

BIOLOGICAL INVASION CONTROL IN A COASTAL FISHERY: A BIOECONOMIC ANALYSIS OF THE BAY OF SAINT-BRIEUC SCALLOP FISHERY (FRANCE)

Marjolaine FRESARD, CEDEM / GdR AMURE, University of Western Brittany,

marjolaine.fresard@univ-brest.fr

Spyros FIFAS, Fisheries Resources Department, IFREMER,

Spyros.fifas@ifremer.fr

Olivier GUYADER, Marine Economics Department / GdR AMURE, IFREMER,

Olivier.guyader@ifremer.fr

ABSTRACT

This paper deals with the economic impact of an aquatic invasive alien species on a coastal shellfish fishery. A slipper-limpet (*Crepidula fornicata*) was accidentally imported some decades ago, has established and is spreading in the bay of Saint-Brieuc (France). This exotic species is acting as a space competitor for common scallop (*Pecten maximus*) harvested by fishers, and then is threatening the long term sustainability of the scallop fishery. Facing this situation, biological invasion is addressed by a control program. The paper presents a bioeconomic model analyzing the invasive process, the social cost of invasion for the scallop fishery and the benefits resulting from a control program. Based on provisional data, a numerical simulation of the invasion of the common scallop fishery of the Bay of Saint-Brieuc (France) is proposed as an illustration, and sensitivity tests are presented.

Keywords: aquatic invasive species; bay of Saint-Brieuc; bioeconomic modeling; common scallop; fisheries management; invasion control; slipper-limpet.

INTRODUCTION

88 species of invasive mollusks have been established in the United States with economic costs of \$1.7 billion annually [1]. Usually, invasive alien species are defined as exotic species that are introduced in an ecosystem and whose establishment and spread can cause environmental and economic harm. The causes of biological invasions are often related with economic activities [2]. Invasions result of human behavior concerning land use, species use in production or consumption and global exchange trade. Then, control of invasive species to reduce the damage is a public good and requires public policy. Assessing the economic impact of invasion require to link ecological and economic relationships [3]. The Convention of Biological Diversity, 1992, underlined to “prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats or species”. Two principles have to be retained: the effect of the invader depends on the exact nature of the interspecific interaction and the correct comparison to measure the effects is an ex-ante and an ex-post invasion scenario [4]. The control of invasive species involves to evaluate the economic benefit of management option compared to no control option. A useful method applied in environmental economics is cost benefit analysis [5].

This paper studies the economic impact of the biological invasion of a commercial fishery by an aquatic invasive species and the benefit of a control program. The case study is located in the bay of Saint-Brieuc (France), where the fishery is seasonally operated by some 250 artisanal boat subject to a limited entry license system [6]. The native species is the common scallop (*Pecten maximus*), and the invasive species is a slipper-limpet (*Crepidula fornicata*). This exotic mollusc was imported by American warships during World War II and has established in many French coastal waters [7]. *Crepidula* is acting as a space competitor for the targeted native species. By reducing scallop juveniles survival [8], *crepidula* spread

threatens the long term viability of scallop fisheries. *Crepidula* was first notice in the bay in 1974 [9] and its stock was estimated to 250 000 tons in 1994 [10]. A control program, based on yearly harvesting campaigns, was established in the bay [11].

This paper presents a bioeconomic model based on the age-structured biological model of the scallop fishery of the Saint-Brieuc bay [13, 14], and on a deterministic logistic model for *crepidula* dynamics [12]. In our model, the negative impact of the biological invasion relies on space competition with the valuable species. The two stocks are linked with a parameter representing the impact of space competition exerted by *crepidula* on scallops, as a function of the level of invasion reached. Following a previous model [15], this model represents the economic impact of an invasive alien species on the profit of harvesting a commercial native species in a bounded ecosystem. This model allows comparisons between ex-ante and ex-post invasion situation, under control or no control strategies with a cost-benefit analysis approach.

The paper has two sections. The first section presents the general bioeconomic model. In the second section, numerical simulations are carried out in order to study the economic impact of invasion and to analyse the net benefit of different scenarios of invasion control.

THE BIOECONOMIC MODEL

Assumptions

H1: The model used here is based on the bay of Saint-Brieuc fishery age-structured bioeconomic model [13, 14] linked to a deterministic logistic model representing the invasive species natural dynamics [12].

H2: The structural bioeconomic model is adjusted on the period 1993-1998 and is suitable for numerical simulation on the period 1999-2010. The period of simulation does not necessary reflect these precise years, it is first of all a methodological analysis.

H3: The scallop fishery is assumed to be affected by the spread of an invasive alien species, which is the only environmental perturbation. There is no diffusion out of the bay.

H4: We study only the effects of invasion on scallop fishing activity. Other components of the model, such as other fishing activity are not considered in the analysis. Impact of slipper-limpet invasion on other harvested species is not well known. It is assumed that scallop harvestable biomass reduction does not induce any reallocation of fishing effort.

H4: The invasive species is a space competitor for the native species inducing stock depletion. This competition is asymmetric: whereas an increasing in the level of invasion induces a decrease in scallop juveniles survival on the floor, the presence of scallops does not impaired the dynamic of slipper-limpets [8, 16]. It is assumed that natural growth of the invasive species can lead to eradication of the native stock by decreasing juveniles settle down opportunity. All areas in the bay are potentially subject to invasion by slipper-limpets. The Saint-Brieuc fishery structural bioeconomic model may account for trophic competition between invasive and native species, but we will not focus on this aspect.

H5: The invasive process is assumed to be spatially homogeneous: the slipper-limpet density grows at a uniform rate in all the bay. The model is not spatially explicit, although it is an oversimplification. In the structural model, the impact of invasion takes the form of a negative relationship between the level of invasion (the invasive stock biomass compared to its ecosystem carrying capacity) and the level of recruitment success. At the present level of biological knowledge, there is no statistically significant relationship between scallop stock biomass and *crepidula* stock biomass. Then, we retain a simple parameter to link the two stocks, reflecting space competition.

H6: For native stock, the elasticity of catch per unit of effort (CPUE) to stock abundance is assumed to evolve with technical progress [14]. For the invasive stock, the elasticity of CPUE to stock abundance may differ from one [12]. This case, which corresponds to the "Hyperdepletion" case [17], could capture

the irreversibility of the invasive process. For harvesting the invasive stock, we consider both “proportionality” and “hyperdepletion” case.

H7: Unit prices, unit costs and fishing effort are exogenous. In the case of common scallop, setting unit prices as exogenous is a simplifying assumption open to criticism, even if prices seem to be relatively little elastic to local supply changes [13].

Equations

Scallops dynamics and harvest

Scallops dynamics and harvesting activity referred to the structural bioeconomic model of the Saint-Brieuc bay [13, 14].

The vessel harvesting function is defined as :

$$y_{vjt} = q_{vjt} (N_{jt}) E_{vst} N_{jt} \quad (Eq.1)$$

where:

y_{vjt} is for each vessel (v) the yearly individual catch per scallop age group (y). Scallops age from 3 to 6 are subject to harvest.

q_{vjt} is the yearly catchability coefficient for each age group of scallops.

N_{jt} is the yearly abundance of age group.

E_{vst} is the annual legal time spent in the scallop fishery by each vessel. Annual legal fishing time is fixed.

The catchability coefficient for each age group of scallops is written as:

$$q_{vjt} (N_{jt}) = \exp \left[\frac{N_{jt}^{kW_v}}{\mathbf{d} + \mathbf{g} N_{jt}^{kW_v}} \right] \quad (Eq.2)$$

The catchability coefficient depends on the level of biomass and individual vessel engine power [14]. The individual growth model of scallops in the Saint-Brieuc bay is expressed by a Von Bertalanffy equation. The natural mortality is approached by analogy with a non-exploited scallop stock located in an area not far from those considered. Scallop recruitment is based on an average recruitment (1993-1998) which fluctuates under a probability of 0.5 [13].

Technical progress is considered by introducing a new parameter, measuring autonomous technical progress (a) in the harvesting function. Considering (a) each year (t) gives:

$$q_{vjt} (N_{jt}) = [1 + \Delta a (t - t_0)] \exp \left[\frac{N_{jt}^{kW_v [1 + \Delta a (t - t_0)]}}{\mathbf{d} + \mathbf{g} N_{jt}^{kW_v [1 + \Delta a (t - t_0)]}} \right] \quad (Eq.3)$$

where: (t_0) is the initial year.

Total individual vessel catch of scallops for each age-group (y_{vst}) is then defined as:

$$y_{vst} = \sum_{j=1}^n y_{vjt} \quad (Eq.4)$$

We assume that the landing price of scallops (p_s) and prices of variable inputs (fuel, gears) are exogenous. The net revenue to be shared (rs_{vt}) between the vessel owner and the crew is defined as:

$$rs_{vt} = p_s y_{vst} (1 - \mathbf{q}) - c_{vs} E_{vst} \quad (Eq.5)$$

where:

c_l is the unit cost of landings,

c_{vs} is the unit cost per day at sea and mainly represents the costs linked to fuel consumption, gear repairs and replacement. Scalloping in the bay is a part time activity and we assume that (c_{vs}) is a variable cost.

We will assume that the net revenue to be shared is a proxy of the scallop activity gross margin. The cumulated time-discounted value of the scallop fishery gross margin (p_s) is defined as:

$$p_s = \sum_{t=1}^n \frac{r t s_{vt}}{(1+a)^t} \quad (Eq.6)$$

where a is the time discount rate.

Invasive species dynamics and space competition

Crepidula dynamics and harvesting activity referred to a logistic bioeconomic model [12].

For crepidula stock, the time variation of biomass (X_{cf}) is equal to the difference between its natural variation (N_{cf}) and fishing mortality (Y_{cf}) [17, 18] :

$$\frac{dX_{cf}}{dt} = N_{cf} - Y_{cf} \quad (Eq.7)$$

The natural growth of crepidula stock biomass follows a logistic path:

$$N_{cf} = r_{cf} X_{cf} \left(1 - \frac{X_{cf}}{K_{cf}} \right) \quad (Eq.8)$$

where:

r_{cf} is crepidula stock intrinsic growth rate,

K_{cf} is the carrying capacity of the ecosystem for crepidula stock.

For crepidula stock, the relation between CPUE (Catch Per Unit of Effort) and biomass is written as:

$$\frac{Y_{cf}}{E_{cf}} = q_{cf} X_{cf}^{a_{cf}} \quad (Eq.9)$$

where:

q_{cf} and a_{cf} are positive parameters,

E_{cf} is the fishing effort devoted to harvest crepidula stock.

The invasive species is a space competitor of the native species. Crepidula invasion induces a decrease in scallop recruitment which is described by:

$$R_{scf} = R_s \mathbf{b} \quad (Eq.10)$$

where:

R_{scf} is the scallop recruitment subject to invasion by crepidula,

R_s is the scallop recruitment without invasion,

\mathbf{b} is the parameter reflecting the negative impact of the level of invasion on scallop recruitment.

with:

$$\mathbf{b} = 1 - \frac{X_{cf}}{K_{cf}} \quad (Eq.11) \quad (0 = \mathbf{b} = 1)$$

In the structural bioeconomic model, the invasion impact on recruitment will generate a decrease in the biomass of scallops aged 1. This reduction will affect each scallop age group with a time lag and thus the harvestable biomass.

Social cost of invasion

We may assess the social cost of invasion as the difference between the net economic benefits arising from the pre-invasion situation and the net economic benefits occurring in the post-invasion situation [15]. In our case study, the economic impact of invasion is the difference between the cumulated time-discounted gross margin of the scallop fishery without (p_s) and with invasion (p_{scf}), that is without and with crepidula effect on scallop recruitment, on the period covered by the model. The social cost of invasion ($|SC_{inv}|$) is written as:

$$|SC_{inv}| = p_s - p_{scf} \quad (Eq.12)$$

Economic result of the control program

In order to reduce the spread of the invasive species and its negative effect, a control program is implemented in the bay of Saint-Brieuc.

For invasive species harvesting activity, we write profit (p_{cf}) as the difference between revenue and cost:

$$|p_{cf}| = P_{cf} Y_{cf} - C_{cf} E_{cf} \quad (Eq.13)$$

where:

P_{cf} is the unit price of scallop,

C_{cf} is the unit cost of effort.

With a zero price for invasive species, p_{cf} is necessarily non-positive, and its absolute value is simply the cost of harvesting this species.

The economic result of the control program (p_{cp}) is the difference between the cumulated time discounted value of the scallop fishery gross margin it generates (p_{scf}) and the cost of control to harvest crepidula ($|p_{cf}|$):

$$p_{cp} = p_{scf} - |p_{cf}| \quad (Eq.14)$$

After studying the control program profitability we will compare the economic result of the control program (p_{cp}) to the invaded scallop fishery gross margin (p_{scf}), under a cost-benefit approach:

if $p_{cp} > p_{scf} \rightarrow$ control program is the best alternative

if $p_{cp} < p_{scf} \rightarrow$ control program is not the best alternative

If the economic result of the control program is higher than the invaded scallop fishery gross margin the control program is the best alternative and helps reducing the invasion cost. If not, the control program is profitable but it is not the best alternative.

NUMERICAL SIMULATION

Except for the scallop fishery bioeconomic model parameters [13, 14], available data are too scarce for a real calibration of the model. We propose here a numerical simulation based on “reasonable” values of parameters. Table I gives these values for the invasive species dynamics, harvest and the invasion impact parameter, which are subject to a high level of uncertainty due to limited empirical knowledge.

Table I: Crepidula dynamics and harvest: estimated parameters (“realistic” value)

<i>Crepidula dynamics</i>			<i>Crepidula harvest</i>			
Biomass X_{cf1994}	Carrying capacity K_{cf}	Growth rate r_{cf1994}	Unit Price P_{cf}	Unit Cost C_{cf}	CPUE	
					Proportionality q_{cf}	Hyperdepletion q_{cf}
250 ^{1 2}	1000 ¹	3 % ²	0 ³	1423 € ⁴	2,963 x 10 ^{-4 3}	9,237 x 10 ^{-10 3}

¹ K tons
² From Hamon and Blanchard (1994).
³ From Frésard and Boncoeur (2006).
⁴ From Anon. (2005).

Social cost of invasion

Numerical simulation

According to the simulation (Table II), the value of the scallop fishery gross margin without invasion is 56757 K€ and the one subject to the invasive spread falls to 44878 K€ on the period 1999-2010. Thus, the social cost of invasion for the scallop fishery is about 11879 K€ (absolute value) on the period. This cost represents a reduction of $\approx 21\%$ of the cumulated scalloping activity gross margin in 11 years. Therefore, the simulation suggests that the invasive species spread can impose significant cost to fishers, under the hypotheses held.

Table II: Social cost of invasion. Numerical simulation (period 1999-2010, time discount rate 5%)

Discounted values in K€	<i>Scallop fishery gross margin</i>		
	<i>No invasion</i>	<i>Invasion</i>	<i>Social cost of invasion</i>
<i>Main simulation</i>	56757	44878	11879

Figure 1 shows the impact of the level of invasion reached on yearly scallop recruitment. As crepidula biomass increases with its dynamics, the level of invasion grows up and yearly recruitment of scallops decreases. In a dynamic perspective, this reduction affects other scallop age groups and induces a gradual decrease in scallop harvestable stock.

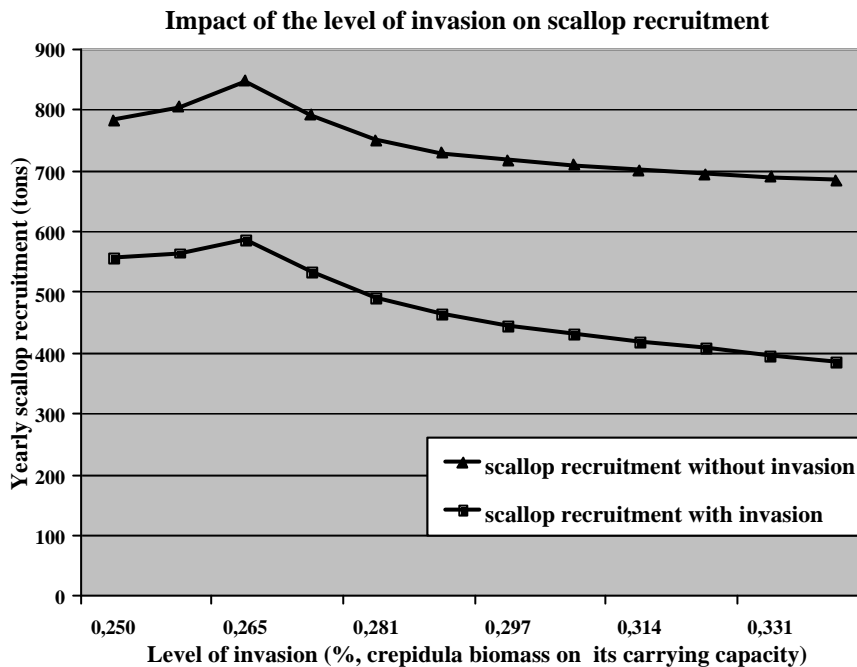


Figure 1. Impact of the invasive process

Sensitivity tests

Sensitivity tests were carried out on three highly uncertain parameters of the invasive process: invasion impact parameter, present growth rate and carrying capacity. Table III displays the impact of these tests on the social cost of invasion.

Table III: Social cost of invasion. Sensitivity tests (period 1999-2010, time discount rate 5 %)

Discounted values in K€	<i>Scallop fishery gross margin</i>		
	<i>No invasion</i>	<i>Invasion</i>	<i>Social cost of invasion</i>
<i>Main simulation</i>	56756	44878	11878
<i>Sensitivity tests</i>			
Invasion impact parameter			
$\beta_1 = 1 - (X_{cf}/K_{cf})^2$	56756	52987	3769
$\beta_2 = 1 - 0,5 (X_{cf}/K_{cf})$	56756	50888	5868
Present growth rate (crepidula)			
$r_1 = 1 \%$	56756	46727	10029
$r_2 = 5 \%$	56756	42861	13895
Carrying capacity (crepidula)			
$K_1 = 625^1$	56756	38474	18282
$K_2 = 2500^1$	56756	51801	4955

¹ in 1000 tons.

Concerning the invasion impact parameter (Figure 2), two scenarios have been run: $\beta_1 = 1 - (X_{ct}/K_{ct})^2$ and $\beta_2 = 1 - 0,5 (X_{ct}/K_{ct})$. Assuming β_1 induces that scallop recruitment is less impacted by the invasion level reached, but is still subject to extinction. Assuming β_2 generates a higher impact than β_1 in the first steps of invasion, but does not lead to extinction of the scallop stock in the long run.

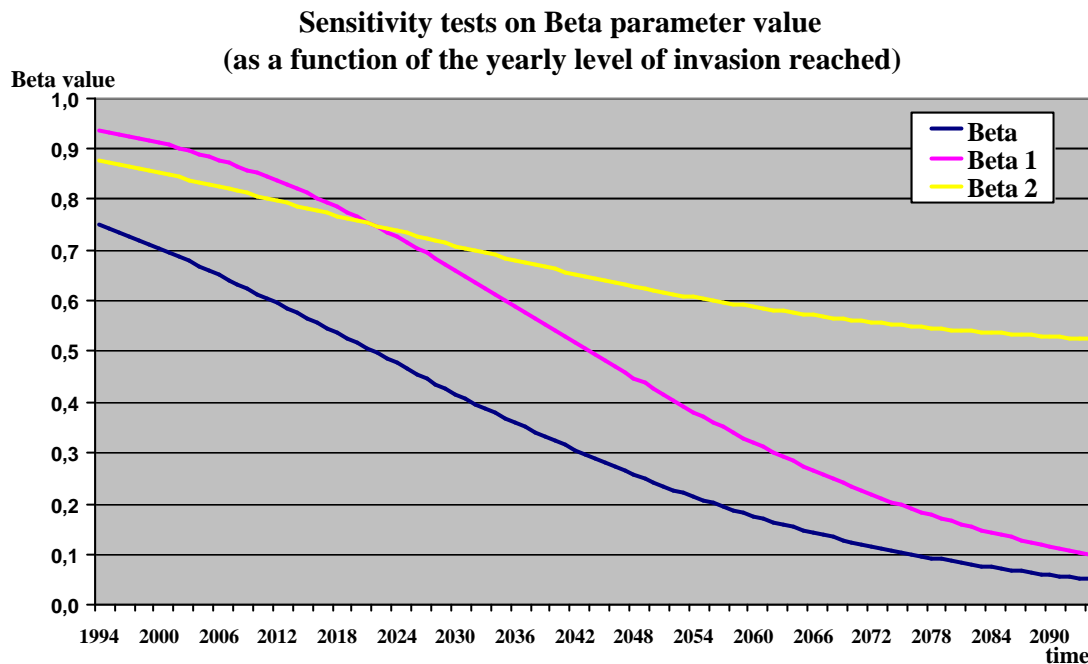


Figure 2. Sensitivity tests on the invasion impact parameter

According to the results of the sensitivity tests, the social cost of invasion decreases in the two scenarios with a higher cost in β_2 due to the present level of invasion reached in the period of simulation. Concerning the present growth rate of the invasive stock, two scenarios have also been run: $r_1 = 1$ percent and $r_2 = 5$ percent. According to the results of the sensitivity tests, the social cost of invasion increases with the value of the present growth rate of the invasive species. Concerning the ecosystem carrying capacity for crepidula, two scenarios have also been run: $K_1 = 625\ 000$ tons (2.5 times the 1994 estimated stock biomass) and $K_2 = 2.5$ million tons (10 times the 1994 estimated stock biomass). According to the tests, the social cost of invasion is a decreasing function of the ecosystem carrying capacity for crepidula, and its value is divided by 3.8 when assuming K_2 instead of K_1 . We can observe that higher the invasion process is, higher the social cost of invasion is.

Economic result of a control program

We now consider the control program which is being implemented in the bay Saint-Brieuc scallop fishery. The strategy of this program relies on two distinct stages, called “rollback” and “containment”. In the first one, there is a high level of crepidula harvesting to decrease significantly the level of invasion. In our case study, the first stage consists of harvesting 100 000 tons of crepidula over five years. In the second stage, the yearly natural surplus produced by the existing biomass is harvested. In our numerical simulation, the containment stage relies on the simple logistic model for crepidula dynamics. In the two stages of the control program, we consider both the two variants of the harvest function (proportional

CPUE and hyperdepletion). In the proportionality case, a_{cf} equals one. In the hyperdepletion case, a_{cf} equals two.

Numerical simulation

According to the simulation (Table IV), crepidula invasion control is profitable in both “proportionality” and “hyperdepletion” cases, on the period 1999-2010. Thus, the present value of the gross margins it generates is higher than the present value of crepidula control costs, on the period. In the “hyperdepletion” variant, the cost of control is higher by 27.5% than in the “proportionality” variant, due to the relatively low level of crepidula biomass to control. Compared to the no control strategy, the control scenario is the best alternative only in the case of “proportionality” variant, generating a benefit of 365 K€ on the simulation period.

Table IV: Net result of a control program. Numerical simulation
(period 1999-2010, time discount rate 5%)

Discounted values in K€	No control	Control scenario	
		“Proportionality” variant	“Hyperdepletion” variant
Scallop fishery gross margin	44878	47481	47481
Crepidula cost of control	0	2238	2854
Net result	44878	45243	44627

Sensitivity tests

Sensitivity tests were carried out on the main uncertain parameters in order to evaluate their influence on results of the simulation (Table V).

Table V: Net result of a control program. Sensitivity tests
(period 1999-2010, time discount rate 5 %)

Discounted values in K€	No control	Net result Control scenario	
		“Proportionality” variant	“Hyperdepletion” variant
<i>Main simulation</i>	44878	45243	44627
<i>Sensitivity tests</i>			
Invasion impact parameter			
$\beta_1 = 1 - (X_{cf}/K_{cf})^2$	52987	43732	43115
$\beta_2 = 1 - 0,5 (X_{cf}/K_{cf})$	50888	49932	49315
Present growth rate (crepidula)			
$r_1 = 1 \%$	46727	47055	46050
$r_2 = 5 \%$	42861	43324	43133
Carrying capacity (crepidula)			
$K_1 = 625^1$	38474	40367	39600
$K_2 = 2500^1$	51801	50580	50112

¹ in 1000 tons.

We test another parameter: the starting date of the program (Table VI). Postponing the starting date of the program modify the economic justification of the control program because the level of invasion addressed by the program and the present value of a set of cash flows are time dependant.

Table VI: Net result of a control program postponed for 5 years. Sensitivity tests (period 1999-2010, time discount rate 5 %)

Discounted values in K€	<i>No control</i>	<i>Net result</i>	
		<i>Control scenario + 5 years</i>	
		<i>“Proportionality” variant</i>	<i>“Hyperdepletion” variant</i>
<i>Main simulation</i>	44878	44183	44111
<i>Sensitivity tests</i>			
Invasion impact parameter			
$\beta_1 = 1 - (X_{cf}/K_{cf})^2$	52987	52105	52033
$\beta_2 = 1 - 0,5 (X_{cf}/K_{cf})$	50888	49935	49862
Present growth rate (crepidula)			
$r_1 = 1 \%$	46727	45807	45278
$r_2 = 5 \%$	42861	42326	42496
Carrying capacity (crepidula)			
$K_1 = 625^1$	38474	38048	37847
$K_2 = 2500^1$	51801	50843	50883

¹ in 1000 tons.

Concerning the main simulation results, postponing the starting date of the program is not desirable. Immediate implementation of the control program generates higher fishery gross margin and control cost than delaying the control program, but the net result is higher in the first case. Thus, immediate implementation of the program is the best alternative as long as the time discount rate is less than 6 % in the proportionality case. As regards the invasion impact parameter, the results of the tests indicate that for β_1 and β_2 the control scenario is profitable but generates a lower net result than the no control strategy, on the simulation period. Delaying the starting date of the control program reduces the difference between the control and the no control strategy, especially in the “hyperdepletion” variant. Thus, sensitivity tests on invasion impact parameter shows that even if the impact of crepidula is less important, postponing the control program reduces the net results difference between no control and control scenario on the simulation period. Then, the more the invasion level reached important is, the more the control scenario justify is. Concerning crepidula present growth rate, the results of the tests shows that the “proportionality” variant case of the control scenario gives the higher results, whatever crepidula present growth rate is. In the “hyperdepletion” case, the control scenario is more desirable than no control only for higher crepidula present growth rate. Increasing the value of crepidula present growth rate lowers the discounted benefit of the control scenario, but it lowers the discounted value of the no control scenario even more. Postponing the control program is not the best alternative whatever crepidula present growth rate is (as for the main simulation). As regards crepidula carrying capacity, result of the tests underlines that the more the present level of invasion reached high is, the more the control program desirable is. With a high present level of invasion, the immediate implementation of the control program is the best alternative, on the simulation period. These results tend to emphasize the importance to extend the model on the long run to capture all the invaded scallop fishery evolution. This is supported by sensitivity tests results: the more the invasion level reached important is, the more the social cost important is and the more the control program benefit high is.

CONCLUSION

Making use of a pluri-species bioeconomic model, this paper has studied the economic impact of the biological invasion of the bay of Saint-Brieuc scallop fishery by an invasive alien species (*Crepidula fornicata*), and the benefit of a control program. The native species stock dynamics is based on a structural model and the invasive species stock on the classical Schaefer one. Concerning the invasive species stock, a variant in the harvest function is used, so called “hyperdepletion”. The invasive process is acting on the native dynamics by reducing the level of its recruitment.

The numerical illustration of the model relies on the available biological and economic knowledge of this case study. The numerical simulation realized on the 1999-2010 period has approximated the economic impact of this invasion, and has shown that crepidula invasion imposes significant cost to the scallop fishery of the Saint-Brieuc bay. Simulations have underlined the importance of the invasion level reached and the starting date of the control program, when assessing its results. However, this model faces several important limits. Some are due to the deficiency of biological knowledge concerning crepidula dynamics and the importance of the interspecific interaction. Modelling scallop dynamics is limited by the high variability of scallop recruitment linked to hydroclimatic conditions, which are not predictable. Other limits are due to the modelling assumptions. In particular, the description of the space competition is limited by the interspecific relation parameter retained, which is an oversimplification. A spatially explicit model could fit better. Fisher’s behaviour is limited by exogenous scallop fishing effort, and by no reallocation of fishing effort. Moreover, the simulation period is too short, the invasive process and its effects on the scallop fishery have to be studied in the long run. Considering scallop prices as exogenous is certainly another significant limitation of the model.

REFERENCES

- [1] Pimentel, D., McNair, S., Janecka, S., Wightman, C., Simmonds, C. O’Connell, C., Wong, E., Russel, L., Zern, J., Aquino, T. and T. Tsomondo, 2001, Economic and Environmental Threats of Alien Plant, Animal and Microbe Invasions, *Agriculture, Ecosystems and Environment*, 84(1): pp.1-20.
- [2] Evans, E.A., 2003, Economic Dimensions of Invasive Species, *Choices* (2nd quarter), pp. 5-9.
- [3] Perrings, C., Williamson, M., Barbier, E.B., Delfino, D., Dalmazzone, S., Shogren, J., Simmons, P. and A. Watkinson, 2002, Biological Invasions Risks and the Public Good: an Economic Perspective, *Conservation Ecology*, 6(1), available online at <http://www.consecol.org/vol6/iss1/art1>.
- [4] Barbier, E.B., 2001, A Note on the Economics of Biological Invasions. *Ecological Economics*, 39, pp. 197-202.
- [5] Hanley, N. and C. Splash, 1993, *Cost-Benefit Analysis and the Environment*, Cheltenham, Elgar.
- [6] Fifas, S., Guyader, O. and J. Boucher, 2003, La Pêcherie de Coquilles Saint-Jacques en Baie de Saint-Brieuc : Productivité et Gouvernance, in *Exploitation et surexploitation des ressources marines vivantes*, L. Laubier, ed., Académie des Sciences, Rapport sur la Science et la Technologie n°17, Lavoisier, Paris.
- [7] Blanchard, M., 1995, Origine et Etat de la Population de *Crepidula Fornicata* (*Gasteropoda prosobranchia*) sur le Littoral Français, *Haliotis*, 24, pp. 75-86.
- [8] Chauvaud, L., Thouzeau, G., Grall, J. and Y.-M. Paulet, 2003, La Crépidule en Rade de Brest: Paradoxe pour le Devenir de la Coquille Saint-Jacques », in *Exploitation et surexploitation des ressources marines vivantes*, L. Laubier, ed., Académie des Sciences, Rapport sur la Science et la Technologie n°17, Lavoisier, Paris, pp. 307-318.
- [9] Dupouy, H. and D. Latrouite, 1979, Le Développement de la Crépidule sur le Gisement de Coquilles Saint-Jacques de la Baie de Saint-Brieuc, *Science et Pêche, Bulletin Institutionnel des Pêches Marines*, 292, pp. 13-19.

- [10] Hamon, D. and M. Blanchard, 1994, *Etat de la Prolifération de la Crépidule (Crepidula fornicata) en Baie de Saint-Brieuc*, Rapport IFREMER, DEL 94-14, Brest, France.
- [11] Anon., 2005, *Programme de Valorisation des Crépidules en Bretagne, Bilan d'Activités 2004*, AREVAL/Côtes d'Armor Développement, Saint-Brieuc, France.
- [12] Frésard, M. and J. Boncoeur, 2006, Controlling the Biological Invasion of a Commercial Fishery by a Space Competitor: A Bioeconomic Model with Reference to the Bay of St-Brieuc Scallop Fishery, *Agricultural and Resource Economics Review*, 35(1), pp. 78-97.
- [13] Guyader, O. and S. Fifas, 1999, *Modélisation Bioéconomique de la Pêcherie de Coquilles Saint-Jacques de la Baie de Saint-Brieuc*, Rapport Interne IFREMER, p. 113.
- [14] Guyader, O., Daures, F. and S. Fifas, 2004, A Bioeconomic Analysis of the Impact of Decommissioning Programs: Application to a Limited-Entry French Scallop Fishery, *Marine Resource Economics*, 19, pp. 225-242.
- [15] Knowler, D. and E.B. Barbier, 2000, The Economics of an Invading Species: A Theoretical Model and Case Study Application, in Perrings, C., Williamson, M. and S. Dalmazzone, eds., *The Economics of Biological Invasions*, Cheltenham: Edward Elgar Publishing Limited.
- [16] Hamon, D., Blanchard, M., Houlgatte, E., Blanchet, A., Gaffet, J.D., Cugier, P., Ménesguen, A., Bassoulet, P., Cann, P., Domalain, D. and A.G. Haubois, 2002, *La Crépidule: Identifier les Mécanismes de sa Prolifération et Caractériser Ses Effets sur le Milieu pour Envisager sa Gestion, Chantier Baie de Saint-Brieuc*, Rapport final programme LITEAU 1^{ère} tranche, IFREMER DEL, Brest, France.
- [17] Hilborn, R. and C. J. Walters, 1992, *Quantitative Fisheries Stock Assessment*, New-York, Chapman and Hall.
- [18] Schaefer, M.B., 1954, Some Aspects of the Dynamics of Populations of Important to the Management of Marine Fisheries, *Bulletin of the Inter-American Tropical Tuna Commission*, 1, pp. 25-56.
- [19] Schaefer, M.B., 1957, Some Considerations of population Dynamics and economics in Relation the Management of Marine Fisheries, *Journal of the Fisheries Research Board of Canada*, 14, pp.669-681.