MSE and dynamic state variable model with sigma function

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Abstract

TBD The EU common fisheries policy is designed for the long-term environmental, economic, and social sustainability of fishing and aquaculture activities. the reform includes making use of the MSY reference points as targets for exploiting commercially important fish stocks. To incentivise individual business to improve selectivity and avoid unwanted catches, the CFP also introduced a landing obligation. and may not necessarily reduce harvest rates but will change the underlying selectivity patterns of harvests. Such behaviors Explicitly modelling Using a state-dependent decision-making model combined We contrast three types of management plans to achieve maximum sustainable yields (MSY) from multiple stocks and compare their effectiveness based on a management strategy evaluation (MSE) that uses a dynamic state variable model including errors in decision-making in its operating model.

Keywords: management stategy evaluation; dynamics state variable model; errors in decision-making; landing obligation; maximum sustainable yield

1 Introduction

Management strategy evaluation (MSE; [7, 20, 21]) seeks to study the implications of management strategies using simulation[18]. Such simulation should include all important processes of a fishery, which is inherently a socio-ecological system, with coupled dynamics of the fishing fleets, the exploited stocks, and their governance[18, 19]. Given the complexity of such a socio-ecological system the uncertainy about the dynamics and feedbacks are consideable. As a result, any forecasted success in achieving goals in a management strategy may thus be inperceivably small compared to the stochasticity in results generated in the system, or worse, be counteracted by unintended consequences of the management strategy. The robustness of management strategies to the uncertainy in the processes that govern fisheries systems thus need to be accounted for [3, 14, 16, 18].

The adaptive response of fishers to their environment is one of the key uncertainties requiring attention in MSE [11]. Simulation tools for such adaptive responses are available in fisheries, borrowing methodology from the more general question of state-dependent foraging decisions in ecological systems [8, 13]. New tools for state-dependent behaviour of individual fishing vessels, translated into behaviour of the fleet and implemented using stochastic dynamic programming [2, 4, 9, 15, 12] have been developed. These models generally predict the effect in the short term (within a fishing trip, or a quota year) by optimizing a utility function and determine which choices best yields the best chance of increasing utility, while keeping track of the state of each individual. The effect of a choice on the utility depends on the economic environment, such as the home port of the vessel and the distance to fishing grounds, and the biological enviroment, such as the spatial distribution of the resources. Using such dynamic variable state models, effects of e.g. relocation costs of marine protected areas have been modelled [9].

Dynamic state variables have also been used to describe discarding behaviour [4, 5, 12]. These studies may shed light on the potential outcomes of the European fisheries management reform of 2013. That reform included using the use of the maximum sustainable yield (MSY) reference points as targets for exploiting commericially important fish stocks and the gradual introduction of a landings obligation (LO) [10]. Indeed, using spatial and temporal distributions of catch rates within a single year, dynamic state variable models forecasted high costs in mixed fisheries in the short term as a result of the LO. These costs result from removing the option to adapt landings to quota by discarding parts of the catch [2]. This will result in fishing effort reallocation and early closures of fisheries once quota have been reached. However, the long term benefits to fisheries that could result from improved selectivity are ignored in those studies. Ignoring the potential for improved selectivity leaves out a key element in the perceived benefit of the LO. Because the LO should provide incentives for the use of more selective gears and for fisheries to move away from areas with high levels of unwanted catch [1, 2], the improved selectivity should lead to higher long term catches. Achieving single species MSY while landing all commercial catches in fisheries targeting multiple species (mixed fisheries) is challenging because achieving the objective for one species may mean missing the objective for another [5, 22]. Forecasting whether such management will be effective depends on understanding the response of individual effort allocation to the management.

To enable longer term prediction of the effects of changes in fisheries management, and thus complete the MSE, one needs to couple the fleet dynamic models that forecast the fleet response to management to biological dynamic models that forecast the fish population responses to the changing fleet response. We present an MSE that encompasses the individual harvester decision-making process and socioeconomic drivers on management effectiveness, i.e. if the fleet dynamic model results in a short term movement of vessels to allocate effort both spatially and temporally, we also expect longer term changes to occur in fish populations and the economy of the fishery [2]. Such combination needs to be responsive to all the drivers that influence and motivate the actual fleet and to respect existing constraints [23]. The drivers will include the (real or perceived) local abundance and catchability of the fished stocks and various resource costs, principally that of fuel. The constraints will include the obvious management-imposed constraints such as levels of total allowable catch, and economical constraints such as the contribution of the annual fines for exceeding catch quotas.

Using a MSE, the main objective of this work is not to reproduce the entire complexity of a real mixed fishery, but to defined plausible hypothesis about population dynamics and then to implemented the processes of interest, i.e., changes in population abundance, to finally measure the effect of the potential consequences associated with the fishers optimal choice location underlying assumption of the current state-dependent behaviour of individual fishing vessels. To understand the fleet dynamics in a spatially and temporally heterogeneous mixed quota-regulated fishery when reducing from unmanaged (unconstrained catch quota) to MSY managed and to compare it with a situation where discards are allowed in order to assess on the biological and economic consequences. If LO and catch quotas are not fully enforced, there will be an incentive to continue discarding. Therefore, this manuscript tends to understand the likely adaptive change in fishing patterns that will help us to understand if this leads to a better balance between quotas and catches.

2 Methods

The managament strategy evaluation framework was used to forecast the dynamics of a hypothetical mixed fishery on two species. The framework consists of an operating model (OM) and a management procedure (MP). In the fishery, there are three essential elements: (i) a collection of size strucured fish stocks, whose dynamics are governed by annual reproduction, growth, migration, and mortality; (ii) a management body that evaluates the fishing pressure and aims to set annual quotas in accordance with fishing mortalities dictated by Hmax reference points; and (iii) a fleet of individual fishers who aim to make the best use of their annual quota. Within this mixed fishery, individual vessels make adaptive choices about fishing location and discarding that depend on the distribution of the resources, and the quota that hold. Each of these elements is discussed in more detail below. The essential elements of the framework are summarized in Figure 1.

The operating model captured the key processes in the dynamics of the fish populations, the fisheries and the management body, and can be thought of as a minimum realistic model [17]. The OM thus includes individual harvester decision-making (including error) and the consequent biomass of fish stocks, including the essential elements for calculating the individual harvester economic performance. The management body used the MP to make its decision on how to respond to the state of the resource (Fig.2). This management procedure thus includes the data collection from the fishery, how these are interpreted, and the harvest control rule (HCR) that dictates the limits that are set to the fishery.

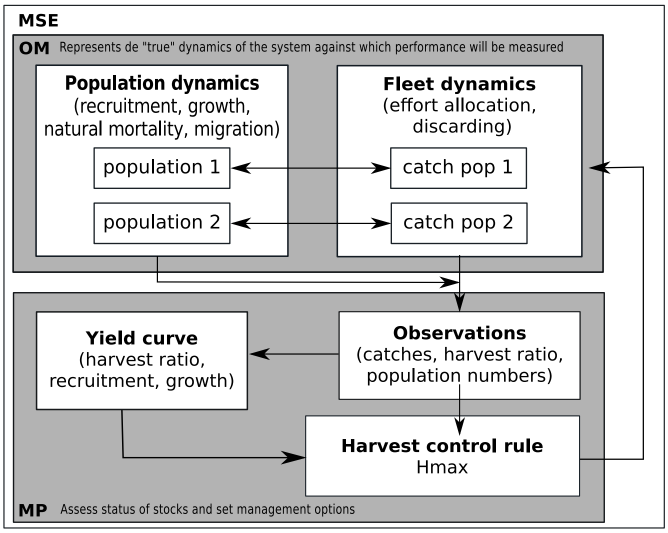

Figure 1: Conceptual overview of the MSE approach, including the OM and the MP components of the framework.

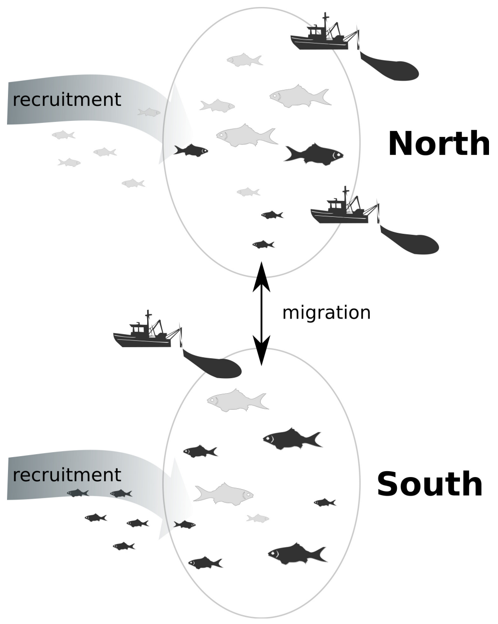

Figure 2: The OM component, including the key processes in the dynamics of the fish populations.

2.1 Population dynamics

To allow the fishery to make spatial and temporal choices, the model needed to be seasonally and spatially explicit. The dynamics of the fish stocks were modelled using an age-structured model that was spatially explicit, with seasonal time steps. In each seasonal time step, fish grow, migrate, and die. The number of fish of stock i of age a at year y, in season s, and area p was written as $N_i(a, y, s, p)$. The ages in the model range between age 0 and age A, the maximum age in the model. The seasons range between season 1 and season S, the last season within each year. Individuals were born at age 0, at the start of each year y, in season 1. The number of new-born individuals $R_i(p)$ in the model was a function of the area p and independent of the size of the adult population. The population numbers at age 0 are thus

$$N_i(0, y, 1, p) = R_i(p). \qquad \text{(Eq. 2.1.1)}$$

Mortality in the model resulted from fishery catches and natural causes such as predation, diseases, and scenesens. The decrease in population numbers was thus the result of the catches ($C_i(a, y, s, p)$) and a natural mortality constant M_i that described natural mortality as a fixed fraction of the population. These mortalities reduced the population numbers among a cohort of fish. Because the model was seasonally structured, the population numbers for seasons 2 to S were dependent on the previous season,

$$N_i(a, y, s+1, p) = N_i(a, y, s, p) - C_i(a, y, s, p) - M_i N_i(a, y, s, p). \qquad \text{(Eq. 2.1.2)}$$

Likewise, the population numbers in season 1 depended on the numbers in season S of the previous year,

$$N_i(a+1, y, 1, p) = N_i(a, y, S, p) - C_i(a, y, S, p) - M_i N_i(a, y, s, p). \qquad \text{(Eq. 2.1.3)}$$

Migration for each species was defined by an array $D_i(a, s, em, im)$ that defined immigration and emigration on a given stock relative to the stock sizes. The size of that array was defined by the number of age classes, seasons and number of areas. emigrants leave area em and move to area im. The emigrated part of the population is then substracted from each of the areas, so that that population numbers per year and season remain unaffected by migration.

Individual body growth was modelled by a von Bertalanffy growth equation to convert numbers to lengths, and an allometric equation to convert length to weight. The weights for individuals in the stock and in the catches are thus calculated as

$$w_i(a, s) = \alpha * (L_{\infty_i} * (1 - \exp^{(-K*(a+(s/S)))}))^{\beta}. \qquad \text{(Eq. 2.1.4)}$$

The realized catches are the sum of all individual catches resulting from the Dynamic State Variable Model. The Dynamic State Variable model inputs consist of the expected individual catch rates, which are random variables. These random variables were normally distributed, with means $\hat{c}_i(a, y, s, p)$ being a function of population size, age dependent catchability $q_i(a)$ in any year, season, and area,

$$\hat{c}_i(a, y, s, p) = N_i(a, y, s, p) * q_i(a) * w_i(a, s). \qquad \text{(Eq. 2.1.5)}$$

The standard deviations $\Sigma_i(a, y, s, p)$ of the catch distributions were constant fraction their means, using a ratio η.

2.2 Fleet dynamics

To simulate a fleet of individual fishing vessels,we used a Dynamic State Variable Model [2, 4, 8, 9, 13, 15]. The model was used to model location choice, same model structure as in [2], but without the choice to discard one or more species and size classes while fishing. Each individual vessels had a set of choices, which include the choice to go fishing in a season, location choice within that season. The model had annual fines for exceeding landings quota as in [2]. In order to calculate state dependent choices during the year, we started by defining the annual fines for exceeding landings quotas at the end of the year:

$$\Phi(C_i, Q_i, F_i) = -\sum_i (\max(0, (C_i - Q_i)) * F_i), \qquad \text{(Eq. 2.2.1)}$$

where C_i was the cumulative annual catches for species i for an individual vessel. These cumulative catches defined the state of the individual. Q_i was the annual individual quota for catches for the different species. Individual quotas were not transferable. F_i was the fine per unit weight for exceeding individual catches quota.

The maximum expected utility between current season s and the end of the year was $V(C_i, Q_i, F_i, s)$, and the model started by setting $V(C_i, Q_i, F_i, S) = \Phi(C_i, Q_i, F_i)$. For preceding seasons, the expected utility depended on individual choices, and each time step individuals chose to visit fishing area p, or to stay in port. While fishing, any combination of the age classes caught of the quota species had to be landed. The expected utility for each state and each time step s was calculated backward using stochastic dynamic programming [8]:

$$V(C_i, Q_i, F_i, s) = max_p(R(p, s) - G(p) - C(p) + E_p[V(C_i', Q_i, F_i, s + 1)]), \qquad \text{(Eq. 2.2.2)}$$

where $R(p, s)$ was the expected immediate contribution of the gross revenue from the sales of fish in a season resulting from choices p (gross revenues resulted from multiplying catches different age classes of species 1, species 2 and prices). Prices of fish were assumed to be dependent over fish age (subsection size dependent pricing). $G(p)$ represented the incurred fuel costs per season from the choice of fishing area p, while $C(p)$ represented the variable operating costs (crew share, gear maintenance and landing costs, Table 1), which in turn depended on the change in cumulative catches and fish prices. The term $E_p[V(C_i', Q_i, F_i, s+1]$ denoted the expected future utility taken over all possible states resulting from choices p. The transition of these states were based on normal distributions of catch rates, using the means and variances for the species, as explained in the model conditioning section, following [15].

Rather than assuming that each individual always made the optimal choice, we assigned a probability to each choice proportional to its expected utility, following [9]. The expected utility for any choice was

$$U(C_i, Q_i, F_i, s) = R(p, s) - G(p) - C(p) + E_p[V(C_i', Q_i, F_i, s+1)]. \qquad \text{(Eq. 2.2.3)}$$

If U^* was the expected utility at the optimal choice for a given t, we set

$$\Delta_p(C_i, Q_i, F_i, s) = U^*(C_i, Q_i, F_i, s) - U(C_i, Q_i, F_i, s), \qquad \text{(Eq. 2.2.4)}$$

and then defined the probability of a choice for a given area and discarding as

$$P_p(C_i, Q_i, F_i, s) = \frac{e^{-\Delta_p(C_i,Q_i,F_i,s)/\sigma}}{\sum_p e^{-\Delta_p(C_i,Q_i,F_i,s)/\sigma}}, \qquad \text{(Eq. 2.2.5)}$$

where σ was a tuning parameter that measured how important it was to be near the optimal choice. A large σ resulted in uniform probabilities of choices, with vessels being distributed uniformly across the different fishing areas. In contrast, a small σ forces vessels to concentrate in the optimal location (but note that σ should be > 0). For computations, we used $\sigma = 5000$.

The dynamic state variable model was solved by iterating backwards in time, while finding the probability distribution choice in terms of location for all possible states, combining the net revenue obtained from the sale of fish and costs of a fishing trip and the effect of the annual fines when exceeding annual quota. Further details for this procedure can be found in [2, 6] and [9].

Once the backward calculations were finished, the forward part is a Monte Carlo simulation where the probabilities of choices were sampled randomly using the probabilities in Eq. 2.2.5. For each year, these forward Monte Carlo simulations determine the fishing effort in each season and area $E(y, s, p)$, and the catches $C_i(a, y, s, p)$ for each age in each season and area. The effort allocation component of the operating model provides the link between the management decisions and the biological component of the operating model.

Table 1: Model parameters.

Population dynamics		
new-born individuals	$R_i(p)$	500
maximum age	A	6
number of areas	p	2
number of seasons	S	12
natural mortality	M_i	0.0001
Asymptotic length	L_{∞_i}	50
Growth rate	K_i	0.6
Length-weight conversion factor	α_i	0.0002
Length-weight isomorphy factor	β_i	3
Migration	D_i	2.5%
Fleet dynamics		
Number of vessels		8000
Fuel costs (Euro fishing season^{-1})		1200
Gear maintenance (Euro fishing season^{-1})		0
Crew share		0%
Landing costs (Euro t^{-1})		0
Optimal choice error	σ	3000
Fishery		
Intial quota (tonnes)		200
catchability	$q_i(a)$	0.000025
effort (p,s)		1
Price of species at mean weight (Euro tn^{-1})	$\bar{p}_i$	30
Slope of species price	γ_i	15
Fine for overshooting quota (Euro tn^{-1})	F_i	3e3
Ratio of standard deviations to catch means	η	0.08

2.2.1 Size dependent pricing

Prices of fish were assumed to be fixed over time but influenced by the body weight of the individuals in the catch, as is commonly observed [24, 25]. Following [24], therelationship between fish price and body weight was modelled as:

$$p_i(a,s) = \bar{p}_i + \gamma_i \times \frac{w_i(a,s) - \bar{w}_i}{\bar{w}_i}, \qquad \text{(Eq. 2.2.6)}$$

where $p_i(a, s)$ is the price of species i at age a and season s. The price was a linear function of the weight of individuals of species i at age a and season s. $\bar{p}_i$ is the price of the species at the mean weight over the age range. The mean weight over the age range is $\bar{w}_i$. γ_i gave the price increase when individual mass was increased by $\bar{w}_i$.

2.3 Case study parameterization

To mimic spatially heterogeneous fish populations in a mixed fishery where fishers make sequential choices on fishing areas, the model was divided into a 'north' and 'south' area, and twelve fishing seasons per year (Table 1). There were two fish species in the model, both of which are caught by the fishery. The annual number of newborns was equal for the two species, and arbitrarily set to 500 per year. The species differed with respect to their nursery grounds: all individuals of species 1 were born in the northern area, while all individuals of species 2 were born in the southern area (Fig. 3). The maximum age that any individual can reach was 6 years old. During their life, individuals grew in length towards the asymptotic length, which was 50 cm for both species (Fig. 4). Conversion from length to weight was also equal for the two species (Table 1). Migration was parameterized so that a gradual diffusion occurred between the two areas, equal to 2.5 percent of the difference in abundance. For the unfished situation this led to a clear segregation of the younger ages over the two areas, while the older ages were equally distributed over the two areas (Fig. 3). Mortality from natural causes such as predation, diseases, and senescence was assumed to be negligible, and M_i set to 0.0001. Although such absence of natural mortality impossible in reality, one could argue that the model thus mimicked long-lived species.

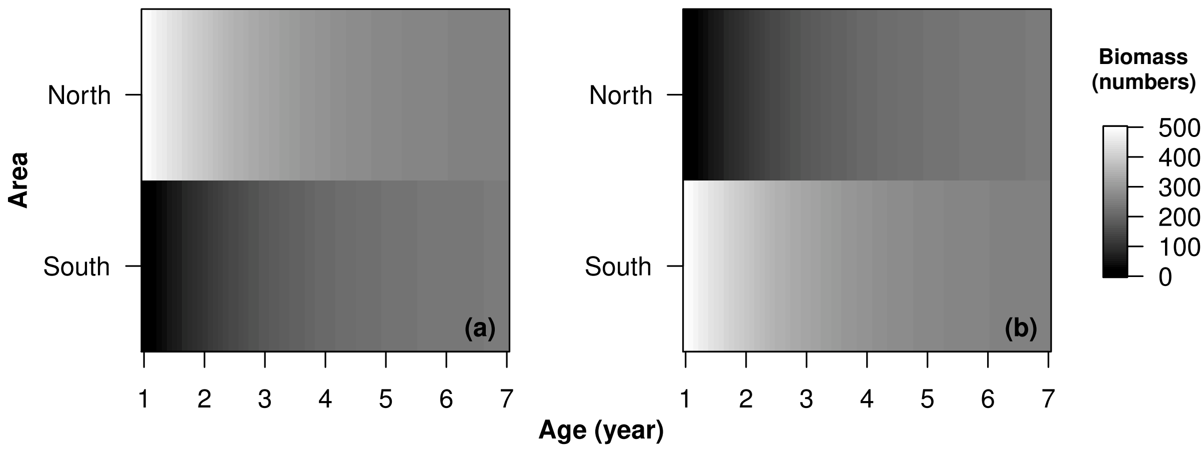

Figure 3: Biomass distribution in numbers over the areas as a function of age when stocks are in virgin stock status for species 1 (a) and species 2 (b). For species 1 nursery ground occurs in the northern area, while species 2 in the southern area (high biomass in white). Over the two areas, initial biomass distribution shows a clear segregation of the younger ages (high and low fish biomass, in white and black respectively), while the older ages show similar distributions (grey colours).

Age-dependent catchability linked the population biomasses to the catches in the fishery, and was thus one of the crucial parameters determining the interaction between the two. In the case study, this age-dependent catchability $q_i(a)$ was assumed independent of age a, and equal for the two species.

The mean prices for the two species were set to 30 thousand euro per ton, ranging between 29 thousand euro per ton for the youngest age and 30.5 thousand ton for the oldest age (Figure 4). The fines for overshooting the quota was set to 3000 thousand euro per ton (Table 1). These high fines combined with an assumed 100% detection of exceeding quotas resulted in model results in which fishers comply with quota regulations.

2.4 Management procedure

The management model encompassed the harvest control rules. The HCRs referenced to biological reference points (Fmsy) to produce management actions in the form of a harvest or effort level: changes in selectivity or spatial and temporal reallocations or restrictions of fishing effort. The input to the fisheries model consisted of the expected

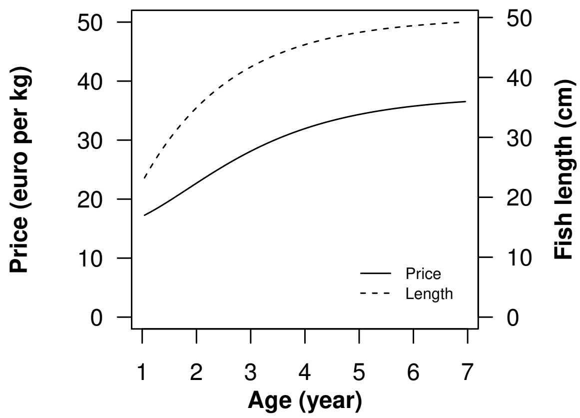

Figure 4: Lengths and prices of the species.

catch rates and the individual quota that were set for each individual in the fleet. These individual quota were set in a management procedure, which mimicked the decisions of a management body. This management body made observations on the state of thedf resources, and the exploitation characteristics of the fishery. In the model, the management body was assumed to collect annual observations of the biomass of the stocks, including the distribution of the biomass over the different ages. These observations stem from fisheries independent observations, such as surveys with known catchabilities. In addition, the management body made annual observations of the catches, including their age distribution.

The observed biomass and catches allowed for estimation of the annual harvest rates (H_i), and the estimation of a yield per recruit curve, that was dependent on fish growth and mortality. The yield curve was dome shaped, with a maximum that is called $H_{i,max}$. Fishing at a harvest rate that is equal to $H_{i,max}$ should lead to maximum sustainable yields. The yield per recruit curve omited the potential effect of the feedback between adult biomass and recruitment, which anyway was absent in the population dynamics, that assumed a constant recruitment. The HCR used by the management body resuslted in annual quotas such that the harvest rate in a year corresponded to $H_{i,max}$. These quotas were then divided equally over the individual vessels in the simulations.

$$Q_{i,y+1} = \frac{\sum([\frac{H_{i,max}(a,y,s)}{H_i(a,s)} \times H_i(a,s) \times sum(N_i(a,y,s,p))] \times w_i(a,s))}{number\ of\ vessels}. \qquad \text{(Eq. 2.4.1)}$$

2.5 Scenarios

The model was set up in three consecutive time windows. In the first window of 10 years, newborns entered the population in the absence of fishing. This resulted in a virgin stock status. Then, the fleet of 8000 vessels started fishing in the absence of any fisheries regulations. This window lasted 15 years and gradually resulted in a situation where the stocks were overfished, i.e. the harvest rates were larger than H_{max}. During this period the fishery was unmanaged, by meaned with unconstrained quota for both species. Finally, to assess the effect of the landing obligation (where discarding is no longer permitted) on the objectives of the MSY, the management procedure started where the HCR, fishing at harvest rates equal to $H_{i,max}$, controls the annual quotas. This last period lasted 15 years.

The two management scenarios considered differ simply by the number of stocks forced to meet the objective of the plan. For this purpose, in a single-species catch quota context: species 1 was the one to do so in first scenario, while in a mixed-fishery context: both species were controlled by HCR in second scenario. The comparison among these scenarios allowed the evaluation of costs and benefits, both economic and in terms of risks to both stock and livelihoods, that resulted from the response of individual effort allocation to meet the objective of the landing obligation regarding the objectives of the CFP, specially the MSY. To be able to analyse the results of this complex actions of implementing the MP and the LO, we simulated the effects of implementing them without any exceptions or flexibility

3 Results

3.1 Catch decisions and location choice

When discarding was allowed, but TACs changed by 15% based on previous year but trying approximate to Fmsy, TACS showed a reduction and discards increased.

The implementation of LO caused an increase in TACs and revenues were higher than when discarding was allowed. Some fishing opportunities are always lost under the landing obligation; the final fishing mortalities are lower than the target fishing mortalities (at least for one species). However, this does not necessarily imply that the catches will be lower with landing obligation than without it. Catches will be reduced in the initial years of landing obligation implementation. However, at Spawning stock biomass increases with LO, the catches will increase too. Although the fishing opportunities are lost due to the choke effect, the biomass of some stocks might increase; after a few years, this extra abundance could be converted into more catches. This implies that are fleets that, in the mid-term, could benefit from the landing obligation.

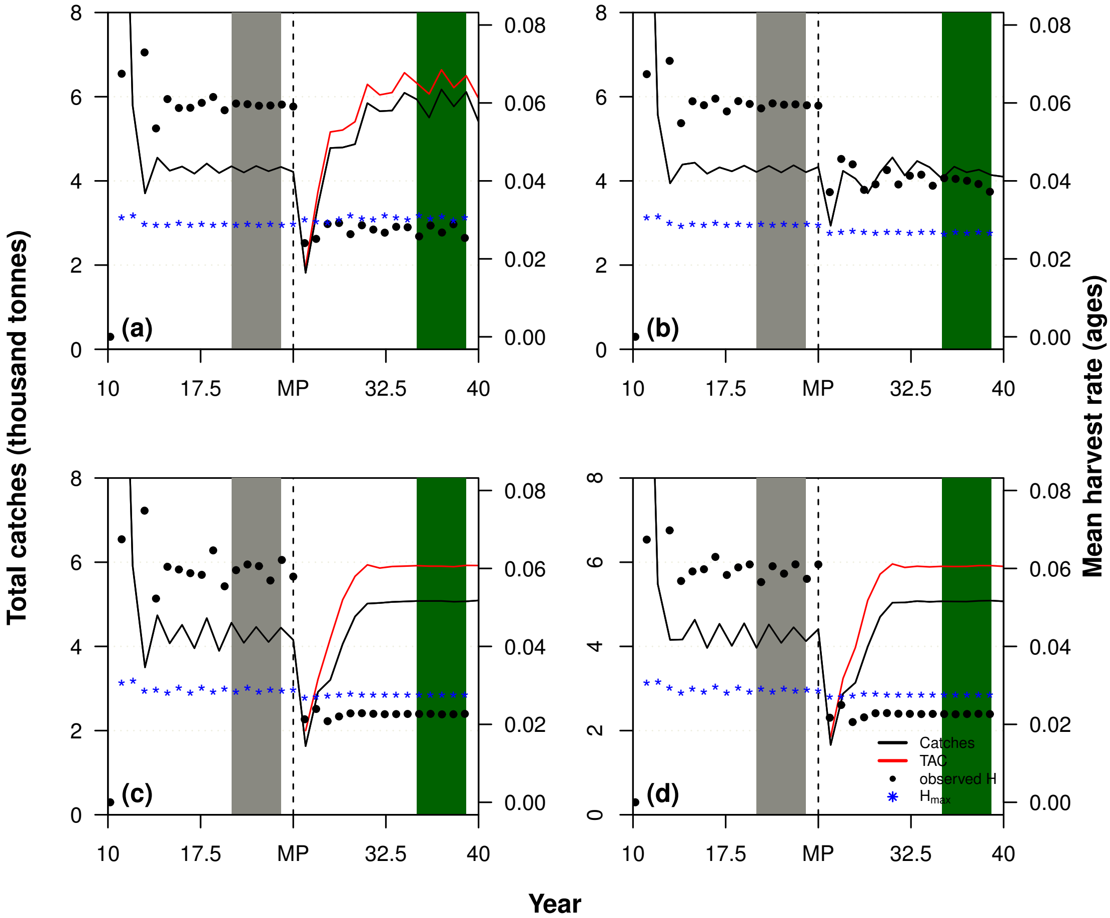

Figure 5: Modelled total annual catches (thousand tonnes) for all vessels and both species: species 1 (a,c) and species 2 (b,d) in relation to the available individual quota (red line). In the top panels only species 1 quota constrained the fishery (a,b), while in the bottom panels both species quota constrained the fishery (c,d). MP year reflects the year where the management plan was introduced. Grey and green areas reflect the pre- and post-manage 5-year period, respectively.

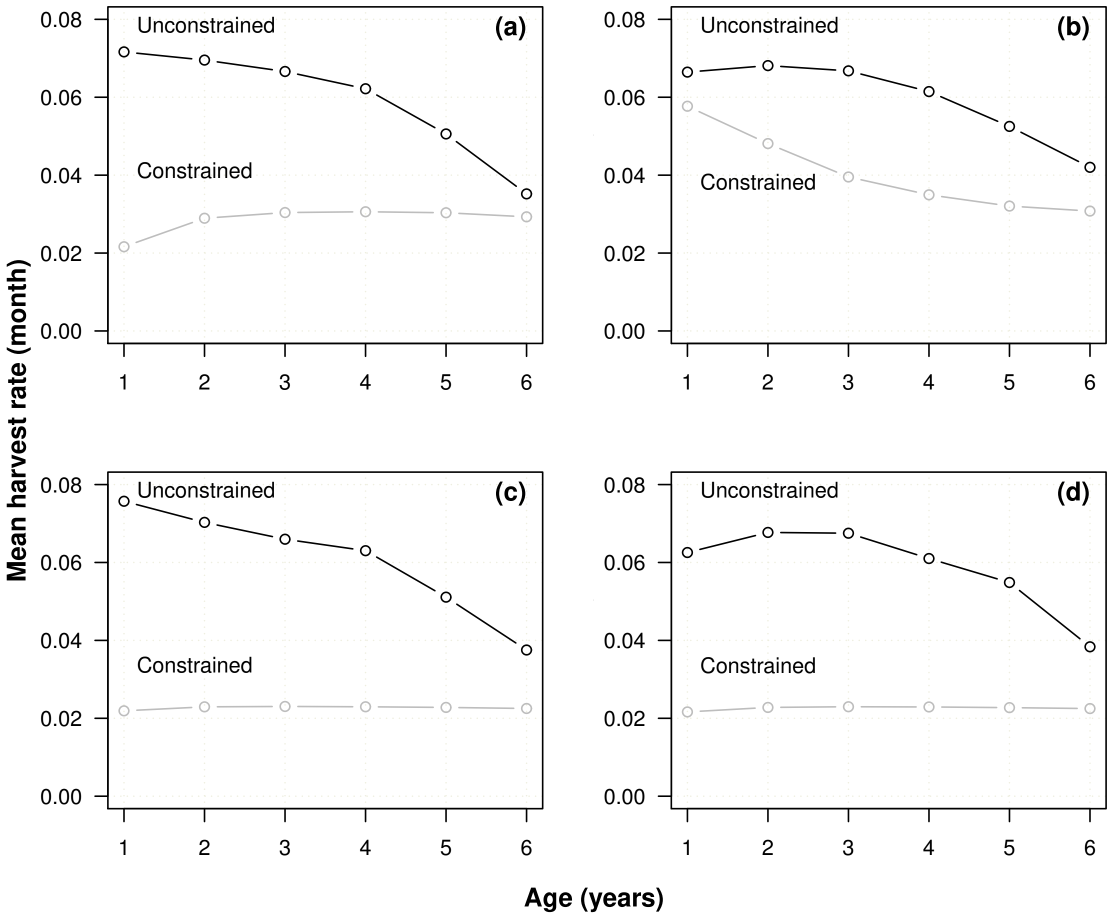

Figure 6: Modelled changes in harvest rates for both species in relation to the catch decision options made based in the availble individual quota: species 1 (a,c) and species 2 (b,d). In top panels only species 1 quota constrained the fishery (a,b), while in bottom panels both species quota constrained the fishery (c,d). Black lines: mean harvest rates during the pre-manage period (unconstrained fishery); grey line: mean harvest rates during the post-manage period (constrained fishery). Periods are relative to the introduction of the management plan (grey and green areas in Fig. 5).

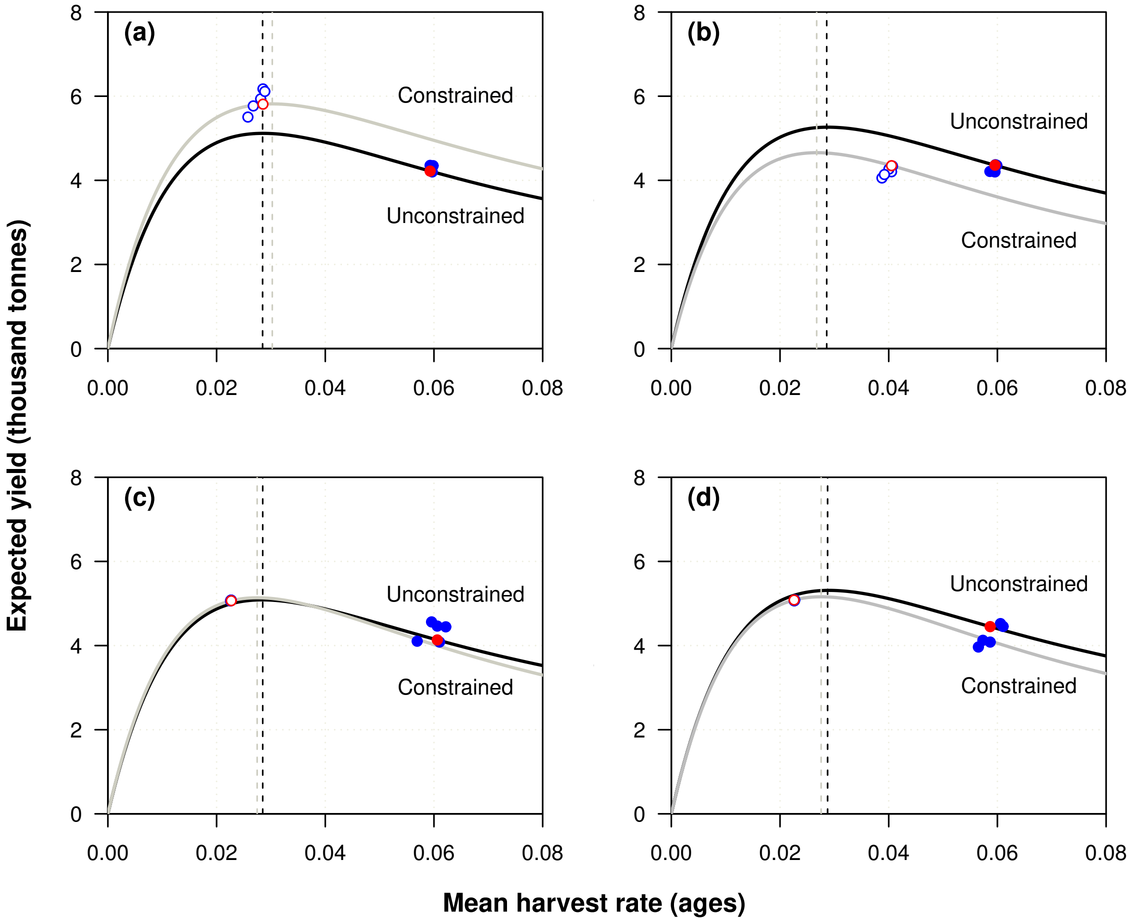

Figure 7: Modelled yield per recruitment curves (thousand tonnes) for both species in relation to the introduction of the management plan: species 1 (a,c) and species 2 (b,d). In top panels only species 1 quota constrained the fishery (a,b), while in bottom panels both species quota constrained the fishery (c,d). Black lines: expected yield during the pre-manage period (unconstrained fishery); grey line: expected yield during the post-manage period (constrained fishery). Periods are relative to the introduction of the management plan (grey and green areas in Fig. 5). Blue dots represent the observed catches at the mean harvest rate for each year during the 5-year period (filled dots: pre-manage period and empty dots: post-manage period), while red dots are the expected yields per recruit. During the post-manage period all species are underharvested to reach Fmsy (a,c,d), except species 2 in the single-stock case scenario which is overharvested due to the abscence of any quota restriction (b).

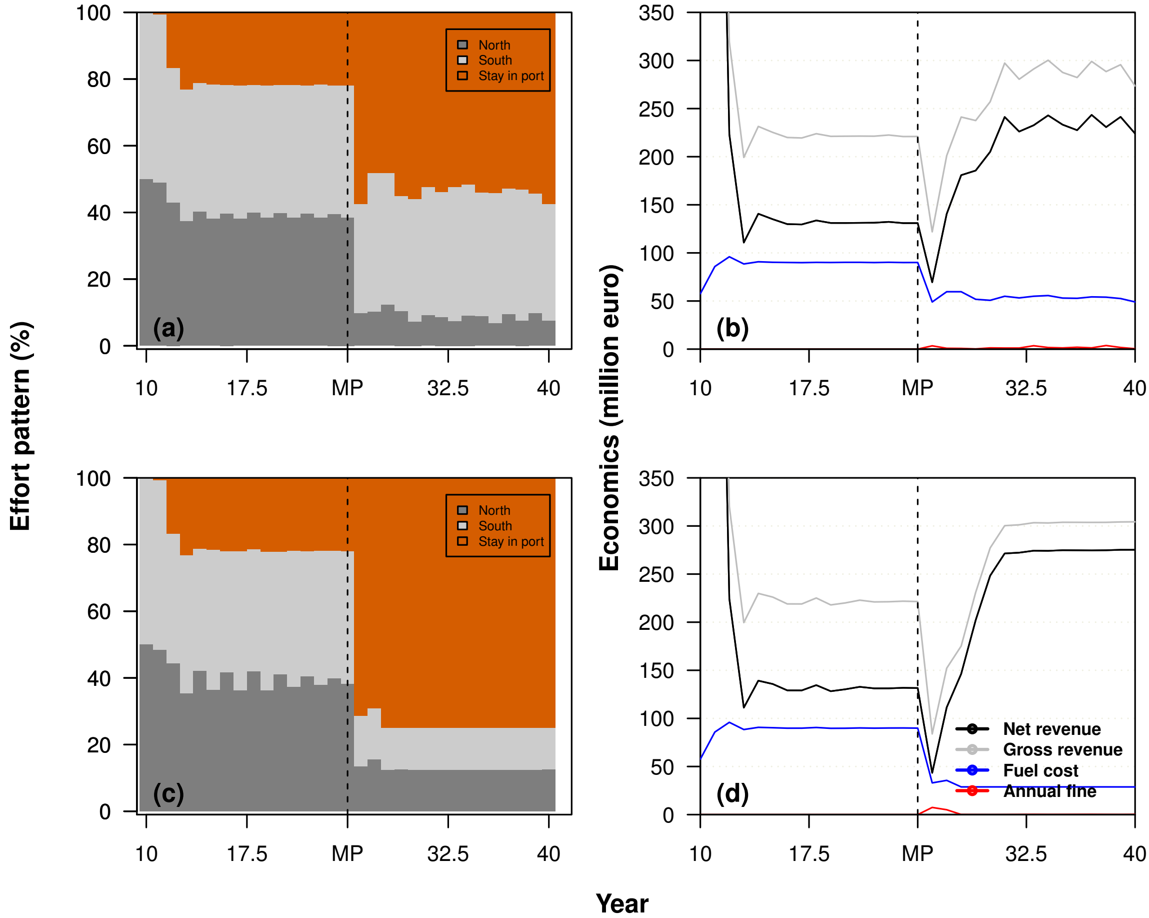

Figure 8: Modelled spatial allocation of effort per year (%) and the respective economic performance when only species 1 has quota limitations (a, b) and both species are quota limited (c,d). Trade-offs between net revenue (black line), gross revenue (grey line), fuel cost (blue line) and annual fines (red line) for the fleet are shown in panels (b,d). MP years reflect the year where the management plan was introduced. In top panels only species 1 quota constrained the fishery (a,b), while in bottom panels both species quota constrained the fishery (c,d)

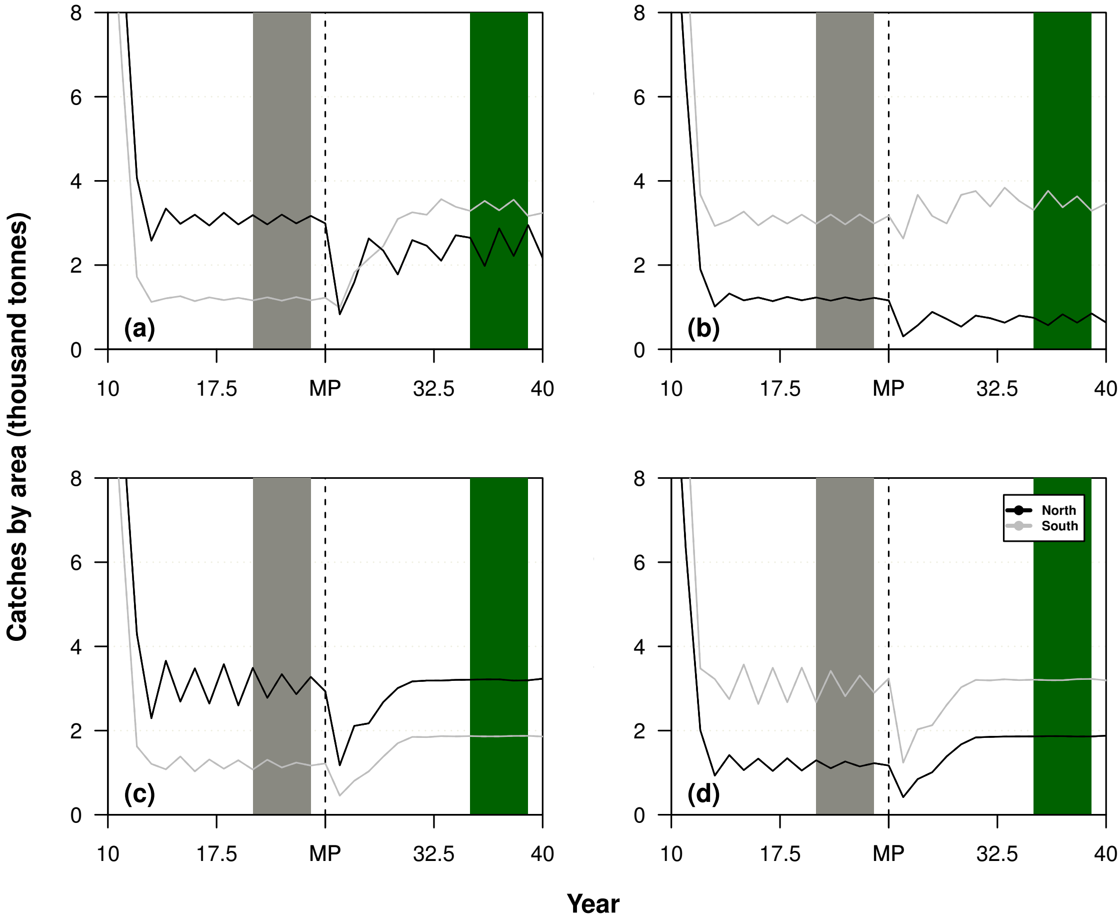

Figure 9: Modelled catches (thousand tonnes/year) by area (blue line: Northern area, red line: Southern area) for both (a,c) species 1 and (b,d) species 2 in relation to the management plan period. In panels (a,b) only species 1 quota constrained the fishery, while in (c,d) both species quota constrained the fishery. MP year reflects the year where the management plan was introduced. Grey and green areas reflect the pre- and post-manage 5-year period, respectively.

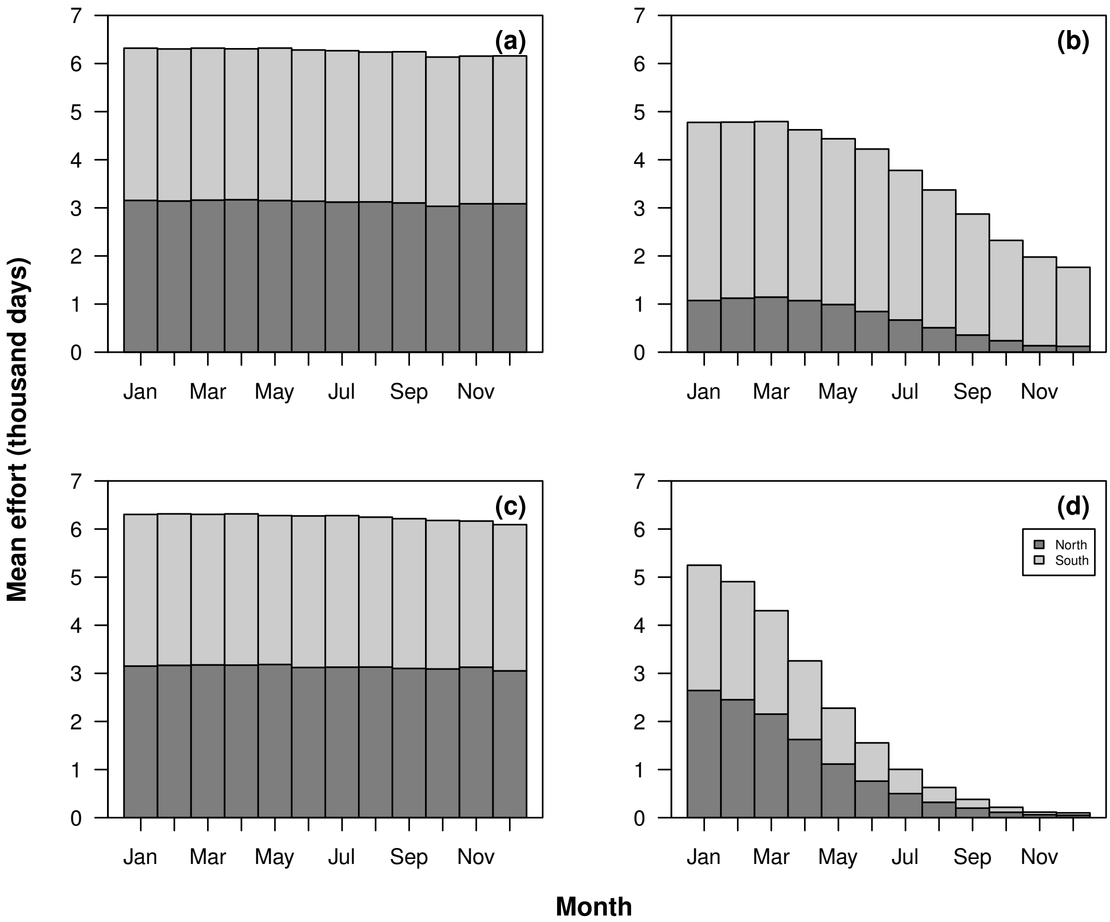

Figure 10: Modelled average spatial allocation of effort (days/month) during the pre-manage (a,c) and post-manage periods (b,d). Periods are relative to the introduction of the management plan (grey and green areas in Fig. 9).

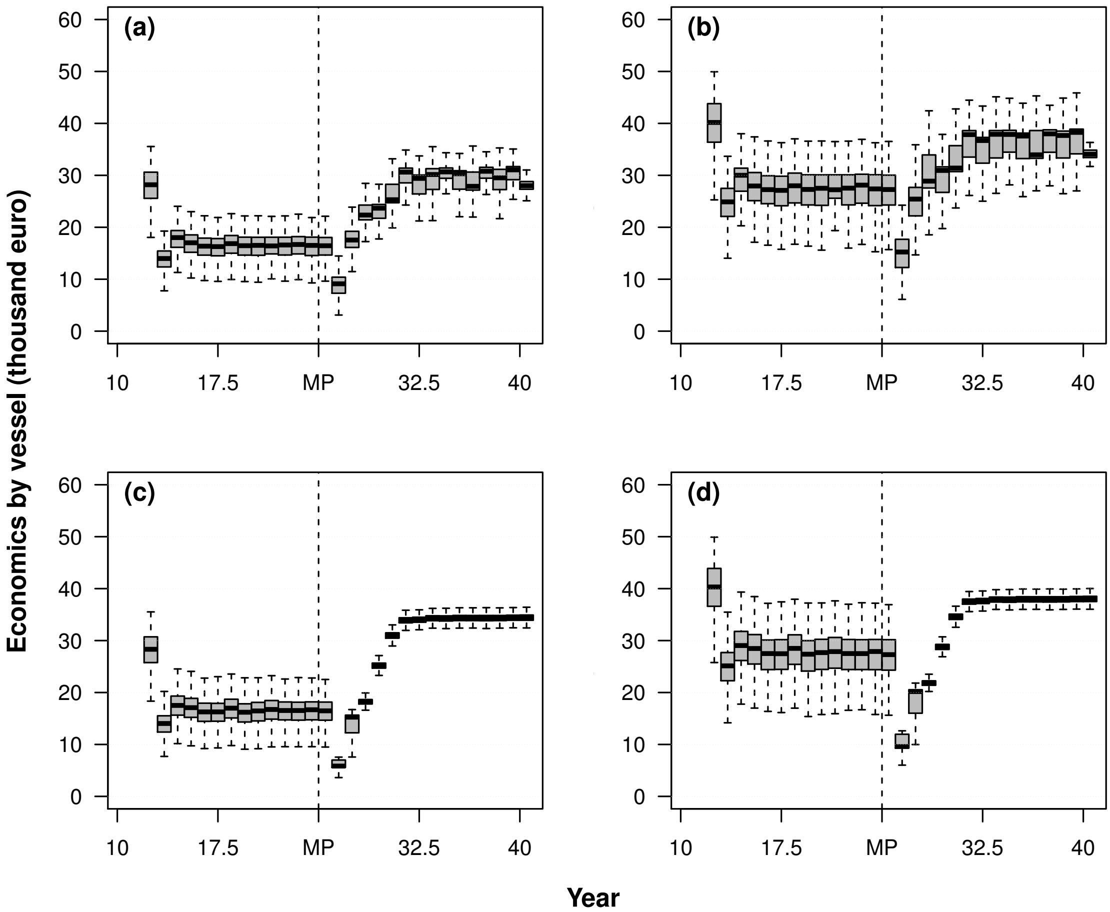

Figure 11: Modelled main economics by vessel (thousand euro/ year): median annual net revenues (a,c) and median grooss revenues (b,d) with the upper and lower limits of the box being the third and first quartile1 (75th and 25th percentile) respectively. MP year reflects the year where the management plan was introduced.

4 Discussion

tbd prellezo 2016, In the mid-term and without any consideration made in terms of the ecosystem functioning as a whole, the results obtained from applying any kind of exemption or flexibility are, simply, negative. Fishing beyond FMSY (even in one year) implies that there will be a penalty in the future. This penalty will come in the form of lower biomasses, that has the mixed effect of increasing the cost of fishing the same level of catches and reducing the total catch due to the lower abundances and the subsequent lower TACs.

The largest yield (or catch) that can be taken from a species' stock over an indefinite period. Fundamental to the notion of sustainable harvest, the concept of MSY aims to maintain the population size at the point of maximum growth rate by harvesting the individuals that would normally be added to the population, allowing the population to continue to be productive indefinitely. Under the assumption of logistic growth, resource limitation does not constrain individuals reproductive rates when populations are small, but because there are few individuals, the overall yield is small. At intermediate population densities, also represented by half the carrying capacity, individuals are able to breed to their maximum rate. At this point, called the maximum sustainable yield, there is a surplus of individuals that can be harvested because growth of the population is at its maximum point due to the large number of reproducing individuals. Above this point, density dependent factors increasingly limit breeding until the population reaches carrying capacity. At this point, there are no surplus individuals to be harvested and yield drops to zero. The maximum sustainable yield is usually higher than the optimum sustainable yield and maximum economic yield

There is an extensive literature on fisheries economic theory in which the Gordon-Schaefer equilibrium production model is central (Gordon 1954, Schaefer 1957, Clark 1983). This theory holds that there is an economic TRP, the Maximum Economic Yield (MEY), which occurs at the effort level yielding the greatest margin of revenue over cost from the resource. For a linear cost curve, this inevitably occurs to the left of MSY on the fishing effort axis. Since Fmey occurs at lower levels of effort than Fmsy, the use of this economic Target Reference Point is less likely to result in biological overfishing than the use of Fmsy.

As a TRP, Fmey is responsive to any changes in the economic environment which affect either the value of fish, or the cost of fishing. It may also be dependent on changes in fish abundance, if market price increases with declining abundance and is independent of the availability of similar resources elsewhere. Subsidies or external economic considerations such as fuel taxes will also affect the location of an economic Reference Point (e.g. Panayotou 1988).

The effect of supply on fish prices may, under certain circumstances, result in higher total profit, or profit per unit catch, when total catch is reduced. This characteristic may be a consideration in setting target fishing levels or catches but is least likely to be effective in situations where fish prices are set by global markets, e.g. the tuna fishery for the canning industry.

The value of a unit weight of the landed catch may vary with the size of individual fish, and in multispecies fisheries with species composition. Both fish size and species composition are functions of fishing mortality, and based on purely economic criteria, may be used as target reference points. Even if the actual target F cannot be estimated, in theory, F could be adjusted in increments until the desirable target catch characteristics are achieved.

In considering TRPs based on economic criteria, it is important to be aware of the effect which the practice of discounting could have on reference points. In evaluating investment projects, including resource management, economists discount the future value of any commodity. Discount rates may be in the order of 10%. In the case of a fishery where the population growth rate does not exceed the discount rate, then a strict application of economic theory would suggest that in the absence of other considerations (such as an economic value placed on recreational use of resources) the whole stock should be harvested now, and the proceeds of their sale invested. Long-lived species with slow growth rates, such as whales, clearly fall into this category. The blatant contradiction between this common economic approach, and the concept of sustainability, constitutes an unresolved paradox (Hilborn and Walters 1992).

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