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Bioeconomic modelling of invasive alien species management

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Ifremer

- Invasive Alien Species (IAS) are exotic species that are introduced, establish, and spread in an ecosystem, causing environmental and economic harm by threatening habitats and native species (CBD, 1992).

- Fisheries level: marine IAS have negative impacts on harvested species by:

Predator-prey relations

Trophic competition

Space competition

…changes in the functioning of marine ecosystems (habitat modification)

=> IAS are recognized as one of the major cause of biodiversity loss at worldwide level (IPBES, 2023).

=> Biological invasions management, which encompasses both prevention and control, is considered as a public good (Perrings et al., 2002) and thus may requires public policies.

Evaluate the economic impacts of IAS on fisheries and the possibilities of control programs

Modelize the dynamics of invasions and their interactions with harvested native species.

First way of including complexity in bio-economics of marine fisheries

Bioeconomic modelling often use a damage function to represent IAS impacts and benefits of IAS control…

…but more **complexity** can be modelized concerning:

- species dynamics
- interspecific relation
- human impacts on IAS dispersal and control

=> We account for complexity by a bioeconomic model of a commercial fishery invaded by a space competitor

Explore the possibilities to sustainable harvesting a native species and controlling an invasive species

A case study: in the Bay of St-Brieuc an invasive species void of market value (slipper-limpet) competes for space with a commercial native species (scallop). This competition is asymmetric.

⇔ The IAS reduces the size of suitable areas for scallop beds (scallop juveniles cannot settle down)

Presentation framework

1. Bioeconomic model of the invaded fishery
2. Dynamic optimisation of the model
3. Numerical illustration of the optimal solution
4. Dynamic simulation of the model with a more realistic native stock dynamics

1. Bioeconomic model of the invaded fishery

(Frésard and Boncoeur, 2006; Frésard, 2008)

- Optimal control models of biological invasions usually relate the damage caused by invasion to the invasive stock size.
  - 1 state variable: invasive stock
  - 1 control variable: control effort of the invasive species
  - Objective: to minimize the discounted flow of damage + control costs

- Wilman (1996) studies the combined dynamics of a native unharvested valuable species, and an invasive species acting as a predator.
  - 2 state variables: native and invasive stocks
  - Objective function and control variable: same as previous

- Our model derives from Flaaten's (1991) competing species one, unlike Flaaten's model we consider (i) an asymmetric competition between species; (ii) a competition influencing the ecosystem's carrying capacity for the native species; (iii) an invasive species void of market value; (iv) an invasive species dispersal coefficient depending on a natural component and on an anthropogenic one.

- In our model, we consider the combined dynamics of 2 harvested species, a native valuable one ($i = 1$) and an invasive one ($i = 2$), void of commercial value and acting as a space competitor:
  - 2 state variables: → native stock biomass X_1 → invaded share of the whole area of the bay X_2
  - 2 control variables: → harvesting effort of the native stock E_1 → cleaning effort of the invaded areas E_2
  - Objective: to **maximize the discounted flow of surplus generated by the combined harvest of both species** (profit generated by harvesting the native stock, minus cost of cleaning invaded areas)

- The two equations of motion describing the dynamics of X_1 and X_2 :

$$(1) \quad \frac{dX_1}{dt} = rX_1\left(1-\frac{X_1}{K(1-X_2)}\right)-q_1E_1X_1$$

space competition

$$(2) \quad \frac{dX_2}{dt} = (s+gE_1)X_2(1-X_2)-q_2E_2X_2$$

effects of native stock fisher's behaviour on invasion

where r, K, s, g, q_1 et q_2 are constant and positive

r	intrinsic growth rate of native stock
K	Carrying capacity of the non-invaded ecosystem for the native stock
q_1	Catchability coefficient
s	Natural dispersal coefficient of invasion
g	Anthropogenic dispersal coefficient of invasion (proportional to the native stock harvesting effort)
q_2	Productivity of cleaning operations (ratio between the number of square metres cleaned per unit of effort and the whole invaded areas)

- The immediate global surplus GS (sum of the profit π of harvesting the native stock minus the cost of cleaning invaded areas):

$$(3)\quad GS = \pi - C_2E_2 = Pq_1E_1X_1 - C_1E_1 - C_2E_2$$

where:

P	is the ex-vessel unit price of native species catch
C_1	is the unit cost of effort devoted to harvesting the native stock
C_2	is the unit cost of cleaning effort

P, C_1 et C_2 are constant and positive.

2. Dynamic optimisation of the model

(Frésard, 2008 ; Frésard and Ropars-Collet, 2014)

The problem for the invaded fishery regulator is to

Determine: (E_1, E_2) over $t \in [0;\infty[$

maximizing $\int_0^\infty GS\, e^{-at} dt$

Subject to: equations of motion (1) and (2)

(4) $X_i(0) = X_{i0}$

(5) $0 \le E_i \le E_{i\max}$

$(i = 1,2)$

the given initial states of native stock and invaded areas

the domains of admissible values that constrain the control variables

where a is the time discount rate assumed constant and positive

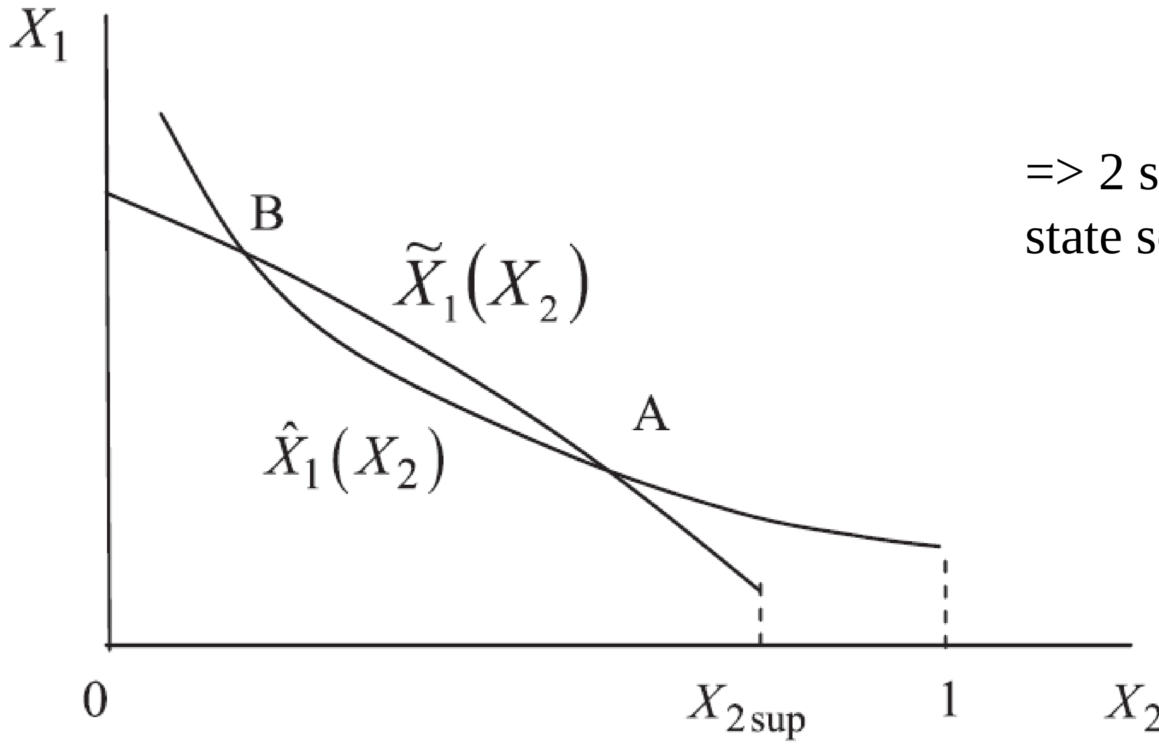
E_{imax} denotes the maximum available effort i

Maximum principle

- Following the standard maximum principle (Pontryaguine et al., 1961) we maximise the current Hamiltonian.

We may derive two curves and study graphically the solution:

First case



=> 2 steady-state solutions

Fig. 1. Economically sustainable harvest of the native species and control of the invasive species. A and B are the two steady-state solutions. $\tilde{X}_1(X_2)$ represents the optimal level of native stock X_1 for a given level X_2 of invaded areas. $\hat{X}_1(X_2)$ represents the level of native stock X_1 that economically justifies the cost of controlling the invaded areas at a given level X_2. X_{2sup} is the breakeven point for harvesting the native stock.

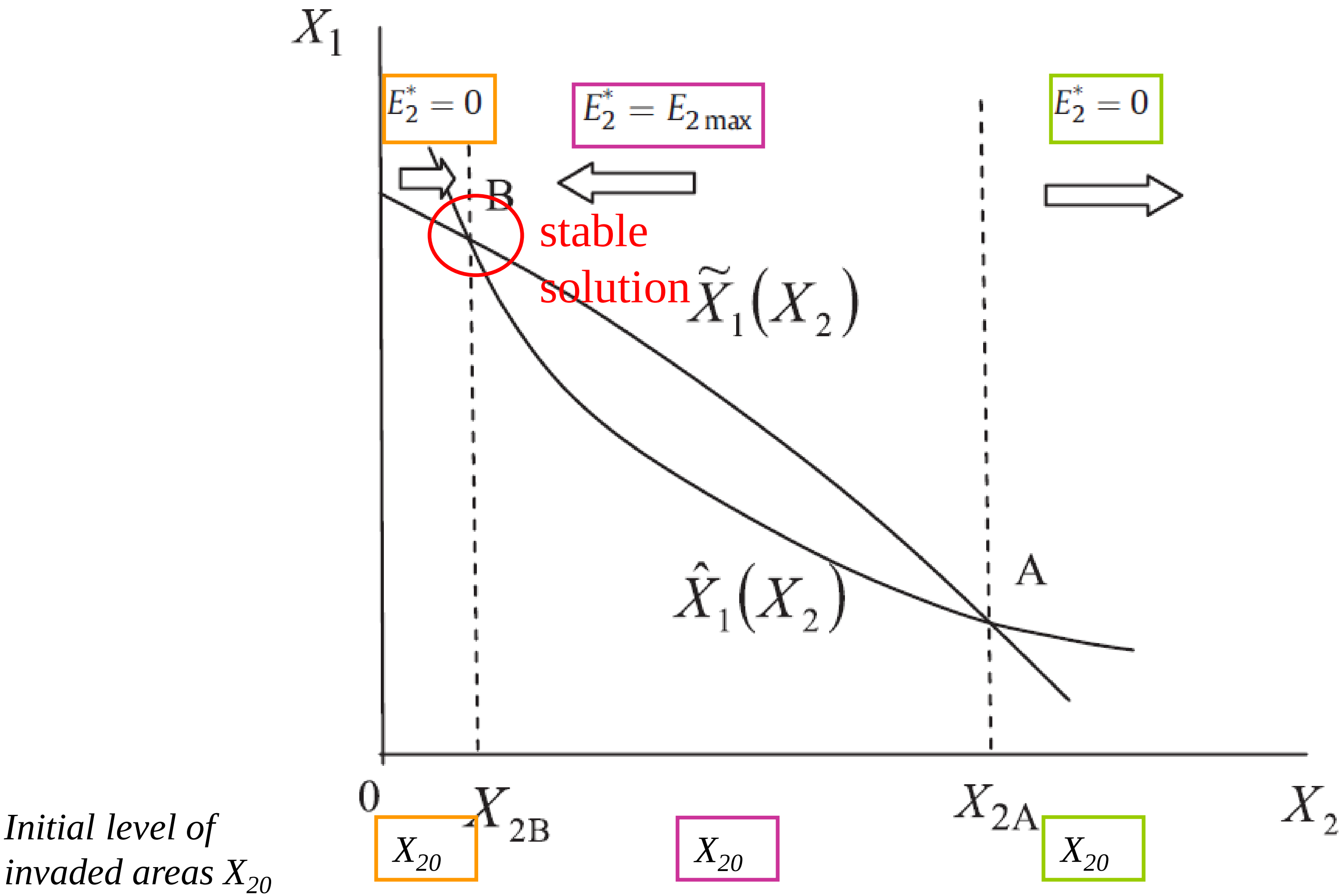


Fig. 2. Stability of a stationary steady-state solution. A and B are the two steady-state solutions. X_{2A} and X_{2B} are the levels of invaded areas corresponding to A and B. $\widetilde{X}_1(X_2)$ represents the optimal level of native stock X_1 for a given level X_2 of invaded areas. $\hat{X}_1(X_2)$ represents the level of native stock X_1 that economically justifies the cost of controlling the invaded areas at a given level X_2.

The optimal effort includes two steps:

1. A “*laisser-faire*” stage ($E_2^* = 0$) or a “rollback” stage ($E_2^* = E_{2max}$) depending of X_{20}

2. A “containment” stage (E_2^* positive and constant) to stabilize the level of invaded areas to its optimal value

2nd case

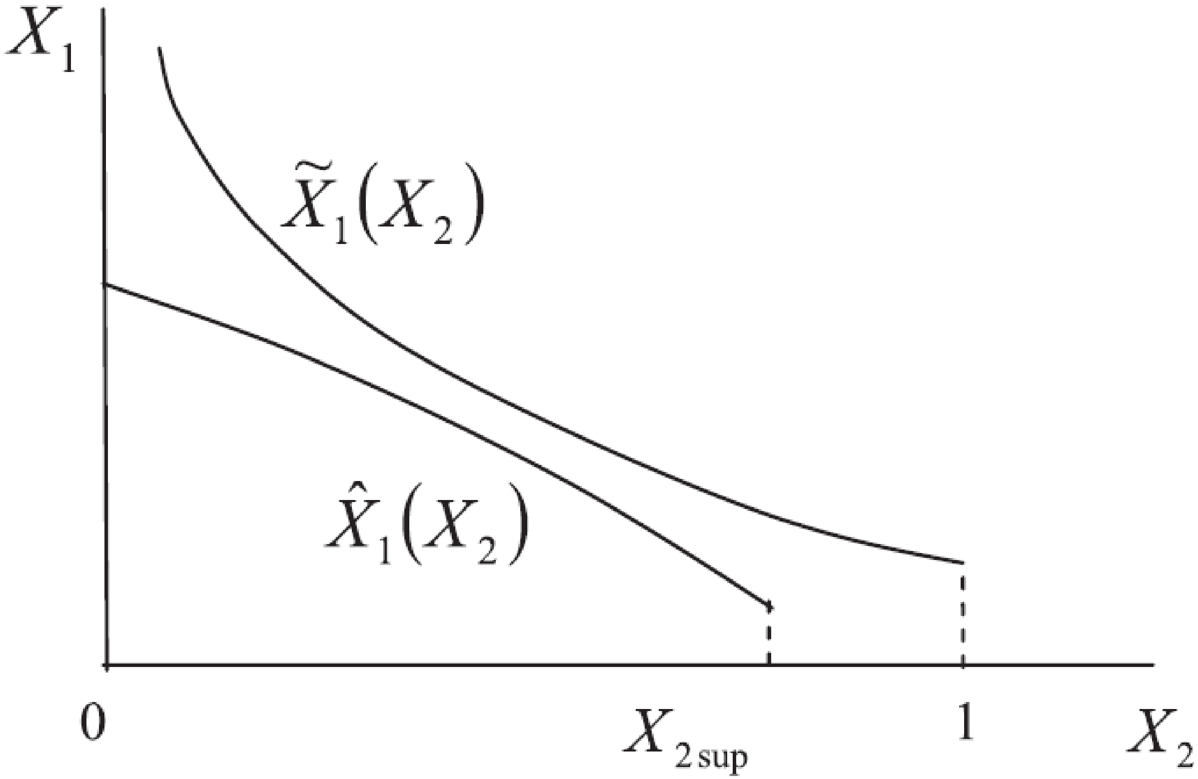


Fig. 3. Quasi-eradication of the native species. $\widetilde{X}_1(X_2)$ represents the optimal level of native stock X_1 for a given level X_2 of invaded areas. $\hat{X}_1(X_2)$ represents the level of native stock X_1 that economically justifies the cost of controlling the invaded areas at a given level X_2. X_{2sup} is the breakeven point for harvesting the native stock.

=> This case corresponds to a situation where harvest costs, natural and anthropogenic dispersal coefficient of invasion and/or discount rate are too high.

Results

•A time-path leading to an optimal steady-state equilibrium where the invasive species is kept under control exists, provided harvesting costs, anthropogenic dispersal coefficients of invasion and time discount rate are moderate.

•However, this time-path is optimal only if the invasion problem is addressed early enough ($X_{20}<X_{2A}$).

•In other circumstances, the optimal time path leads to an asymptotic eradication of the native stock (quasi-eradication linked to G-S model).

•In this case, the fishery will close once the invasion has reached a level corresponding to the breakeven point for harvesting the native stock.

3. Numerical illustration of the optimal solution: the St-Brieuc scallop fishery case (Frésard and Ropars-Collet, 2014)

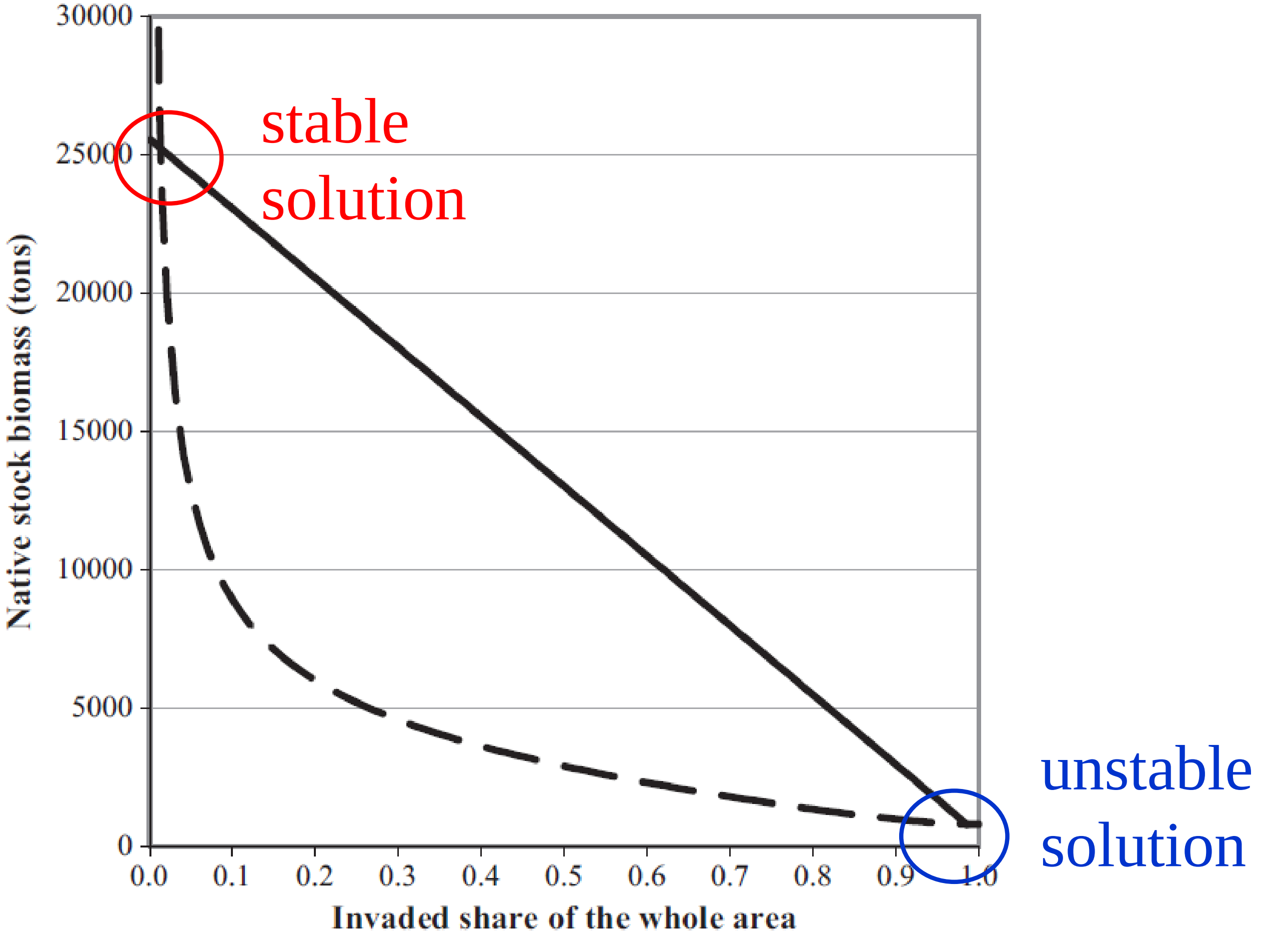


Fig. 4. Steady state solutions of the invaded fishery. ——Optimal level of native stock X_1 (common scallop) for a given level X_2 of invaded areas by slipper-limpet. – – Level of native stock X_1 that economically justifies the cost of controlling the invaded areas at a given level X_2.

Table 3
Sustainable harvest of the native species (common scallop) and control of the invasive species (slipper-limpet) in the Bay of Saint-Brieuc (France): variables value of the optimal stable solution.

Variable	Description	Optimal value
X_1	Native stock biomass	25225 (tons)
E_1	Harvesting effort of the native stock	4869 (hours)
Y_1	Native stock catch	8659 (tons)
X_2	Invaded share of the whole area of the bay	0.0129
E_2	Cleaning effort of the invaded areas	100 (hours)
Y_2	Invaded share of the whole area cleaned	0.00047

=> The optimal stable solution represents a high level of the scallop stock (25225 tons, MSY is about 27000 tons in the model) and a very low level of invaded areas (1,29%)

Insights

•It is nearly always optimal to control the invasion: if the initial level of invaded areas is less than X_{20} = 0,9851, then the optimal solution can be reached. In other circumstances, the optimal time path leads to an asymptotic eradication of the native species (X_{2sup} = 0,9852).

•Except for extreme values of parameters tested (ex-vessel price of scallops, unit cost of scallops fishing effort, unit cost of invaded areas cleaning effort, total dispersal rate of invasion and time discount rate) the optimal solution seems rather insensitive to parameters variations. The optimal size of the invasion is still very low.

<=> These results are linked to the high profitability of the scallop fishery (compared to the cost of cleaning the invaded areas).

4. Dynamic simulation of the model with a more complex and realistic native stock dynamics

(Frésard and Fifas, 2008; Fifas and Frésard, 2014)

•Although the logistic growth model has already been applied to this scallop stock dynamics, its recruitment is highly dependent on hydroclimatic conditions => a stochastic component fits well (Ricker function) to capture its variability.

•Furthermore, linked to the harvesting scheme an age-structured model is more adapted and a catch capacities model was developed.

⇒ We modelized a more complex scallop stock dynamics (used in different projects –PhDthesis, GT partenarial Bio-économique, ANR Comanche).

⇒ The negative impact of the space competition exerted by slipper-limpet directly reduces the success of recruitment.

$$GR1_{inva} = (1-X_2)GR1$$

⇔ The abundance of scallops age class 1 is linked to the dynamics of invaded areas (still a growth logistic function of invasion).

⇒ The invasion control program:

- simulate a “roll-back” stage and a “containment” stage ⇔ decrease and stabilize the invaded share of the whole areas of the bay of St-Brieuc
- is compared to a “*laisser-faire*” scenario

- Main result of the simulation:

Under realistic parameters values, the immediate control of the IAS is the best alternative (higher gross surplus).

Concluding remarks

In both numerical applications:

-The invaded fishery can be controlled ⇔the initial level of invaded areas is not too high and the current parameters values allow it.

-The control of invasion allows the long-term viability of the scallop fishery

These results are linked to the high profitability of the scallop fishery studied (limited fishing time: low cost of effort and high level of scallop catches)

⇔Application of the model to other case studies => ≠ results

Thank you for your attention!

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- Appendix: parameters values used in the numerical illustration of the optimal solution

Table 2
The Bay of Saint-Brieuc scallop fishery invaded by slipper-limpet: parameters value.

Parameter	Description	Value
r	Intrinsic growth rate of native stock	0.649
K	Carrying capacity of the non-invaded ecosystem for the native stock	54252 (tons)
q_1	Catchability coefficient of native stock	7.05×10^{-5}
P	Ex-vessel unit price of native species catch	2000 (€ per ton)
C_1	Unit cost of fishing effort	113 (€ per fishing hour and per boat)
s	Natural spatial dispersal coefficient of invasion	[0; 0.045]
g	Anthropogenic spatial dispersal coefficient of invasion	$[0; 6 \times 10^{-6}]$
q_2	Productivity of cleaning operations	3.675×10^{-4}
C_2	Unit cost of cleaning effort	1423 (€ per hour of cleaning)

Main economic and technical data concerning harvesting activities and biological data concerning scallop dynamics were econometrically estimated by Frésard and Boncoeur (2006). The productivity of cleaning operations and the intrinsic growth rate of dispersal of invasion are derived from Frésard (2008). We assume the values of its two components, s and g. Ex-vessel unit price of native species, unit cost of fishing effort and unit cost of cleaning effort are calculated on the basis of empirical observations by Frésard and Boncoeur (2006).