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RESEARCH ARTICLE **ARAŞTIRMA MAKALESİ**

Understanding the status of key fish stocks in the Turkish Black Sea: A graphical approach to sustainable management

Karadeniz'deki önemli balık stoklarının durumunun anlaşılması: Sürdürülebilir yönetim için grafiksel bir yaklaşım

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Abstract: Fish stocks are critical components of aquatic ecosystems, providing essential food sources for humanity and supporting the complex balance of marine food webs. Effective management of these resources is crucial for meeting global food demands and preserving aquatic biodiversity. In this study, we assess fishing pressures—categorized as low, high, and extreme—on six key fish stocks in the Turkish waters of the Black Sea: horse mackerel (*Trachurus mediterraneus*), the Black Sea anchovy (*Engraulis encrasicolus*), sprat (*Sprattus sprattus*), whiting (*Merlangius merlangus euxinus*), bluefish (*Pomatomus saltatrix*), and the Atlantic bonito (*Sarda sarda*) and provide important findings to protect fish stocks. By applying dynamic modeling and stability analysis solely to landing data, we create graphical representations that illustrate the current trends of these stocks, through growth and fishing mortality curves. Our findings reveal that although certain stocks have shown an upward trend over the past 15 years, they remain exposed to high levels of fishing mortality. To support sustainable management, this study establishes the Maximum Sustainable Yields (MSYs) for each stock based on their present conditions and identifies stable equilibrium points where stocks can be sustained over the long term. This method also provides an opportunity to analyze state of fish stocks when only landing data is available.

Keywords: Black Sea fishery, fishing pressures, sustainable fisheries, fishery model, overfishing

Öz: Balık stokları, su ekosistemlerinin temel bileşenleridir; insanlık için çok önemli bir gıda kaynağı sağlarken, besin zincirinin karmaşık dengesine de katkıda bulunurlar. Bu balık stokların etkin bir şekilde yönetimi, gıda taleplerini karşılamak ve denizlerdeki biyolojik çeşitliliği korumak açısından kritik öneme sahiptir. Bu çalışmada, Türkiye'nin Karadeniz kıyısındaki altı ana balık stoğu – istavrit (*Trachurus mediterraneus*), hamsi (*Engraulis encrasicolus*), çaça (*Sprattus sprattus*), mezgit (*Merlangius merlangus euxinus*), lüfer (*Pomatomus saltatrix*) ve palamut (*Sarda sarda*) – düşük/yüksek/aşırı avlanma seviyelerine göre incelenmiştir ve bu stokların korunmasına dair önemli bulgular sunulmuştur. Sadece av istatistikleri kullanılarak dinamiksel bir inceleme ve denge analiziyle, balık stoklarının mevcut dinamiklerini grafiksel temsiller kullanarak analiz ettik. Bu grafikler, balık stoklarının büyüme eğrileri ve balıkçılık kaynaklı avlama (ölüm) eğrilerine dayanarak oluşturulmuştur. Araştırmamız, bazı stoklarda son 15 yılda artış eğilimi gözlense de hala yüksek düzeyde avlanma oranına maruz kaldıklarını ortaya koymaktadır. Bu sorunu ele almak için çalışmamız, her bir balık stoğunun mevcut durumuna bağlı olarak Maksimum Sürdürülebilir Verim (MSV) değerlerini belirlemekte ve bu stokların uzun vadede sürdürülebilir kalabileceği denge noktalarını tespit etmektedir. Bu yöntem, avlanma verileri dışında herhangi bir veri bulunmadığında balık stoklarını analiz etme fırsatı da sunmaktadır.

Anahtar kelimeler: Karadeniz balıkçılığı, av baskıları, sürdürülebilir balıkçılık, balıkçılık modeli, aşırı avlanma

INTRODUCTION

Fish populations are essential to marine ecosystems, maintaining ocean balance and providing a vital food source for humans (Sumaila and Tai, 2020). However, overfishing remains a significant challenge, leading to the depletion of many fish stocks globally (Hilborn, 2012). Such overfishing has also caused the decline of native species and the degradation of entire ecosystems (Nogrady, 2023; Cheikh et al., 2024). Therefore, effective management and conservation of marine ecosystems is fundamental to the sustainability of fisheries and habitats.

One of the well-known habitats for fish stocks facing overfishing is the Black Sea, and it has always been a rich habitat for fish and supported many communities along its shores (Salihoglu et al., 2017; Demirel et al., 2020). However, fish populations are now under significant threat due to increased fishing and environmental problems like pollution and habitat damage (Daskalov, 2002; Nastase et al., 2024; Damir et al., 2024). More fishing, driven by economic needs and new technology, is putting a lot of stress on fish and disrupting the balance of the ecosystems (Llope et al., 2011; Raykov and Duzgunes, 2017). These challenges underscore the urgent need for sustainable management practices to safeguard the future of this invaluable resource and the communities that depend on the habitat.

The specific fish stocks focused on in the present study are horse mackerel, the Black Sea anchovy, sprat, whiting, bluefish, and the Atlantic bonito. Each of these fish stocks has an important role in keeping the Black Sea ecosystem balanced and healthy. However, our primary reason for selecting these species was their high level of landings and their importance in fisheries.

Our main goal of the study was to determine whether these fish populations on the Turkish side of the Black Sea were subject to low, high, or extreme (overfishing) fishing pressure. To evaluate this, we analyzed time-dependent growth and fishing mortality curves derived from the logistic model presented in the material and method section. In assessing the status of these fish populations, we also investigated whether it was possible to maintain the populations at a positive equilibrium for sustainable fishing through a graphical stability analysis. Additionally, we calculated the Maximum Sustainable Yields (MSYs) of these fish populations based on their current status to support maintaining their biomass around a positive equilibrium.

Mathematical modeling serves as a common approach in fishery management, particularly in scenarios with limited or solely landing data (Kot, 2001; Neubert, 2003; Demir, 2019; Demir and Lenhart, 2020). Nonetheless, relying only on mathematical models is inadequate for understanding species dynamics and mitigating the risks of overfishing. Therefore, it is important to combine stability analyses into mathematical models to prevent overfishing and attain a stable equilibrium point, ensuring sustainable fisheries (Kot, 2001; Demir, 2023).

To sum up, this study began by introducing a single-species model (logistic model) (1), followed by the presentation of graphical stability analysis. We then estimated the parameter values of the logistic model. After the parameter estimation, we investigated the time-dependent intrinsic growth and fishing mortality rates over time in graphs. These graphs not only presented fishing status as low, high, or extreme depending on the relation between the intrinsic growth rate (r) and fishing mortality rate (F) but also presented stability conditions for each fish stock. Finally, we present our findings in the results section, followed by a conclusion.

MATERIALS AND METHODS

In our model given in Eq.1, we estimated four parameters: initial biomass (N_0), intrinsic growth rate (*r*), carrying capacity (*K*) and fishing mortality rate (*F*). The number of data points should be at least equal to or larger than the number of parameters being estimated (John, 2015). Our literature review indicated that a minimum of 8 data points is generally considered sufficient to detect a clear pattern in simple linear trends (Jenkins and Quintana, 2020). However, fish stocks typically do not follow simple linear trends due to the complexity of marine ecosystems and various environmental factors. Therefore, in our study, we considered 15 data points to effectively portray the current trends in fish populations. This approach balances the acquisition of sufficient data for trend analysis while avoiding older data that may not reflect the current status of the fish stocks. It is important to state that we are not interested in very old time series data since we only focus on the current status of fish stocks in our study to understand their current status.

We used landing data obtained from the Turkish Statistical Institute for the years 2008 to 2022 (TUIK, 2023). Since this study only considered landing data in stock assessment on the southern part of the Black Sea, we used the landing data collected only from this particular region (specified as West Black Sea (TR8) and East Black Sea (TR9) regions in TUIK data sources). Our study uses graphical visualization to assess fishing pressure levels and determine whether a fish population is experiencing high or extreme exploitation. Fishing pressure is mainly related to fishing mortality rate as indicated in Figure 2 and it refers to the intensity of fishing activity on a particular fish population. We did not include catch per unit effort (CPUE) data, as it is not always available for each fish stock. Instead, we support the landing data with stability analysis and compare our findings in the discussion section with studies that incorporate CPUE and additional data.

We first introduced the logistic model (1) designed to facilitate the analysis of trends and patterns in the size of fish stocks. This model served as a foundational tool, enabling us to investigate the time-dependent intrinsic growth and fishing mortality rates. We visualized these rates over time to discern when the population growth curve surpasses or falls below the fishing mortality curve. When the growth curve exceeds the fishing mortality curve, the population tends to increase, whereas when the growth curve falls behind the fishing mortality curve, the fish stock tends to decrease. Therefore, a comprehensive analysis could provide valuable insights into whether the fish populations in the study area were subjected to low, high, or extreme fishing pressure.

Furthermore, the graphical approach facilitates stability analysis to determine whether a fish population can reach a positive stable equilibrium point for a sustainable fishery. By using this graphical method, we identified key indicators of fish population dynamics and obtained essential information regarding their status, including fishing pressure levels, trends in population biomass, intrinsic growth and fishing mortality rates, and MSYs. We also assessed whether the population could remain at a positive equilibrium point for a sustainable fishery. By leveraging these techniques, we aimed to understand the status of fish stocks when only landing data is available. This is not a new technique and it has been used in stability analysis of the logistic (fishery) models (Kot, 2001).

Model formulation and description

The dynamics of fish stock were described by the following model (Schaefer, 1954), which is a first-order differential equation. This model considered fish stocks growing logistically and being harvested by the term $FN(t)$ where F is a constant fishing mortality and $N(t)$ represents the amount of fish stock in the system at time *t.*

$$\frac{dN(t)}{dt} = rN(t)\left(1 - \frac{N(t)}{K}\right) - FN(t) \qquad (1)$$

Here, initial condition $N(0) = N_0$. The growth term of fish stock was modeled using a logistic equation with an intrinsic growth rate of r and a carrying capacity of K. All the coefficients and initial conditions in the model are positive and have upper bounds. Note that in the equation $F = fq$, f represents fishing effort and q is the catchability rate. In the absence of catch per unit effort (CPUE) data, the catchability rate cannot be determined. Thus, in the study, we assumed $q = 1$, and the fishing mortality rate was directly represented by the fishing effort as $F = f$.

Stability analysis of the model

We examined the stability of the model (1), graphically. The hump-shaped curve corresponds to the density-dependent growth term and the straight line corresponds to the harvest term (or fishing mortality term, see Figure 1). When we investigated the model stability by setting, $\frac{dN(t)}{dt} = 0$ in Eq. 1, we obtained two equilibrium points as $N(t) = N_1^* = 0$ and $N(t) = N_2^* = K\left(1 - \frac{F}{r}\right)$. These equilibrium points were obtained from the equality of the growth term and harvest term as

$$rN(t)\left(1 - \frac{N(t)}{K}\right) = FN(t)$$

The equilibrium point, $N_1^* = 0$ is unstable, but $N_2^* = K\left(1 - \frac{F}{r}\right)$ is stable (see the left plot in Figure 1). When the population biomass is within the range of 0 and N_2^*, the growth term is greater than the harvest term which implies $\frac{dN(t)}{dt} > 0$ in Eq. 1, resulting in an increase in population biomass up to N_2^*. Since population biomass goes from zero to the positive equilibrium point N_2^*, the equilibrium point, $N_1^* = 0$ is called an unstable equilibrium point. On the other hand, $\frac{dN(t)}{dt} < 0$ in Eq.1 when population biomass surpasses N_2^*, leading to a decline in population biomass towards N_2^*. In both cases, when population biomass is below or above the equilibrium point $N_2^* = K\left(1 - \frac{F}{r}\right)$, the biomass of the population approaches towards to the equilibrium point N_2^*. Thus, N_2^* is a stable equilibrium point. Furthermore, in the case of $F = r$, we only have one equilibrium point since $N_1^* = N_2^* = 0$ and this equilibrium point is stable from the right side (see the right plot in Figure 1). This situation indicates severe overfishing, putting fish populations at risk of extinction.

In short, we obtained two equilibrium points: one at zero (N_1^*) and the other at a positive value (N_2^*). Based on the graphical stability analysis, we observed that the first equilibrium point, N_1^* = 0, was unstable, while the second equilibrium point, $N_2^* = K\left(1 - \frac{F}{r}\right)$ was stable. We expected the fish population biomass to remain around this stable point. To help the system stay near this stable point, we provided the current MSYs as MSY= $\frac{rK}{4}$ for each stock, ensuring that the equilibrium point is maintained without shrinking or approaching zero.

The method for investigating the status of fish stocks

By investigating the growth and harvest terms in our model (Eq. 1), we can gather insights into the status of the fish stock and determine whether it is experiencing overfishing. Mainly, we will see three main district statuses for fish stocks: (a) low fishing mortality case, (b) high fishing mortality case, and (c) severe fishing mortality case (Figure 2) (Kot, 2001). Note that although two plots from Figure 1 are also presented in Figure 2, we provide different explanations for the two figures. In Figure 1, we explain the stability analysis using grey arrows to represent the direction of biomass changes, while in Figure 2, we focus on the fishing status of the stocks.

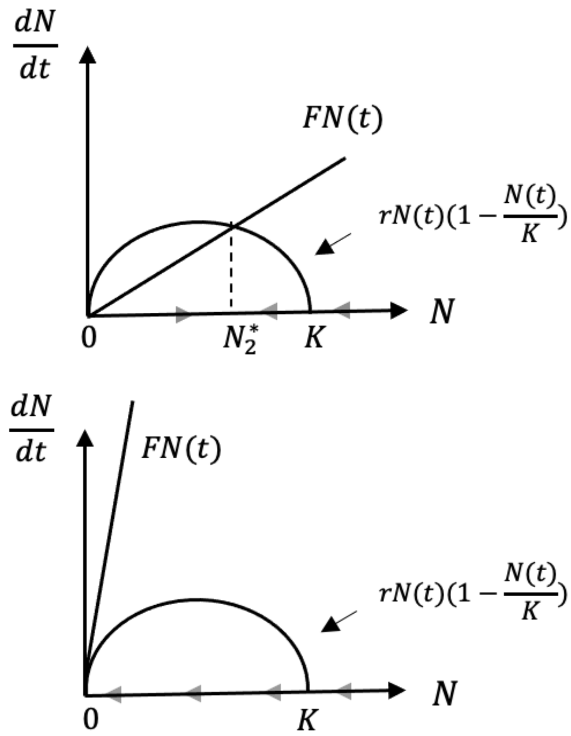

Figure 1. Graphical visualization of the stability analysis. The grey arrows indicate the direction of changes in population biomasses (stocks)

In our model dynamics, we used the estimated fishing mortality rate, F. On the other hand, when examining the 15-year average growth curve corresponds to the term $rN(t)\left(1 - \frac{N(t)}{K}\right)$ and average fishing mortality curve corresponds to the term $FN(t)$ for each month, as shown in the bottom plots of Figures 3-8, we need to extend the fishing mortality rate from a seasonal to a yearly basis to match with the growth term. The growth term is active throughout the year, but the harvest term is seasonal, typically from September to April, with no fishing mortality occurring from May to August.

To create a continuous curve for the entire year, we make a simple assumption. For example, for the horse mackerel stock, we estimated in the parameter estimation section below that the fishing mortality rate was F = 0.431 during the 7-month fishing season (from September to April). During the remaining 5 months (from May to August), there was no fishing mortality. To approximate a continuous annual fishing mortality rate, we assumed that the total harvest effort applied over 7 months is spread evenly across the entire year. This approach yields a constant annual fishing mortality rate. We calculated this by considering how the total harvest effort for 7 months would be distributed over 12 months, resulting in:

$$F^* = \frac{F * 7}{12} = \frac{0.431 * 7}{12} = 0.2514$$

where F was the estimated fishing mortality rate for the 7-month period and F^* for 12 months. This method allowed us to calculate a constant fishing mortality rate that applies throughout the entire year, facilitating comparison with the continuous growth term. Also, note that we used these calculated rates (F^*) to obtain 15-year average growth curves and fishing mortality curves presented in plots *c* and *d* of Figures 3-8 and used F for plots *a* and *b* in Figures 3-8.

Consequently, upon determining the fishing mortality rates outlined in Tables 1-6 (see results section below), we employ the adjusted fishing mortality rates (F^*) rather than F to generate plots *c* and *d* illustrated in Figures 3-8. This method enabled us to capture growth and harvest curves for stability analysis and address one of the scenarios presented in Figure 2. This method is not new; it was originally developed by Schaefer (1954) and is well presented in Kot (2001).

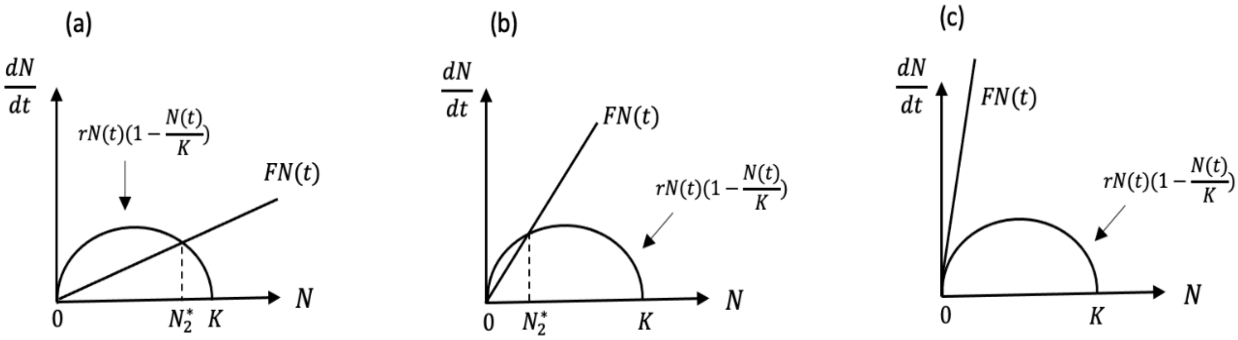

Figure 2. Visualization of the low fishing mortality harvest (case a), high fishing mortality harvest (case b) and severe overfishing harvest (case c)

In Figure 2, the X-axis represents the biomass of fish stock in tonnes, while the Y-axis illustrates the rate of changes in the fish stock's biomass over time. It is noteworthy that when the harvest line surpasses the bell-shaped growth curve, the rate of change of $\frac{dN(t)}{dt}$ in Eq. 1 becomes negative, indicating a decline in the fish stock's biomass. Conversely, when the harvest line falls below the growth curve, the rate of change is positive, signaling an increasing trend in the fish stock's biomass. Based on data and parameter estimations from the model, we projected the status of six important fish stocks on the Turkish side of the Black Sea, including horse mackerel, the Black Sea anchovy, sprat, whiting, bluefish, and the Atlantic bonito.

It is noteworthy that if we only identify one equilibrium point, this point is deemed unstable, leading to the eventual extinction of the fish stock due to severe overfishing mortality (see plot c in Figure 2). Conversely, the presence of two equilibrium points signifies stability (see plots a and b in Figure 2). In such cases, the positive second equilibrium point is stable, indicating that the fish stock will tend towards this equilibrium point over the long term and we aim to determine the values of the second equilibrium point for each fish stock, allowing us to comprehensively grasp the current status of these stocks.

Moreover, the positioning of this equilibrium point concerning the peak of the growth curve holds significance. If it occurs before the peak (plot b in Figure 2), it suggests that the population faces high fishing mortality. Conversely, if it occurs after the peak (plot a in Figure 2), the population is experiencing low fishing mortality. Thus, as the size of area A (plot a in Figure 2) decreases due to the interaction point between the growth term and the harvest term, the equilibrium point shifts from low to high fishing pressure, potentially even reaching extreme fishing pressure. These analyses provide critical insights into the dynamics of fish stocks and help guide efforts toward sustainable management practices.

Thus, this study primarily focuses on equilibrium points to assess the status of fish populations based on their positions. Therefore, we do not analyze dynamics outside these equilibrium points. In Plots d of Figures 3–8, fish biomass fluctuates between the first equilibrium point ($N_1^* = 0$) and the second equilibrium point ($N_2^* > 0$). When fishing pressure decreases, N_2^* increases; otherwise, it declines toward zero.

Parameter estimation

The parameters of the model (1) for each specific fish stock were estimated using the annual landing data between the years 2008 and 2022 (TUIK, 2023), with the Ordinary Least Squares (OLS) method used to minimize the sum of the squares of the differences between the observed annual landing data and the model's predictions. The goodness of fit was assessed by calculating the relative error (e_r) of the fit using the following formula:

$$e_r = \min\left(\frac{\sum_{k=1}^{n}\left(H_k - \widehat{H}_k\right)^2}{\sum_{k=1}^{n}(H_k)^2}\right)$$

where H_k and $\widehat{H}_k$ are the exact and estimated annual landing data, respectively. The term $\widehat{H}_k$ represents the harvest term, $FN(t)$, in our model. To determine the total estimated landing for each fish stock, we sum the estimated harvest over the specified fishery season. For instance, the fishing season for anchovy in the Turkish waters of the Black Sea spans from September to January (Gücü et al., 2017). Accordingly, we calculate the total estimated harvest, ($FN(t)$), over this time period. An ode45 solver with fmincon from the Optimization Toolbox of MATLAB is used in the parameter estimation. See Tables 1-6 for estimated parameters and Figures 3-8 for model fits for each fish stock. Since we fitted model (1) using annual landing data, the parameter units are expressed on a yearly basis. Additionally, to mitigate the risk of converging to a local minimum during parameter estimation, we used 100 different starting points. These starting points were selected based on the initial parameter ranges provided in Tables 1–6, ensuring a more robust minimization of the discrepancy between the observed landing data and the model's estimated values.

In the parameter estimation process, we initially defined a rough range for each parameter based on values reported in the literature to ensure biological plausibility and to accurately capture fish stock trajectories. For anchovy parameters, including growth rate (*K*) and fishing mortality (*F*), we selected values from previous studies that analyzed these factors in similar fish stocks (STECF, 2017; Salihoğlu et al., 2017; Akkuş and Gücü, 2022). Fishing mortality rates for anchovy, sprat, horse mackerel, and whiting were determined based on findings from stock assessments and studies (STECF, 2017; Salihoğlu et al., 2017; Kasapoğlu, 2018). Additionally, the parameter ranges for intrinsic growth rate (*r*), carrying capacity (K), and fishing mortality (*F*) for the Atlantic bonito and bluefish were derived from studies focusing on population dynamics and species-specific modeling (Akkuş and Gücü, 2022; Daskalov et al., 2020). The intrinsic growth rate (*r*) for fish populations generally varies between 0.05 and 1, as reported in global fishery databases and ecological studies (Patrick and Cope, 2014; Daskalov et al., 2020; FishBase, 2025). Thus, we specified the initial ranges of parameters depending on the studies and then made parameter estimations.

After that MATLAB's Optimization Toolbox identified the best value within the specified range, which we used as the estimated parameter value. For example, in the estimate of intrinsic growth rate (*r*) for horse mackerel, we initially set the range to 0.1-0.8. After the estimation process suggested a value of around 0.26, we refined the range to 0.2-0.3. We conducted similar preliminary analyses for all parameters, narrowing down the best intervals. After determining these intervals, we estimated all parameters simultaneously for each fish stock. Once the estimation was complete, we double-checked to ensure that none of the estimated parameters reached the upper or lower bounds of the initial ranges. Additionally, note that we estimated parameters for the entire period, rather than focusing on the initial, middle, or final years. We provided a single estimate that applies to the whole period.

RESULTS

In this section, we looked into the examination and simulation of the current status of fish stocks, based on parameter estimations unique to each fish stock. Our primary focus lay in determining whether fish stocks are subject to low or high fishing mortality, or if they are facing severe overfishing. We initiated our examination with a focus on horse mackerel and subsequently looked into the analysis of other species in the following subsections.

The current status of horse mackerel

We conducted harvesting operations between September and April targeting the horse mackerel fishery on the Turkish side of the Black Sea (STECF, 2017). Based on parameter estimations outlined in Table 1, the Maximum Sustainable Yield (MSY) is estimated at 11405 tonnes from the formula, MSY$=\frac{rK}{4}$. Over the years 2008 to 2020, we observed a decreasing trend in this fishery, followed by signs of an increase in the last two years. While it's challenging to discern two equilibrium points from the bottom left plot in Figure 3, our analysis reveals two equilibrium points: $E_1 = 0$ and $E_2 \cong 12000$ tonnes, as illustrated in the bottom right plot of Figure 3.

Our assessment of fish stocks and stability graphs indicates that the fish stock has been experiencing high fishing mortality since the second positive equilibrium, remaining on the left side of the peak in the bell-shaped growth curve (as shown in the bottom left plot (*c*) of Figure 3). Currently, the annual maximum instantaneous biomass ranges between 5000 and 8000 tonnes in 15 years (see the top right plot (*d*) in Figure 3). With the second equilibrium point at around 12000 tonnes (as depicted in the bottom right plot of Figure 3), the fish stock in this fishery has the potential to boost its instantaneous biomass by up to 12000 tonnes. This is because the growth curve exceeds the fishing mortality curve by the same margin, indicating a promising opportunity for biomass increase. When harvesting horse mackerel at or below the MSY level, there is the potential for the fish stock to increase its instantaneous biomass up to 12000 tonnes. This increase in biomass consequently leads to an elevation in the MSY of this fishery due to the enhanced stock abundance. Thus, to obtain a sustainable fishery for horse mackerel, it is recommended to harvest around or below the MSY estimated in the study.

There may be some confusion when interpreting plot b in Figure 3, as it shows the maximum biomass level ranging from approximately 5000 to 6000 tonnes at the beginning of each year, while our model estimates the maximum sustainable yield (MSY) for horse mackerel stocks to be 11405 tonnes. However, this discrepancy arises because the blue curves in the plot represent the biomass-harvest dynamics rather than the total annual biomass. Since harvesting occurs on a weekly basis between September and April, the cumulative estimated landings are distributed throughout this period rather than being reflected as a single peak in biomass.

Table 1. Parameter descriptions and estimated parameter values for horse mackerel

Parameters	N_0	K	r	F	$\frac{rK}{4}$	e_r
Description	Initial biomass of fish stocks	Carrying capacity	Intrinsic growth rate	Fishing mortality rate	Maximum sustainable yield	Relative errors of fits
Unit	Tonnes	Tonnes	$year^{-1}$	$year^{-1}$	Tonnes	-
Initial range	$5e^4$ - $10e^4$	$1e^5$-$3e^5$	0.2 - 0.3	0.35-0.55	-	-
Horse mackerel	7518	186214	0.254	0.431	11405	0.29

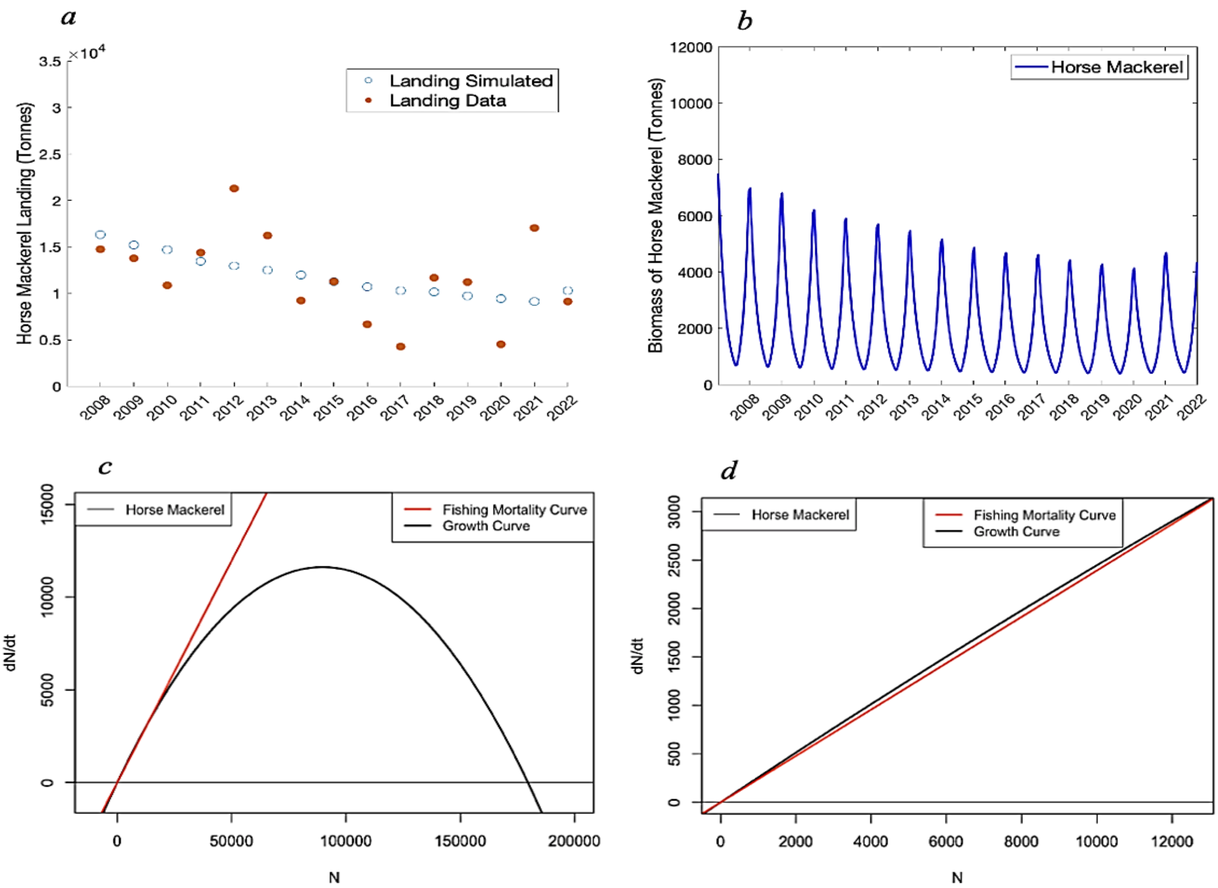

Figure 3. The plot (*a*) denotes the model fit with annual landing data, and the plot (*b*) is the instantaneous change in the fish stock (biomass) with the estimated parameters in Table 1. The plot (*c*) represents the visualization of fish status, the X axis denotes fish stock biomass in terms of tonnes (*N*) and the Y axis denotes the rate of change (dN/dt) in the 15-year average fishing mortality curve (F^*) and growth curve over 15 years. The plot (*d*) is a zoomed version of the plot (*c*) and shows the positive equilibrium point around *N*=12000 tonnes.

The current status of the Black Sea anchovy

We applied the harvest between September and January for the Black Sea anchovy fishery on the Turkish side of the Black Sea (Gücü et al., 2017). The estimated MSY is 169512 tonnes depending on the parameter estimation for this fishery (see Table 2). We have two equilibrium points $E_1 = 0$ (unstable)and $E_2 \cong 230000$ (stable). As indicated in the bottom left plot (*c*) in Figure 4, similar to the horse mackerel, the anchovy population has been also experiencing high fishing mortality in the last 15 years since the second positive equilibrium, remaining on the left side of the peak in the bell-shaped growth curve (as shown in the bottom left plot (*c*) of Figure 4). The annual maximum instantaneous biomass of anchovies fluctuates between 130000 tonnes and 170000 tonnes. However, it has the potential to surge to 230000 tonnes (see the bottom-right plot (*d*) in Figure 4), as indicated by the growth curve consistently surpassing the fishing mortality curve until reaching the 230000-tonnes biomass value.

To achieve an instantaneous biomass increase of up to 230000 tonnes for the anchovy fishery, it's crucial to maintain the annual harvest of anchovy at or below the MSY estimated in this study. Implementing this strategy not only leads to immediate biomass increases but also ensures long-term benefits. As the fish stock reaches stability at 230000 tonnes, the MSY will increase over time, securing the sustainability of anchovy fisheries in the long term.

Table 2. Parameter descriptions and estimated parameter values for the Black Sea anchovy

Parameters	N_0	K	r	F	$\frac{rK}{4}$	e_r
Description	Initial biomass of fish stocks	Carrying capacity	Intrinsic growth rate	Fishing mortality rate	Maximum sustainable yield	Relative errors of fits
Unit	Tonnes	Tonnes	$year^{-1}$	$year^{-1}$	Tonnes	-
Initial range	$1e^5$ - $3e^5$	$1e^6$-$3e^6$	0.3-0.4	0.5-0.9	-	-
Black Sea anchovy	148929	1765750	0.384	0.68	169512	0.32

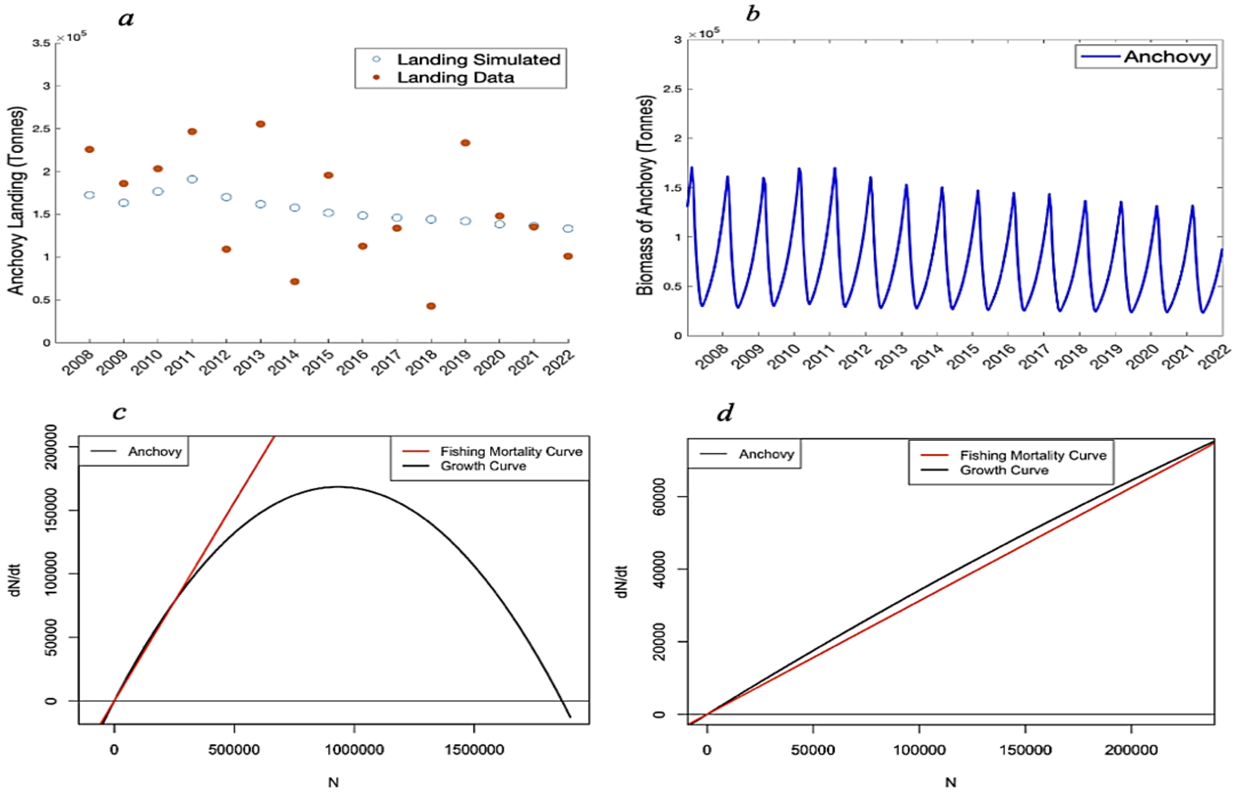

Figure 4. The plot (*a*) denotes the model fit with annual landing data, and the plot (*b*) is the instantaneous change in the fish stock (biomass) with the estimated parameters in Table 2. The plot (*c*) represents the visualization of fish status, the X axis denotes fish stock biomass in terms of tonnes (*N*) and the Y axis denotes the rate of change (dN/dt) in the 15-year average fishing mortality curve (F^*) and growth curve over 15 years. The plot (*d*) is a zoomed version of the plot (*c*) and shows the positive equilibrium point around *N*=230000 tonnes.

The current status of sprat

We conducted harvesting operations between January and April 15th targeting the sprat fishery on the Turkish side of the Black Sea (Zengin and Dincer, 2006; Özsandikçı, 2020). Based on the parameter estimation for this fishery (see Table 3), the MSY is estimated at 36835 tonnes. We captured two equilibrium points for the sprat fishery: $\mathrm{E}_1 = 0$ (unstable) and $\mathrm{E}_2 \cong 55000$ tonnes (stable). Therefore, despite observing a decreasing trend between the years 2008 and 2022 in this fishery, the fish stock does not reach zero due to the existence of two equilibrium points, with the second being stable and being positive at $\mathrm{E}_2 \cong 55000$ tonnes. Consequently, while this fish population does not face severe overfishing, it does experience high fishing mortality.

The annual maximum instantaneous biomass of sprat fluctuates between 20000 tonnes and 50000 tonnes, showing a declining trend. However, there is an opportunity to stop this decreasing trend and enhance this biomass up to 55000 tonnes, as indicated by the growth curve consistently exceeding the fishing mortality curve by this margin. To achieve this improvement, it is advisable to harvest the sprat population around the Maximum Sustainable Yield (MSY) estimated in the study. This approach would allow us to strike a delicate balance between preserving the health of the sprat population and ensuring the continued sustainability of the fishery on the Turkish Side of the Black.

Table 3. Parameter descriptions and estimated parameter values for sprat

Parameters	N_0	K	r	F	$\frac{rK}{4}$	e_r
Description	Initial biomass of fish stocks	Carrying capacity	Intrinsic growth rate	Fishing mortality rate	Maximum sustainable yield	Relative errors of fits
Unit	Tonnes	Tonnes	$year^{-1}$	$year^{-1}$	Tonnes	-
Initial range	$3e^4$ - $7e^4$	$7e^5$-$9e^5$	0.1 - 0.3	0.4 - 0.8	-	-
Sprat	50009	805964	0.183	0.628	36835	0.41

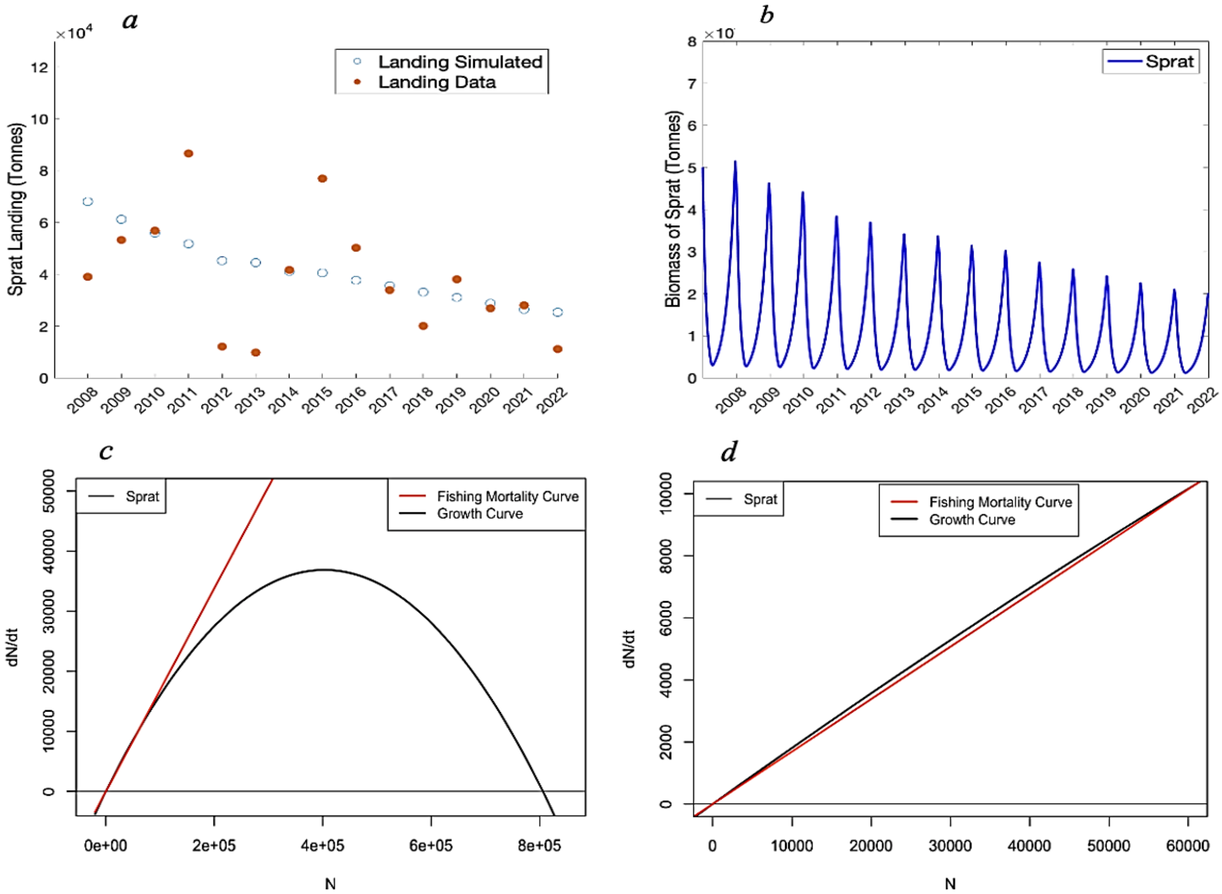

Figure 5. The plot (*a*) denotes the model fit with annual landing data, and the plot (*b*) is the instantaneous change in the fish stock (biomass) with the estimated parameters in Table 3. The plot (*c*) represents the visualization of fish status, the X axis denotes fish stock biomass in terms of tonnes (*N*) and the Y axis denotes the rate of change (dN/dt) in the 15-year average fishing mortality curve (F^*) and growth curve over 15 years. The plot (*d*) is a zoomed version of the plot (*c*) and shows the positive equilibrium point around *N*=55000 tonnes.

The current status of whiting

We applied our harvest operations between September and April 15th targeting the whiting fishery on the Turkish side of the Black Sea (STECF, 2017). The estimated MSY stands at 8158 tonnes, dependent on the parameter estimation for this fishery, as outlined in Table 4. Our analysis reveals two equilibrium points: $E_1 = 0$ and $E_2 \cong 8000$ tonnes, as illustrated in the bottom plot of Figure 6. Despite observing a high fishing mortality in this fishery since the second positive equilibrium, remaining on the left side of the peak in the bell-shaped growth curve (as shown in the bottom left plot (*c*) of Figure 5), there hasn't been a sharp decline in the whiting stock. The underlying reasons remain unclear; however, we have noticed consistent oscillations in this fishery every five years. Further investigation is needed to understand the dynamics driving these fluctuations.

The annual maximum instantaneous biomass of whiting fluctuates between about 5000 tonnes and 7000 tonnes. However, it has the potential to surge to 8000 tonnes (see the bottom-right plot (*d*) in Figure 5), as indicated by the growth curve consistently surpassing the fishing mortality curve until reaching the 8000-tonnes biomass value which is stable. Thus, to obtain a sustainable fishery for whiting, it is recommended to harvest around or below the MSY estimated in the study.

Table 4. Parameter descriptions and estimated parameter values for whiting

Parameters	N_0	K	r	F	$\frac{rK}{4}$	e_r
Description	Initial biomass of fish stocks	Carrying capacity	Intrinsic growth rate	Fishing mortality rate	Maximum sustainable yield	Relative errors of fits
Unit	Tonnes	Tonnes	$year^{-1}$	$year^{-1}$	Tonnes	-
Initial range	$5e^3$ - $8e^3$	$6e^4$-$8e^4$	0.3 - 0.6	0.6 - 0.8	-	-
Whiting	6523	68174	0.463	0.723	7891	0.17

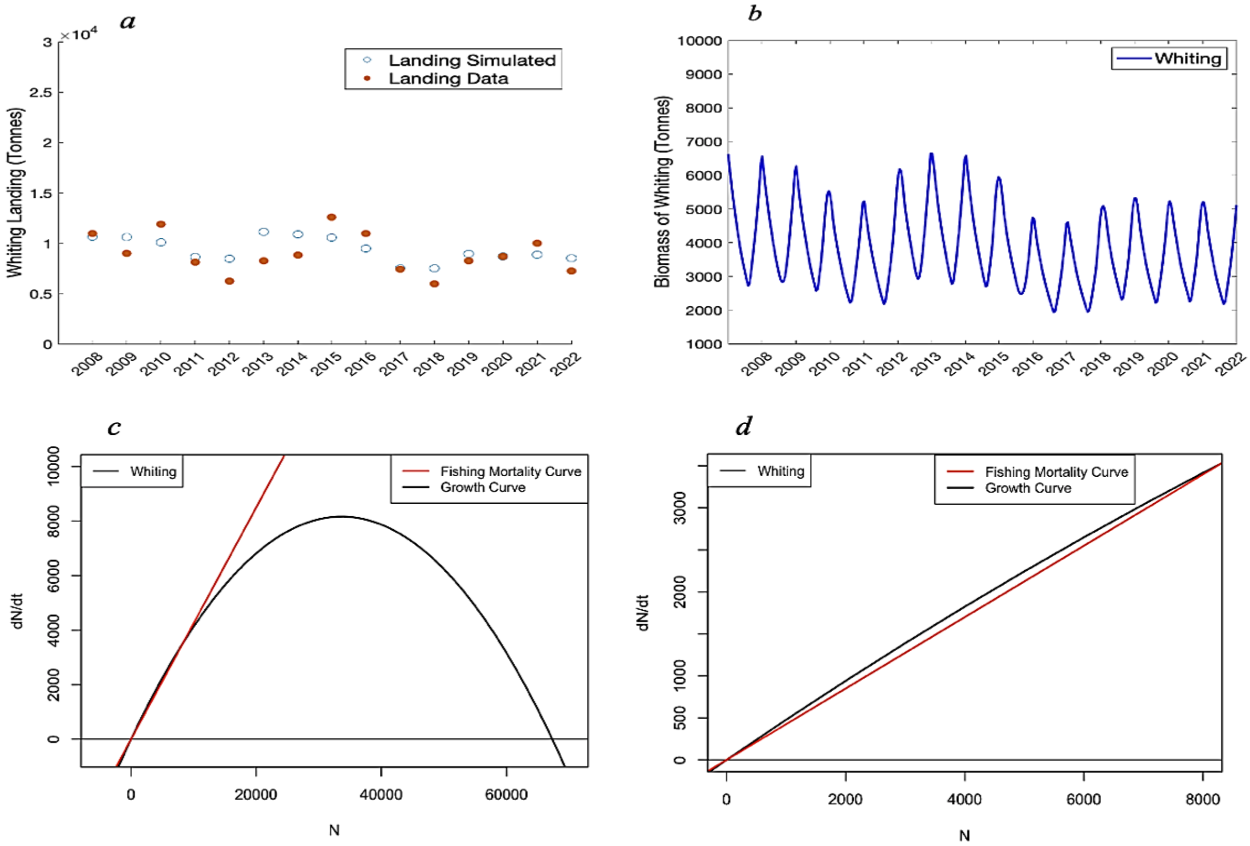

Figure 6. The plot (*a*) denotes the model fit with annual landing data, and the plot (*b*) is the instantaneous change in the fish stock (biomass) with the estimated parameters in Table 4. The plot (*c*) represents the visualization of fish status, the X axis denotes fish stock biomass in terms of tonnes (*N*) and the Y axis denotes the rate of change (dN/dt) in the 15-year average fishing mortality curve (F^*) and growth curve over 15 years. The plot (*d*) is a zoomed version of the plot (*c*) and shows the positive equilibrium point around *N*=8000 tonnes.

The current status of bluefish

We applied harvesting operations between September and January targeting the bluefish fishery on the Turkish side of the Black Sea (Gücü et al., 2017). The estimated MSY stands at 4087 tonnes, dependent on the parameter estimation for this fishery (see Table 5). Despite observing fluctuations in the fishery landing, there is a clear increasing trend over time (see the top-left plot in Figure 7). Our analysis reveals two equilibrium points: $E_1 = 0$ and $E_2 \cong 6000$ tonnes, as illustrated in the bottom right plot (*c*) of Figure 7. This indicates that while the annual maximum instantaneous fish biomass has fluctuated between 1500 tonnes to 3500 tonnes, as shown in the top right plot (*d*) of Figure 7, it has the potential to increase up to 6000 tonnes since the equilibrium point, $E_2 \cong 6000$ is stable.

Hence, it is crucial to harvest this fish stock around or below the MSY estimated in the study. This approach serves the dual purpose of maintaining a sustainable fishery and aiming to attain its maximum potential biomass of 6000 tonnes for current status. By following this recommendation, we endeavor to achieve a harmonious balance between harvesting bluefish and safeguarding the long-term health and productivity of the fishery on the Turkish Side of the Black Sea.

Table 5. Parameter descriptions and estimated parameter values for bluefish

Parameters	N_0	K	r	F	$\frac{rK}{4}$	e_r
Description	Initial biomass of fish stocks	Carrying capacity	Intrinsic growth rate	Fishing mortality rate	Maximum sustainable yield	Relative errors of fits
Unit	Tonnes	Tonnes	$year^{-1}$	$year^{-1}$	Tonnes	-
Initial range	$1e^4$ - $3e^4$	$8e^4$-$12e^4$	0.1 - 0.3	0.4 - 0.6	-	-
Bluefish	1459	95623	0.171	0.471	4087	0.43

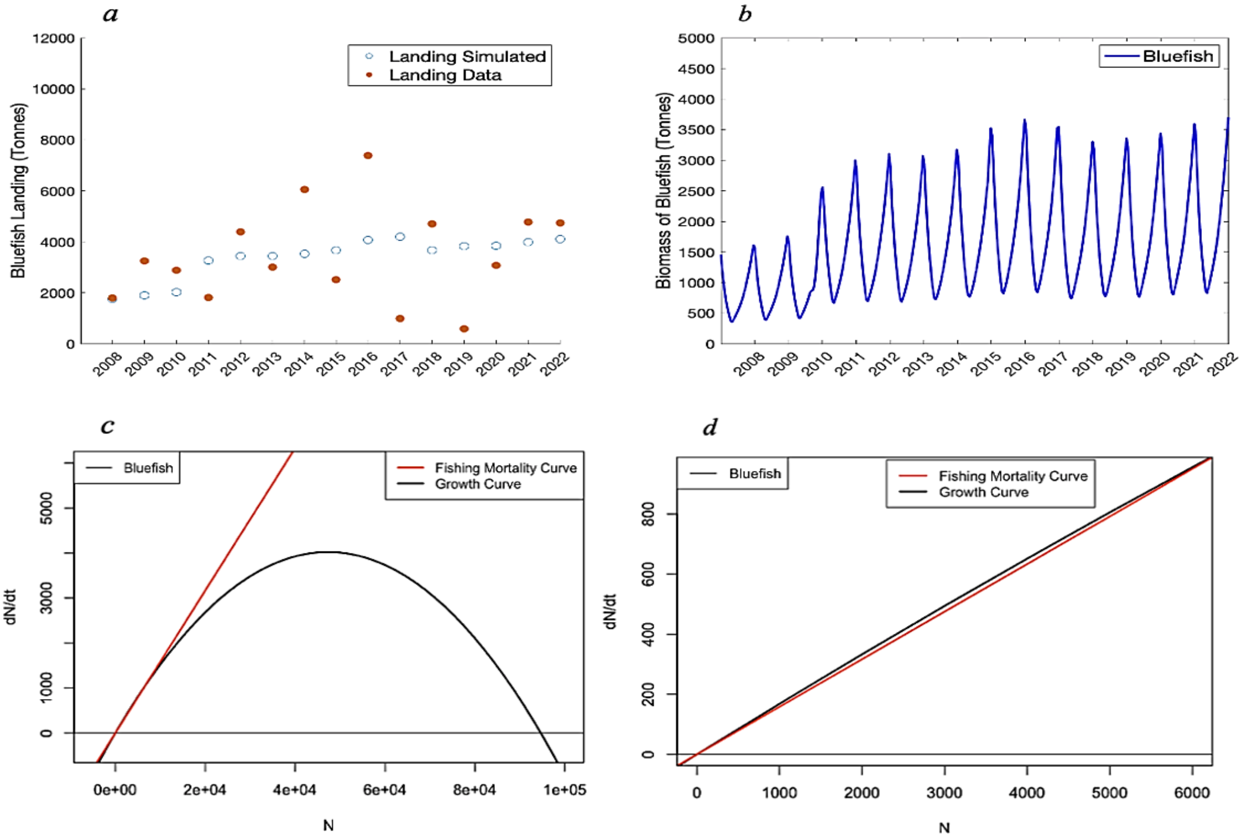

Figure 7. The plot (*a*) denotes the model fit with annual landing data, and the plot (*b*) is the instantaneous change in the fish stock (biomass) with the estimated parameters in Table 5. The plot (*c*) represents the visualization of fish status, the X axis denotes fish stock biomass in terms of tonnes (*N*) and the Y axis denotes the rate of change (dN/dt) in the 15-year average fishing mortality curve (F^*) and growth curve over 15 years. The plot (*d*) is a zoomed version of the plot (*c*) and shows the positive equilibrium point around *N*=6000 tonnes.

The current status of Atlantic bonito

We conducted harvesting operations from September to December for the Atlantic bonito fishery on the Turkish side of the Black Sea (Gücü et al., 2017). The estimated Maximum Sustainable Yield (MSY) is 16032 tonnes based on parameter estimations specific to this fishery (see Table 6). Despite fluctuations in fishery landing, a noticeable upward trend persists over time.

Our analysis reveals two equilibrium points: $E_1 = 0$ and $E_2 \cong 40000$ tonnes. This indicates that although the annual maximum instantaneous fish biomass has varied between 6000 tonnes to 19000 tonnes, as illustrated in the top-right plot (*c*) of Figure 8, it has the potential to rise up to 40000 tonnes (see the bottom-right plot (*d*) in Figure 8), as indicated by the growth curve consistently surpassing the fishing mortality curve until reaching the 40000 tonnes. To achieve an instantaneous biomass increase of up to 40000 tonnes for the Atlantic bonito, it's crucial to maintain the annual harvest of the Atlantic bonito at or below the MSY estimated in this study.

Table 6. Parameter descriptions and estimated parameter values for the Atlantic bonito

Parameters	N_0	K	r	F	$\frac{rK}{4}$	e_r
Description	Initial biomass of fish stocks	Carrying capacity	Intrinsic growth rate	Fishing mortality rate	Maximum sustainable yield	Relative errors of fits
Unit	Tonnes	Tonnes	$year^{-1}$	$year^{-1}$	Tonnes	-
Initial range	$4e^4$ - $8e^4$	$5e^5$-$8e^5$	0.05 - 0.2	0.2 - 0.4	-	-
Atlantic bonito	5864	640318	0.100	0.281	16032	0.49

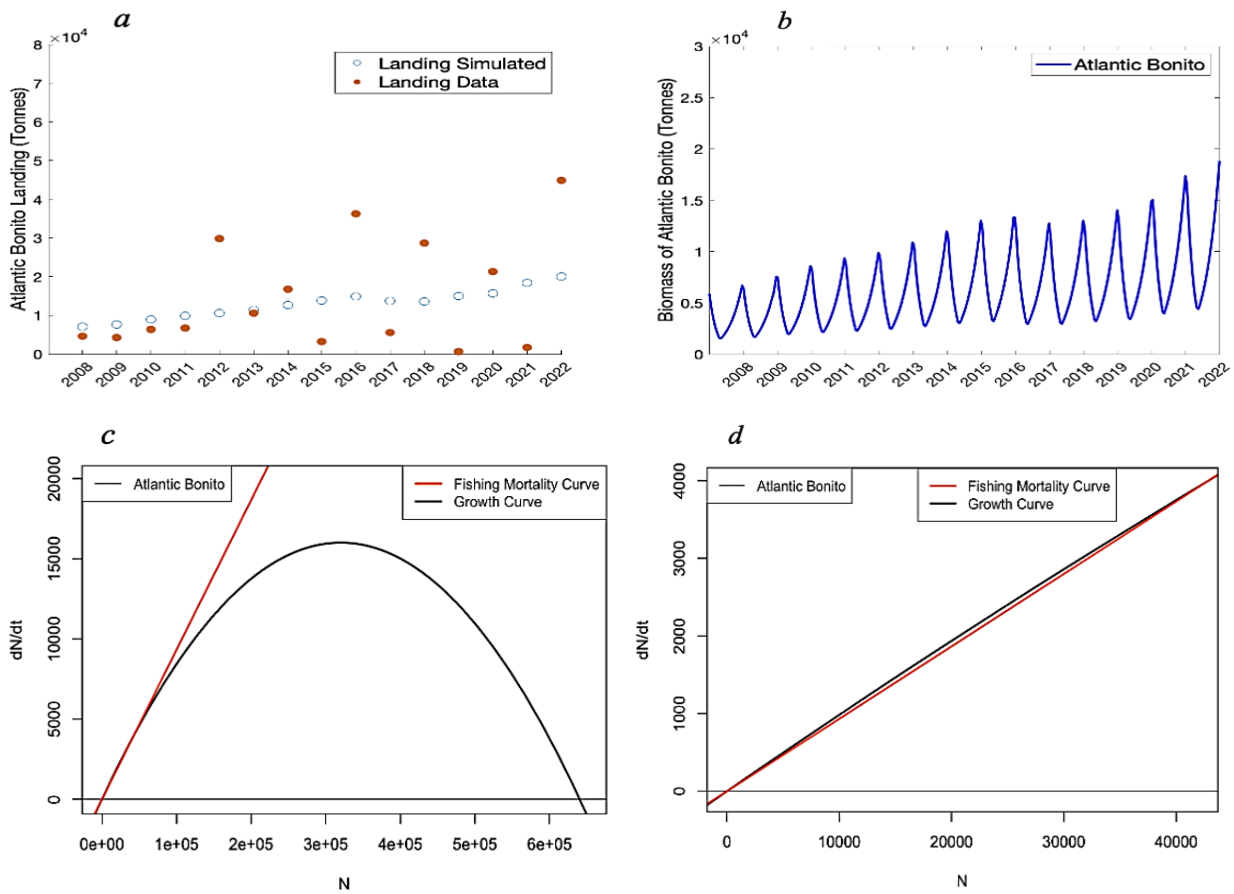

Figure 8. The plot (*a*) denotes the model fit with annual landing data, and the plot (*b*) is the instantaneous change in the fish stock (biomass) with the estimated parameters in Table 6. The plot (*c*) represents the visualization of fish status, the X axis denotes fish stock biomass in terms of tonnes (*N*) and the Y axis denotes the rate of change (dN/dt) in the 15-year average fishing mortality curve (F^*) and growth curve over 15 years. The plot (*d*) is a zoomed version of the plot (*c*) and shows the positive equilibrium point around *N*=40000 tonnes.

Sensitivity analysis of the parameters

To determine the key parameters influencing fish stock dynamics and assess how small variations impact model outcomes, we performed a sensitivity analysis. This analysis employed Latin Hypercube Sampling (LHS) alongside the Partial Rank Correlation Coefficients (PRCC) method, following the approach described by Marino et al. (2008). Using the parameter ranges specified in Table 7, we generated samples from a uniform distribution and incorporated them as inputs to simulate system (1) over 15 years. The total fish stock yield or biomass served as the output variables. Table 7 presents the PRCC values and parameter ranges used in the sensitivity analysis of parameters for each fish stocks. We selected these ranges based on their biological significance, as outlined in the parameter estimation section, while ensuring that the estimated parameter values in Tables 1–6 remain within their respective lower and upper bounds.

The sensitivity analysis indicates that the parameters r, K and F are statistically significant, as evidenced by their high PRCC values. Among these, the intrinsic growth rate (r) has the greatest influence on model outcomes, followed by the carrying capacity (K) and then the fishing mortality rate (F). Our sensitivity analysis for each fish stock indicates that the initial condition is not statistically significant, meaning the model outcomes are not sensitive to initial conditions. Figure 9 provides a representative plot from the sensitivity analysis of the anchovy population.

It is also worth noting that the positive correlation between fishing mortality rate (F) and annual yield weakens as the fishing mortality rate increases (Figure 9). This outcome is expected, as the sensitivity analysis spans 15 years rather than a single year. Higher fishing mortality rates impact future yields, preventing a perfectly positive correlation between increased fishing mortality and annual yield.

Table 7. Results of sensitivity analysis with partial rank correlation coefficient (PRCC) with respect to the output of total yields at final time. We used ranges (0.01,1) for the parameters *r* and *F* for all the species in the sensitivity analysis.

	PRCC values				Parameter ranges used in sensitivity analysis	
Parameters	$N(0) = N_0$	K	r	F	$N(0) = N_0$	K
Description	Initial biomass of fish stocks	Carrying capacity	Intrinsic growth rate	Fishing mortality rate	Initial biomass of fish stocks	Carrying capacity
Horse mackerel	0.05	0.61	0.76	0.51	5000-20000	100000-300000
Black Sea anchovy	0.04	0.53	0.76	0.44	100000-300000	1000000-3000000
Sprat	0.01	0.59	0.74	0.43	20000-200000	500000-2000000
Whiting	0.08	0.58	0.69	0.37	2000-20000	30000-200000
Bluefish	0.05	0.57	0.69	0.41	1000-10000	50000-200000
Atlantic bonito	0.04	0.63	0.72	0.40	2000-20000	300000-1000000

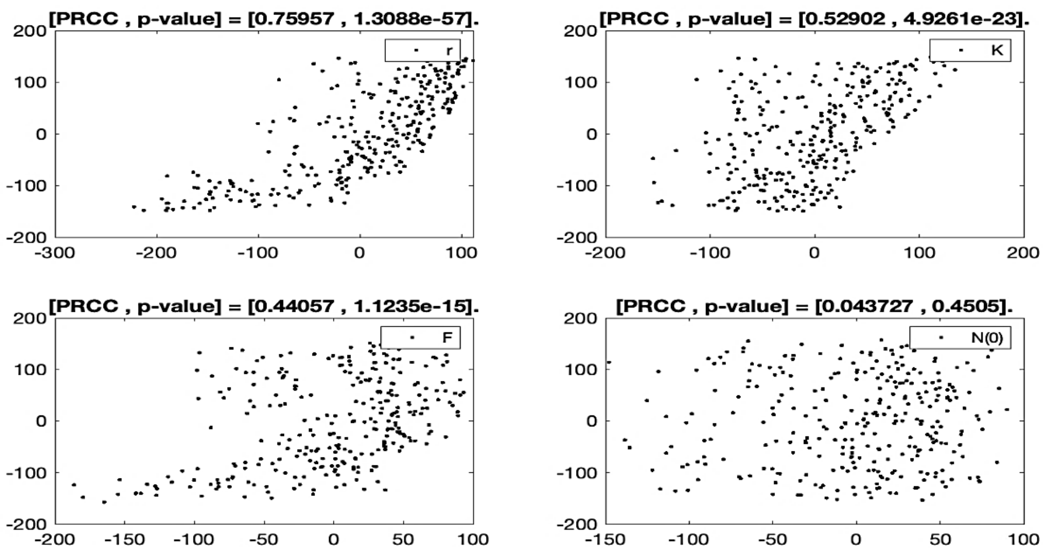

Figure 9. Visualization of sensitivity analysis for anchovy population: X axis denotes the variation of parameters with the ranked initial range of parameters given in Table 2 and Y axis denotes the change in the annual anchovy yields as we vary parameters in X axis.

Our sensitivity analysis was initially based on the total yield at the final time. However, when conducted using the biomass of the fish stock at the final time, the results differ slightly. As shown in Table 8 and Figure 10, the significance and sensitivity levels of the parameters increase, with the exception of the initial conditions. Thus, regardless of the scenario at the final time, the initial condition has no significant impact on the model outputs.

Table 8. Results of sensitivity analysis with partial rank correlation coefficient (PRCC) with respect to the biomass of fish stock at final time. We used ranges (0.01,1) for the parameters *r* and *F* for all the species in the sensitivity analysis.

	PRCC Values				Parameter ranges used in sensitivity analysis	
Parameters	$N(0) = N_0$	K	r	F	$N(0) = N_0$	K
Description	Initial biomass of fish stocks	Carrying capacity	Intrinsic growth rate	Fishing mortality rate	Initial biomass of fish stocks	Carrying capacity
Horse Mackerel	0.09	0.80	0.81	-0.73	5000-20000	100000-300000
Black Sea anchovy	0.04	0.78	0.82	-0.71	100000-300000	1000000-3000000
Sprat	0.01	0.77	0.80	-0.66	20000-200000	500000-2000000
Whiting	0.03	0.80	0.76	-0.61	2000-20000	30000-200000
Bluefish	0.08	0.77	0.81	-0.60	1000-10000	50000-200000
Atlantic Bonito	0.03	0.77	0.80	-0.60	2000-20000	300000-1000000

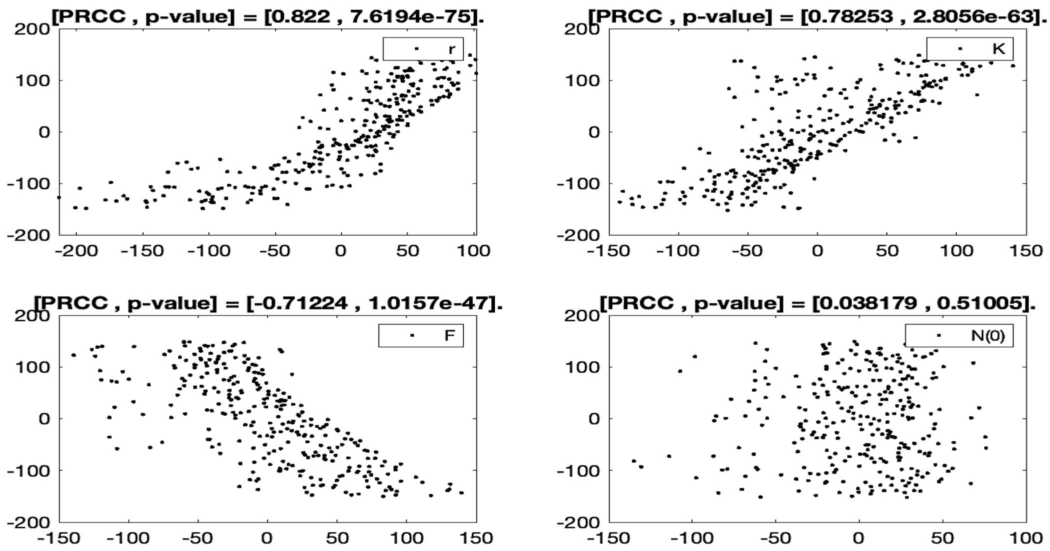

Figure 10. Visualization of sensitivity analysis for anchovy population: X axis denotes the variation of parameters with the ranked initial range of parameters given in Table 2 and Y axis denotes the change in the biomass of anchovy stock as we vary parameters in X axis.

DISCUSSION

Overall, the study's findings shed light on the dynamics and fishing pressure levels of the six fish stocks on the Turkish side of the Black Sea. Our analysis of different fish stocks, including horse mackerel, the Black Sea anchovy, sprat, whiting, bluefish, and the Atlantic bonito, revealed valuable insights into their fishing status and potential for sustainable management by implementing MSYs.

Our sensitivity analysis revealed that the initial conditions of fish stocks have no significant impact on the model results, as the correlation between initial conditions and biomass at the final time is close to zero. In contrast, the parameters r, K and F are statistically significant, meaning any variation in these parameters strongly influences the model outputs. Therefore, we compared our parameter estimates to the rates reported in the literature.

The annual landing data and our model fits indicated that the fish stocks: horse mackerel, anchovy, whiting, and sprat were in a decreasing trend. Atlantic bonito and bluefish stocks were on an increasing trend even if we saw sharp ups and downs in these fish stocks over the years (see Figures 7 and 8). Depending on the method for investigation of fish stocks given in the material and method section, all the fish stocks covered in the study were experiencing high fishing mortality on the Turkish side of the Black Sea. To address the high fishing pressure on these fish stocks, this study offered the Maximum Sustainable Yields (MSYs) for their management. Implementing the estimated MSYs for these fisheries could mitigate the high fishing pressure and alleviate its adverse impacts on the Turkish side of the Black Sea. Despite these fish stocks experiencing high fishing mortality, there is optimism that they can attain the second equilibrium point and prevent severe overfishing if the estimated MSYs are applied for each fishery.

Upon examining the horse mackerel fishery, our investigation reveals promising potential. With an estimated MSY of 11405 tonnes, the fishery showcases a positive trajectory despite historical fluctuations. The presence of two equilibrium points suggests stability, emphasizing the opportunity for sustainable harvesting practices. Harvesting the horse mackerel around the MSY estimated in this study could be pivotal in maintaining the fishery's health and productivity while ensuring its long-term sustainability. The estimated fishing mortality rate was about 0.44 in this study, but this rate was 0.65 between the years 2008 and 2011 in the study presented by Kasapoğlu (2018). This might relate to the reduction in harvesting efforts for horse mackerel fishery in recent years.

In a similar fashion to the horse mackerel fishery, the anchovy fishery also exhibits a declining trend, coupled with a high fishing mortality rate of approximately 0.69. Despite these challenges, the anchovy fishery boasts an estimated MSY of 169512 tonnes. Despite fluctuations in landings attributed to this high fishing mortality rate, the fishery maintains stability, evident from the capture of two equilibrium points based on landing data between 2008 and 2022. Harvesting anchovy around the MSY not only promises to sustain the fishery but also maximizes its potential biomass, underlining the importance of adhering to sustainable harvesting practices.

The MSY was estimated as 244000 between the years 1963 and 2014 (Akkuş and Gücü, 2022) and estimated as 222250 tonnes between the years 2002 and 2017 (Demir and Lenhart, 2020). However, in our study, the MSY is estimated as 169512 tonnes between the years 2008 and 2022. This discrepancy suggests that the status of anchovy fishing may have worsened in recent years, as indicated by the decline in the estimated MSYs from 1963 to 2022. A lower MSY indicates that the fishery may be experiencing decreased productivity or facing overexploitation, which could be a cause for concern regarding the sustainability of anchovy stocks. Moreover, the constant fishing mortality rate was estimated as 0.48 between the years 2002 and 2017 (Demir and Lenhart, 2020) and 0.5 between the years 2005 and 2014 (Akkuş and Gücü, 2022) but in our estimate, the fishing mortality rate is estimated as 0.69 between the years 2008 and 2022. This may be related to the choice of model selection. We used a single equation but the study (Demir and Lenhart, 2020) used a food chain model consisting of 4 tropic levels and considered the effect of predators on anchovy. Or, it may be related to the increased fishing mortality rate of anchovy fishery in recent years.

Similarly, the sprat fishery has displayed a concerning declining trend over the years, raising significant questions about its long-term sustainability. Despite the presence of two equilibrium points, the fishery suffers from high fishing mortality, as evidenced by the fishing mortality rate of approximately 0.63 as given in Table 3 and depicted in Figure 5. This estimate coincides with the estimate of 0.64 obtained for the single year 2014 in the study presented by Özsandikçı (2020). Our findings necessitate the implementation of careful management strategies to avoid further decline. As highlighted in the results section, it is imperative to apply the estimated MSY to ensure the sustainability of the sprat fishery.

We estimated the MSY as 7891 tonnes for the whiting fishery. Despite encountering high fishing mortality, the fishery maintains stability with two equilibrium points. However, the consistent oscillations observed every five years warrant further investigation into the underlying factors influencing the fishery's dynamics. The estimated fishing mortality rate is about 0.72 above the 0.69 estimated in STECF (2017) and below 0.76 estimated in Kasapoğlu (2018).

In contrast, the bluefish fishery, with an estimated MSY of 4087 tonnes, shows a clear increasing trend over time. The presence of two equilibrium points indicates potential for sustainable harvesting practices, underscoring the importance of adhering to MSY guidelines to ensure the fishery's long-term viability. It also has the potential to increase its biomass up to 6000 tonnes when the estimated MSY is applied in the long term (see the bottom right plot in Figure 7).

Finally, the Atlantic bonito fishery presents an intriguing scenario, with an MSY estimated at 16032 tonnes. Despite fluctuations in landing rates, the fishery displays a consistent increasing trend, with two equilibrium points suggesting stability. Harvesting the Atlantic bonito around the estimated MSY offers promising prospects for sustaining the fishery while maximizing its potential biomass. The MSY for Atlantic bonito was estimated at approximately 17000 tonnes, with a range of 14700 to 19800 tonnes, according to the study by Daskalov et al., (2020). It's worth noting that our estimated MSY for Atlantic bonito, which stands at 16032 tonnes, closely aligns with this result. In Daskalov et al., (2020), the study period ranged from the 1950s to 2016. However, in our study, we focused on the more recent period from 2008 to 2022. According to these studies, while the carrying capacity of Atlantic bonito in the Black Sea has increased, there has been a decline in its intrinsic growth rate.

Limitations and benefits of model selection

There have been many data-limited stock assessment methods primarily requiring landing data to assess the current status and abundance of fish populations, including CMSY, OCOM, JABBA, SPICT, and DBSPR (Dick and MacCall, 2011; Froese, 2017; Zhou, 2017; Winker et al., 2018; Bouch et al., 2021; Froese, 2023). Similar to these methods, we only used landing data in our analysis. Our analysis mainly depended on time-dependent graphs of intrinsic growth and fishing mortality rates. These graphs not only provided these rates but also provided equilibrium points and the status of fishing pressure such as low, high, or extreme fishing. Thus, the main benefit of the method we used was obtaining such outputs in a single graph. Additionally, we could obtain the biomass dynamics of fish populations and MSYs from the logistic model. This method was not new but served as an alternative to the approaches mentioned above (Kot, 2001). Our main reason for choosing this method was its graphical simplicity when analyzing data-limited fish stocks. Additionally, it was important to include stochasticity in a fishery assessment method, as it allowed in the surplus production models (Schaefer, 1954; Fox, 1970). In the model used in this study, stochastic elements and optimal control tools could be incorporated into the mathematical model for further analysis (Demir and Lenhart, 2021; Demir, 2024), or conducting a sensitivity analysis if required (Aslan et al., 2022; Marino et al., 2008). Therefore, using this mathematical model has provided flexibility for conducting additional analyses.

Single-species models tend to oversimplify the ecosystem by disregarding interspecies interactions, such as competition, predation, and mutualism, which can significantly influence the target species' population dynamics (Demir, 2019). This lack of complexity can make the model less accurate in predicting changes driven by ecological or environmental shifts, including those caused by climate change or invasive species introductions (Bellard et al., 2013; Mainali et al., 2015; Demir and Lenhart, 2020). Furthermore, a narrow focus on a single species may lead to unintended ecological consequences, as management efforts aimed at benefiting one species could inadvertently harm others and disrupt overall ecosystem stability (Botsford et al., 1997).

On the other hand, in the absence of detailed information and data, this approach can still be valuable if applied cautiously (Beverton and Holt, 1957). In this study, rather than relying directly on model outputs from the single-species model such as $E_{0.1}$, $E_{0.5}$, E_{max}, E_{cur}, $F_{0.1}$, $F_{0.5}$, F_{max}, F_{cur}, SPR, B, and B_{max}, we focused on examining the direction of change in the size of fish stocks to understand when the population stock size increases or decreases. Given that changes in fish stock size are directly influenced by the intrinsic growth rate and fishing mortality rate, we not only conducted a stability analysis but also captured the current levels of fishing pressure. Thus, instead of using the estimated rates directly to assess fish stock status, we used them to indicate periods when fish stock sizes were trending upward or downward in our graphs (Figures 3-8). We first examined fishing pressure levels based on these trends and then analyzed the potential for achieving positive equilibrium points to prevent overfishing of these stocks.

Limitations of data

Since we used a deterministic model that does not account for noise and measurement errors, our parameter estimates may be affected by errors in the data. For instance, landing data often excludes discards, which can represent a significant portion of the total catch. Additionally, underreporting or misreporting in landing data is common, potentially introducing biases into the analysis. To address these limitations, a stochastic state-space model can be employed, allowing for the incorporation of both measurement and process errors. It is also worth noting that incorporating additional data, such as CPUE or independent survey data, can improve parameter estimates and enhance model accuracy. However, our approach remains still applicable even in the absence of such data.

CONCLUSION

In conclusion, despite the inherent limitations of single-species models, our approach demonstrates their potential utility when detailed ecological data is lacking. By focusing on the direction of stock changes rather than absolute biological reference points, we identified patterns of increasing and decreasing stock trends, enabling us to assess fishing pressure levels effectively. This method provides a practical framework for fishery management, offering valuable insights into sustainable harvest levels and equilibrium points to mitigate overfishing risks while promoting stock stability if the estimated MSY for each fish stock is applied.

We implemented this method to assess which fish stocks are experiencing high fishing pressure and to identify those at risk of overfishing. By categorizing these stocks according to their levels of fishing pressure—low, high, or extreme—we gained a clearer understanding of their status and potential vulnerabilities (Figures 3-8). To further validate our findings, we conducted a graphical stability analysis to ensure that the stock sizes could reach a positive, stable state, supporting a sustainable fishery over time. This approach offers an effective strategy for managing fish populations in data-limited stock assessments, ultimately contributing to long-term resource stability and sustainability. Thus, our investigation reveals that, despite an increasing trend in some stocks over the past 15 years, they remain subject to high fishing mortality. This study also identifies stable equilibrium points, indicating conditions under which these stocks can be sustained long-term.

Overall, this study presents a graphical investigation not only to analyze the stability of stocks (Figure 1) but also to understand and capture important features of the current status of fish stocks such as MSYs, stable equilibrium points, and fishing mortality levels of fish stocks such as low fishing mortality case, high fishing mortality case, extreme fishing mortality case (Figure 2). Such investigations can help sustainable management practices in maintaining the health and productivity of fisheries on the Turkish side of the Black Sea.

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There are no funding sources to declare in this study.

CONFLICT OF INTEREST

The author declares no conflict of interest.

ETHICAL STATEMENT

No ethical approval is required for this study.

DATA AVAILABILITY

For questions regarding datasets, the corresponding author should be contacted.

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