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Biological, economic and social viability of a mesopelagic fishery in the Bay of Biscay

Dorleta Garcia[a,*], Marga Andrés[a], Iosu Paradinas[a], Paula Alvarez[a], Guillermo Boyra[a], Rolf A. Groeneveld[b]

[a] AZTI, Marine Research, Basque Research and Technology Alliance (BRTA), Sukarrieta, Spain
[b] Environmental Economics and Natural Resources Group, Wageningen University, Netherlands

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ABSTRACT

A recently estimated high mesopelagic biomass level, along with the increasing demand for raw material for fish oil and fishmeal, has sparked interest on exploiting mesopelagic populations. However, their exploitation is controversial due to their ecological role as primary prey for other populations and as CO_2 sequestrators. Therefore, before starting a new fishery, the three pillars of sustainability, ecological, economic and social, should be assessed. In the Bay of Biscay *Maurolicus muelleri* is the main mesopelagic species. Based on data collected over an eight-year period, a simulation model was implemented to assess the biological, economic and social performance of different fleets and exploitation levels. The conditioning of the population dynamics model presented several challenges, as the available survey index did not cover the full population distribution every year and the population had never been exploited in the Bay of Biscay. To overcome these problems an absolute population index was estimated using a spatio-temporal model, which was later used to adjust an age structured population dynamics model. Both models were fitted using Bayesian statistics to account for inherent uncertainty. The fishery was conditioned by identifying the most suitable fleet and estimating the initial investment and operational costs. The social pillar was approached through the social cost of carbon. The estimated biomass of *M. muelleri* in the Bay of Biscay fluctuated around 1.2 million tonnes. When it comes to exploitation, an industrial fishery may generate profits while maintaining a sustainable biomass level under good efficiency conditions. However, it would be challenging to recover the initial investment. Additionally, the estimated added value generated by this fishery would not be able to compensate for public costs associated with the impacts on carbon sequestration.

1. Introduction

The global population growth is projected to result in a 60 % increase in the demand for food by 2050 (Gatto et al., 2023). This will lead to a higher demand for fish oil and fish meal (FAO, 2020). Increasing the productivity of already exploited stocks or exploring the exploitation of new resources are the alternatives to meeting this demand. Mesopelagic populations, which have not been heavily exploited historically, are considered a suitable source for fish oil and fish meal (Olsen et al., 2020). Three mesopelagic surveys conducted between 2016 and 2017 in the North East Atlantic (Grimaldo et al., 2020) found that lipids and protein content in *M.muelleri* samples were suitable for animal feed and human consumption, and according to Paoletti et al. (2021) they are also suitable for nutraceutical production. This suggests that they could contribute to satisfying the increasing demand for fish protein, improving food security and nutrition (Pauly et al., 2021; Zhu et al., 2023). Additionally, an acoustic survey conducted during the Malaspina 2010 Circumnavigation Expedition, revealed that the estimated abundance of mesopelagic biomass (100 billion metric tonnes) could be 10 times larger than previously estimated (Irigoien et al., 2014). Therefore, commercial exploitation of mesopelagic resources could present a lucrative opportunity for the fishing and aquaculture industry.

Fisheries in European Union (EU) waters are governed by two main management policies that aim to protect marine ecosystems in the EU; the Common Fisheries Policy (CFP) (Salomon et al., 2014) and the Marine Strategy Framework Directive (MSFD) (Long, 2011). The CFP emphasizes that fishing should contribute to environmental, economic and social sustainability and that fish stocks should be harvested at

* Corresponding author.
E-mail address: dgarcia@azti.es (D. Garcia).

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levels consistent with maximum sustainable yield. The overall goal of the MSFD is to maintain healthy, productive and resilient marine ecosystems while securing a more sustainable use of marine resources. The exploitation of fisheries resources is directly linked with three of the descriptors of the MSFD, which highlight the importance of maintaining biodiversity, ensuring the health of commercial fish species, and maintaining elements of the food webs at levels that support long-term abundance and reproductive capacity. Therefore, before implementing any new fishery, it should be demonstrated that it aligns with these principles. Standal and Grimaldo (2020, 2021) analyzed the institutional framework for the development of mesopelagic fisheries and observed that, unlike currently exploited species, there is a lack of management systems to regulate potential fisheries.

Monte Carlo simulation of the socio-ecological system is an appropriate way to forecast the biological, economic and social impact of a new fishery, similar to what is done for existing fisheries in a management strategy evaluation framework or similar approaches (Punt et al., 2016). The quality and accuracy of the forecast depend on how well the dynamics of the different elements in the system (e.g. biological population and exploitation) are represented in the simulation. Additionally, in a managed system, the exploitation of the system should be governed by management strategies that need to be included in the simulation. Productivity of the population, driven by recruitment, individual growth and natural mortality, are crucial factors in the performance of management strategies (Rademeyer et al., 2007). This is important not only in biological terms but also in economic terms, as higher productivity leads to higher catch per unit of effort, and therefore increases the profitability of the fishery.

Since the publication of the study by Irigoien and colleagues (2014), the biology and exploitation of mesopelagic resources have received growing attention. There are several recent studies assessing the potential implementation of a commercial mesopelagic fishery. In a recent paper Schadeberg et al. (2023) identified two predominant ideas in scientific literature about the mesopelagic zone (1) the exploitation of fish resources and (2) the role of the mesopelagic zone as a carbon sink. Prellezo (2018) and Paoletti et al. (2021) used a similar economic approach considering mesopelagic fishery as an opportunity when fleets cannot fish other species. However, they did not consider the productivity of the stock and the productivity of the fishing effort itself which are key drivers of the profitability of the fishery. Dowd et al. (2022) focused on the ecological role of mesopelagic populations and used an Ecopath with Ecosim model to assess the economic value of a potential fishery. Kourantidou and Jin (2022) used a bioeconomic species-centric model (deYoung et al., 2004) to analyse the profitability of a fishery for given values of stock productivity. None of the studies that include stock dynamics in the model (Dowd et al., 2022, Kourantidou and Jin, 2022) focus on an existing fishing fleet with specific characteristics. Recently, Prellezo et al. (2024) evaluated the impact of a potential mesopelagic fishery in the Bay of Biscay from an ecosystem services perspective. The results were highly uncertain, mainly due to the uncertainty in the biomass of mesopelagic populations.

In this study we complemented the existing literature providing abundance estimates for *M. muelleri* in the Bay of Biscay using a single stock Bayesian population dynamic model. While other mesopelagic species like *Benthosema glaciale* and *Myctophum punctatun* are present in the area, *M. muelleri*'s shallower vertical distribution makes it more accessible to fishing, and information on its dynamics is also less limited. Furthermore, we identified the most appropriate fleet to exploit the stock. The biological, economic and social performance of the fishery under a management system based on maximum sustainable yield was assessed using a forward simulation based on the best available knowledge about population dynamics. Biological sustainability was assessed using target and limit biomass reference points as recommended by Mildenberger et al. (2022) and used worldwide (ICES, 2022). While biological objectives and reference points are consistent and well accepted worldwide, there are not broadly used economic and social objectives. In Australia, maximum economic yield has been a primary target reference point since 2007 (Norman-López and Pascoe, 2011), but in Europe the CFP does not have quantitative economic objectives. However, at the operative level, the basic regulation of the CFP includes socio-economic operational indicators with corresponding thresholds (STECF 23–07). Profitability and return on fixed and tangible assets (ROFTA) (Curtin and Keatinge, 2018) were chosen to evaluate the ability of the fleets to generate resource rents and to assess the viability of the initial investment. Social indicators associated directly with the fishing activity used by the Scientific, Technical and Economic Committee for Fisheries (STECF) were unsuitable because they were either not calculable, or proportional to the economic indicators. As mesopelagic resources play an important role in ocean carbon biological pump (Boyd et al., 2019; Cavan et al., 2019; Hoagland et al., 2019; Pinti et al., 2023), at social level, we assessed whether the added value generated by the fishery, which reflects the added value for society, could offset public climate costs, namely the social costs of CO_2 that is no longer sequestered by the exploited population.

2. Material and methods

M. muelleri is a mesopelagic species whose geographic distribution is limited to the North Atlantic region, from the Barents Sea and Iceland to the Mediterranean Sea (Rees *et al.*, 2020). In the Eastern Atlantic, the species is found along the European coastline, from Norway to the northwest coast of Africa. To date, no studies on the population structure of *M. muelleri* in the northeast Atlantic have been published. At a local level, Suneetha and Nævdal (2001) used allozyme analysis and selected morphological measurements to show that the individual fjord populations in western Norway and the offshore location in the North Sea were genetically distinct units. Partial isolation likely plays a significant role in this genetic divergence. In a more recent study, Rodríguez-Ezpeleta et al. (2017) analyzed a population from the Bay of Biscay and concluded, based on genome-wide single nucleotide polymorphism data, that these individuals form an undifferentiated genetic unit. This does not imply that the *M. muelleri* population in the Bay of Biscay is an isolated population. However, for the purpose of this analysis we assumed they are, as available surveys in the Northeast Atlantic cover only limited areas (Vastenhoud et al. 2023).

2.1. Biological data

Biological data, including age at length, maturity and weight at length, of *M. muelleri* were collected during a series of acoustic JUVENA surveys (Boyra et al., 2013), conducted in September in the Bay of Biscay between 2013 and 2020. Additionally, two more cruises contributed to the collection of samples in this area: the international mackerel and horse mackerel egg surveys in spring 2019 and 2022 and the BIOMAN surveys in spring 2020 and 2021. An analysis of the data can be found in Alvarez et al. (2023). Natural mortality was estimated by the model (see Sections 2.3 and 3.2).

2.2. Abundance

The JUVENA acoustic survey provides an estimate of *M. muelleri* biomass in absolute units. The survey is designed to sample juvenile anchovy every autumn, but it also samples the main pelagic species present in the area of distribution of anchovy up to 500 m deep. The Bay of Biscay is sampled in linear transects, perpendicular to the coastline, until the zero-biomass mark of anchovy is reached. Consequently, the survey's spatial coverage varies yearly depending on the presence of juvenile anchovy and does not cover the whole distribution of the *M. muelleri* population in the Bay of Biscay. The nautical area scattering coefficient (s_A) allocated to *M. muelleri* was used to produce spatial distribution maps and vertical profiles. The abundance in numbers was obtained by dividing *M. muelleri*'s s_A by the mean backscattering coefficient of *M. muelleri* (obtained from Sobradillo et al., 2019) and multiplying by the sampled area. The subsequent multiplication by the mean weight provided biomass in the studied area (Fig. 1) (see Doray et al. 2021 for further details).

In order to obtain an estimate of the absolute abundance in the entire region, not just the surveyed area, an extrapolation was conducted using a spatio-temporal model that included bathymetry as an explanatory variable. The model included two components, a constant spatial effect across years with intensity variations for different years (i.e. temporal trend effect) and a spatio-temporal field that changed based on a correlation parameter.

The dataset consisted of approximately 250,000 samples divided over 8 years (2013–2020). The response variable was kilograms with a large proportion of zero values, resulting in a zero inflated continuous process. The literature has proposed various approaches to deal with zero inflated continuous observations, such as adding a small constant to all observations, creating a hurdle or delta model (Paradinas et al., 2022), or using a Tweedie distribution (Tweedie, 1984) as we did in this study. The Tweedie distribution is a special case of the exponential dispersion family. In this analysis we used the compound Poisson-Gamma distribution which allows a continuous transition between observations with zero individuals, coming from a Poisson distribution, and continuous positive observations. Therefore, by using the Tweedie distribution we assumed that zero observations are part of the abundance process as opposed to the assumption of independence in hurdle models. In summary, this approach allows to model data with many zero observations and positive observations as being generated by the same underlying process. Mathematically:

$$Y \sim \text{tweedie}(\lambda, \alpha, \gamma) \tag{1}$$

where Y represents the kilograms in each sample, the parameter λ is the mean of the Poisson distribution (which provides the mass at zero) and $\alpha\gamma$ is the mean of the Gamma distribution (which provides the abundance given presence). Therefore, the expected value, μ, is equal to the product of the three parameters and was log-transformed in the spatio-temporal model:

$$\log(\mu) = \text{f}(\textit{bathymetry}) + \text{f}(\textit{space} * \textit{time}) + \text{f}(\textit{time}) \tag{2}$$

We used Bayesian hierarchical spatial and spatio-temporal models using R-INLA (Rue et al., 2009) to fit the proposed Tweedie model. The spatiotemporal effect consisted of a spatial component and a first-order autoregressive effect that connected consecutive spatial patterns through a correlation parameter. Environmental effects are rarely linear in habitat modeling; thus, the bathymetric effect was fitted using a non-linear effect through a second order random walk. Lastly, the temporal trend was modeled using an unstructured random effect.

The extrapolated index was considered an absolute biomass estimate

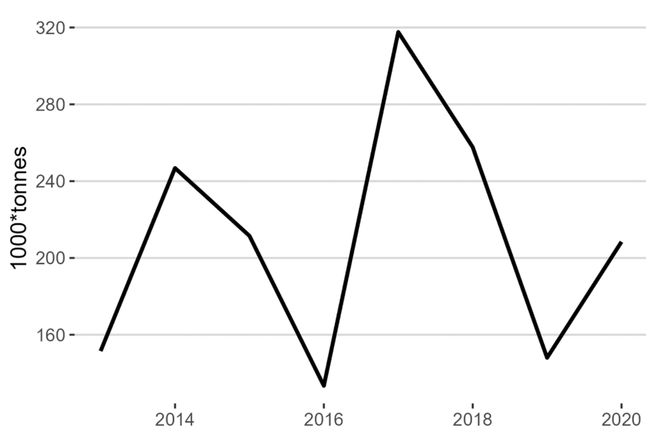

Fig. 1. Biomass, in thousand tonnes, of time series from the Juvena acoustic survey from 2013 to 2020.

of the population in the Bay of Biscay. The biomass was disaggregated into age groups using the observed age proportions in the biological samples and the weight at age data (Alvarez et al., 2023).

2.3. Bayesian population dynamic model

Based on the extrapolation of the JUVENA survey, which provided an estimate of number of individuals at age of the *M. muelleri* population in the Bay of Biscay, a Bayesian age structured population model was applied to the available data. Since this population has not been harvested, there was no catch data to allow estimating the scale of the population, so it was necessary to assume that the index was absolute. The classical exponential survival model was used for population dynamics:

$$N_{a+1,y+1} = N_{a,y} \bullet \exp(-M_y) \tag{3}$$

where subscripts a and y refer to the age and year respectively, and N is the number of individuals. Individuals older than 2 were rarely observed in the data, so three age groups were considered, ages 0–2. Natural mortality (M) was a parameter in the Bayesian model, with a uniform prior distribution with bounds at 0.1 y^{-1} and 3 y^{-1} being used.

Recruitment (R) was modeled using a log-normal distribution with mean equal to R_0 and standard deviation equal to σ_{R_0}:

$$R_y \sim LN(R_0, \sigma_{R_0}) \tag{4}$$

numbers at age in the first-year data, 2013, also followed a log-normal distribution with mean $\widetilde{N}_{a,1}$ and standard deviation equal to $\sigma_{\widetilde{N}_{a,1}}$:

$$N_{a,1} \sim LN(\widetilde{N}_{a,1}, \sigma_{\widetilde{N}_{a,1}}) \tag{5}$$

The observation equation was given by:

$$\log(I_{a,y}) \sim N(\log(\mu_{I_{a,y}}), \varphi_{I_a}) \tag{6}$$

where the mean of index $I_{a,y}$ was obtained as:

$$\log\left(\mu_{I_{a,y}}\right) = \log(q_a) + \log(N_{a,y}) + \log\left(\exp(-\alpha_y \bullet M) - \exp(-\beta_y \bullet M)\right) - \log(\beta_y - \alpha_y) - \log(M) \tag{7}$$

where q_a is an age dependent catchability constant over time, and α_y and β_y denote the starting and ending time of the survey in the year y, in percentage, respectively. Log catchability of the index followed a normal distribution with mean equal to μ_q and standard deviation equal to σ_q:

$$\log(q) \sim N\left(\mu_q, \sigma_q\right) \tag{8}$$

Log normal distribution is usually used to model catchability and ensures values are positive.

And the precision of the index φ_{I_a} followed a gamma distribution with parameters s_1 and s_2:

$$\varphi_{I_a} \sim \text{gamma}(s_1, s_2) \tag{9}$$

The prior value for q was equal to 1, for all ages, with a narrow gamma distribution that made the index quite precise, consistent with the assumption of the index being an absolute index of biomass.

The model was fitted to each of the 5000 samples drawn from the abundance index model in Section 2.2. In turn, 5000 iterations of the Markov chain were retained for each of the 1000 Bayesian model fits, which resulted in 2.5e^7 iterations. The Bayesian model was fitted using a big thinning (200 iterations) to avoid autocorrelation in the natural mortality parameter.

2.4. Fleet and economic data

Several factors were considered in the selection of the most suitable fleet: the financial risks, the fishing area, the fishing gear, the vessel size, the opportunity costs, if the fleet would be strongly affected by the landing obligation, the age of the vessels and the ship owner willingness to exploit the new resource. Technical descriptions of all the Basque fleets were assessed, effort patterns (from logbooks) were analyzed and economic data (from STECF, 2023) served to estimate opportunity costs. Finally, with all the results, a survey among ship owners (representing 40 % of the targeted vessels) was carried out to assess their willingness to exploit the resource. The fleet targeting cod (referred here as the "Cod fleet") resulted as the most suitable fleet and the unique fleet that showed interest on a possible exploitation of the mesopelagic population. Furthermore, the viability of a new fleet formed by new vessels was also explored, referred to here as the "Brand-new fleet".

The Cod fleet consists of four vessels and only operates five or six months each year, leaving a long period of time when they could harvest the mesopelagic fish with null opportunity costs. However, the machinery required to process *M. muelleri* onboard is not compatible with their current operations in the cod fishery. The catch would need to be stored in refrigerated seawater tanks at 1.5 degrees or in ice filled boxes. Moreover, the fleet would need to invest in fishing gear and a suction pump to bring the fish onboard, at an estimated cost of 285 000 euros per vessel, as reported by a Basque fishing gear producer and Prellezo et al. (2024).

M. muelleri is a species that deteriorates quickly, and the method of fish conservation onboard determines the length of the fishing trip. Trials conducted in the North Sea (Paoletti et al., 2021) have shown that the maximum duration of a fishing trip targeting *M. muelleri* is three days.

The investment required to buy a new vessel in the Brand-new fleet was estimated to range from 70 to 86 million euros (local shipyard pers. comm. and Standal and Grimaldo 2020). For the calculation of the economic performance indicators, the mean value was used.

Prices were obtained from conversations with the Basque processing industry and from Kourantidou and Jin (2022). Kourantidou and Jin (2022) brought together the price per kilogram of landed mesopelagic fish in different parts of the world. In Spain, the price ranged between 0.243 and 0.860 €/kg based on Groeneveld et al. (2021) and Prellezo et al. (2024) provided a more precise estimate between 0.260 and 0.5 €/kg. In Denmark and Norway the minimum prices are around 40 % higher, but the maximum prices in Denmark were below the 0.860 €/kg suggested by Groeneveld et al. (2021). Moreover, in a personal communication with a Spanish processing company they stated that they could pay 0.1 €/kg. An intermediate median value of 0.30 €/kg was finally used for the price in the Cod fleet. In the brand-new fleet, the fish are processed onboard to obtain fish oil and fish meal which leads to a different price. One kilogram of *M. muelleri* produces 0.06 kg of oil and 0.25 kg of fish meal, with an average price of 1.8 €/kg and 1.5 €/kg, respectively, (EUMOFA, 2021; Kourantidou and Jin, 2022). Thus the price per kilogram of catches in the Brand-new fleet could be around 0.48 €/kg.

2.5. Social cost of carbon

The vertical migration of mesopelagic populations contributes to oceanic carbon export from the epipelagic zone to deeper layers (Boyd et al., 2019; Pinti et al., 2023). Thus, commercial exploitation of those populations could reduce oceanic carbon sequestration. This impact can be monetized using the social costs of carbon, which expresses the value of the damages to society caused by an incremental metric ton of CO_2 emissions (Tol, 2011; Groeneveld et al., 2023; Prellezo et al., 2024). Estimates of social costs of carbon range from 40 to 380 euros per ton of CO_2 equivalent, where CO_2 equivalent is defined by the European Environment Agency as a metric measure used to compare the emissions from various greenhouse gases based on their global warming potential. Rennert et al. (2022) estimated the social cost of carbon as 169 €/tn of CO_2.

Estimates of fish-mediated carbon sequestration are usually measured in export per m^2 (Hudson et al., 2014; Ariza et al., 2015; Saba et al., 2021) and there are only a few estimates per unit of biomass in the scientific literature. Based on the estimation of the total carbon export from epipelagic layers to deeper layers by vertically migrating species proposed by Davison et al. (2013) and Groeneveld et al. (2022), the estimated loss of sequestered carbon from reducing biomass by one kg is 5.1 kg of CO_2 per year. This estimate could be too high according to Prellezo et al. (2024), who recently estimated the value between 0.43 and 4.77 tonnes of CO_2 equivalents per tonne of mesopelagic fish biomass. Thus, we considered two possible values in our analysis, 2.6 kg/year and 5.1 kg/year per kg of biomass.

2.6. Conditioning of the simulation model

2.6.1. Biological component

The output of the Bayesian population dynamics model was used as the basis for conditioning the starting conditions and forward projection of the simulation model. The model was implemented in FLBEIA (Garcia et al., 2017), a bio-economic simulation algorithm that follows the management strategy evaluation (MSE) approach (Punt et al., 2016) and allows the incorporation of uncertainty in almost all the parameters of the model. However, in this analysis we did not conduct a classical MSE analysis which aim is to identify management strategies that are robust to uncertainty. Instead, we evaluated, by means of simulation, the biological, economic, and social viability of a potential fishery under the best available knowledge about the population dynamics of *M. muelleri* and available economic data.

The historical part of the model, from 2013 to 2020, was conditioned using the biological data described in Alvarez et al., (2023) and the population numbers at age estimated by the model in Section 2.3. The biological data, except for natural mortality, did not include uncertainty. To condition numbers at age and natural mortality 5000 samples were randomly selected from the $2.5 \bullet 10^7$ iterations resulting from fitting the Bayesian model to the abundance index samples.

Since *M. muelleri* is an unexploited population, the biomass has been fairly stable over time, making it impossible to reliably adjust a stock-recruitment relationship. Beverton and Holt model (Beverton and Holt, 1957) was used to simulate recruitment in the projection. The asymptotic recruitment was approximated by the mean recruitment estimated in the historical period and the steepness was obtained using the natural mortality distribution estimated by the Bayesian model and the variance-covariance values in the Fishlife library (Thorson, 2023) for *M. muelleri*. In each iteration steepness was calculated as a sum of a correlation component with natural mortality and a random component:

$$h = \vartheta_0 + \vartheta_1 \bullet M + \varepsilon$$

ε followed a normal distribution, $N(0,\sigma_\varepsilon)$, where ϑ_0, ϑ_1 and ε were constrained to result in a probability distribution for h with a mean and standard deviation equal to the values in Fishlife library for *M. muelleri* and bounded by the range [0.2,1).

The asymptotic recruitment changed by iteration. Further uncertainty was introduced by adding a multiplicative log-normally distributed error to the recruitment value obtained from the stock-recruitment model curve.

2.6.2. Fleet component

The Baranov catch equation was used to simulate catches (Baranov, 1918). In this model, catchability serves as the parameter that governs fleet productivity, and three different catchabilities were tested for each fleet based on their storage capacity and ability to fill their storage space.

According to logbooks, the Cod fleet typically catches around 25 tonnes per day, with a maximum capacity of approximately 50 tonnes. Moreover, a survey of ship owners indicated that pelagic fishery could potentially reach a maximum daily catch of 100 tonnes. Therefore, for the Cod fleet, a production of 25, 50 and 100 tonnes per day was used to estimate low, medium and high catchability levels, respectively. For the Brand-new fleet the highest catchability was calculated assuming a maximum production of 500 tonnes per day as per Standal and Grimaldo (2020). Additionally, medium and low catchability levels were calculated from the high catchability value assuming that the high catchability was 50 % higher than the medium catchability, and the low catchability was half the medium catchability.

The selectivity of the fleet was modeled using a logistic curve. The L50 parameter (the size at which 50 % of the individuals are selected) in the selectivity curve calculated by Vastenhoud et al. (2023) and the mean length of individuals of age 0, are both equal to 28 mm. Thus, to condition the logistic curve, it was assumed that only half of the individuals of age 0 were vulnerable to fishing and that age 1 and age 2 individuals were fully vulnerable.

The maximum effort for the vessels in the Cod fleet was set at 125 days and at 250 days for the vessels in the Brand-new fleet.

Prices were simulated using a lognormal distribution with mean equal to 0.30 €/kg and 0.48 €/kg and a coefficient of variation of 20 %, in the Cod fleet and the Brand-new fleet, respectively.

Capital costs, including annual depreciation and opportunity costs of capital, were estimated by considering the treasury bill yields and existing depreciation costs as well as the new investments. Opportunity costs due to the current fishing activity were null for both fleets, as the allocated effort to *M. muelleri* corresponded with inactivity periods of the Cod fleet and the Brand-new vessels fleet was not performing any effort before. For the Cod fleet, fixed costs were shared in equal parts between both fisheries, the cod and the mesopelagic fishery, according to the proportion of effort implemented in each of the fisheries (50 %). Variable costs were assumed to be similar for both fisheries and were obtained from the STECF AER Economic and Transversal data (STECF, 2023). In the case of the Brand-new vessels fleet, costs were estimated considering data from a similar fishery (krill fishery) (CCAMLR, 2021) and from costs of mesopelagic fishery estimated by Standal and Grimaldo (2020).

2.6.3. Management

The ICES maximum sustainable yield (MSY) harvest control rule was used to determine annual total allowable catch (TAC) in each iteration. This rule has three parameters: B_{lim}, MSY $B_{trigger}$ and an F_{target}. When the biomass is above MSY $B_{trigger}$, the catch advice is based on F_{target}, and when it falls below, the fishing mortality level is reduced linearly until it reaches B_{lim}. Below B_{lim}, a conservative approach was taken, resulting in zero catch advice. Since the stock's unexploited condition made it impossible to estimate the biomass level at which recruitment is impaired (B_{lim}), a conservative approach was applied by defining B_{lim} as 25 % of the virgin biomass (ICES, 2022). MSY $B_{trigger}$ was set at 40 % higher than B_{lim}, following the usual ICES approach (Hauge et al., 2007).

2.7. Scenarios

Catchability is the parameter that controls the productivity of the fleet per unit of effort and is highly influential on the exploitation level of the stock and the economic performance of the fleet. However, since this is a new fishery, it was not possible to estimate it. To address for the uncertainty in this parameter three different catchability scenarios were tested using values described in Section 2.6.2. These three values provided enough contrast in potential catchability values, with the upper bound based on the literature and expert judgment. Furthermore, scenarios with one, two or three vessels for the Brand-new fleet were evaluated to evaluate the impact of increasing fleet capacity on the exploitation of the stock. As the Cod fleet consists of already existing vessels, a single configuration was tested with all four of them. This resulted in twelve scenarios, three catchability scenarios for the Cod fleet and nine scenarios for the Brand-new fleet. The twelve scenarios, along with their distinguishing characteristics, are listed in Table 1.

2.8. Performance indicators

The three pillars of sustainability (biological, economic and social) were assessed through a range of indicators calculated in the steady state:

- Biological sustainability was assessed using *"the depletion level"* calculated as one minus the ratio between spawning stock biomass (SSB) in the steady state and SSB in unfished condition. The depletion level was compared against B_{lim} and MSY $B_{trigger}$. Maturity ogive and weight at age data to compute SSB were obtained from Alvarez et al. (2023).
- Economic sustainability was assessed using *"Profitability"* and *"Return on fixed tangible assets (ROFTA)"*. Profitability is calculated as gross surplus divided by gross value and represents the percentage of revenue retained as profit. This value was compared against the reference value used by the STECF (Scientific, Technical and Economic Committee for Fisheries) for the European large-scale fleet (10 %, STECF, 2023). ROFTA was calculated as the sum of net profit and opportunity costs of capital divided by tangible asset value, i.e, vessel depreciated replacement value. This indicator measures the capital productivity, i.e., profits in relation to the capital invested, which has a reference value of 25.6 % for Spanish large vessels (STECF, 2023).
- The social impact was measured by calculating the percentage of the cost of CO_2 that is no longer sequestered due to the reduced population and is compensated by the added value of the fishing activity (estimated as landings multiplied by price). The added value, unlike profits, does not consider the fishing costs and reflects the value that the fleet generates for society. Therefore, it makes sense to evaluate whether the increase in added value (i.e social benefits) offsets the reduction in sequestered CO_2 (i.e social costs). Mathematically:

$$Comp_{CO2_s} = \frac{(B_0 - B_s) \bullet CO2eq \cdot SCC}{Added\ Value_s} \bullet 100 \tag{10}$$

where the subscript s corresponds with the scenario, B_0 with the virgin biomass, B_s is the biomass in the steady state under exploited conditions, $CO2eq$ represents CO_2 equivalent, and SCC is the social cost of carbon. Two alternative values were used for CO2eq, 2.6 (Prellezo et al. 2024) and 5.1 kg/year per kg of biomass (Groeneveld et al. 2022), and social cost of carbon equal to 169 €/t was taken from Rennert et al. (2022).

All the indicators were assessed in the steady state. Furthermore, the effort performed by the fleet, measured in fishing days, was used to explain the results.

Table 1
Characteristics of the 12 simulated scenarios.

Scenario	Fleet	Catchability	Number of vessels
1	Cod fleet	low	4
2	Cod fleet	medium	4
3	Cod fleet	high	4
4	Brand-new-fleet	low	1
5	Brand-new-fleet	medium	1
6	Brand-new-fleet	high	1
7	Brand-new-fleet	low	2
8	Brand-new-fleet	medium	2
9	Brand-new-fleet	high	2
10	Brand-new-fleet	low	3
11	Brand-new-fleet	medium	3
12	Brand-new-fleet	high	3

3. Results

3.1. Abundance index

The bathymetric effect, as indicated by the fitted data, showed a clear preference for the 200–400 m bathymetry band. Additionally, the spatial distribution of *M. muelleri* exhibited significant variations from year to year as illustrated in Fig. 2. The estimated average biomass in the Bay of Biscay ranged between 0.5 and 1.5 million tonnes, reaching its peak in 2016 and 2017.

3.2. Bayesian population dynamic model

The mean of the prior for initial population numbers and recruitment was derived from observed values in the abundance index. Low precision was assumed for these priors. Assumed priors and estimated posteriors for key model parameters are illustrated in Fig. 3. Generally, the posteriors were narrower, and the median posterior differed from the median of the prior, indicating that data from the abundance index was informative for estimating those parameters. Recruitment estimates (Fig. 3a) were mostly higher than the prior value with a narrower distribution. For the catchability of the log-index a narrow prior distribution with mean equal zero was utilized to support the assumption of absolute abundance index (Fig. 3d). The estimated abundance in 2013 for age 1 was higher than the prior value with a bimodal narrow distribution (Fig. 3b). For age 2 the posterior distribution was similar to the prior distribution but narrower (Fig. 3c). The model estimates deviated slightly from the assumption of the index being an absolute index of biomass (i.e., $q = 1$), increasing the catchability of ages 0 and 1 and reducing that of age 2. The data was informative enough to estimate natural mortality, resulting in a posterior distribution, centered in 1.41 y^{-1}, with a coefficient of variation of 13 %, much narrower than the prior (Fig. 3e).

Estimated spawning stock biomass (SSB) and recruitment are depicted in Fig. 4. SSB fluctuated around 0.75 million tonnes, while recruitment fluctuated around 112 billion individuals. The confidence intervals were large in certain years (such as the initial year for SSB or 2017 for recruitment) but overall, the intervals were not excessively wide. The coefficient of variation was approximately 50 % for recruitment and 34 % for SSB.

3.3. Steepness and stock-recruitment relationship

The distribution of steepness and the stock recruitment relationship are shown in Fig. 5. The steepness distribution had the same shape as that of natural mortality and the median value was estimated at 0.64. The confidence intervals in Fig. 5 only reflect the parametric uncertainty in the stock-recruitment process. Subsequently, a lognormal error around the stock-recruitment model was introduced with a median of 1 and a coefficient of variation of 50 %, the same as in the historical estimates. No autocorrelation was considered because historical deviations showed low correlation.

3.4. The reference points in the harvest control rule

B_0 was estimated as the median estimated spawning stock biomass over the entire time series (676,631 tonnes), which corresponded with $B_{lim} = 0.25{\cdot}B_0 = 169{,}157$ tonnes and MSY $B_{trigger}$ $1.4{\cdot}B_{lim} = 267{,}406$ tonnes. With this definition MSY $B_{trigger}$ was above B_{msy}, contradicting the ICES goal of defining MSY $B_{trigger}$ as a lower bound of B_{msy} when fishing the population at F_{msy}. However, it aligns with the recommendation of Mildenberger et al. (2022) for short-lived stocks. F_{target} was calculated as the average of the real F_{msy} in each model iteration. The median of the fishing mortality level at maximum sustainable yield in each of the iterations was equal to 1.01 y^{-1}.

3.5. Performance indicators

In the projection, the biomass under commercial exploitation decreased in the initial years of the exploitation and then the whole system reached a steady state. By 2035 the system had already been stable for several years.

The results obtained in the steady state were largely explained by the effort levels exerted by the fleets in each scenario (Fig. 6). The Cod fleet was almost always, more than 99 % of the iterations, limited by the maximum annual effort it could perform. The Brand-new fleet with one vessel was limited by maximum annual effort in more than 99 % of the iterations, and the number of iterations decreased to 85 % and 68 % in the case of medium and high catchability, respectively. The higher the catchability or the number of vessels, the bigger the number of iterations where the fleet was not able to perform all its effort as a result of low, or even null, catch advice because the biomass was below B_{lim}. So much so that in the scenario with 3 vessels and the highest catchability, the fleet was constrained by the catch limit in most of the cases (88 %).

The level of depletion reached in each scenario, depended primarily on the type of fleet (vessel type) and then on catchability (Fig. 6). The Cod fleet resulted in lower depletion than the Brand-new fleet. Depletion levels increased with catchability, but the increase depended on the fleet type and the number of vessels. In scenarios with 2 and 3 vessels the difference in the depletion level was low due to the fleet being constrained by the total allowable catch rather than capacity, as in other scenarios. For the same reason, in those scenarios the depletion level in the medium and high scenarios was similar. In the Cod fleet, the depletion level was always lower than 0.75 (i.e SSB $> B_{lim}$), and the probability of having a depletion level higher than that at MSY $B_{trigger}$ was lower than 3 %. In the Brand-new fleet with one vessel, the depletion level was consistently below the limit reference point in most iterations (p(SSB$<$ B_{lim}) < 3 %). As the number of vessels increased, so did the risk of depletion, but the 75th percentile always remained below the limit. When there was only one vessel, the number of iterations with

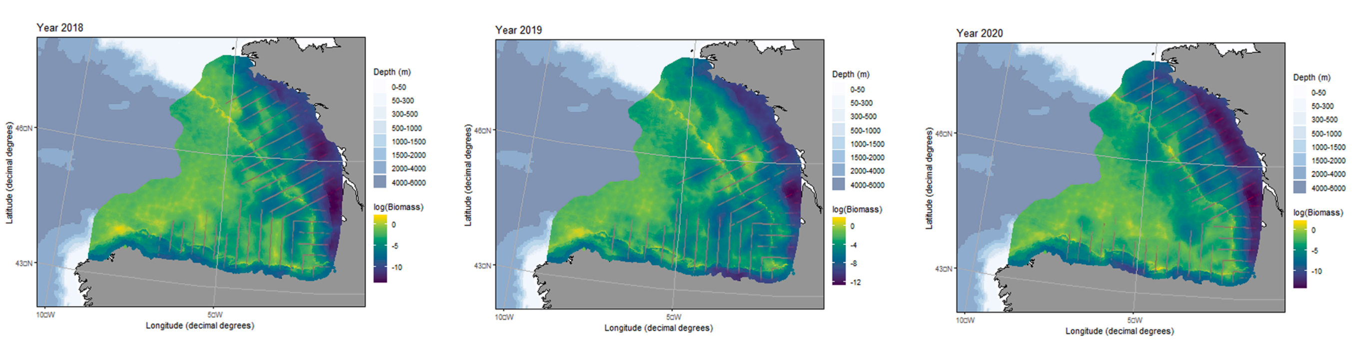

Fig. 2. *M. muelleri* log-biomass distribution predictions in the Bay of Biscay from 2018 to 2020 and sampling transects perpendicular to the coastline done in the Juvena survey. Biomass is measured in kilograms.

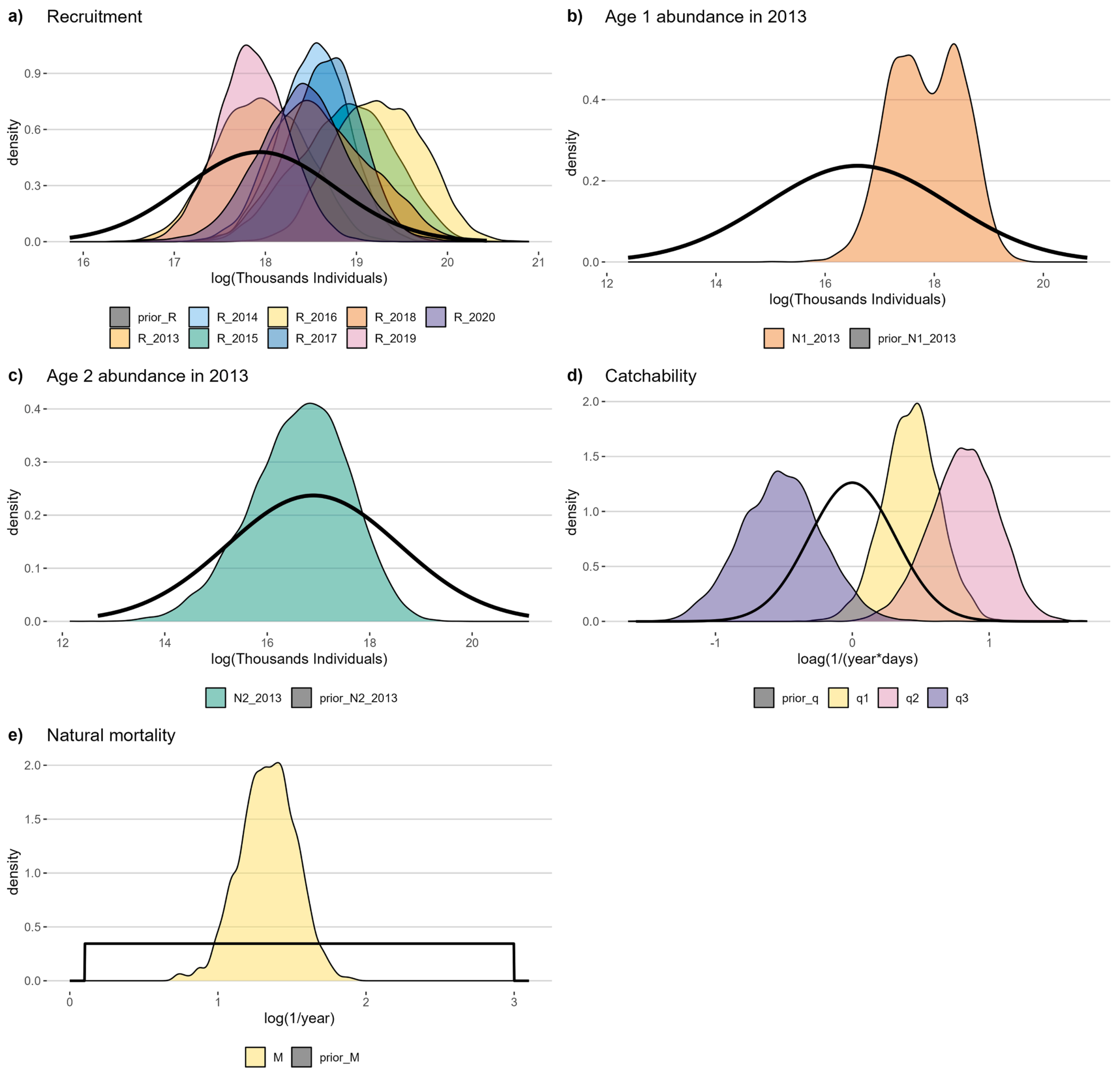

Fig. 3. Priors (black line) and posteriors (colored density functions) in the Bayesian assessment model, Recruitments in the whole time series (a), the initial numbers in 2013 for ages 1 (b) and 2 (c), the catchabilities of ages 0–2 (d) and the natural mortality (e).

SSB below MSY $B_{trigger}$ was equal to or less than 6 %. This probability increased to 29 % in the scenario with three vessels and high catchability.

In the steady state, the median profitability never exceeded the 10 % threshold for any of the fleet (Fig. 6). Only the scenario with high catchability in the Cod fleet or the Brand new fleet with one vessel resulted in a positive median profitability level, with a 41 % probability of being above 10 %. The Brand-new fleet, with one vessel and medium catchability, one vessel and low catchability or two vessels and high catchability, was able to reach the profitability threshold with probabilities of 30 %, 20 % and 20 % respectively. For the rest of the scenarios this probability was below 12 % and in the worst case (Cod fleet with low catchability), the probability was close to 0 (0.2 %).

When analyzing profits in relation to the invested capital using the ROFTA indicator (Table 2), economic performance was worse than when analyzing profitability. In the high catchability scenario, where the median was close to the objective, the ROFTA value was equal or higher than the threshold in only 18 % of the iterations for the Brand-new fleet and 17 % for the Cod fleet. In other catchability scenarios the probability was lower and in the case of the Cod fleet with low catchability none of the iterations reached the threshold.

The fishing activity was unable to compensate for the reduction in CO_2 sequestration in all scenarios tested. Only in a few iterations (≤5), the Brand-new fleet with medium or high catchability was able to cover the costs. Furthermore, the costs outweighed the profits significantly, ranging between 5 and 13 times higher depending on the scenario and assumed value of sequestered CO_2 per tonne (Table 3).

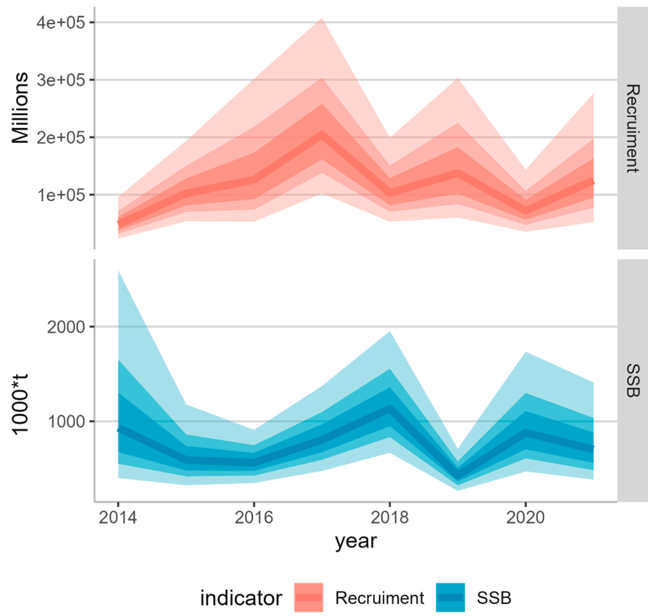

Fig. 4. Sampled recruitment and SSB from the 1000 Bayesian model estimates. The solid line indicates the median and the lighter bands the 50 %, 75 % and 95 % confidence intervals, respectively.

4. Discussion

We evaluated the biological, economic and social viability of a mesopelagic fishery in the Bay of Biscay. The modeling process presented several challenges, from estimating the population dynamics of an unexploited population to determining catchability. We addressed these challenges using a Bayesian approach to estimate population dynamics and defining various contrasting scenarios. This approach helped us consider some of the existing uncertainties. The current Cod fleet, operated by four vessels, along with a fleet utilizing only one vessel and capable of processing *M. muelleri* catch onboard, could be biologically sustainable and economically profitable only if they were able to achieve a sufficiently high catchability rate. This could also provide an additional source of fish protein to the market. However, when considering the initial investment, the long-term viability of the fishery seemed doubtful. Moreover, the gross value of the fishing activity was insufficient to offset the cost of the CO_2 that was no longer being sequestered by the population.

The estimated abundance of *M. muelleri* was around 1.20 million tonnes. This took into account the species' biology in the area, incomplete survey coverage, and the spatio-temporal structure of the scientific survey providing the annual abundance index. Additionally, the available data allowed us to estimate the natural mortality rate at 1.41 y^{-1}. When the fishery was primarily constrained by its maximum annual effort, the exploitation of the population was biologically sustainable. However, as the fleet expanded and catchability increased, activity shifted from being effort-limited to TAC-limited. While the TAC limitation reduced the risk of over-exploitation to less than 5 % in most scenarios, it was not precautionary in cases of high catchability or multiple vessels in the fishery.

From an economic standpoint, several studies suggest that mesopelagic exploitation may not be a viable alternative to existing commercial fisheries due to low landing values (Hidalgo and Browman, 2019). Nevertheless, factors such as the landing obligation, Brexit or other regulations could lead to excess in capacity that could be utilized for harvesting mesopelagic species (Hidalgo and Browman, 2019). In our study, we specifically examined a fleet capable of allocating effort to a mesopelagic fishery. We also analysed the viability of a Brand-new fleet solely focused on fishing *M. muelleri* and processing the catch on-board.

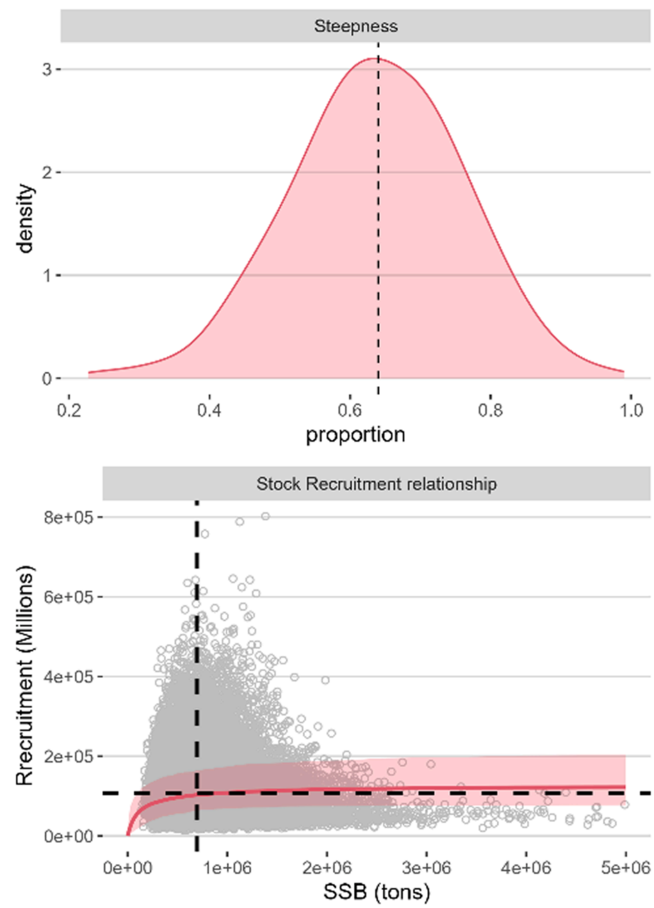

Fig. 5. Density plot of steepness and Beverton and Holt stock-recruitment model used to project the population forward in the simulation. The vertical lines in the density plot correspond with the median of the distribution. The solid line in the stock-recruitment plot indicates the median value and the lighter bands the 95 % credible intervals, the points indicate the estimated values from the 5000 Bayesian model fits. The vertical and horizontal black dashed lines indicate the recruitment and biomass at unfished condition.

Profitability depended on vessels' ability to achieve a high catchability. However, even with high catchability, the likelihood of a profitable fishery was only around 40 %. Furthermore, when factoring in the initial investment, the objective was achieved with a low probability (approximately 15 %) in scenarios with high catchability. In the most profitable scenarios, that were also biologically sustainable, the fishery would provide 3900 **or** 6700 tonnes of fish oil to the food market for the Cod fleet and Brand-new fleet, respectively, and 16,500 or 28,000 tonnes of fish meal respectively. However, from a social perspective, the economic income generated by the fishing activity did not offset the loss of oceanic carbon sequestration in the majority of iterations.

The estimated mean biomass of *M. muelleri* fell between the two estimates available for the area: Prellezo et al. (2024) and Vastenhoud et al. (2023). The former estimated a biomass level five times lower, while the latter, estimated it to be three times higher. Vastenhoud et al. (2023) extrapolated the number of individuals observed in the acoustic survey (Sobradillo et al., 2019) directly, assuming that recruits are not caught and mature quickly. However, the biological sampling associated with the acoustic data in Sobradillo et al. (2019) shows that recruits are indeed caught in the sampling and do not mature quickly enough to assume that all the fish caught are mature. In this work we accounted for associated biological data directly which could explain the differences obtained. Furthermore, when extrapolating the data in Sobradillo et al. (2019) to the whole area, Vastenhoud et al. (2023) did not consider the spatio-temporal correlation and the opportunistic sampling of

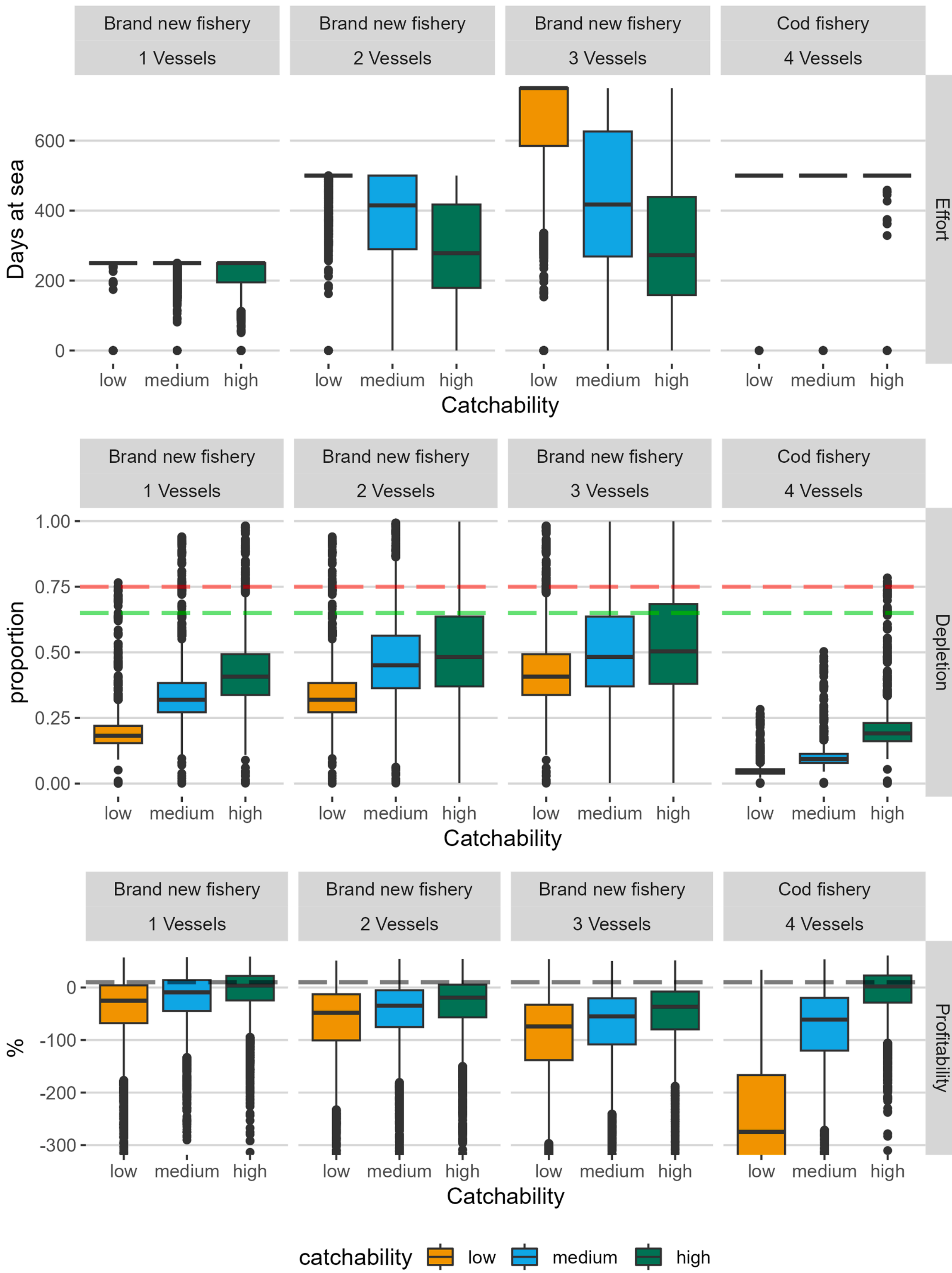

Fig. 6. Boxplots of the effort (top row), depletion level (middle row) and profitability (bottom row) in the steady state in each scenario. The columns correspond with the fleet used in each scenario, Cod fleet or Brand-new fleet with different number of vessels. In turn each plot shows three different catchability scenarios low (yellow), medium (blue) and high (green). The horizontal dashed lines in the depletion plot indicate a depletion level corresponding to an SSB level equal to B_{lim} (red dashed line) and corresponding to MSY $B_{trigger}$ (green dashed line). The horizontal line in the profitability plot corresponds with 10 % profitability.

Table 2
Probability of having a Fixed Tangible Assets (ROFTA) value above 25.6 % in the steady state for each fleet and catchability scenario. For the Brand-new fleet only the '1 vessel' scenario is shown.

Fleet	Catchability	Probability
Brand-new fleet	low	5 %
Brand-new fleet	medium	12 %
Brand-new fleet	high	18 %
Cod fleet	low	0 %
Cod fleet	medium	2 %
Cod fleet	high	17 %

Table 3
Ratio between the social cost of the CO_2 no longer sequestered by the population and the added value of the fleet, $Comp_{CO_2}$.

Fleet	Catchability	2.6		5.1	
		Median	95 % CI	Median	95 % CI
Brand-new fleet	low	5	(2,12)	9	(4,24)
Brand-new fleet	medium	5	(2,18)	10	(5,34)
Brand-new fleet	high	6	(2,29)	11	(5,56)
Cod fleet	low	6	(3,14)	12	(6,28)
Cod fleet	medium	6	(3,15)	13	(6,30)
Cod fleet	high	7	(3,18)	13	(7,36)

M. muelleri in the anchovy directed survey. The ecosystem model used in Prellezo et al. (2024), only covers the continental shelf, while here we consider the entire Bay of Biscay. Moreover, stock assessment models, like the one used here, are considered to provide a more detailed representation of the historical development of stock abundance (Howell et al., 2021), as they rely on fewer assumptions and are specially designed to fit data collected in national data collection programs. Thus, we believe that the abundance estimate provided here represents an improvement over the existing estimates in the literature.

The Bayesian model estimated a precise posterior distribution for natural mortality. The 95 % credible interval included the lowest values estimated by Vastenhoud et al. (2023) but did not include values higher than 1.69 y^{-1}. Estimates in Vastenhoud et al. (2023) come from empirical relationships between life history parameters and natural mortality found for other fish populations and are subject to great uncertainty. Our estimate comes from a direct observation of survivors in the acoustic survey and is likely more adjusted to the reality of this particular population.

Vastenhoud et al. (2023) also analysed the profitability of a potential fishery in the Bay of Biscay. They found that the price of the fish should be between 1.6 and 5.0 €/kg for the fishery to be profitable. Here, with a much lower price, provided that the catchability was high, the fishery could be profitable. The discrepancy is explained by the difference in the costs of both fleets, and the fact that in Vastenhoud et al. (2023) the vessels need to cover the fuel costs from the North Sea to the Bay of Biscay.

The study relies on several assumptions and five of them are key: distribution of the stock, its productivity, the catchability of the fleets, preservation of the good quality of the catch and the amount of CO_2 sequestered per tonne of biomass. A fundamental assumption of most stock assessment models is that the modeled population is closed to migration and emigration. Thus, significant mobility of the individuals between different areas in the North Atlantic could violate this assumption and lead to biased estimates of abundance. In terms of the productivity of the stock, we used the variance-covariance estimates available in the FishLife library (Thorson, 2023) to account for the correlation of steepness with natural mortality and the inherent variability estimated for steepness in this population. The three catchability values used represent a very rough estimation of possible values, based on the capacity of the fishers to fill in the storage capacity in a trip of three days. However, the results are clear: without the ability to have an efficient fleet, the activity would not be profitable. In the two most profitable scenarios, the catch per unit of effort 95 % credibility interval amounted to [50,380] tonnes per day for the Cod fleet, and [340,1000] for the Brand-new fleet, which is possible according to the storage capacity. Previous experiences with commercial vessels achieved a catch per hour from 0 to 40 tonnes, or from 0.4 to 16 tonnes/hour (estimated by Sintef using data from Liegruppen AS company, personal communication). Considering that a tow can last six hours, and the ship executes three tows per day, the catch per day could be between 0 and 720 tonnes per day. Thus, the highest catch per day could be too high, and the median would be close to the maximum observed value. Given the existing uncertainty, practical at-sea trials in the Bay of Biscay may be necessary to ensure the profitability of any potential future fishery. Regarding the quality of the catch, despite experimental trials in the North Sea demonstrating that *M. muelleri* individuals can maintain good quality properties for up to three days (Vastenhoud et al., 2023), catches in the JUVENA survey deteriorated quicker, possibly related to the warmer conditions in the Bay of Biscay. Thus, mechanisms to maintain the good quality of the individuals, such as keeping the catch in cold water and ice, should be tested. Moreover, a recent study by Zhu et al. (2023) with *M. muelleri* from the Bay of Biscay discovered that apart from being an important source of nutrients, its concentration of undesirable substances, such as cadmium was also high. Therefore, it is highly recommended that before exploiting it, it is proven that their concentration is within safe levels. Finally, CO_2 sequestration depends on several factors, such as ocean dynamics, fish biomass, depth or where the feeding take place among others (Baumas et al., 2021, Aksnes et al., 2023). The estimates used here are based on Davison et al. (2013) whose estimation is focused on southern California, and also on Prellezo et al. (2024), whose estimate is based on the Bay of Biscay but is very uncertain. Additionally, we assumed a linear relationship between CO_2 sequestration and the amount of biomass at sea, which is not necessarily true. Furthermore, the social cost of carbon is assumed fixed in the projection period, but studies indicate that it may increase from 1.3 % to 3.9 % per year (Anthoff et al., 2011). Additionally, Rennert et al. (2022) stated that social cost of carbon in the long run is highly sensitive to the discount rate due to the long residence time of CO_2. Therefore, the estimates of social cost of carbon could be underestimated and the inability of the fleet to cover these costs could be even more severe.

Several authors advocate for the commercial fishing of mesopelagic resources as a new source of nutrition, highlighting the need to ensure sustainable management of the populations (Standal and Grimaldo, 2020, Fjeld et al., 2023, Gatto et al., 2023). This requires the implementation of scientifically sound stock assessment and reference points (Standal and Grimaldo, 2020). Here we have implemented a stock assessment model tailored to what we know about the *M. muelleri* population in the Bay of Biscay and we have also calculated reference points. The model could be improved as more information becomes available. However, if the population were to be commercially exploited eventually, it could be important to introduce fishing gradually and implement biological and commercial fishing sampling programs that provide the data needed to facilitate a suitable management of the stock. As demonstrated here, until the uncertainty about population dynamics (i.e productivity of the stock) is reduced, the sustainability of the population should be ensured by limiting the capacity to one vessel. Furthermore, acknowledging the need to move towards an ecosystem-based fisheries management, being an unexploited resource, and to avoid the same failures as in the past, the limits to the exploitation of the resource should be defined in an ecosystem context. This should ensure not only the sustainability of the population itself but also a population level that guarantees the feeding of its predators and limits the loss in CO_2 sequestration. The MSY target should be replaced by a more conservative management target that considers the ecological role of the species and ensures a biomass level at sea that supports the sustainability of its main predators and CO_2 sequestration levels that are consistent with climate targets. Calculating reference points in an ecosystem model is challenging due the high complexity of the system, but ecosystem models such as those used by Prellezo et al. (2024) could be used to find an adequate target. Under the current MSY framework they concluded that the predators of *M. muelleri* such as tunas would be negatively impacted by its exploitation and direct competitors such as anchovy or shrimp could be benefitted. Finally, the role of *M. muelleri* as CO_2 sequestrator, through its direct and indirect effects on the gravitational, diffusive, and migrant (active) fluxes (Aksnes et al., 2023), is significant. Therefore, exploiting this population could disrupt a part of the oceanic carbon pump (Rolf *et al.* 2024), that contrast with EU's aims to reduce CO_2 emissions by 50 % since 1990.

The M. muelleri biomass estimates were interpolated using a spatio-temporal model based on opportunistically collected data. However, due to the low correlation levels inferred by the model across years, spatiotemporal interpolations provide rather vague biomass estimates. Therefore, if commercial exploitation of M. muelleri is considered in the future, we suggest extending the survey to cover the entire area of species distribution. Additionally, it would be valuable to implement a monitoring program for an initial period to better understand the population dynamics of this species. Furthermore, the M. muelleri population in the Bay of Biscay could belong to a larger M. muelleri population and genetic studies should be conducted to define adequate assessment units in the Northeast Atlantic.

If a *M. muelleri* fishery were to be implemented, there would be several regulatory issues to consider and overcome. The use of pelagic or semi-pelagic trawl by Spanish vessels in the Spanish exclusive economic zone of the Northwest and Cantabrian Sea is prohibited (Real Decreto 1441/1999). Regarding mesh size, while Regulation (EU) 2019/1241 establishes a minimum mesh size of 16 mm for pelagic species, trials in Norway used a mesh size of 11 – 12 mm and other studies suggested a mesh size of 7–10 mm (Valinassab et al., 2007, Sobradillo et al., 2019). The potential bycatch of other species with such small mesh sizes should be explored to assess the impact of the potential fishery in the entire ecosystem. Although it is not expected to be high, given the high spatial isolation of *M. muelleri.* Furthermore, the population distribution could extend to areas beyond national jurisdiction where the biodiversity beyond national jurisdiction agreement applies. This agreement adopted in 2023 under the United Nations Convention on the Law of the Sea, aims to conserve and sustainably use marine biodiversity. It requires an environmental impact assessment for planned activities that are expected to have an impact. Therefore, if the stock were to be commercially exploited over time, the extent of its distribution would need to be clarified and, if necessary, an environmental impact assessment carried out. This assessment could build on the analysis presented in this paper but should also include ecosystem considerations such as the impact on other species and the carbon pump.

In conclusion, the fishery of *M. muelleri* could be profitable if the catchability is high enough and the production of fish meal and fish oil is of high quality to be marketable. Furthermore, until uncertainty about population dynamics is reduced, limiting capacity seems to be the best way to ensure the sustainability of the population. However, while the profits might be able to cover operational costs, they are not sufficient to cover the necessary investments to start the exploitation of the fishery. Therefore, either these initial investments are subsidized, at least in part, by the public sector, or the fishery would not be profitable. Furthermore, the amount of CO_2 no longer sequestered by the exploited population would hardly be compensated by the added value created by the fishery. In a climate change context, this could be a valid argument to prevent the exploitation of the population.

CRediT authorship contribution statement

Garcia Dorleta: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Andres Marga:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Alvarez Paula:** Writing – review & editing, Project administration, Funding acquisition, Data curation. **Paradinas Iosu:** Methodology, Formal analysis. **Boyra Guillermo:** Writing – review & editing, Validation, Data curation. **Groeneveld Rolf:** Writing – review & editing, Formal analysis.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used https://www.editmyenglish.com/ in order to support the editing work in the revision process, it was not used for the first version of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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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Appendix

The data and the code use to conduct all the analysis in this manuscript are available in zenodo.org through the following link: Supplementary material https://zenodo.org/records/14005895

Data availability

The code and data is shared now through zenodo. Link available in the manuscript

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