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Catch estimates and bioeconomic analysis of bait digging: the case of the tube worm *Diopatra neapolitana*

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Abstract:

There has been an extensive review on the environmental and commercial significance of fishery species in European coastal lagoons in addition to a representative indexing of fishing fauna. However, the economic effects of fishery and particularly bait digging to the local economy are scarce while the impacts of the activity to the stock reserves of different baits are poorly explored.

To this end, the current study has estimated the digging effort and rate of the species *Diopatra neapolitana*, which is captured through a bait digging activity. The study area was located in Ria de Aveiro coastal lagoon at northwest Atlantic coast of Portugal, which is a mesotidal lagoon with extensive intertidal mud and sand flat areas exposed during low tide. Different management scenarios of open-access, maximum sustainable yield (MSY) and maximum economic yield (MEY) were explored through a bioeconomic analysis.

The results show that in the southern parts of the lagoon, the digging effort is higher along spring tides except autumn season while the annual catch was estimated at 9,000kg yr⁻¹. In the northern parts the lack of sufficient data prohibited seasonal analysis. However, the annual catch was estimated to

probably exceed 36,000kg yr⁻¹.

The bioeconomic results have shown that the open access scenario can provoke a gradual depletion of *Diopatra neapolitana* reserves if only the diggers will conduct digging activity two times within a day. The maximum sustainable yield scenario (MSY) has shown that the digging activity has not reached the maximum allowed effort if only the daytime activity is taken into account. The maximum economic yield (MEY) scenario however indicated that the diggers may be currently close to maximum catch by considering only the daytime workout. The current economic benefits of bait digging may encourage new bait catchers to practice this activity given the low profitability in other similar employment sectors. The results should be further clarified through the introduction of biological production modeling as well spatial and temporal dynamic analysis.

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Per Stålnacke

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1. Summary

Bait digging activity is practiced in the Ria de Aveiro lagoon's intertidal mudflats, mainly in the lagoon's channels Canal de Mira and Canal de Ovar. The polychaete *Diopatra neapolitana* (Delle Chiaje, 1841) which is locally known as “*casulo*”, is dug in these mudflats to be sold as live bait for recreational and professional fishing. In Ria there are professional bait diggers, i.e., licensed to catch the bait, and recreational diggers that should only catch for their own use.

In this study, the total annual catch and the catch per unit effort (CPUE) of “*casulo*” are estimated from independently assessed analysis. Two survey agents sampled these two areas, Canal de Mira and Canal de Ovar, by boat or by car, during one-year period (October 2012 - October 2013). The agents counted the number of diggers in the lagoon's mudflats and interviewed them at the end of the digging session to assess the amounts collected.

The results show that, in Canal de Mira, the catch is higher during spring tides in all seasons except in autumn, and that CPUE is higher during spring tides in all seasons. Mean daily catch is higher in spring tides, except in autumn, and the highest values were recorded in the summer. The total annual catch in the period study was over 9,000 kg yr⁻¹. In Canal de Ovar, the low number of observation did not enable the comparison between different seasons and tide levels, but it was possible to estimate that the total annual catch was over 36,000 kg yr⁻¹.

This study also performed an economic assessment on the revenues generated by this activity through the implementation of a bioeconomic static model for Canal de Mira in the period 2012/2013. The bioeconomic results have shown that the open access scenario can provoke a gradual depletion of *casulo* reserves if only the bait diggers will conduct the activity two times within a day. Otherwise, the excess digging can be hardly achieved. The current study has investigated only the case of one digging session per day and further research should be conducted for the exploration of the potential that this activity occurs twice a day.

The maximum sustainable yield scenario (MSY) has shown that the bait digging activity has not reached the maximum allowed effort of 5.22 hrs/day (per digger) if only the daytime activity is taken into account. The maximum economic yield (MEY) scenario however indicated that the bait diggers may be currently close to maximum digging effort of the 4.22 hrs/day (per digger) by considering only the daytime workout. The MEY scenario indicates that the bait diggers have also probably attained the maximum daily income from *casulo* catch given that the tidal constraints in Ria de Aveiro do not allow more than a four (4) hours digging activity.

It seems that if a daytime digging activity only takes place in Canal de Mira then the catching conditions are now nearly to optimal in economic and biological terms. The bait diggers attain the highest possible income given the tidal constraints while the stock reserves are caught in a sustainable manner. However,

more data should be collected and analyzed for the enhancement of the current study.

Two previous studies conducted in Canal de Mira indicated a total annual catch of over 45,000 kg in 2001/2002 (Cunha et al., 2005), and of over 29,000 kg in 2007/2008 (Freitas et al., 2011). The causes of this decrease are not yet known. Taking into account that the results of the present study indicate that the bait diggers do not have an economic incentive to overfish the Canal de Mira stock, the possibility exists that the steady decrease may be due to the changing of environmental conditions. However, a high uncertainty remains because biological production estimates, based for example on general production or on dynamic models, have not been developed, calling for further research in order to better understand these results.

2. Introduction

In the shallow subtidal and intertidal flats of the Ria de Aveiro lagoon several digging activities take place every day, such as shellfish and bait catch, to be used, respectively, for human consumption or sold as live bait for both professional and recreational fisheries respectively (Cunha et al., 2005). In general, shellfish species like cross-cut carpet shell (*Ruditapes decussatus*), pullet carpet shell (*Venerupis corrugata*) or common cockle (*Cerastoderma edule*) are amongst the most caught species and they are for self-consumption or sold to middlemen. In many cases, the middlemen export them to Spain after a depuration treatment has been conducted. The baitworms, like solitary tube worm, (*Diopatra neapolitana*), catworm (*Nephtys hombergii*) and ragworm (*Hediste diversicolor*) are either sold by bait diggers to fishermen, local and national fishing stores or self-used as live bait for fishing (Cunha et al., 2005). These benthic macroinvertebrates are captured during low tide periods by using artisanal handheld instruments (like arrows, shovels, hoes, etc.) (Cunha, 2004).

The solitary tube worm is a sedentary carnivorous polychaete species, 15-50 cm long, which lives inside a membranous tube buried in intertidal mudflats (Fauvel, 1923; Leguerrier et al., 2004) as presented in Figure 1:



Figure 1. *Diopatra neapolitana*: polychaete and membranous tube (left); tube buried in the mudflat (right) (Photo credits: H. Queiroga and R. Calado)

In the *casulo* digging activity, diggers usually cut the anterior part of the worm's body (approximately 10-15 cm) using a hoe or a shovel-like hand-made instrument (Cunha, 2004). For the bait digging activity, bait diggers begin at ebbing and the digging takes place close to the water line, following the water movement; when flooding starts, the bait digging is complete. Some diggers wash the catches before leaving the mudflats so as to remove the attached sediment. Afterwards, the worms are separated into portions of 20 to 21 individuals, per unit of sale, wrapped in newspaper (to prevent them from desiccation) and delivered to those who have ordered these baits.

The technique used in the *casulo* digging activity is distinguishable from the capture of other shellfish species. When using the hoe, diggers take advantage of gravity for the descendant movement of the instrument; using the shovel-like hand-made instrument, its iron blade is buried in the sandy substrate by pushing a perpendicular crosspiece at the top with the digger's foot. Both of these instruments cut the anterior part of the solitary tube worm's body and the sediment is then manually searched and the worm and the corresponding tube are placed in a bucket (Cunha, 2004). The regenerative ability of *casulo* is known, since it survives the loss of a few segments by predation (Pires et al., 2012). However bait digging activity could decrease the survival of the posterior part that remains in the tube, since more than 20 segments are usually caught by bait diggers (Pires et al., 2012).

This bait digging activity has been studied in Canal de Mira in two different time periods: 2001/2002 (Cunha et al., 2005) and 2007/2008 (Freitas et al., 2011). In the first study, conducted between May 2001 and April 2002, Cunha et al. (2005) estimated the total annual catch in this period to be around 45000 kg yr⁻¹, with a standard error of 4,955 kg yr⁻¹. The second study performed in the same area of the lagoon was conducted between December 2007 and November 2008 by Freitas et al. (2011) and estimated catches to be around 29000 kg yr⁻¹, with a standard error of 5,135 kg yr⁻¹.

The *casulo* digging is regulated by Decree Law no. 1102-B/2000, 22 of November 2000, altered by Ordinance no. 1228/2010, 6 of December 2010. This document states that the digging activity for commercial purposes must be made by registered and licensed diggers. Diggers must register until the 31st of August and their card is valid for two years; they must also require a license, which is valid for one calendar year. In the majority of the cases, diggers do not have their licenses updated. The Ordinance does not specify a maximum amount of catch for this species. However, a more recent document, Ordinance no. 14/2014, 23 of January 2014, states that the daily catch limit for annelids is 0,5 litres per practitioner, without including the tubes in this limit.

The present study aims to provide an estimate regarding the polychaete's *Diopatra neapolitana* (Delle Chiaje, 1841) annual catch and catch per unit effort (CPUE) in Ria de Aveiro lagoon and to provide a better understanding of its economic features. To this end, the catch and CPUE of this activity were estimated throughout one year period (2012-2013) in two areas of the lagoon while a static analysis of bio-economic equilibria was conducted afterwards.

3. Study site description

The Ria de Aveiro (40°38'N, 08°45'W) is a shallow coastal lagoon located in the north-west coast of Portugal and is connected to the Atlantic Ocean through a single inlet. The lagoon forms a unique mesotidal wetland area, characterized by four main channels with several branches forming islands, inner basins and mudflats. In the south, the two narrow and elongated Mira and Ílhavo channels are about 25 km and 15 km long, respectively; in the centre, the Espinheiro Channel is about 17 km long; and in the north, the S. Jacinto-Ovar Channel is about 29 km long (Figure 2). It is 45 km in length (NNE-SSW), 10 km wide and in a spring tide covers an area of approximately 83 km² and 66 km² of wetland at high water and low water, respectively (Dias et al., 2000). According to the 2011 census (INE, 2012), the Ria has a population of 353,688 inhabitants in the watershed area.

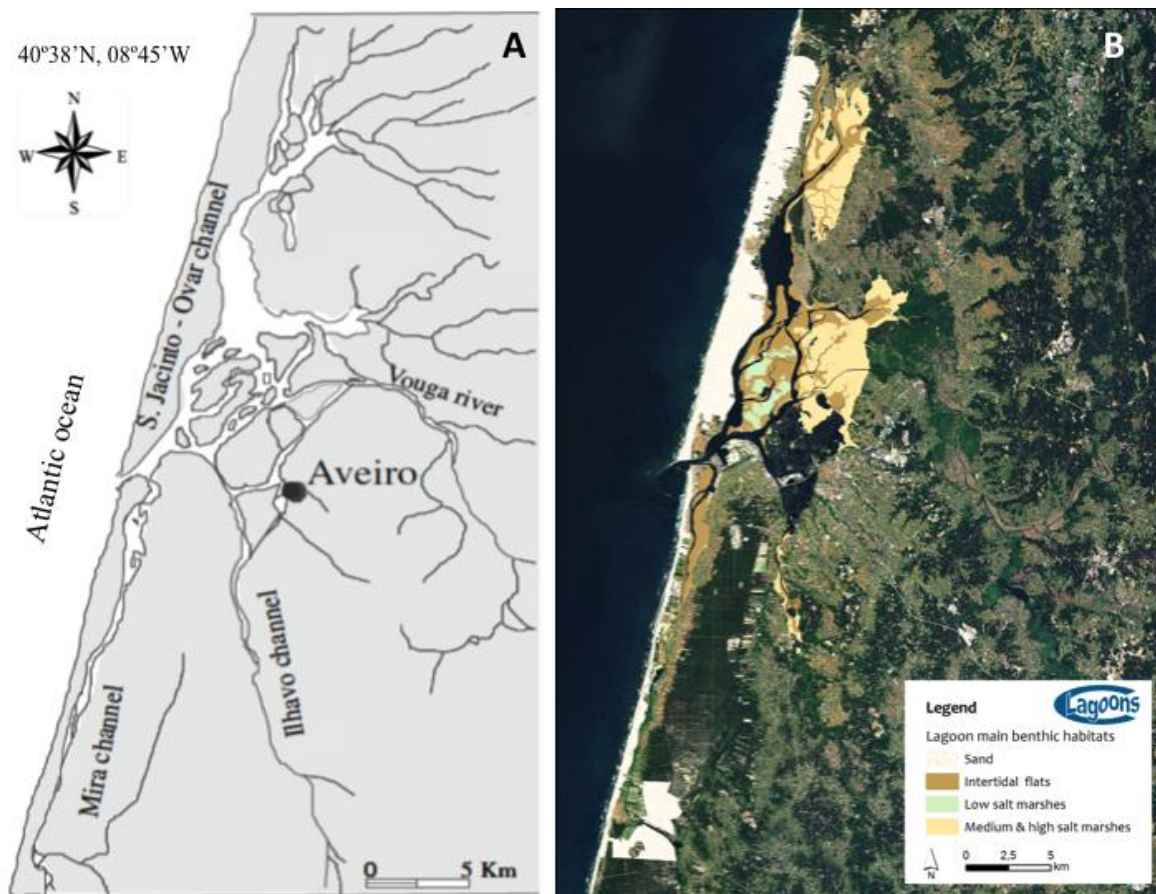


Figure 2. The Ria de Aveiro main channels (A) and the main benthic habitats (B)

4. Methods

4.1 Sampling strategy

In Ria de Aveiro, the bait digging activity is conducted in the mudflats exposed during low tide periods. It is practiced by individual diggers as well as by groups of diggers that collect *casulo* together upon previous order by one or several local bait stores (Cunha et al., 2005; Freitas et al., 2011). These groups of diggers usually depart from various source points (homes, working places, small harbours, anchoring sites) concentrate on known bait digging grounds and return to their starting locations together once the amount ordered is captured.

Given the geomorphological complexity of the Ria de Aveiro and the movement patterns of the bait diggers, it is therefore more efficient to estimate the catch by surveying the digging grounds, than by collecting data at discharge points. Furthermore, given the fact that *casulo* diggers perform their activity using a technique that allows researchers to easily distinguish them from other diggers, surveys were conducted by selecting several strategic points and reaching these points by car or by boat while binoculars were used to better count the number of diggers operating on the mudflats.

Because the Ria de Aveiro lies in a temperate zone, biological production and bait digging change seasonally. Furthermore, many of the shellfish digging activities in the Ria also depend on tides. The tides may allow or obstruct the accessibility to fishing grounds for benthic species; influence the operation of fishing gear; affect the behaviour of the target species. Catch and CPUE of bait digging change seasonally and also depend on tidal range. Average tidal range at the Ria de Aveiro is 2 m, as predicted by the tide tables of the national Hydrographic Institute (Instituto Hidrográfico, 2014). Tides were classified as neap or spring tides when tidal range was $\leq 2\text{m}$ or $>2\text{m}$, respectively. The spring tides expose a larger area and accordingly allow more intensive bait digging in the mudflats.

This study covered a whole year, from October 2012 to October 2013, and survey dates were randomly ascribed to each combination of season and tide amplitude for daytime low tides.

We initially estimate the catch or as better known in fisheries, the “fishing effort” (E) of *casulo* activity. However, for a better suitability of the fishing effort term to our analysis we have renamed it as “digging effort” so as to better represent the relevant activity. Still however the letter E indicates the relevant effort. To estimate E we applied methods based on the progressive counting method of Hoenig et al., 1993).

The progressive counting method (Hoenig et al., 1993) involves having survey agents repeatedly travelling a route encompassing the target area and counting all diggers throughout the day. In this context, we employed survey agents travelling a route around the study area and counting the number of diggers in each sampling mudflat every 45 minutes. We also conducted on-site interviews to estimate catch per unit effort (CPUE), based on the method of Pollock et al. (1997), in which bait diggers were randomly selected and interviewed after the digging session has ended.



Figure 3. Casulo digger searching the sediment for the worm (Photo credits: S. Xenarios)

The two major *casulo* digging areas in the Ria de Aveiro are located in the Canal de Mira, in the south of the lagoon, and in the Canal de Ovar, in the north of the lagoon (Figure 4).

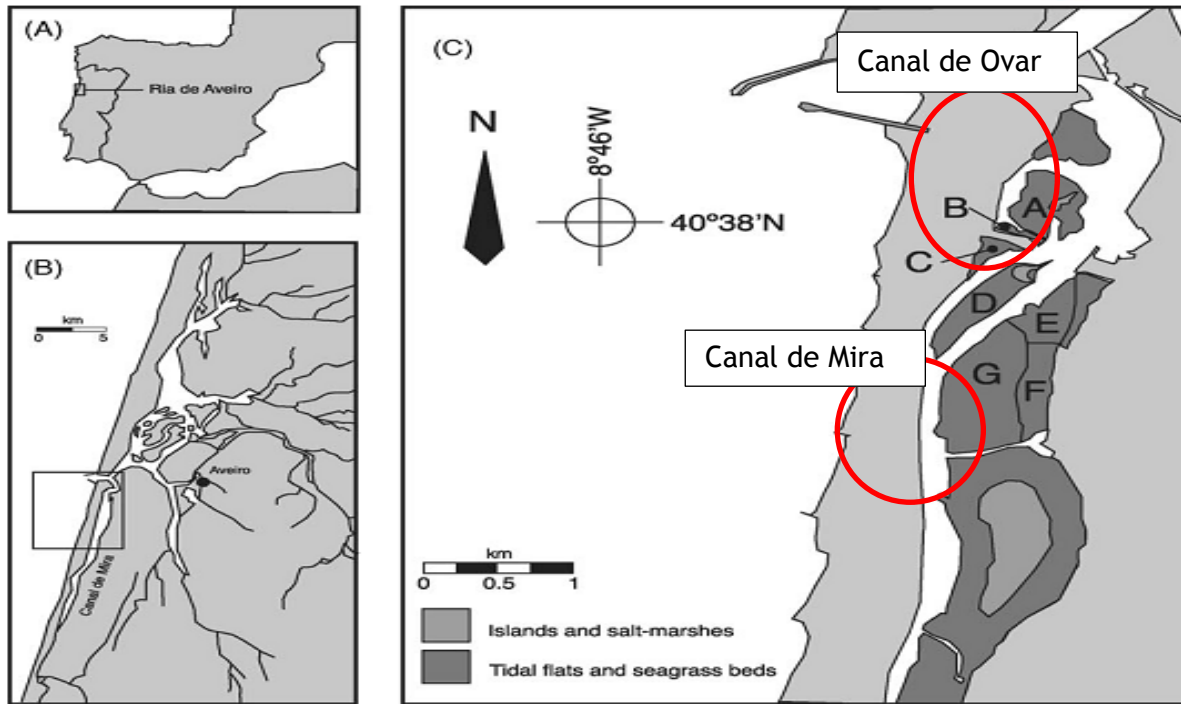


Figure 4. Sampling areas in Ria de Aveiro.

In the Canal de Mira, the surveying agent typically conducted 3 or 4 complete circuits around the area by car, starting immediately before the bait diggers entered the mudflats while these were still inundated. Interviews were conducted as soon as the bait diggers have finished the activity and were about to leave the mudflats. The total catch of the day was recorded, based on counts of the bucket's contents or based on digger's declarations followed by visual inspection of the bucket. In the latter case, all *casulo* diggers use 10 litres buckets which have helped to visually crosscheck the amount of *casulo* stated by the diggers.

In the northern part of the Ria, Canal de Ovar, the *casulo* banks are located on islands that cannot be surveyed from the shore. These mudflats were visited by boat and, because of the length of the trip, only one circuit could be completed in each survey date. Hence, interviews were conducted before the end of the digging session, and the total catch was estimated based on the orders each digger had for the day. In order to minimize counting errors and biases, the same two surveying agents conducted all surveys and made independent counts, which were then cross-checked and agreed. Due to the large geographical area to cover, Canal de Mira and Canal de Ovar were surveyed in different dates. Because of logistic constrains, a much smaller sampling was conducted in Canal de Ovar, which restricted the analysis of *casulo* digging. Therefore, also the tidal trends were not analysed in the Canal de Ovar.

4.2 Statistical analysis

The Effort (E) spent for the catch of the caulo is based on the distribution of diggers (counts) over time, and is algebraically expressed as diggers*min. The catch per unit effort (CPUE) counts the number of polychaetes caught per digger per min, based on the on-site interviews, and is algebraically expressed as $\text{Catch}/(\text{digger} \cdot \text{min})^{-1}$. It is noted that the CPUE is an indicator frequently used in bioeconomic modeling of fishery. As noted by the Food Agricultural Organization (Cochrane and Garcia (Eds), 2009), the CPUE measures “the quantity of fish (casulo in our study) caught (in number or in weight) with one standard unit of fishing (digging in our study) effort. CPUE may be used as a measure of economic efficiency of fishing (casulo in our study) as well as an index of fish abundance”.

We inspected the effects of seasonal (four levels: winter, spring, summer and autumn) and of tidal range (two levels: spring tides and neap tides) on daily catch and on the CPUE of individual diggers. For this, two quantities were analysed separately, using 2-way orthogonal ANOVA. As indicated above, this detailed analysis was only made for the data collected in the South region. Whenever necessary, the data were log-transformed in order to homogenise variances.

Total annual catch of the *casulo* digging in Canal de Mira was estimated according to Cunha et al. (2005). This helped in estimating the average daily catch for each season and tidal range combination as a product of the daily average E by the daily average CPUE. Since the daily catch is estimated as an outcome of these two variables, its distribution is complex. Therefore, we estimated 95% confidence intervals for the catch by using bootstrap techniques. We first generated 1000 pairs of daily values of E and CPUE in each combination of season and tidal range, assuming normal distributions of each variable. We then multiplied the values, in order to obtain bootstrapped estimates of daily catch. Estimates of total catch in each season and tidal combination were then obtained by the multiplication of these values by the number of days in each of those combinations. A distribution of annual values of catch was afterwards conducted by summing the values of the different combinations of season and tidal range. Confidence intervals were obtained by finding the first and last 2.5% percentiles.

For the *casulo* digging in Canal de Ovar, we estimated 95% confidence intervals for the catch by also introducing bootstrap techniques as described above. However, given that the low number of surveys did not allow an analysis of seasonal and tidal trends, the estimates of total catch were obtained for the whole year, by multiplying the bootstrapped estimates of average daily catch by 365 days.

4.3 Economic assessment of *Diopatra neapolitana* and management implications

There are two previous studies on the annual production of the *casulo* digging in the Canal de Mira, Ria de Aveiro (Cunha et al. 2005, Freitas et al. 2011), which indicated a smaller catch in the latter study. However, there is a knowledge gap on the potential effects of *casulo* digging activity to the stock of this species.

To this end, the current study attempted to elaborate an economic assessment on the income generated by *casulo* and the management plans to be introduced under different regulatory frameworks. This study implemented a bioeconomic static model for the bait digging activity conducted in the period of October 2012 - October 2013. The case of open-access bioeconomic equilibrium is initially presented while the Maximum Sustainable Yield (MSY) and Maximum Economic Yield (MEY) scenarios are shown.

4.3.1 Catch and Effort

The principles of bioeconomic model indicate that the natural growth of a fish species (the *casulo* in our case) should follow a steady pattern as presented in Figure 5 below:

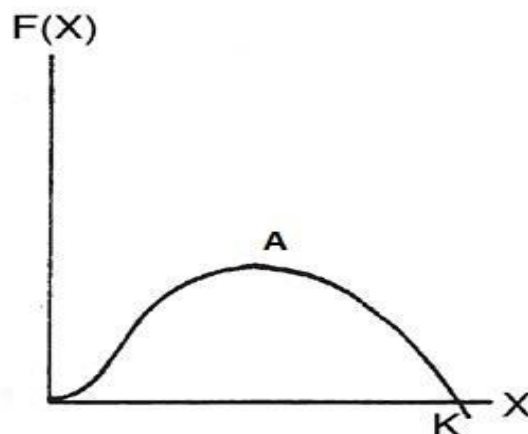


Figure 5. Assumptive Growth Curve of *casulo* species without catch, Source: Flaaten, 2010.

Where, X = *casulo* biomass, K = carrying capacity of the species and F = Growth Function rate.

As shown in Figure 5, an initial logistic population growth $F(X)=r X(1-X/K)$ is observed which initially increases the stock *casulo*. Growth rate culminates at point A. From this point and onwards the growth rate decreases until the point where the population reaches its carrying capacity, K . Then, $X=K$ is the natural equilibrium in the absence of digging.

The situation is altered in the case where a digging activity occurs as presented in Figure 6. In this case, the catch or harvest as we may say (H) seems to go along

with a high function of digging effort (E). Two catching estimates activities are presented for high (X_L) and low (X_H) stock *casulo* levels respectively.

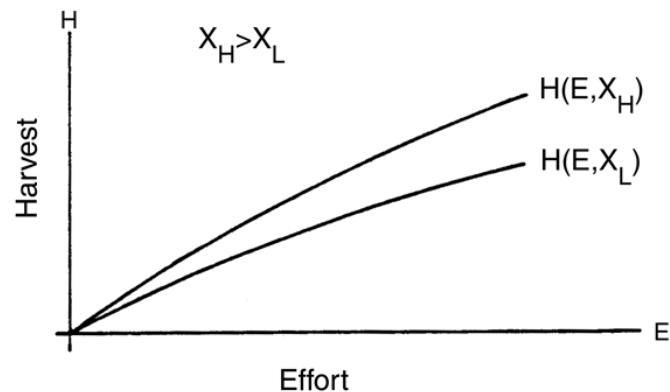


Figure 6. Catch estimates as a function of effort and stock, Source: Flaaten, 2010.

The catch, actually represents a short-run production function of *casulo*. The catch indicates the numbers of *casulo* caught on a daily basis while the effort represents the time spent fishing. As shown, the higher effort indicates a higher *casulo* catch (harvest) which however does not apparently increase in a proportional manner. However, this function represents only the short-run relationship between the catch and effort parameters.

When the bait digging is projected on a long term basis in juxtaposition with the biomass reserves, the following figure 7 is drawn as presented below:

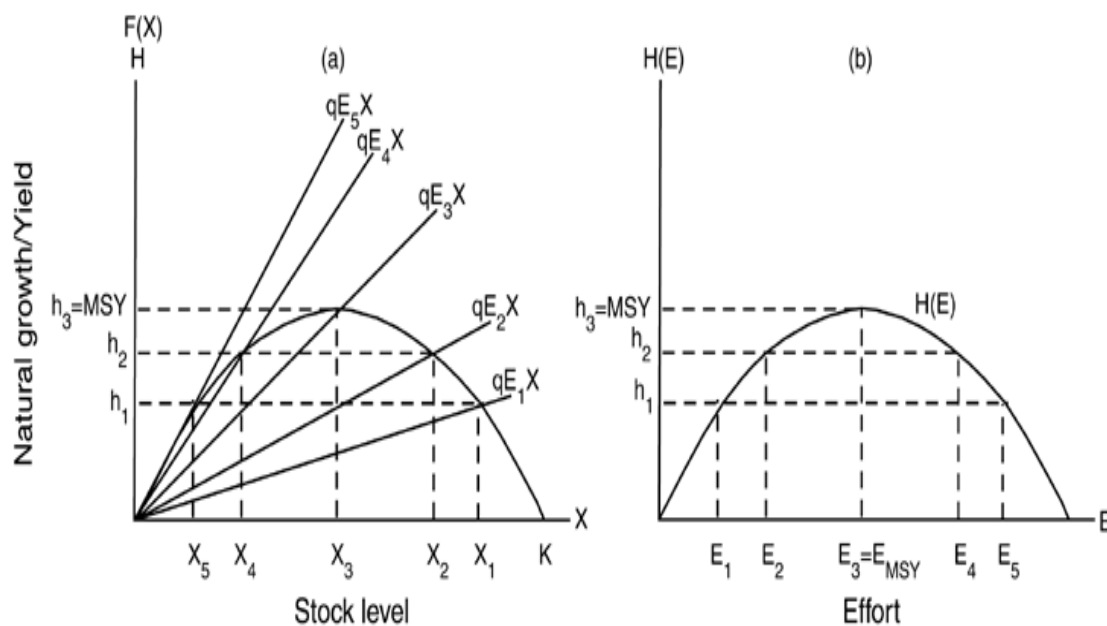


Figure 7. Biomass reserves and bait digging activity, Source: Flaaten, 2010

We may first explain the left part (a) of figure 7 where the relation of digging effort with the stock level is elaborated. In principle, five (5) short-run efforts estimates are presented ($E_{1,2,3,4,5}$, X) as straight lines for five different catch levels. In the case of the smallest effort E_1 the catch curve crosses the growth curve at stock level X_1 and catch h_1 . This means, that a small effort maintains a high stock level at the expense of a relatively small catch.

When we move to E_2 , a bit higher effort is presented which entails a lower stock level but also a bigger catch. If we however move to E_4 effort we notice that although the catch may be equal to E_2 the stock level has been significantly decreased from X_2 to X_4 . A similar situation is presented when the effort E_5 decreases the stock to the point X_1 although a much smaller effort, E_1 , could produce the same catch and sustain the stock level.

The maximum sustainable yield (MSY) is presented with the effort E_3 and the stock level X_3 respectively. The five indicative activities in combination with the suggested stock level may depict a natural-growth stock-level curve. This curve is represented as a sustainable-catch curve in diagram (b) of Figure 7. The sustainable-catch curve shows a long-run equilibrium catch for given levels of effort. In total five different equilibrium points are shown which correspond to different effort and catch levels.

There may be however the case that a digging activity is not identified with the five indicative equilibrium points as shown in (b) diagram of Figure 7. For instance, we may assume that some bait diggers use effort E_1 to catch a virgin stock of *casulo* species. Initially, the catch will be significantly greater than h_1 since the stock level K is bigger than X_1 , and the diggers will continue their activities. This means that the stock will decrease to the point that catch equals the natural growth of the stock as shown in E_1X_1 line in diagram (a) of Figure 7. There, catch equals natural growth, and an equilibrium has been established. Reversely, the bait diggers may exert lower (higher) effort than E_1 level. Then, the catch will be equally lower (higher) and the stock will grow (diminish) until an equilibrium other than X_1 has been reached. It is however quite difficult to identify the time needed for the transition periods between different equilibrium points.

4.3.2 Bioeconomic approach

This Section will present the theoretical background of economic effects of fishing under different management scenarios. The case of open-access, maximum sustainable yield and maximum economic yield scenarios will be shown through diagrammatic and algebraic formulas.

In first, the total revenues and costs associated with the *casulo* catch should be measured. Then, the averages and marginal values of the total costs and revenues should be estimated for the valuation of the economic benefits derived by different management scenarios.

The total revenues derived by the *casulo* catch should be identified with the sustainable-catch curve presented in diagram (b) of Figure 7. Similarly to the sustainable-catch curve, the total revenues are measured against the exerted effort. In algebraic terms, the total revenues are presented as below:

$$TR = p * H(E) \dots \text{Eq.1}$$

Where p is the price and H is the catch dependent on the effort E .

The total cost of a bait digging session could be a function of the fixed and variable costs related to the catch estimates of *casulo*. In the terms of fixed costs, the *casulo* digging does not demand much gearing when conducted from the sea shore except for simple tools (i.e. shovel, bucket). Hence, our analysis is focused on the variable costs requested for the bait digging activity.

The variable costs are mostly concentrated on the opportunity and traveling costs demanded for the *casulo* digging. The opportunity costs are expressed through the time spent by a digger for the entire undertaking. The equivalent of the time spent to digging is valued by the earnings to be potentially acquired if the digger was working as an unskilled labourer in another economic sector. Also, the travelling costs are estimated through the gas expenses required to reach and leave the bait digging areas. The total cost function should be expressed through the following formula:

$$TC(E) = a E \dots \text{Eq.2}$$

Where a is constant unit of effort E .

From the total revenues and cost functions we can provide the relevant average and marginal values respectively. In particular, the average revenue per unit of effort is:

$$AR(E) = TR(E) / E \dots \text{Eq.3}$$

While the marginal revenues per digging effort are:

$$MR(E) = dTR(E) / dE \dots \text{Eq.4}$$

Accordingly, the total and marginal costs functions are presented as below:

$$MC(E) = TC(E) / E \dots \text{Eq.5}$$

and

$$MC(E) = dTC(E) / dE \dots \text{Eq.6}$$

The average and marginal values of revenues and costs determine the different management scenarios as presented in Figure 8 below:

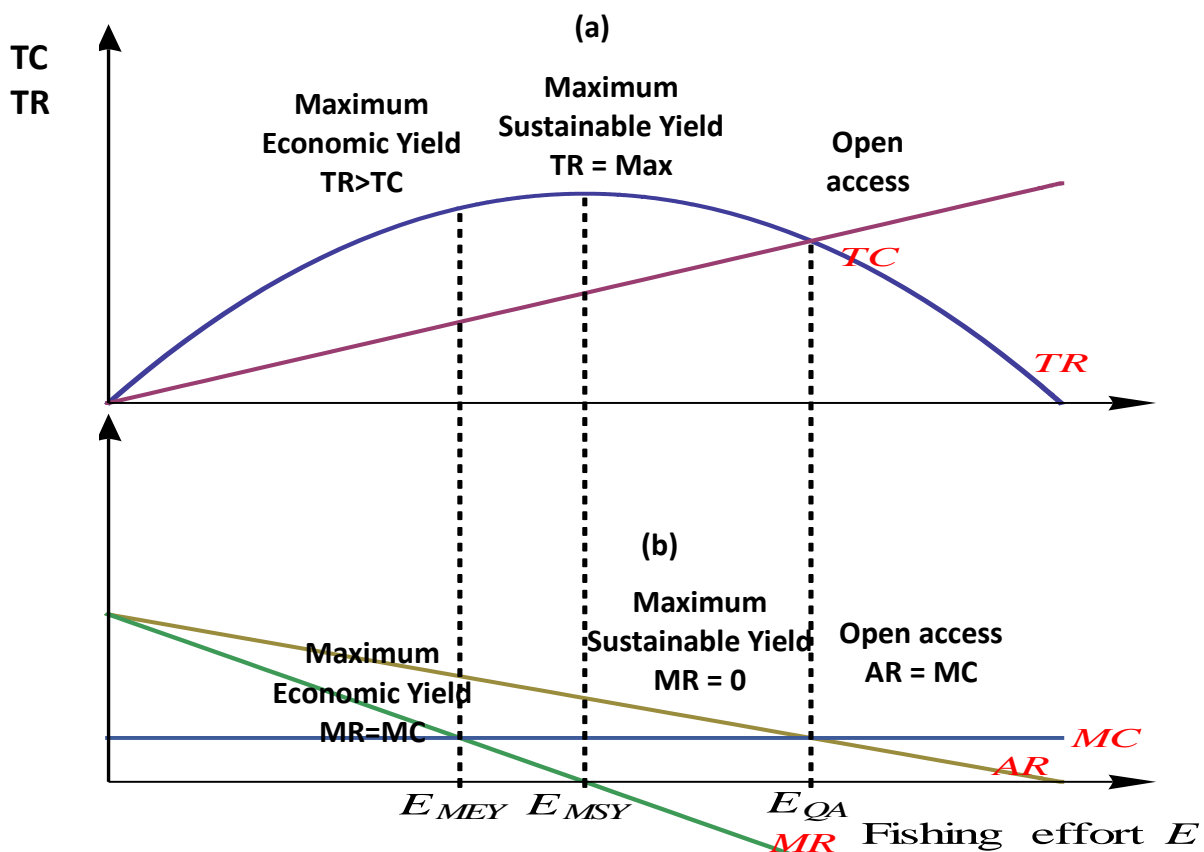


Figure 8. Economic approach under different management scenarios, Source: Flaaten, 2010, modified by S. Xenarios

In particular, part (b) of Figure 8 presents the intersections between the marginal and average costs and revenues. The relevance of these intersections with the total costs and revenues is mirrored in part (a) of Figure 8.

As shown in part (b) of Figure 8, the marginal cost is an almost steady horizontal line. This is because the marginal costs are considered to be homogenous and constant for each digger without presenting any significant variation. In other words, each digger is equipped with the same gearing while he/she spends an equal time for reaching and leaving the digging mudflat. Also, the time spent for the digging activity is almost similar for each digger. The average and marginal revenues follow the same patterns underlined in the production-function theory. In simple terms, the higher the digging effort in term of hours spending, the lower the average and marginal revenues should be.

In part (b) of Figure 8, the total revenues are identified with the sustainable-catch curve presented in part (b) of Figure 7 while the total costs represent the digging activity in terms of effort as shown in different equilibrium points of part (a) in Figure 7.

Initially, we may consider that the *casulo* activity takes place as an open-access digging activity without any particular property rights and regulatory policies. We also assume that the price of *casulo* for the period examined is the same across time and quantity. In this case, the equilibrium point for the open-access case should be defined in the point where the average revenues (AR) equal the marginal costs (MC) or else $AR=MC$. In this point, the TC should be also equalized with the TR as presented in part (a) of Figure 8.

In fact, in an open access scenario, the diggers will join the activity if the average revenues are higher than the marginal costs. They will also stop digging once the cost per unit is getting higher than the average revenues. The intersection between the marginal costs and average revenues signifies an economic equilibrium under an open access management scenario.

The open access equilibrium does not ensure the sustainability of *casulo* reserves as implied in the diagram (a) of Figure 8. We recall that the total revenues are identified with the sustainable-catch curve presented in diagram (b) of Figure 6.

Thus, we will try to identify how the digging will provide a sustainable income by also preserving the population of the species. A sustainable digging of *casulo* population can be achieved at the point where marginal revenues are no longer positive as presented in diagram (b) of Figure 8. The attainment of the zero marginal revenues is also mirrored in part (a) of Figure 8 as the highest point of the total revenues curve. At this point, a maximum sustainable yield (MSY) has been attained which ensures the sustainable digging rate of *casulo* species in the long run. We may recall that the same digging rate is also depicted in diagram (a) of Figure 7 through the catch E_3 and stock level X_3 respectively.

However, the MSY point does not also foster the maximum economic benefits for the *casulo* diggers. As shown in diagram (b) of Figure 7 the marginal revenue line is getting below the marginal costs quite earlier before it reaches the zero point. In other words, the *casulo* diggers have an economic loss for each extra hour they spent for digging after the point that the marginal revenues line has intersected the marginal costs line. Thus, the maximum benefits could be only attained at the intersection point between the marginal costs and revenues as shown in diagram (b) of Figure 8. This point is known as the maximum economic yield (MEY) equilibrium and can ensure the highest benefits for the diggers in relevance to the effort spent for this activity. The attainment of the highest economic benefits can be also noticed in diagram (a) of Figure 8. There, the total revenues appear to surpass the total costs at the highest possible extent by anticipating a sustainable digging in economic and biological terms.

The implementation of the biological and economic approaches to our study will be presented in the following section.

5. Results

5.1 Results on mean, annual catches and CPUE

The mean digging effort (Figure 9) was found to be higher in spring tides in all the four seasons, except for autumn. Winter was the season in which the mean digging effort was higher and spring was the season that presented the lowest values.

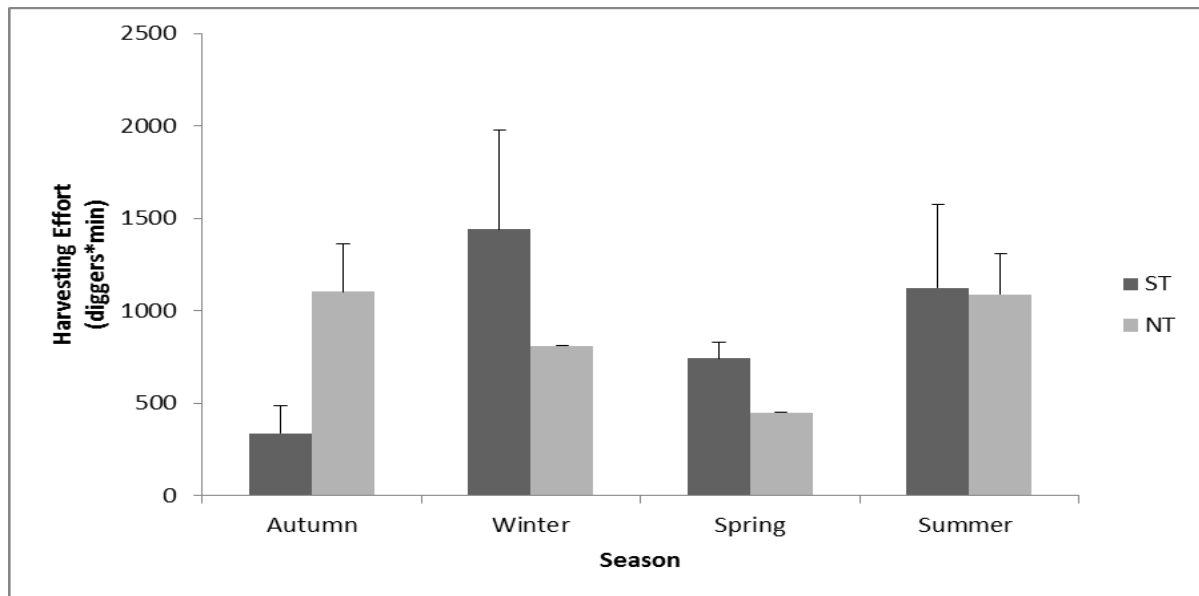


Figure 9. Mean daily values of digging effort for seasonal and tidal ranges

Where ST = spring tide; NT = neap tide.

Significant effects of season, tidal range and their interaction on effort (Table 1) were not detected as presented in Table 1 below:

Table 1. Seasonal and tidal effects to digging effort in Canal de Mira

Source of variation	Sum of Squares	df	Mean Squares	F _s	p
Season	918469	3	306156	1,254	0,325
Tide	9400	1	9400	0,038	0,847
Season x Tide	1430135	3	476712	1,957	0,164
Error	3661807	15	244120		

Note: df= degrees of freedom; Fs= value of the F test; p= probability value.

The CPUE was higher in spring tides, in all four seasons (Figure 10). The season with the highest average value of CPUE was autumn while again in spring the lowest values were found.

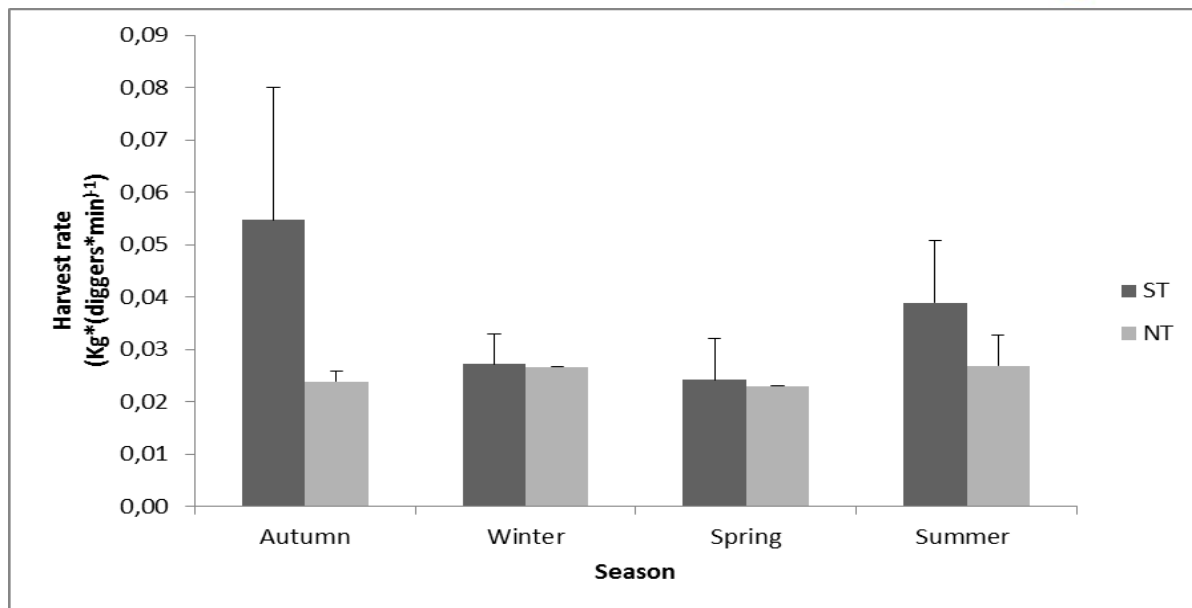


Figure 10. Mean daily values of CPUE for seasonal and tidal ranges

Significant effects of season, tide and their combination on CPUE were not detected (Table 2).

Table 2. Seasonal and tidal effects to CPUE in Canal de Mira

Source of variation	Sum of Squares	df	Mean Squares	F _s	p
Season	0,000	3	0,000	0,522	0,669
Tide	0,000	1	0,000	1,465	0,244
Season x Tide	0,000	3	0,000	0,579	0,637
Error	0,000	15	0,000		

Note: df= degrees of freedom; F_s= value of the F test; p= probability value.

Mean daily catch (Figure 11) was usually higher in spring tides, except in autumn. Summer's daily production was the highest (ranging from 43 to 29 kg d⁻¹, in spring and neap tides, respectively). Daily production in winter (39 to 21 kg d⁻¹, in spring and neap tides, respectively) and autumn (18 to 26 kg d⁻¹, in spring and neap tides, respectively) reached intermediate values. The lower values were recorded in spring and neap tides (17 to 10 kg d⁻¹) respectively.

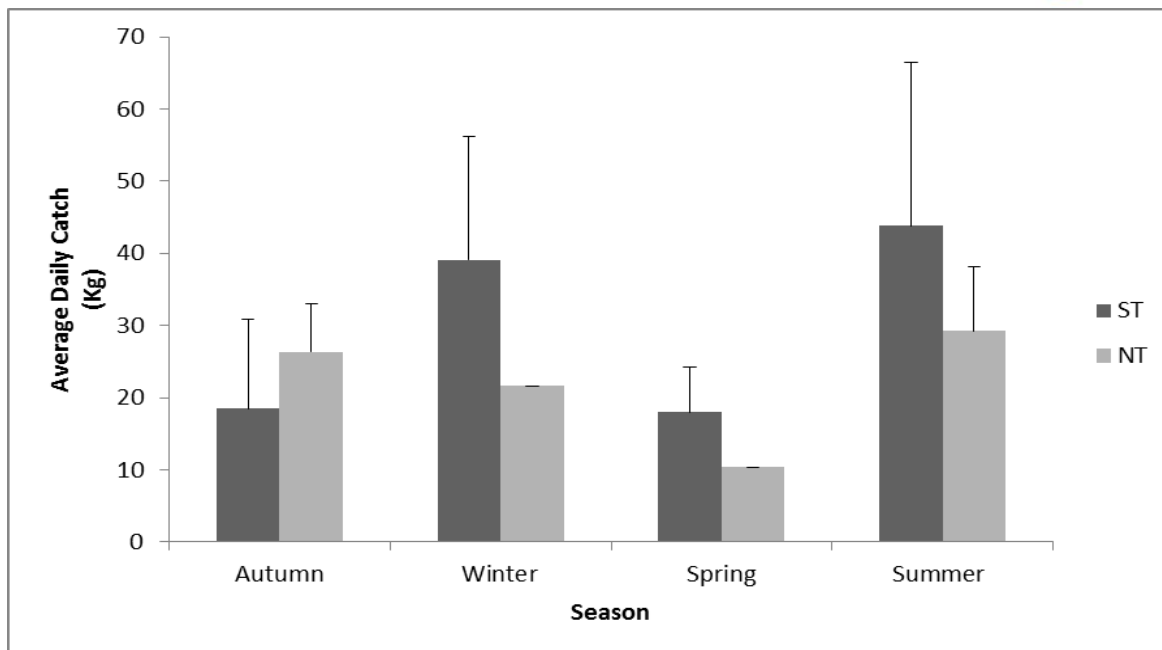


Figure 11. Mean daily values of catch according to season and tidal range for casulo digging

In Canal de Mira, the estimated annual catch was 9,328 kg (with a standard error of 1,417 kg and 95% confidence limits of 4,004 kg and 15,483 kg). In Canal de Ovar, the estimated total annual catch was 36,163 kg (with a standard error of 1,258 kg and 95% confidence limits of -29,432 kg and 135,526 kg). For the entire lagoon, the estimated annual catch of bait digging was 45,401 kg.

5.2 Findings of the bioeconomic modeling

5.2.1 Catch and Effort Implications

The catch and the CPUE data of the survey along the period 2012-2013 shows some trends that may provide some inferences for the digging activity in Ria Aveiro. As presented in Figure 12, the catch is plotted against the digging effort for all diggers along the observation days. A clear trend is presented among the digging activities which foresees that the increase in digging effort in terms of hours will accordingly trigger an increase in the total catch of *casulo*. The findings are in full accordance with the theoretical background presented in Figure 6 which indicates the catching trends of a fishing species in the short run.

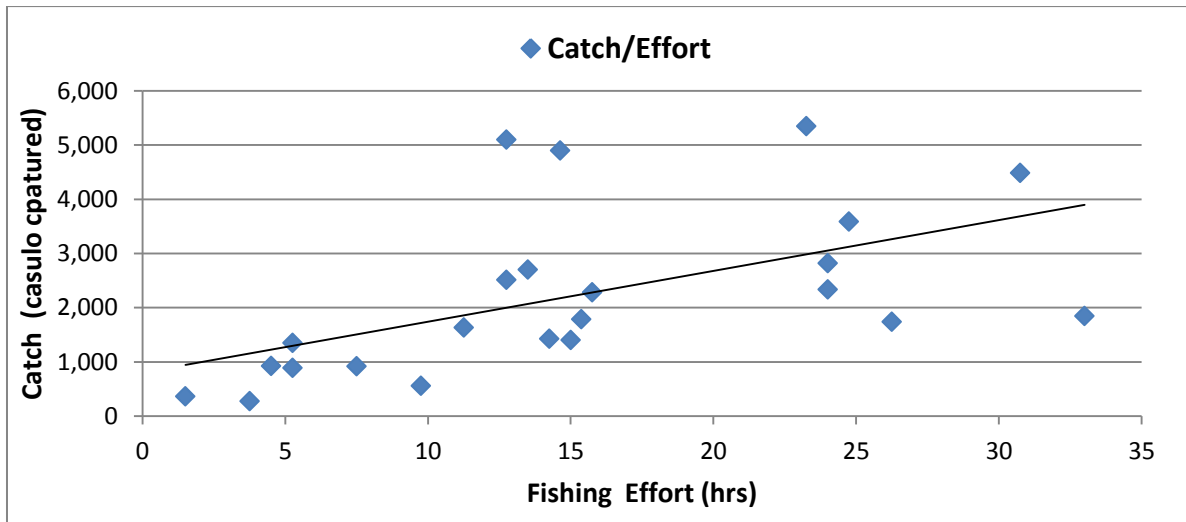


Figure 12. Catch of casulo as a function of effort.

In turn, the CPUE as a function of the digging effort is deployed in Figure 13.

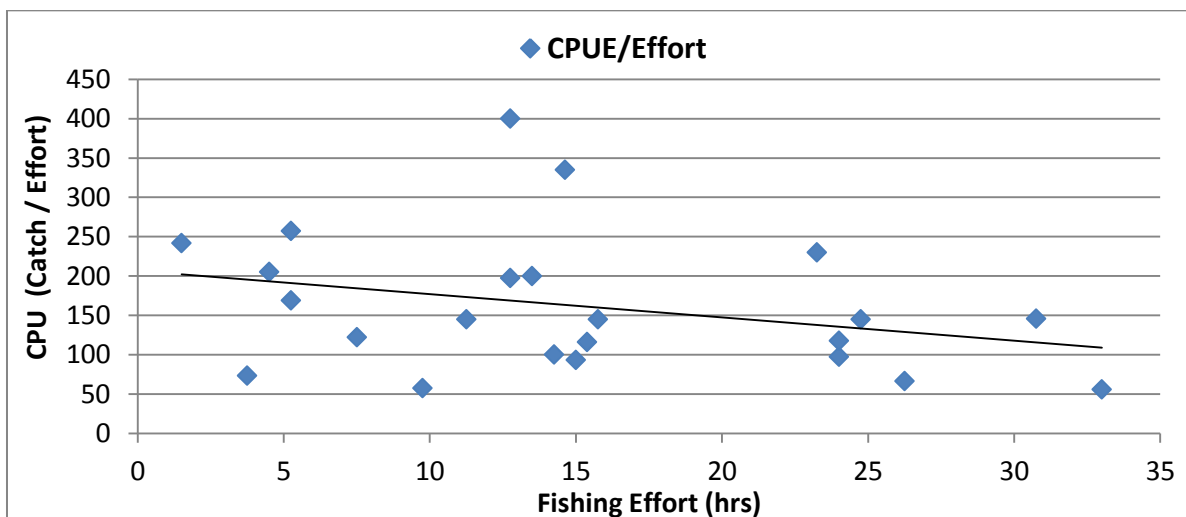


Figure 13. CPUE of casulo as a function of effort.

Figure 13 presents a moderate but distinctive downward slope of the CPUE for the period 2012-2013. This downward slope suggests that the higher digging effort may decrease the CPUE and hence the economic efficiency and stock reserves of *casulo* species.

5.2.2 Open-end, MSY and MEY scenarios

The economic analysis for the open-access scenario identified when the total revenues will intersect the total costs and profits will be then eliminated. As presented in Figure 14, the total revenues surpass the total costs for the digging effort conducted along the surveyed days.

The total revenues are about to intersect total costs in 38.08 hrs/day when all the diggers are counted for each day. The corresponding effort for each digger is

counted on 8.92 hrs/day. The intersection point between the total revenues and costs signals the elimination of profits for the digging activity.

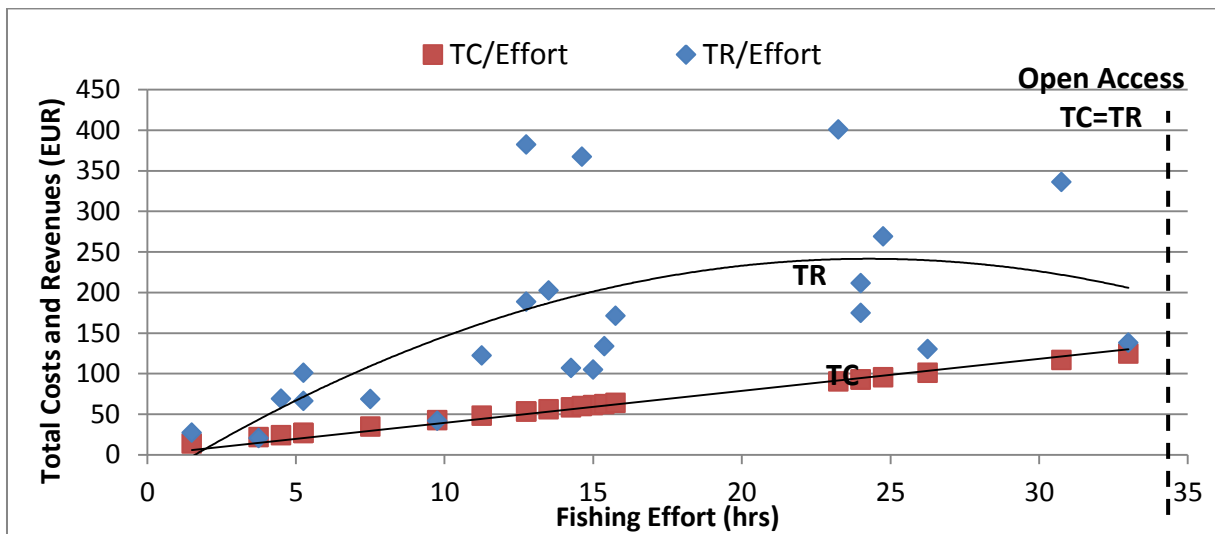
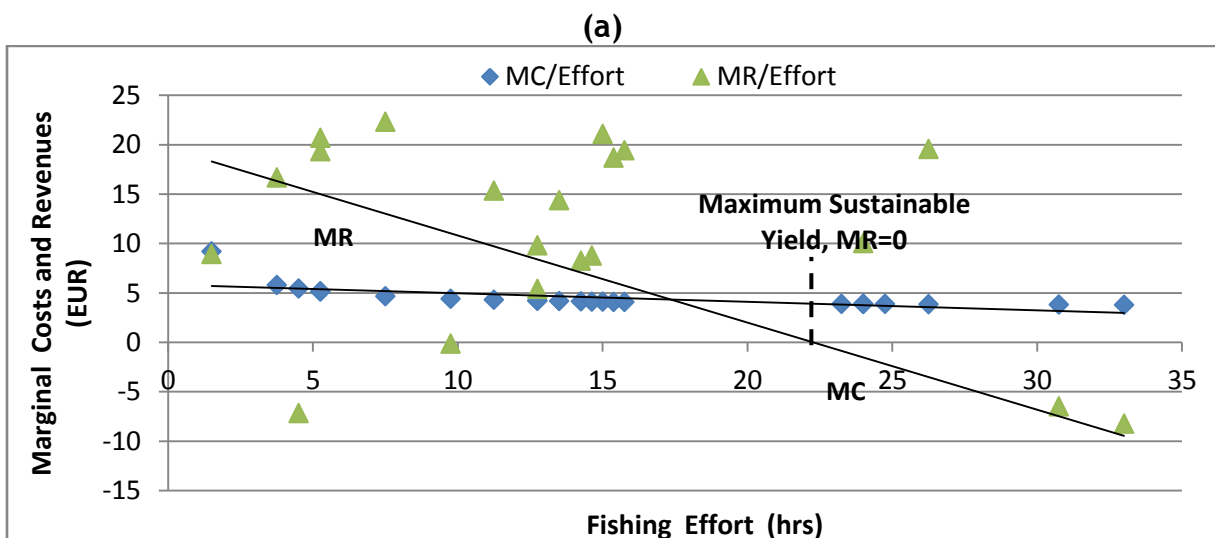


Figure 14. Results of the Open-Access Scenario

In turn, the Maximum Sustainable Yield (MSY) scenario identifies the point where the marginal revenues should be set to zero while at the same instance the total revenues should be maximized. As shown in Figure 15a, the marginal revenues are ceased at the 22.27 hours/day for all diggers or otherwise at 5.22 hours/day per digger.

At this point, as presented in Figure 15b, the total revenues are maximized and appear to largely overcome the total costs. In particular, the total revenues are identified on 239.68 EUR/day for all diggers or 56.16 EUR/day for each digger. Correspondingly, the total costs are mounted at 87.77 EUR/day for all diggers or 20.57 EUR/day for each digger. The difference between the total revenues and costs for each digger reveals a profit of 35.6 EUR/day or else 6.82 EUR/hr.



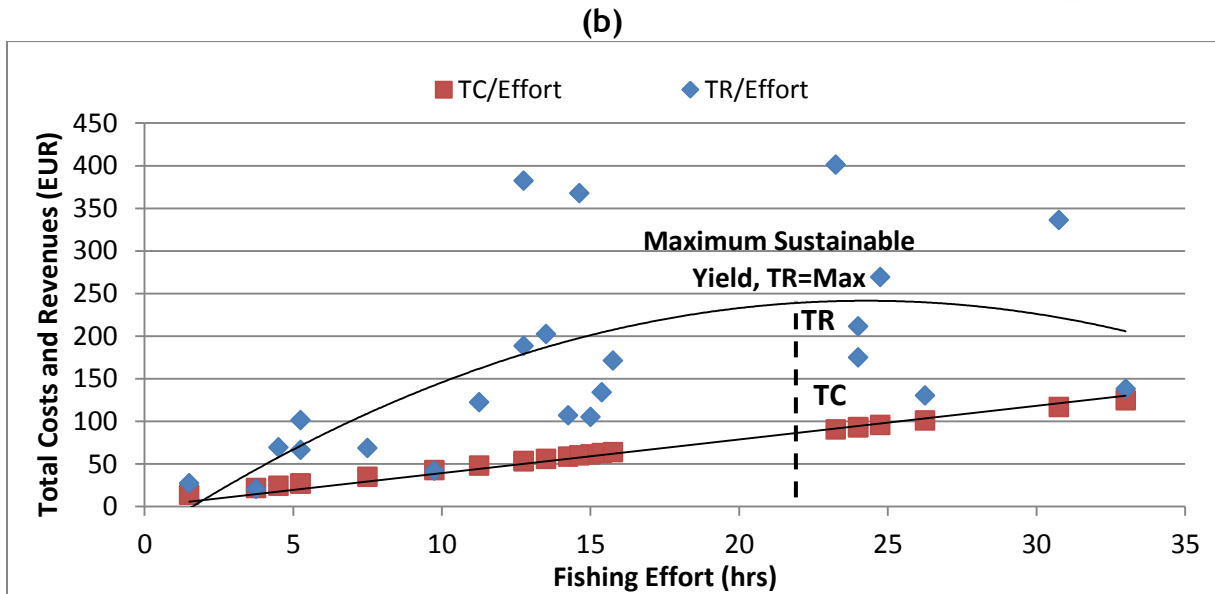
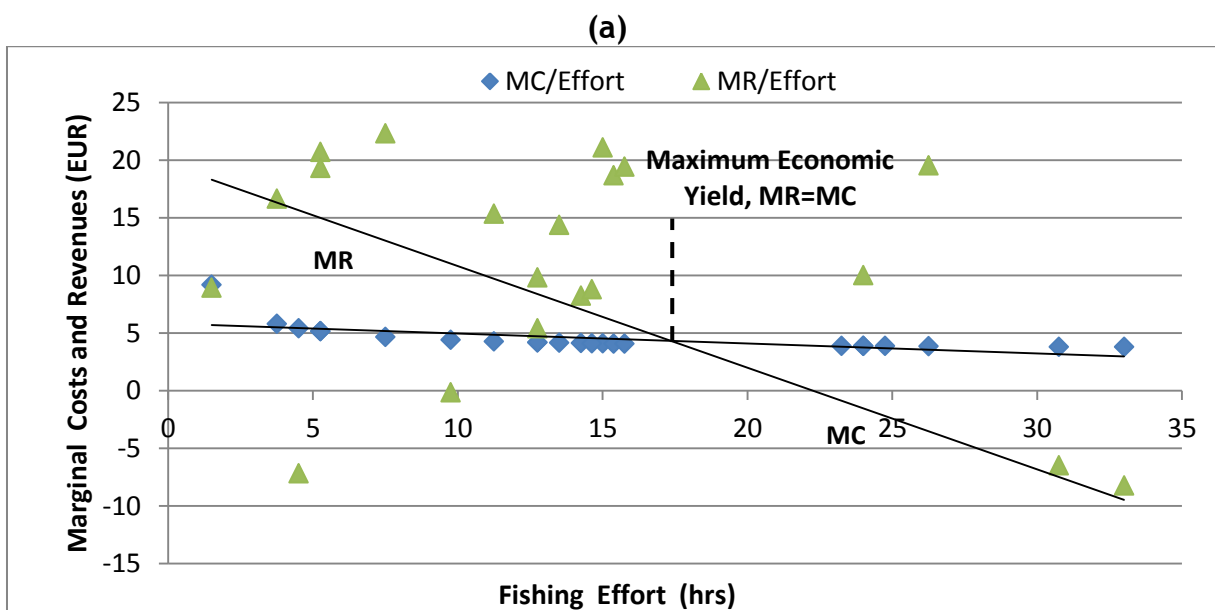


Figure 15. Results of the Maximum Sustainable Yield (MSY) scenario.

Finally, our data analysis has also captured the Maximum Economic Yield (MEY) scenario where the marginal revenues intersect with marginal costs while the total revenues should surpass the total costs with the highest possible difference. As noted in part (a) of Figure 16, the marginal revenues intersect the marginal costs at the 17.24 hrs/day for all diggers or else at 4.07 hours/day per digger. At this point, the total revenues are getting to 219.10 EUR/day for all diggers or 51.34 EUR/day for each digger as presented in part (b) of Figure 16. Correspondingly, the total costs are pointed at 68.43 EUR/day for all diggers or 16.03 EUR/day for each digger. The MEY scenario assumes a profit of 35.3 EUR/day or else 8.68 EUR/hr for each digger.



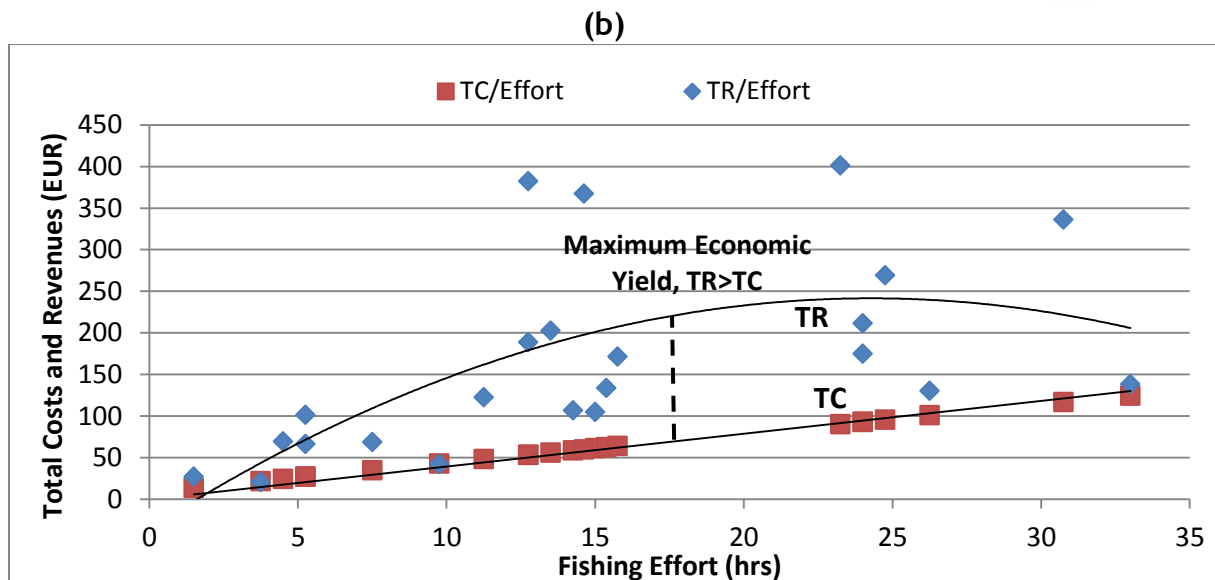


Figure 16. Results of the Maximum Economic Yield (MEY) scenario

6. Discussion and concluding remarks

In Canal de Ovar, even though an analysis on season and tidal range combination was not performed, the estimated annual catch was 36,163 kg. yr⁻¹ (Freitas et al., 2001) suggested that this area could be used by bait diggers as a new digging ground and proves that it is of great importance to conduct this activity. The results obtained for Canal de Mira demonstrate that season, tidal range and their combination have a non-significant effect on digging effort (Figure 9, Table 1) as well as on CPUE (Figure 10, Table 2).

However, higher values of both annual catch and CPUE were found in spring tides, in all seasons except autumn regarding effort. This numerical difference shows that during this higher amplitude tides there are more diggers taking advantage of the exposed area of the mudflats, since they can explore a larger area in one tide. Moreover, along with catch, the CPUE is also bigger in all seasons' spring tides, meaning diggers are catch more in one tide. These results show the influence of tidal range in the success rate of the bait digging activity.

The mean daily catch and CPUE was found to be higher in spring tides, except in autumn which may be due to fact that diggers join the activity for recreational purposes as well. The difference could be also due to seasonal variations of biomass.

In Canal de Mira, the estimated annual catch was 9, 328 kg yr⁻¹. When compared to the annual catch estimates of the previous two studies, the decrease is evident: from over 45,000 kg yr⁻¹ in 2001/2002 (Cunha et al., 2005), to 29,000 kg yr⁻¹ in 2007/2008 (Freitas et al., 2011) and to 9,000 kg yr⁻¹ in 2012/2013. Even though a decrease can be observed, there are some uncertainties regarding the

actual causes. Without the development of further studies regarding biological production, based for example general production models or on dynamic models, it is not possible to assess whether this decrease is due to overexploitation, decrease of digging effort and/or rate or biological and environmental fluctuations.

The national legislation may have also played an important role for the catch of *casulo* given the recent changes (i.e. introduction of a maximum catch per bait digger, simplification of the licensing process). A better understanding of the effects of this legislation in the digging effort and digger's revenues may be necessary in future studies.

The bioeconomic analysis has indicated the maximum amount of digging effort that each bait digger could exert under different management scenarios. Also, the economic benefits derived by each scenario were inferred. As shown in the open-access scenario, each bait digger could expand the digging activity for 8.92 hrs/day and minimize the profits. The sampling survey has captured the daytime activities of each digger which were limited to maximum of four (4) hours per day. In this case, the maximum effort described in the open-access scenario could be hardly attained.

Based on previous surveys there are indications that bait diggers in some instances work in a second tide, during spring and summer when two high amplitude low tides occur during day-light hours (very early morning and early evening), or during low tides during the night, albeit with much less intensity. The digging activity may therefore have been underestimated. It is highly unlikely, however, that this possible underestimation of effort would result into a pooled maximum effort of 8.92 hrs/day. However, no survey has been conducted during the present study to account for a second daily tide, and this should be explored in future studies.

In the case of the maximum sustainable yield (MSY) scenario, it reveals a 5.22 hours/day maximum effort per individual which still seems unattainable given the current tidal constraints. More closer to the current conditions appears to be the maximum economic yield (MEY) scenario of 4.07 hours/day effort which could be practiced by each digger on a daytime basis. Interesting is the case that in the MSY scenario the *casulo* diggers can earn more revenues per day if working the maximum daily effort (5.22 hours) than in the case of the MEY scenario. However, the hourly revenues are distinctively higher (8.68 EUR) in the case of MEY than in the MSY scenario (6.82 EUR). This difference indicates that the diggers may currently earn the highest possible income per day if working only on the daytime where the digging activity cannot exceed the 4 hours due to the tidal constraints.

However, it should be strongly mentioned that the results are based only on the time period 2012-2013 and monthly observations. A more detailed and longer time-series data is necessary to firmly conclude on the aforementioned findings. Also, biological production estimates should be developed, based, for example, on general production or on dynamic models.

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Glossary

(Source: Cochrane, K.L and Garcia S.M (Eds), slightly modified by S. Xenarios)

Bioeconomic model. A set of mathematically expressed functional relationships between biological characteristics of the resource base (e.g. a fishery resource) and the economic (and sometimes social) characteristics of its use by man. As an abstraction from reality, the validity of a bioeconomic model depends on the explicit or implicit assumptions about the biological and human processes it represents (modified from FAO [1998a]).

Biological overfishing (or excess digging in our study). Catching such a high proportion of one or all age classes in a fishery as to reduce yields and drive stock biomass and spawning potential below safe levels. Can involve both growth overfishing and recruitment overfishing. With reference to a surplus production model, biological overfishing occurs when fishing levels (casulo reserves in our study) are higher than those required for extracting the maximum sustainable yield (MSY) of a resource.

Carrying capacity. (1) The maximum population of a species that a specific ecosystem can support indefinitely without deterioration of the character and quality of the resource. It represents the point of balance between reproduction potential and environmental constraints. (2) The level of use which a natural or man-made resource can sustain over a long period of time. For example, the maximum level of recreational use, in terms of numbers of people and types of activity that can be accommodated before the ecological value of the area declines (Scialabba, 1998).

Catch per unit of effort (CPUE). The quantity of fish (casulo in our study) caught (in number or in weight) with one standard unit of fishing (digging in our study) effort; for example number of fish (casulo in our study) taken per 1000 hooks per day or weight of fish, in tons, taken per hour of trawling. CPUE is often considered an index of fish (casulo in our study) biomass (or abundance). Sometimes referred to as catch rate. CPUE may be used as a measure of economic efficiency of fishing as well as an index of fish (casulo in our study) abundance. Also called catch per effort, fishing success, availability (modified from FAO [1998a]).

Equilibrium. A situation which exists after the specified conditions (e.g. fishing pressure, environmental conditions and population parameters such as growth, mortality and recruitment) have been in effect long enough to affect all ages for the whole exploited life and the system, while probably varying in the short-term, will therefore remain essentially unchanged with time. Also referred to as steady state.

Fishing (digging in our study) effort. The amount of fishing gear of a specific type used on the fishing grounds over a given unit of time, for example hours trawled per day, number of hooks set per day or number of hauls of a beach seine per day. When two or more kinds of gear are used, the respective efforts must be adjusted to some standard type before being added (FAO, 1997).

Maximum economic yield (MEY). When relating total revenues from fishing (digging in our study) to total fishing (digging in our study) effort in a surplus production model, the value of the largest positive difference between total revenues and total costs of fishing (including the cost of labour and capital) with all inputs valued at their opportunity costs.

Maximum sustainable yield (MSY). The highest theoretical equilibrium yield that can be continuously taken (on average) from a stock under existing (average) environmental conditions without affecting significantly the reproduction process. Also referred to sometimes as potential yield.

Open access. A condition of a fishery in which anyone who wishes to fish (dig in our study) may do so. The access to the resource is free to all because there is no ownership of the resource. This condition should not be confused with 'common property', a form of communal ownership of the resource and control of the access to it.

Opportunity cost. The benefit foregone by using a scarce resource for one purpose instead of its next best alternative. Typically applied to capital and labour inputs to reflect their real costs to society as against their costs to a private entrepreneur which may be lower or higher because of subsidies, taxes and various kinds of market distortions (Gittinger, 1992). An amount a fisherman (digger in our study) could earn for his time and investment in another business or occupation (Roberts, 1995).

Overfishing (excess digging in our study). A generic term used to refer to the state of a stock subject to a level of fishing effort (digging effort in our study) or fishing mortality such that a reduction of effort would, in the medium term, lead to an increase in the total catch. Often referred to as overexploitation and equated to biological overfishing, it results from a combination of growth overfishing (excess digging in our study) and recruitment overfishing and occurs often together with ecosystem overfishing and economic overfishing.

Property right.

1. A type of resource ownership by an individual, a group (communal rights and Common property) or the state (state property and public property). Property refers to a 'bundle' of rights including (1) access - the right to enter and enjoy non-subtractive benefits; (2) withdrawal - the right to harvest and subtract; (3) management - the right to regulate; (4) exclusion - the right to defend the property and (5) alienation - the right to transfer, lease, sell all or part of this bundle of rights. Some of these rights may be further subdivided. The granting or acquisition of all five main rights characterizes full property or ownership (Ostrom, 2000).

2. In Roman Law, property rights compound the right to use a tangible or intangible asset (*usus*), the right to harvest and appropriate the returns from the asset (*fructus*) and the right to give, sell and destroy the asset or its returns (*abusus*). The last of these is the foundation of complete ownership. Since these rights are opposable to anyone, they are absolute property rights. Any one or more of the first three rights (access, management and exclusion or *usus*, *fructus* and *abusus*) may be transferred. The concept of usufruct (*usufructus*) defined as the right of using the returns of someone else's asset is also potentially useful in fisheries. Full ownership will only be transferred if all four absolute rights are transferred together (Kerrest, 2002).

Scenario. A plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about key driving forces (e.g. rate of technology change, prices) and relationships. Scenarios are neither predictions nor projections and sometimes may be based on a 'narrative storyline.' Scenarios may be derived from projections but are often based on additional information from other sources (Alcamo et al., 2003).

Stock. (1) The part of a fish (*casulo* in our study) population which is under consideration from the point of view of actual or potential utilization (Ricker, 1975). (2) A group of individuals in a species occupying a well-defined spatial range independent of and more or less genetically isolated from other stocks of the same species. Random dispersal and directed migrations due to seasonal or reproductive activity can occur. Such a group can be regarded as an entity for management or assessment purposes. Some species form a single stock (e.g. southern bluefin tuna) while others are composed of several stocks (e.g. albacore tuna in the Pacific Ocean comprises separate Northern and Southern stocks). The impact of fishing on a species cannot be reliably determined without knowledge of this stock structure.

Sustainability. Ability to persist in the long term. Often used as a 'short hand' for sustainable development. Characteristic of resources that are managed so that the natural capital stock is non-declining through time, while production opportunities are maintained for the future (Sutinen, 2000).