MSE and dynamic state variable model with sigma function

Nekane Alzorriz

European Commission, Joint Research Centre (JRC), Sustainable Resources Directorate, Water and Marine Resources Unit, Via Enrico Fermi 2749, 21027 Ispra, Italy.

nekane.alzorriz@gmail.com

Jan Jaap Poos

Wageningen Marine Research, PO Box 68, 1970 AB IJmuiden, The Netherlands.

janjaap.poos@wur.nl

December 19, 2017

Abstract

TBD 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

The new Common Fisheries Policy marks a number of key changes to European fisheries management, including the introduction of multi-annual management plans aimed at achieving the Maximum Sustainable Yield (MSY) for all stocks and the gradual introduction of a landings obligation (LO) to encourage more selective fishing practices. Their implementation cannot be seen in isolation from each other as strategies aimed at one objective may have consequences for achieving the other. LO and catch quotas should provide incentives for change in the fisheries, including adoption through taking up selective gears and spatiotemporal effort allocation.

Fisheries management typically focuses on the sustainable exploitation of single target species, but the potentially negative effects on, for example, reaching other species conservation objectives, should also be evaluated. Achieving single species MSY in complex and dynamic fisheries targeting multiple species (mixed fisheries) is challenging because achieving the objective for one species may mean missing the objective for another [15]. There is no unique way of translating the single-species MSY objective to the multispecies case. Maximisation of yield from one stock will generally require different strategies than maximisation of yield from another. Whatever the management regime, the performance of management strategies is conditioned by population dynamics, but also by exploitation dynamics, and particularly by the response of the fleets to management measures. Management strategy evaluation (MSE; [13, 14, 16]) seeks to study the likely implications of potential harvest policies, or strategies, by evaluating management scenarios on the operation of a mixed fishery and on the fished stocks by including stakeholders and by assessing its robustness to uncertainty.

There is a substantial literature addressing the question of effort allocation in fisheries and the more general question of state-dependent foraging decisions in ecological systems [4, 9]. New tools for state-dependent behaviour of individual fishing vessels, translated into behaviour of the fleet and implemented using stochastic dynamic programming [1, 2, 7, 11] have been developed. These models generally predict the effect in the short term (within a year) by optimizing an objective function and determine which area best suits this behaviour given the set of incentives that exist (which may also depend on factors such as size, home port, distance to fishing grounds and expected catch rates). Effects of e.g. relocation costs of marine protected areas, the implementation of the landings obligation, have been modelled under these approaches. In contrast, to enable longer term prediction accounting for the impact of these choices on the populations and consequently on the future yields, this fleet dynamic model should be coupled to a biological dynamic model where the feedback between fleet and stock dynamics are explicity modelled.

MSE involves building a simulation model for the entire process under study, complex enough both to address the current knowledge and uncertainty on the dynamics of fish stocks under fishing pressure, the effect on fishers of variations in stock status and availability, and their responses to those changes and those in management regimes [16]. At the same time being simple enough to build and calibrate reliably with the available data. More comprehensive MSEs may also take the effects of the fishery on the broader environment, and economic and social effects into account [5, 8]. In such modelling framework, advice and management systems can be quantitatively evaluated through simulation testing [6, 10].

We review the potential of MSE, emphasazing the role of individual harvester decision-making 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 [1]. Such combination needs to be responsive to all the drivers that influence and motivate the actual fleet and to respect existing constraints [16]. 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 essential elements of the MSE framework that we followed is summarized in Figure 2. The operating model (OM) aimed capturing the key processes in the dynamics of the fish population given the best knowledge available, and can be thought of as a minimum realistic model [12]. The OM was built using a set of models of the dynamics of fish stocks under fishing pressure and coupled with the effect on fishers of variations in stock status and availability (sections 2.1 and 2.2 respectively). This resulted in simulated measurements (called "observation model") such as 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 observation data were then passed to the "management model" (section 2.3). The management model encompassed the harvest control rules (HCR). The HCR 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. Costs and benefits, both economic and in terms of risks to both stock and livelihoods, could be computed and compared across different scenarios and management procedures (section 2.3).

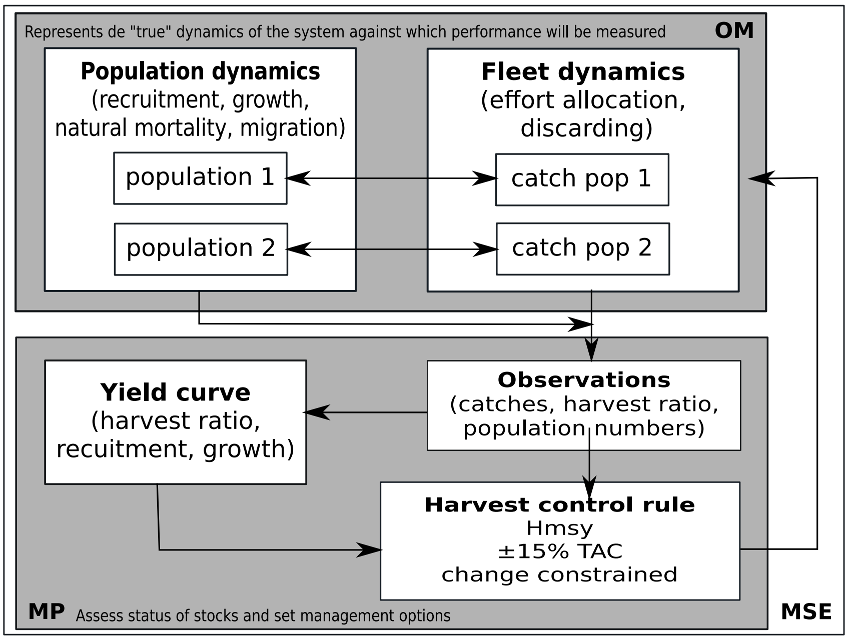

Figure 1: The conceptual framework and how it was mapped.

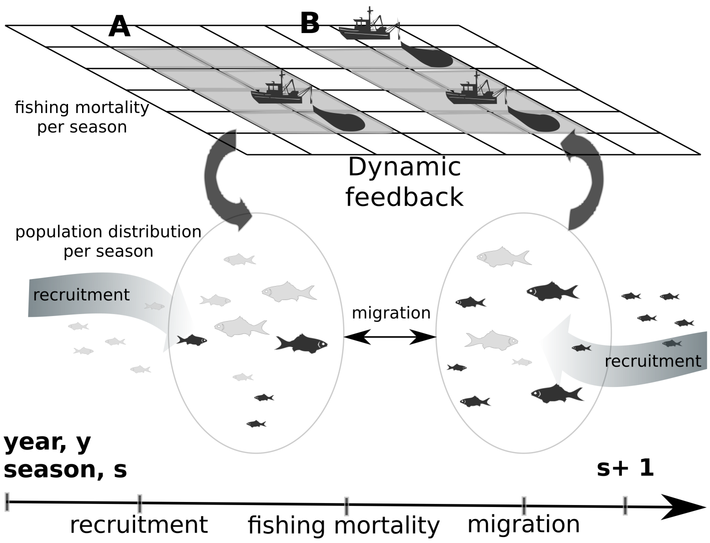

Figure 2: The conceptual framework and how it was mapped.

2.1 Stock structure and dynamics

For purposes of model simplicity, we considered a hypothetical mixed fishery on two species. The fishery was modelled in a individual based dynamic state variable model.

In order to allowed for fishing effort allocation, the model was seasonally (6 seasons) and spatially (areas A and B) explicit. The dynamics of the two fish species were governed by a simple age-structured model that is also seasonally and spatially explicit. The age structured model for the fish species was based on 4 cohorts, and individuals were assumed to be born at age 0, and in season 1. The number of fish i of age a at year y, in season s and area p was written as $N_i(a, y, s, p)$. The number of new-born individuals in the model was independent of the size of the adult population, but was function of area p ($R_i(p)$). Numbers of recruits were set to 100 individuals during the first season, and spawning population of species 1 ocurred in area A, while species 2 did so in area B. Thus, individuals could be born in each of the areas, such that:

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

Moreover, combining the weight-based von Bertalanffy growth equation ($L\infty = 20$, $k = 0.093$), with the age-weight relationship ($W = L\infty * (1 - e^{-k*a})$); weight per fish was higher for the older fish. Mortality in the model could occur from catches in the fishery, and natural causes such as predation, diseases, and scenesens. However, for simplicity we assumed that his natural mortality was negligible. Althought such absence of natural mortality impossible in reality, one could argue that the model thus mimics long-lived species. The decrease in population numbers was thus the result of the catches ($C_i(a, y, s, p)$), which were in turn a function of age dependent catchability $q(a)$, and fishing effort $E(y, s, p)$ in any time, season, and area.

$$C_i(a, y, s, p) = q(a) * E(y, s, p), \qquad \text{(Eq. 2.1.2)}$$

and

$$N_i(a, y, s, p) = N_i(a, y, s, p) - C(a, y, s, p). \qquad \text{(Eq. 2.1.3)}$$

It was assumed that fishing mortality ocurred before migration ocurred. Migration for each species was defined by a matrix Mig that defines the impact of migration (.e.

immigration-emigration) on a given stock was also dependent on the relative sizes of the stocks. The size of that matrix was defined by the number of age classes, seasons and number of immigrants into area p (im) and emigrants leaving area p (em) in the model. A 20 % constant migration during any season was set between areas. The migration in population numbers ($Mig(a, 1, s, im, em)$) was thus the proportion ($P(a, y, s, i, em, im)$) of the population available or vulnerable to fishing after migration occurs.

$$Mig(a, 1, s, im, em) = Mig(a, 1, s, im, em) + N(a, y, s, em) * P(a, y, s, i, em, im), \tag{Eq. 2.1.4}$$

and then population numbers

$$N(a, y, s, im) = N(a, y, s, im) + Mig(a, 1, s, im, em). \tag{Eq. 2.1.5}$$

2.2 The dynamic-state variable model

To simulate the process of monitoring the stock, we developed models for state-dependent behaviour of individual fishing vessels, translated into behaviour of the fleet and implemented using stochastic dynamic programming [1, 2, 4, 7, 9, 11]. A dynamic state variable model [4, 9] was used to model location choice, extending the model structure in [2]. In order to accommodate each individual vessels set of choices, the model may be constrained by individual vessels quota for the individual species and will respond by changing their fishing pattern in terms of: (i) whether or not to go fishing in one of the two areas (A and B), and (ii) whether to discard one or more species and age class combinations. The model had annual fines for exceeding landings or catch quota as in [1]). In order to calculate state dependent choices during the year, we started by defining the annual fines for exceeding landings or catch quotas at the end of the year:

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

where C_i was the cumulative annual landings or catches for species i for an individual vessel. These cumulative landings defined the state of the individual. Q_i was the annual individual quota for landings or catches for the quota species. Individual quotas were not transferable. In order to reduce computation time, we set quota only for two species. F_i was the fine per unit weight for exceeding individual landings or catch quotas was set to $3x10^3$ Euro day^{-1}. These high fines combined with an assumed 100% detection of exceeding quotas resulted in model results in which fishers comply with quota regulations.

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 (A, B and including area 0: staying in port), and to keep or discard any combination of the age classes caught of the quota species. This discarding was defined by a matrix d. The size of that matrix was defined by the number of species under quota constraints and the number of age classes. Each element could take the value 0 (discard) or 1 (keep on board and land). The expected utility for each state and each time step s was calculated backward using stochastic dynamic programming [4]:

$$V(C_i, Q_i, F_i, s) = max_{p,d}(R(p, d, s) - G(p) - C(p) + E_{p,d}[V(C_i', Q_i, F_i, s+1])), \quad \text{(Eq. 2.2.2)}$$

where $R(p, d, s)$ was the expected immediate contribution of the gross revenue from the sales of fish in a season resulting from choices p, and d (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 2.2.1). $G(p)$ represented the incurred fuel costs per season from the choice of fishing area a, 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 landings and fish prices. The term $E_{p,d}[V(C_i', Q_i, F_i, s + 1]$ denoted the expected future utility taken over all possible states resulting from choices p, and d. 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 [11].

Rather than assuming that each individual always made the optimal choice, we assigned a probability to each choice proportional to its expected utility, following [7]. The expected utility for any choice was

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

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

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

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

$$P_{p,d}(C_i, Q_i, F_i, s) = \frac{e^{-\Delta_{p,d}(C_i,Q_i,F_i,s)/\sigma}}{\sum_p \sum_d e^{-\Delta_{p,d}(C_i,Q_i,F_i,s)/\sigma}}, \qquad \text{(Eq. 2.2.5)}$$

where σ was a tuning parameter that measures how important was to be near optimal. A high value of sigma resulted in uniform probabilities of choices, and that vessels were distributed uniformly among the different fishing areas. In contrast, if sigma was small then all vessels concentrated in the optimal location (but note that σ should be > 0). For computations, we used $\sigma = 40$ (noting that Δ ranged from 0 to $\sim 2x10^3$, but was generally of the order of $1x10^2$ in magnitude).

The dynamic state variable model was solved by iterating backwards in time, while finding the probability distribution choice in terms of location and discarding behaviour 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 [1, 3] and [7].

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. This was done for 700 individual vessels.

Table 1: Model and fishery conditioning.

model		**Fishery variable costs**		**Fishery**	
number of vessels	700	fuel costs (Euro day^{-1})	150	q	0.0005
σ	40	gear maintenance (Euro day^{-1})	0	effort (p,s)	1
number of areas	2	crew share	35%	CPUE	mean($pop * q * wts(yy-2:yy)$)
number of seasons	6	landing costs (Euro t^{-1})	0	CPUE dev	$0.08 * CPUE$
intial quota Q_{sp1} and Q_{sp2}	200				

2.2.1 Size dependent pricing

Prices of fish have been assumed to be fixed over time but influenced by the size of the catch. Common knowledge and case studies indicate that size and weight of a fish could be important attributes when determining its economic value [17, 18]. Therefore, the resulting data of mean weights and average prices were used for further analysis. We fitted linear mixed models, using mean price and mean body weight as the response variable and covariate, respectively. Thus, following [17], the statistical models took the form:

$$pw_i \sim p_i\bar{w_i} + \beta_0 \times \frac{w_i - \bar{w_i}}{\bar{w_i}}, \qquad \text{(Eq. 2.2.6)}$$

where p is the mean price of species i, $\bar{w_i}$ is the mean weight of the corresponding weight classes, and the fraction corresponded to the standarization of the mass relative to the mean observed individual catch mass over all ages classes. β_0 gave the price increase when individial mass was increased by $\bar{w}$. We used mean prices of 150 Euro kg^{-1} for both species.

Table 2: Linear mass-prices estimated based on mean prices per mass age-classes. The price slopes β_0 were assumed to be similar to mean prices.

Market value (Euro kg^{-1})		age			
		1	2	3	4
Scenario I					
	species 1	778	1354	1780	2096
	species 2	778	1354	1780	2096
Scenario II					
	species 1	778	1354	1780	2096
	species 2	778	1354	1780	2096

2.3 Endogenously determined quotas

The two management strategies we considered differ by the formulae used to determine exploitation rates (HCR). These manegemet strategies were chosen such that, if the management model was the correct model of reality, the corresponding equilibrium state of the system would meet the objective of the plan. For this purpose, each strategy was implemented after a period where the fishery was unmanaged, by meaned with unconstrained quota for both species.

Table 3:

	Scenario I *(landings selectivity)*	**Scenario II** *(fulll avoidance of discards)*
Discarding	Allowed	Not allowed
Manager catch perception	$C = L + D$	$C = L\ (D = 0)$
Selectivity (l_{ratio})	$\neq 1$	$= 1$
Yield per recruitment model	based in F_L	based in F_C

1. **Scenario I: Landings selectivity**, under this scenario the fishery is under landings selectivity, only landings contribute to yield. Fishing mortality accounts for all catches, regardless wether these catches are landed or discarded.

2. **Scenario II: Fulll avoidance of discards**, this scenario contemplates the LO with landings selectivity only and fulll avoidance of discards.

HCRs in the form of quotas were determined endogenously by simple and relatively linear reduction in catch if fishing mortality exceeded Fmsy. This required that fishing mortality for each stock must not exceed Fmsy, which was a limit reference point. An Optimum Yield (OY) was determined based on a MSY that must prevented overfishing, and that could be reduced from the MSY limit to take into account social, economic and precautionary considerations. Therefore, quota was determined by a set of harvest control rule parameters consisting of the exploitaion rate at MSY.

The resulted biomass harvested rate in a year y, depended in the manager catch perception (based in Table 1) and the standing biomass:

$$H_{a,y,s} = \frac{C_{i(numbers)}(a,y,s,p)}{C_{i(numbers)}(a,y,s,p) \times B_{i(numbers)}(a,y,s,p)}, \quad \text{(Eq. 2.3.1)}$$

$$l_{ratio}(a,y,s) = \frac{L_{i(numbers)}(a,y,s,p)}{C_{i(numbers)}(a,y,s,p)}, \quad \text{(Eq. 2.3.2)}$$

Through a yield per recruitment model, knowing growth, harvest rates and recruitment we can estimate how much to reduce the quota for achieving the MSY.

$$H_{MSY} = YIELDCURVE..., \quad \text{(Eq. 2.3.3)}$$

$$Q_{MSY} = \frac{\sum([\frac{H_{MSY}}{\bar{H}} \times H(a,s) \times l_{ratio}(a,s) \times B_{(numbers)}(a,s)] \times wts)}{number\ of\ vessels}, \quad \text{(Eq. 2.3.4)}$$

$$Q(y+1) = \max(\min(Q_{MSY}, Q(y) \times 1.15), Q(y) \times 0.85), \quad \text{(Eq. 2.3.5)}$$

3 Results

Scenario I:

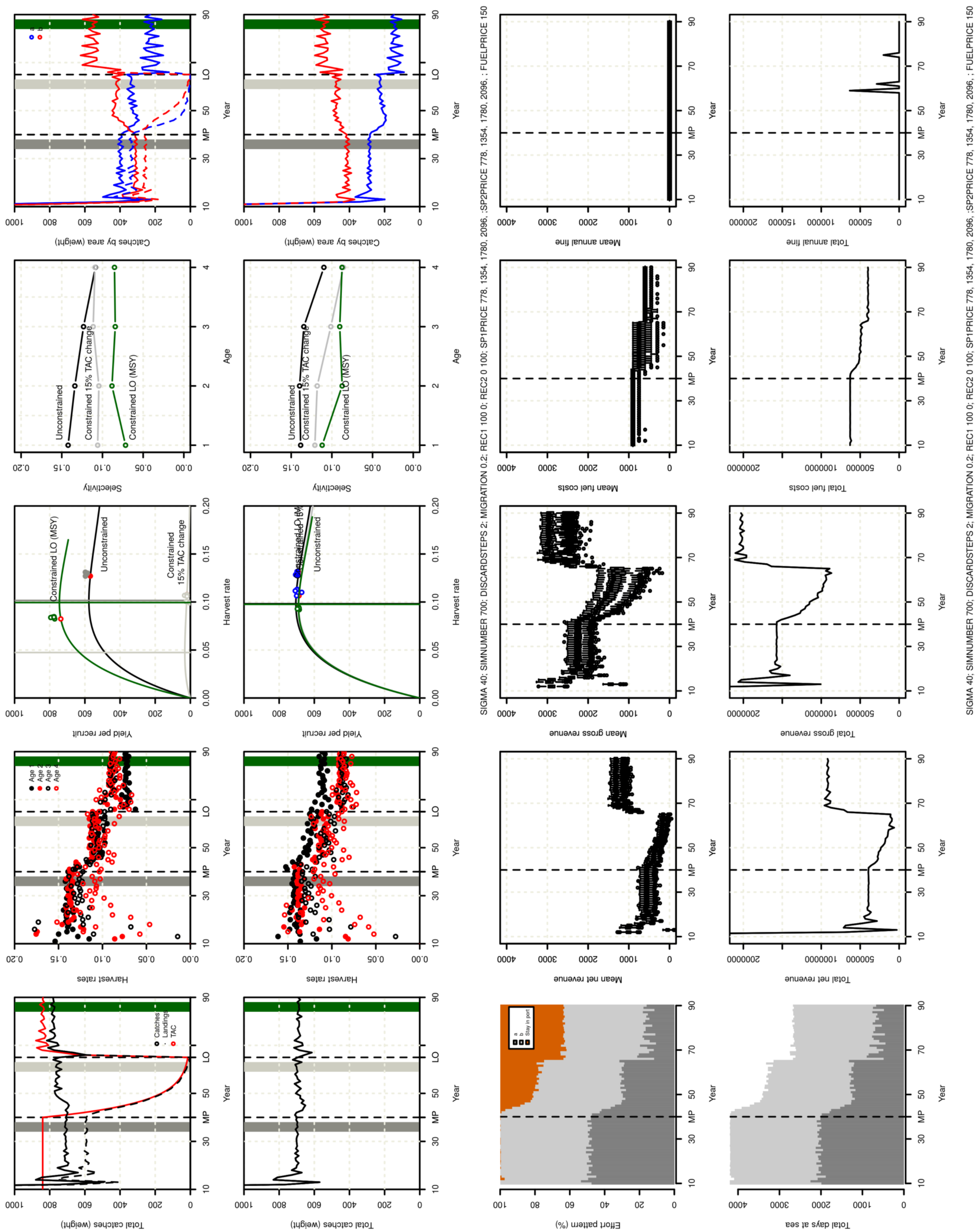

Figure 3:

Scenario II:

3.1 Simulated 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.

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).

Acknowledgements

The content of this paper does not reflect the official opinion of the European Commission. Responsibility for the information and views expressed in this paper relies entirely with the authors.

References

[1] N. Alzorriz, E. Jardim, and J. J. Poos. Likely status and changes in the main economic and fishery indicators under the landing obligation: the Basque trawl fishery case study. *TBD*, x:xxx–xxx, 2018.

[2] J. Batsleer, K. G. Hamon, H. M J van Overzee, A. D. Rijnsdorp, and J. J. Poos. High-grading and over-quota discarding in mixed fisheries. *Reviews in Fish Biology and Fisheries*, 25(4):715–736, 2015.

[3] J. Batsleer, A. D. Rijnsdorp, K. G. Hamon, H. M J van Overzee, and J. J. Poos. Mixed fisheries management: Is the ban on discarding likely to promote more selective and fuel efficient fishing in the Dutch flatfish fishery? *Fisheries Research*, 174:118–128, feb 2016.

[4] C. W. Clark and M. Mangel. *Dynamic state variable models in ecology: Methods and applications.* Oxford University Press, New York, 2000.

[5] C. M. Dichmont, R. A. Deng, A. E. Punt, N. Ellis, W. N. Venables, T. Kompas, and Y. Ye. Beyond biological performance measures in management strategy evaluation: bringing in econ- omics and the effects of trawling on the benthos. *Fisheries Research*, 94:238–250, 2008.

[6] C. M. Dichmont, N. Ellis, R. H. Bustamante, R. Deng, S. Tickell, R. Pascual, H. Lozano-Montes, and S. Griffiths. Evaluating marine spatial closures with conflicting fisheries and conservation objectives. *Journal of Applied Ecology*, 50(4):1060–1070, 2013.

[7] N. A. Dowling, C. Wilcox, M. Mangel, and S. Pascoe. Assessing opportunity and relocation costs of marine protected areas using a behavioural model of longline fleet dynamics. *Fish and Fisheries*, 13(2):139–157, jun 2011.

[8] E. A. Fulton, A. D. M. Smith, and D. C. Smith. Quantitative MSE of Alternative Management Strategies for Southeast Australian Fisheries. Technical Report June, CSIRO, 2007.

[9] A. I. Houston and J. M. McNamara. *Models of Adaptive Behaviour*. Cambridge University Press, Cambridge, 1999.

[10] L. T. Kell, I. Mosqueira, P. Grosjean, J. M. Fromentin, D. Garcia, R. Hillary, E. Jardim, S. Mardle, M. A. Pastoors, J. J. Poos, F. Scott, and R. D. Scott. FLR : an open-source framework for the evaluation and development of management strategies. *ICES J Mar Sci*, 64(i):640–646, 2007.

[11] J. J. Poos, J. A. Bogaards, F. J. Quirijns, D. M. Gillis, and A. D. Rijnsdorp. Individual quotas, fishing effort allocation, and over-quota discarding in mixed fisheries. *ICES Journal of Marine Science*, 67(2):323–333, oct 2010.

[12] A. E. Punt and D. S. Butterworth. The effects of future consumption by the cape fur seal on catches and catch rates of the cape hakes. 4. modelling the biological interaction between cape fur seals arctocephalus pusillus pusillus and the cape hakes merluccius capensis and m. paradoxus. *South African Journal of Marine Science*, 16(1):255–285, 1995.

[13] K. J. Sainsbury, A. E. Punt, and A. D. M. Smith. Design of operational management strategies for achieving fishery ecosystem objectives. *ICES Journal of Marine Science: Journal du Conseil*, 57(3):731–741, jun 2000.

[14] Stephen J. Smith. Analysis of data from bottom trawl surveys. *NAFO Scientific Council Studies*, 28(28):25–53, 1996.

[15] C. Ulrich, Y. Vermard, P. J. Dolder, T. Brunel, E. Jardim, S. J. Holmes, A. Kempf, L. O. Mortensen, J. J. Poos, A. Rindorf, and Handling editor: Emory Anderson. Achieving maximum sustainable yield in mixed fisheries: a management approach for the north sea demersal fisheries. *ICES Journal of Marine Science*, 74(2):566–575, 2017.

[16] W. N. Venables, N. Ellis, A. E. Punt, C. M. Dichmont, and R. A. Deng. A simulation strategy for fleet dynamics in Australia's northern prawn fishery: Effort allocation at two scales. *ICES Journal of Marine Science*, 66(4):631–645, 2009.

[17] F. Zimmermann, M. Heino, , and S. I. Steinsham. Does Size Matter? A Bioeconomic Perspective on Optimal Harvesting when Price is Size-dependent. *Canadian Journal of Fisheries and Aquatic Sciences*, 68:1651–1659, 2011.

[18] F. Zimmermann and M. Heino. Is size-dependent pricing prevalent in fisheries? The case of Norwegian demersal and pelagic fisheries. *ICES Journal of Marine Science*, 70:1389–1395, 2013.