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Population dynamics and stock assessment of the white anglerfish, *Lophius piscatorius* (Actinopterygii, Lophiiformes, Lophiidae), in the central Mediterranean Sea (GSA 12)

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Abstract

The white anglerfish, *Lophius piscatorius* Linnaeus, 1758, is a demersal species of great ecological and commercial importance in Tunisian waters. This study uses data-limited assessment methods to evaluate the population dynamics and stock status of this species in northern Tunisia (GSA 12). Growth parameters were estimated from size-frequency data, collected at Bizerte fishing port in 2025, using ELEFAN functions (Electronic LEngth Frequency ANalysis) implemented in the TropFishR package. Lengths at sexual maturity (L_{m50} and L_{m95}) and natural mortality (M) were derived from empirical equations. Stock status was evaluated using the Catch MSY Monte Carlo model (CMSY++ model), which was applied to catch data from 1995 to 2024 and was complemented by length-based models (Length-based Bayesian Biomass "LBB", the length-based indicator method "LBI" and length-Based Spawning Potential Ratio "LBSPR"), which used size data from 2024 and 2025. The best-fitting growth model (ELEFAN SA standard) yielded an asymptotic length (L_∞) of 89.29 cm, a growth coefficient (K) of 0.369 year^{-1} and a growth performance index (φ') of 3.469, indicating moderate growth. The estimated lengths at maturity (L_{m50} = 47.1 cm; L_{m95} = 56.52 cm) suggest that *L. piscatorius* reaches sexual maturity at a relatively large size compared to its maximum size. Natural mortality (M = 0.19 year^{-1}) was low, signifying that population dynamic was strongly influenced by fishing mortality rather than natural processes. The stock assessment results from CMSY++, LBB, LBI, and LBSPR provided complementary evidence on stock status, but did not allow a definitive conclusion regarding the sustainability of the stock. Estimates of $B/B_{MSY} > 1$ (CMSY++ and LBB) and F/F_{MSY} = 0.904 (CMSY++) suggest that fishing pressure remains below critical thresholds. Demographic indicators from LBI showed a proportion of mature individuals (P_{mat} = 0.4652) and proportion of mega-spawners (P_{mega} = 0.1015) were below the reference point, a moderate proportion of optimally sized individuals (P_{opt} = 0.3975), suggesting that the size structure of the catch is not fully consistent with the reference pattern and that improvements in size selectivity may be beneficial. However, the LBSPR-derived spawning potential ratios (SPR = 39% in 2024 and 40% in 2025) are close to the recommended reference point of 40%, indicating that the stock is close to the limit of full reproductive sustainability, and any increase in fishing effort could compromise spawning biomass in the medium term. Overall, the *L. piscatorius* stock in GSA 12 should be considered to be operating close to several biological reference levels and a precautionary approach should be adopted to preserve the spawning stock and the population's size structure.

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Keywords

data-limited methods, growth, GSA 12, *Lophius piscatorius*, Mediterranean Sea, stock assessment

Introduction

The white anglerfish, *Lophius piscatorius* Linnaeus, 1758, is a demersal fish representing the family Lophiidae, widely distributed throughout the northeastern Atlantic and the Mediterranean Sea (Caruso 1983; Ungaro et al. 2002; Thangstad et al. 2006; Barcala et al. 2019). *Lophius piscatorius* is a predator found on the continental shelf at various depths, ranging from 50 to 1000 m (Coleman 2019), depending on specific seabed temperature and salinity conditions (Barcala et al. 2019). Due to its commercial value and the quality of its flesh, the white anglerfish is an important resource targeted by bottom trawlers in several Mediterranean countries (Colmenero et al. 2017). In Tunisia, this resource is primarily targeted by bottom trawling, which accounts for the majority of this genus's catch in the region (DGPA 2025).

Knowledge of the biological and demographic parameters of exploited populations is essential for the sound management of fishery resources (Mili et al. 2026a). Studies on growth, mortality, recruitment and reproduction provide essential information for stock assessment and the development of appropriate management measures (Colmenero et al. 2017). Despite the existence of several studies on *L. piscatorius* focusing on its distribution, biology and reproduction across the Mediterranean (Ungaro et al. 2002; Colmenero et al. 2017; Barcala et al. 2019), knowledge regarding populations in Tunisian waters (central Mediterranean) remains limited and focuses more on specific aspects such as diet (Negzaoui-Garali et al. 2008) and parasites (Mansour et al. 2013). The focus is often on *Lophius budegassa* Spinola, 1807 rather than *L. piscatorius* leaving a significant gap in information regarding the structure of the exploited populations. Furthermore, despite the commercial importance of this resource in Mediterranean fisheries, knowledge of its biology and ecology remains limited, particularly in the central Mediterranean (Landa et al. 2001; Farina et al. 2008).

The *L. piscatorius* fishery in central Mediterranean (northern Tunisia, GSA 12) is considered to be a data-poor fishery in which the available biological and fisheries data are limited, fragmentary and insufficient to apply conventional stock assessment methods. This situation is particularly common for benthic resources (Lleonart and Maynou 2003; Lloret and Font 2013; Osio et al. 2015; Colloca et al. 2017; Klaoudatos and Theocharis 2026; Mili et al. 2026a, 2026b).

Given these constraints, data-limited models are attracting growing interest in the field of stock assessment and the study of population dynamics (Froese et al. 2012; Thorson et al. 2013; Carruthers et al. 2014; Dowling et al. 2015; Thorson et al. 2015; Free et al. 2017; Kokkalis et al. 2017; Taylor and Mildenberger 2017; Schwamborn et al. 2019; FAO 2020; Mili et al. 2026a, 2026b).

The Electronic Length Frequency Analysis (ELEFAN) method is widely used to estimate growth from length-frequency data in fisheries with limited data (Pauly and David 1981). Several studies have shown that this method provides reliable estimates (Taylor and Mildenberger 2017; Schwamborn et al. 2019; Wang et al. 2020, 2021; Zhou et al. 2022). Among the most used data-poor models are catch-based models (CMSY++; Froese et al. 2021) and length-frequency-based models, such as the Bayesian Length-Based Biomass method (LBB; Froese et al. 2018), the Length-Based Indicators method (LBIs; Froese 2004) and the Length-Based Spawning Potential Ratio method (LBSPR; Hordyk et al. 2015a).

The presently reported study aims to investigate the population dynamics and assess the stock of the species *L. piscatorius* in the central Mediterranean (GSA 12) by applying various data-poor models based on size frequencies (ELEFAN, LBB, LBI and LBSPR) and fishing catches (CMSY++). This study constitutes an essential first step towards addressing the knowledge gap and will establish a reference data source for future scientific work on this species in northern Tunisia (GSA 12), providing updated biological and fisheries parameters that can be incorporated into future stock assessments and comparative analyses at the Mediterranean scale.

Material and methods

Study site. This study was conducted in the northern region of Tunisia (central Mediterranean), which corresponds to GFCM Geographical Sub-Area 12 (GSA 12). Samples of *Lophius piscatorius* Linnaeus, 1758, taken from landings of bottom trawl catches, were collected at the fishing port of Bizerte (37°15′55.65″N, 009°53′34.26″E), one of the region's main fishing ports (Ben Salem and Franquesa 2005; Abidli et al. 2021; Mili et al. 2026a) during 2024 and 2025 (Fig. 1). A total of 1881 individuals were collected, ranging in size from 10.6 cm to 89.1 cm.

Measurement of samples. The total length (TL) of each *L. piscatorius* individual was measured to the nearest millimeter, from the most anterior point of the head to the tip of the caudal fin, using an ichthyometer and a measuring tape, in accordance with the standard fisheries biology protocol (Mili et al. 2026b). Stratified random sampling

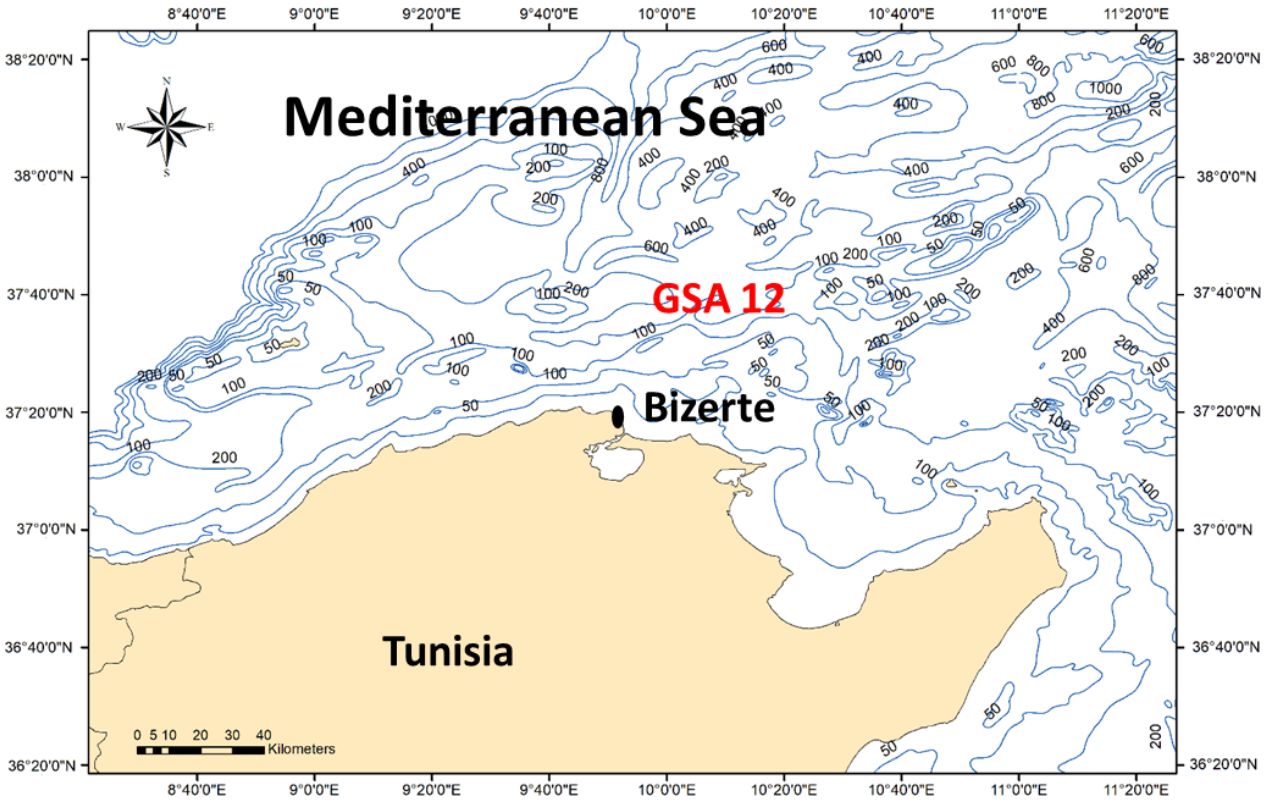

Figure 1. A bathymetric map of northern Tunisia showing the geographical sub-region (GSA 12) and the fishing port of Bizerte.

was carried out during night-time landings at the Bizerte fishing port, as this is when bottom trawlers return from their fishing trips and the species is landed. Over the two-year monitoring period (2024–2025), a total of 111 sampling surveys were conducted, comprising 65 in 2024 and 46 in 2025. Each survey involved systematically measuring the TL of *L. piscatorius* individuals from a randomly selected subset of the daily landings to obtain coverage of the size structure across the fishing season.

Catch data. Catch data for *L. piscatorius* from northern Tunisia (GSA 12), covering the period 1995–2024, were obtained from the Directorate-General for Fisheries and Aquaculture. After collection, the data were verified and standardized in tonnes to ensure consistency and to facilitate their use in subsequent analyses.

Life-history traits. The life history parameters of *L. piscatorius* were estimated using size-frequency data. Growth parameters (L_∞, K) were determined using the electronic length frequency analysis (ELEFAN) algorithm implemented in the TropFishR package, based on fish size data collected in 2025. Natural mortality (M) was estimated using the M_empirical function, based on growth parameters (L_∞ and K), the mean seabed temperature of the Mediterranean Sea (13°C; Raimbault 2022) and the maximum observed age (T_{max} = 24 years; Fishbase: 120179) in accordance with the empirical methods proposed by Pauly (1980) and Hoenig (1983), using the TropFishR package (Mildenberger et al. 2025). The length at which 50% of individuals reach sexual maturity (L_{m50}) was calculated using the empirical equation by Froese and Binohlan (2000), while the length corresponding to 95% of mature individuals (L_{m95}) was estimated using the empirical equation proposed by Prince et al. (2015). The theoretical zero-length age parameter (t_0) was estimated from the L_∞ and K parameters using Pauly's (1979) empirical equation, implemented in R using the TropFishR package (Table 1).

Stock assessment models. The following data-limited models were applied to assess stock status of the *L. piscatorius* stock in northern Tunisia (GSA 12).

Catch MSY Monte Carlo model (CMSY++). The assessment of the status of *L. piscatorius* stock was carried out using the CMSY++ method, based on catch data covering the period 1995–2024. The species' resilience is considered to be medium (FishBase: 120179). Accordingly, the resilience category was used to define the prior range for the intrinsic rate of population increase (r), following Froese et al. (2017) and Froese et al. (2021). The prior range for r was defined according to the species' resilience, following the classification proposed by Froese et al. (2017) (Table 2). A medium resilience prior (r: 0.2–0.8 year^{-1}) was assigned to the species. The CMSY++ algorithm then automatically derived prior ranges for carrying capacity (K) from the catch time series using the relationship between maximum catch and r (Froese et al. 2017, 2023). The model subsequently identified viable r-k pairs using an iterative Monte Carlo approach and selected the best estimates based on their fit to the catch data.

Table 1. Method and Empirical Formula used to estimate life-history traits of *Lophius piscatorius* from the northern Tunisian coast (GSA 12).

Parameter	Method/Empirical formula	Reference
L_{max}	Maximum length recorded for the species during sampling	
L_{∞}	ELEFAN	Pauly and David 1981; Mildenberger et al. 2017, 2025
K		
L_{m50}	$Log(L_m) = 0.8979*log(L_{\infty})–0.0782$	Froese and Binohlan 2000
L_{m95}	$L_{m95} = 1.2* L_{m50}$	Jennings et al. 2001; King 2007; Prince et al. 2015
M	Empirical formulas for the estimation of natural mortality using TropFishR package	Mildenberger et al. 2025
t_0	–10^(–0.392 – 0.275*log10($L\infty$) – 1.038*log10(K))	Pauly 1979

L_{max}, maximum length recorded for the species during sampling; L_{∞}, asymptotic length; K, growth rate; t_0, the theoretical zero-length age parameter; M, Natural mortality; L_{m50}, the length at which 50% of individuals reach sexual maturity; L_{m95}, the length corresponding to 95% of mature individuals.

Table 2. Prior ranges for intrinsic growth rate (resilience *r*) and relative biomass (*B/K*) categories used in CMSY++ model (Froese et al. 2017).

Resilience/Intrinsic growth rate (*r*)	Prior *r* range
High	0.6–1.5
Medium	0.2–0.8
Low	0.05–0.5
Very low	0.015–0.1
Depletion rate	**Prior relative biomass (*B/K*) range**
Very strong depletion	0.01–0.2
Strong depletion	0.01–0.4
Medium depletion	0.2–0.6
Low depletion	0.4–0.8
Nearly unexploited	0.75–1.0

r: intrinsic growth rate; *B/K:* relative biomass range.

This approach enables the estimation of key population dynamics parameters, including the intrinsic rate (r), carrying capacity (K) and maximum sustainable yield (MSY), based on catch time series and biological assumptions regarding resilience (Froese et al. 2021). It also provides key indicators of stock status, such as the B/B_{MSY} and F/F_{MSY} ratios, which allow the assessment of biomass relative to the sustainable level and the exploitation intensity of *L. piscatorius* in northern Tunisia, respectively.

Length-based indicators (LBI). The length-based indicator method was proposed by Froese (2004). In this study, we used the size structure of *L. piscatorius* catches recorded during 2024–2025, as well as the species' biological parameters such as the maximum observed catch length (L_{max}), the asymptotic length (L_{∞}) and the estimated length at maturity (L_{m50}). This approach enabled the estimation of three main indicators: the proportion of individuals caught post-maturity (P_{mat}), the proportion of individuals caught at optimal size (P_{opt}), and the proportion of large spawners (P_{mega}) (Froese 2004).

The values obtained were compared with the reference thresholds proposed by Froese (2004) to assess the level of exploitation of the *L. piscatorius* stock in GSA 12 and to identify any imbalances in the demographic structure of the catches.

Length-based Bayesian Biomass (LBB). The LBB model was applied to a series of measured length-frequency data for *L. piscatorius* collected during 2024–2025. The biological parameters required for the analysis, including asymptotic length (L_{∞}), length at maturity (L_{m50}), were estimated in this study. Whereas M/K was estimated by the LBB model from the length-frequency data using a Bayesian prior (Froese et al. 2018).

This model is based on a Bayesian approach and the von Bertalanffy growth model, which allows estimation of several key indicators of exploited population dynamics, such as the F/M, B/B_0, and B/B_{MSY} ratios (Froese et al. 2018). A sensitivity analysis was conducted using alternative biological estimates reported by Colmenero unpublished[1] to assess the potential propagation of uncertainty associated with the biological parameters used in the LBB analysis.

Length-Based Spawning Potential Ratio (LBSPR). The LBSPR model is based on the calculation of the spawning potential ratio (SPR) using biological data on the growth and maturity of the species. The model estimates the exploitation rate (F/M) and the stock's residual spawning potential (Hordyk et al. 2015a, b).

In this study, the size frequencies of *L. piscatorius* collected during the period 2024–2025 were used as input data for the LBSPR model as well as the biological parameters L_{∞}, M/K, L_{m50} and L_{m95}. To assess the robustness of the estimated values of F/M and SPR in the context of variability in the biological input parameters, a sensitivity analysis was carried out using published alternative estimates for L_{m50}, L_{m95} and M/K.

Statistical analysis. The statistical analysis of the data was performed using R software (version 4.3.3), which was also used to generate the illustrative graphs. The analysis of the size-frequency distribution of the white anglerfish *L. piscatorius* was carried out using the 'tidyverse' package. ANOVA, followed by a Tukey's post hoc test, was applied to identify significant interannual variations.

[1] Colmenero AI (2017) Towards biological and ecological knowledge of *Lophius* spp. In the NW Mediterranean Sea for a sustainable fishery. PhD Thesis, Universitat de Barcelona, 251 pp.

To assess the annual variability in *L. piscatorius* production, a descriptive analysis comprising the mean, standard deviation and coefficient of variation (CV %) was carried out. In addition, a linear regression analysis was performed to examine the temporal trend in production. Furthermore, the non-parametric Mann–Kendall test, using the Kendall package, was used to identify a monotonic trend in the time series.

Results

Production. Total production of *Lophius piscatorius* in northern Tunisia rose from 8 tonnes in 1995 to 93 tonnes in 2024 (DGPA 2025). Figure 2 shows that production levels for this species were relatively low, with an upward trend between 1995 and 2000, followed by a period of fluctuating production between 2005 and 2010. Since 2010, production has shown growth, gradually reaching high levels, with a peak recorded in 2019 at 144 tonnes (DGPA 2025). White anglerfish is mainly caught using bottom trawling, which accounted for nearly 98% of the production of this species in 2024.

Statistical analysis of the production time series reveals a mean of 53.59 tonnes and a standard deviation of 38.89 tonnes. The coefficient of variation (CV = 73%) indicates high interannual variability in production, reflecting significant fluctuations from one year to the next during the study period. Despite this high variability, trend analyses highlight a significant increase in production over time. Indeed, the linear regression shows a positive slope of 3.48 t · year^{-1} ($\beta = 3.481$; $t = 6.774$; $P = 2.34 \cdot 10^{-7}$), indicating a mean annual growth in production. This trend is corroborated by the non-parametric Mann–Kendall test, which reveals a positive and significant monotonic trend ($\tau = 0.554$; $P = 1.85 \cdot 10^{-5}$). Furthermore, the model's coefficient of determination ($R^2 = 0.621$) indicates that most observed variability in production is explained by the trend over time. These results demonstrate that production exhibits both high interannual variability and a general upward trend from 1995 to 2024.

Demographic structure. A total of 1881 individuals of *L. piscatorius* were sampled between 2024 and 2025. Table 3 presents the descriptive analysis of total length (TL). The mean size of individuals measured in 2024 (46.45 ± 11.88 cm) is smaller than that recorded in 2025 (47.12 ± 13.46 cm). The mean total length recorded during 2024–2025 was 46.71 ± 12.52 cm (Table 3).

Table 3. Annual distribution of total length for *Lophius piscatorius* samples collected from the northern Tunisian coast (GSA 12) in 2024 and 2025.

Year	Sample size	Minimum [cm]	Maximum [cm]	Mean ± SD [cm]
2024	1153	10.6	89.1	46.45 ± 11.88
2025	728	20.3	88.2	47.12 ± 13.46
Total (2024–2025)	1881	10.6	89.1	46.71 ± 12.52

The distribution of total lengths for *L. piscatorius* between 2024 and 2025 revealed a broader size distribution in total length in 2025, while showing comparable overall body sizes between the two years (Fig. 3). This trend is accompanied by a broadening of the distribution, suggesting an increase in the heterogeneity of the size structure. These patterns may reflect interannual differences in growth and recruitment dynamics, as well as the influence of fishing pressure on the stock structure of *L. piscatorius* in northern Tunisia (GSA 12). However, a one-way ANOVA, followed by a Tukey's post hoc test, revealed no significant interannual variations in total length of *L. piscatorius* between 2024 and 2025 ($P = 0.517 > 0.05$).

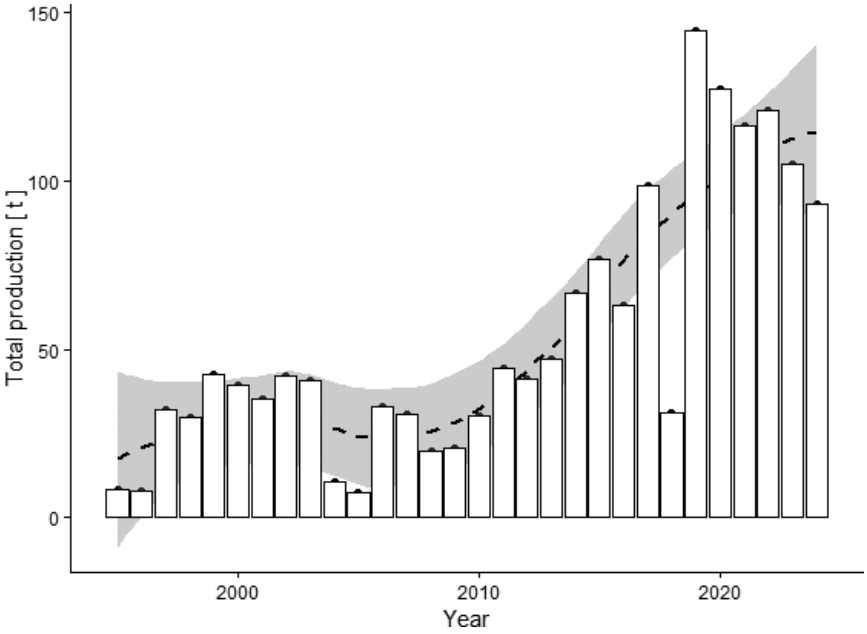

Figure 2. Annual production of *Lophius piscatorius* in northern Tunisia (GSA 12) between 1995 and 2024.

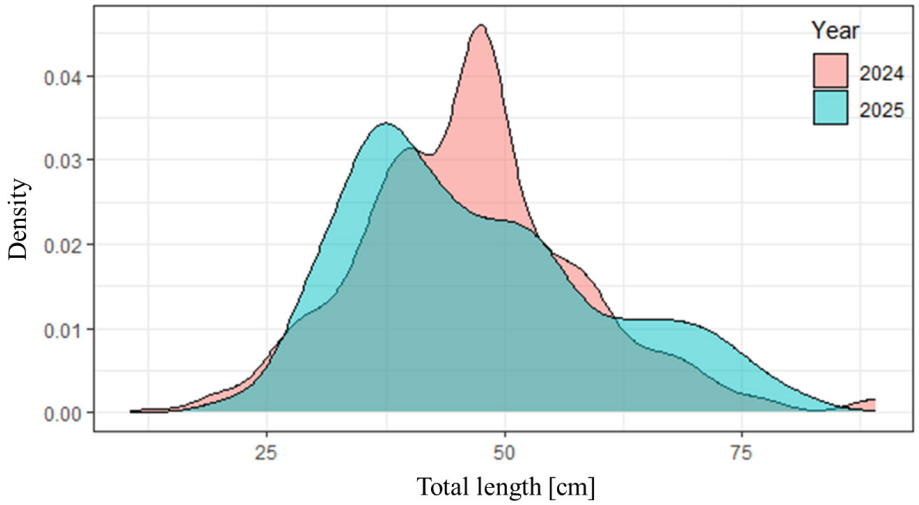

Figure 3. Frequency distributions of the total lengths of *Lophius piscatorius* in the northern Tunisian coast (GSA 12) by years (2024 and 2025).

Growth parameters. Growth parameters of *L. piscatorius* were estimated using two optimization algorithms, ELEFAN with Genetic Algorithm (ELEFAN GA) and ELEFAN with Simulated Annealing (ELEFAN SA), based on the standard and seasonal versions of the von Bertalanffy model (Table 4). The estimates showed good consistency between the two approaches, while revealing some differences in growth estimates and the effect of seasonality.

Table 4. Estimated von Bertalanffy growth parameters for *Lophius piscatorius* in the northern region of Tunisia (GSA 12) using ELEFAN GA and ELEFAN SA methods according to standard and seasonal models.

Method	Parameter	ELEFAN GA	ELEFAN SA
Standard value	L_∞	85.79	89.29
	K	0.30	0.369
	t_{anchor}	0.578	0.358
	φ'	3.346	3.469
	$R_{n\text{-}max}$	0.16	0.146
Seasonal oscillation	L_∞	81.70	91.34
	K	0.29	0.355
	t_{anchor}	0.619	0.158
	C	0.499	0.097
	t_s	0.504	0.765
	φ'	3.294	3.472
	$R_{n\text{-}max}$	0.16	0.146

L_∞, asymptotic length [cm]; K, growth rate; t_{anchor}, time of the year when length of cohort equals zero (scale from 0 to 1); C, seasonality factor; t_s, time of the year when growth accelerates (scale from 0 to 1); φ', growth performance index; $R_{n\text{-}max}$, fitting score.

The standard model fitted using ELEFAN GA yielded an asymptotic length (L_∞) of 85.79 cm, a growth coefficient (K) of 0.30 year^{-1} and a growth performance index (φ') of 3.346, with a goodness-of-fit index ($R_{n\text{-}max}$) of 0.16. The application of the seasonal model resulted in a decrease in the asymptotic length (L_∞ = 81.70 cm) and growth coefficient (K = 0.29 year^{-1}), accompanied by a decline in the performance index (φ' = 3.294). The seasonal amplitude value (C = 0.499) suggests a moderate modulation of growth over the year, while t_s (0.504) indicates that the slowdown in growth would occur approximately halfway through the annual cycle. However, the fact that the $R_{n\text{-}max}$ index has not improved indicates that the inclusion of the seasonal component does not improve the representation of the size frequency data.

Furthermore, the estimates obtained by ELEFAN SA show a different pattern. The standard model yielded a higher estimate of L_∞ (89.29 cm) associated with a higher growth coefficient (K = 0.369 year^{-1}) and the performance index observed (φ' = 3.469), for an $R_{n\text{-}max}$ of 0.146. When seasonality was incorporated, the asymptotic length increases to 91.34 cm and K decreases. The estimated seasonal variation is very low (C = 0.097), indicating virtually uniform growth throughout the year. The estimated t_s value places the start of the oscillation towards the end of the annual cycle, but given the low value of C, this oscillation remains of little biological significance. The performance index was high (φ' = 3.472), and $R_{n\text{-}max}$ remains unchanged, confirming that the inclusion of seasonality does not improve the model fit. Although the ELEFAN GA standard model provided a higher $R_{n\text{-}max}$ value (0.160) than the ELEFAN SA standard model (0.146), the difference in fit goodness was relatively small (0.014). The two algorithms produced comparable estimates of the growth parameters: L_∞= 85.79 cm and K = 0.300 year^{-1} for the ELEFAN GA model, and L_∞= 89.29 cm and K = 0.369 year^{-1} for the ELEFAN SA model. Therefore, the ELEFAN SA standard model was selected not only based on the goodness of fit index, but also on the overall consistency and stability of the estimated growth parameters. The ELEFAN SA standard model yielded higher estimates of asymptotic length, growth coefficient and growth performance index, whereas the ELEFAN GA model produced comparatively lower estimates. Although the ELEFAN GA model provided a higher $R_{n\text{-}max}$ value, this difference

was small and both algorithms produced comparable estimates of the growth pattern. Therefore, the difference in $R_{n\text{-}max}$ was not considered significant enough to establish clear superiority of one algorithm over the alternative. Consequently, the ELEFAN SA standard model was considered as the preferred representation of *L. piscatorius* growth in northern Tunisia, based on a comparison of alternative models.

Overall, estimated L_∞ values ranged from 81.70 to 91.34 cm, confirming that *L. piscatorius* is a moderately large species. Growth coefficients (K = 0.29–0.369 year^{-1}) suggest relatively rapid growth during the early life stages, followed by a gradual decrease in growth rate as they approach their maximum size. Similarly, the relatively high growth performance indices (φ' = 3.294–3.469) suggest substantial growth potential.

The selected standard ELEFAN SA model, together with the low seasonal amplitude (C = 0.097) estimated by the seasonal version, provides no strong evidence that a seasonal growth component is required to describe the available length-frequency data. The absence of an improvement in $R_{n\text{-}max}$ after introducing seasonality suggests that the standard model provides an adequate representation of the observed growth pattern. However, the higher seasonal amplitude estimated by ELEFAN GA (C = 0.499) was not accompanied by an improvement in model fit, suggesting that the estimate does not provide sufficient quantitative evidence to justify incorporating a strong seasonal component into the growth model.

The theoretical age at zero length (t_0), estimated using Pauly's (1979) empirical equation based on the selected growth parameters, was –0.332 years.

Natural mortality rate (*M*). Table 5 presents the results of the estimation of natural mortality for *L. piscatorius* using three empirical approaches. Estimates of natural mortality varied among the empirical methods used, ranging from 0.174 to 0.481 year^{-1} (Table 5). Hoenig's (1983) joint equation produced an estimate of 0.19 year^{-1}, whereas Hoenig's fish equation and Pauly's (1980) length-based equation produced estimates of 0.174 and 0.481 year^{-1}, respectively. The estimate from the Hoenig joint equation (M = 0.19 year^{-1}) was used as the baseline value for subsequent analyses. The relatively low baseline estimate of M is consistent with the life-history characteristics of the long-lived *L. piscatorius* and suggests that fishing mortality could be a significant source of additional mortality in exploited populations.

Table 5. Estimation of natural mortality (M) of *Lophius piscatorius* using different empirical methods (Hoenig and Pauly).

Method	M [year^{-1}]
Hoenig 1983 [joint equation]	0.19
Hoenig 1983 [fish equation]	0.17
Pauly 1980 [length equation]	0.48

M, Natural mortality.

Reproductive parameters. The sizes at sexual maturity (L_{m50}) of *L. piscatorius* in northern Tunisia (GSA 12) were estimated using empirical relationships based on our data (Table 6). The L_{m50} (47.1 cm) was calculated using the allometric relationship by Froese and Binohlan (2000), based on the asymptotic length (L_∞). The length at 95% maturity (L_{m95} = 56.52 cm) was estimated using an approximation derived from logistic maturation models commonly used in stock assessments (Jennings et al. 2001; King 2007; Prince et al. 2015). The results show that *L. piscatorius* reaches sexual maturity at a size, corresponding to 53% of L_∞ for L_{m50} and 63% for L_{m95}, indicating a gradual entry into the reproductive phase and a spread of maturation within the population.

Table 6. Summary of life-history traits estimated for *Lophius piscatorius* in the northern region of Tunisia (GSA 12).

L_∞	K	t_0	M	L_{m50}	L_{m95}
89.29 cm	0.37 year^{-1}	–0.33 year	0.19	47.10 cm	56.52 cm

L_∞, asymptotic length; K, growth rate; t_0, the theoretical zero-length age parameter; M, Natural mortality; L_{m50}, the length at which 50% of individuals reach sexual maturity; L_{m95}, the length corresponding to 95% of mature individuals.

The population dynamics of *L. piscatorius* in northern Tunisia imply that the intermediate size classes play a crucial role in stock renewal, while larger individuals provide a stable but less abundant reproductive contribution due to their lower abundance.

Stock assessments of *L. piscatorius* using Length-based indicator (LBI). The LBI analysis indicates that the *L. piscatorius* stock in northern Tunisia (GSA 12) is characterised by a relatively low proportion of individuals caught above the estimated length at maturity. The estimated length at maturity (L_{mat}) was 47.09 cm, while the optimal length for exploitation (L_{opt}), estimated using the LBI model, was 50.80 cm. The corresponding L_{opt}+10% and L_{opt}-10% values were 55.88 cm and 45.72 cm, respectively.

The proportion of mature individuals in the catch P_{mat} was 46.52%, compared to the target value of 100% proposed by Froese (2004). The proportion of fish caught around the optimal exploitation size P_{opt} was 39.75%, which is also substantially below the target value of 100% (Table 7). This indicates that a relatively small proportion of the catch is concentrated around the estimated optimal

Table 7. Length-based indicators (P_{mat}, P_{opt}, and P_{mega}) and reference values for stock assessment of *Lophius piscatorius* in the northern region of Tunisia (GSA 12).

Parameter	Froese_catch [%]	Froese_tar [%]
P_{mat}	46.52	100
P_{opt}	39.75	100
P_{mega}	10.15	20

P_{mat}, the proportion of fish caught that is larger than the length at maturity (L_{mat}); P_{opt}, proportion of fish within the optimum length range (L_{opt}±10%); P_{mega}, the proportion of fish larger than the mega-spawner length (L_{mega}).

size. Furthermore, the proportion of mega-spawners P_{mega} was 10.15%, which is below the precautionary reference level of 20% also proposed by Froese (2004). The LBI results suggest that a significant proportion of the catch comprises individuals below the reference lengths for maturity and mega-spawning, raising concerns about size structure and the selectivity of fishing gear.

Stock assessments of *L. piscatorius* using Length-based Bayesian Biomass (LBB). To determine the status of *L. piscatorius* stock in northern Tunisia, we also used the LBB model. The parameters used as inputs for the LBB model are L_∞ and L_{m50}, which were derived from our results (Table 6), while prior *M*/*K* (1.5) was estimated using the LBB model. The parameter values used include: L_∞ (89.29 cm) and L_{m50} (47.1 cm), as well as size frequency data from 2024 and 2025. Table 8 shows the reference points estimated by the LBB model. The estimated *F/M* (0.39) and *F/K* (0.44) values indicate moderate exploitation of *L. piscatorius* in the northern Tunisia. The estimated B/B_{MSY} and B/B_0 ratios of 1.6 and 0.59, respectively, indicate that the biomass is above the level corresponding to MSY. The LBB analysis estimates a first-catch size (L_c) of 36 cm, which is smaller than the optimal size ($L_{c\text{-}opt}$ = 47 cm), resulting in a $L_c/L_{c\text{-}opt}$ ratio of 0.75, indicating that fish are being caught too early relative to the optimal exploitation. The L_{mean}/L_{opt} ratio of 0.8 confirms that the catch structure is dominated by individuals smaller than the optimal size. Conversely, the L_{95th}/L_∞ ratio of 0.94 suggests that large individuals are still present in the population.

Table 8. Reference points estimated by the LBB model (LBB outputs) for *Lophius piscatorius* in northern Tunisia (GSA 12).

Parameter	Value
L_c	36
L_{c_opt}	47
L_{mean}/L_{opt}	0.80
L_c/L_{c_opt}	0.75
L_{95th}/L_∞	0.94
B/B_0	0.59
B/B_{MSY}	1.60
F/M	0.39
F/K	0.44
Z/K	1.60

LBB: Length-Based Bayesian Biomass method. L_∞, asymptotic length [cm]; L_{opt}, optimal length [cm]; L_C, length at first capture [cm]; L_{mean}, mean length in catch [cm]; L_{95th}, 95th percentile length [cm]; *F*, fishing mortality; *M*, natural mortality; *B*, current biomass; B_0: unexploited biomass; B_{MSY}, biomass at maximum sustainable yield.

The results of the LBB model indicate that the stock is in good condition, but fishing is focused on individuals smaller than the optimal size, which could reduce the long-term efficiency of fishing operations (Table 8; Fig. 4).

An alternative sensitivity analysis was conducted to evaluate the potential effect of uncertainty in the biological parameters used in the LBB model. This analysis used alternative published estimates of the biological parameters (L_∞ = 146.92 cm and L_{m50} = 51.3 cm; Colmenero unpublished[1]). The resulting LBB estimates differed from those obtained using our estimated parameters. The estimated L_c remained unchanged at 36 cm, whereas $L_{c\text{-}opt}$ increased from 47 to 89 cm. Consequently, the L_{mean}/L_{opt} and $L_c/L_{c\text{-}opt}$ ratios decreased from 0.80 to 0.57 and from 0.75 to 0.41, respectively. The B/B_0 ratio decreased from 0.59 to 0.068, and the B/B_{MSY} ratio decreased from 1.60 to 0.18. Conversely, the estimated *F/M*, *F/K*, and *Z/K* ratios increased from 0.39, 0.44, and 1.60 to 2.90, 3.80, and 5.10, respectively. These results suggest that several LBB based stock status indicators are sensitive to the biological inputs, particularly the estimates of biomass depletion and fishing mortality.

Stock assessments of *L. piscatorius* using Length-Based Spawning Potential Ratio (LBSPR). The results of the LBSPR model show that the stock status of *L. piscatorius* in northern Tunisia remained stable between 2024 and 2025. Selectivity lengths decreased, with SL_{50} falling from 34.30 cm to 34.02 cm and SL_{95} from 45.51 cm to 44.95 cm for 2024 and 2025, respectively (Fig. 5). This indicates that individuals become vulnerable to capture at smaller sizes in 2025 than in 2024. The *F*/*M* ratio decreased from 0.66 to 0.63, reflecting a reduction in the exploitation of this resource. At the same time, the SPR has increased from 0.39 to 0.4, indicating an improvement in the population's reproductive potential (Fig. 5).

The comparison between the observed values and those estimated by the LBSPR model shows good consistency, with more stable and biologically plausible estimates, reflecting the model's ability to smooth out variations in the size data while retaining the main trends in stock dynamics (Table 9; Fig. 5).

The SPR estimate for 2024 is characterized by a narrower confidence interval (0.34–0.44), indicating a high degree of precision compared to 2025 (0.30–0.50). Furthermore, the substantial overlap in the confidence intervals observed between the two periods, for both the *F/M* ratio and the SPR, indicates that variations remain small relative to the uncertainty associated with the estimates. Moreover, the uncertainty intervals overlap with the adopted reference level of 40%. Consequently, the LBSPR results indicate a stock level close to the precautionary reference level.

The LBSPR results indicate that the spawning potential ratio (SPR) of *L. piscatorius* in northern Tunisia was estimated to be 39% in 2024 and 40% in 2025. According to the reference thresholds proposed by Hordyk et al. (2015a), an SPR below 40% indicates moderate exploitation of the stock, with the potential for overfishing if fishing pressure increases. While the 2025, SPR value meets the precautionary target, the 2024 estimate falls below this threshold. Consequently, while the stock is not currently overfished, it is operating close to the limit of sustainable reproductive capacity and requires careful monitoring to prevent a decline in spawning biomass.

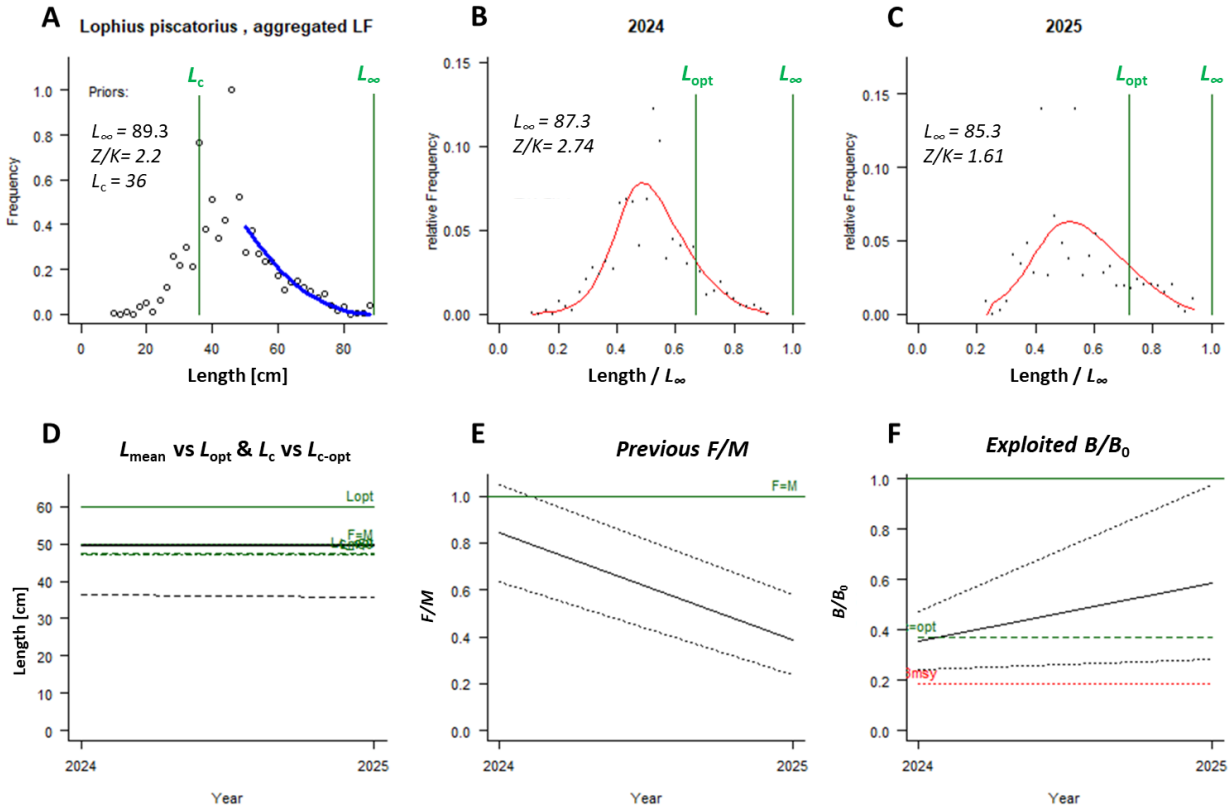

Figure 4. Graphical outputs of LBB for *Lophius piscatorius* in northern Tunisia (GSA 12). (**A**) aggregated length frequency (LF) and a priori data for L_c, L_∞, and Z/K. (B + C) The dots represent LF data for the first and last year, and the red line represents the fit of the data to the LBB principal equation. (**B**) data from 2024. (**C**) data from 2025. (**D**) mean length (L_{mean}, black bold curve) relative to L_{opt}, and L_c (black dashed curve) relative to $L_{c\text{-}opt}$. (**E**) relative fishing mortality F/M (black curve), with approximate 95% credibility limits (dotted lines), and a reference level ($F = M$, green horizontal line). (**F**) relative biomass B/B_0 (black curve) with approximate 95% credibility limits (black dotted lines), and a proxy for B_{MSY} (green dotted line), as well as 0.5 B_{MSY} (red dotted line).

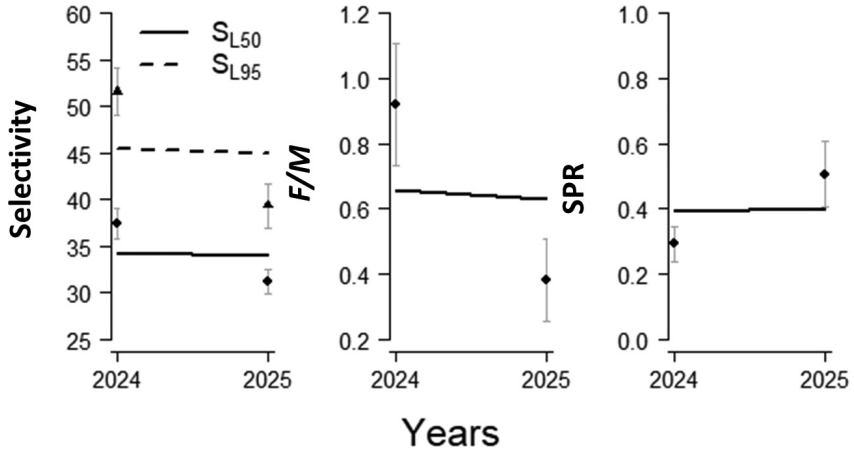

Figure 5. LBSPR estimates of *Lophius piscatorius* from the northern region of Tunisia (GSA 12) between 2024 and 2025; the black points represent the observed estimates with their 95% confidence intervals; the black lines correspond to the final estimates from the LBSPR model; selectivity panel (left side), F/M panel (middle) and SPR panel (right side).

The sensitivity analysis showed that the LBSPR estimates were relatively robust to alternative values of the biological parameters. In 2024, SL_{50} and SL_{95} changed from the baseline values of 34.30 cm and 45.51 cm to alternative values of 34.21 cm and 45.37 cm, respectively, while F/M ratio changed from 0.65 to 0.66 and SPR from 0.39 to 0.36. In 2025, SL_{50} and SL_{95} changed from the baseline values of 34.02 cm and 44.95 cm to alternative values of 33.91 cm and 44.76 cm, respectively, while F/M remained at 0.63 and SPR decreased to 0.37. Despite the small variation in SPR, the overall pattern between the two sampling years remained consistent, indicating that the main conclusions of the LBSPR assessment were not substantially affected by the alternative biological parameter values.

Table 9. Results of the LBSPR model for *Lophius piscatorius* in northern Tunisia (GSA 12). Observed and estimated values of parameters with 95% CI for 2024 and 2025.

Parameter	2024		2025	
	Observed	Estimated	Observed	Estimated
SL_{50} [cm]	27.46 (25.83–29.09)	34.30 (32.67–35.93)	31.20 (29.88–32.52)	34.02 (32.70–35.34)
SL_{95} [cm]	51.57 (49.00–54.14)	45.51 (42.94–48.08)	39.35 (36.95–41.75)	44.95 (42.55–47.35)
F/M	0.92 (0.73–1.11)	0.66 (0.47–0.85)	0.38 (0.25–0.51)	0.63 (0.50–0.76)
SPR	0.292 (0.239–0.344)	0.39 (0.34–0.44)	0.506 (0.405–0.606)	0.4 (0.30–0.50)

SL_{50}, selectivity length at 50%; SL_{95}, selectivity length at 95%; *F/M*, fishing mortality to natural mortality; SPR, spawning potential ratio; CI95%, confidence interval 95%.

Stock assessments of *L. piscatorius* using Catch MSY Monte Carlo model (CMSY++). The CMSY++ model results for *L. piscatorius* show a gradual increase in catches since the early 2010s, with a marked acceleration from 2015 onwards and a relative stabilization in recent years close to MSY (Fig. 6).

The results indicate a moderate intrinsic growth rate (r = 0.353) and a carrying capacity (K = 1.16 *10^3 t) that can sustain a stable biomass level in the long term. MSY is achieved at an intermediate biomass (B_{MSY}), while fishing mortality at MSY (F_{MSY}) constitutes the reference threshold for sustainable exploitation (Table 10). The stock biomass in the final year (2024) was estimated at 0.738 thousand tonnes, corresponding to a B/B_{MSY} ratio of 1.18. Although the estimate suggests that biomass was above MSY, the uncertainty interval includes values below 1, indicating that biomass may potentially be below the MSY reference level. Thus, fishing mortality in 2024

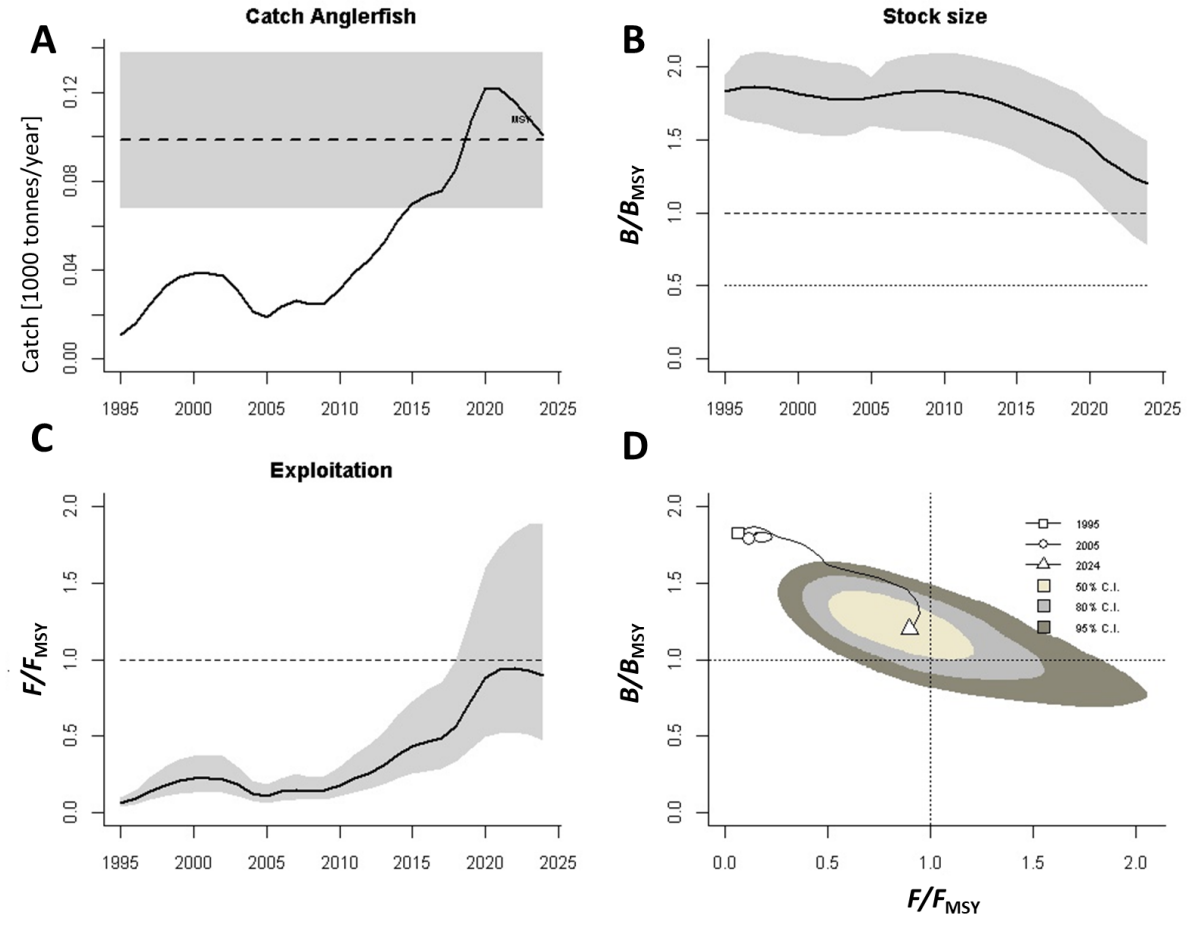

Figure 6. Graphical output of CMSY++ for ***Lophius*** *piscatorius* from the northern region of Tunisia (GSA 12). **(A)** trends in catches compared with MSY; **(B)** relative total biomasses predicted by the model compared with B_{MSY}; **(C)** relative exploitation compared with F_{MSY}; **(D)** Kobe diagram showing the trajectory of B/B_{MSY} compared with F/F_{MSY}.

Table 10. Management outcome based on CMSY++ analysis of *Lophius piscatorius* in the northern Tunisian coast (GSA 12).

Parameter	Value	95% CI
r	0.353	0.206–0.491
K	1.160	0.865–1.82
Maximum fishing mortality rate F_{MSY}	0.176	0.103–0.245
Maximum sustainable yield MSY [thousand t · yr–1]	0.102	0.0664–0.148
Biomass corresponding to the maximum sustainable yield BMSY [thousand t]	0.579	0.433–0.911
		2.5th–97.5th percentile
Biomass last year (2024) [thousand t]	0.738	0.381–1.26
Fishing mortality last year (2024)	0.136	0.073–0.28
Last year's B/B_{MSY} (2024)	1.180	0.766–1.51
Exploitation F/F_{MSY} (2024)	0.904	0.445–2.00

r, represents resilience or intrinsic growth rate; *K*, maximum stock size or carrying capacity; MSY, maximum sustainable yield; *B*, biomass level; *F*, fishing mortality rate; B_{MSY}, biomass at MSY level; F_{MSY}, fishing mortality at MSY level; B/B_{MSY}, biomass relative to B_{MSY}; F/F_{MSY}, fishing mortality relative to F_{MSY}; CI, 95% confidence interval.

is estimated at 0.136, corresponding to a ratio of F/F_{MSY} = 0.904. Although the point estimate was below 1, the uncertainty interval extended above 1, indicating that fishing mortality may potentially exceed F_{MSY}. Therefore, the point estimate should be interpreted with caution.

According to the CMSY++ model estimates (Table 10 and Figs 6, 7), the *L. piscatorius* stock in northern Tunisia (GSA 12) has moved towards a state of stable biomass, with fishing pressure close to the reference threshold. The point estimates indicate a biomass above B_{MSY} (B/B_{MSY} = 1.18) and a fishing mortality rate below F_{MSY} (F/F_{MSY} = 0.904). However, given the substantial uncertainty associated with these estimates, particularly with regard to F/F_{MSY}, it cannot be stated that the stock is being exploited sustainably. Therefore, the possibility that fishing mortality exceeds F_{MSY} cannot be excluded. This suggests that the stock is being fished at a level nearing MSY, and that continuous monitoring is required to ensure exploitation will not exceed sustainable levels.

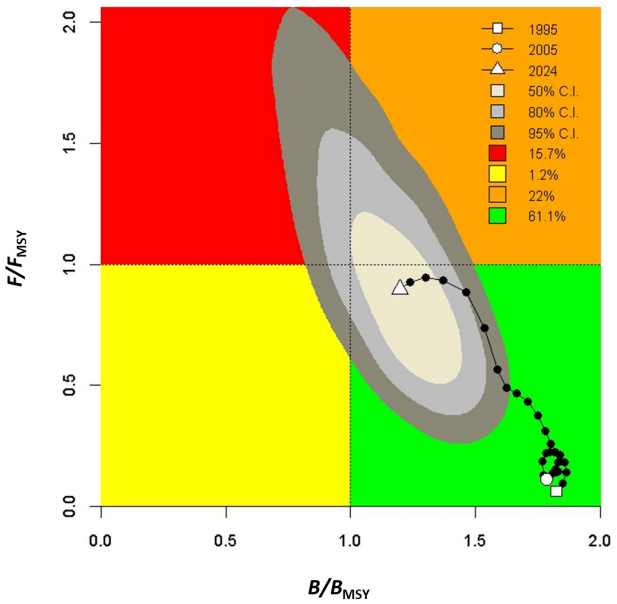

Figure 7. Kobe diagram of *Lophius piscatorius* from the northern region of Tunisia (GSA 12) showing the trajectory of B/B_{MSY} compared with F/F_{MSY}. Color-coded quadrants: green (sustainable), red (overexploited), yellow (recovering), and orange (overfishing).

A retrospective analysis of the CMSY++ model shows that the estimates of biomass (B/B_{MSY}) and exploitation rate (F/F_{MSY}) are consistent across the different terminal years (2021, 2022 and 2023). The retrospective trajectories showed broadly consistent patterns across terminal years (Fig. 8), although noticeable differences were observed compared with the full model run, particularly for recent F/F_{MSY} and historical B/B_{MSY} estimates.

Discussion

Population structure and growth. The sizes of *Lophius piscatorius* in the northern region of Tunisia (GSA 12) ranged from 10.6 to 89.1 cm, with a mean of 46.71 cm (±12.52 cm). These values are consistent with other studies. Indeed, several authors indicate that the size of individuals caught ranges between 11 and 142 cm in the northeastern Atlantic and the Mediterranean (Ofstad and Laurenson 2007; Coleman 2019). Similarly, studies carried out as part of the MEDITS program have shown a predominance of small and medium-sized individuals in Mediterranean catches, while the largest specimens can exceed 100 cm (Ungaro et al. 2002). The mean size observed in our study falls within the range of sizes reported for this species.

The biological parameters estimated for *L. piscatorius* in northern Tunisia (GSA 12) indicate a life history strategy typical of demersal species with moderate growth rates (Pineiro and Saínza 2003; Hirota et al. 2022). Among the models tested, the standard ELEFAN SA model was selected as the appropriate representation of growth, providing estimates of L_∞ = 89.29 cm, K = 0.369 year^{-1} and φ' = 3.469. Although the ELEFAN GA model produced a higher goodness-of-fit index ($R_{n\text{-}max}$ = 0.160 compared to ELEFAN SA), the difference was relatively small (0.014). Therefore, model selection was not based solely on the goodness-of-fit index, but it considered the overall consistency and stability of the estimated growth parameters, as well as their comparison with the published information available for *L. piscatorius*. Therefore, biological information and growth estimates were considered alongside statistical performance when selecting the final

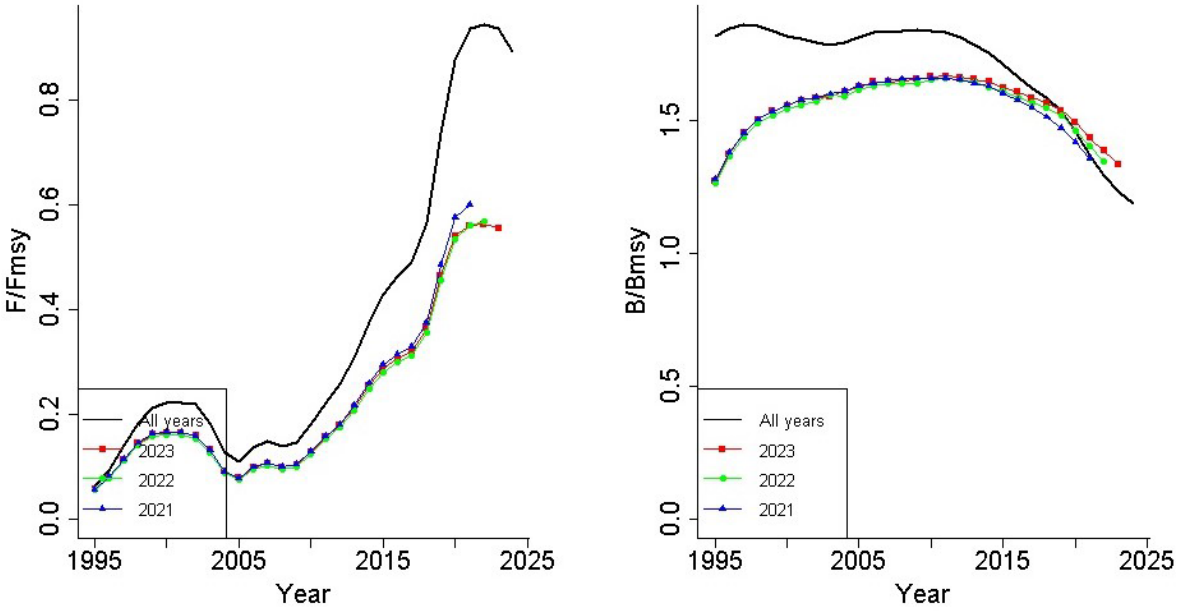

Figure 8. CMSY++ retrospective analysis for *Lophius piscatorius* from the northern region of Tunisia (GSA 12).

growth model (Burnham and Anderson 2002; Tredennick et al. 2021). Colmenero unpublished[1] reported substantially different growth parameters for *L. piscatorius* in the northwestern Mediterranean: L_∞ = 146.92 cm and K = 0.114 year^{-1}, highlighting the spatial variability in growth estimates for the species.

The estimated asymptotic length obtained in this study is lower than that reported for the northeastern Atlantic populations (210.7 cm) (Crozier 1989; Landa et al. 2001, 2008; Dyb unpublished[2]; Laurenson unpublished[3]; Ofstad and Laurenson 2007). In contrast, the growth coefficient (K = 0.369 year^{-1}) obtained in the presently reported study is relatively higher than that reported in the Atlantic, where values range from 0.05 to 0.20 year^{-1} (Crozier 1989; Landa et al. 2001, 2008; Dyb unpublished[2]; Laurenson unpublished[3]; Ofstad and Laurenson 2007).

The relatively high growth rate and a moderate asymptotic length, suggest a faster growth rate but a smaller maximum size than that observed in the Atlantic. Similar patterns have been observed for several demersal species occurring in both regions and are attributed to environmental conditions between Mediterranean Sea and northeastern Atlantic (Quignard and Tomasini 2000; Stergiou and Moutopoulos 2001). These differences are consistent with the colder, more productive environmental conditions in the Atlantic, which favor a slower metabolism but allow for prolonged growth, enabling fish to reach larger sizes (Pauly 1980; Atkinson 1994; Pörtner and Knust 2007). According to the temperature–size rule (Atkinson 1994), ectothermic organisms living in cold waters tend to grow more slowly but reach larger final sizes. In contrast, the Mediterranean is characterized by higher temperatures, persistent oligotrophy and significant seasonal variability in food availability (Bosc et al. 2004; Coll et al. 2010; Malanotte-Rizzoli et al. 2014).

These conditions accelerate metabolism and lead to rapid growth in the early life stage, but limit the potential to reach large sizes (Pauly 1980; Pörtner and Farrell 2008; Audzijonyte et al. 2019). This pattern is consistent with the K and L_∞ values observed in our study (GSA 12), as well as with estimates reported for other Mediterranean demersal fish stocks (Colloca et al. 2013; STECF 2020). According to Beverton and Holt (1959), fish of the same genus tend to grow more rapidly in warm waters. Still, L_∞ is smaller in warm waters than in cold waters. Other factors that may explain the differences observed between areas could include methods used to collect samples such as depths and type of fishing gear (Ofstad and Laurenson 2007).

Furthermore, fishing pressure may also contribute to these differences in growth. Studies on Atlantic stocks have shown that heavily exploited populations may exhibit changes in life history traits, including compensatory growth and earlier maturation (Landa et al. 2008; ICES 2024). This phenomenon can lead to apparent differences in growth parameters between regions that are exploited differently.

The inclusion of a seasonal growth component did not improve model performance in either optimization approach (Pauly and David 1981; Mildenberger et al. 2017). The absence of a marked seasonal pattern suggests that growth *L. piscatorius* in GSA 12 may occur continuously throughout the year, although this interpretation should

[2] Dyb JE (2003) Population studies of *L. piscatorius* along the Møre coast and in the North Sea. Cand. scient Thesis, University of Bergen, 105 pp. [In Norwegian]

[3] Laurenson CH (2003) Aspects of the biology and fishery for monkfish *Lophius piscatorius* Linneaus, 1758, in waters around the Shetland Isles, Northeastern Atlantic. PhD thesis, University of Aberdeen, Department of Zoology, 306 pp.

be considered cautiously because length-frequency approaches may have limited ability to detect weak seasonal fluctuations (Schwamborn et al. 2019; Liu et al. 2021).

The selected growth model (ELEFAN SA standard) suggests that *L. piscatorius* exhibits continuous, non-seasonal growth in GSA 12. This contrasts with the seasonal growth patterns observed for some temperate demersal species, but is consistent with the relatively stable thermal conditions in the deep waters of the Mediterranean (Tselepides et al. 2023), where seasonal temperature fluctuations have limited impact on benthic metabolic rates.

Moreover, the estimated value of t_0 is comparable to those reported in several studies on *L. piscatorius* in various regions of the Atlantic, such as in Spanish and Portuguese waters (–0.38 years; Landa et al. 2001), Norway (–0.34 years; Dyb unpublished[2]) and the Irish Sea (–0.38 years; Crozier 1989). This similarity suggests that the fitted growth model accurately describes the initial growth phase of the species.

Overall, a comparison with other Atlantic and Mediterranean studies suggests that the GSA 12 population exhibits accelerated biological characteristics (higher K and lower L_∞), but retains traits typical of species vulnerable to exploitation: moderate growth, late maturity and low natural mortality. This combination indicates a strong dependence of population dynamics on the protection of large individuals, in line with the conclusions of previous studies on the biology and management of this species (Landa et al. 2008; Colmenero et al. 2017; ICES 2024).

Sexual maturity. The estimates of sexual maturity derived from this study are in close agreement with those reported for the northwestern Mediterranean, where the length at first maturity was estimated at 51 cm for combined sexes and up to 60 cm for females (Colmenero et al. 2017). Additionally, Laurenson et al. (2008) reported an L_{m50} of 102 cm for female in Scottish waters. These results confirm that *L. piscatorius* reaches maturity at a large size relative to its maximum size. This is an important characteristic of its reproductive strategy that implies increased vulnerability to fishing targeting medium- and large-sized classes. However, in this study, the estimates of size at first maturity were obtained from empirical analytical approaches, without direct biological verification, which constitutes a methodological limitation. Nevertheless, such methods are widely used, particularly in the context of stock assessments and have been shown to provide robust and reproducible estimates of size-at-maturity, particularly when direct biological observations are unviable (Froese and Binohlan 2000; Prince et al. 2015; Medeiros-Leal et al. 2025; ICES 2023, 2024).

Natural mortality. The estimate of natural mortality using different empirical methods showed that Hoenig's (1983) method (M = 0.19 year^{-1}) appears to be the most biologically realistic for *L. piscatorius*. This method is based on the maximum observed age, a parameter linked to natural mortality and well suited to long-lived species (Hoenig 1983; Then et al. 2015). The estimated value is consistent with the biological characteristics of *L. piscatorius*, late sexual maturity and long life-traits associated with low rates of natural mortality. Similar values have been reported for other long-lived demersal species, confirming the validity of age-based estimators for this genus (Then et al. 2015).

However, Pauly's equation (1980) yielded significantly higher estimates of natural mortality. This method is widely used because it takes into account growth parameters and temperature, its application to long-lived demersal species should be approached with caution (Hewitt and Hoenig 2005; Then et al. 2015). Indeed, the equation's strong dependence on temperature can lead to an overestimation of natural mortality, particularly in warm environments, where an increase in metabolic activity is thought to lead directly to an increase in mortality (Pauly 1980; Then et al. 2015). However, this assumption does not necessarily reflect the population dynamics of benthic species such as *L. piscatorius*, whose longevity, demersal lifestyle and low population turnover may mitigate the direct effect of temperature on natural mortality (Hoenig 1983; Gislason et al. 2010; Then et al. 2015). Several studies have shown that temperature-based models tend to overestimate the natural mortality of long-lived fish compared with age-based approaches (Hewitt and Hoenig 2005; Then et al. 2015). Therefore, the estimated natural mortality is low and consistent with accepted values for long-lived and demersal species (Pauly 1980; Hoenig 1983; King 2007; Then et al. 2015). In the northeastern Atlantic, similar estimates of low natural mortality have been used in ICES assessments, reflecting a species whose dynamics are strongly influenced by fishing mortality rather than by natural processes (de Oliveira et al. 2013; ICES 2018). This means that even small variations in fishing effort can have a significant impact on the age structure and spawning biomass of *L. piscatorius* in the GSA 12 region.

Assessment of *L. piscatorius* stock in GSA 12. The results obtained from CMSY++, LBB, LBI and LBSPR provide complementary information on the exploitation status of *L. piscatorius* in northern Tunisia (GSA 12), but are not fully concordant. Overall, these approaches do not provide unequivocal evidence of severe stock depletion, however, they also do not support the definitive classification of the stock as sustainably exploited.

The results do not suggest severe depletion of the GSA 12 stock, although it is not sufficient to classify the stock as sustainable. CMSY++ estimates suggest that the biomass is above B_{MSY} and the fishing mortality is below F_{MSY}; however, the uncertainty intervals encompass less favorable states. LBB results are highly sensitive to biological parameterization, and LBSPR estimates show that the sustainable yield reference level (SPR) is close to the precautionary reference level of 40%. The combined evidence supports a precautionary approach, suggesting that fishing mortality should not be increased, and that improvements in selectivity and monitoring require further evaluation.

The biomass estimates relative to maximum sustainable yield (B/B_{MSY}) obtained using both the CMSY++ and LBB methods are greater than 1, which, according to the criteria proposed by Froese et al. (2017, 2018), indicates that the stock is being fished sustainably. Similarly, the values for F/F_{MSY} (0.904; CMSY++) and F/M (0.39; LBB) indicate fishing pressure below biologically critical thresholds. However, these estimates should be interpreted with caution due to the uncertainty associated with the CMSY++ assessment. In particular, the 95% confidence interval for F/F_{MSY} (0.445–2.00) extends above 1, indicating that fishing mortality may exceed F_{MSY}. Similarly, the 95% confidence interval for B/B_{MSY} (0.766–1.51) includes values below 1. The CMSY++ results suggest that the stock is currently close to the B_{MSY} and F_{MSY} reference points rather than indicating a substantial biomass surplus or low fishing pressure. These results support a precautionary approach, whereby further increases in fishing pressure should be avoided. Although the estimate of F/F_{MSY} is below 1, the uncertainty interval extends above 1. Therefore, fishing mortality cannot be considered below the F_{MSY} reference point. This interpretation is consistent with the precautionary approach, as any significant increase in fishing effort could cause the exploitation rate to exceed the sustainable reference point. Similar interpretations have been reported for well-managed *L. piscatorius* stocks in the northeastern Atlantic, where maintaining fishing mortality close to, but below, F_{MSY} has contributed to the recovery and long-term stability of several populations (ICES 2022, 2023, 2024).

The demographic indicators obtained using the LBI method provide additional insight into the biological condition of the stock. The proportion of mature individuals in the catch (P_{mat}), substantially below the 100% according to Froese (2004), indicating that a considerable proportion of individuals are captured before reaching the estimated length at maturity. Similarly, the proportion of mega-spawners (P_{mega}) is substantially below the minimum reference level of 20% (Froese 2004), suggesting that large individuals contributing disproportionately to reproductive output are relatively poorly represented in the catch. Given the importance of large femels for population replenishment, as their fecundity, egg quality and larval survival can increase with body (Berkeley et al. 2004; Hixon et al. 2014; Barneche et al. 2018). However, the low proportion of mega-spawners observed in GSA 12 warrants particular attention to retain a substantial component of reproductively valuable individuals, which may enhance the resilience of the stock to current fishing pressure.

The relatively low proportion of fish captured at the optimal exploitation size (P_{opt} = 39.75%) suggests that harvesting is not fully optimized. According to Froese (2004), optimal exploitation aims to maximize the proportion of fish harvested near the size that maximizes yield per recruit while allowing individuals sufficient opportunity to produce. In the presently reported study, the low P_{opt} indicates that a considerable fraction of the catch consists of fish harvested before reaching this optimal size. This interpretation is further supported by the LBB results, where the estimated length at first capture (L_c = 36 cm) remained below the estimated optimal capture length ($L_{c\text{-}opt}$), as reflected by the relatively low $L_c/L_{c\text{-}opt}$ (0.75) and L_{mean}/L_{opt} (0.80) ratios. These indicators suggest that improvements in fishing gear selectivity and a reduction in the capture of smaller individuals could potentially improve yield while reducing pressure on younger fish (Ahrens et al. 2020; Pellowe and Leslie 2020; Vasilakopoulos et al. 2020; Mantopoulou et al. 2024). The LBI results point to potential opportunities for optimizing exploitation through improved size selectivity rather than providing evidence of severe stock depletion.

Sensitivity analysis revealed that the LBB estimates were highly sensitive to biological parameterization. The use of alternative published estimates led to substantial changes in the results, indicating that biomass depletion and fishing mortality estimates derived from the LBB model are highly dependent on the biological parameters used as inputs. These results are consistent with earlier studies of the LBB approach, which showed that key stock-status indicators, such as F/M and B/B_{MSY}, can be influenced by uncertainty or bias in biological parameters, including L_∞ and M/K (Froese et al. 2018; Pons et al. 2020; Croll et al. 2023). Therefore, the favorable stock status indicated by the baseline LBB model should be interpreted with caution. Sensitivity analysis shows that uncertainty in biological parameters, particularly those related to growth and mortality, can affect biomass and exploitation estimates based on the LBB model. Pons et al. (2020) demonstrate the importance of using reliable and life-cycle-specific parameters for stocks to reduce uncertainty and potential bias in stock condition estimates derived from the LBB model. Nevertheless, the low $L_c/L_{c\text{-}opt}$ and L_{mean}/L_{opt} ratios, which are constant for both parameterizations, suggest that improving size selectivity and reducing the capture of small individuals may remain an appropriate management strategy for *L. piscatorius* in GSA 12.

The LBSPR analysis provides a precautionary perspective by evaluating the reproductive capacity of the exploited stock. The estimated spawning potential ratio lies very close to the 40% reference level recommended by Hordyk et al. (2015a). Although this value does not suggest an immediate risk of recruitment decline, it indicates that the stock has a limited capacity to resist increased fishing pressure. Stocks with SPR values close to the precautionary threshold remain biologically sustainable, but their reproductive potential can decline rapidly if fishing mortality increases (Hordyk et al. 2015a, 2015b; Prince and Hordyk 2019; Coscino et al. 2024). Therefore, the current exploitation level should be regarded as approaching the upper limit of sustainable fishing rather than providing a substantial safety margin.

Although the different assessment methods provide complementary information, their results should not be interpreted as providing fully independent evidence of sustainability. CMSY++ point estimates suggest that the

biomass is slightly above the B_{MSY} threshold, and that the fishing mortality is close to the F_{MSY} threshold. However, the associated uncertainty allows for less favorable states. LBI indicates that mature and large individuals are not strongly represented in the sampled catches. Meanwhile, LBB results demonstrate sensitivity to the biological parameters used. LBSPR indicates that the SPR is close to the 40% precautionary reference level. Taken together, these results indicate that the stock is not depleted, but may be operating close to several biological reference levels, which supports the need for a precautionary management approach.

The results obtained in this study show a more favorable population structure compared with those reported from other regions where *L. piscatorius* is being restored.. In the Mediterranean, studies by Colloca et al. (2013) showed that several demersal fish populations exhibit signs of overexploitation, characterized by a reduction in the abundance of large individuals and a decline in reproductive biomass. In contrast, the low proportion of mature individuals and mega-spawners observed in GSA 12 suggests that the demographic structure of the Tunisian *L. piscatorius* population remains relatively altered.

In the northeastern Atlantic, several studies highlighted the vulnerability of *L. piscatorius* to fishing pressure due to its slow growth, relatively late maturity and long lifespan (Duarte et al. 2001; Landa et al. 2008; Farina et al. 2008). Duarte et al. (2001) and Landa et al. (2008) showed that certain Atlantic stocks had undergone periods of heavy exploitation, leading to a decline in spawning biomass. However, more recent assessments by ICES (2022, 2023, 2024) indicate an improvement in several Atlantic stocks thanks to appropriate management measures. The B/B_{MSY} values observed in this study are comparable to those associated with stocks considered to be sustainably exploited in the northeastern Atlantic.

However, the interpretation of length-based indicators should remain cautious. The reference targets proposed by Froese (2004), such as P_{mat} = 100% and P_{mega} = 20%, represent biological reference values rather than universally applicable management objectives. In commercial fisheries, achieving this target is rarely realistic because fishing gears capture mixtures of immature and mature individuals. Although maintaining at least 20% mega-spawners is considered sufficient to preserve reproductive capacity in many species, this threshold may underestimate the requirements of long-lived predators such as *L. piscatorius*, whose largest females contribute disproportionately to population replenishment (Berkeley et al. 2004; Hixon et al. 2014; Barneche et al. 2018).

Although none of the assessment methods indicates that *L. piscatorius* is currently overexploited in GSA 12, several biological indicators suggest that precautionary management should be maintained. In particular, the proximity of the estimated fishing mortality to the F_{MSY} reference point and SPR values close to the recommended threshold indicate that the stock has limited capacity to support further increases in exploitation. Maintaining current fishing mortality while improving size selectivity could constitute a precautionary management objective aimed at preserving stock productivity and reproductive potential over the long term.

The conservation of large spawners deserves particular attention. Numerous studies have demonstrated that old and larger females contribute disproportionately to population renewal through higher fecundity, improved egg quality and enhanced larval survival (Berkeley et al. 2004; Hixon et al. 2014; Barneche et al. 2018). The low proportion of mega-spawners observed in GSA 12 may represent a potential concern for the stock's resilience. Preserving these individuals should remain a priority, particularly if future changes in fishing effort or environmental conditions reduce recruitment success.

This presently reported study highlights the usefulness of integrating several complementary length and capture assessment methods in data limited fisheries. The combined application of CMSY++, LBB, LBI, and LBSPR provides a broader assessment of stock condition by examining different aspects of the stock from data-limited models. While each approach relies on specific assumptions, their combined application helps to identify areas of agreement as well as sources of uncertainty associated with any single method and provides a more comprehensive evaluation of stock condition. However, it is important to consider the uncertainty associated with length-based methods and the representativeness of the samples when using these results to support future management decisions.

Study limitations. This study has several limitations that must be taken into account when interpreting the results. Firstly, the assessments carried out using size-frequency-based approaches (LBSPR and LBB) are based on a set of assumptions regarding growth, natural mortality and fishing gear selectivity. In particular, the estimation of the *M/K* ratio, a key parameter in these models, remains subject to a degree of uncertainty that may influence estimates of spawning potential (SPR) and exploitation indicators. Secondly, the analyses rely primarily on available landing data, the quality of which may be affected by biases inherent in fisheries data collection systems. Under-reporting of catches and incomplete coverage of certain fleets could lead to an incomplete picture of the actual exploitation of the stock. Furthermore, the representativeness of length frequency data obtained from commercial bottom trawl landings at the port of Bizerte can be affected by various factors, including gear selection, market sorting of catches, discard practices, and seasonal fishing cycles. The representation of certain size classes may be affected by these factors, which could impact length-based estimates. Therefore, the results should be interpreted as reflecting sampled commercial landings rather than the entire exploited GSA 12 population. Future assessments would benefit from broader spatial, temporal, and gear coverage to reduce this uncertainty. Thirdly, taxonomic uncertainty remains due to the morphological similarity between *L. piscatorius* and *L. budegassa*. Although identification procedures are applied, potential identification errors

cannot be entirely ruled out and could affect the observed size structure as well as the derived estimates. Finally, the spatial and temporal coverage of the analyzed data remains limited by the availability of observations. The results obtained should therefore be regarded as a representation of the stock's status in the context of the sampling carried out, rather than as an exhaustive description of its dynamics. Despite these limitations, the consistency of the findings derived from the various approaches used lends relative robustness to the general trends identified.

Conclusion

This study provides the first comprehensive evaluation of the population dynamics and exploitation status of *Lophius piscatorius* stocks in the central Mediterranean (GSA 12), using complementary approaches based on limited-data methods (CMSY++, LBB, LBI, and LBSPR).

The estimated biological parameters (K, L_{∞}, L_{m50}, L_{m95}, and M) confirm a life history strategy typical of demersal species, characterized by moderate growth, relatively late maturity and low natural mortality. These characteristics make *L. piscatorius* sensitive to variations in fishing pressure, highlighting the importance of conserving larger individuals to maintain the reproductive potential and long-term sustainability of the stock. Overall, the available evidence does not suggest severe depletion of the *L. piscatorius* stock in GSA 12. However, the uncertainty associated with data-limited assessment methods prevents the stock status from being classified as sustainable. CMSY++ indicates that fishing mortality is close to the F_{MSY}, while LBB results are highly sensitive to biological parameterization and LBSPR estimates place the safe biological catch reference level (SPR) close to the 40% precautionary reference level. Therefore, the stock should be considered to be operating close to several biological reference levels.

Therefore, a precautionary management approach should be maintained, with a particular focus on preserving the spawning biomass and size structure of the population. Maintaining fishing mortality at current levels, improving fishing selectivity and protecting large spawners could help to reduce the risk of future stock depletion. Potential management options could include increasing the minimum landing size above the estimated length at first capture (Lc = 36 cm), improving gear selectivity and strengthening information on fishing effort, vessel activity and catch composition. Enhanced monitoring could improve the quality of fisheries-dependent data and support future stock assessments.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Artificial Intelligence (AI) use

The authors accept full responsibility for the content of the manuscript, including the disclosure of any use of AI.
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Data availability

The datasets generated and/or analyzed during this study are available from the corresponding author upon reasonable request.