Aquat. Living Resour. 19, 299–305 (2006)
© EDP Sciences, IFREMER, IRD 2006
DOI: 10.1051/alr:2006031
www.edpsciences.org/alr

Aquatic
Living
Resources

Costs and benefits of stock enhancement and biological invasion control: the case of the Bay of Brest scallop fishery

Marjolaine Frésard[a] and Jean Boncoeur

CEDEM / GdR AMURE, UBO-IUEM, 12 rue Kergoat, C.S. 93837, 29238 Brest, France

Received 24 October 2005; Accepted 11 September 2006

Abstract – This paper deals with the economic impact of the invasion of a scallop fishery by an exotic shellfish that was accidentally imported some decades ago. The invasive alien species, a slipper-limpet, *Crepidula fornicata,* is a space competitor for local scallops, and its spread threatens the sustainability of the ongoing scallop restocking program. Facing this invasion, the local fisheries committee has initiated a containment project intending to make the restocking program consistent with the exotic species presence in the fishery. The issue is complicated by the occurrence of occasional toxic micro-algae blooms affecting the scallop fishery. The paper presents a model dealing with the economic impact of the invasive process, and a methodology for cost-benefit analysis of invasion management. According to numerical simulation, the invasion is a serious threat to the economic viability of the restocking program, and invasion management would help maintaining the long term sustainability of the fishery. Sensitivity tests highlight the importance of long term equilibrium scallop catches on the program result, depending on scallop farming technical performance and ecosystem disturbance.

Key words: Invasive alien species / *Crepidula fornicata* / *Pecten maximus* / Fisheries management / Cost-benefit analysis / Harmful algal blooms / Eastern Atlantic Ocean

Résumé – Coûts et bénéfices du repeuplement et du contrôle d'une invasion biologique : le cas de la pêcherie de coquilles Saint-Jacques de la rade de Brest. Cet article traite de l'impact économique de l'invasion d'une pêcherie coquillière par une espèce exotique, *Crepidula fornicata*, importée accidentellement. Cette espèce envahissante est un compétiteur spatial pour l'espèce exploitée et son extension menace la soutenabilité du programme de repeuplement concernant cette dernière. Face à cette invasion, le comité local des pêches a formulé un projet de contrôle visant à rendre compatible le programme de repeuplement et la présence de l'espèce exotique. La question est compliquée par l'occurrence de blooms de micro-algues toxiques affectant la pêcherie coquillière. L'article présente une méthodologie permettant d'évaluer le coût combiné de l'invasion biologique et des blooms toxiques pour le programme de repeuplement, ainsi que le surplus économique attendu du contrôle de l'invasion. Une simulation numérique met en évidence la menace que constitue l'invasion pour la viabilité du programme de repeuplement et montre qu'une gestion de l'invasion favoriserait la viabilité de ce programme sur le long terme. Les tests de sensibilité réalisés soulignent l'importance du niveau d'équilibre des captures, dépendant des performances techniques du programme de repeuplement et des perturbations de l'écosystème.

1 Introduction

Biological invasions are supposed to be one of the most important causes of biodiversity loss worldwide (Glowka et al. 1994; Wilcove et al. 1998). Although exotic species can spread by means of natural dispersal, alien species introduction is often an important component of human-induced global change (Vitousek et al. 1997). For instance, over the past five centuries, global oceanic trade has lead to the redistribution of a vast number of marine organisms along the coastal margins of the world (Carlton 1989). The use of exotic species in economic activities, the conversion of habitat and the liberalization of markets with expansion of exchange and mobility of people cause an increase of invasions all around the planet (Dalmazzone 2000).

Whatever their origin, biological invasions are liable to be an economic problem (Perrings et al. 2000): they often impose real costs on society by altering the relative abundance of harvested and non-harvested species and by changing ecological services. According to Pimentel et al. (2005), the economic damages caused by invasive species and the cost of their

---

[a] Corresponding author: `marjolaine.fresard@univ-brest.fr`
ICSR'05, 8th Int. Conf. Shellfish Restoration, Brest, France
`http://www.ifremer.fr/icsr05/`

control amount to \$ 120×10^9 (i.e. 120 billion) per year in the United States. The economic impact of a biological invasion depends on the nature of the interaction between native and invasive species (Barbier 2001).

Even when their origin is anthropic, the effects of invasive alien species are external to the market, because the costs they impose are not borne by the activities causing the invasion. Furthermore, common property regimes of aquatic systems require collective action. Because common pool resources are non-exclusive, anyone has a strong incentive to take a free ride on the efforts of others, which may lead to less control than is socially desirable. Thus, the control of invasions is in the nature of a public good and requires public policy. This control should involve economic analysis in order to guarantee the efficiency of public policies. A classic method for this purpose is cost-benefit analysis, which evaluates the social yield of public projects and may be applied to environmental economics (Hanley and Spash 1993). A program of invasion control is economically justified if the expected present value of the benefits it generates is greater than the expected present value of the control costs.

This paper deals with the case of the biological invasion of the Bay of Brest (France) by an exotic shellfish (*Crepidula fornicata*), which was accidentally imported some sixty years ago. This slipper-limpet is a space competitor for the native harvested species *Pecten maximus* (Chauvaud et al. 2003), and its expansion causes damage to the local scallop fishery. More specifically, it threatens the sustainability of the restocking program that has been developed since 1983 to overcome the consequences of a stock collapse in the 1960s (Boncoeur et al. 2003). Facing this situation, the local fishers committee has elaborated a new project intending to combine scallop restocking and invasion control.

The case is complicated by the episodic occurrence of harmful micro-algae blooms in the bay. Harmful algal blooms are suspected to bear some relation with the increase in nutrients inputs from land-based sources and activities, such as agriculture (GESAMP 2001; van den Bergh et al. 2002). In this paper, we focus on blooms of the dinoflagellate *Karenia mikimotoï* (also known as *Gymnodium* cf. *nagasakiense*), which have been reported in the Bay of Brest waters since the early 1980s, and are responsible for high mortalities of scallop juveniles (Chauvaud et al. 1998).

The paper presents a methodology for assessing the combined economic impact of biological invasion and micro-algae blooms on the restocking program, and the economic yield of the invasion control project proposed by fishers. A numerical simulation, followed by sensitivity tests, illustrates this methodology.

2 Material and methods

2.1 Modelling the scallop-restocking program with algal blooms

The scallop-restocking program of the Bay of Brest relies on the operation of an aquaculture unit producing juveniles that are sown in the bay to enhance natural recruitment[1]. It was initially intended to restore the spawning stock biomass, and was reoriented towards sea-ranching after empirical investigations brought results apparently at odds with the assumption of a stock-recruitment relationship (Boucher and Dao 1989). The production of aquaculture juveniles took off during the second part of the 1990s, and, at the beginning of the present decade, it provided approximately two thirds of total scallop landings from the bay. The program is now operated on a cost-recovery basis, with the license yearly paid by fishers covering approximately its operating cost (Boncoeur et al. 2003).

Let M be the annual gross margin (value of landings minus fishing effort costs) provided to fishers by the program under equilibrium conditions, and L be the total amount of licenses they pay each year to cover its operating cost. Writing the time-discount rate as a and assuming permanent equilibrium, we may express the present value of the program as:

$$V_I = (M - L)\left[\lim_{m\to\infty}\sum_{t=1}^{m}(1+a)^{-t}\right] = \frac{M-L}{a}. \qquad (1)$$

Recurrent blooms of *K. mikimotoï* disturb the equilibrium of the program. When they occur, as in years 1995 and 2002, these micro-algae blooms severely reduce the output of the aquaculture unit, by increasing the mortality of juveniles. As it is not possible, with the present knowledge, to assess the distribution of probabilities concerning their occurrence and severity, we will simply assume that, every k years, they reduce fishers gross margin M by a given proportion α. For the continuation of the analysis, it will be convenient to express these episodic reductions in terms of impact on the average annual gross margin. Let β be the average rate of reduction in the annual gross margin due to blooms occurring every k years. In terms of present values, this rate is such that the cost of each bloom is equal to the difference between the sum of "uncorrected" gross margins over k years and the sum of the corresponding "corrected" gross margins. If the time discount rate is zero, β is simply equal to α / k. In the more realistic case where $a \neq 0$, determining β requires to make an additional assumption concerning the date of impact of the first bloom. Assuming that it occurs at year τ $(1 \leq \tau \leq k)$, we get:

$$\beta = \alpha\frac{a(1+a)^{k-\tau}}{(1+a)^k - 1}. \qquad (2)$$

As τ is unknown with equal probabilities for each year of interval $[1\ ,\ k]$, it is reasonable to take the centre of this interval. We then get the following value for β:

$$\beta = \alpha\frac{a(1+a)^{0.5(k-1)}}{(1+a)^k - 1}. \qquad (2a)$$

---

[1] Scallop larvae are produced in a hatchery-nursery. Juveniles are raised during 6 to 10 months in cages at sea (intermediate culture). When their size reaches 3 cm, they are sown in the bay, some of them on natural beds, and the others in a restricted area closed to fishing for three years. The minimum harvesting size (10.5 cm) is normally reached when scallops are 3 years old. Aquaculture scallops may be identified by a "stress ring" on their shell due to their sowing in natural environment.

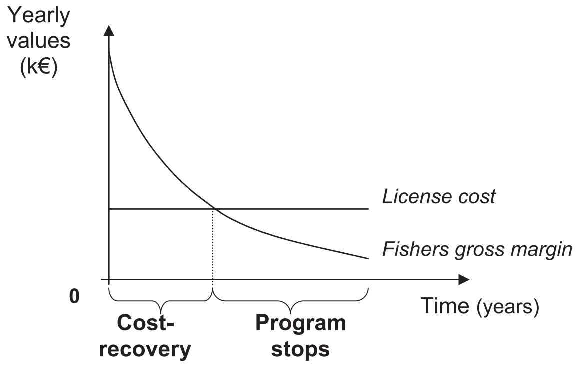

Fig. 1. Life duration of the restocking program with invasion.

Taking into account the recurrent cost of micro-algae blooms brings the average value of the yearly gross margin down to:

$$M' = M(1-\beta) \tag{3}$$

and, provided this average gross margin is larger than the annual operating cost of the program (L), the present value of the restocking program becomes:

$$V_{I'} = \frac{M'-L}{a}. \tag{4}$$

Our numerical simulation makes use of available data concerning the restocking program, complemented by the results of a field survey of fishers' activity (Alban et al. 2001). According to these data, the operating cost of the program (L) is 342 000 € per year, and the gross margin it generates (M) is 913 000 € under normal conditions (reference period: 2000–2001). We assume a 5% time discount rate. As regards algal blooms, we suppose that their periodicity (k) is 5 years, and that a bloom reduces the gross margin by 80% (α) when it impacts scalloping.

2.2 Accounting for the impact of *C. fornicata* invasion on the scallop-restocking program

The invasion of the bay by *C. fornicata* imposes two additional costs on the program: (i) a direct cost, because fishers must scrape *C. fornicata* fixed on scallop shells on board (*C. fornicata* are released in the bay, up to now there is no processing of this species even if it increases its dispersal); (ii) an indirect cost, due to the gradual reduction of habitat suitable for scallops (when *C. fornicata* density reaches a certain level in a given zone, it becomes impossible for scallop juveniles to settle in this zone). We assume that space colonisation by *C. fornicata* decreases the scalloping zone at an annual rate noted b. We also assume that the catch per unit effort (CPUE) is not significantly altered in areas that are still harvestable, and that, each year, fishers dredge the entire harvestable zone with a constant rate of effort per unit area.

Under these assumptions, the direct cost of invasion reduces the average gross margin by a percentage noted γ, and the indirect cost results in a gradual shrink of this average gross margin at rate b. The program is supposed to stop when this process has led the gross margin below its operating cost (Fig. 1). Let M'' be the average gross margin taking into account the direct cost of invasion:

$$M'' = M'(1-\gamma). \tag{5}$$

The end-year of the program, n, is the integer part of:

$$\tilde{n} = \frac{\ln L - \ln M''}{\ln(1-b)}. \tag{6}$$

Taking into account both direct and indirect costs of invasion results in reformulating the present value of the restocking program as:

$$V_{I''} = \sum_{t=1}^{n} \frac{M''(1-b)^t - L}{(1+a)^t} = M'' \sum_{t=1}^{n} \left(\frac{1-b}{1+a}\right)^t - L \sum_{t=1}^{n} \frac{1}{(1+a)^t}. \tag{7}$$

To estimate the direct cost of invasion, we multiply the time devoted to scallop scraping (an average of 15.5 hours per ton, according to interviewed fishers) by the opportunity cost of labour (estimated on the basis of the minimum legal wage). The situation is more complicated with the indirect cost of invasion, as published literature provides very limited quantitative information concerning the invasive process. Up to now, an estimation of biomass has been published for only one year (18 600 tons of fresh weight in 1995, according to Chauvaud et al. 2003), and only estimations concerning the areas where the presence of *C. fornicata* was noted can be compared: these areas, which were not significantly different from zero in 1950, represented 25% of the total surface of the bay in 1978 (Coum 1979), and rose to 50% of this surface in 1995[2] (Chauvaud et al. 2003) and more recent observations suggest that the invasion has speeded up since that date (Guérin 2004). No population dynamics model concerning *C. fornicata* is available, and the competition with scallop is described only in qualitative terms. Therefore, our numerical simulation has merely an illustrative character. We will assume that the rate of reduction of harvestable surfaces (b) is equal to 10% per year, a rate corresponding approximately to a cumulated reduction of 2/3 in a decade, and of 95% in 30 years.

The total cost of invasion for the restocking program may be expressed, in absolute value, as the difference ($V_{I'} - V_{I''}$) between its net present value assuming no invasion and its net present value under invasion conditions.

2.3 Combining the restocking program with a local program of invasion control

Complete eradication of *C. fornicata* from the bay is not technically realistic under present conditions. In order to keep scallop-restocking economically sustainable, the Local Fisheries Committee has elaborated a new program combining restocking and invasion control. This new program will be named hereafter "program II", in order to distinguish it from the above described "traditional" restocking program, which will be referred to as "program I". Program II has not started yet, and is still subject to possible revisions. Therefore, what we present here is based on provisional data.

---

[2] Areas where the density of *C. fornicata* is at least equal to 1 individual per m^2.

Table 1. Timetable of program II (restocking + local invasion control). M: annual gross margin (value of landings minus fishing effort costs); L: annual total amount of licenses; C: yearly cleaning cost; b: rate of decrease in harvestable area.

Year	Area cleaned and sown	Cleaned area harvested	Costs of program II	Gross margin
0	-	-	I*	-
1	[1]	-	$C + L$	$M''(1-b)$
2	[2]	-	$C + L$	$M''(1-b)^2$
3	[3]	-	$C + L$	$M''(1-b)^3$
4	[1]	[1]	$C + L$	M'
5	[2]	[2]	$C + L$	M'
6	[3]	[3]	$C + L$	M'
7	[1]	[1]	$C + L$	M'
8	[2]	[2]	$C + L$	M'
9	[3]	[3]	$C + L$	M'
etc.	etc.	etc.	etc.	etc.

* To be renewed each g years.

The philosophy of the new program is to concentrate all the sowings on a limited area where *C. fornicata* have been previously removed. The time schedule of the combined cleaning, sowing and harvesting operations is described in Table 1. Each year, a zone of 300 ha is cleaned up, and 10 million aquaculture juvenile scallops are sown intensively in this area (this quantity corresponds to the normal yearly output of the aquaculture unit). The area is closed to fishing for three years, after which scallops are harvested. Program II works with three such areas, on a crop rotation basis that has already been experienced in program I for part of the sowings. Year 0 of program II is devoted to the acquisition of a boat specially designed for cleaning operations. Let I be the value of this initial investment, and g be its expected life-duration. Cleaning operations start at year 1, with an annual operating cost C. Harvesting the cleaned areas starts at year 4, before which fishers continue to harvest infested areas. Assuming that the yearly average fishers gross margin is the same in program II as it was in program I (except for invasion costs), we may write the net present value of program II as:

$$V_{II} = -\frac{I}{1-(1+a)^{-g}} + \sum_{t=1}^{3} \frac{M''(1-b)^t - L - C}{(1+a)^t} + \frac{M' - L - C}{a(1+a)^3}. \tag{8}$$

On the right-hand side of relationship (8), the first term is the cost of the initial investment and of its periodic renewal, the second term is the present value of the program during the transitional period, and the third term is the present value of the program corresponding to its permanent regime (starting at year 4). Alternatively, the net present value of program II may be expressed as:

$$V_{II} = M'\left[(1-\gamma)\sum_{t=1}^{3}\left(\frac{1-b}{1+a}\right)^t + \frac{1}{a(1+a)^3}\right] - \left(\frac{I}{1-(1+a)^{-g}} + \frac{L+C}{a}\right) \tag{8a}$$

where the first term on the right-hand side is the present value of fishers gross margin (first during the transitional period, then in the permanent regime), and the second term is the present value of total program costs.

The economic surplus expected from program II is the difference ($V_{II} - V_{I''}$) between its net present value and the net present value of program I (under invasion conditions).

Our numerical simulation of program II makes use of the draft that was provided to us by the Local Fisheries Committee (CLPMEM du Nord-Finistère 2001). According to this document, the value of the initial investment (I) is 152 k€, and the yearly cleaning cost (C) is 132 k€. We assume the life duration of initial investment (g) is 15 years.

3 Results

3.1 Main simulation

Results of the numerical simulation are displayed in Table 2. According to this simulation, recurrent algal blooms cut the initial net present value of the "traditional" restocking program (program I) by approximately 25%, and the invasive process reduces it by approximately two thirds. By far the largest part of the negative impact of the invasive process is due to its indirect cost (decrease in harvestable area), the opportunity cost of time devoted to scallop shells scraping being marginal. Moreover, the invasive process makes program I unsustainable: after 7 years of operation, the gross margin generated by this program is expected to fall below its operating cost. The simulation suggests that sustainability may be recovered by combining restocking and local control of the invasive process (program II), and that such a combination could reduce the cost of invasion by 55%, in present value terms.

3.2 Sensitivity tests

In order to assess the robustness of the simulation results, several sensitivity tests have been performed (Tables 3 and 4). Two of these tests concern the "normal" gross margin M (quantities landed and average landing prices). The four other tests concern respectively the time-discount rate (a), the frequency of algal blooms (k), the rate of decrease in harvestable areas due to invasion by *C. fornicata* (b), and the yearly cleaning cost of program II (C).

According to these tests, the simulation results are particularly sensitive to the technical performance of the restocking program (a parameter which is not stabilized), and to the cost of cleaning operations in program II. This cost is little known, since cleaning operations have not started yet, and disposal of removed *C. fornicata* is still a question to be settled. As regards biological parameters, sensitivity tests suggest that uncontrolled consequences of harmful micro-algae blooms occurring more than every two years would definitely ruin the economic sustainability of the restocking program, whether or not associated to local invasion control. As regards the impact of invasion, a variation in the rate of decrease in harvestable areas between 5% and 20% per year would significantly affect

Table 2. Results of the main simulation.

Net present value (k€)	Program I (Restocking)	No bloom, no invasion	V_I	11 414
		Blooms, no invasion	$V_{I'}$	8500
		Blooms and invasion	$V_{I''}$	973
	Program II (Restocking + local invasion control)		V_{II}	5134
Life-duration of program I submitted to blooms and invasion (years)			n	7

Table 3. Results of sensitivity tests.

Impact on endogenous variables		Program net present value (k€)				End-year of
	Parameter	Program I			Prog. II	Prog. I
Tested parameters	value	V_I	$V_{I'}$	$V_{I''}$	V_{II}	n
Annual harvest (undisturbed conditions)	123 tons[1]	2170	732	0	−2416	0
	350 tons[2]	21 420	16 909	2817	13 308	11
Average price	2.96 € per kg[3]	5474	3509	170	268	3
	5.85 € per kg[4]	18 884	14 778	2354	11 255	10
Time discount rate	3%	19 023	14 159	1022	8883	7
	15%	3805	2850	785	1441	7
Frequency of algal blooms	Never	11 414	11 414	1562	7966	9
	2 years	11 414	4114	257	872	4
Rate of decrease in harvestable area	5% per year[5]	11 414	8500	1953	5315	15
	20% per year[6]	11 414	8500	399	4809	3
Yearly cleaning cost (program II)	264 k€[7]	11 414	8500	973	2494	7
	396 k€[8]	11 414	8500	973	−146	7

[1] Average yearly harvest during 1995-2001, and 53% of main simulation. [2] Theoretical yield of juvenile sowing, and 151% of main simulation. [3] Minimum yearly average price during the past 20 years (constant euros), and 70% of main simulation. [4] Maximum yearly average price during the past 20 years (constant euros), and 138% of main simulation. [5] 95% reduction in harvestable area after 59 years. [6] 95% reduction in harvestable area after 23 years. [7] Planned cost multiplied by 2. [8] Planned cost multiplied by 3.

Table 4. Sensitivity tests (continued): break-even points of program II.

	Gross margin M	Time discount rate a	Blooms frequency k	Rate of decrease in harvestable area b	Cleaning cost C
[1] Main simulation	913 k€	5%	5 years	10%	132 k€
[2] Break-even point[1]	609 k€	28%	1.82 years	1%	340 k€
[2] / [1]	0.67	5.60	0.36	0.10	2.58

[1] Value of considered parameter such that ($V_{II} - V_{I''} = 0$), with main simulation values for other parameters.

the life-expectancy of program I, but would have only limited consequences on the present value of program II.

Compared to program I, program II would fall below break-even if one of the following conditions was fulfilled, ceteris paribus: (*i*) equilibrium gross margin M falling by one third below its reference value; (*ii*) time-discount rate set at 28%; (*iii*) harmful consequences of micro-algal blooms occurring at least each 1.82 years on the average; (*iv*) harvestable areas decreasing by only 1% per year; (*v*) cleaning costs in program II reaching 2.58 times their reference level. Condition (*ii*) is unlikely, and it is probably so with condition (*iv*): with a 1% annual decrease rate, it would take 138 years to reduce the harvestable zone by 75%. The likeliness of conditions (*iii*) and (*v*) is difficult to assess, due to lack of empirical evidence. Condition (*i*) should be considered seriously, for both technical and economic reasons: the technical performance of the aquaculture unit is not fully stabilized, and scallop landings prices, which are exogenous to the fishery, are unstable. Moreover, a combination of several factors (e.g. slumping landings prices combined with more frequent algal blooms in the bay) could accelerate the damage to the program.

4 Discussion

According to the simulation presented in the former section of this paper, the invasive process, combined with recurrent harmful micro-algal blooms, should be considered as a serious threat to the sustainability of scallop sea-ranching in the Bay of Brest. The consequences of the invasive process are different from those of algal blooms: while the latter result in severe but discontinuous reductions in the output of the program, invasion of the bay by *C. fornicata* induces a downward trend which may not be perceptible in the short run, but might be more harmful in the long run. On the other hand, controlling the impact of *C. fornicata* proliferation on scallop sea-ranching could be a less ambitious challenge than limiting the occurrence of algal blooms: while the latter is a task concerning the integrated management of the bay and its coastal zone, the former could be handled by a program combining restocking with limited invasion control, according to our simulation.

However, this simulation suffers from several important limits. For some key-parameters, such as the rate of decrease in harvestable areas or the frequency of algal blooms, conventional values were adopted due to the lack of empirical data. For other parameters such as fishers gross margin under equilibrium conditions, the impact of algal blooms or the cost of *C. fornicata* removal, quantitative data used in the simulation are based on limited empirical evidence. Sensitivity tests help to assess the robustness of the simulation results, considering the uncertain value of various parameters. For this purpose, parameters were tested one by one. But it might be useful to extend sensitivity tests to scenarios where several parameters deviate from there basic value.

Some simplifying assumptions concerning the technical aspects of scalloping should also be underlined. We supposed that the average time devoted to scraping a ton of scallops did not depend on the level of invasion, and that the average fishing effort necessary for harvesting one ton of scallops was the same in program II as in program I. Both assumptions are not accurate pictures of reality. However, relaxing them, while complicating the model structure, would not significantly alter its conclusions, since scrapping cost and direct harvesting cost represent but a small part of landings value.

At a deeper level, some conceptual aspects of the model underlying the simulation are open to criticism. In this field, a major limit is the weakness of the model bio-ecological substratum. It affects the dynamics of each population considered separately, but also their interaction.

As regards the dynamics of each stock, there is greater concern with the invasive stock than with the resident stock. In the latter case, the recruitment of individuals that are provided by the program is artificial, and the high variability of natural recruitment mainly due to hydroclimatic conditions suggests limited interaction between aquaculture and natural scallops. In the case of the invasive stock, available empirical data are too scarce for setting up a population dynamics model, but it seems reasonable to assume a logistic growth of invaded area, with a carrying capacity related to the total area suitable for habitat. As a consequence, the rate of decrease in areas that are suitable for scallops would vary over time (in absolute value) from $r.X_0/K$ to r, where r is the intrinsic expansion rate of *C. fornicata*, K is the carrying capacity, and X_0 is the initial invaded area. Such an implication is at odds with our assumption that scalloping areas decrease over time at a constant rate. This assumption corresponds to the asymptotic behaviour of the logistic model, and may be considered as an acceptable approximation only if the degree of invasion is high enough. Empirical evidence on this topic is limited. From the comparison of data concerning the presence of *C. fornicata* in 1978 (Coum 1979) and in 1995 (Chauvaud et al. 2003), and assuming that this presence follows a logistic curve with a maximum of 80% of the total surface of the bay that is suitable for colonisation, we can infer that *C. fornicata* was present in approximately 80% of its potential extension area in 2005. This result provides very incomplete information about the degree of invasion, which also depends on the density of *C. fornicata* in colonised zones (a topic which is documented for year 1995 only – Chauvaud et al. 2003).

Concerning the interaction between invading and invaded species, our model is also subject to criticism. It assumes that making a given zone unfit for scalloping is a discrete process, with unchanged scallop density (and, hence, CPUE) as long as *C. fornicata* density has not reached a critical level. An alternative would be to model the invasion as progressively lowering CPUE in invaded areas. This question is difficult to settle, because experimental data on the impact of *C. fornicata* on bivalve basibionts are scarce and contradictory, which calls for a species-specific approach under different environmental settings (Thieltges et al., in press; Thieltges 2005). In the present case study, growing and survival of scallops that have settled in a given area are not affected by the presence of *C. fornicata*, but juveniles cannot settle in areas where the density of *C. fornicata* is too high (Chauvaud et al. 2003). Our modelling approach intends to capture this process, though considering scallop density as unchanged until invasion has reached a critical level is certainly a simplifying assumption.

Considering micro-algal blooms and *C. fornicata* invasion as two independent processes is another subject of concern. Though *C. fornicata* is clearly a space-competitor for scallop, it has been argued that it also plays a positive role by limiting the occurrence of harmful micro-algal blooms (Ragueneau et al. 2002). This thesis, which calls for a precautionary approach in attempts to fight invasion (Chauvaud et al. 2003), is still a matter of scientific controversy. Up to now, the alleged relationship between *C. fornicata* biomass and probability of algae blooms has not been quantified. Should this be done, such a relation could be included in our model. It would result in lowering the evaluation of the social cost of invasion, but it might have only a limited effect on the yield of the local control program that was studied in this paper: the total area where *C. fornicata* are to be removed according to this program (900 ha) represents less than 1% of the total invaded area (90 km^2 in 1995), which implies that this operation could hardly modify significantly the probability of algal blooms.

5 Conclusion

Two major purposes were assigned to the model presented in this paper: (i) to assess the cost of the biological invasion of an inshore fishery by a space-competitor; (ii) to assess the economic yield of a program aimed at locally controlling this invasion. The contingent side of this model is due to some particular characteristics of the fishery used as a case-study, among which the association of aquaculture and capture fishing (sea-ranching). Though this case is not unique, it is by far less frequent than the polar cases of "pure" aquaculture or capture fishing. However, the methodology that was adopted has a fairly general scope. Belonging to the category of cost-benefit analysis applied to environmental matters, it relies on the concept of net present value of the fishery, i.e. the algebraic sum of future discounted benefits and costs of operating the fishery under given conditions. Making use of this tool, one may express the cost of invasion (in absolute value) as the difference between the net present values of the non-invaded fishery and of the same fishery submitted to invasion. Similarly, the economic surplus generated by the control program is expressed as the variation in the net present value of the invaded fishery due to the carrying out of this program. These concepts are easily transferable to invaded fisheries with characteristics differing substantially from the one we used as a case study. However, in many cases, it is likely that a major constraint is the scarcity of reliable quantitative information on the invasive process and its consequences on the dynamics of the native targeted species.

Acknowledgements. We acknowledge Jean-Pierre Carval (*CLPMEM du Nord-Finistère*), the "Invabio II" program team (*IUEM*, *UBO*), Laurent Chauvaud (*Lemar*, *IUEM-UBO*) and Elisabeth Nézan (*Ifremer*) for their documentary help and comments. We also acknowledge two anonymous referees for their helpful comments.

References

Alban F., Kervarec F., Le Lec G., Le Floc'h P., Boncoeur J., 2001, L'impact socio-économique du programme de production artificielle de coquilles Saint-Jacques en rade de Brest. Etude réalisée pour le CLPM du Nord-Finistère et financée dans le cadre du programme européen PESCA, Rapport final, CEDEM, Université de Bretagne Occidentale, Brest, 71p.

Barbier E.B., 2001, A note on the economics of biological invasions. Ecological Economics 39, 197-202.

Boncoeur J., Alban F., Dao J.C., 2003, Complementarity between aquaculture and small-scale fishing: the Bay of Brest scallop case. Bull. Aquac. Assoc. Can. 103, 19-26.

Boucher J., Dao, J.C., 1989, Repeuplement et forçage du recrutement de la coquille Saint-Jacques. In: Troadec J.P. (Ed.) L'homme et les ressources halieutiques, Éditions Ifremer, Plouzané, pp. 313-358.

Carlton J.M., 1989, Man's role in changing the face of the ocean: biological invasions and implications for conservation of near-shore environments. Conserv. Biol. 3, 265-273.

Chauvaud L. Thouzeau G., Paulet Y.M., 1998, Effects of environmental factors on the daily growth rate of *Pecten maximus* juveniles in the Bay of Brest (France). J. Exp. Mar. Biol. Ecol. 227, 83-111.

Chauvaud L., Thouzeau G., Grall J., Paulet Y.M., 2003, La crépidule en rade de Brest : un paradoxe pour le devenir de la coquille Saint-Jacques. In: Laubier L. (Ed.) Exploitation et surexploitation des ressources marines vivantes, Académie des Sciences, Rapport sur la Science et la Technologie No. 17, Lavoisier, Paris, pp. 307-318.

CLPMEM du Nord-Finistère, 2001, Programme pour l'élimination et la substitution des crépidules en rade de Brest. Dossier de demande d'aide communautaire relative à un investissement dans le secteur des pêches maritimes et de l'aquaculture, Brest, 16 p.

Coum A., 1979, La population de crépidules *Crepidula fornicata* (L.) en rade de Brest : écologie et dynamique. PhD Thesis, University of Western Brittany, Brest.

Dalmazzone S., 2000, Economic factors affecting vulnerability to biological invasions. In: Perrings C., Williamson M., Dalmazzone S. (Eds.) The Economics of Biological Invasions, Cheltenham, Elgar, pp. 17-30.

GESAMP (IMO/FAO/UNESCO-IOC/WMO/WHO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) and Advisory Committee on Protection of the Sea, 2001. Protecting the oceans from land-based activities – Land-based sources and activities affecting the quality and uses of the marine, coastal and associated freshwater environment. Rep. Stud. GESAMP No. 71.

Glowka L., Burhenne-Guilmin F., Synge H., 1994, A guide to the convention on biological diversity. UICN, Gland, Switzerland.

Guérin L., 2004, La crépidule en rade de Brest: un modèle biologique d'espèce introduite proliférante en réponse aux fluctuations de l'environnement. PhD Thesis, University of Western Brittany, Brest.

Hanley N., Spash C., 1993, Cost-Benefit Analysis and the Environment. Cheltenham, Elgar.

Perrings C., Williamson M., Dalmazzone S. (Eds.), 2000, The Economics of Biological Invasions. Cheltenham, Elgar.

Pimentel D., Zuniga R., Morrison D., 2005, Update on the environmental and economic costs associated with alien-invasive species in the United States. Ecol. Econ. 52, 273-288.

Ragueneau O., Chauvaud L., Leynaert A., Thouzeau G., Paulet Y.M., Bonnet S., Lorrain A., Grall J., Corvaisier R., Le Hir M., Jean F., Clavier J., 2002, Direct evidence of a biologically active coastal silicate pump : Ecological implications. Limnol. Oceanogr. 47, 1849-1854.

Thieltges D.W., 2005, Impact of an invader: epizootic American slipper limpet *Crepidula fornicata* reduces survival and growth in European mussels. Mar. Ecol. Prog. Ser. 286, 13-19.

Thieltges D.W., Strasser M., Reise K., 2006, How bad are invaders in coastal waters? The case of the American slipper limpet *Crepidula fornicata* in western Europe. Biol. Inv., in press.

van den Bergh J.C.J.M., Nunes P.A.L.D., Dotinga H.M., Kooistra W.H.C.F., Vrieling E.G., Peperzak L., 2002, Exotic harmful algae in marine ecosystems: an integrated biological-economic-legal analysis of impacts and policies. Mar. Pol. 26, 59-74.

Vitousek P.M., D'Antonio C.M., Loope L.L., Rejmanek M., Westbrooks R., 1997, Introduced species: a significant component of human-caused global change. N.Z. J. Ecol. 21, 1-13.

Wilcove D.S., Rothenstein D., Dubow J., Phillips A., Losos E., 1998, Quantifying threats to imperiled species in the United States. Bioscience 48, 607-615.