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Fisheries Reference Points under Varying Stock Productivity and Discounting: European Anchovy as a Case Study

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Abstract

European anchovy (*Engraulis encrasicolus*) is the main commercially exploited fish stock in the Black Sea region, providing a vital source of livelihood and revenue for local communities and national economies. In recent decades, the Black Sea anchovy stock has faced many human-induced threats, including overfishing, eutrophication, invasive species, and climate change while these threats have raised concerns about the status and long-term productivity of the stock. To ensure sustainable levels of exploitation under potential future changes in stock productivity, we here estimate and compare a suite of biological and economic reference points under different levels of stock productivity and discount rates using an age-structured bioeconomic model setup. Our model simulations showed that optimal fishing mortalities achieving maximum sustainable yield (F_{MSY}) and maximum economic yield (F_{MEY}) increase at higher stock productivity but are always lower than the historically high mean levels of exploitation. Furthermore, we illustrate that the stock biomass at maximum economic yield (B_{MEY}) is larger than the stock biomass at maximum sustainable yield (B_{MSY}) at all stock productivities and discount rates, except at low stock productivity under high levels of discounting (i.e., 10%, 20%). By illustrating the ecological and economic benefits of reducing exploitation rates, we expect that our estimated reference points can add value to the decision-making process for the management of the European anchovy fishery and ensure long-term sustainable management even under future climate-driven changes in stock productivity.

Keywords: European anchovy; age-structured; bioeconomic model; fisheries reference points; stock productivity; Black Sea; Turkey.

Introduction

Target reference points are commonly used in fisheries management around the world to ensure that stocks are exploited sustainably (Grafton *et al*., 2010; Hutchings *et al.*, 2010; Kompas *et al*., 2010; Froese *et al*., 2011; van Deurs *et al*., 2021). However, the effectiveness of reference points, including maximum sustainable yield (*MSY*) and maximum economic yield (*MEY*), and the potential trade-offs that arise from their use are subject to considerable debate (Clark and Munro, 1975; Christensen, 2010; Sumaila & Hannesson, 2010; Guillen *et al*., 2013; Kanik & Kucuksenel, 2016; Holma *et al*., 2019). This debate partially stems from different definitions, as well as the type of model setup used to estimate reference points, notably in terms of representing age structure, single- vs multi-species considerations, and discounting (Pascoe *et al*., 2015; Hoshino *et al*., 2018). The resulting discrepancies can be clearly illustrated by several contrasting findings from the available literature. This point can be clearly illustrated by contrasting examples from the available literature. For instance, Grafton *et al*. (2007) compared the economic effectiveness of stock biomass at *MEY* (B_{MEY}) against the stock biomass at *MSY* (B_{MSY}) and found that B_{MEY} is greater than B_{MSY}, even when integrating the consumer surplus into the bioeconomic model. Likewise, Kompas *et al*. (2010) showed that B_{MEY} is much greater than B_{MSY}, hence arguing that the use of *MEY* brings a win-win outcome for both conservation and exploitation as it ensures both economic and ecological benefits (Clark and Munro, 1975; Dichmont *et al*., 2010). In contrast to these studies, Merino *et al*. (2015) investigated *MSY* and *MEY* under different scenarios for a Mediterranean multispecies trawl fishery and found that the fishing effort to achieve *MSY* is considerably lower than the fishing effort at *MEY*. Likewise, Christensen (2010) suggests that the added value of harvest at *MSY* for society would be much greater than the harvest at *MEY*. In addition, Tahvonen *et al*. (2018) showed, using an age-structured model, that *MEY* results in a slightly lower economic steady-state biomass compared to the biomass at MSY. Given the clear disagreements in the literature, it becomes important to assess and compare ecological and economic reference points and their variability under different sets of biological and economic conditions.

Around one-third of the world's total marine fisheries capture is constituted by small pelagic species of which anchovy is the backbone of pelagic fisheries around the world (FAO, 2020). The European anchovy (*Engraulis encrasicolus*) is the key commercial species in the Black Sea, especially for the Turkish purse-seine fleet. This fishery supports livelihoods at the local and national scale, with an annual economic value of over a hundred million Euro (Goulding *et al.*, 2014), in addition to multiple employment opportunities and value in different industries (e.g., processing, market chains) with considerable indirect and induced effects on the Turkish economy (Chashchin, 1996; Daskalov, 2003; STECF, 2014). Despite calls for a regional management plan agreed upon by all countries, the Black Sea anchovy fishery is under an open-access regime regulated at the national level (Gücü *et al.*, 2017). In Turkey, the only influential management measure is a seasonal closure (from the 15th of April to the 1st of September) excluding large-scale (industrial) fishing vessels (i.e., purse-seiners) while small-scale fishers are allowed to capture small quantities of anchovy year-round.

In recent decades, the anchovy stock has faced significant human-induced threats such as overexploitation (Castilla-Espino *et al*., 2014). Furthermore, pollution and outbreaks of invasive species (i.e., ctenophore *Mnemiopsis leidyi*) (Knowler & Barbier, 2005) caused pronounced shifts in the status and productivity of the stock. In addition to anthropogenic pressures, eutrophication and climate variability profoundly altered the Black Sea ecosystem by influencing the level of primary production and the carrying capacity of several species (Polonsky *et al*., 1997; Daskalov, 2003; Oguz *et al*., 2006; Daskalov *et al*., 2007). In particular, large-scale changes in ocean-atmospheric forcing, illustrated by the North Atlantic Oscillation (NAO) index were shown to influence temperature, precipitation, nutrient concentration, and primary production in the region (Oguz *et al*., 2006). The effect of the NAO channeled either through changes in temperature or nutrient availability, has been argued to also affect the recruitment and productivity of the Black Sea anchovy stock (Gücü *et al*., 2018). Given the importance of the Black Sea anchovy for local and national economies, modeling frameworks evaluating flexible management targets accounting for changes in stock productivity are needed to ensure long-term sustainable exploitation. Such frameworks are currently largely absent therefore, ecological, and economic reference points and their sensitivity to changes in stock productivity are missing. Consequently, the generic, precautionary exploitation rate as advocated by Patterson (1992) is currently used for the management of this fishery (STECF, 2014). To inform sustainable fishery management of the European anchovy stock in the Black Sea, we develop an age-structured bioeconomic model to estimate and compare biological and economic reference points (i.e., *MSY* and *MEY*), as well as assess their variability under various levels of stock productivity and discounting.

Material and Methods

Data

Stock assessment data on the number-at-age (*N*), weight-at-age (*w*), maturity-at-age (*Mat*), natural mortality at-age (*M*), fishing mortality (*F*), and spawning stock biomass (*SSB*) for the Black Sea anchovy were obtained from the Scientific, Technical and Economic Committee for Fisheries (STECF, 2014). Historical stock assessment estimates of recruitment at-age zero (*R*) and *SSB* were included to extend the time series from 1987 until 1967 (Knowler, 2007). Since the earlier recruitment values were reported in tons, we converted the estimates to the number of individuals by dividing by the mean weight-at-age zero reported in the stock assessment (STECF, 2014). In addition to the biological data, economic information on fishing effort and the cost of Turkish purse-seiner vessels (n_{Total}=264 vessels) in the Black Sea were collected through, phone and face-to-face interviews. The interviews were restricted to vessel owners/license holders, excluding small-scale artisanal fishermen. The thirty fishermen responding to the survey represent a random subset of actors homogenously distributed across coastal provinces. The interviews were conducted from April to August 2016. The interviews lasted for twenty minutes each and followed a set of standard questions regarding both technical (i.e., number of fishing hours, fishing days, and total fishing vessels), as well as economic aspects (e.g., all operational cost items fuel, labor, food, fishing, and vessels licenses). Results from the survey show that each vessel conducts anchovy fishing approximately 60 days per year and operates on average 15 hours per fishing day. The total fishing hours per vessel were therefore estimated at an average of 900 hours per year. The mean annual cost per vessel was estimated at €72,648, while the unit cost of fishing effort amounted to €80.72. The unit cost of fishing was calculated by dividing the total annual expenses by the amount of fishing effort in hours. Finally, for the anchovy price in Turkey, we used an average price of €0.91 per kg which was the price for 2016 (TURKSTAT, 2017) (Table 1). We fully acknowledge that the economic data received may not fully explain the total variation in effort and fishing costs among all commercial anchovy fishermen in space and over time. Hence, to test the sensitivity and robustness of results to potential variation and uncertainty in these estimates, we performed a formal sensitivity test of all input parameters, including also prices and the unit costs estimates (see the section on Estimation of reference points below).

Table 1. The economic parameters of the model.

Fishing Parameters	
Annual effort in hours per vessel	900
Annual effort in number of fishing days per vessel	60
Total number of vessels	264
Mean proportion of total catch by Turkey	0.715
Proportion of discard	0.14
Economic Parameters	
Unit price of anchovy (€)	0.91
Unit cost of fishing (€)	80.72
Annual cost per vessel (€)	72,648

Model Setup

To estimate and compare ecological and economic reference points, we developed and applied a coupled bioeconomic model framework (Fig. 1) that consists of a standard age-structured cohort model and a bioeconomic model based on available information and parameters described in the earlier section (Table 1).

Population dynamic model

The population dynamic simulations were performed by first estimating recruitment success (*R/SSB*) based on a stock-recruitment (*S-R*) model fitted to the available data (Table 2; Fig. S1). We applied a standard linearized Ricker formulation (Hilborn, 1985) with log-transformed recruitment success (*R/SSB*) estimates as a response:

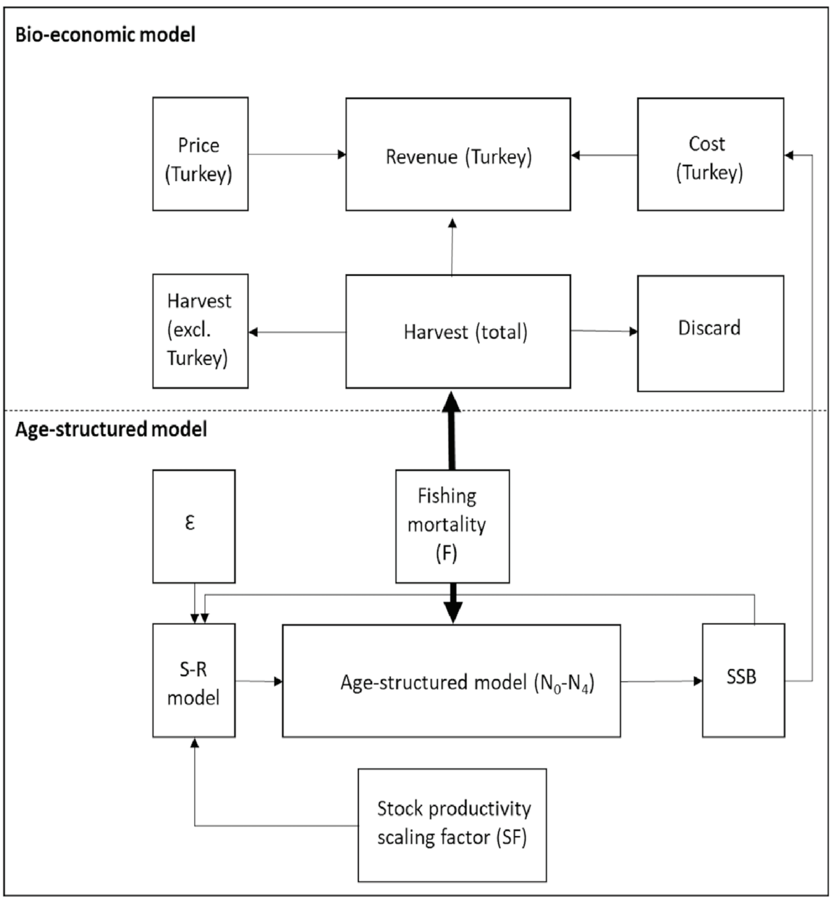

Fig. 1: A schematic representation of the coupled bioeconomic model setup, consisting of a standard age-structured population model using numbers (*N*) and a stock-recruitment (*S-R*) model estimating recruits-per-spawner based on the spawning stock biomass (*SSB*), a scaling factor aimed at representing changes in stock productivity (*SF*), and on resampled noise from the *S-R* model (ε). The bioeconomic model is linked to the population model through fishing, where the total revenue of the Turkish fishery was calculated based on the resulting level of optimal harvest (e.g., *MEY*) (in tonnes), the price (in € per ton) and the total annual cost of fishing (in €) which in turn was scaled relative to the stock biomass.

Table 2. The results of the fitted stock-recruitment model for the Black Sea anchovy where α and β are estimated regression coefficients corresponding to the model intercept and slope of the effect of *SSB*, respectively. The parameter δ refers to the fixed effect accounting for slight differences in means between the historical and recent assessments. δ is the offset to the intercept for the assessment period. The overall adjusted *R-square* amounts to 71.2% explained variance and the residual error to 0.32 on 41 degrees of freedom. (See Fig. S1 for confidence intervals of parameters and predicted recruits per spawner).

	Estimate	Std. Error	t-value	p-value
α (Intercept)	6.47	0.43	15.2	<0.00***
β (SSB)	-1.53	0.22	-6.67	<0.00***
δ (Assessment)	0.82	0.09	8.445	<0.00***

$$log\left(\frac{R}{SSB}\right)_t = \alpha + \beta SSB_t + \delta_A + \varepsilon_t \tag{1}$$

where α and β were estimated regression parameters; SSB_t the spawning stock biomass; and ε_t the error term at year *t*. To account for potential methodological differences between assessments (i.e., before and after 1988), we added an additional fixed effect factor δ corresponding to the stock assessment period (*A*). To fit the model, we used a standard linear regression where parameters are estimated using maximum likelihood. After having fitted the *S-R* model, we started the population dynamic simulations by first defining several objects having the model outputs. These include a matrix of estimated numbers-at-age, as well as vectors of the estimated harvest (*H*), spawning stock biomass (*SSB*), and total stock biomass (*TSB*) at each time step over the simulation period. The first values of *H*, *SSB,* and *TSB* at the beginning of the simulation period (t=0) were given by:

$$H_{t=0} = \sum_{a=0}^{4}\left(\frac{F_a}{(F_a+M_a)} * (1 - e^{(-(F_a+M_a))}) * N_{a,t=0} \times w_a\right) \tag{2}$$

$$SSB_{t=0} = \sum_{a=0}^{4}\left(N_{a,t=0} \times Mat_a \times w_a\right) \tag{3}$$

$$TSB_{t=0} = \sum_{a=0}^{4}\left(N_{a,t=0} \times w_a\right) \tag{4}$$

where *N*, *F*, *M*, *w,* and *Mat* are vectors of mean numbers, fishing mortality, natural mortality, weight, and maturity-at-age (a) dependent on whether the model was used for hindcasting past dynamics, or for scenario simulations, the starting values (i.e., at *t*=0) correspond to the year 1988, or the mean values from the stock assessments, respectively. The numbers-at-age are distributed among 5 age classes (from 0 to 4+), where the plus group includes all fish 4 years and older. After having defined and created the output objects we performed the population dynamic simulations for each consecutive time step by first transforming the predicted *R/SSB* (i.e., derived from the fitted *S-R* model; *Eq. 1*) to non-logarithmic form and multiplying with *SSB* to get the predicted number of recruits at-age 0 in each time step as follows:

$$N_{t,0} = e^{(\alpha+\beta\times SSB_{(t-1)}+\delta)} \times k \times SSB_{(t-1)} \tag{5}$$

where *α*, *β,* and δ are the fitted regression parameters (Table 2), *SSB* is the spawning stock biomass at the timing of spawning (*t-1*). The parameter *k* is a scaling factor on recruitment success, aiming to reflect the potential environmentally driven change in stock productivity, including any underlying factors potentially influencing recruitment success (e.g., the number of offspring produced and/or juvenile survival). To represent the population dynamics, we then used a standard age-structured cohort model formulation as follows:

$$N_{a,t} = N_{(a-1),(t-1)} \times e^{-\left(F_{(a-1)}+M_{(a-1)}\right)} \tag{6}$$

where $N_{a,t}$ is the numbers-at-age, *a*, for the simulation year *t*, *M* and *F* are natural and fishing mortalities for each age class, respectively. The sum of *H*, *SSB,* and *TSB* across age classes and for each time step *t* are given by:

$$H_t = \sum_{a=0}^{4}\left(\frac{F_a}{(F_a+M_a)} * (1 - e^{(-(F_a+M_a))}) * N_{a,t} \times w_a\right) \tag{7}$$

$$SSB_t = \sum_{a=0}^{4}\left(N_{a,t} \times Mat_a \times w_a\right) \tag{8}$$

$$TSB_t = \sum_{a=0}^{4}\left(N_{a,t} \times w_a\right) \tag{9}$$

Economic Model

By adding economics into the population dynamic model, we quantified the profits from the fishery over the simulation period. The key control variable in the bio-economic model is fishing mortality. The general profit function, *Π*, was denoted as follows:

$$\Pi_t = p \times S_T\left((1 - S_D) \times H_t\right) - C_t \tag{10}$$

where *p* is the fixed unit price of the anchovy and H_t is the annual anchovy catch (following Equations 2 and 7), S_T is the mean share of the total catch by Turkey (72%) and S_D was the percentage of discards in the total catch (i.e., 14%) (Tutar, 2014). C_t is the stock-dependent cost function that can be expressed as follows:

$$C_t = c \times E \times (TSB_{mean}/TSB_t) \tag{11}$$

where *c* is the cost parameter or the unit cost of effort expressed through the annual harvesting cost per vessel, and *E* is the fishing effort expressed through the number of vessels (*N*=264) in the Turkish fishery. Although our economic data do not allow for parameterizing more-elaborate cost functions linking unit costs to yield, biomass,

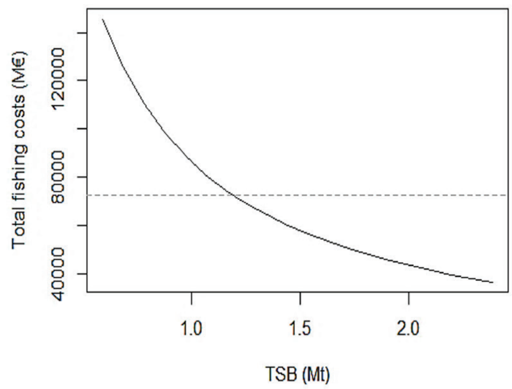

Fig. 2: The introduced non-linear dependency of total fishing costs on stock size relative to the mean total stock biomass (*TSB*) from 2010 to 2014. The dashed horizontal line shows the total fixed annual cost estimate of the Turkish purse-seine fishery (Table 1).

or other aspects, such as skills of skipper, vessel characteristics, or fleet type (Sandberg, 2006), we followed the approach by Grafton *et al*. (2007) by allowing total fishing costs to vary non-linearly with stock size (i.e., costs decline with increasing stock size). This was achieved by scaling the fixed costs proportional to the mean *TSB* level (from 2010-2014) compared to the simulated *TSB* in any given year *t* (TSB_{mean}/TSB_t). Consequently, a decrease in stock size compared to the mean generates a corresponding increase in fishing cost (Fig. 2).. Finally, the sum of discounted net benefits (i.e., the net present values; *NPV*) over the 50-year simulation period under the discount rate *r* is given by:

$$NPV = \sum_{t=1}^{50} \frac{\Pi_t}{(1+r)^{t-1}} \quad (12)$$

Estimation and Sensitivity of Reference Points

Prior to estimating reference points, we assessed the degree to which the coupled model succeeds in representing the historical population dynamics. The hindcast simulations were initialized based on the historical numbers-at-age in 1988 and run forward forced by the values of *F*-at-age, weight-at-age, maturity-at-age, and natural mortality at-age from the stock assessment. The predictive accuracy of the hindcast was assessed by comparing the mean and range of the simulated *SSB* dynamics with observed *SSB* estimates (STECF, 2014) after 1,000 stochastic simulations, where, in each year, Gaussian noise was added to the recruitment predictions (i.e., resampled randomly from the residuals (error terms) of the fitted *S-R* model; *Eq. 1*). Thereafter, we used the coupled model set-up to simulate the stock dynamics and revenue under different fishing and stock productivity scenarios by changing either the mean level of fishing mortality or varying the introduced scaling factor (*k*) on the recruitment predictions (given in *Eq. 5*). The scaling factor aims to represent the environmental effects of increasing or decreasing the number of recruits-per-spawner, such as climate-driven changes in primary productivity and carrying capacity of the stock (Polonsky *et al*., 1997; Daskalov, 2003; Oguz *et al*., 2006) and/or biotic interactions caused by for instance the invasive comb jellyfish *Mnemiopsis leidyi* (Knowler & Barbier, 2005; Knowler, 2007). Based on the model simulations, ecological and economic reference points were then estimated by optimizing long-term yield or revenue with respect to a fixed level of fishing mortality throughout the simulation period (with levels of *F* constrained between 0 and 5 during optimization). F_{MSY} was estimated as the level of exploitation that achieves B_{MSY}. This was achieved by defining the level of *F* that minimizes the difference between *SSB* and B_{MSY} as follows:

$$\min_F \, [SSB_t - B_{MSY}] \quad (13)$$

$$B_{MSY} = K * 0.5 \quad (14)$$

Although numerous definitions of B_{MSY} exist (Punt *et al*., 2014), we used the standard derivation from Schaefer (1954) where B_{MSY} equals half of the theoretical carrying capacity (*K*) of the stock (*Eq. 14*) where the population growth rate is assumed at its maximum. *K* was estimated directly from the model and corresponds to the equilibrium biomass obtained when running model simulations under no fishing (*F=0*), hence equaling the virgin, unfished biomass, which is often abbreviated as B_0. Consequently, *MSY* is the yield of the fishery when the stock is fished at F_{MSY}. F_{MEY}, is estimated as the fishing mortality at *MEY* which produces maximum net present values over the simulation period. Consequently, *MEY* is the yield where the net present values, *NPV*, is maximized over the period as follows:

$$\max_F \sum_{t=1}^{50} NPV \;\; (15) \quad (15)$$

The sum of discounted net present values when maintaining the stock size at B_{MSY} (i.e., NPV_{MSY}) is given by the associated revenue and harvest costs (*Eq. 10-12*) with F_{MSY} and profits over time $\Pi_{MSY(t)}$ and the discount rate *r* as follows:

$$NPV_{MSY} = \sum_{t=1}^{50} \frac{\Pi_{MSY(t)}}{(1+r)^{t-1}} \quad (16)$$

Likewise, NPV_{MEY} is the sum of discounted net present values given by the associated revenue and harvest costs (*Eq. 10-12*) when exploited at F_{MEY} with profits over time

$\Pi_{MEY(t)}$ and the discount rate, r as follows:

$$NPV_{MEY} = \sum_{t=1}^{50} \frac{\Pi_{MEY(t)}}{(1+r)^{t-1}} \quad (17)$$

The sum of net discounted benefits at *MSY and MEY* fishery over the simulation period was divided by the duration of the simulation period to calculate the mean annual net discounted benefits. To evaluate the influence of changes in stock productivity (k) on the reference point estimates, we performed two scenarios representing a 50 percent increase or decrease in *R/SSB* in addition to the control scenario maintaining the scaling factor on *R/SSB* at a fixed level of one (i.e., $k=1$). For each scenario, we estimated the fishing mortality, biomass, yield, and *NPV* achieving both *MSY* and *MEY*. To further illustrate the dependency and degree of change in reference points under various levels of stock productivity, we estimated the reference points across a range of values of the scaling factor k (i.e., ranging from 0.5 to 1.5). We also assessed the sensitivity of the results to changes in the discount rates used. This testing was performed by respectively changing the discount rate to low (r=0.01), medium (r=0.1), and high (r=0.2) levels at each level of stock productivity. Finally, we performed a formal sensitivity test of the estimated reference points (i.e., F_{msy} and F_{mey}) to variations and non-linearities in all other ecological and economic input variables following a generic *Global Sensitivity Analysis* (*GSA*) method by Pianosi *et al*. (2016) (available from: https://www.safetoolbox.info/info-and-documentation/). The tested ecological parameters include the fitted regression coefficients of the *S-R* model (Table 2) that were randomly bootstrapped from their respective 95% confidence interval (*CI*) (Fig. S1), while the economic parameters, i.e., price (p) and unit cost (c), were randomly drawn from a range representing ±25% of the fixed estimates (Table 1). All statistical analyses were conducted using *R software (www.r-project.org) Version 3.5.1* (R Core Team, 2014).

Results

Simulations based on our coupled bioeconomic model well explained the historical dynamics and interannual variability in recruitment success and hindcasted *SSB* when they were validated against observed values throughout the period (Fig. S1; Fig. 3). In addition, simulated mean annual profits are well in line with available data on the mean annual revenue of the Turkish anchovy fishery from 2006 to 2010 (Goulding *et al*., 2014) (Fig. S2). Furthermore, a long-term stochastic model simulation forced with random noise (resampled from the residuals of the *S-R* model) displayed pronounced temporal variability at both decadal and interannual time scales (Fig. 4), reflecting the observed highly variable population dynamics of the anchovy in the Black Sea and beyond (Schwartzlose *et al*., 1999; Lindegren *et al*., 2013a, b; Checkley *et al*., 2017). Conversely, the deterministic model runs (excluding random noise) revealed a stable population dynamic, with the population approaching an equilibrium population size after approximately 10-20 years. The estimated reference points showed lower values of exploitation compared to the historical mean fishing mortalities. Besides, our simulations illustrated that F_{MSY} was greater than F_{MEY} across all productivity scenarios and discount rates, except at medium and high discount rates in the lowest productivity scenario where F_{MEY} was slightly higher than F_{MSY} (Table 3). Additionally,

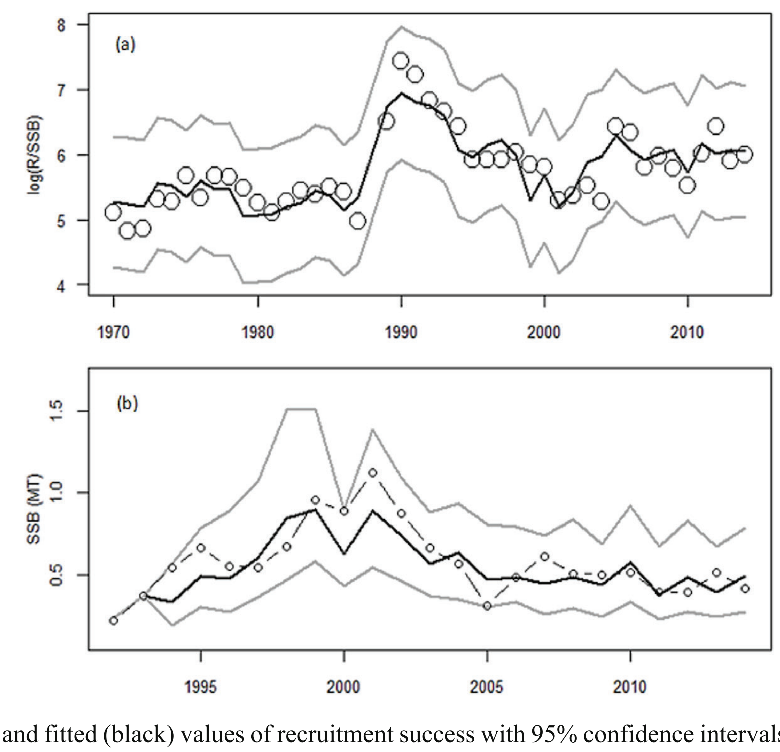

Fig. 3: Observed (circles) and fitted (black) values of recruitment success with 95% confidence intervals (gray) based on the fitted *S-R* model (a). Observed (circles) and hindcasted estimates of spawning stock biomass (*SSB*; black) with 95% confidence intervals (gray) based on the age-structured population model (b).

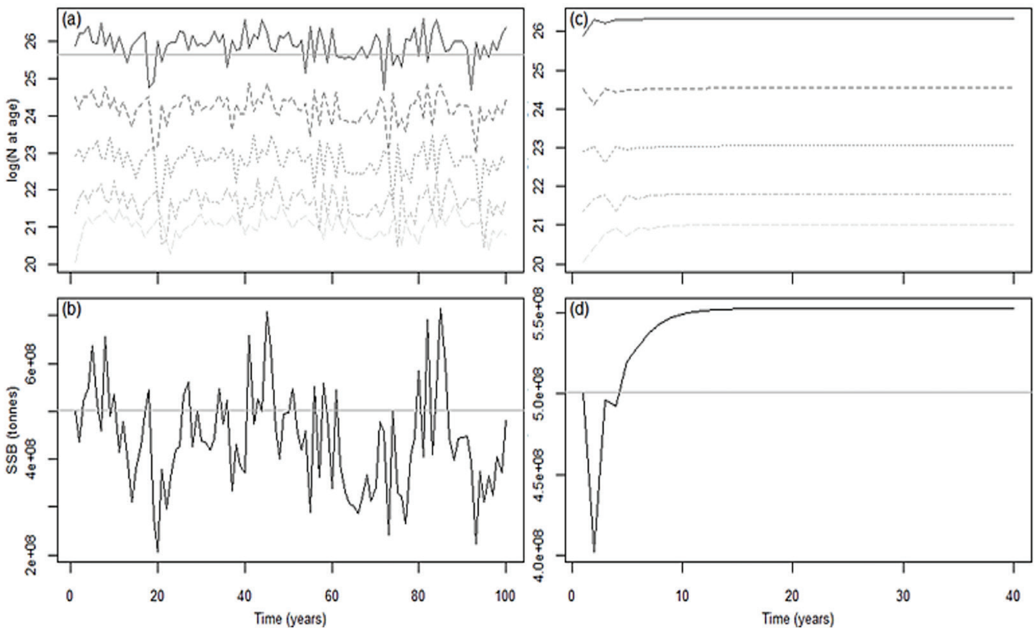

Fig. 4: Examples of the model simulations showing simulated log (numbers-at-age) and spawning stock biomass (*SSB*) under a stochastic (a, b) or a deterministic (c, d) run. The stochastic simulation was forced with random noise (resampled from the residuals of the *S-R* model) and a fixed fishing mortality maintained at the estimated value of F_{MSY}.

there was an increase in F_{MEY} with higher discount rates in all scenarios. In terms of the biomass reference points, our results showed that B_{MSY} was lower than B_{MEY} at the steady-state (Table 3). This was clear in the control- and positive productivity scenarios at all discount rates while in the negative productivity scenario, B_{MSY} was slightly higher than B_{MEY} at medium or high levels of discounting rate (*r=0.1, 0.2*). Interestingly, the differences between B_{MSY} and B_{MEY} values were larger when productivity was increased. In the positive productivity scenario, the model simulations yielded higher and more similar NPV_{MSY} and NPV_{MEY} values at low, medium, and high discount rates compared to base and negative productivity scenarios.

When estimating reference points across the entire range of stock productivity, both F_{MEY} and F_{MSY} increased with higher productivity (Fig. 5a). However, at high levels of productivity, F_{MEY} started to saturate, while F_{MSY} levels continued to increase with only a weak sign of leveling off at high stock productivity. Consequently, differences between F_{MEY} and F_{MSY} were increasing in parallel with the productivity increase, showing that *MEY* can be achieved at significantly lower exploitation compared to *MSY* in case of increased and unchanged stock productivity. This was also reflected in the biomass reference points, where under increasing levels of stock productivity B_{MEY} becomes increasingly larger than B_{MSY} (Fig. 5b). However, on the opposite end of the productivity gradient and under extremely high discounting, F_{MEY} slightly exceeds F_{MSY}. This also caused B_{MEY} to become slightly smaller than B_{MSY} and lead to a lower number of recruits if exploited at low stock productivity and high discounting (Fig. 5c). Finally, the additional sensitivity test showed that reference point estimates were rather insensitive to the overall variation in all the other input parameters (Fig. S3). However, the overall variation in reference point estimates was disproportionally caused by parameter uncertainty in the *S-R* model, while uncertainty and variations in the economic parameters yielded only moderate variation in the estimated reference points.

Discussion

Our study presented and compared for the first-time estimates of *MEY* and *MSY* for the Black Sea anchovy fisheries based on an age-structured bioeconomic model. Our results showed that the historical fishing mortalities were greater than both the estimated reference points (F_{MEY} and F_{MSY}), regardless of simulated changes in stock productivity or the discount rates used. Hence, our analysis suggested that the current exploitation level should be reduced to maximize both future yield and revenue while ensuring a larger and healthy stock size in the long term. Although our recommendations conformed with the current management advice on the Black Sea anchovy to decrease fishing mortalities (STECF, 2014), our results give more detailed insights beyond the generic, precautionary exploitation rate for a small pelagic fish (Patterson, 1992) that forms the basis of the current management recommendations. Moreover, our model simulations illustrated that the potential changes in stock productivity (i.e., using our simple scaling factor on recruitment success), as would arise from either natural or human-induced drivers (e.g., climate change, invasive species, eutrophication), may have the potential to result in substantial variations in biological and economic reference points. Hence, we reinforce the need for further work to better understand the key underlying factors affecting the stock productivity of Black Sea anchovy and its variation in space and time (Gücü *et al*., 2018), including both environmental- and ecological aspects determining the food web structure and population dynamics at large (Lindegren *et*

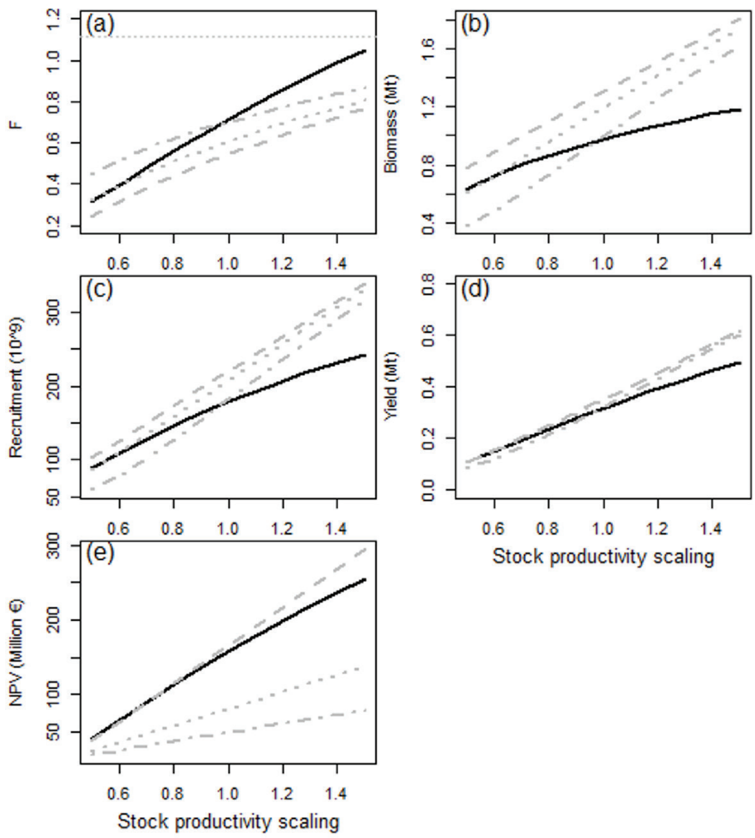

Fig. 5: Estimated fishing mortalities (a), total stock biomass (b), recruitment (c), yield (d) and *NPV* (e) when exploited at *MSY* (black) and *MEY* (light gray) across a range of stock productivities and levels of discounting (i.e., 1% (dashed), 10% (dotted) and 20% (dot-dashed)). The horizontal dashed line in (a) shows the mean long-term *Fs* over the study period.

Table 3. Fishing mortalities, Biomasses and Net Present Values (NPVs) of the anchovy fisheries by discount rates and productivity scenarios.

	Discount Rates*	F_{MSY}	F_{MEY}	F_{MSY}/F_{MEY}	B_{MSY}	B_{MEY}	B_{MSY}/B_{MEY}	NPV_{MSY} (€)	NPV_{MEY} (€)
Unchanged Productivity	High	0.40	0.70	0.57	6.15E+05	2.87E+05	2.14	4.01E+07	4.85E+07
	Medium	0.40	0.62	0.64	6.15E+05	3.65E+05	1.68	7.81E+07	9.01E+07
	Low	0.40	0.58	0.69	6.15E+05	4.13E+05	1.49	2.20E+08	2.45E+08
Positive Productivity	High	0.51	0.85	0.61	7.47E+05	4.13E+05	1.81	6.60E+07	7.83E+07
	Medium	0.51	0.80	0.64	7.47E+05	4.56E+05	1.64	1.32E+08	1.53E+08
	Low	0.51	0.77	0.66	7.47E+05	4.80E+05	1.56	3.76E+08	4.34E+08
Negative Productivity	High	0.23	0.83	0.28	3.88E+05	9.06E+02	428.63	1.46E+07	2.25E+07
	Medium	0.23	0.43	0.53	3.88E+05	1.38E+05	2.82	2.59E+07	3.26E+07
	Low	0.23	0.33	0.69	3.88E+05	2.49E+05	1.56	6.60E+07	7.38E+07

*High Discount Rate: 0.2; Medium Discount Rate: 0.1; Low Discount Rate: 0.01.

al., 2009; Li & Convertino, 2021). To that end, fisheries management should account for such environmental impacts and adjust exploitation rates, accordingly, as has been suggested in other studies including small pelagic fish (Mackenzie *et al*., 2007; Eero *et al*., 2012; Bartolino *et al*., 2014; Lindegren & Brander, 2018). However, such considerations are rarely included in the tactical fishery management (Lindegren *et al*., 2010;), despite the evidence that accounting for these environmental influences would serve to create a win-win outcome from both conservation and exploitation perspectives (Holma *et al*., 2019). In a bioeconomic evaluation of tuna fisheries, Kompas *et al*. (2010) demonstrated that B_{MEY} should be greater than B_{MSY} and that the derived payoffs of the B_{MEY} should also be greater. These findings are well in line with Grafton *et al*. (2007; 2010) presenting examples of other fisheries in which B_{MEY} exceeds B_{MSY}, irrespective of the discounting rate. Our results, showing that B_{MEY} generally exceeds B_{MSY} across productivity scenarios and levels of discounting (Fig. 5b), are in line with these previous findings in the literature, suggesting that *MEY* is beneficial for the fishery economy (Bromley, 2009). However, other studies have argued the opposite (Christensen, 2010), partly because the economically optimum stock size with discounting may result in a long-term decline in stock size below *MSY* or even to extinction (Clark & Munro, 1975; Clark *et al*., 2010). Consequently, the general perception that B_{MEY} exceeds B_{MSY} may not necessarily apply in all cases, especially since a suite of endogenous and exogenous factors may affect the relationship between these reference points. For instance, Tahvonen *et al*. (2018) using a similar age-structured model setup found that "endogenous optimization of mesh size" led to slightly lower B_{MEY} compared to B_{MSY}. Similarly, our model simulations illustrated that under very low stock productivity B_{MSY} slightly exceeded $B_{MEY.}$, simply because of somewhat higher levels of exploitation ($F_{MEY} > F_{MSY}$). However, note that it is only clear at high levels of discounting (*r*=20%). This would incentivize short-term gains and higher exploitation rates, leading to lower recruitment and stock biomass at *MEY* compared to fishing at *MSY* (Fig. 5b, c). Furthermore, this would result in lower *NPVs* (Fig. 5e) as fishing costs increase steeply at lower stock biomass (Fig. 2).

Taken together our results show that discount rates or other externally driven changes in stock productivity (or the overall carrying capacity of the ecosystem for that matter) may influence the estimation of reference points, particularly the degree to which B_{MSY} exceeds B_{MEY} or not. Although the slightly higher level of exploitation at F_{MEY} caused B_{MEY} to drop just below B_{MSY}, it is noteworthy that the population size in our simulations was still capable of producing enough recruits to remain stable and avoid stock collapse (i.e., decline towards zero), while at the same time providing some yield and revenue (primarily from fishing the 0-group). This is due to the underlying *S-R* model that predicted increasingly higher recruits-per-spawner at the low stock size. This prediction in turn compensated for the low stock size under the poor productivity scenario. However, it is worth mentioning that prediction uncertainties become larger at the low stock biomass level (i.e., since it is well beyond the range of values used for fitting the *S-R* model; Fig. S2). Consequently, reference point estimations in such extreme cases should be considered highly uncertain. Nevertheless, our example highlights that ecological factors, internal to the population, notably fast growth, early maturation, and high fecundity of anchovy (Lisovenko & Andrianov, 1996) may ensure a viable population regardless of exploitation under F_{MEY} or F_{MSY}. Nonetheless, such a claim may not necessarily hold for other species, especially for long-lived, slowly growing species with low fecundity that are typically most at risk of overfishing (Dulvy *et al*., 2003). As shown in our analysis, discounting had a substantial effect on the economic reference points and the simulated population dynamics. High discount rates typically incur severe economic losses in the fisheries (Grafton *et al*., 2010; 2012; Kompas *et al*., 2010). That is because high discount rates are largely due to the uncertainty perceived with respect to market dynamics based on present and future landings. Döring & Egelkraut (2008) recommended reducing fishers' long-term uncertainty by guaranteeing specific shares of total future landings and profits, e.g., by restricting the number of fishing licenses and/or introducing a system of individual transferable quotas (*ITQs*) (Grafton *et al*., 2010; 2012; Kompas *et al*., 2010; Gücü *et al*., 2017). In the absence of *ITQs*, the key harvest control rule for the Black Sea anchovy fisheries that may reduce overexploitation is effort limitation. However, a decrease in effort and jobs in the sector would lead to potential direct and indirect economic losses in different anchovy fishing-related sectors (Norman-López & Pascoe, 2011). To reduce overcapacity and limit fishing effort, the Turkish Ministry of Agriculture and Forestry recently conducted a buyback program with the aim of removing unproductive vessels from the fishery (Ünal and Göncüoglu-Bodur, 2020). However, due to the removal of inefficient vessels (i.e., vessels with low catch, inactive vessels) from the fleet, high fishing mortalities remain by increased fishing hours and/or potentially increased number of fishers per vessel. Consequently, additional management actions and regulations are inevitable to reduce effort and ensure the long-term ecological- and economic sustainability of the Black Sea anchovy fisheries.

Conclusion

The Black Sea anchovy is the ecologically and economically most important species for Turkish fisheries. Environmental variability (caused by either biotic or abiotic factors) has historically had a substantial impact on stock productivity. As shown by our model simulations, any potential future changes in stock productivity, either positive or negative, will have a direct influence on the status of the stock and fishers' income. Hence, adapting to or mitigating the effects of such environmentally induced variation in stock productivity is necessary to ensure economic stability and sustainability of fisheries in the climate change (Lindegren & Brander, 2018). However, adapting fishing mortalities in line with the reference points suggested in this study is far from trivial and requires effective management measures and governance frameworks to reduce overcapacity and achieve both long-term ecological and economic sustainability. For instance, to ease acceptance and compliance of management regulations by fishermen, management authorities may need to find ways to compensate fishers in the short run for potential losses in their fishery rents or to incentivize fishermen to invest in alternative sources of income and livelihoods, even beyond fishing (Allison & Ellis, 2001). Furthermore, management reforms in access rights to the fishery, including *ITQs* or additional reductions in fleet overcapacity may be considered along with the compensation schemes to help achieve long-term sustainability of the anchovy fisheries in the Black Sea. Finally, management of Black Sea anchovy needs to embrace a regional ecosystem-based approach to management agreed upon by all fishing nations to avoid overcapacity and ensure sustainability and a fair share of total allowable catches and their revenues among the Black Sea countries.

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Data Availability Statement: The data that is used and support the findings are publicly available. Catch and price statistics of the anchovy are openly available by the Turkish Central Statistical Database via the link: https://biruni.tuik.gov.tr/medas/?kn=97&locale=tr. Biological parameters of the anchovy stock assessment are available in the report STECF-14-14, EUR 26896 via <https://doi.org/10.2788/63715>. Economic survey data of the anchovy fishing fleet can be made available upon request.

Disclaimer: The results of this publication, "Comparison of Fisheries Reference Points under Varying Stock Productivity: The Black Sea Anchovy as a Case Study," reflect only the authors' view. Conflict of Interest: The authors declare that they have no conflict of interest.

Data Availability: The data is available either in the paper or upon request: Ecological and economic data will be shared on a reasonable request to the corresponding author.

Authors' Contribution: ST: Sezgin Tunca; ML: Marko Lindroos, MLI: Martin Lindegren. ST is the corresponding author and conceptualized the research idea. ST, ML, and MLI developed the research idea and ST and MLI prepared the coding setup. ST performed the model simulations with assistance from MLI. ST drafted the first version of the article. ST, ML, and MLI revised and edited the final article.

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Supplementary Data

The following supplementary information is available online for the article:

Fig. S1: Boxplot of bootstrapped regression coefficients of the fitted S-R model (see Table 2), including the intercept (A), the slope of spawning stock biomass (*SSB*) (B) and the fixed effect factor of assessment (C), as well as the resulting predictions of recruits-per-spawner, as well as 95% confidence intervals (grey dashed) at each level of observed *SSB* when back-transformed from the log-values of the linearized Ricker model.

Fig. S2: Boxplot of model derived estimates of profit (m€) versus an available estimate of the mean annual revenue of the Turkish anchovy fishery from 2006 to 2010 (Goulding *et al.,* 2014; dashed line). The model simulations represent mean annual profit based on 1,000 runs using the mean fishing mortality during the corresponding time-period and randomly resampled errors of the S-R model as input.

Fig. S3: Sensitivity of estimated reference points F_{msy} (top) and F_{mey} (bottom) to uncertainty in model input parameters, including each of the parameters individually and the combined global sensitivity (“Total”). The parameters a, b, d were randomly bootstrapped from the 95% CI of the fitted regression coefficients of the *S-R* model (Table 2; Fig. S1), while the economic parameters, price (*p*) and unit cost (*c*) were randomly drawn from a range representing ±25% of the fixed estimates (Table 1).