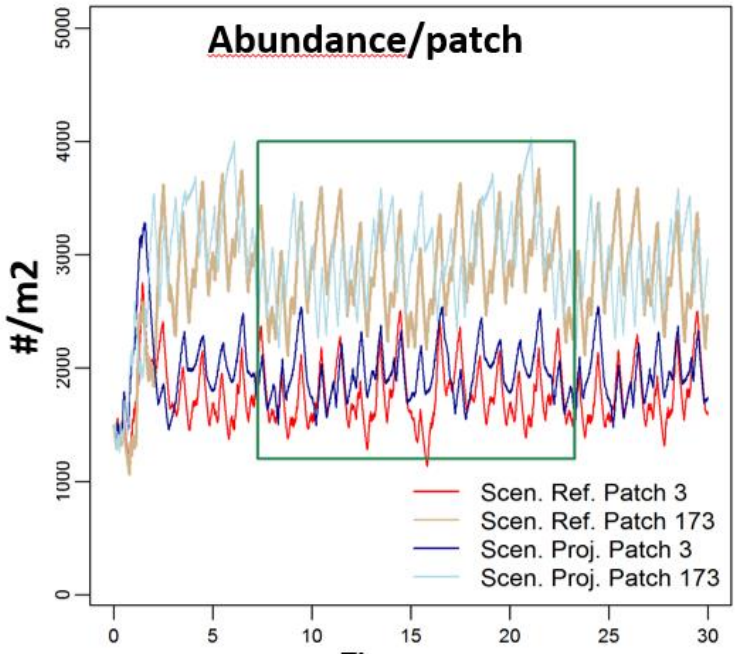


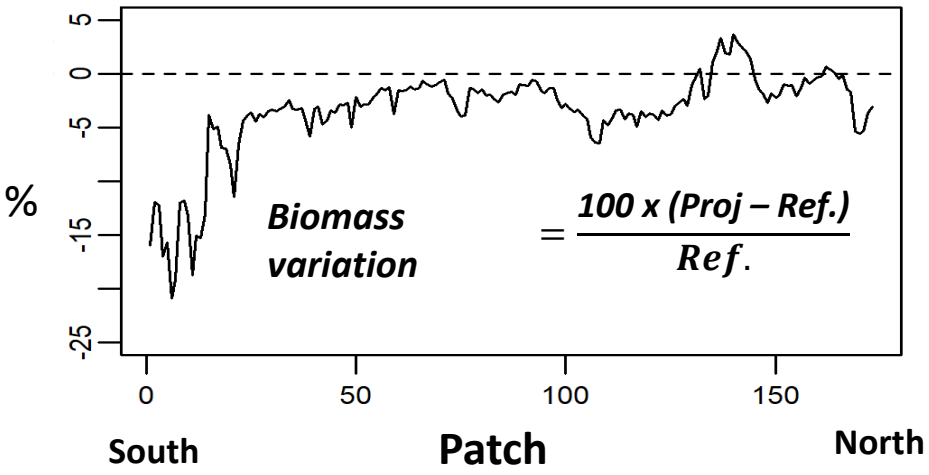
Set of 173 patches
Connectivity matrix

Response of colonisation rate to climate

Effects of global warming on population structure and dynamics

- Steady state: local control due to competition for space
- Inter-annual fluctuations: environmental forcing/biological traits
- Spatial differences
- Differences beween temperature scenarios





Agent based model: an unifying framework

- Definition (from Piou & Bommel)
  - Mechanistic models that describe explicitly some unique and autonomous entities of a system
  - Importance of interactions: more than the sum of the parts
  - The dynamics emerge from the interactions among entities (agents, individuals, collectives…)
  - Complex systems: Set of components interacting in a non-linear way among them and with their environment
  - Stochastic properties

- Agents are discrete entities
  - Agents, even if from same species or same age, have some specificities (e.g. positions…)
  - Interactions among agents are mostly at local scales
  - Agents may decide and eventually adapt their behavior depending on their state and their environment
  - Agents own history may have a very high importance
  - Knowledge emerge from agents' behaviors

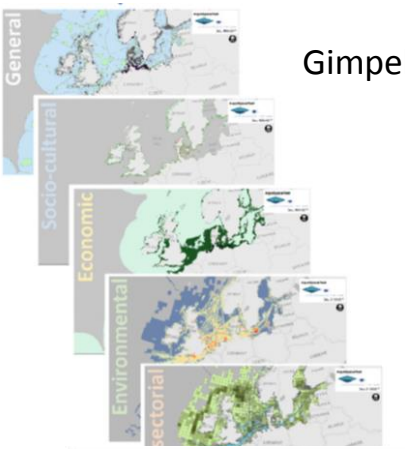
Take home messages

- Spatial scales and resolution depend on physical, biological, social entities

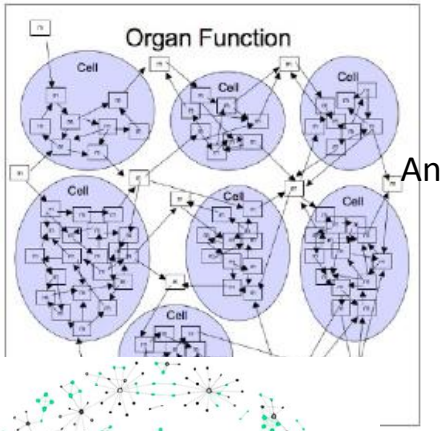
- Ecological concepts allow modelling spatial interactions
  - Dynamic Energy Budget
  - Species niche
  - Landscape ecology
  - Connectivity
  - Epidemiology (SEIR)

- Agent based models (ABM) is an unifying framework for multiple scales modelling
  - Habitats : abiotic agents
  - Hosts, pathogens: biotic agents
  - Farmers and managers: human agents

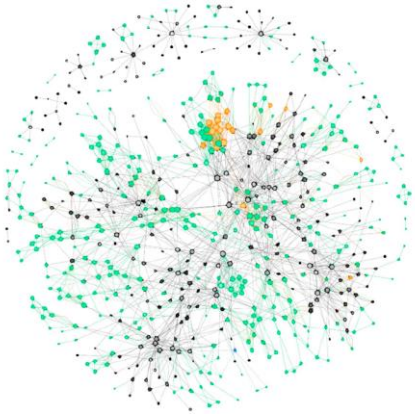
- Novel tools to analyse complex spatial networks: network analysis, connectivity matrix



Gimpel et al., 2018



An et al., 2008



Jones et al., 2019