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Trade-offs between employment and profitability in a Mediterranean Sea mixed bottom trawl fishery

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A B S T R A C T

The exploitation of mixed fisheries leads to trade-offs between fisheries rent, production (landings) and resource conservation because harvest rent cannot be optimized simultaneously for all species. Additionally, the exploitation of mixed fisheries by heterogeneous fleets complicates their management because of the necessity to allocate catch or effort quotas, under some criterion of efficiency or equitability. The allocation of fishing opportunities impacts directly on the availability of jobs in fisheries. To analyse the trade-offs between employment and profits in mixed fisheries, an optimization bioeconomic model was built for the three bottom-trawl fleet segments operating in the Catalonia demersal fishery (NW Mediterranean Sea). The fishery is subject to a multiannual management plan to align fishing effort with the fisheries mortality that would produce the maximum sustainable yield. The optimal effort allocation among the three fleet segments were compared subject to alternative fisheries management policies: (i) maximum sustainable yield, (ii) maximum economic yield, (iii) maximum labour remuneration, (iv) pretty good yield, and (v) equilibrium biomass larger than biomass at maximum sustainable yield, taking into account the multispecies nature of the fishery. The results show that all management policies provide higher profits than current. In the first three scenarios, high profitability can be made compatible with a lower number of better paid jobs, because the optimal allocation of effort in most scenarios would imply a reduction in the number of vessels. The results also show that the current number of vessels and effort distribution (which are the result of a historical process, rather than the results of a management strategy) are far from any optimum.

1. Introduction

The rational exploitation of mixed, or multispecies, fisheries leads inevitably to trade-offs between the quantity of landings, fisheries rent and resource conservation because harvest rates cannot be optimized simultaneously for all species, due to different biological productivity (Clark, 1990; Hilborn et al., 2012). Additionally, the optimal management of heterogeneous fleets in mixed fisheries needs to address the problem of capacity (fleet size or number of vessels) and, consequently, jobs. That is, once an optimal harvest rate has been established how are fishing effort or allowable catches to be distributed among fleets participating in the fishery?

The management objective enshrined in many fisheries regulations, and particularly in the EU Common Fisheries Policy (EU Reg. 1380/2013, 2013), is to maintain stock biomass at levels that can produce the maximum sustainable yield (MSY), what is considered a conservation objective. It is well known that this optimum on biological grounds results in lower stock biomass and fisheries rent than the harvest rate producing the maximum economic yield (MEY) (Clark, 1990; Hilborn et al., 2012; Pascoe et al., 2015). The application of these single species management concepts to multispecies fisheries increases the difficulty of optimal management, because of different biological productivity of the different species, and also because the existence of technical interactions that make it impossible to simultaneously achieve optimal harvest rates for all species (Paulik et al., 1967; Clark, 1990). When the management objective is to avoid overfishing of all target stocks of a multispecies fishery, then the different biological productivities of different species lead to loss of potential yield from the more productive species (Hilborn et al., 2012). For instance, attempting to rebuild stock biomass levels as quickly as possible to pre-specified B_{MSY} targets had a very high cost in socio economic terms (jobs and revenue lost) in the US West Coast groundfish mixed fishery (McQuaw et al., 2021), highlighting the trade-off between conservation and social and economic objectives.

Adding social considerations to the management of mixed fisheries, such as attempting to maximize employment or labour remuneration, makes their optimal management even more complicated. The prevailing view is that the social objective, which normally is expressed as the maximization of employment, cannot be reconciled with conservation or economic (profitability)

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objectives (Mardle et al., 2002; Hilborn, 2007). However, Asche et al. (2018) showed that it is possible to reconcile what they called the "three pillars" (conservation, economic and social objectives) in specific cases, particularly for fisheries under harvest-rights management.

In an attempt to optimize the exploitation of fisheries, the optimal fishing mortality can be calculated conditional to pre-specified management objectives. To the traditional "biological" or conservation objective of (multispecies) maximum sustainable yield (MMSY), other objectives can be added, such as the (multispecies) maximum economic yield (MMEY), or the (multispecies) maximum labour remuneration (MMLab). A relatively new concept, the so-called "pretty good yield" (PGY: (Hilborn, 2010; Rindorf et al., 2017); here MPGY: multispecies PGY), proposes setting optimal fishing mortality at those levels of F that permit to obtain a specified proportion (or larger) of MSY, for instance ≥80% of MSY. A fishery managed under the PGY objective would produce yields close to MSY at F levels typically lower than F_{MSY} (Rindorf et al., 2017) helping to maintain fish stocks at relatively high biomass levels.

Fisheries management in the Mediterranean Sea has traditionally been based on effort control (limiting fisheries entry and, in recent years, encouraging exit) and technical measures, with no restriction on output (that is, no limits to catches are set, contrary to other European fisheries) ("Mediterranean Regulation": EU Reg. 1967/2006, 2006; Penas Lado, 2016). This management framework has been ineffective in ensuring the sustainable exploitation of Mediterranean fisheries, because they continue to suffer from excessive harvest rates, low economic profitability and overcapacity (Vasilakopoulos et al., 2014; Maynou, 2020; Sánchez-Lizaso et al., 2020), which is particularly evident in demersal mixed fisheries exploited primarily by bottom trawl.

Western Mediterranean multispecies demersal fisheries exploited by Spanish, French and Italian fleets are currently managed under a Multi Annual Plan (MAP) for the period 2020–2024, in addition to the existing management scheme (EU Reg. 1967/2006, 2006), with the explicit objective of aligning fishing mortality with F_{MSY} by Jan. 1st, 2025 for the five main fish stocks in the area (European hake *Merluccius merluccius*, red mullet *Mullus barbatus*, Norway lobster *Nephrops norvegicus*, deep-water rose shrimp *Parapenaeus longirostris* and red shrimp *Aristeus antennatus*) (COM/2018/0115 final – 2018/050 (COD)). The main instrument to achieve this objective is to set annual values of Total Allowable Effort (TAE) for the bottom trawl fleet, establishing a reduction of up to 40% by the end of 2024. In this multispecies demersal fishery all fleets (bottom trawl and small scale boats) have legal access to all stocks and they are caught in different proportions by each fleet. Hence, each fleet and fleet segment contributes differently to overall fishing mortality, employing different amounts of input factors (labour, capital). The utilization of economic input factors is notoriously inefficient in Mediterranean fisheries (Da-Rocha et al., 2020) and the blanket reduction of up to 40% of fishing effort for all trawl fleet segments, enshrined in the MAP, may contribute to exacerbate the problem of inefficiency, while it will not necessarily achieve the stated conservation levels.

This study explores the trade-offs of optimal fishing effort allocation in a typical Mediterranean Sea demersal mixed fishery, the bottom trawl fishery of Catalonia, exploited by three fleet segments of different technical and economic characteristics using the modelling framework of Sgardeli et al. (2019).

Table 1
Fleet size (Number of Vessels) and catch shares ($c_{i,j}$) of the two target species (HKE: European hake; ARA: red shrimp) and other commercial by catch (OTH) from average values in the period 2017–2019. Fleet segments classified according to vessel overall length class (VL). VL1218: 12 to 18 m LOA, VL1824: 18 to 24 m LOA and VL2440: 24 to 40 m LOA.

	Fleet size (NV)	HKE (t)	ARA (t)	OTH (t)	Total (t)
VL1218	57	15.8%	3.7%	24.9%	1486.5
VL1824	117	47.7%	36.2%	46.6%	5612.2
VL2440	50	36.5%	60.1%	28.6%	3541.7
Total	224	1101.5	546.8	8992.1	10 640.4

2. Material and methods

2.1. Case study

The Catalonian demersal fishery is a multispecies fishery exploited mainly by otter bottom trawlers, with additional catches by small scale units employing a variety of fishing gear, as in other Mediterranean demersal fisheries (Sánchez-Lizaso et al., 2020). As shown in Fig. 1A annual landings have decreased from 12–15 000 t in the early years of the 21st c. to about 8 000 t in 2017–2019 (data for 2020 are shown in Fig. 1 but not included in subsequent analyses). Demersal fishery revenues (Fig. 1B) have fluctuated at ca. 60 M€ along the study period, with a decreasing trend since 2007. Fig. 1C shows the evolution of landings for the three bottom trawl fleet segments, categorized by vessel length class, and the small scale units combined. The figure shows that landings decreased for all fleets over the study period. The evolution of revenues (Fig. 1D) shows that the overall decrease in fleet landings was accompanied by a reduction in fleet revenues for all segments, with the notable exception of the large trawlers class. The landings and revenues of small scale fleets have also decreased and amount in recent years to 5% or less of the demersal fishery, in volume and value (Fig. 1C, D). Note that the decrease in landings follows the trend of decreasing fishing boats in the area, as observed in general in Mediterranean EU member states (Maynou, 2020; Sánchez-Lizaso et al., 2020).

The implementation of the Western Mediterranean MAP divides the activity of demersal fleets in two métiers: boats practicing the continental shelf mixed fishery and boats practicing the deep water crustacean fishery. All fishing units can operate by law any of the two metiers, but in practice, the fleet segment with the largest units (VL2440) has more activity (fishing days) on the deep water fishery, while the smallest units (VL1218) tend to restrict their activity to the continental shelf. The main species in volume and value of the continental shelf mixed fishery is the European hake, while the deep water fishery targets the red shrimp. These two species were selected as main species for the bioeconomic model, and combined they amount to 20% and 42% of the landings and revenues, respectively, in recent years (Fig. 1A and B).

Table 1 shows the importance of landings for the two main target stocks as well as the relative distribution of landings and fishing effort by fleet segment. The fleet segment comprising the mid-size boats (VL1824) makes up ca. half of the entire fleet (52%) and produced more than half of the landings in recent years. The large vessel class (VL2440) is more active in the deep-water crustacean fishery and produced 60.1% of the red shrimp landings. The smallest vessel class (VL1218) had low landings of the two target species and overall low productivity (26 t/boat/year compared to 48 t/boat /year for class VL1824 and 71 t/boat/year for class VL2440).

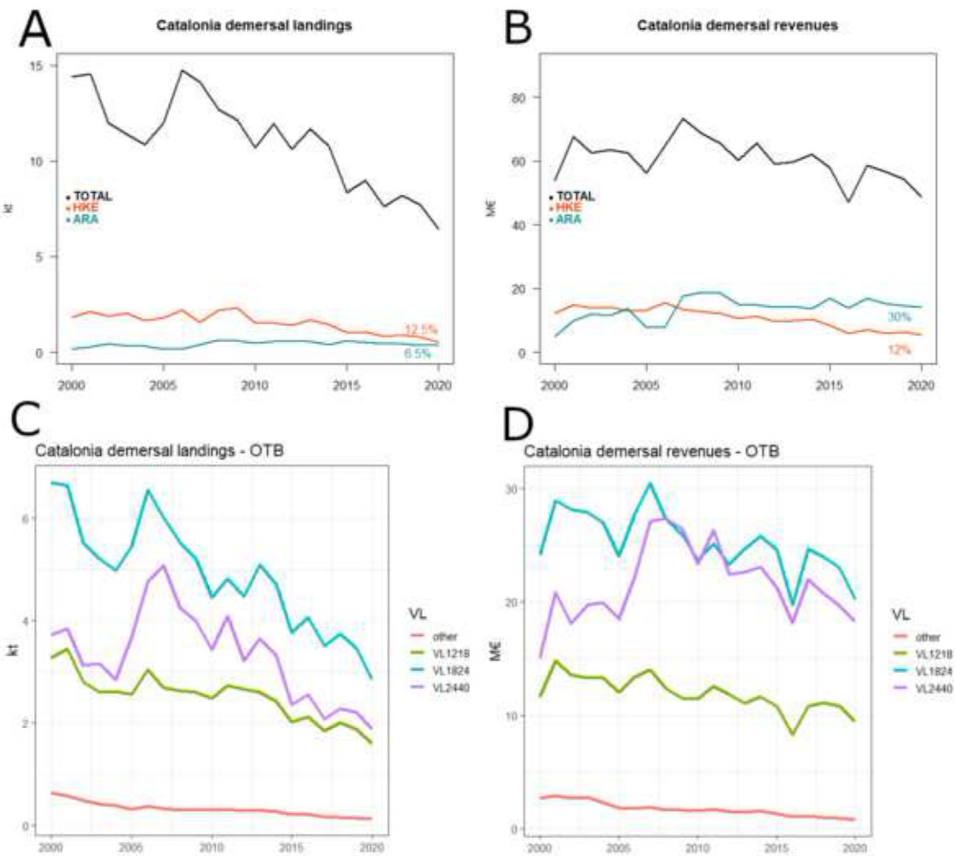

Fig. 1. Upper panels show the total demersal landings (A) and revenues (B) of the bottom trawl (OTB) fleet in Catalonia, highlighting the contribution of the two main species in the model application: European hake (HKE) and red shrimp (ARA). The percentages represent the relative contribution of these two main stocks to total production, averaged over 2017–2019. Lower panels show the landings (C) and revenues (D) of the three OTB segments, categorized according to vessel overall length class (VL), with the contribution by small scale fishing units ("other"). Vessel length classes: VL1218 12 to 18 m LOA, VL1824 18 to 24 m LOA and VL2440 24 to 40 m LOA.

2.2. Bioeconomic model

An adaptation of the fisheries bioeconomic model of Sgardeli et al. (2019) was used to explore the optimal levels of fishing mortality and fishing effort distribution across the three main bottom trawl fleet segments, under different optimization constraints. The biological sub-model follows the general Pella–Tomlinson formulation of a fisheries surplus production model (Pella and Tomlinson, 1969) for three stocks that define the demersal fishery: European hake (representing the continental shelf métier), red shrimp (representing the deep water métier) and other species (commercial bycatch). The economic submodel deviates from the formulation in Sgardeli et al. (2019) and is an adaptation of the economic component of the MEFISTO model (Maynou, 2019).

In the general Pella–Tomlison formulation the expected equilibrium yield (Y) of a fish stock subject to fishing mortality F is (Schnute and Richards, 2002; Sgardeli et al., 2019):

$$Y = FK\left(1-(n-1)\frac{F}{r}\right)^{\frac{1}{n-1}} \tag{1}$$

where K is the stock's carrying capacity, r is the intrinsic growth rate of the stock and n is a parameter of asymmetry of the Pella–Tomlinson production function.

Following Sgardeli et al. (2019), in fisheries managed through effort control and assuming a proportional relationship between fishing effort and fishing mortality, an F target can be achieved by setting a combination of individual efforts for each fleet. Based on the current (t = 0) effort levels of each fleet j, E_j^0, the new effort levels can be defined by:

$$E_j^{new} = \mu_j E_j^0 \tag{2}$$

where μ_j are multipliers of the current effort levels. The new effort levels of each fleet are combined to produce a new fishing mortality for each species i:

$$F_i^{new} = \sum_j F_{i,j}^{new} = \sum_j q_{i,j}E_j^{new} = \sum_j q_{i,j}\mu_j E_j^0 \tag{3}$$

where $q_{i,j}$ is the catchability of each fleet, assumed to be constant in time. Eq. (3) is equivalent to:

$$F_i^{new} = \sum_j \mu_j F_{i,j}^0 \tag{4}$$

where $F_{i,j}^0$ is the partial fishing mortality by stock and fleet. Following the formulation of Sgardeli et al. (2019) for the fleet model, the partial fishing mortalities of each fleet, $F_{i,j}^0$, can be computed from the fleets' catch shares ($c_{i,j}$ in Table 1), that is, the proportion of the total catch of each species by each fleet:

$$F_{i,j}^0 = F_i^0 x_{i,j}^0 = F_i^0 \frac{C_{i,j}^0}{C_i^0} \tag{5}$$

Finally, assuming that catch shares remain constant in time, the target fishing mortality can be expressed in terms of the current fishing mortality, effort multipliers and catch shares:

$$F_i^{new} = F_i^0 \sum_j \mu_j x_{i,j}^0 \tag{6}$$

Substituting Eq. (6) into Eq. (1), the yield at equilibrium Y for each species i can be expressed in terms of the effort multipliers:

$$Y_i = F_i^0 \left(\sum_j \mu_j x_{i,j}^0 \right) K_i \left(1 - (n_i - 1) \frac{F_i^0 \sum_j \mu_j x_{i,j}^0}{r_i} \right)^{\frac{1}{n_i - 1}} \quad (7)$$

The economic sub-model was based on the MEFISTO model (Maynou, 2019). In this model, typically applicable to Mediterranean fisheries where labour remuneration follows a share basis (Guillen et al., 2015), the private profits of the enterprise are computed from the value of landings, reduced by the common costs (CC), labour costs and fixed and other variable costs. That is, the value of landings or revenues for each fleet j is:

$$R_j = \sum_i Y_{i,j} p_{i,j} \quad (8)$$

where $p_{i,j}$ is unit price of landings per species and fleet.

The common costs (CC_j) in the case study fishery are the first sale taxes (proportional to revenues through a coefficient τ), and the fuel costs (CF_j), directly related to fishing effort (E_j):

$$CC_j = \tau \cdot R_j + CF_j \cdot E_j \quad (9)$$

The remuneration to the crew (labour costs) in this share-based remuneration scheme are a fraction γ of the landings value once the common costs are deducted:

$$LC_j = (R_j - \tau \cdot R_j - CF_j \cdot E_j) \cdot \gamma_j \quad (10)$$

Finally, the private profits of each fleet are:

$$\pi_j = (R_j - \tau \cdot R_j - CF_j \cdot E_j) \cdot (1 - \gamma_j) - VC_j \cdot E_j - (FC_j + KC_j) \quad (11)$$

where VC_j are variable costs proportional to effort, FC_j are fixed costs, KC_j are capital costs. The latter two are fixed in the sense that they do not depend on actually using the boat for fishing.

2.3. Model parameters

The values of the economic parameters are shown in Table 2, which were derived primarily from the electronic appendix to the European Union fisheries Annual Economic Report (AER, 2019), except for fish ex-vessel prices that were obtained from local sources. The Spanish economic data provided in AER (2019) correspond to FAO AREA 37.1.1, which is a geographical unit larger than that covered by the study fishery, and the data were disaggregated by unit of effort (number of days and vessels per year) and scaled to the case study fleets following the method in Section 6 "AER Report Methodology" (AER, 2019, pp. 462–463) to obtain the fuel, variable, fixed and capital costs. The tax of first sale (τ) in Catalonia is 16% (10% of sales value added tax plus 6% of various duties to the Fishers' Association that organizes the fish sale process). The share to the crew remuneration (γ_j) was derived from the labour costs reported in the electronic annex to AER (2019).

The parameters of the biological sub-model were estimated with SPiCT, a software package to fit non-equilibrium surplus production models to fisheries data, using library *spict* v. 1.3.4 (Pedersen and Berg, 2017) of the R language v. 3.6.3. The surplus production model in SPiCT follows the classical Pella–Tomlinson model, reparametrized following the approach of Fletcher (1978) with an additional additive observation error term to facilitate model identifiability and numerical convergence (Pedersen and Berg, 2017). The input data to the estimation model were capture data by stock (European hake, red shrimp and other commercial catches of the bottom trawl fleet segments) and a corresponding fisheries-dependent standardized cpue index, for the period 2000–2019. The standardized cpue index was built, for each stock, based on a commercial fisheries data set for Catalonia that reports monthly catches per vessel, port, and fishing gear for the period 2000–2019. The model used raw cpue (kg/vessel/month) as the dependent variable and year, month, gear, port and vessel length overall as possible explanatory variables. A Generalized Linear Model (GLM) with the Gamma distribution function for the log-transformed dependent variable was built with all the possible combinations of explanatory variables ($2^5 = 32$ candidate models) and the best fitting model was selected based on the model structure with lowest AICc (Maunder and Punt, 2004; Anderson, 2008). In the case of hake and "other" the model with explanatory variables "year", "vessel length" and "fishing gear" was selected, while in the case of red shrimp only "year" and "vessel length" were retained. The annual cpue indices for hake and "other" were standardized to a vessel of length overall 16 m for fishing gear OTB, while for the red shrimp cpue index the reference vessel size was taken as 22 m. The parameters of the biological model estimated by SPiCT are shown in Table 3.

2.4. Optimization

The optimal set of effort multipliers for the three bottom trawl fleets were computed for the following management objectives: (i) maximizing private profits, MMEY (Eq. (11)); (ii) maximizing labour remuneration (wages) MMLab (Eq. (10)); (iii) maximizing multispecies MSY, MMSY; (iv) maximizing profits subject to pretty good yield, MPGY; and (v) maximizing profits subject to maintaining equilibrium biomass B_{eq} above B_{MSY} for all species, MBeq > Bmsy.

Labour remuneration and maximum private profits can be obtained by finding the optima of Eqs. (10) and (11) in terms of the equilibrium yield (Eq. (7)) and the effort multipliers μ_j. The objective functions to maximize, which are interpreted as the social and economic objectives, respectively, become:

$$LC[\mu_j] = (R_j[\mu_j] - \tau \cdot R_j[\mu_j] - CF_j \cdot \mu_j \cdot E_{j,0}) \cdot \gamma_j \quad (12)$$

$$\pi[\mu_j] = (R_j[\mu_j] - \tau \cdot R_j[\mu_j] - CF_j \cdot \mu_j \cdot E_{j,0}) \cdot (1 - \gamma_j) - VC_j \cdot \mu_j \cdot E_{j,0} - (FC_j + KC_j) \quad (13)$$

Note that in this model, and consistent with the WM MAP, only effort in terms of fishing days (activity) is optimized and not the number of vessels (capacity).

The biological objective, in terms of maximum sustainable yield, can be derived from the biomass dynamics equations for each species:

$$MSY = r \cdot K \cdot n^{-n/(n-1)} \quad (14)$$

with corresponding $F_{MSY} = r/n$. The optimal effort allocation becomes:

$$\sum_j \mu_j x_{i,j}^0 = F_{MSY,i,j} / F_{i,j}^0 \quad (15)$$

For the fourth objective, the values of fishing mortality at PGY corresponding to 80% of MSY can be found by solving the following equation for each species (Sgardeli et al., 2019: Appendix):

$$\left(\frac{F_{PGY}}{F_{MSY}} \right)^n - \frac{n}{n-1} \left(\frac{F_{PGY}}{F_{MSY}} \right)^{n-1} + \frac{0.8^{n-1}}{n-1} = 0 \quad (16)$$

The optimal effort allocation producing MMEY subject to PGY ("MPGY") is obtained by setting the inequality constraint:

$$\frac{F_{pgy-,i}}{F_{i,j}^0} \leq \sum_j \mu_j x_{i,j}^0 \leq \frac{F_{pgy+,i}}{F_{i,j}^0} \quad (17)$$

where $F_{pgy-,i}$ and $F_{pgy+,i}$ are the lower and upper, respectively, fishing mortalities that would produce 80% of the fisheries yield at MSY for each species.

Table 2
Parameters of the economic submodel. Annual mean and minimum/maximum values calculated for the Catalonia fleet from electronic annex to AER (2019). Days at sea are the average number of days for each vessel of the fleet. Catches and annual costs are given per fleet.

	Symbol	VL1218	VL1824	VL2440	Total
Fleet size	NV	57	117	50	224
Days at sea per year (DAS)	E	188	203	209	
Catches (t)	Y	1486.52	5612.21	3541.66	10 640.39
Fish ex-vessel price (€/kg)[a]	p_{HKE}	7.88 (7.21–8.92)	8.19 (6.10–8.46)	8.04 (6.35–8.35)	
	p_{ARA}	38.56 (35.82–43.93)	38.92 (35.93–40.94)	39.85 (36.81–40.03)	
	p_{OTH}	5.76 (5.54–5.82)	6.64 (6.40–7.04)	9.09 (8.88–10.52)	
Fuel cost (k€/yr)	CF	3454 (3200–3550)	16 131 (15 000–17 500)	9020 (8500–10 000)	28 606 (26 700–31 050)
Share to the crew	γ	37.7% (35–39)	38.7% (36–39.5)	41.4% (40.–42)	
Variable cost (k€/yr)	VC	5472 (5200–5800)	20 225 (18 000–22 000)	11 629 (10 500–12 500)	37 326 (33 700–40 300)
Fixed cost (k€/yr)	FC	857 (800–1000)	2688 (2500-2950)	2337 (2150–2550)	5882 (5450–6500)
Capital cost (k€/yr)	KC	55 (40–68)	305 (270–380)	1060 (850–1150)	1420 (1160–1600)
Crew size (#/v)[b]		3.08 (2.10–4.20)	4.20 (3.50–6.10)	5.25 (4.60–7.90)	

[a]Fish ex-vessel price corresponds to a recent average (2016–2019) and was obtained from the Fisheries Service of the Autonomous Government of Catalonia, available through: http://agricultura.gencat.cat/ca/ambits/pesca/.
[b]Crew size as number of persons, full time equivalent (FTE), including the owner-operator

Table 3
Parameters of the biological surplus production model (HKE: European hake; ARA: red shrimp; OTH: other commercial by catch).

	HKE			ARA			OTH		
	Estimate	sd	90% C.I.	Estimate	sd	90% C.I.	Estimate	sd	90% C.I.
r (yr^{-1})	1.860	0.622	0.641–3.078	3.285	2.420	0.581–18.576	1.898	0.238	1.862–2.162
K (t)	3308.9	1.355	1825.3–5998.5	1945.0	2.027	486.7–7773.6	27 220	0.244	16 849–28 086
F_{MSY} (yr^{-1})	0.788	1.349	0.438–1.419	0.289	2.030	0.072–1.159	0.946	0.238	0.846–1.437
MSY (t)	1875.6	1.075	1628.4–2160.4	386.6	1.275	240.1–622.4	12 130.1	0.027	12 074–12 787
B_{MSY} (t)	2380.0	1.332	1356.7–4175.0	1363.3	2.0	350.4–5304.3	14 110.3	0.244	8734–14 559
n	8.034	1.654	2.996–21.540	9.212	1.944	2.503–33.910	2.2	0.102	1.855–2.596
$F_{current}$ (yr^{-1}, avg. 2017–2019)	0.850			0.307			1.328		
F_{PGY}80% MSY	0.532–0.890		0.296–0.959	0.198–0.322		0.080–1.290	0.679–1.327		0.607–2.016

The fifth management objective, obtaining the MMEY while maintaining equilibrium biomass B_{eq} above B_{MSY} for all species can be obtained by optimizing private profits with the following constraint:

$$\sum_j \mu_j x^0_{i,j} \leq \frac{r_i}{n_i F^0_{i,j}} \tag{18}$$

The constrained optimization problems were solved with function solnp of R library *Rsolnp* v. 1.15, which is a port by Ghalanos and Theussl (2015) of the general optimizer based on non-linear programming developed by Y. Ye for MATLAB (Ye, 1989). The unconstrained maxima were solved with the function optim with method 'L-BGFS-B', bundled with the standard R library *stats* v. 3.6.3.

The uncertainty in the results of the SPiCT stock assessments was propagated to the optimization of effort allocation by running the optimizer 5000 times[1] under each of the five management objectives. The biological parameters of each species (r, K, n) were sampled from the multivariate log-normal distribution constructed from the covariance matrix of these parameters obtained from the SPiCT stock assessment. A modification of the code provided by Sgardeli et al. (2019) was used to perform the analyses in R 3.6.3.

3. Results

The biomass at equilibrium for the three stocks is shown in Fig. A.1 of the Appendix which shows that each stocks responds differently to the management policies under study, as could be expected from their different biology and current exploitation status. Four socio-economic indicators were extracted from the optimization results of the bioeconomic model at equilibrium under the five management scenarios: aggregate landings and profits, number of jobs, average annual remuneration per crew member. The results are shown as box plots in Fig. 2, compared to the values at statu quo (i.e. maintaining the current effort allocation among the three fleets) and to the values obtained by applying a 40% effort reduction across all fleets, as specified in the NW MAP. Fig. 2A shows that the total landings would be maximum at MMSY (median value of 13 241 t), as can be expected, but management under MMLab would generate the second best amount of landings (13 048 t). Profits (Fig. 2B) were maximized under the MMEY management objective, as expected, reaching a median of 61.2 M€, but under MMLab the profits would reach the second best value of 57.6 M€, approximately twice the profits obtained at statu quo (28.9 M€). The number of jobs at equilibrium (Fig. 2C) were low at MMSY, MMEY or MMLab, similar to the S40% scenario, with a maximum of 2462 jobs (FTE) under the MBeq > Bmsy strategy. This value is slightly higher than the number of jobs under statu quo, 2387. Conversely, the average labour remuneration per crew member (Fig. 2D) was highest under MMEY (24 312 €/yr) and the optimization results for average wage were parallel to the results for profits (Fig. 2B), with a second best scenario for management under MMLab (22 280 €/yr), closely followed by the S40% case. These values are more than twice the average wage under statu quo (11 380 €/yr). Fig. 2 also shows that any alternative management strategy would perform better, in terms the four selected indicators, than maintaining the statu quo effort allocation, except for jobs.

Fig. 3 provides a summary two-dimensional plot ("biplot") of the ordination by principal components of the optimization results. The biplot shows that management objectives S40%, MMSY, MMEY and MMLab tend to produce high values of profits and wages, while SQ, MPGY or MBeq > Bmsy correlate with higher number of jobs. The indicators jobs and profits/average wage appear opposite in the biplot, indicating that high average wages and high employment are not compatible in this fishery. The indicator landings had low correlation with the other three indicators and tends to increase under MMSY only.

[1] Note that the optimizers converged only between 20 and 25% of the times.

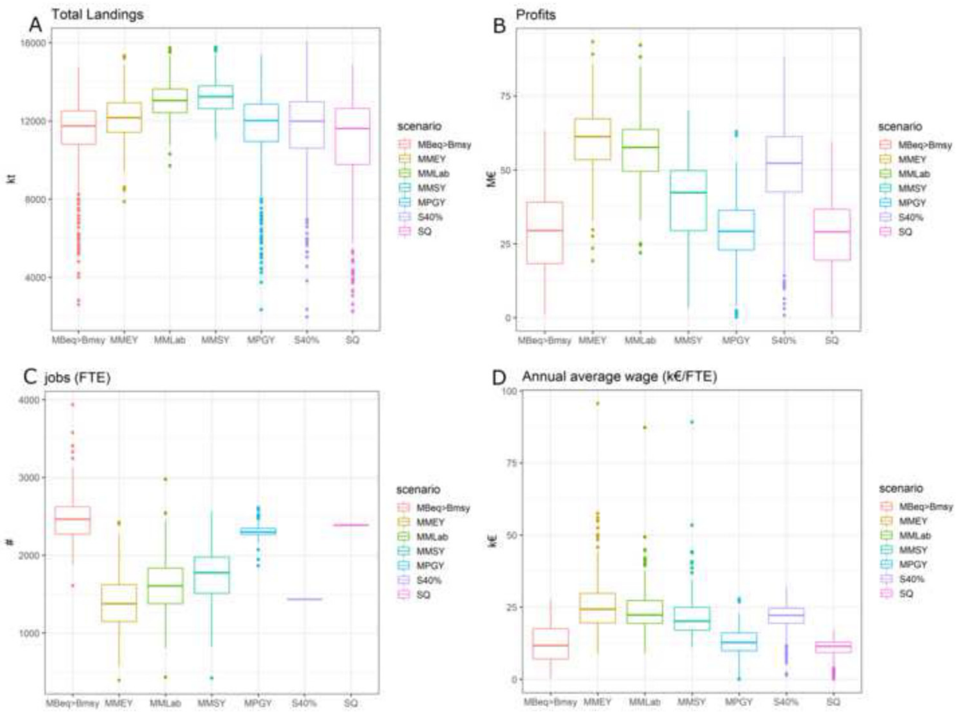

Fig. 2. Indicators at equilibrium of the bioeconomic model applied to the Catalonia bottom trawl fishery under different management objectives: SQ, statu quo; S40%, reduction of 40% from statu quo; MPGY, multispecies Pretty Good Yield; MMSY, multispecies Maximum Sustainable Yield; MMLab, multispecies Maximum Labour Remuneration; MMEY, multispecies Maximum Economic Yield; MBeq-Bmsy, multispecies Biomass at equilibrium larger than B_{MSY}. The box plots show the 50% (median), 25% and 75% percentiles ("interquartile range") of the data distribution, along with ±1.5 interquartile range and outliers.

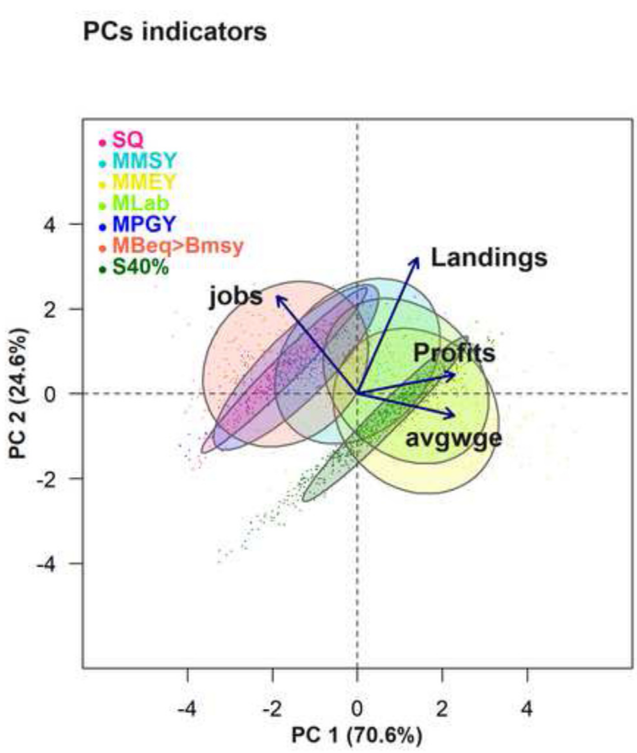

Fig. 3. Biplot of the principal component analysis of optimization objectives and four selected indicators. Management objectives as in Fig. 2.

The relative effort allocation among fleets is shown in Fig. 4 for the different management objectives. With the objective of maximizing multispecies yield, the optimal solution results in practically doubling the effort for the larger trawlers (median $\mu_C = 1.96$) and reducing to practically 0 the effort of the other two fleets. Optimizing for labour remuneration yielded a high relative effort for the large trawlers ($\mu_C = 1.78$), while keeping the activity of the small trawl class to half of current levels ($\mu_A = 0.54$, although with high variability). The effort levels of the mid-size vessels, which is the class containing ca. half of the fleet, had an optimum at 0 also under MMEY. Under this management objective, the optimum level of activity of the small size fleet was more than double than present levels ($\mu_A = 2.36$, with high variability) and the level of the large size fleet would need to be reduced by 90% ($\mu_C = 0.10$). The optimum levels of effort allocation for management objectives MBeq > Bmsy and MPGY were not markedly different from statu quo, although the levels of the mid-size class were estimated at higher values than statu quo ($\mu_C = 1.50$ for MBeq > Bmsy and $\mu_C = 1.14$ for MPGY), while the effort levels of the other two fleets were lower.

4. Discussion

The analysis of optimal effort allocation among the three trawl fleet segments operating in the Catalonia demersal fishery with Sgardeli et al. (2019) model demonstrated the difficulty to quantify the optimal amount of input (fishing effort) to obtain a specified amount of output (landings, profits or labour remuneration, for instance) in multispecies fisheries exploited by heterogeneous fleets. That is, the different management objectives examined (e.g., maximize the amount of landings, maximize profits or maximize employment) appear to conflict with each other. For example, the indicator "landings" was uncorrelated with the socio-economic indicators. "Landings" increased only under MMSY, suggesting that a management strategy attempting to maximize multi species landings cannot simultaneously provide high wages/profits and high number of jobs. Employment,

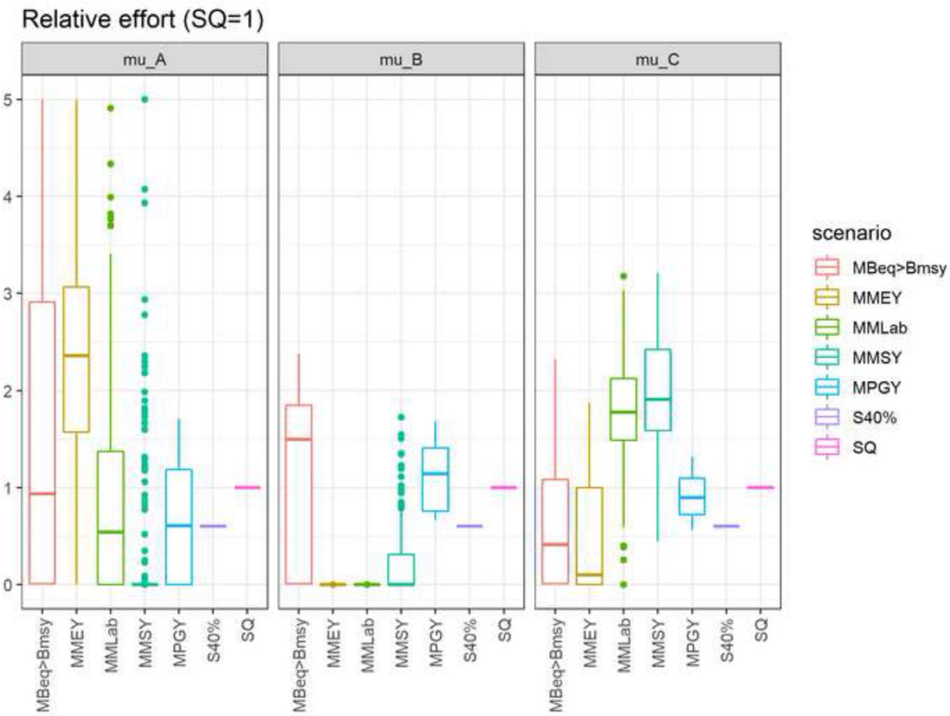

Fig. 4. Relative effort allocation (μ_j) that optimizes the multispecies objective indicated for three bottom trawl fleets in Catalonia. μ_A: relative effort of fleet VL1218; μ_B: relative effort of fleet VL1824; μ_C: relative effort of fleet VL2440. Management objectives as in Fig. 2.

in terms of number of jobs, was inevitably reduced when maximizing landings, economic yield or the total labour remuneration. Instead a lower number of higher quality jobs was obtained; that is, higher wages per crew member for a reduced fleet size, because as discussed by Guillen et al. (2015) in a share-based system of remuneration fisheries workers capture part of the fisheries rent. Hence, those objectives that attempt to maximize profits and wages could be compatible, but high wages or profits would not be compatible with high employment. The social objective in fisheries should move beyond merely focusing on employment (Hilborn, 2007) and consider remuneration to crew members, both in absolute terms and relative to other sectors of the economy (quality of employment).

Some management objectives resulted in drastic reductions of effort allocated to certain fleets (especially the mid-size vessel class VL1824, which is at present the more numerous comprising 52% of the trawl fleet). In particular, the objectives of maximizing labour remuneration (MMLab) or economic yield (MMEY) resulted in this fleet disappearing from the fishery under these management objectives. Fisheries policy objectives usually avoid (implicitly or explicitly) strong changes to fleet composition or activity, with the result that fisheries exploitation continues to be suboptimal and fishing capacity excessive. The results of the application of a General Equilibrium Economic model by Da-Rocha et al. (2020) also showed that the Spanish Mediterranean fishery is economically inefficient, with excessive, low productive fishing units and low equilibrium wages. The size and composition of the fleet operating at present in the case study, as elsewhere in the Mediterranean Sea, are the result of a historical process and have never been considered in terms of efficiency. Hence, fleet size and composition, which are directly related to fishing effort and fishing mortality, can be very far from any of the possible optima that fisheries managers could contemplate as policy targets. Naturally, the strong reduction in the number of fishing days resulting in optimal effort equal to zero for fleet VL1824 in scenarios MMEY and MMLab would produce a social cost in terms of unemployment, which fisheries managers necessarily must assess. The model could be expanded by taking into account the opportunity cost of labour (Danielsen and Agnarsson, 2020), although for South European fisheries this is very difficult to take into account because jobs in fisheries are mostly unqualified jobs.

It is well known that achieving F_{MSY} for all target stocks in a multispecies fishery exploited by heterogeneous fleets is generally not possible (Clark, 1990; Hilborn et al., 2012) and alternative approaches for mixed stock fisheries based on the concept of multispecies pretty good yield have been considered (Rindorf et al., 2017), whereby most species can be fished at levels of F different from F_{MSY} but providing a yield close to MSY. However, MPGY in this case study did not produce landings, profits or labour remuneration much different from the statu quo. The results also show that the conservation objective of maintaining "healthy stocks" (biomass at equilibrium larger than biomass at MSY) did not produce indicators markedly different from statu quo. Despite the low socio-economic performance of these two objectives in this study, compared to MMEY or MMLab objectives, other studies have shown that fishing at the low F_{MSY} range helps reduce the risk of stock collapse and contributes to meet F_{MSY} targets in multispecies fisheries (Hilborn, 2010; Thorpe et al., 2016).

The main pillar of the reformed Common Fisheries Policy (EU Reg. 1380/2013, 2013) is to achieve the optimum exploitation of fisheries target stocks at a specified point in time, which in the Western Mediterranean MAP (COM/2018/0115 final – 2018/050 (COD)) is operationalized as reaching F_{MSY} by 2025 with the main management measure of reducing up to 40% of Total Allowable Effort (fishing days). However, comparing the results regarding optimal allocation of fishing effort obtained here (Fig. 4) and the up to 40% reduction in fishing effort across all fleets established in the MAP it is apparent that the plan does not go in the direction of optimizing employment or profitability (Fig. 2B and C). The Common Fisheries Policy implicitly assumes that sustainable fishing of European stocks at MSY will provide social and economic benefits, but in practice it is not obvious how conservation, social and economic objectives can be met simultaneously with the instruments set in the Regulation and in particular for Mediterranean fisheries. Asche et al. (2018) examining the three dimensions or "pillars" of sustainability in world fisheries show that they are rarely compatible and when they can be reconciled, it is under management regimes based on property rights. Danielsen and Agnarsson (2020) in a comparative study of different Faroese fleets also show that private profits and crew remuneration are higher, and stock conservation status is better, in rights-based fisheries than in fisheries managed by effort control (although the Faroese model of effort allocation is not homologous to the Mediterranean model). The meta-analysis of Oostdijk and Carpenter (2020) provides evidence pointing to the higher probability of reducing overfishing in management systems with quota limits and individual allocation. Fisheries management based on catch quotas imply adaptive management because quotas are set on a time-defined basis (usually annually), while effort-based regimes are more difficult to adapt to the available fishing opportunities. Additionally, when effort restrictions are implemented, fisheries management must face the risk of increasing fishing mortality by means of investment in technology ("technological creep") (Marchal et al., 2007).

A strong reduction of capacity and reallocation of fishing effort among fleets as optimal solution to the sustainable and socioeconomically viable exploitation of Mediterranean fisheries may be less dramatic than it appears. Over the last two decades, a strong reduction in the number of fishing vessels has already been observed (Maynou, 2020; Sánchez-Lizaso et al., 2020), due in part to the low economic performance of Mediterranean fishing fleets, and in part to an ageing active population in fisheries with low intergenerational replacement (Gómez and Maynou, 2021). Tokunaga et al. (2019), in an analysis of management objectives for Japanese fisheries, remarked also on the ageing and decreasing fishermen's population in Japan and concluded that this situation may be an opportunity to move towards a rights-based management system with individual quotas. Additional and alternative employment in the maritime economy (package and processing or other value-adding activities in fisheries, aquaculture or tourism; Jeffery et al., 2021; Gómez and Maynou, 2021) might contribute to alleviate the short-term social problems generated by a strong management action.

CRediT authorship contribution statement

Francesc Maynou: Conceptualization, Methodology, Software, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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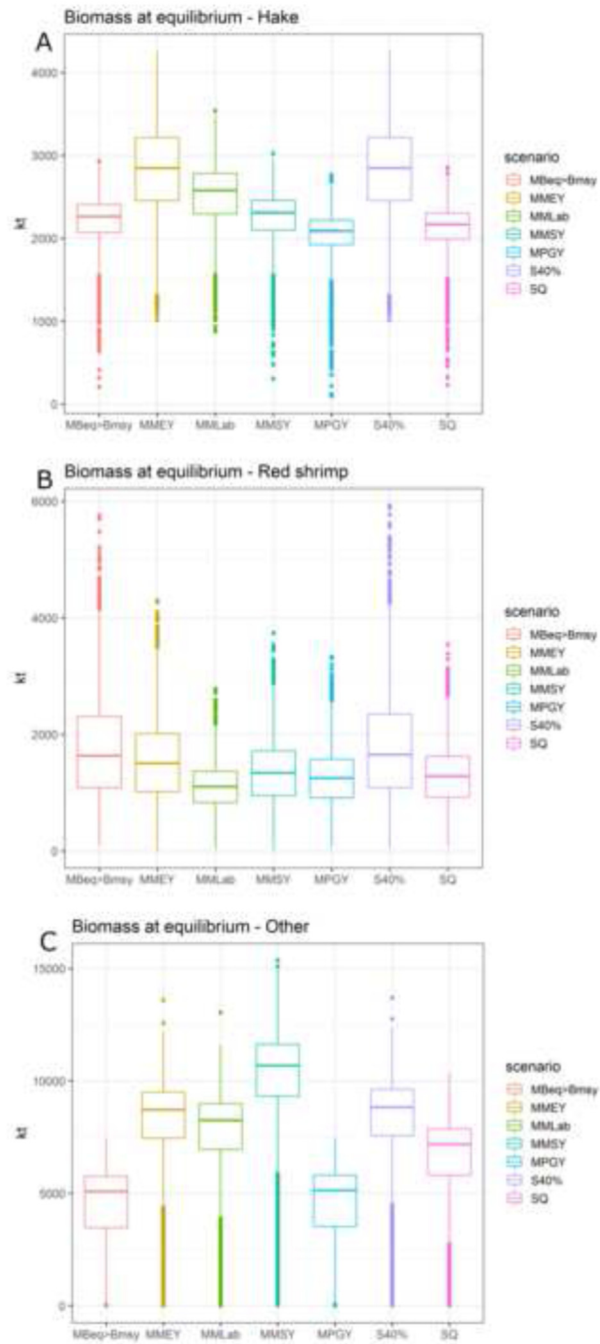

Fig. A.1. Biomass at equilbrium of the two main stocks and combined stock under different optimization scenarios.

Appendix. Biomass at equilibrium under the different scenarios tested

The biomass at equilibrium for each stock under the different optimization scenarios and the statu quo cases is shown in Fig. A.1. The figure shows that each stock responds differently to the management options and it is not possible to have the maximum biomass at equilibrium for all three stocks simultaneously. For hake (Fig. A.1, top) the highest biomass values were produced for scenarios MMEY and S40%, while for red shrimp it was MBeq > Bmsy and for the combined stock of other commercial species the highest value is obtained under MMSY.

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