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A system dynamics model for the management of the gooseneck barnacle (*Pollicipes pollicipes*) in the marine reserve of Gaztelugatxe (Northern Spain)

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ABSTRACT

The gooseneck barnacle (*Pollicipes pollicipes*) is a highly exploited species in Spain and Portugal due to the great commercial demand and the high prices in the market. Due to the inaccessibility of the Gaztelugatxe coastal area (Basque Country, Northern Spain), the gooseneck barnacle has maintained one of the greatest populations of the Basque coast in this area. Declared as a marine reserve by means of the 229/1998 (Basque Government) Decree, a 2 years moratorium in the gooseneck shellfishing was established. Facing the possibility of the gooseneck barnacle fishery opening in the area of the biotope, it was noticed the need for the development of a management tool, capable to think over the different management decisions: from the complete conservation of the system to the sustainable exploitation of the resource, joining together different social and biological factors, allowing the protection of the firsts (protection of the stock) and the development of the seconds (fishery activity). Based on the population dynamics of the gooseneck barnacle, a system dynamic model dominated by one positive and three negative loops was developed. The positive loop portrays the reproductive and maturation process, ultimately producing more adult gooseneck barnacles. The negative loops cause the stabilisation as the different stages of the population expire due by natural causes and exploitation of the resource. According to the model results, the best management decision is the maintenance of the moratorium. Taking into account the dispersion capability of larvae, other areas near the reserve, and subjected to commercial exploitation like Ogoño, Izaro and cape Villano, will benefit from the protection of Gaztelugatxe production. In the case of exploitation, the best management decision, which maximises captures and minimises the stock looses in a sustainable manner, is an alternate exploitation between Aketxe and Gaztelugatxe coastal areas of the marine reserve.

1. Introduction

The distribution area of the gooseneck barnacle (*Pollicipes pollicipes*) comprises the exposed intertidal rocky areas of the northeastern Atlantic, from the south of Brittany (France) to the northwest of Africa and the Mediterranean (Barnes, 1996). It is a heavily exploited species in Spain and Portugal, due to the great commercial demand and the high prices in the market (Bernard, 1988; Goldberg, 1984), resulting in the overexploitation of the stocks (Cunha and Weber, 2001). From the numerous species distributed all around the world, only two are present along Basque coast; one of these, *Pollicipes pollicipes*

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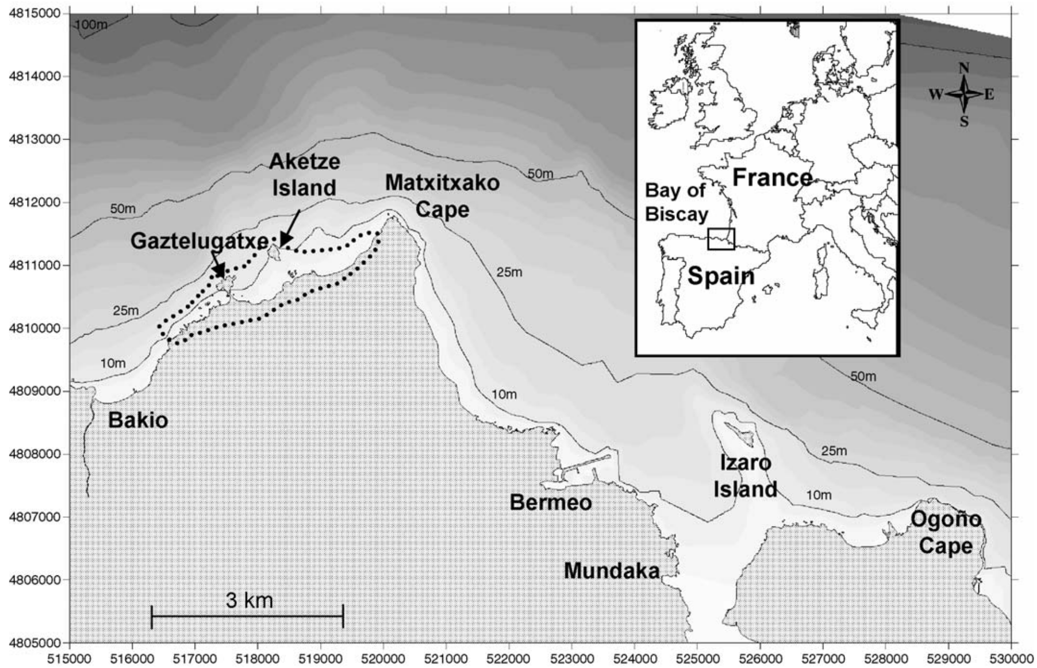

Fig. 1 – Geographic location and limits (dotted line) of the Gaztelugatxe marine reserve. The coordinates are in UTM.

(also, *P. cornucopiae*) is strictly littoral and forms dense aggregates, over the wave-exposed rocky shore of the intertidal zone. The first works relating to the gooseneck barnacle on the Basque coast date to 1892 (Bolívar, 1982), according to the review undertaken by Barnes (1996). The other species, *Lepas anatifera*, is pelagic and always adhered to floating objects. The first of the species mentioned is the only one of economic interest (Molares, 2004). Due to the inaccessibility of the Gaztelugatxe coastal area (Fig. 1), the gooseneck barnacle has maintained one of the greatest populations of the Basque coast in this area (Borja et al., 2000)[1].

Following the work undertaken by Borja et al. (2000), the Gaztelugatxe coastal zone was declared as a marine reserve trough the 229/1998 (Basque Government) Decree[2] establishing a 2 years moratorium for the shellfish fishery, including, among other species, the gooseneck barnacle. At the end of it, the competent authority in the management of the marine reserve would decide to maintain or open this moratorium (Article 5, paragraph b).

Facing the possibility of the gooseneck barnacle fishery opening in the area of the marine reserve, the need for the development of a management tool was noticed, capable of assisting different management decisions: from the complete conservation of the system, to the sustainable exploitation of the resource — this would join together different social and biological factors, allowing the protection of the stock and the development of the fishery activity. According to Sterman (1988), the best solution is the development of a system dynamic model applied to the modelisation and knowledge of complex systems (in the case of the present contribution, the population structure and dynamics of the gooseneck barnacle established by Borja et al. (2004), and its relationship with the surrounding environment and potential human activity).

The main objective of the tool was to provide answer to questions formulated by the resource managers of the administration: (i) is it possible the resource exploitation in the reserve? and, if the answer is positive, (ii) how many fishermen can support the system without the progressive collapse of the stock? (iii) what happens when reducing the minimum legal length for capture or modifying the capture season? (iv) which management decisions would be the appropriate in order to allow the sustainable exploitation of the resource?

2. System description

A system dynamics model consist of a set of relationships between key variables, expressed in terms of differential and algebraic equations that are solved numerically, to simulate behaviour over time (Wakeland et al., 2003). The model is dominated by one positive and three negative loops (Fig. 2).

The positive loop portrays the reproductive and maturation process, ultimately "producing" more adult gooseneck barnacles. In the absence of any stabilising, this loop would result in the exponential growth of the gooseneck population. As in other populations dynamic models, such as those described by Holland and Brazee (1996), Van Den Belt et al., (1998), Borja and Bald (2000), Bald and Borja (2001), Sampson (2001), Graves and Stave (2003) and Wakeland et al. (2003), the negative loops cause the stabilisation as the different stages of the population expire.

[1] This work was undertaken in 1995 and, afterwards, published as Borja et al. (2000).

[2] Decreto 229/1998 (País Vasco), de 15 de septiembre, por el que se declara Biotopo protegido el área de Gaztelugatxe (BOPV núm. 188, de 2 de octubre de 1998).

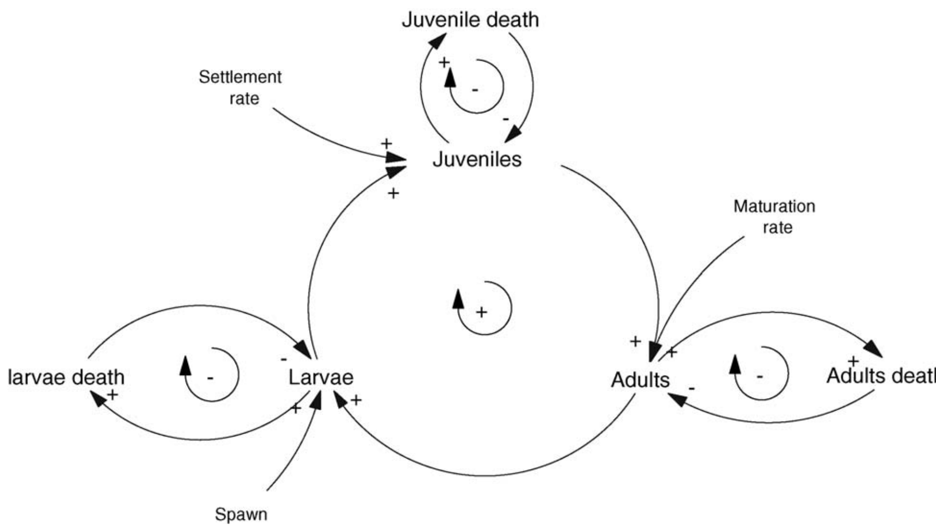

Fig. 2 – Causal loop diagram model, for the gooseneck barnacle management model.

3. Model development

The stock and flow diagram represents a simple ageing chain, in which the gooseneck barnacles begin as eggs, eggs hatch to produce larvae, larvae mature to become juveniles and finally, adult gooseneck barnacles (both exploited and non-exploited) (Fig. 3).

The gooseneck barnacle population, from each of the areas of the marine reserve (Gaztelugatxe and Aketxe), was divided into three classes: (i) juveniles (those with a capitulum length <10 mm, according to Cruz and Hawkins (1998) and Cruz (1993); (ii) non-exploited adults (those with a capitulum length <17 mm, according to Borja et al. (2004); (iii) exploited adults (>17 mm). Table 1 shows the population structure used in the model (percentage of individuals for each class), based upon the work undertaken by Borja et al. (2004). The initial number of individuals for each class was then calculated, by multiplying the total number of individuals in the marine reserve by the corresponding percentage for each class (Table 1). The total number of individuals was calculated by multiplying the average values of density (2627 individuals m^{-2}), percentage of coverage (43.6%) and spatial distribution area (2512 m^2) calculated for the Gaztelugatxe and Aketxe areas of the reserve (Borja et al., 2004). The stock in kilograms of each class is the result of multiplying the number of individuals by the average weight, as calculated by Borja et al. (2004) for each class (Table 1).

Based upon the growth rates obtained by Goldberg (1984) (4.55 mm $month^{-1}$ for juveniles and 2.25 mm $month^{-1}$ for adults), together with the average length of each class, the maturation rates (in percentage) for each class were derived as 24.68% for juveniles and 3.53% for non-exploited adults (Table 1). For the settlement rate, the percentage of individuals below 2 mm was considered (Hoz and García, 1993). In the case of the Gaztelugatxe marine reserve, this was 1.4% (Borja et al., 2004).

In general, the mortality at each length class is the result of a natural mortality, together with a fishing mortality, which in the case of juveniles and non-exploited adults, is equal to zero (Table 1). As Molares and Freire (2003) have stated, the factors regulating the dynamics of the gooseneck barnacle population (natural mortality, transport, larval survival, etc.) have not been studied deeply. Consequently, due to the absence of adequate references, they have been determined in the present contribution by progressive approximation, until achieving stability of the population; this is characteristic of non-exploited gooseneck barnacle populations (Girard, 1982). Another fundamental characteristic, described by Girard (1982) and Pineda and Caswell (1997), is the larval survival increment when there is an increase of the suitable substrate area for settlement. In order to reproduce this effect, the natural mortality for juveniles decreases to 50%, when the resource density reaches values below 1.25 kg m^{-2}.

On the other hand, another limitation of the model can be related to the relationship with the environment. For example,

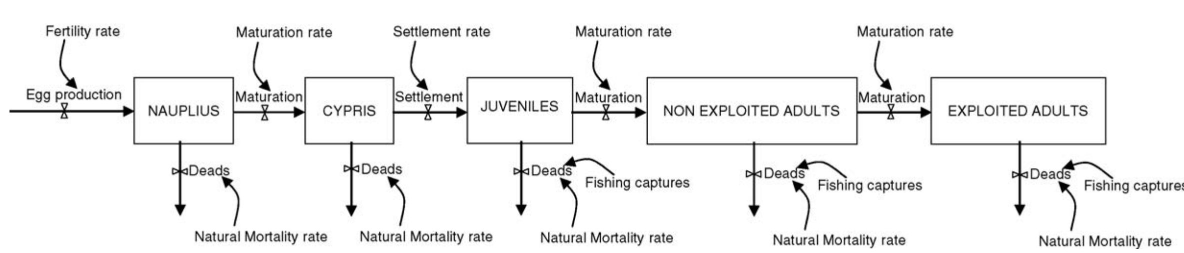

Fig. 3 – Stock and flow diagram of the gooseneck barnacle population dynamics model.

Table 1 – Biological parameters used in the model (for details, see text)

Variable	Units	Larvae		Juveniles	Non-exploited adults	Exploited adults	Reference
		Nauplius	Cypris				
	%	–	–	50	35	15	Borja et al. (2004)
Average length	mm	–	–	5.21	23.77	14.71	Borja et al. (2004)
Average fresh weight	g	–	–	0.022	3.14	0.46	Borja et al. (2004)
Initial number	*n*	6.22×10^{10}	6.22×10^{7}	1.45×10^{6}	1×10^{6}	423418	Borja et al. (2004)
Initial stock	kg	–	–	36	3152	195	Borja et al. (2004)
Maturation rate	%	0.001	–	0.24	0.035	–	Borja et al. (2004)
Growth rate	%			24.68	3.53	–	Goldberg (1984)
Settlement rate	%	–	1.4	–	–	–	Hoz and García (1993)
Egg production	*n*	–	–	–	8690	69299	Cruz and Araújo (1999)
Fertility rate	%	–	–	–	See Table 2	See Table 2	Barnes (1992)
Natural mortality rate	%	95.51	94.33	38	25.35	3.84	Borja et al. (2004)
Daily capture rate	kg shellsfisher^{-1} day^{-1}	–	–		2		Borja et al. (2004)
Days for capture	%	–	–	–	0.7		Borja et al. (2004)
Initial month for captures	Month	–	–	–	October		Decree 198/2000[a]
Duration of fishing season	Month	–	–	–	7		Decree 198/2000[a]

[a] Decreto 198/2000, de 3 de octubre, por el que se aprueba el Reglamento de Pesca Marítima Recreativa.

Borja et al. (in press) have demonstrated the close relationship between wave energy and the gooseneck standing stock, within unexploited areas. These sources of variation will be included in further improvements of the model.

Due to the geographical proximity of the Gaztelugatxe and Aketxe areas, the reproduction and maturation dynamics of nauplius and cypris larvae constitute a common pool for both areas, due to the spawning of larvae during their planktonic phase by physical factors (Lauzier, 1999b; Molares and Freire, 2003). The production of new nauplius larvae, by adults, is the result of multiplying the egg production by the fertility rate for each type of adults (exploited and non-exploited). The production number depends upon the capitulum length (Cruz and Araújo, 1999). Hence, according to the average capitulum length of the adult population in the Gaztelugatxe marine reserve (Table 1), an 8690 and 69 299 eggs production was established for non-exploited and exploited adults, respectively. The number of fertilized oviductal sacs determined by Barnes (1992) was considered as the fertility rate for egg production (Table 2). Due to the absence of published references on this particular subject, based upon the processes described by Pineda (2000) and the zooplankton study undertaken by Borja et al. (2000), within the context of the marine reserve, the natural mortality rate of nauplius and ciprys larvae, as well as the maturation rate for nauplius (Table 1), were determined on the basis of a situation of stability of the population.

The fishing capture for a length class depends on their fishing mortality rate, the percentage of days for capture (70% according to Borja and Bald (2000) and Bald and Borja (2001)), the initial month for captures (October) and the duration of the capture season (7 months) (Fig. 4 and Table 1). Based upon the daily capture rate for shellfishers (Table 1), the final number of sustainable shellfishers can be calculated.

4. Results

Due to the similar stock availability in the Gaztelugatxe and Aketxe areas (Borja et al., 2004), the model structure and initial conditions required for modelling, the results presented in

Table 2 – Reproductive status of gooseneck barnacle (*Pollicipes pollicipes*) obtained in Biarritz (France)

Date	Number of individuals examined	Individuals with oviductal sacs (%)	Fertilized oviductal sacs (%)	
			Biarritz	Belle-Ile
27 Oct.	25	0	16.0	2
27 Nov.	20	0	0	0
28 Dec.	20	0	0	0
24 Jan.	37	0	0	0
24 Feb.	15	0	0	0
24 Mar.	15	20.0	0	0
28 Apr.	23	30.4	21.8	0
24 May.	37	91.9	73.0	29.9
23 Jun.	20	90.0	85.0	54.6
21 Jul.	20	80.0	85.0	48.0
25 Aug.	30	50.0	80.0	38.0
30 Sep.	55	28.3	54.3	8

Adapted from Barnes (1992) and Belle-Ile (Girard, 1982).

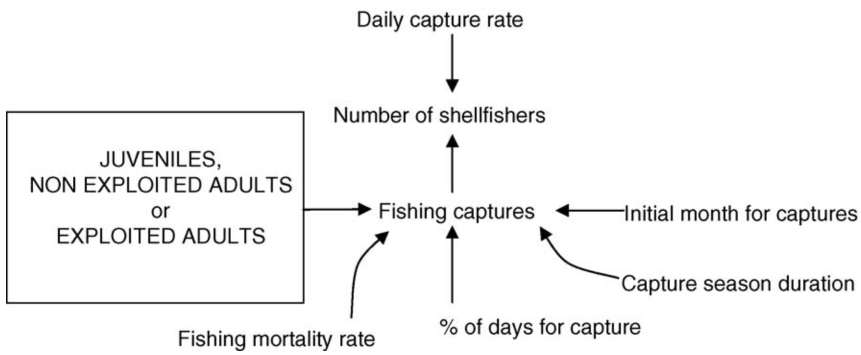

Fig. 4 – Stock and flow diagram for fishing captures.

this section refer only to the Gaztelugatxe coastal area; this is in order to avoid an unnecessary extension of the tables and figures. Table 3 summarises the results obtained for each of the eight different management decisions or cases modelled. For each case, the aim was to simulate the sustainable limit of the resource, from which a progressively decrease of stock can be observed. For this purpose, successive increasing fishing efforts, were applied until this limit was reached (named as *maximal sustainable fishing effort*), together with the modification of other parameters such as the fishing period, captures duration, harvested areas, etc. In all cases, the temporal limit for the modelling was established upon 10 years.

The first case fits the model results with the gooseneck barnacle stock evaluation obtained by Borja et al. (2004) (Case 1). For the second to fourth cases, the maximal sustainable fishing effort in the Gaztelugatxe and Aketxe areas, covers a capture season duration of even months, starting in October: (i) for individuals above the legal length for capture (Case 2); (ii) for individuals below the legal length for capture (Case 3); for individuals above the legal length for capture and an annual alternate capture between both areas (Case 4). For the fifth to sixth cases, the maximal sustainable fishing effort in Gaztelugatxe and Aketxe areas, covers a capture season duration of 5 months, starting in October: (i) for individuals above the legal length for capture (Case 5); (ii) for individuals above the legal length for capture and an annual alternate exploitation between both areas (Case 6). Finally, the last two cases modelise a maximal sustainable fishing effort in only one of the

Table 3 – Results from the different simulated cases

	CASE 1[a]	CASE 2[b]	CASE 3[c]	CASE 4[d]	CASE 5[e]	CASE 6[f]	CASE 7[g]		CASE 8[h]	
							SJ	AK	SJ	AK
Stock (kg)	3450	2715	2706	2680	2757	2633	1199	2807	1139	2783
Captures (kg)	0	506.80	508.43	1015.89	544.46	1055.87	771.43	0	1568.40	0
Captures in respect to stock (%)	0	18.11	18.23	35.31	19.71	14.9	61.22	0	99.06	0
Daily average captures for shellfishers (kg day^{-1})	0	2	2	2	2	2	2	0	2	0
Shellfishers (no.)	0	1.21	1.21	2.42	1.81	3.52	1.84	0	3.73	0
Fishing mortality rate for exploited adults (>17 mm) (%)	0	4.8	4.8	9.8	7.3	14.9	20	0	53	0
Fishing mortality rate for non-exploited adults (<17 mm) (%)	0	0	0.1	0	0	0	0	0	0	0
Initial month for captures	–	Oct	Oct	Oct	Oct	Oct	Oct	–	Oct	–
Capture season duration (months)	–	7	7	7	5	5	7	–	7	–
Captures periodicity	–	Annual	Annual	Biannual	Annual	Biannual	Annual	–	Biannual	–

Key: SJ = Gaztelugatxe; AK = Aketxe.

[a] Case 1: results obtained by Borja et al. (2004).

[b] Case 2: maximal sustainable fishing effort in Gaztelugatxe and Aketze, for individuals above legal length for capture.

[c] Case 3: maximal sustainable fishing effort in Gaztelugatxe and Aketze, for individuals below legal length for capture.

[d] Case 4: maximal sustainable fishing effort in Gaztelugatxe and Aketze, for individuals above legal length for capture and alternate captures, between both areas.

[e] Case 5: maximal sustainable fishing effort in Gaztelugatxe and Aketze, for individuals above legal length for capture and a reduction on the capture season duration, to 5 months.

[f] Case 6: maximal sustainable fishing effort in Gaztelugatxe and Aketze, for individuals above legal length for capture, alternating annually captures between both areas and reduction of capture season to 5 months.

[g] Case 7: maximal sustainable fishing effort in only one of the marine reserve areas and over individuals above legal length for capture.

[h] Case 8: maximal sustainable fishing effort in only one of the marine reserve areas, for individuals above legal length for capture and establishment of a close season every 2 years.

Table 4 – Measured (Borja et al., 2004) vs. modelled results of stock, in July 2002, for the Gaztelugatxe and Aketxe areas

Stock	Units	Observed	Modelled	Deviation (%)
Gaztelugatxe	kg	3450	3346	3.01
Aketze	kg	3559	3382	4.97

The degree of deviation (%) between both observations is shown.

marine reserve areas. The capture season began in October and the duration is of 7 months: (i) for individuals above the legal length for capture (Case 7) and (ii) individuals above the legal length for capture and the establishment of a close season every 2 years (Case 8).

4.1. *Case 1*

The model output fit well with the stock results obtained by Borja et al. (2004), in July 2002, for the Aketxe and Gaztelugatxe areas (Table 4). The maximal deviation percentage was established as 10% (Borja and Bald, 2000; Bald and Borja, 2001). The extension of the model over 10 years provided an average stock for each of the areas (Gaztelugatxe and Aketxe) of 3558 kg, with a standard deviation of 237 kg, which represents an average deviation of 6% (Fig. 5).

4.2. *Case 2*

The maximal fishing mortality rate, without the progressive decrease of the resource, was calculated as 4.8% for the exploited adults (Table 3). With this fishing effort, the stock decreases and tends to stabilise around 2715 kg, with an average capture volume of 506 kg per season (approximately 18% of the total stock at the beginning of the season) (Table 3). The number of shellfishers that the system is able to support is about 1.21, for each coastal zone and capture season (Table 3).

4.3. *Case 3*

In this case, the maximal fishing mortality rate for exploited adults (above legal length) was maintained at 4.8% (Table 3). The maximum fishing effort for individuals below legal length was calculated at a fishing rate of 0.1% (Table 3). In a similar way to the previous case, the stock decreases and tends to stabilise around 2706 kg, with an average capture volume of 508 kg per season (approximately 18% of the total stock, at

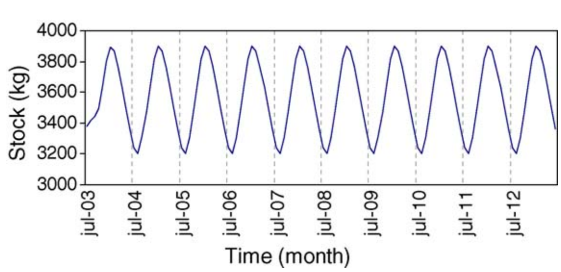

Fig. 5 – Evolution of gooseneck barnacle stock in the Gaztelugatxe coastal area simulated by the model over a 10-year period.

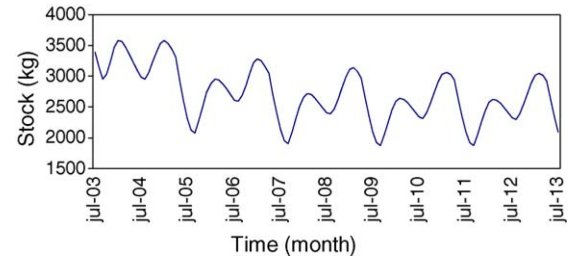

Fig. 6 – Evolution of gooseneck barnacle stock in the Gaztelugatxe coastal area applying an annual alternate maximal sustainable fishing effort between the Gaztelugatxe and Aketxe areas for individuals above the legal length for capture.

the beginning of the capture season) (Table 3). The number of shellfishers that the system is able to support is about 1.21, for each coastal zone and capture season (Table 3).

4.4. *Case 4*

The maximum fishing effort that the system is able to support corresponds to a fishing rate of 9.8% (Table 3). The stock decreases, until it stabilises around an average value of 2680 kg (Fig. 6), with an average capture volume of 1015 kg per season (approximately 35% of the total stock at the beginning of the capture season) (Table 3). The number of shellfishers that the system is able to support is about 2, for each coastal zone and capture season (Table 3).

4.5. *Case 5*

The maximum fishing effort that the system is able to support corresponds to a fishing rate of 7.3%. The stock decreases until it stabilises around an average value of 2757 kg, with an average capture volume of 544 kg per season (approximately 19% of the total stock at the beginning of the capture season) (Table 3). The number of shellfishers that the system is able to support is about 1.81, for each coastal zone and capture season (Table 3).

4.6. *Case 6*

The maximum fishing effort that the system is able to support corresponds to a fishing rate of 14.9% (Table 3). The stock decreases until it stabilises around an average value of 2633 kg, with an average capture volume of 1055 kg per season (approximately 36% of the total stock at the beginning of the capture season) (Table 3). The number of shellfishers that the system is able to support is about 3.52, for each coastal zone and capture season (Table 3).

4.7. *Case 7*

The maximum fishing rate that the system is able to support corresponds to a fishing rate of 20%. The stock in the Gaztelugatxe coastal area decreases, then stabilises around 1199 kg, with an average capture volume of 771 kg per season (approximately 61% of the total stock, at the beginning of the capture season) (Table 3). The number of shellfishers that the system is able to support is about 1.84, for each coastal zone and capture season (Table 3). Due to the common larval pool of both of the coastal areas, the stock in Aketxe decrease to an average value of 2807 kg, due to the removal of reproductive individuals that contribute to this common pool at Gaztelugatxe.

4.8. Case 8

The maximum fishing effort that the system is able to support corresponds to a fishing rate of 53%. The stock decreases in Gaztelugatxe until it stabilises around an average value of 1139 kg, with an average capture volume of 1568 kg per season (approximately 99% of the total stock at the beginning of the capture season) (Table 3). The number of shellfishers that the system is able to support is about 4, for each coastal zone and capture season (Table 3). In a similar way to Case 7, due to the common larval pool of both coastal areas, the stock at Aketxe decrease to an average value of 2783 kg, due to the removal of reproductive individuals that contribute to this common pool in Gaztelugatxe.

5. Discussion

The passive management (by means of captures prohibition and the establishing of minimal lengths for capture) of the gooseneck barnacle fishery tends towards a progressive decrease of the resource, as has been observed in Canada (Jamieson et al., 1999; Lessard et al., 2003). Facing the possibility of the gooseneck barnacle fishery opening in the area of the Gaztelugatxe marine reserve, the need for the development of a management tool was noticed; this should be, capable of considering the different management decisions: from the complete conservation of the system, to the sustainable exploitation of the resource. Such an approach should integrate different social and biological factors, allowing the protection of the stock and the development of the fishery as recommended by Borja et al. (2004).

Some management proposals have been developed by Lauzier (1999a,b), in Canada, such as the establishment of: (i) closed seasons; (ii) closed areas; (iii) maximal capture volumes; (iv) a minimal sustainable biomass level (50% of the initial biomass at the beginning of the capture season); (v) rotational captures, between different areas; (vi) control of the fishing effort. The first results of this management plan have been described by Lessard et al. (2003). In the present work, a system dynamic model has been developed, in order to model the effects of different management decisions over gooseneck barnacle resource in the Gaztelugatxe marine reserve. Some of them are coincident with the proposals of Lauzier (1999a,b).

The model developed in this contribution has some important assumptions, as commented below:

(i) As Molares and Freire (2003) have stated, the processes that regulate the dynamics of the gooseneck population (such as natural mortality, stock-recruitment relationships, transport and survival of larvae, etc.), has been poorly studied. Consequently, the natural mortality rates of larvae, juveniles and adults has been established here trying to reproduce the observations realised by Girard (1982), i.e. the higher mortality rates of juveniles than adults;
(ii) In accordance with Girard (1982) and Pineda and Caswell (1997), the larval mortality was reduced in a 50% when the stock density reaches values below 1.25 kg m^{-2}. This effect can explain the fast recovery observed in the field by shellfishers, when the resource is facing the impact of natural or anthropogenic phenomena;
(iii) The variety of processes that affect the maturation and settlement of larvae, some of them described by Pineda (1994), and the lack of specific information about the rates of this processes, result in the arbitrary definition of the natural mortality rate of larvae;
(iv) The maturation rates of juveniles and adults are constant thorough the year, but some authors have described a greater maturation during spring and summer, as available the food and water temperature increases (Cruz, 1993);
(v) The settlement rate of larvae is constant thorough the year, but some authors, such as Hoz and García (1993), have described maximal settlement rates during May and August.

The remainder of the initial conditions for modelling are based upon the results obtained by Borja et al. (2004), related with the population structure and stock availability in the marine reserve: similarly, upon the different bibliographic sources, related with growth and reproduction of the gooseneck barnacle. As more ecological data on the gooseneck barnacle becomes available, it is very recommendable that revision of the model parameters in order to determine if the values obtained during the calibration are in the same range as those derived from new ecological studies. In this sense, the effects of the abiotic and biotic environment on the gooseneck barnacle population can only be mediated indirectly by means of altering the population parameters included in the model. Therefore, environment is only implicitly included in the model. For instance, this means that the population is only implicitly connected to its food resources, and that the explicit compartment limitation in mass-balance models, with explicit consumption of food resources, like those developed by Pauly et al. (2000), Vasconcellos and Gasalla (2001), Duarte and Garcia (2004), Gasalla and Rossi-Wongtschowski (2004) and Jiang and Gibbs (2005) among others, is not available in this model. Therefore, the population regulation mechanisms must accomplish this limitation.

When the effects of the different management decisions over the evolution of the stock and captures are compared (Table 3), the best management decision is the maintenance of the moratorium for gooseneck barnacle captures in the marine reserve (Case 1, see Fig. 5). The conservation of populations or species is undertaken for different reasons (Hill et al., 1998): (i) their rare character or restricted distribution; (ii) their tendency to decline; (iii) to represent a great part of their distribution; (iv) to be a key species for others; (v) their great richness; (vi) and their great economic, aesthetic, symbolic or recreational value, etc.

In the case of exploitation, the best management decisions are those which are able to maximise, at the same time, the captures and the number of shellfishers and minimise the stock losses, as a consequence of this exploitation. Taking into account this approach, the best management decision is an alternate exploitation, between the Aketxe and Gaztelugatxe coastal areas (Case 4, see Fig. 6); this is consistent with the management recommended by Lauzier (1999a,b), for the sustainable exploitation of gooseneck barnacle in Canada and Brittany (Girard, 1982).

The second management decision is similar to the preceding approach, with a capture season reduction to 5 months (Case 6). In this case, the number of shellfishers by capture season and coastal area is greater, but it encompasses a social concern derived from an important reduction in the capture season.

The third management decision is exploitation in the Aketxe and Gaztelugatxe areas, with a reduction in the capture season to 5 months (Case 5). This measure reduces the stock to approx. 693 kg, due to the capture of 544 kg per season and coastal area, by a number of shellfishers of 1.81. In a similar way to the previous case, the main objection to this measure is the social cost of the capture season reduction.

The fourth management decision, two groups measures at the same time, as they show identical results. Such measures permit the exploitation in both coastal areas; for individuals above the legal length, in the first case, and for individuals above and below the legal length, in the second (Cases 2 and 3). The fifth management decision is the exploitation in a single coastal area of the marine reserve (Case 7). In this case, the stock reduction is markedly greater than the rest of the management measures; from the point of view of the biological security of the resource, this is not very appropriate. The captures are lower than those described for the best first case, where the stock reduction is also notably lower. The main interest in this measure is the demonstration of how the protection of some areas can permit the conservations of others, as they act like spawning pools of larvae that nourish and sustain the exploited areas. This effect has been described in relation with other species, such as the clam (*Ruditapes decussates*) in the Urdaibai estuary in the Basque Country (Borja and Bald, 2000; Bald and Borja, 2001) and in relation to other fishery resources (Nakagawa, 1994). In fact, one of the main management measures adopted in Canada, for the conservation of *Pollicipes polymerus* populations, is the permanent closing of some areas (Lauzier, 1999a,b).

Hence, it is very probable that the capture prohibition in the marine reserve permits not only its own conservation, but also the maintenance of other exploited areas, such as those of Izaro and Ogoño Cape; this is due to the physical larval transport from the marine reserve to those areas. These processes are the main factors that regulate the stock-recruitment relationships of benthic invertebrates, like the gooseneck barnacle (Freire and García-Allut, 2000; Pineda, 1994, 1999, 2000; Pineda and Caswell, 1997; Pineda and López, 2002).

Finally, the sixth management decision is the exploitation of only one of the two coastal areas of the marine reserve, with an establishment of a close season every 2 years (Case 8). This measure is related to a considerable decrease in the stock, together with a great increase in captures and shellfishers; however, they remove more than 90% of the resource which is, in turn, not very suitable from the point of view of the biological security of the resource.

One of the key elements in the success of resource conservation is the control and monitoring activity over shellfisher' captures (Girard, 1982). The failure in this subject has been described by Lauzier (1999a,b), as one of the main problems in the management of the gooseneck barnacle in Canada. It is also been demonstrated that the exploitation of the gooseneck barnacle has effects over the ecosystem, within it is integrated (Jamieson and Levings, 2001; Jamieson et al., 1999; Lauzier, 1999a,b).

Due to their geographical proximity to the Basque Country, combined with the spatial and temporal range of the application of management measures for the gooseneck barnacle, one of the more interesting examples is the case of the Galician coast (Northern Spain). The management of this species began with the establishment of close seasons in some areas; and actually tends to share responsibility for management between the fisheries authorities and the shellfishers, through the "cofradias" (Molares and Freire (2003). Annually, an exploitation plan is developed (number of shellfishers, exploited areas susceptible for exploitation, economical and production objectives, stock management, capture rates, number of working days, etc.) (Molares and Freire, 2003). This plan is developed by the shellfishers; later, this is evaluated by the administration (Molares and Freire, 2003).

6. Conclusions

The best management decision for the conservation of the gooseneck barnacle resource in the marine reserve of Gaztelugatxe, together with adjacent areas which are the subject of exploitation, is the maintenance of the moratorium. Such approach permits the maintenance of a resource that act as a spawning pool of larvae, which nourish and sustain the exploited areas.

In the case of exploitation, the best management decision is an annual alternate exploitation of Gaztelugatxe and Aketxe coastal areas, which allows the recovery of the resource after the capture season.

The model developed makes important assumptions which could be subject to improvement; this is mainly in those aspects related with the better knowledge of the planktonic phase behaviour of the gooseneck barnacle (growth, mortality, transport and settlement). Changes in this phase have important consequences in the ulterior juvenile and adult structure. Better knowledge is acquired also in those aspects related with the growth process and the mortality of juveniles and adults, in relation to the environment. For such an improvement in the knowledge future works would be required on: (i) resource stock monitoring; (ii) growth estimation of individuals; (iii) age determination, by means of the study of growth rings in the calcified parts of individuals; (iv) inclusion of environmental factors affecting recruitment and biomass.

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REFERENCES

Bald, J., Borja, A., 2001. Estudio de los recursos de almeja y berberecho en Mundaka y Plentzia (1998–2000). Informes Técnicos (Departamento de Agricultura y Pesca, Gobierno Vasco) 93, p. 80.

Barnes, M., 1992. The reproductive periods and condition of the penis in several species of common cirripedes. Oceanogr. Mar. Biol. Ann. Rev. 30, 483–525.

Barnes, M., 1996. Pedunculate cirripedes of the genus *Pollicipes*. Oceanogr. Mar. Biol. Ann. Rev. 34, 303–394.

Bernard, F.R., 1988. Potential fishery for the gooseneck barnacle *Pollicipes polymerus* (Sowerby, 1833) in British Columbia. Fish. Res. 6, 287–298.

Bolívar, I., 1982. Lista de la colección de crustáceos de España y Portugal del Museo de Historia Natural de Madrid. Actas de la Sociedad Española de Historia Natural de Madrid 21, 124–125 and 139.

Borja, A., Bald, J., 2000. Estado de los recursos marisqueros del País Vasco en 1998–1999 (con especial atención a almeja y berberecho). Informes Técnicos (Departamento de Agricultura y Pesca, Gobierno Vasco) 86, p. 78.

Borja, A., Bald, J., Muxika, I., Liria, P., 2004. El recurso marisquero de percebe (*Pollicipes pollicipes*) en el biotopo protegido de Gaztelugatxe y en áreas explotadas de Bizkaia. Informes Técnicos (Departamento de Agricultura y Pesca, Gobierno Vasco) 101, p. 112.

Borja, A., Liria, P., Muxika, I., Bald, J., in press. Relationships between wave exposure and biomass of the goose barnacle (*Pollicipes pollicipes*, Gmelin, 1790) in the Gaztelugatxe marine reserve (Basque Country, Northern Spain). ICES J. Mar. Sci.

Borja, A., Valencia, V., Castro, R., Franco, F., Bald, J., Uriarte, A., Mendizábal, M., Aguirrezabalaga, F., 2000. Establecimiento de las bases técnicas de conocimiento del área de San Juan de Gaztelugatxe con vistas a su posible declaración como reserva marina. Informes Técnicos (Departamento de Agricultura y Pesca, Gobierno Vasco) 87, p. 152.

Cruz, T., 1993. Growth of *Pollicipes pollicipes* (GMELIN, 1790) (Cirripedia, Lepadomorpha) on the SW coast of Portugal. Crustaceana 65 (2), 151–158.

Cruz, T., Araújo, J., 1999. Reproductive patterns of *Pollicipes pollicipes* (CIRRIPEDIA: LEPADOMORPHA) on the southwestern coast of Portugal. J. Crustacean Biol. 19 (2), 260–267.

Cruz, T., Hawkins, S.J., 1998. Reproductive cycle of *Pollicipes pollicipes* at Cabo de Sines, south-west coast of Portugal. J. Mar. Biol. Assoc. UK 78, 483–496.

Cunha, I., Weber, M., 2001. Actividad reproductora del percebe *Pollicipes pollicipes* en el norte de Portugal. En: D. G. d. P. y. A. G. d. Cantabria (Ed.), Libro de resúmenes VII Congreso Nacional de Acuicultura. Santander. pp. 173–175.

Duarte, L.O., Garcia, C.B., 2004. Trophic role of small pelagic fishes in a tropical upwelling ecosystem. Ecol. Model. 172 (2–4), 323–338.

Freire, J., García-Allut, A., 2000. Socioeconomic and biological causes of management failures in European artisanal fisheries: the case of Galicia (NW Spain). Mar. Policy 24, 375–384.

Gasalla, M.A., Rossi-Wongtschowski, C.L.D.B., 2004. Contribution of ecosystem analysis to investigating the effects of changes in fishing strategies in the South Brazil Bight coastal ecosystem. Ecol. Model. 172 (2–4), 283–306.

Girard, S., 1982. Etude du stock de pouces-pieds de Belle-Ile et de son exploitation. Memoire de fin d'etudes ENSAR, 79.

Goldberg, H., 1984. Posibilidades de cultivo de percebe, *Pollicipes cornucopiae* Leach, en sistemas flotantes. Inf. Téc. Inst. Esp. Oceanogr. 19, 13.

Graves, Y.V., Stave, K.A., 2003. A model to understand population decline of the devil's hole pupfish (*Cypronodon diabolis*) and support habitat management decisions. In: Proceedings of the 21st System Dynamics International Conference, vol. 19, New York.

Hill, S., Burrows, M.T., Hawkins, S.J., 1998. Intertidal reef biotopes (volume VI). An overview of dynamics and sensitivity characteristics for conservation management of marine SACs. Scottish Association for Marine Science (UK Marine SACs Project), p. 84.

Holland, D.S., Brazee, R.J., 1996. Marine reserves for fisheries management. Mar. Resour. Econ. 11 (3), 157–171.

Hoz, J.J., García, L., 1993. Datos para el estudio de la distribución y reproducción del percebe, *Pollicipes cornucopiae* (Leach), en Asturias. Publc. Espec. Inst. Esp. Oceanogr. 11, 65–71.

Jamieson, G.S., Levings, C.O., 2001. Marine protected areas in Canada — implications for both conservation and fisheries management. Can. J. Fish. Aquat. Sci. 58, 138–156.

Jamieson, G.S., Lauzier, R., Gillespie, G., 1999. Phase 1 framework for undertaking an ecological assessment of the outer coast rocky intertidal zone. Research Document 99/209 Fisheries and Oceans Canada, Canadian Stock Assessment Secretariat, Ottawa, p. 33.

Jiang, W., Gibbs, M.T., 2005. Predicting the carrying capacity of bivalve shellfish culture using a steady, linear food web model. Aquaculture 244 (1–4), 171–185.

Lauzier, R.B., 1999a. Framework for goose barnacle (*Pollicipes polymerus* Sowerby, 1833) fishery in waters off the west coast of Canada. Research Document 99/198 Fisheries and Oceans Canada, Canadian Stock Assessment Secretariat, Ottawa, p. 24.

Lauzier, R.B., 1999b. A review of the biology and fisheries of the goose barnacle (*Pollicipes polymerus* Sowerby, 1833). Research document 99/111 Fisheries and Oceans Canada, Canadian Stock Assessment Secretariat, Ottawa, p. 30.

Lessard, J., Osborne, J., Lauzier, R., Jamieson, G., Harbo, R., 2003. Applying local and scientific knowledge to the establishment of a sustainable fishery: the west coast Vancouver island goose barnacle fishery experience. Putting Fishers Knowledge to Work: 11 (1) 36–40. In: Haggan, H., Brignall, C., Wood, L. (Ed.), Fisheries Centre Research Report, University of British Columbia, Vancouver, Canada.

Molares, J., 2004. Desarrollo e Implantación de un Sistema de Información Geográfica Orientado a la Ordenación Integral de la Pesquería de los Recursos Marinos Específicos: Percebe, Erizo, Longueirón y Navaja. http://sigremar.cesga.es.

Molares, J., Freire, J., 2003. Development and perspectives for community-based management of the goose barnacle (*Pollicipes pollicipes*) fisheries in Galicia (NW Spain). Fish. Res. 65 (13), 485–492.

Nakagawa, Y., 1994. Resource management of Japanese littleneck Tapes philippinarum on propagation grounds in Notsuke Bay of eastern Hokkaido. Fish. Eng. Jpn. Suisan Kogaku 31 (2), 127–132.

Pauly, D., Christensen, V., Walters, C., 2000. Ecopath, ecosim, and ecospace as tools for evaluating ecosystem impact of fisheries. ICES J. Mar. Sci. 57 (3), 697–706.

Pineda, J., 1994. Spatial and temporal patterns in barnacle settlement rate along a southern California rocky shore. Mar. Ecol. Prog. Ser. 107, 125–138.

Pineda, J., 1999. Circulation and larval distribution in internal tidal bore warm fronts. Limnol. Oceanogr. 44 (6), 1400–1414.

Pineda, J., 2000. Linking larval settlement to larval transport: assumptions, potentials and pitfalls. Oceanogr. East. Pac. 1, 84–105.
Pineda, J., Caswell, H., 1997. Dependence of settlement rate on suitable substrate area. Mar. Biol. 129, 541–548.
Pineda, J., López, M., 2002. Temperature, stratification and barnacle larval settlement in two Californian sites. Cont. Shelf Res. 22, 1183–1198.
Sterman, J.D., 1988. A skeptic, guide to computer models. In: Grant, L. (Ed.), Foresight and National Decisions: The Horseman and Bureaucrat.
Sampson, D., 2001. FindFMSY: a fishery simulator for exploring constant harvest rate policies. http://hmsc.oregonstate.edu/projects/findmsy.
Van Den Belt, M., Deutsch, L., Jansson, A., 1998. A consensus-based simulation model for management in the Patagonia coastal zone. Ecol. Model. 110, 79–103.
Vasconcellos, M., Gasalla, M.A., 2001. Fisheries catches and the carrying capacity of marine ecosystems in southern Brazil. Fish. Res. 50 (3), 279–295.
Wakeland, W., Cangur, O., Rueda, G., Scholz, A., 2003. A system dynamics model of the Pacific Coast Rockfish Fishery. In: Proceedings of the 21st International Conference of the System Dynamics Society, vol. 26, New York City.