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Artisanal fisheries analysis using System Dynamics: the case of dredge fisheries in Portugal

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Artisanal fisheries analysis using System Dynamics: the case of dredge fisheries in Portugal

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Abstract

This paper aims to develop a management model to promote the sustainability of artisanal fisheries, considering socio-economic and environmental dimensions. The model is based on System Dynamics and intends to simulate the behaviour of the artisanal dredge fisheries in the south coast of Portugal. The model includes the four main species and the two fleets that integrate this system. The indicators selected for this model were classified according to the DPSIR framework. Different scenarios were studied to assess the impact of regulatory measures on system's sustainability and help decision makers to identify the most appropriate measures to achieve their objectives.

1. Introduction

Human demand for fish resources is growing worldwide, particularly in large urban centers of developing countries. Artisanal fisheries play an important role for supporting local and regional markets. According to the Food and Agriculture Organization of the United Nations (FAO), small scale marine fisheries account for 40% of the marine fish taken for human consumption (FAO, 1998). The sustainable development of artisanal fisheries is essential to guarantee the preservation of the exploited ecosystems and the socio-economic stability of fishermen communities. To ensure the sustainability of artisanal fisheries, updated information about the whole system under analysis is required to improve stakeholders' communication and to provide accurate pictures of the sector status. Data on artisanal fisheries are scarce, thus limiting the possibilities of establishing appropriate analysis for supporting management strategies and initiatives. In this paper, we developed a System Dynamics model incorporating relationships between social, economic and biological variables for a case study of artisanal fisheries in the south coast of Portugal. This model aims to support the design of regulatory measures to promote artisanal fisheries sustainability. The Driving force, Pressure, State, Impact, Response (DPSIR) framework proposed by the European Environmental Agency (EEA, 1999) has been used to select the indicators to integrate the simulation model.

The paper is structured as follows. Section 2 includes a brief description of System Dynamics concepts as well as the description of the model constructed. The section 3 describes the case study. Section 4 presents the results of the simulations and discusses their managerial implications. Section 5 concludes.

2. Review of system dynamics applied to fishery systems

System Dynamics is a set of conceptual tools which enable the comprehension of both structure and dynamics of complex systems. An insightful guide of System Dynamics methodology is provided by Sterman (2000). According to this author, System Dynamics is based on Systems Thinking (see Checkland, 1999; Rosenhead, 1989), taking a system-level view which enables the modeling of the causal structure of the system (e.g. cause–effect interrelationships, feedback loops, delays, non-linearity). Simulations based on System Dynamics models allow the perception of the delayed and systemic impacts of alternative policies in a time-compressed manner.

Systems Thinking is the recognition that the system under analysis is complex and integrates connections between its composing variables. It considers that a change made at a given time will ripple through the system and will impact other variables instantaneously or over time because they are connected in some way. The construction of System Dynamics models is normally preceded by the systems thinking phase, which identifies the variables composing the system and the possible linkages between them. As Forrester (2007) notes, "Some people feel they have learned a lot from the systems thinking phase. But they have gone perhaps only 5 percent of the way into understanding systems. The other 95 percent lies in the system dynamics structuring of models and simulations based on those models. It is only from the actual simulations that inconsistencies within our mental models are revealed. Systems thinking can be a first step toward a dynamic understanding of complex problems, but it is far from sufficient".

As Sterman (2000) explains, the objective of a System Dynamics model is not to be a predictive tool that generates accurate results of the future considering resources and outcomes. Rather, it should be considered as a policy analysis tool that provides stakeholders the means to explore and assess alternative configurations of the system. This methodology has been widely applied in many different areas, including water management (Wang, X. et al. 2011), animal production (Tedeschi, L.O. et al. 2011) and coastal ecosystem (Arquitt, S. and Johnstone, R. 2008). The work developed by Ford (1999) provides an insightful description of how System Dynamics can be used to model and simulate environmental systems. There are few studies that use System Dynamics to model fishery systems. Regarding this theme, the studies by Bueno and Basurto (2009), BenDor et al. (2009) and Yndestad and Stene (2002) are important contributions.

Bueno and Basurto (2009) studied small-scale fisheries of sessile bivalve molluscs in Mexico. A simulation model was developed considering institutional and ecological variables, whose results showed that even small changes in variables' relationship can transform an apparently resilient system into a failed one. BenDor et al. (2009) studied the interactions between economic and ecological dimensions of a multi-species and multi-agent fishery. This study considered the regeneration capacity of fish populations as an indicator of natural resources condition, and the profits, employment and social cohesion as socio-economic indicators. The scenarios developed included changes in fishers behavior, and the results showed that planned fishing quotas and cooperative market mechanisms can solve some aspects of overfishing conflicts. Yndestad and Stene (2002) modelled the capelin fishery in the Barents Sea considering the main aspects affecting the natural evolution of capelin (e.g. growth, recruitment and mortality), natural predation from other species, and captures. It concluded that the catch rate should be adjusted according to the link between the stage of climate cycles and the state of natural characteristics of species.

3. Case study

3.1. Background

The focus of the analysis reported in this paper concerns dredge fisheries in Algarve. Artisanal vessels dedicated to dredge fisheries can be classified into two fleet segments: local fleet and coastal fleet. Local fleet vessels have an overall length lower than 9 meters and the coastal fleet vessels have an overall length between 9 and 14 meters. This fishing activity is performed with dredges towed by boat to harvest bivalves from the seabed. The four main bivalve target species in the south coast of Portugal are: surf clam (*Spisula solida*), donax clam (*Donax trunculus*), razor clam (*Ensis siliqua*) and striped venus (*Chamelea gallina*). These species are illustrated in Figure 1.

Figure 1. Target species of dredge fisheries in Algarve coast.

Two types of dredges can be used in this fishery: the grid dredge (GD), where the catch is retained in a metallic grid, and the traditional dredge (TD), where the catch is retained in a net bag attached to the dredge mouth. The GD is the most recent dredge, that was introduced in 2000. At the moment, the TD is only used for targeting razor clams, while the GD is used to catch the other species. A detailed description of this fishing gear can be found in Gaspar *et al.* (2003). Technical characteristics of dredge vessels and gears are regulated. Dredge vessels are limited to a maximum power of 73,5 kW.

It is defined by legislation a season closure period between 1st May and 15th June, which represents 46 days per year. Extraordinary interdictions are imposed when episode of biotoxins occur. In addition, if the biological stock of species is very low, the fisheries can also be interdicted for that species (e.g., this occurred for two months, in March and April 2006, for all target species of dredge fisheries in Algarve. Fisheries are allowed six days per week (between Sunday and Friday) and each vessel can make a single trip per day. The Portuguese south coast has four main harbours with registered dredge fishing vessels: Faro, Olhão, Tavira and Vila Real de Santo António (VRSA). The vessels that operate from each of these harbours choose fishing locations that minimize the navigation time between the harbour and the bivalve beds. The area where each target species lives can be defined according to specific depths: surf clam within 3 and 12 m of depth, donax clam within 0 and 5 m of depth, razor clam within 3 and 11 m of depth and striped venus within 3 and 15 m of depth. Figure 2 shows the four main harbours and the bathymetric lines of 10, 20 and 30 meters depth.

Figure 2. Harbours and bathymetric lines in the South coast of Portugal.

3.2 Model description

3.2.1 Identification of indicators

This section presents the indicators selected to construct the system dynamics model. The indicators are presented according to the DPSIR framework.

In 1993 the Organization for Economic Co-operation and Development (OECD) proposed the Pressure, State, Response (PSR) framework (OECD, 1993). This approach was enhanced by EEA

(1999) leading to the Driving force, Pressure, State, Impact, Response (DPSIR) framework. This framework is an enhancement of the PSR framework, with the inclusion of two new categories: Driving forces (D) and Impact (I). The DPSIR framework has been suggested for the selection of fisheries indicators by FAO (1999) and EEA (2002). However, few studies applied the DPSIR framework with exclusive focus on fisheries. The EEA (2002) report and the studies performed by Mangi *et al.* (2007) and Knudsen *et al.* (2010) are significant contributions concerning this issue.

Driving force indicators describe socio-economic needs and motivations that impel the existence of human activity. Pressures are the human actions that can induce environmental change. The state may refer to natural systems status, to socio-economic status or to a combination of both. Impacts are the negative effects caused by human activities on the ecosystem and society. Impact indicators can encompass both ecologic and socio-economic aspects. Responses are all the measures adopted by society with the aim to improve the status of the system. These can correspond to preventive, adaptive or curative actions.

The FAO (1999) guidelines also suggest the classification of fisheries indicators within the four main dimensions of sustainability: economic, social, environmental and institutional. Following the criteria suggested by FAO (1999), environmental indicators allow the measurement of the natural ecosystem features, such as the characterization of the species involved, physical and chemical parameters of the ecosystem. Economic indicators are related to the description of vessels, devices, demand of the sector, consumption, profits of the activity, fishing effort made and the economic value of landings. Social indicators relate to the characterization of the community involved in the fishing activity, including employment / unemployment, number of fishers, traditions, culture and education level. The institutional dimension considers the actions made by society, government and other institutions with the aim to improve the fishing activity. The Table 1 present the summary of the variables selected to construct the simulation model, which are organized according to the DPSIR framework and classified within the four dimensions of sustainability proposed by the Commission on Sustainable Development indicator framework. The data for the indicators selected were provided by the Portuguese General Directorate of Fisheries and Aquaculture (DGPA) and the National Laboratory of Marine Research (INRB-L/IPIMAR), and concerns the period from 1996 to 2009. This data were used to construct the relationships among the variables of the model.

Table 1. Indicators included in the System Dynamics model.

Indicator	Dimension	Description	Units
Driving forces			
Fixed costs	Economic	Annual cost of license renewal and vessel and gear maintenance. • FC_j^t – fixed cost of one vessel from fleet j in year t.	Euro /vessel
Variable costs	Economic	Annual landing taxes (commission of the auctions authority and contributions to the social regime), cost of fuel, crew insurance, and contributions to producer organisations. • VC_j^t – variable cost of one vessel from fleet j in year t.	Euro / vessel
Fuel price	Economic	Price of fuel for the fishing activity • F^t – price of fuel in year t.	Euro / l
Fuel consumption	Economic	Average consumption of fuel per trip for coastal vessels and local vessels • $FuelC_j^t$ – average consumption of fuel per trip of a vessel from fleet j	l / trip
First sale price of target species	Economic	Average price of each target species in the wholesale market. • FSP_i^t – First sale price of species i in year t.	Euro /kg
Pressures			
Fishing trips	Economic	Annual number of fishing trips performed by a vessel of each fleet. • FT_j^t – fishing trips of one vessel from fleet j in year t.	
Number of vessels	Economic	Number of active vessels in each fleet • NV_j^t – number of vessels operating in fleet j in year t.	
Crew members	Social	Average number of fishermen in the crew, per vessel, for each fleet. • CM_j^t – average number of fishermen in one vessel of fleet j	
Landings	Economic	Annual landings per species (in weight) per vessel for each fleet. • $L_{i,j}^t$ – landings of species i of one vessel from fleet j in year t.	tonnes
State			
Biologic stock	Environmental	Biologic stock available in the system for each species • S_i^t – biologic stock of species i in year t.	tonnes
Natural growth	Environmental	Natural growth for each species. • NG_i^t – natural growth of species i in year t.	tonnes
Impact			
Profitability per fisherman	Economic	Average annual profitability per fisherman for each fleet. • PF_j^t – profitability of fishermen from fleet j in year t.	Euros
Responses			
Quotas per species	Institutional	Daily limits of captures per species • QS_i^t – daily quotas of species i in year t.	kg / trip
Quotas for total captures	Institutional	Daily limits of captures (including all species) per vessel per fleet • QT_j^t – daily quotas for total captures per vessel of fleet j in year t	kg / trip

3.2.2. Modelling the relationships between variables

This section describes the system dynamics model for dredge fisheries in Algarve, developed using the Vensim PLE Plus software. The simulation model considers the coastal fleet (CF), the local fleet (LF) and the four target species separately, i.e. surf clam (SC), donax clam (DC), razor clam (RC) and striped venus (SV), using an annual periodicity. Figure 3 presents a simplified view of the System Dynamics model developed. The four main blocks on the left represent the variables associated to the stock and captures of the four species and the two main blocks on the right relate to the economic variables for each fleet. Darker boxes refer to the DPSIR variables reported on Table 1. Lighter boxes are auxiliary variables.

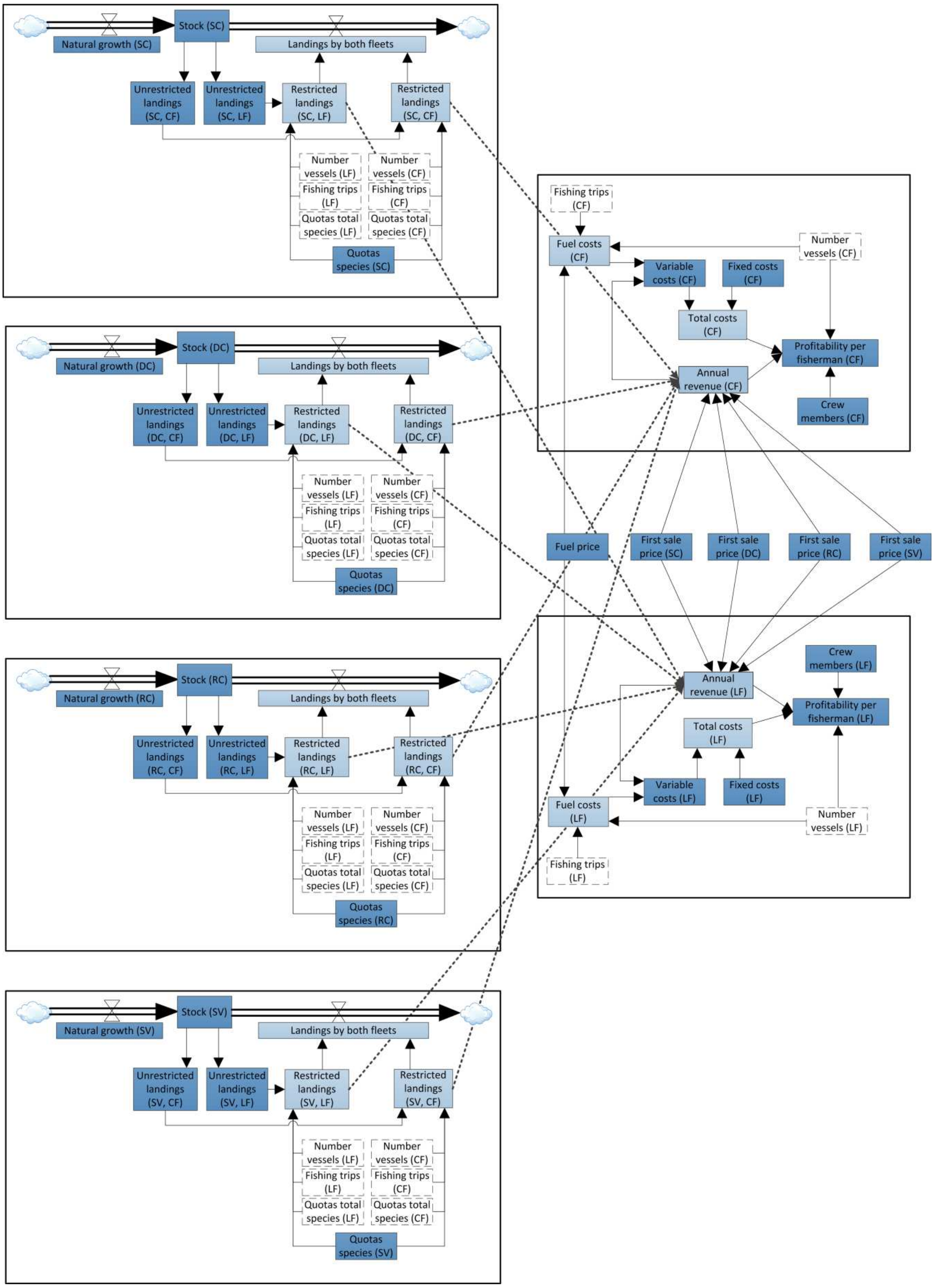

Figure 3. Simplified view of the System Dynamics model developed.

We will first describe in detail the blocks associated to each target species. The model calculates the evolution of biological stock of each species as the difference between the natural growth and the landings of both fleets. For each year, the natural growth of each species was estimated based on historical data according to expression (1). It was obtained as the difference between the stock estimates for two consecutive years, plus the landings of the fleets.

$$NG_i^t [= (BS]_i^{t+1} - BS_i^t) + \sum_j L_{i,j}^t \qquad (1)$$

Figure 4 shows the results obtained for the evolution of natural growth estimated from the historical records between 1996 and 2009, for the target species considered in the model.

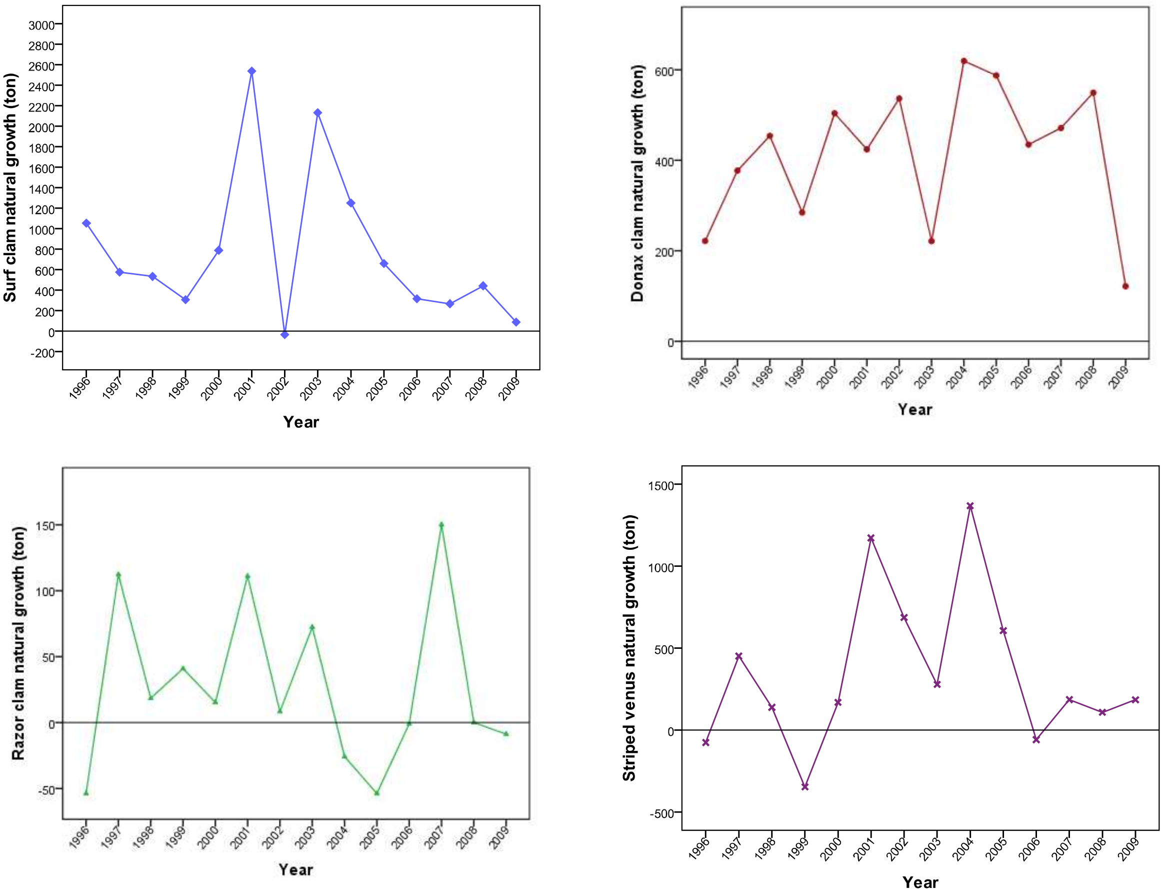

Figure 4. Observed natural growth of target species.

The natural growth of surf clam was included in the System Dynamics model as being equal to the average value observed in the historical records (429 tons, estimated excluding the peaks observed in years 2001 and 2003). To allow for the occurrence of peaks in natural growth we modeled the peaks with a frequency of one every 15 years (with a magnitude of 2336 tons, estimated as the average of years 2001 and 2003). The natural growth of striped venus was modeled considering the average value observed in historical records (194 tons, excluding the peaking years 2001 and 2004). The occurrence of peaks is modeled with a frequency of one every 14 years (1270 tons, calculated as the average values observed in 2001 and 2004). The natural growth of donax clam and razor clam was modeled considering the average value of all years observed (415 tons for donax clam and 34 tons for razor clam).

To model the landings of each species by each fleet, it was investigated its relationship with the stock levels of the target species, as well as the fishing effort dedicated to other species. It was found that the landings could be best explained based on the stock level of the corresponding target species (for donax clam, razor clam and striped venus), and for the case of surf clam it should be also included the landings of striped venus. The regression equations used to model the evolution of the landings are shown in Table 2, using the time period comprised between 1996 and 2009 for all cases except the costal landings of donax clam, which considered the time period between 1996 and 2001 since the last years would not provide a significant relationship.

Table 2. Landings of each species by each vessel (in ton).

		Significance	
	Local fleet	**R^2**	**p-value**
Surf clam	$L^t_{\mathrm{SC,LF}} = 0.317 + 0.008 \cdot S^t_{SC} - 0.585 \cdot L^t_{\mathrm{SV,LF}}$	0.854	0.000
Donax clam	$L^t_{\mathrm{DC,LF}} = 4.917 + 0.013 \cdot S^t_{DC}$	0.202	0.107
Razor clam	$L^t_{\mathrm{RC,LF}} = -0.169 + 0.002 \cdot S^t_{RC}$	0.910	0.000
Striped venus	$L^t_{\mathrm{SV,LF}} = -0.249 + 0.005 \cdot S^t_{SV}$	0.777	0.000
	Coastal fleet	**R^2**	**p-value**
Surf clam	$L^t_{\mathrm{SC,CF}} = 12.575 + 0.034 \cdot S^t_{SC} - 1.397 \cdot L^t_{\mathrm{SV,CF}}$	0.678	0.002
Donax clam	$L^t_{\mathrm{DC,CF}} = 1.837 + 0.036 \cdot S^t_{DC}$	0.832	0.011
Razor clam	$L^t_{\mathrm{RC,CF}} = 0.065 + 0.007 \cdot S^t_{RC}$	0.718	0.000
Striped venus	$L^t_{\mathrm{SV,CF}} = 1.667 + 0.011 \cdot S^t_{SV}$	0.565	0.002

The landings described above represent the annual weight captured by one vessel of each fleet. These landings need to be limited by the respective quotas per trip, that limit the weight captured per species, as well as the total weight of the captures from all species. This requires information on the quota limits (for each species and the total capture, including all species), the number of vessel in each fleet, and the number of fishing trips each vessel does per year.

Concerning the quotas, the historical records are shown on Table 3. The quotas per species are identical for both fleets, whilst the quotas for total captures depend on vessel GRT. In the System Dynamics model, we assumed that local vessels have a GRT equal to 3.89 ton, and local vessels have a GRT equal to 9.25 ton, so the values shown in Table 3 correspond to this GRT value. In the system dynamics model, the simulation assumed that the quotas in future years would be identical to the values corresponding to the last revision of legislation, which occurred in 2005.

Table 3. Daily quotas per species and per vessel inserted into the model (in kg/trip).

Quotas	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005 - 2009
Surf clam (QS_{SC}^{t})	--	--	--	--	--	200	200	400	400	225
Donax clam (QS_{DC}^{t})	--	--	--	--	--	220	150	150	150	150
Razor clam (QS_{RC}^{t})	--	--	--	--	--	100	50	50	50	30
Striped venus (QS_{SV}^{t})	--	--	--	--	--	100	200	200	200	250
All species for GRT = (QT_{LF}^{t})	200	200	120	120	200	300	300	600	600	390
All species for GRT = (QT_{CF}^{t})	200	200	200	200	200	300	300	600	600	390

Concerning the number of vessels in each fleet, the historical records are shown in Table 4. For the system dynamics simulations, we considered the number of vessels to be constant and equal to the average values of the historical records: 25 local vessels and 22 coastal vessels.

Table 4. Number of vessels in each year.

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Number of local vessels (NV_{LF}^{t})	16	18	19	23	23	27	28	28	31	28	28	29	28	26
Number of coastal vessels (NV_{CF}^{t})	20	20	21	21	21	23	24	24	26	25	24	25	24	14

Concerning the annual number of fishing trips per vessel, the historical records are shown in Table 5. We explored the impact of the stock levels for each species in the number of trips, but only found a significant relationship between the stock levels of surf clam and the annual number of fishing trips done by coastal vessels. Therefore, for the local fleet, since no clear trend over time was found, we considered in the system dynamics model that the number of fishing trips would be equal to the average value of the historical records (equal to 115).

Table 5. Annual number of fishing trips per vessel for each fleet.

	2001	2002	2003	2004	2005	2006	2007	2008	2009
Number of fishing trips of local vessels (NV^t_{LF})	109	133	128	114	138	94	113	107	101
Number of coastal vessels (NV^t_{CF})	146	156	162	165	155	107	132	114	118

The regression model used to predict the fishing trips of a coastal vessel is shown in expression (2). This regression has $R^2 = 0.616$ and p value = 0.012.

$$FT^t_{CF} = 121.771 + 0.02 \times S^t_{SC} \qquad (2)$$

The economic variables shown on the right side of Figure 5 are explained next. The revenue of each fleet is obtained as the product of the landings of each species and their first sale price. The first sales prices observed for each species between 1996 and 2009 are shown in Table 6.

Table 6. First sale prices per species.

First sale price	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Surf clam (FSP^t_{SC})	0.86	1.05	1.01	0.83	0.71	0.73	1.00	0.79	0.67	0.67	0.67	0.67	1.18	1.33
Donax clam (FSP^t_{DC})	2.45	2.16	1.54	1.69	1.92	2.04	2.07	2.09	2.09	2.08	2.07	2.12	3.06	3.42
Razor clam (FSP^t_{RC})	1.27	1.68	1.28	2.65	2.84	2.51	2.66	0.00	2.00	2.53	2.66	na	na	na
Striped venus (FSP^t_{SV})	1.97	1.24	0.94	1.54	1.83	1.98	1.99	1.91	2.00	1.99	2.00	1.99	2.01	2.00

In the system dynamics model, we considered that the prices would increase 2.5% per year, using the prices in 2009 as the base value.

Concerning the costs, these include variables and fixed costs. The fixed costs include the maintenance of gears, and are assumed to be equal to 420 Euros per vessel and per year. The variable costs correspond to fuel costs, crew insurance, commissions paid to auction authorities, contributions to social regime and producers associations. The fuel cost is given by the product of fuel consumption, number of vessels, number of fishing trips and fuel price. The fuel consumption was assumed to be equal to the average value estimated from historical records, and is equal to 81 liters for a local trip and 122 liters for a coastal trip. The historical records of fuel prices and vessel consumption per trip for each fleet are shown in Table 7. Fuel price is modeled to increase 10% annually, taking the 2009 value as a starting point. The other components of the variable costs were considered to be equal to 20% of the annual vessel revenue.

Table 7. Fuel price (in €/liter) and fuel consumption (l/trip) implemented in the model in each year.

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Fuel price (F^t)	0,268	0,273	0,268	0,268	0,325	0,246	0,298	0,312	0,373	0,493	0,546	0,550	0,678	0,492
LF consumption ($FuelC^t_{LF}$)	na	na	na	na	na	93	65	67	80	59	102	92	na	92
CF consumption ($FuelC^t_{CF}$)	na	na	na	na	na	143	116	114	131	118	147	122	na	84

Finally, the profitability per vessel is obtained as the difference between revenue and costs. The profitability per fisherman can be obtained by dividing the profitability per vessel by the number of members of the crew. The crew members of one vessel are assumed to be constant over the years: a local vessel is assumed to carry 2 fishermen, and a coastal vessel 3 fishermen.

4. Simulation results

4.1. Validation

The model was simulated considering the period between 1996 and 2009. The results from this simulation were compared with the respective historical records for validation proposes. The rules which define the behavior of some variables were adjusted to best describe historical trends. Concerning the natural growth of surf clam and striped venus, the model simulates peak years for the years in which peaks were observed (i.e. 2001 and 2003 for surf clam, 2001 and 2004 for striped venus). The natural growth of donax clam was defined considering the respective average value between 2002 and 2009, which is 429 tons per year with and associated standard deviation of 189 tons. Between 1996 and 2001, a linear regression was made (3) since in these years an increasing tendency was identified, with a p-value of 0.061and R Square of 0.538.

$$NG^t_{DC} = -77234.648 + 38.837 \cdot t \tag{3}$$

The number of vessels for each fleet was defined following the exact historical records for the time period considered (see Table 4). Similarly, the quotas per species and per vessel were included into the model following the exact historic values observed (see Table 3).

The first sale price was defined as the average value observed between 1996 and 2009 (i.e. constant and equal to the average value observed in all years, note that the increase of 2.5 % is only active from 2010 onwards). The fuel price was reproduced as the exact historical values observed between 1996 and 2009 (see Table 7).

The Spearman's rank correlation was applied to assess the statistical dependence between the observed and simulated homologous variables. For the pairs of variables with no significant correlation results, we applied the classic Kolmogorov-Smirnov Two-Sample test (K-S) to assess whether the distributions obtained from simulations are difference from those observed in the historical records. Figure 5 presents the simulation results and the observed data concerning the biologic stock variable.

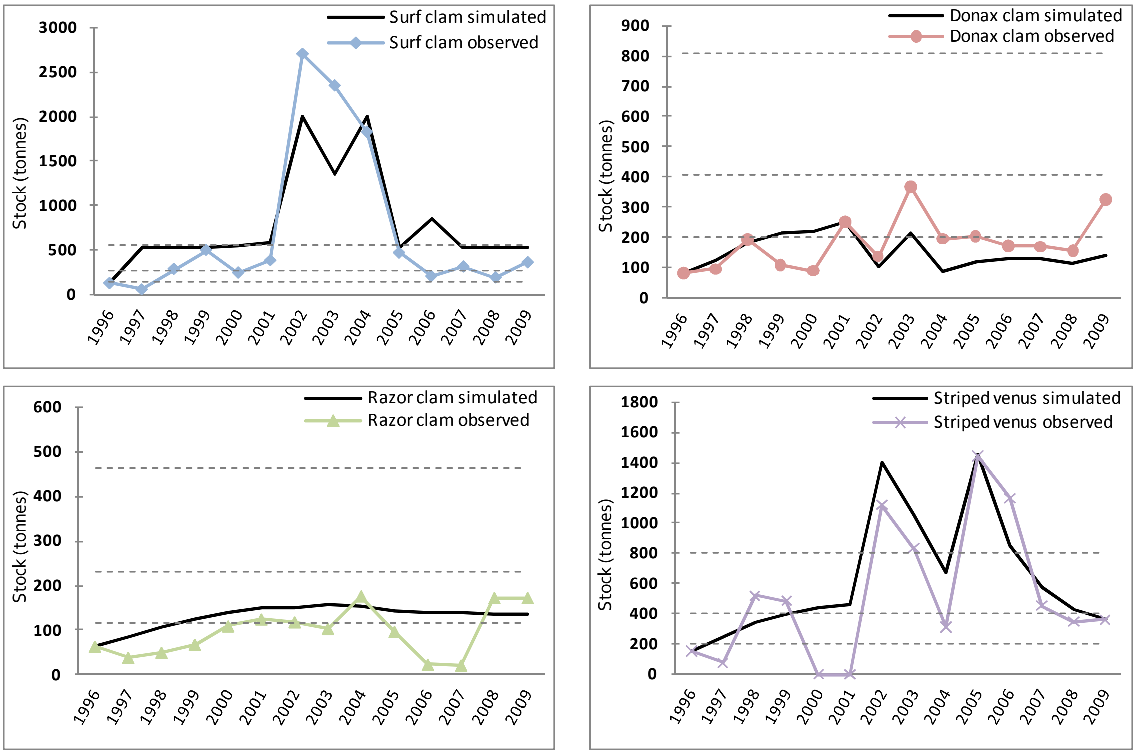

Figure 5. Evolution of the biologic stock of target species observed and simulated between 1996 and 2009.

The simulation results seem to follow similar tendencies to the respective data observed. The simulated stock of surf clam evolves stably between 1996 and 2001 and peaks in 2002 and in 2004 due to the simulation of peaks in the respective natural growth. Since 2005 this stock evolves steadily. The Spearman correlation rho obtained for this pair of variables (i.e. surf clam biologic stock observed and simulated) was 0.669, with a p-value of 0.009, indicating the validity of the results obtained for this variable. The simulated stock of donax clam and of razor clam evolves identically to the historical data. Although it was not possible to obtain a significant correlation for these pair of variables, the K-S test does not reject the equality of distributions followed, with a p-value of 0.060 and 0.617 for donax clam and for razor clam stock, respectively. The results concerning the stock of striped venus followed the observed data, especially from 2001 onwards. Between 1996 and 2000 the simulation presented a systematic evolution while in the historical data some oscillations were noticed. The Spearman correlation was significant for this pair of variables with a rho of 0.585 and a p-value of 0.028. The results concerning the mean fish landings per vessel are presented in Figures 6 and 7 for local and coastal fleets respectively.

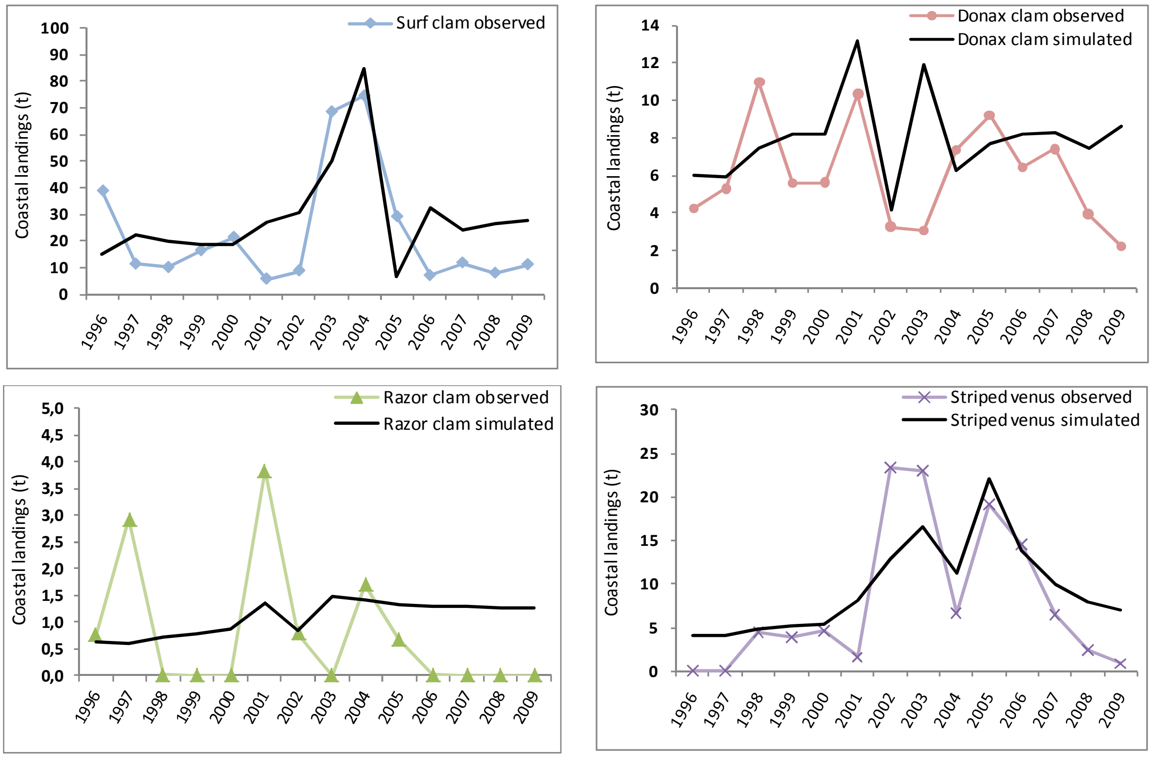

Figure 6. Evolution of the mean fish landings of each target species per coastal dredge vessel between 1996 and 2009.

As it was defined in Table 2, the landings of surf clam are dependent on the striped venus landings, for both fleets. This relationship is more noticeable for the coastal fleet than for the local fleet (since the coastal fleet catches more quantities of this species) and for the years where peaks of striped venus occurred. Accordingly, the peaks observed in striped venus stock in 2002 and in 2005 originated lower volumes of surf clam landings. This relationship represents well the reality observed. For example in 2002 the surf clam stock was very high and the respective captures were low as in 2002 the striped venus peaked as well and the fishing effort was directed mainly to striped venus. This fishermen behavior is justified due to the fact that the price of striped venus in first sale is higher than surf clam. It was not possible to obtain significant correlation results for the surf clam landings in both fleets. However, for the coastal fleet The K-S test revealed significant results (p=0.060) for the landings of surf clam.

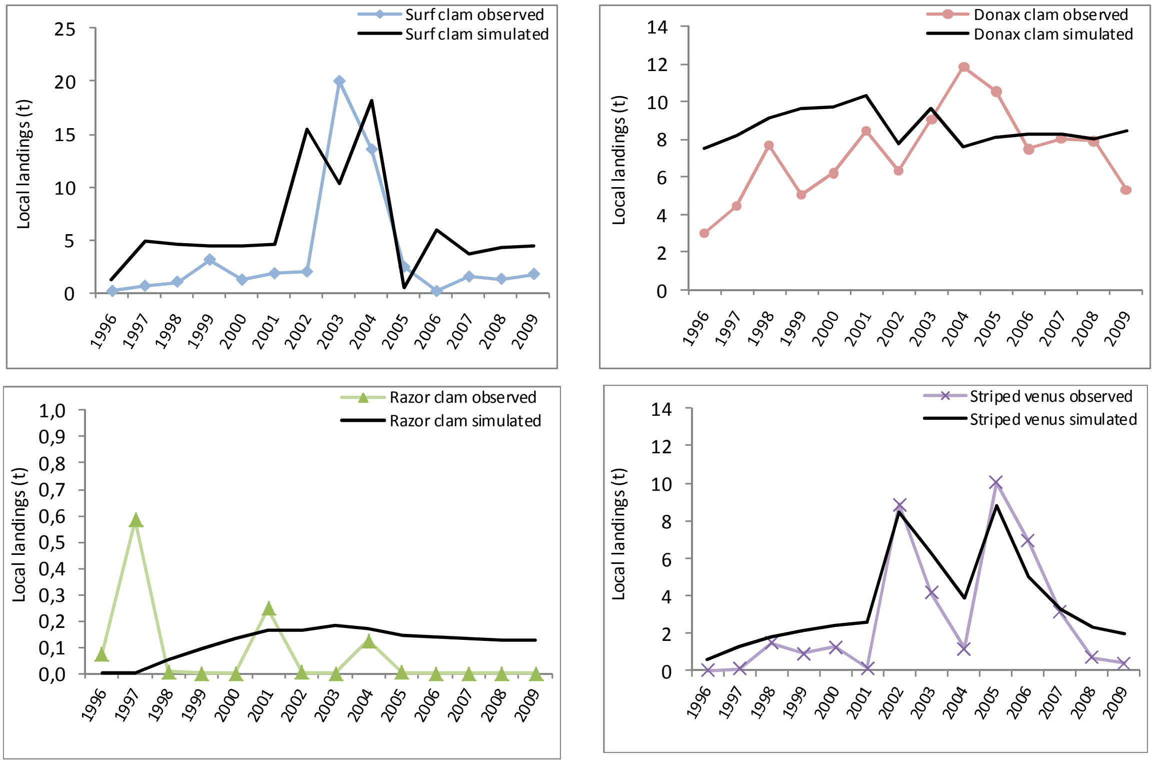

Figure 7. Evolution of the mean fish landings of each target species per local dredge vessel between 1996 and 2009 Values observed and simulated.

The landings of donax clam, razor clam and striped venus evolved following the respective stock. Significant correlation results were noticed only for striped venus local (Spearman's rho of 0.833; p=0.000) and coastal (Spearman's rho of 0.837; p=0.000). The landings of donax clam presented significant results concerning the K-S test, with a p-value of 0.060 and 0.153 for coastal and local landings, respectively. The razor clam landings did not present any significant results concerning the statistical tests performed.

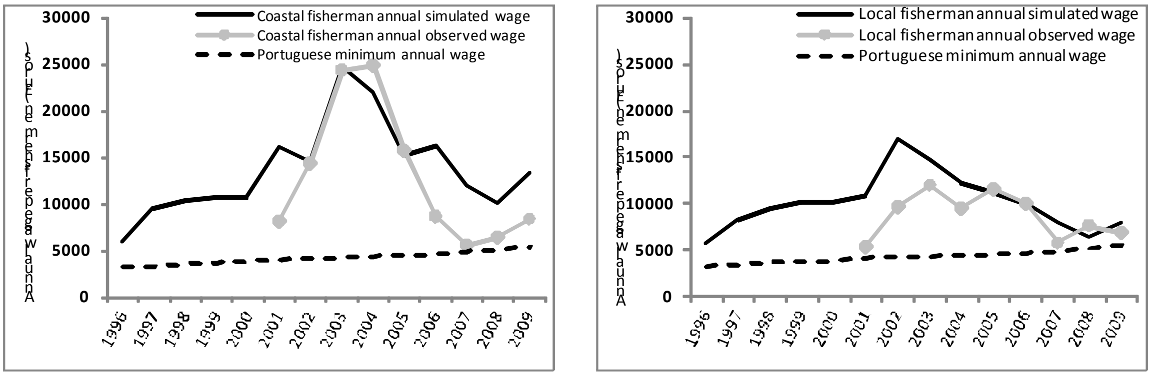

Figure 8. Evolution of the mean annual wage per fisherman of each dredge fleet segment observed and simulated between 1996 and 2009. Portuguese minimum wage (dashed line) is included as a reference.

Figure 8 presents the results obtained concerning the annual wage per fisherman of each dredge fleet segment. From the analysis of this figure it can be observed that the simulated results are similar to historical data. For the coastal fleet there is a very good adjustment between 2002 and 2005, and for other years there are similar trends but with variations. For the local fleet similar trends were observed between the predicted and observed values, in particular there is a good adjustment between 2005 and 2009. Regarding statistical tests, the profitability per fisherman of the coastal fleet presented significant correlation with a Spearman's rho of 0.783 and a p-value of 0.013. Although the profitability per fisherman of the local fleet did not evidence significant correlation results, the K-S was significant (p=0.699), supporting the match between the simulated and the observed distributions of this variable.

4.2. Base scenario

Base scenario assumes that the system will evolve following the relationships observed in the past. This scenario was simulated considering the period comprised between 2009 and 2020, changing the biologic stock inputs to the real data observed in this variable in 2009. Base scenario results were used to assess the sustainability of the system and to compare the results obtained with other scenarios.

Figure 9 presents the observed biologic stock of each target species as well as the homologous simulated results under the base scenario simulation. Figure 9 also includes three dashed lines for each species that are indicative of the quality of the stock of each species, separating each plot into four distinct zones (bad, medium, good and very good), with higher stock's quality for higher stock values. The surf clam presents a stable and high level of stock between 2009 and 2016. The surf clam stock peaks in 2017 due to the simulation of a peak in the respective natural growth. Although the biologic stock of donax clam is low, since it remains stable over time, this does not represent a critical aspect concerning biologic sustainability. The razor clam presents always medium values of stock. The striped venus stock is medium between 2009 and 2018, and was pushed up in 2019, year where the model simulates the occurrence of a peak in the natural growth of this species. Base scenario indicates a sustainable evolution of the system considering the biological dimension.

The base scenario results concerning the annual wage per fishermen for each dredge fleet segment are detailed in Figure 10. The dashed line included in this Figure refers to the annual Portuguese minimum salary observed in 2009 as this value is taken as a reference to the assessment of economic sustainability.

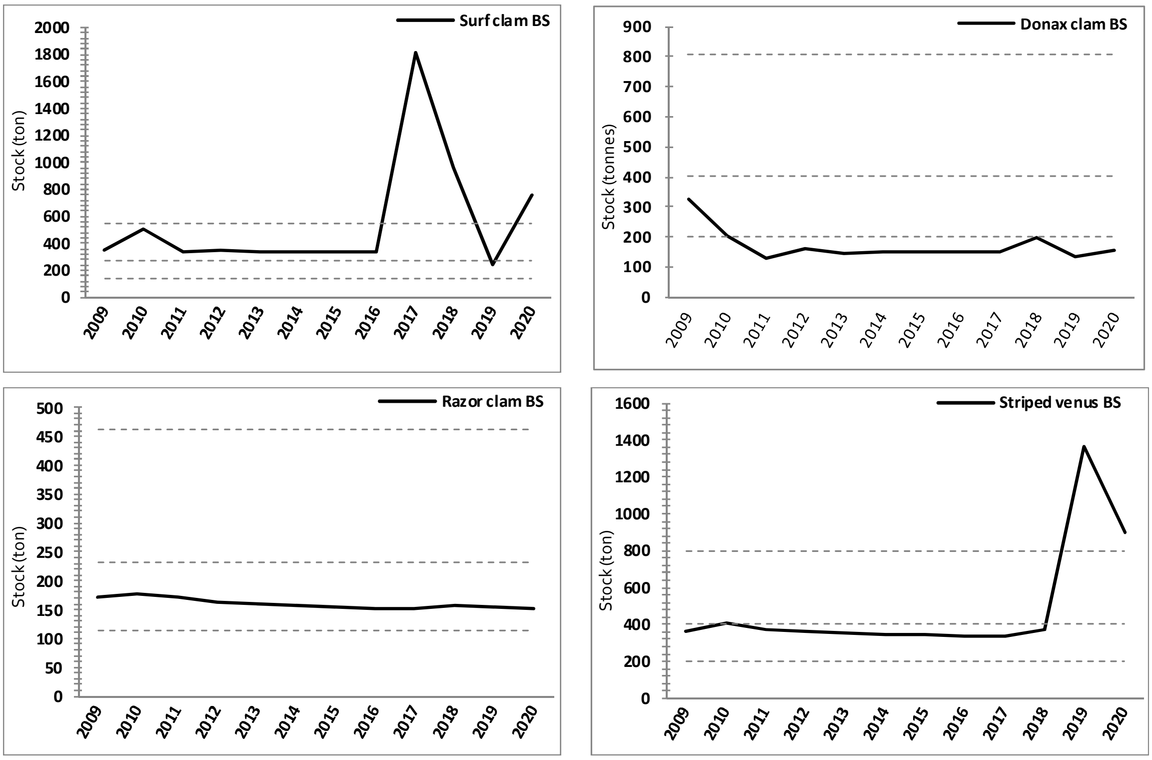

Figure 9. Predicted evolution of the biologic stock of target species simulated in the base scenario.

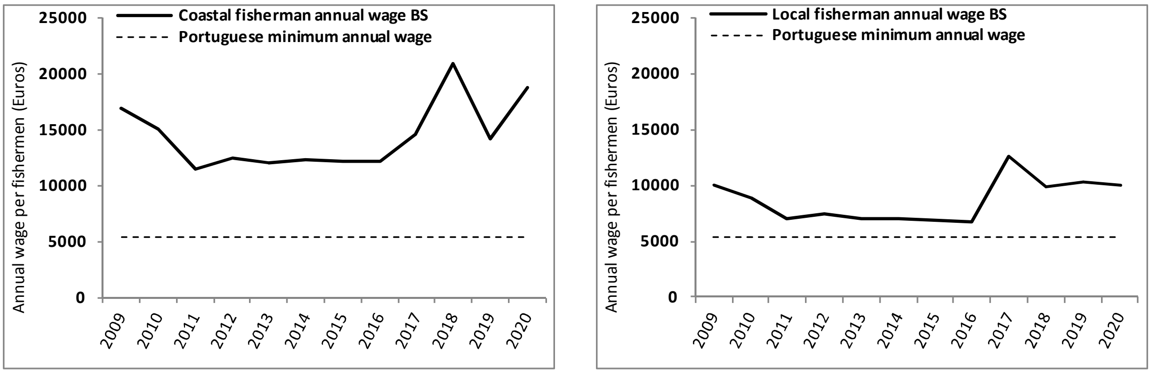

Figure 10. Predicted evolution of annual wage per fisherman of each dredge fleet segment in the base scenario.

The analysis of the predicted years indicate the sustainability of both fleet segments considering the economic dimension, as the wage per fishermen is always higher than the Portuguese minimum annual wage.

Scenario 1

Scenario 1 simulates the permanent reduction of 5 vessels in both fleet segments. This reduction would imply the loss of 22% of total jobs (10 local and 15 coastal fishermen), representing a deterioration of social sustainability. The results obtained concerning the evolution of stock for all species are shown in Figure 11.

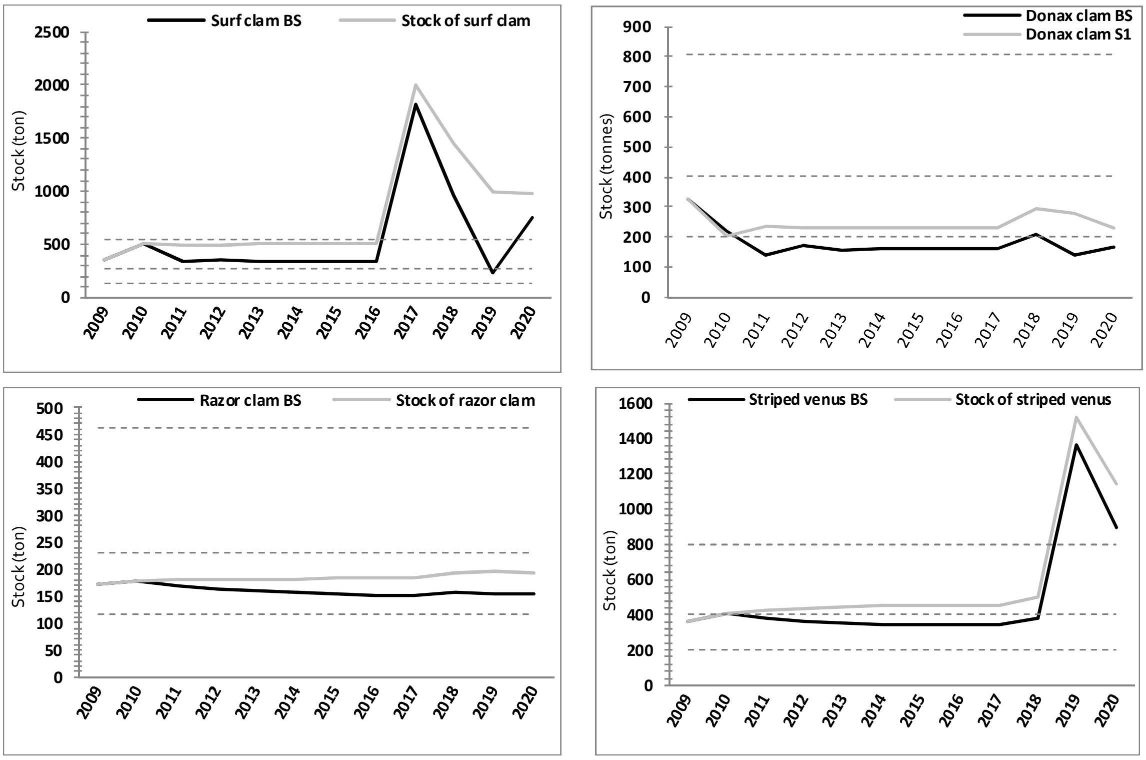

Figure 11. Predicted evolution of the biologic stock of target species. Values simulated in base scenario and in scenario 1.

All species noticed an increase in their biologic stocks, which relates to the lower fishing effort allocated to them. Since the stock of all species increased, the landings per vessel increased as well (the landings per vessel depend on the respective stock). The results concerning profitability per fisherman under this scenario are presented in Figure 12. The reduction of 5 vessels in both fleets represents a reduction in the fishing effort leading to the increase of all species' biologic stock. Due to this recovery, each vessel which continues operating from 2010 onwards is able to catch more in scenario 1 than in base scenario. Accordingly, the annual wage per fishermen in scenario 1 is also greater than in base scenario. This scenario ensures biologic and economic sustainability. However the social sustainability is worsened, as this scenario implies the permanent loss of 25 direct jobs.

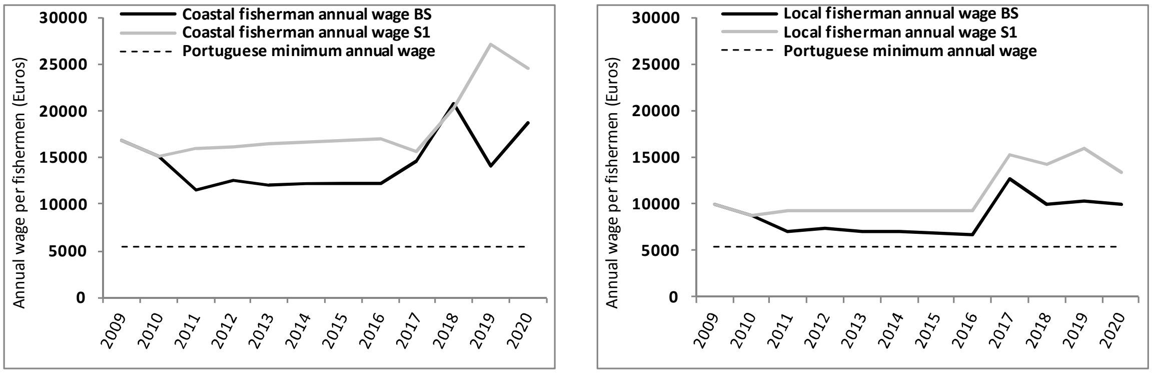

Figure 12. Predicted evolution of annual wage per fisherman of each dredge fleet segment in the base scenario and in scenario 1.

Scenario 2

Scenario 2 studies the impact of closing the exploitation of surf clam for one year (in 2010), with the objective to improve the biological sustainability of this species. Although the stock of surf clam was high in 2009, the number of juveniles was low, indicating that this species may have its reproduction hampered in subsequent years. Therefore, this scenario aims to test the response of the system to regulatory measures intended to protect this species during one year. This closure measured will be simulated together with the introduction of two new assumptions. The first assumption increases the surf clam first sale price by 10% in 2010, and this new price will prevail in subsequence years. The second assumption increases the fishing effort over the other species during the interdiction period (year 2010) by 10% in the local fleet and by 20% in the coastal fleet. The results obtained concerning the evolution of stock of each species are shown in Figure 13.

The stock of surf clam increased in 2011 due to the closure implemented in 2010. This recovery is lost in 2012 due to the reopening of the surf clam fishery. The stocks of razor clam and striped venus decreased marginally in 2011 whereas Donax clam stock declined significantly in 2011 and recovered for the values of 2010 recovered one year later.

Figure 14 shows the predicted evolution of the mean landing per coastal vessel for scenario 2, and takes the homologous variables from base scenario as a reference. Similar evolutions were observed for the local fleet and therefore graphs are not shown.

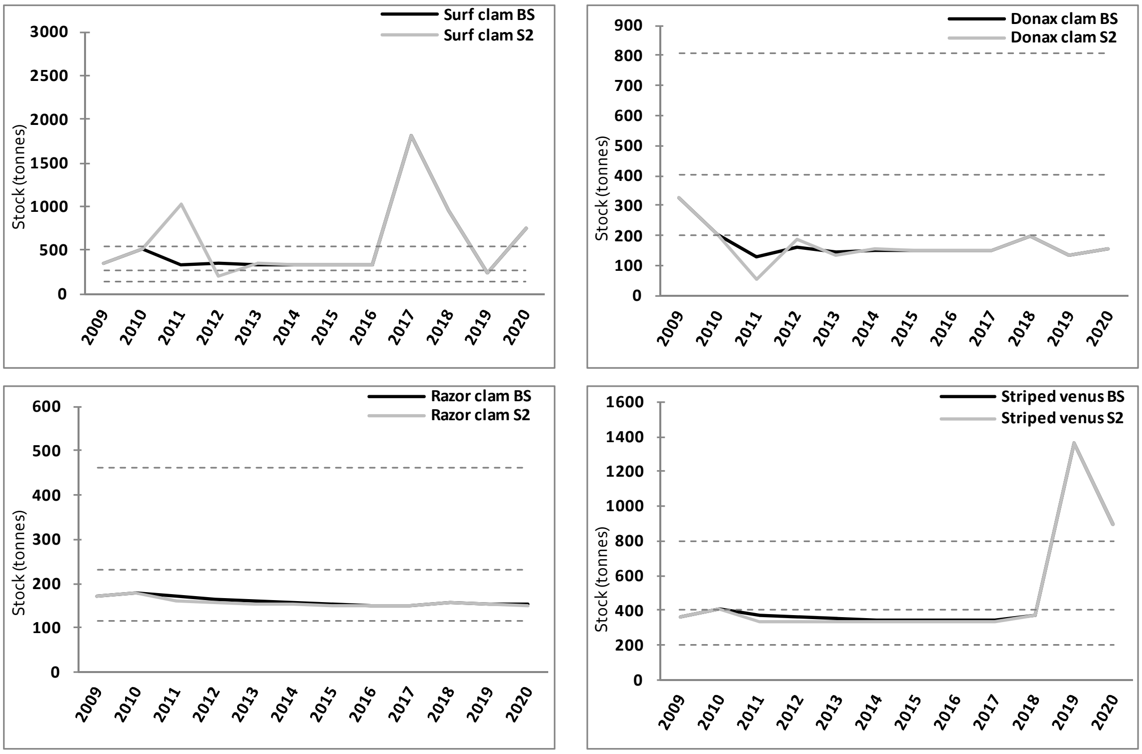

Figure 13. Predicted evolution of the biologic stock of target species. Values simulated in base scenario and in scenario 2.

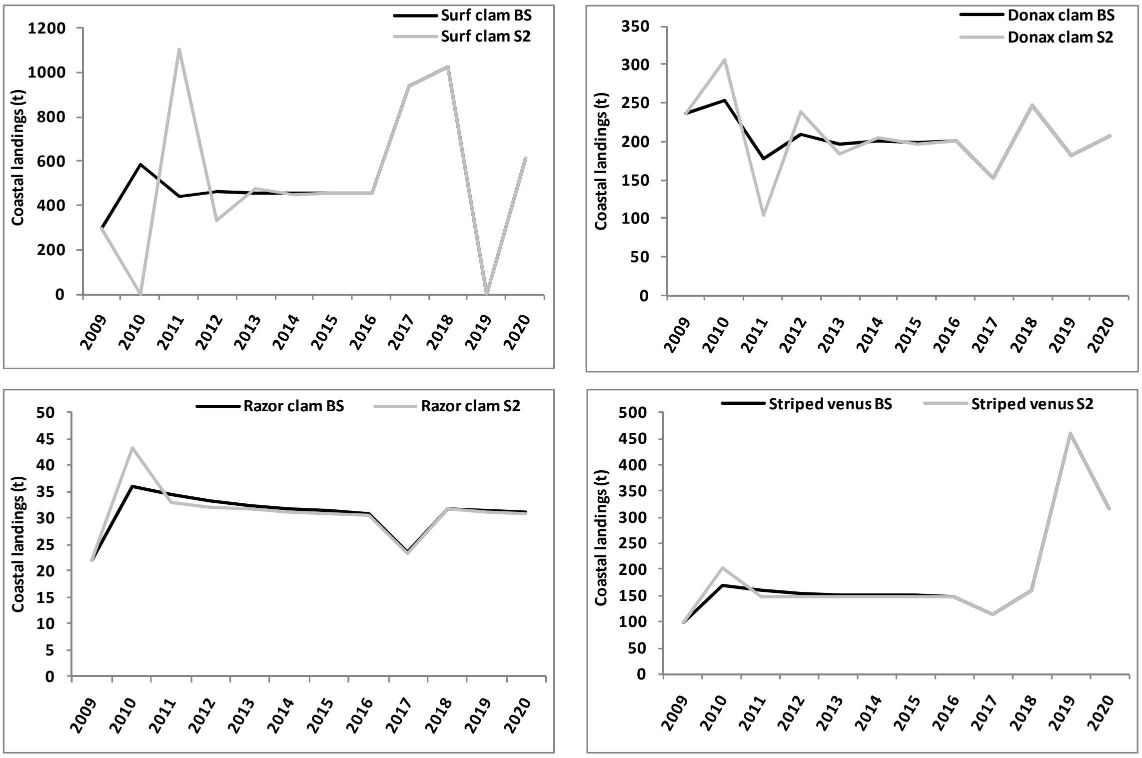

Figure 14. Predicted evolution of fish landings per dredge coastal vessel and target species. Values simulated in base scenario and in scenario 2.

The landings of surf clam are null in 2010 and peak in 2011 as this year presented higher stock of surf clam. The catches of the other three species were higher in 2010 reflecting the increase in fishing effort (second assumption). Donax clam landings decreased in 2011 due to the deterioration observed in its stock, but it recovered in the following year. The evolution of all species in the long term follows similar tendencies to those observed in base scenario. The average annual wage per fisherman obtained is presented in Figure 15.

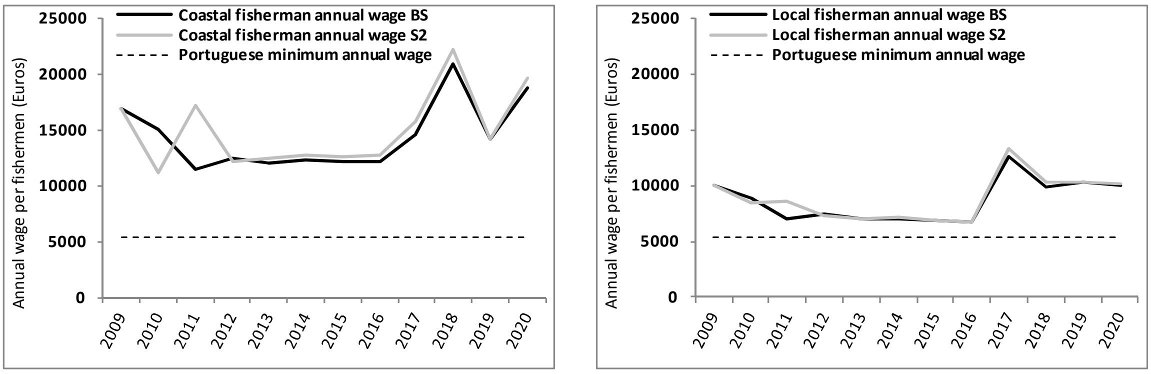

Figure 15. Predicted evolution of annual wage per fisherman of each dredge fleet segment. Values simulated in base scenario and in scenario 2.

Scenario 2 originates lower profits in 2010 indicating that the closure of surf clam fishery is not compensated by the fishing effort increase simulated in that year. The increase in profit observed from 2010 onwards is related to the increase in first sale price of surf clam introduced in 2010 (first assumption). The profitability peak recorded in 2011 is also linked to the surf clam landings increase. The higher profits obtained since 2011 are compensatory of the profit loss incurred in 2010 for both fleets.

5. Conclusions

This paper uses the System Dynamics modelling approach to analyse the dynamics of artisanal dredge fisheries in the south coast of Portugal. It demonstrates the advantages of developing System Dynamics simulation models in fisheries, including the study of ecological and economic aspects of the system by forecasting potential impacts of the implementation of different regulatory measures.

The variables selected to construct the simulation model were organized according to the DPSIR framework. The relationships established between the variables selected were based on the analysis of historical data, including the application of the linear regression model and descriptive statistics.

The simulation model was validated through the comparison of simulation results for the period comprised between 1996 and 2009 and the homologous historical records. The base scenario simulation allowed predicting the evolution of the system, assuming that the behavior of the system remains as observed in the past. This analysis indicated that artisanal fisheries may evolve with no problems of sustainability, although the stock of donax clam should be followed with special care.

Scenarios 1 and 2 allowed the assessment of the potential impacts linked to different regulatory measures. The formulation and analysis of scenarios can help decision makers to identify the most appropriate measures to achieve a given objective. In addition, the presentation of the simulation results to stakeholders can be used as a starting point to attract public interest in this subject, and guide discussions on artisanal fisheries regulation. Furthermore, it can help fisherman to understand and accept the options followed by administrative authorities concerning artisanal fisheries regulation.

Acknowledgements

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