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Original Article

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Generalized depletion models have proven useful to provide management information for data-limited fisheries. These models are suitable for stocks with fast depletion and recruitment inputs that reset the depletion. The Mediterranean common dolphinfish (*Coryphaena hippurus*) fishery shows these dynamics, being seasonally exploited mainly by fish aggregation devices in small-scale fisheries from four countries and as bycatch by longline fisheries. These fleets operate on separate fishing grounds, and with distinct effort–catch dynamics. This led to the development of a multiannual five-fleet generalized depletion model applicable to a monthly database of effort, catch, and mean weight from 2008 to 2019. Results showed a high natural mortality rate (0.25 month^{-1}) and wide intra-season fluctuations in biomass. Annual recruitment fluctuates around 10 million individuals, and it has been stable along the analysed period. Exploitation rate only exceeded 40% during the peak month of catches, being much lower the rest of the season, indicating that this stock is fished within sustainable limits. We provide here the first estimation of reference points for the management of the shared dolphinfish Mediterranean stock and show that generalized depletion models can be extended to complex fisheries with multiple fleets with different effort–catch dynamics.

Keywords: *Coryphaena hippurus*, data-limited fisheries, Mediterranean fisheries, small-scale fisheries, stock assessment.

Introduction

The dolphinfish fishery in the western and central Mediterranean is important from cultural, food security, and economic points of view. Quetglas *et al.* (2016) found that this fishery is the largest small-scale fishery in the region in terms of volume of landings and economic value. Accordingly, it has been a priority for the General Fisheries Commission for the Mediterranean (GFCM) for stock assessment and management for nearly a decade. The Mediterranean dolphinfish fishery is a complex data-limited fishery, exploited by multiple national fleets with two different fishing gears, lacking age composition and fisheries-independent data while also having gaps in records of effort and catch. In general, the management of data-limited fisheries is challenging since conventional stock assessment methods cannot be applied under such severe data limitations (Chrysafi and Kuparinen, 2015). These obstacles have led to the development of alternative methods to assess a stock status in terms of abundance and exploitation rates (Thorson *et al.*, 2015), as well as reduce the uncertainties of parameters estimation within these methods (Geromont and Butterworth, 2015a; Kokkalis *et al.*, 2017). These stock assessment methods for data-limited fisheries have different data requirements and are suited to different fishing particularities (Chrysafi and Kuparinen, 2015; Geromont and Butterworth, 2015b; Dowling *et al.*, 2019).

Dolphinfish is a large epipelagic and highly migratory species from tropical and subtropical oceans that has been a fishing resource in all regions where it is found since ancient times (Palko *et al.*, 1982). The Mediterranean Sea constitutes the northern limit of its Atlantic regional distribution, where four coastal countries are mainly involved in its fishery: Italy, Malta, Spain, and Tunisia (Figure 1) (Moltó *et al.*, 2020). Recent genetic evidence suggests that the Mediterranean dolphinfish population has a coherent genetic structure (Sacco *et al.*, 2017; Maggio *et al.*, 2018), consistent with the view of a common stock across the region. The main fishery is a small-scale fishery composed of small boats that target juvenile individuals (the recent young of the year cohort, from 20 to 40 cm fork length) using fish aggregation devices (FADs). Dolphinfish shelter beneath floating objects, so they are captured with a small modified seine net once aggregated within the FAD. Every summer, the stock appears in the western and central Mediterranean (Massutí and Morales-Nin, 1995) when juveniles are recruited as they approach the coast to feed and become available to the fishery (Massutí and Morales-Nin, 1995; Massutí *et al.*, 1998). The opening of the fishery is legally established in the Mediterranean (Recommendation GFCM/30/2006/2) on 15 August, delayed to 25 August in the case of Spain due to state regulation (Orden OAA/1688/2013), and extends until 31 December. The involved fleets are allowed to deploy FADs in their respective

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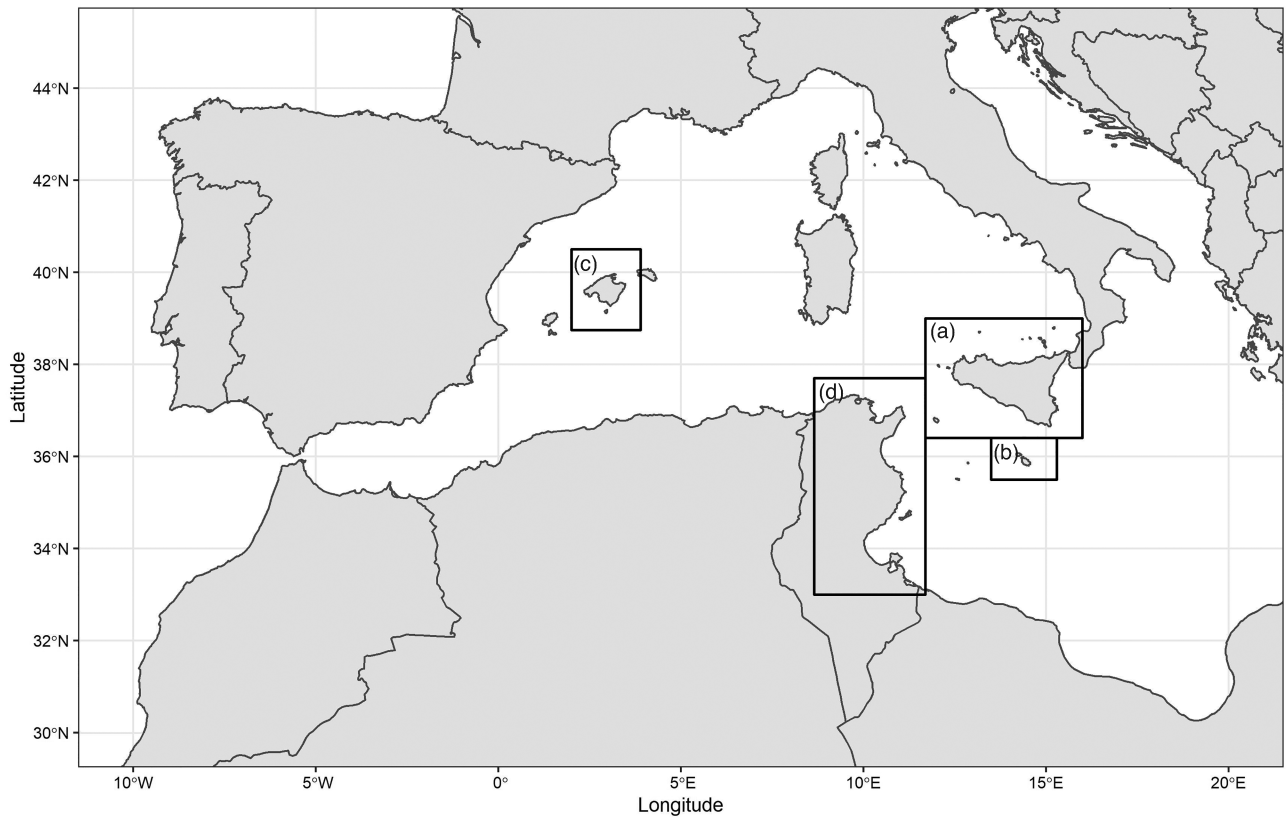

Figure 1. Map of the study region with the different Mediterranean countries fishing grounds highlighted in black squares: (a) Italy, (b) Malta, (c) Spain, and (d) Tunisia.

fishing grounds (Figure 1), moored in fixed swaths during the whole fishing season. This fishery deploys approximately 30% of the moored FADs worldwide (Morales-Nin, 2011).

Fleet dimensions and composition, effort and catches differ among FAD fleets (FAO-CopeMed II, 2019; Moltó *et al.*, 2020). Tunisia has the largest fleet (44% of fishing vessels in the region) followed by Italy (30%), Malta (20%), and Spain (6%) (FAO-CopeMed II, 2019). The Italian FAD fleet has landed the largest catches in weight over the period covered by the study, 2008 to 2019, with 37%, followed by Tunisia (31%), Malta (15%), and Spain (6%). Moreover, juveniles and adult dolphinfish are captured by the longline fishery as bycatch, representing 11% of the total catch.

The species presents an exceptionally fast growth rate, increasing up to 40 cm length within the fishing season. When the water cools and fish attain a certain length, they migrate away from the fishing grounds (Massutí and Morales-Nin, 1995; Massutí *et al.*, 1998). In consequence, this stock experiences extremely high intra-annual fluctuations with high biomass input prior to the fishing season along with fast depletion (FAO-Copemed II, 2016).

Some regional stock assessments have been attempted for this fishery. Lleonart *et al.* (1999) performed an adapted virtual population analysis (VPA) for a single cohort in the Mallorca Island fishery with the week as a time unit. Further trials were performed by a working group on this species in the framework of the CopeMed (Coordination to Support Fisheries Management in the western and central Mediterranean) regional project from the Food and Agriculture Organization of the United Nations (FAO), using different methodologies such as a non-equilibrium production model (IFOX) based on catch per unit effort (CPUE) data, the Jones length cohort analysis applied to the annual average catch-length composition, and a monthly depletion estimator based on catches and CPUE (Aires-da-silva *et al.*, 2016; Moltó *et al.*, 2020). However, the results of these analyses were not conclusive due to limited or incomplete input data and therefore, poor goodness of fit diagnostics. Thus, only approximated exploitation indices could be obtained, but no abundance reference points (Moltó *et al.*, 2020). Despite the lack of formal evaluation of the Mediterranean dolphinfish stock, the GFCM has introduced some management measures to the FAD Mediterranean fishery, such as the fishery closure. Recently, the GFCM has called for a future multiannual management plan for the Mediterranean dolphinfish fishery, including the assessment of the stock and determining the adequacy of the fishing effort exerted (Recommendation GFCM/43/2019/1). However, as pointed out by a recent review (Moltó *et al.*, 2020), a formal stock assessment of this fishery is currently missing, and is a research priority for the countries involved in the fishery.

This study develops a new stock assessment methodology for the Mediterranean dolphinfish stock and obtains reference points from abundance and exploitation rates. To achieve this, we extended the multiannual generalized depletion framework (Roa-Ureta, 2015; Roa-Ureta *et al.*, 2019, 2020) to the relatively large number of national fleets, exhibiting distinct fishing dynamics while operating on the stock. The fundamental premise of these mechanistic models is that at any time step, the catch results from the nominal fishing effort and latent stock abundance, not needing that the response of catch to effort and abundance be linear, thus directly accommodating features such as hyper-stability or hyper-depletion and effort saturability or synergy (Roa-Ureta, 2012). The model has proven to be useful for stocks similar to our dolphinfish case study, characterized by short-life spans, fast growth, high recruitment inputs to the fishery, and fast depletion (Roa-Ureta, 2012, 2015; Maynou, 2015; Lin *et al.*, 2017; Roa-Ureta *et al.*, 2020; Maynou *et al.*, 2021). However, this type of models has not been used at a large scale, involving multiple national fleets. The four FAD fleets differ substantially in capture magnitude and efficiency among the countries, and to this, a different fleet is added, the longline fleet that captures dolphinfish as bycatch (Moltó *et al.*, 2020). We developed a multiannual five-fleet generalized depletion model version considering the five fleets involved in this fishery and estimated dozens of parameters using statistical inference based on maximum likelihood.

Material and methods

Data acquisition and treatment

The information required for the multiannual generalized depletion (MAGD) model is the total monthly catch, total fishing effort, and mean individual body weight to convert the catches in weight into numbers of fish. Data to build the necessary database were provided by the originating countries (Italy, Malta, regional government of the Balearic Islands, and Tunisia) and gathered in the framework of the FAO regional projects CopeMed and MedSudMed (Assessment and monitoring of the fishery resources and the ecosystems in the Straits of Sicily). It covered the period from 2008 to 2019 for the four countries involved in the FAD fishery and the longline fleet. For stock assessment purposes, the longline fleet data (11% of total catch during the period) were aggregated across the four countries as it was highly dominated by one country. (Italy accounted for 94% of the total longlines catch.) Therefore, we had a five-fleet case to fit the MAGD model. Monthly mean lengths were obtained separately from fishery monitoring programs (Cabanelas, 2004; Besbes Benseddik and Besbes, 2005; Morales-Nin *et al.*, 2005a). These mean lengths were transformed to mean weight averaging the length–weight relationships for both sexes combined available in the region, reported from the Balearic Islands and Tunisia (Massuti´ *et al.*, 1999; Benseddik *et al.*, 2011):

$$W = 0.5 * (0.0113 + 0.0081) * L^{0.5*(2.9605+3.0669)},$$

where W is the weight in grams and FL is the fork length in centimetres.

The database was composed of country, year, month, total FAD catches (tonnes), total FAD effort (number of trips), total longlines catches (tonnes), total longlines effort (million hooks), mean weight (grams) for the FAD catches, and mean weight (grams) for the longlines catches. This database had 576 rows (12 years × 12 months × 4 countries) and nine columns. There were missing data in five out of nine variables. The most serious case was the missing fishing effort by the Tunisian FAD fleet for the whole time series. Nearly 60% of monthly mean weight data in FAD and longline fleets, close to 35% of effort data from the longline fleets and 25% of effort data from the FAD fleets, and catch data from the longline fleets were missing, while the FAD catch data was complete. The pattern of missing data is shown in Figure 2. Out of 576 observations, 148 had missing data only for mean weight from either the FADs or the longline fleets, 127 had complete data, and 84 observations were missing data in all five variables. Other combinations of missing data were less frequent. Eliminating the Tunisian FADs fishery, which missed all fishing effort data, was not an option. Given the similarities between the Italian and Tunisian FADs fisheries with respect to (i) geographical proximity (Figure 1), (ii) landings levels, and (iii) fleet dimension and technical vessel characteristics (see further details about fleet characteristics in Moltó *et al.* (2020)), we used the Italian effort–catch data as well as month and year as predictor variables to impute the missing Tunisian effort data with predictive mean matching (package *mice* v.13, Van Buuren and Groothuis-Oudshoorn, 2011) from the statistical language R v.4.0.4 (R Core Team, 2021). The same methodology was used to impute the remaining interspersed missing data in the database, except that for those imputations, we used the existing data of each FAD or longline fleet as predictors to impute the missing data of that fleet. The resulting data are shown in Figures 3 and 4. Annual totals for catch, monthly totals for effort of FAD and longline fleets, and annual totals of effort by fleet are shown in Figures S1–S4 of the Supplementary material. It can be observed that the FAD fleets differ in the magnitude of catches and yield (Figure 3a), thus explaining the need to build a five-fleet model. For instance, the Maltese fleet, characterized by larger boats, is more efficient with respect to the unit of fishing effort available in the databases.

Stock assessment model

As outlined above, we defined five fleets: FAD Italy, FAD Malta, FAD Spain, FAD Tunisia, and aggregated longlines. The multiannual five-fleet generalized depletion model (Equation 1) is based on the two fleets model (Roa-Ureta, 2015), which is based on the non-linear relationship between the catchability and fish abundance, and open population dynamics due to episodic recruitment pulses exogenous to the dynamics along the time period. These recruitment pulses are analysed and interpreted as perturbations that reset the depletion. Fleets are considered as complementary, providing additive information on fish abundance:

$$C_t = \sum_{f=1}^{5} k_f E_{f,t}^{\alpha_f} e^{-M/2} N_t^{\beta_f},$$

$$C_t = \sum_{f=1}^{5} k_f E_{f,t}^{\alpha_f} e^{-M/2} \left(N_0 e^{-Mt} - e^{-M/2} \left[\sum_{i=1}^{i=t-1} C_i e^{-M(t-i-1)} \right] + \sum_{j=1}^{j=12} I_{f,j} R_{f,j} e^{-M(t-\tau_{f,j})} \right)^{\beta_f}, \quad (1)$$

where C_t is the true catch in number of individual fish at month t for all fleets, calculated as the sum of the monthly catch of each fleet, which is, in turn, predicted by the observed effort E deployed by fleet f and dolphinfish abundance N in the fishing grounds. The monthly catch of each fleet is determined by a proportionality constant, the scaling k, which is comparable to catchability, having units of effort^{-1}. Fishing effort effect on catch is modulated by the effort-response parameter α and abundance is modulated by the abundance-response parameter β. Thus, the monthly catch of each fleet is the result of two causes, effort and abundance, with effort being an observed variable and abundance being a latent variable. In

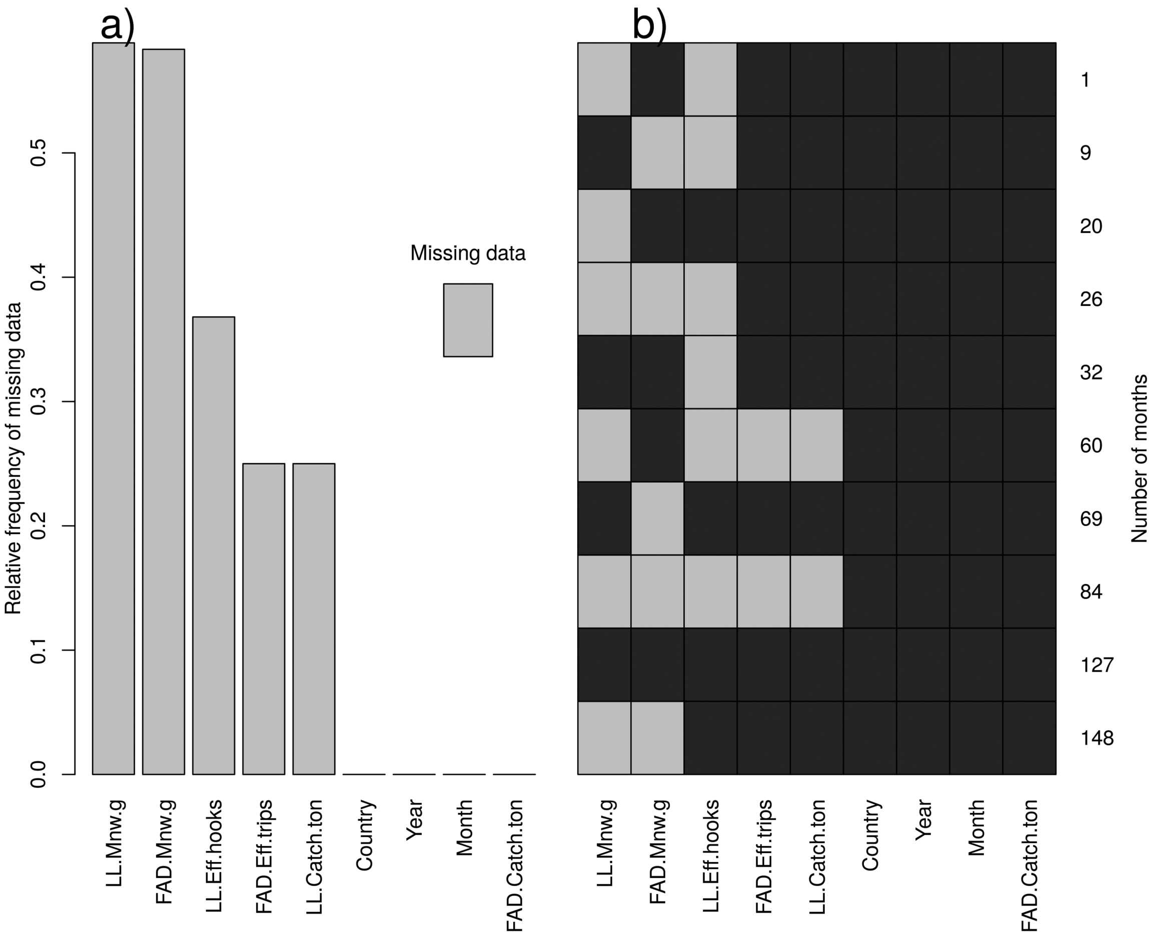

Figure 2. Pattern of missing data in the database of dolphinfish fishing in the Mediterranean compiled by Italy, Tunisia, Spain, and Malta upon request from the GFCM. (a) Frequency of missing data by variable in the database. Country (a synonym for fleet), Year, Month, and FAD.Catch.ton have no missing data and are included for completeness. (b) Pattern of missing data by combination of variables: most frequent missing data combinations are at the bottom and less frequent missing combinations at the top. LL: longlines; Mnw.g: mean body weight in grams; Eff: fishing effort; and Catch.ton: catch in tonnes.

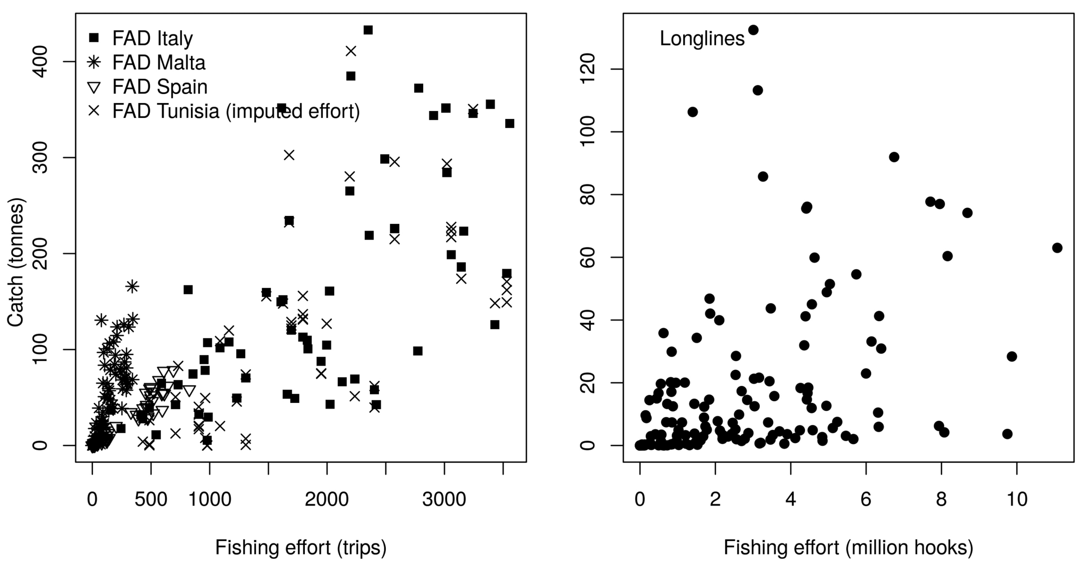

Figure 3. Monthly effort and catch data (2008–2019), original and imputed, for the five-fleet fishing for dolphinfish in the Mediterranean Sea.

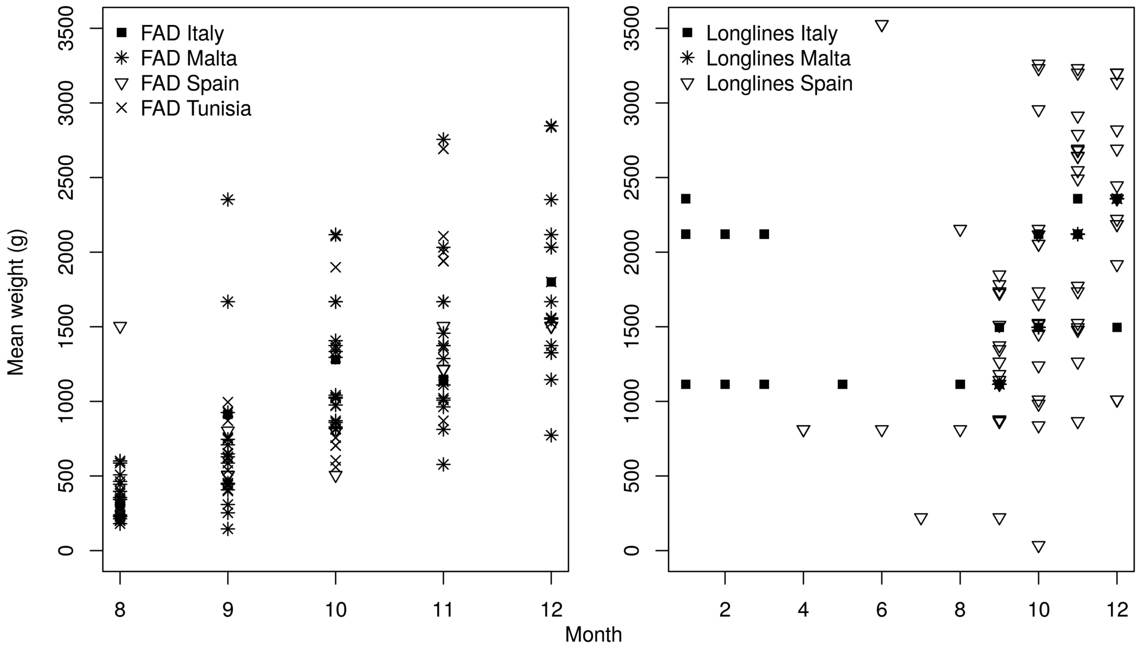

Figure 4. Monthly mean weight data (2008–2019), original and imputed, for the five fleets fishing for dolphinfish in the Mediterranean Sea.

the second line of the equation, the latent abundance available to each fleet is made explicit and expanded with Pope's formula (Pope, 1972) (second sum inside parentheses, with C_i as the catch by all fleets) and the input of abundance (third sum inside parentheses) corresponding to the annual recruitment R accruing to the fleet as a part of the total recruitment, which is the sum of recruitment pulses to each fleet in year j ($j = 1\ldots12$). Parameter N_0 is the number of fish in the month before the first month of the time series (December 2007) that survive to the start of the first month of the time series (January 2008), and M is the monthly natural mortality rate, both estimated inside the model. These two parameters are common to all fleets as they are characteristic of the stock and independent of fishing operations. The variable I_j is an indicator that takes the value of 0 before the input of recruitment and 1 afterwards. Parameters τ_j are the month in which recruitment happens in each year for each fleet. Although in this model the fleets provide complementary information to estimate abundance, the model does not assume that the fleets provide independent information. This is noted in Pope's expansion, second summand of Equation 1, where the catch of fleet f at time t depends on the cumulative catch by all fleets up to time t-1. Finally, the $e^{-M/2}$ term plays the role of translating the model from continuous to discrete time by setting all non-observed variables that change in time to the mid-interval of discrete time steps (see the proof in the Supplementary material of Roa-Ureta, 2012).

Having 12 years (2008–2019) of monthly data from five fleets, the model results in 77 differentiable parameters to be estimated: N_0, M, five k, α and β, and 60 recruitment parameters (12 years × 5 fleets). For this multidimensional optimization problem, we have 384 pairs of observations of effort and catch, not counting the months when the FAD fishery is closed (January to July).

The above equation describes the process model, the postulated mechanism linking the true catch C_t to effort and abundance, which is assumed to be fairly complete and exact, with negligible process error. The statistical model is composed of observation error that occurs when observing catch. Under the statistical model, the observed catch in the data is a random time series χ_t whose expected value corresponds to the deterministic time series C_t in Equation 1. Thus, the stock assessment model is completed with a statistical model where χ_t has a probability density. In this work, two distributions for χ_t were tested for each fleet, normal and lognormal, corresponding with additive or multiplicative random processes generating catch observations. In order to implement the normal and lognormal distributions to the catch data of each fleet, we used adjusted profile approximations to the exact likelihoods of each density. These approximations eliminate the dispersion parameters, which are considered a nuisance (see Roa-Ureta, 2012), to reduce the dimensionality of the optimization problem. These are

$$l_p(\theta; \{\chi_{1,t}, E_{1,t}\}, \ldots, \{\chi_{5,t}, E_{5,t}\})$$
$$= \frac{T-2}{2}\sum_{f=1}^{5}\begin{cases} log\left(\sum_{i=1}^{T}(\chi_{f,t} - C_{f,t})^2\right) Normal \\ log\left(\sum_{i=1}^{T}(log(\chi_{f,t}) - log(C_{f,t}))^2\right) Lognormal, \end{cases} \quad (2)$$

where l_p is the total negative log-likelihood function, θ is the vector of parameters to be estimated, $\{\chi_{f,t}, E_{f,t}\}$ are the catch and effort data of the five fleets, $C_{f,t}$ is the true catch of fleet f according to the process model, and $T = 144$ is the total number of months. These negative log-likelihood functions are minimized numerically as a function of θ to estimate maximum-likelihood parameter values and their covariance matrix.

This stock assessment methodology has been implemented in R v.4.0.4 (R Core Team, 2021) using a customized version of the *CatDyn* R package (Roa-Ureta, 2018). *CatDyn* calls *optimx* v.2020–4.2 (Nash and Varadhan, 2011; Nash, 2014) to run several numerical methods in a single call. In this work we used the "SPG" and "CG" methods because they are better at dealing with high-dimensional optimization problems. Thus, a total of 64 model variants, (32 likelihood combinations and two numerical algorithms for optimization) were fitted to the data.

A key process in the statistical fit of any non-linear model is to set good, tentative values (initial values) for the parameters to be estimated before submitting the data model combination to the numerical optimization. This procedure avoids falling in a local maximum of the likelihood function during the numerical optimization, which would yield biased parameters estimates. *CatDyn* contains a specialized graphical output to explore initial values for all parameters to be estimated before they are submitted to numerical optimization. For the initial value of the natural mortality rate (M), *CatDyn* has a function that uses the Hoenig's empirical formula (Then *et al.*, 2015) to produce a reasonable initial value for M with the maximum observed age as input. Considering the results reported by Massutí *et al.* (1999), Gatt *et al.* (2015), and Oxenford (1999), which indicate that the average maximum expected lifespan of dolphinfish in the western central Atlantic and the Mediterranean Sea, respectively, is 2 years, the initial value of M was set at 0.2 month^{-1}. Further initial values such as those for N_0, the fishing operational parameters (scaling k, effort response α, and abundance response β, for each fleet), and the 60 recruitment pulses (5 fleets × 12 years) were set by examining the exploratory graphical displays of model predictions and tuning them to approach the observed data with reasonably good residual diagnostics.

The selection of the model with the best parameters estimates among the 32 likelihood combinations and two numerical methods could not be based entirely on the Akaike information criteria (AIC) because the different model versions were fitted with different likelihood functions. The AIC was considered for comparing models fit with the same likelihood as part of the selection process. Further selection criteria were based on quality diagnostics, namely the size of numerical gradients, biological realism, distribution of residuals, successful calculation and size of asymptotic standard errors, and the size of pair-wise correlations between parameter estimates (Roa-Ureta, 2012). In the case of numerical gradients, it is desirable that all of them are close to zero, but in multidimensional optimization problems (our problem involved optimizing a 77-dimensional log-likelihood), this benchmark could be unattainable, so practitioners often settle for less ambitious goals, such as having all gradients <1 (Lee *et al.*, 2011; Anderson *et al.*, 2014; Hurtado-Ferro *et al.*, 2015; Thorson *et al.*, 2015). After numerical optimization, the best model version should have the lowest AIC when compared with versions fitted with the same likelihood, lowest numerical gradients, natural mortality close to that expected given dolphinfish lifespan, residuals centred on zero and with evenly distributed dispersion, lowest estimates of standard errors, and pairwise correlations centred on zero.

Because the fishing effort data for the Tunisian FAD fleet were imputed by predictive mean matching using Italian FAD fleet data, a further sensitivity test of the impact of effort data imputation was implemented by running the finally selected model under two alternative scenarios of Tunisian FAD fishing effort: doubling the imputed effort and setting up half the imputed effort data homogeneously across the 144 months of data.

The model in Equation 1 estimates the regional average natural mortality rate M over the study period, and it predicts total fish abundance at each of the 144 monthly time steps, N_t. Furthermore, the model considers the observed catch in numbers by fleet as data, χ_t, and predicts the catch by fleet expected under the model for every time step, C_t. Therefore, it is possible to calculate the fishing mortality rate at every month from Baranov's catch equation:

$$C_{f,t} = N_t \frac{F_{f,t}}{F_{f,t} + M} \left(1 - e^{-(F_{f,t}+M)}\right). \tag{3}$$

After numerical optimization, *CatDyn* resolves Baranov's F_t equation at every time step using the known values of M, N_t and either the observed (χ_t) or predicted (C_t) catch using *R*'s *uniroot* function. Note that in solving for F from Equation 3, we are using the continuous-time formulation of Baranov equation, discretized to match the magnitudes of monthly catch and abundance. Therefore, we assume that the discretization of the Baranov equation incurs just a small bias in the estimation of F.

Recruitment hypotheses

In seasonal fisheries based on juveniles such as the Mediterranean dolphinfish FAD fishery, a baseline hypothesis for the timing of recruitment in each year to each fleet (parameter τ_j of the process model), is to assign the pulse to the first month of the fishing season (August in our case). In the case of the longline fishery, as the bycatch occurs year-round, the τ_j may occur at any month. This baseline timing hypothesis can be improved by examining optimization results and changing some recruitment timings accordingly. Therefore, these non-differentiable τ parameters can be estimated by maximum likelihood by fitting alternative τ_j (i.e. varying the recruitment months) for each fleet and year combination, and selecting the fit that maximizes the likelihood. In our case, the τ parameters for the FAD fleets were initially evaluated using the baseline hypothesis that recruitment happens in the first month of the fishing season (August), while the τ parameters for the longline fleet were initially evaluated using the non-parametric catch spike statistics (Roa-Ureta, 2015), auxiliary statistics that point out months with catches that are too high for the exerted effort. The only exception was for the Spanish fleet in the last season (2019), when the start was officially delayed to September.

After choosing the model variant with the best parameter estimates under numerical, statistical, and biological criteria mentioned above with the baseline recruitment hypothesis, four further recruitment hypotheses were evaluated by changing some recruitment months for some fleets (the 60 τ_j non-differentiable parameters). The reason for this further exploration and refinement was that the standard errors of some recruitment pulses estimated in the best model variant had either large standard errors, or they could not be computed (a sign of anomalies in the Hessian matrix). Thus, it seemed necessary to try and further refine the timing parameters τ_j for those particular recruitment pulses. The second hypothesis (H2) posed that recruitment to all FAD fleets in all years happen at different months, excluding August, but including September, October, November, and December. Under this hypothesis, the month of recruitment in each FAD fleet–year combination was determined by examining the catch spike statistic. The third hypothesis (H3) posed that recruitment to all FAD fleets in all years happens in the second month of the season, September. The fourth hypothesis (H4) postulated that recruitment pulses happened mostly in September with some exceptions of recruitment pulses happening in August. Finally, the fifth hypothesis (H5) was similar to H4 but with more recruitment pulses happening in August, as suggested by the results obtained from the fitting of the model under H4. The months of recruitment for the different fleets under the different recruitment hypotheses are summarized in Table S1 of the Supplementary material. The final best model from the shortlist of five models (H1–H5) was selected based on the AIC. In this case, the comparison of AIC values is valid because the five versions were fitted with the same likelihood functions.

Exploitation rate as reference point

Depletion models are not population dynamics models and therefore they do not provide estimations of biological reference points based on stock productivity. Nevertheless, as explained above, these models estimate both natural and fishing mortality. Patterson (1992) empirically explored the effect of different magnitudes of the ratio of fishing mortality to total mortality, which is the instantaneous exploitation rate, on the stability of stock biomass over 5–10 year projections of stocks of fish having similar life history as the dolphinfish. His results clearly pointed out 40% as a threshold above which stock biomass declines and below which stock biomass rebuilds. In addition, the GFCM includes the instantaneous exploitation rate at 40% as a valid reference point for the management of small Pelagic fish (Resolution OTH-GFCM/36/2012/1). Therefore, we use Patterson's 40% exploitation rate as a limit reference point for the sustainable exploitation of the Mediterranean dolphinfish stock. The specific reference point is the fishing mortality at 40% exploitation rate,

$$F_{E40\%} = \frac{EM}{1-E}\,, \tag{4}$$

where E is the exploitation rate. We computed $F_{E40\%}$ from $E = 0.4$ and the estimate of natural mortality from the depletion model and compared it with the estimated fishing mortality for each of the five fleets and the total fishing mortality in the last year of the time series, 2019, also from the depletion model.

Results

Out of 64 model variants under hypothesis H1 for recruitment timing submitted to optimization, 32 yielded successful convergence results, but 29 of those showed poor gradient values (several gradients over 3, absolute value) leaving three variants to be further considered. These three remaining fits that yielded better gradient results were further examined to determine their biological realism. Two of these better variants produced too high natural mortality estimates (0.423 and 0.457 month^{-1}) compared to the expected natural mortality based on the dolphinfish lifespan. These natural mortality rates per month would imply that dolphinfish live just up to 9 or 10 months. In addition, these two fits had other shortcomings, such as a large proportion of standard errors that could not be computed during numerical optimization and poor correlation structure. Therefore, only one of these three fits yielded biologically realistic results that were numerically superior in terms of quality of optimization results and statistically more reliable in terms of standard errors of estimates and correlation between estimates. This variant was defined by normal probability distributions for the Italian FAD, Tunisian FAD, and longline catch data; lognormal distributions for the Maltese FAD and Spanish FAD catch data, and the SPG method for numerical optimization.

The selected fit, run under the recruitment hypothesis H1 (Table S1, Supplementary material), had the best numerical, biological, and statistical properties. However, it still produced poor statistical precision in recruitment parameters for the four FAD fleets and some recruitment pulses for the longline fleets (standard errors > two times the estimate value). Then, a new variant with the same likelihood model for each fleet and numerical optimization method was run under hypothesis H2 (Table S1, Supplementary material), which sets the recruitment pulses at varying months as suggested by the catch spike statistic. This variant yielded a biologically unrealistic natural mortality rate estimate (0.07 month^{-1}, which corresponds to 5 years of lifespan according to Hoenig's empirical formula). Then a new variant was fit with identical settings but with recruitment timings according to hypothesis H3 (Table S1, Supplementary material), which sets the recruitment pulses to FAD fleets in September with a few exceptions. It yielded poor gradients for many parameters. Therefore, hypotheses H2 and H3 were excluded from further consideration. The remaining three hypotheses (H1, H4, and H5, Table S1, Supplementary material) produced similar total monthly biomass estimates. For instance, at the end of the last season (2019), the biomass was estimated at 3024 tonnes under H1, 4331 tonnes under H4, and 3973 tonnes under H5. These three hypotheses also yielded similarly low gradients and capacity to calculate nearly all standard errors. The examination of pairwise correlation coefficients between estimates under the three recruitment timing hypotheses (Figure 5) shows that all three hypotheses yielded excellent correlations, although they were more concentrated around zero under the hypotheses H4 and H5. Furthermore, the model fitted under H5 yielded much lower standard deviations for recruitment pulses and a very precise estimate of natural mortality. Finally, computing the AIC (H1: 6446.776; H4: 6420.201; and H5: 6410.241) suggests that H5 is the best model, showing the lowest AIC by a large margin.

The estimates of the parameters are summarized in Table 1, and the fit of the model to data is presented in Figure 6. The model fitted the data well for all FAD fleets, particularly the Italian and the Spanish catch data, while it did not fit well the longline catch data, mostly because the model could not predict several high catches. Model diagnostics based on deviance residuals and quartiles are shown in Figure S5 (Supplementary material). For all fleets, deviance residuals were well-centred around zero and the residual cloud was shapeless. However, although the q–q plot fell mainly on the diagonal, there were several exceptions in the monthly catches of the FAD Maltese fleet, FAD Spanish fleet, and the aggregate longline fleet, pointing to the inability of the model to predict a few extreme values of monthly catch in some fleets. The best model produced precise estimates of natural mortality and fishing operational parameters scaling (k), effort response (α), and abundance response (β) in all FAD fleets, though the precision of the estimates of recruitment parameters was poor for all FAD fleets (Table 1). Recruitment parameter estimates for the aggregated longline fleets presented better precision for some years (2009, 2010, 2011, and 2019). Natural mortality M was remarkably high, estimated at 0.25 month^{-1} with high statistical precision (Table 1). This estimate is consistent with a lifespan of 2 years. Initial abundance N_0 (December

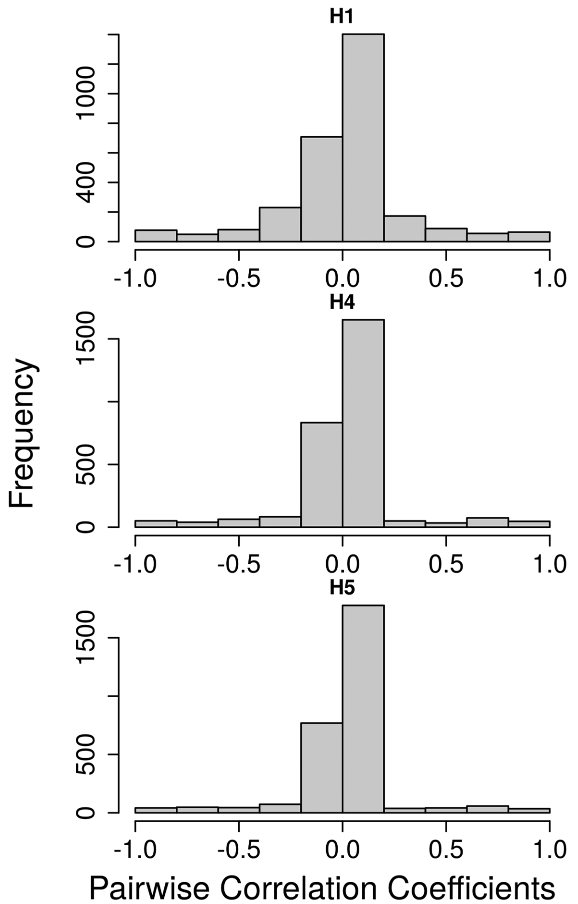

Figure 5. Histogram of correlation coefficients between parameter estimates of the three best multiannual five-fleet generalized depletion models under recruitment timing hypothesis H1, H4, and H5.

2007) was close to the estimates of recruitment, in the order of a few million fish, indicating that the stock has short memory of past abundance. The fishing operational parameters α and β of the FAD fleets (except Spain) had saturable effort response ($\alpha < 1$) and slightly hyper-depleted abundance response ($\beta > 1$) (Table 1). This means that as more units of effort (fishing trips) are deployed, catch margins get gradually smaller (saturable gear, except Spanish FADs), and as abundance decreases due to natural and fishing mortality, the catch decreases even faster (hyper-depletion). On the other hand, the effort of the longline fleet was very saturable, with an α estimate of 0.34, which is typical of bycatch, while its abundance response was, contrary to FAD fleets, hyper-stable, so catch remains stable while abundance drops.

Concerning the recruitment time series, the model estimated annual recruitments in the order of 10 million fish per year, a few million per fleet, with the Italian and Tunisian FAD fleets getting the larger fractional recruitments. The aggregate recruitment amount shows that it has remained relatively stable after a slight decrease in 2012, fluctuating around 10 million recruits until 2019 (Figure 7a). The annual exploitation rate (annual catch over mean annual biomass) has stayed close to 40% over the whole time series (Figure 7b), while the instantaneous exploitation rate (F over $F + M$) approaches 40% in just one or two months during each season since 2010 (Figure 7c). Monthly biomass experiences a precipitous decline each season, consistent with remarkably high natural mortality, but monthly catches do not get close to biomass because the lowest biomass occurs before the start of the FAD fishing season (Figure 7d).

The sensitivity test conducted to analyse the impact of the Tunisian FAD fishing effort imputation using the Italian FAD fleet data showed that the only parameter impacted by doubling or halving the imputed fishing effort was the scaling parameter (k) of the Tunisian fleet (Figure 8).

Table 2 shows the target or limit reference point, the fishing mortality at 40% exploitation rate, compared with the estimated fleet-specific and total fishing mortality from the last year of fishing. It is evident that the fleets are fishing within sustainable limits as defined by the exploitation rate at 40% both individually and collectively. However, the estimated total fishing mortality has a large standard error, and is reduced substantially by the low exploitation by longlines before the FAD fishing season.

Discussion

Generalized depletion models have been valuable tools to obtain fish abundance, mortality, and harvesting indicators for management in the context of data-limited fisheries. They have been successfully applied in several stocks of species with similar biological characteristics to dolphinfish such as fast growth, high dependence of abundance on the most recent recruitment inputs, and fast abundance depletion. In addition, given that these models treat fishing effort as a separate predictor (unlike models based on CPUE), some particularities of this fishery such as concentrating the stock of juveniles, interruptions or high variations in effort due to bad weather, or catch limits imposed in some regions (see Moltó *et al.*, 2020 for further details) are accounted for through specific mechanisms. Thus, estimates of abundance and mortality rates, which are important to calculate reference points useful for management, are not affected. The model flexibility made it possible straightforward adaptation to important complexities of the Mediterranean dolphinfish fisheries, namely four artisanal fleets with different catch dynamics exploiting juvenile fish over a 5-month season, three longline fleets fishing the bycatch of adult and juvenile fish year-round, gaps in fisheries and biological data, and lack of biological composition and fishery independent data. The model adaptation led to the development of a multiannual five-fleet generalized depletion model that allowed determining exploitation reference points for the first time for this shared stock.

Further complex aspects of the fishing dynamics connected to the spatial arrangement of fishing grounds (Figure 1) that are probably also relevant were not included. It is likely that during the FAD fishing season and during the fishing by longlines, parts of the stock move from one fishing ground to another and to outside areas, thus introducing pulses of emigration from some fishing grounds with possible complementary pulses of immigration in other fishing grounds, especially those occupied by the Italian and Tunisian fleets which are contiguous. In this regard, Moltó *et al.* (2020) have reported a negative correlation between catches of Italian and Tunisian fleets, suggesting the existence of out-flows complemented with in-flows in these two fishing grounds. Another interesting aspect of the spatial dynamics is that apparently, the magnitude of recruitment pulses differs within a year and across the fishing grounds. Figure 6 shows that only in 2012 all fishing grounds had relatively lower recruitment while in

Table 1. Maximum-likelihood parameter estimates of the best multiannual five-fleet generalized depletion model (H5) with normal probability distribution for Italian FAD, Tunisian FAD, and longline aggregated catch data, lognormal distribution for the Maltese and Spanish FAD catch data, and SPG method for numerical optimization. Rec: recruitment. *C.V.*: coefficient of variation in percentage (100 × standard error divided by the estimated value). NA: not available.

Fleet	Parameter	Timing	Estimate	C.V. (%)
Common Parameters	M		0.2459 month^{-1}	4.4
	N_0		3142.6×10^3	127.4
FAD Italy	Rec. 2008	2008–8	2097.7×10^3	149.0
	Rec. 2009	2009–8	2406.9×10^3	143.9
	Rec. 2010	2010–9	2780.0×10^3	204.4
	Rec. 2011	2011–9	2231.3×10^3	197.6
	Rec. 2012	2012–10	162.3×10^3	139.0
	Rec. 2013	2013–8	1621.7×10^3	184.2
	Rec. 2014	2014–9	2040.0×10^3	200.4
	Rec. 2015	2015–9	2453.5×10^3	194.3
	Rec. 2016	2016–8	1039.4×10^3	162.6
	Rec. 2017	2017–8	842.4×10^3	177.3
	Rec. 2018	2018–8	1164.2×10^3	234.5
	Rec. 2019	2019–8	1395.8×10^3	175.6
	k		2.6634×10^{-6} $trips^{-1}$	NA
	α		0.7879	NA
	β		1.4252	NA
FAD Malta	Rec. 2008	2008–8	2250.8×10^3	143.0
	Rec. 2009	2009–9	3443.1×10^3	179.0
	Rec. 2010	2010–9	2780.0×10^3	204.4
	Rec. 2011	2011–9	3255.3×10^3	151.1
	Rec. 2012	2012–9	2501.4×10^3	184.1
	Rec. 2013	2013–9	3198.7×10^3	199.3
	Rec. 2014	2014–9	2040.0×10^3	200.4
	Rec. 2015	2015–9	2453.5×10^3	194.3
	Rec. 2016	2016–9	3153.0×10^3	192.3
	Rec. 2017	2017–9	2298.7×10^3	191.0
	Rec. 2018	2018–9	3292.0×10^3	160.8
	Rec. 2019	2019–9	3293.0×10^3	172.8
	k		1.0201×10^{-4} $trips^{-1}$	55.4
	α		0.7087	11.2
	β		1.2003	6.7
FAD Spain	Rec. 2008	2008–9	4140.3×10^3	216.8
	Rec. 2009	2009–9	2057.4×10^3	259.4
	Rec. 2010	2010–9	2780.0×10^3	204.4
	Rec. 2011	2011–9	1738.6×10^3	231.8
	Rec. 2012	2012–9	2501.4×10^3	184.1
	Rec. 2013	2013–8	1621.7×10^3	184.2
	Rec. 2014	2014–9	2040.0×10^3	200.4
	Rec. 2015	2015–8	1254.1×10^3	142.7
	Rec. 2016	2016–8	1274.5×10^3	141.3
	Rec. 2017	2017–8	1039.3×10^3	154.6
	Rec. 2018	2018–8	1964.1×10^3	172.4
	Rec. 2019	2019–10	763.7×10^3	115.8
	k		1.9130×10^{-8} $trips^{-1}$	25.0
	α		1.2483	3.5
	β		1.7348	2.0
FAD Tunisia	Rec. 2008	2008–8	1847.1×10^3	160.4
	Rec. 2009	2009–9	3443.1×10^3	179.0
	Rec. 2010	2010–9	3375.4×10^3	178.5
	Rec. 2011	2011–9	1738.6×10^3	231.8
	Rec. 2012	2012–9	2501.4×10^3	184.1
	Rec. 2013	2013–9	4161.9×10^3	154.5
	Rec. 2014	2014–9	2040.0×10^3	200.4
	Rec. 2015	2015–9	2453.5×10^3	194.3
	Rec. 2016	2016–9	3153.0×10^3	192.3
	Rec. 2017	2017–9	2298.7×10^3	191.0
	Rec. 2018	2018–9	2453.3×10^3	202.9
	Rec. 2019	2019–9	3293.0×10^3	172.8
	k		2.1462×10^{-5} $trips^{-1}$	21.0
	α		0.5185	25.4
	β		1.4709	4.3

Table 1. Continued

Fleet	Parameter	Timing	Estimate	C.V. (%)
	Rec. 2008	2008–9	6009.3×10^3	151.1
	Rec. 2009	2009–10	1586.2×10^3	44.7
	Rec. 2010	2010–11	2174.2×10^3	35.5
	Rec. 2011	2011–10	4161.7×10^3	24.2
	Rec. 2012	2012–10	126.9×10^3	158.0
	Rec. 2013	2014–12	116.1×10^3	148.6
	Rec. 2014	2014–10	191.8×10^3	158.9
Longlines	Rec. 2015	2015–9	1935.3×10^3	226.9
	Rec. 2016	2016–10	869.3×10^3	89.1
	Rec. 2017	2017–9	1721.5×10^3	235.7
	Rec. 2018	2018–9	1442.4×10^3	288.2
	Rec. 2019	2019–11	1887.8×10^3	39.2
	k		1.5500×10^{-2} *million hooks*$^{-1}$	163.6
	α		0.3375	64.7
	β		0.7879	25.0

all other year's recruitment was relatively high in some fishing grounds and relatively low in others. This suggests that either the global recruitment pulse shifts its centre of gravity year to year, thus creating differential magnitudes entering each of the fishing grounds or that local conditions vary year to year, thus causing varying survival across the spatial layout of fishing grounds. Given the high number of parameters in the model and the statistical imprecision in recruitment magnitudes estimates, it is probably beyond the capacity of the data to include any such spatial dynamics in the model. The salient point is that data-poor fisheries, even complex ones, can be assessed with elementary fishery data (catch, effort, and mean weight or mean length in the catch) yielding results that are useful for management oriented to sustainability.

Parameters estimated showed that this stock experiences high natural mortality, estimated as 0.25 month^{-1}, equivalent to 3 year^{-1}. This estimation was very precise, with an asymptotic standard error of just 4% of the estimated value, and resulting from the model fitted to observed data. This natural mortality is unlike other reported natural mortality rates for dolphinfish stocks that were empirically calculated based on the length composition, somatic growth parameters, and water temperature (Pauly, 1980), such as 1.74 year^{-1} for the Mediterranean stock (Lleonart *et al.*, 1999), 1.17 year^{-1} in south-west India (Benjamin and Kurup, 2012), 1.3 year^{-1} in the eastern Pacific Ocean (Zúñiga-Flores, 2009), and 2.56 and 0.66 year^{-1} in the western Atlantic (Oxenford, 1999). Our analytical natural mortality rate estimate is higher than all previous empirical estimates. It is also closer to the expected magnitude given the previous knowledge of dolphinfish lifespan and the fact that it includes both juveniles (from FAD catches) and adults (from longline catches). More generally, the estimation of the natural mortality rate within a stock assessment model is considered difficult, and yet the value of this rate has a strong impact on abundance estimates, productivity of the stock, exploitation rates, and biological reference points (Lee *et al.*, 2011; Maunder and Wong, 2011; Powers, 2014). It is common to fix the natural mortality rate at a value obtained from some external source (Lee *et al.*, 2011; Maunder and Piner, 2015), a practice that compromises objectivity. Maunder and Piner (2015) were pessimistic about the prospects of estimation of the natural mortality rate within the stock assessment model, advising the use of external estimates from better, indirect methods (Then *et al.*, 2015) with exceptions, while Lee *et al.* (2011) conclude that it is necessary to have informative biological composition data (age or length) to reliably estimate the natural mortality rate. Our work here with a short-lived fish, and other instances of stock assessment with generalized depletion models with long-lived fish and invertebrates (Roa-Ureta, 2015; Roa-Ureta *et al.*, 2020) and short-lived invertebrates (Roa-Ureta *et al.*, 2020, 2021), shows that this may not be the case. Generalized depletion models routinely produce reliable estimates of the natural mortality rate within the stock assessment model without using biological data. In the present application, the estimated natural mortality rate was highly reliable, with just a 4% estimation coefficient of variation and consistent with the rapid dynamics and short longevity of the stock. The excellent statistical precision of the estimate was due to its very high value, ~0.25 month^{-1}, making it easy to define it inside the model given the steep drops in catch over the fishing season (Figure 6). In other words, the rapid life history of the stock and the swift drop in monthly catches over a season created excellent contrast in the data to estimate natural mortality without biological composition data.

The estimated recruitment patterns showed relative stability since 2012, with around 10 million recruits. On the other hand, the instantaneous exploitation rate showed that only the months of peak captures are slightly over 40%, mostly one or two of the five months in which the fishery operates each year. For the rest of the season, this rate is considerably lower. In terms of individual fleets, only the Tunisian and Italian fleets, which present the largest number of captures, are ~20% in the peak capture months. Furthermore, when comparing the reference point defined as the fishing mortality rate at 40% exploitation rate (following Patterson, 1992), with actual fishing mortalities estimated for each fleet and all fleets together, we found that the fishing is happening at fishing mortality rates well below the reference point. Therefore, we contend that the estimated exploitation rate and the stability in recruitment support the notion that the western and central Mediterranean dolphinfish stock is not overfished and is not undergoing overfishing.

The stock assessment model can be improved in several of its aspects. For instance, nearly all recruitment estimates have coefficients of variation >100%. One possible way to improve recruitment magnitudes precision would be to improve the data from the two most important fisheries in terms of vol-

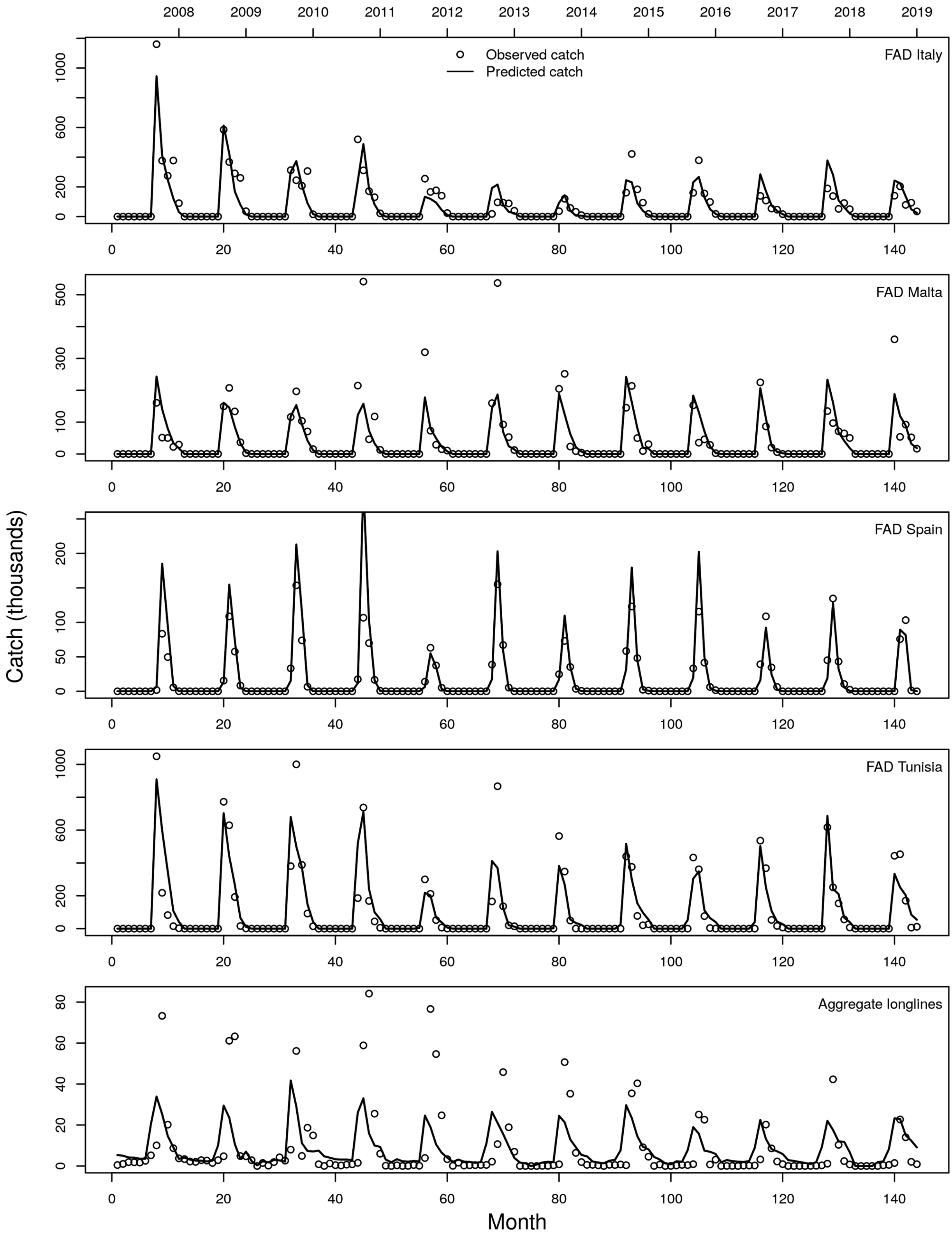

Figure 6. Fit of the best multiannual five-fleet generalized depletion model (under recruitment timing hypothesis H5) to the observed catch data for the five fleets fishing for dolphinfish in the Mediterranean Sea.

ume of catch; the Italian and Tunisian FADs fisheries. Further, obtaining independent data of the Tunisian effort, currently imputed from the Italian FAD fleet, should further improve the model results. We partially tested the impact of imputing Tunisian effort data from Italian effort and catch data by doubling or halving the effort, and the only affected parameter was the scaling *k*, while all the other estimates remained unchanged. However, this test related to the total magnitude

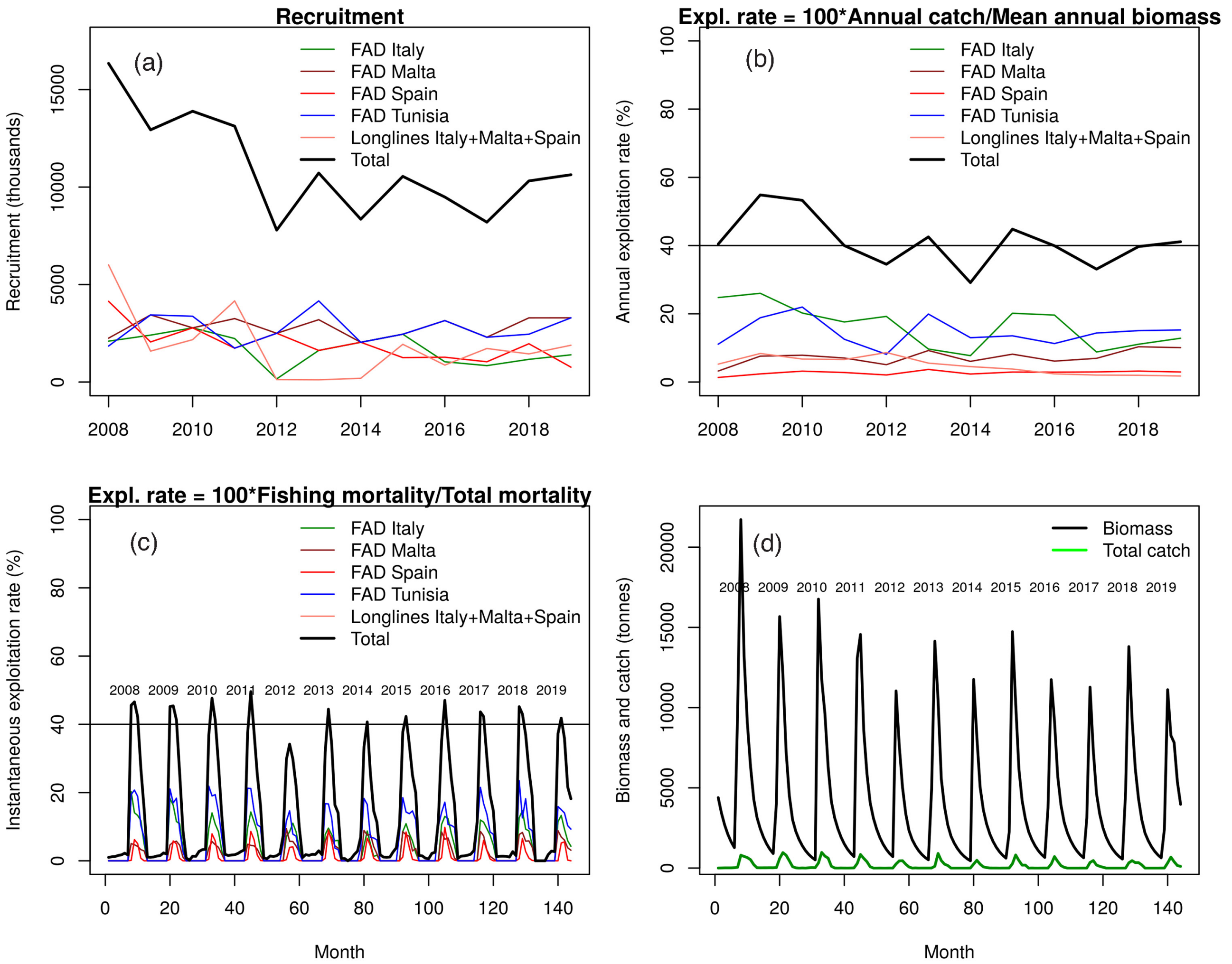

Figure 7. Recruitment magnitudes (a), annually aggregated exploitation rates (b), instantaneous exploitation rates (c), and biomass-catch (d) time series from the best multiannual five-fleet generalized depletion model (under recruitment timing hypothesis H5) of the Mediterranean dolphinfish fisheries.

of imputed effort, not to the connection between effort and catch, which was borrowed from the Italian fleet, and therefore the true impact of the imputed data cannot be entirely ascertained.

The incorporation of environmental drivers could additionally improve the estimates of recruitment magnitudes and their statistical precision. The abundance of stocks whose age composition includes a small number of cohorts is substantially determined by the latest input of recruits, which is likely determined to a certain extent by environmental fluctuations and/or regional conditions (Lehodey *et al.*, 2006; Peck *et al.*, 2021). Although generalized depletion models have not been fitted with auxiliary environmental data, other newly developed depletion models have been supplemented with recruitment indices through formal statistical inference (Feenstra *et al.*, 2017).

Another improvement for the stock assessment model would be to obtain monthly data on weight or length for each fleet to avoid data imputation. The monthly weights (derived from lengths) were obtained from some pilot projects in several countries, aiming at obtaining length–frequency data in some years. Fortunately, this fishery is based on a large cohort of juveniles which show one of the highest growth rates in Teleost fish (Moltó *et al.*, 2021). This enabled us to reconstruct the approximate average fish lengths of landed fish for each month in each country, given that enough length composition data were available. For the Maltese FAD fleet, complete time series were available. However, only five data points were available for other fleets such as the Italian FAD fleet and were recycled over the years. In the Balearic Islands, one solution to improve the data quality has been the recent adoption of automatic extraction of fish size and fish numbers from the fish auction using artificial intelligence (Palmer *et al.*, 2022). Apart from obtaining more complete monthly mean lengths for all fleets, the disaggregation of the entire database of catch, effort, and mean lengths into shorter time steps such as weeks or fortnights might facilitate the optimization process to obtain more precise recruitment magnitudes estimates. This approach is feasible with generalized depletion models (Roa-Ureta, 2012). For some of the countries, these data are available (Balearic Islands), but they are not available for the whole region, so in this work, we have chosen the monthly time step as it was available for all fleets.

As a final aspect for improving the stock assessment model, it should be noted that the large number of parameters to be estimated (77 in this application and increasing by 5 new parameters each new year of data) makes it advisable to migrate the programming code connected to optimization

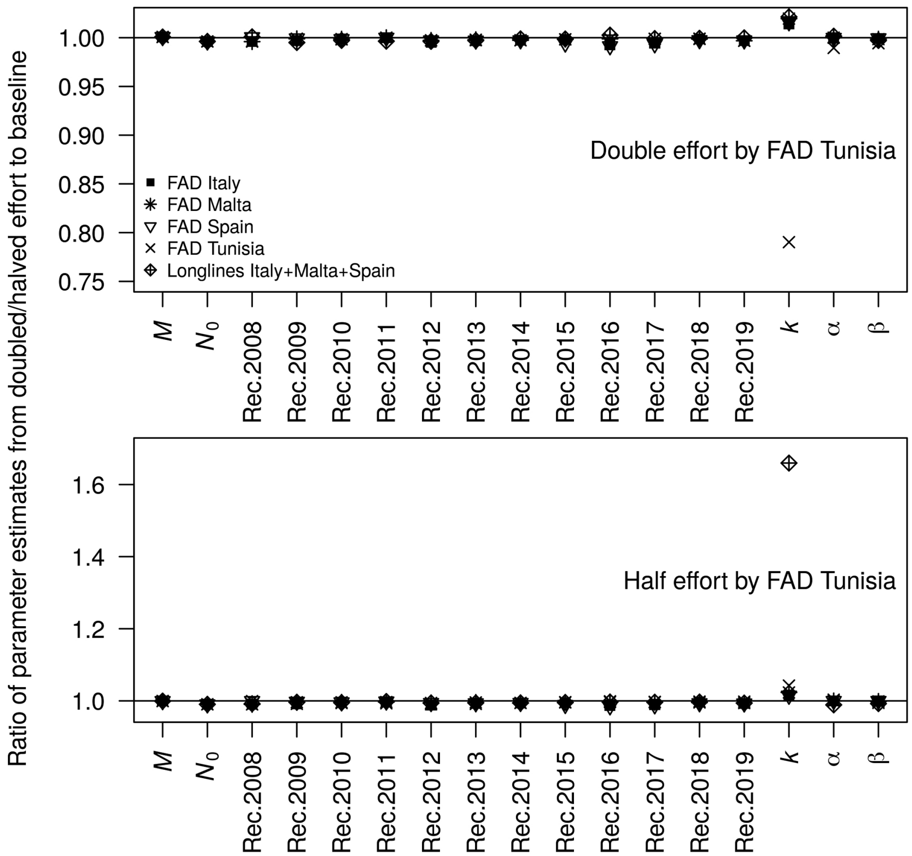

Figure 8. Impact of doubling (top) or halving (bottom) the imputed Tunisian fishing effort on parameter estimates of the best multiannual five-fleet generalized depletion model (under recruitment timing hypothesis H5) for the Mediterranean dolphinfish fishery.

Table 2. Target or limit fishing mortality *F* under Patterson's (1992) 40% exploitation rate and estimated fishing mortality rates by fleet and total in the last year, 2019.

Reference point	Fleet	Estimate (standard error)
F at 40% exploitation rate (month^{-1})		0.1639 (0.0733)
Mean *F* during last season (month^{-1})	FAD Italy (August to December)	0.0301 (0.0134)
	FAD Malta (August to December)	0.0265 (0.0236)
	FAD Spain (September to December)	0.0115 (0.0134)
	FAD Tunisia (August to December)	0.0507 (0.0496)
	Longlines (May to December)	0.0015 (0.0020)
	Total (May to December)	0.0781 (0.0881)

from R numerical methods based on derivative-free function evaluations, gradient methods, and Newton-like methods, to automatic differentiation in AD Model Builder (ADMB, Fournier *et al.*, 2012) or Template Model Builder (TMB, Kristensen *et al.*, 2015). This does not require complete abandonment of the obvious advantages of conducting the modelling from R. R packages such as GLMM ADMB (Skaug *et al.*, 2016) and SPiCT (Pedersen and Berg, 2017) use ADMB and TMB, respectively, for optimization in the background while the user runs the process from R. Migrating to auto-differentiation may alleviate the problem of having large coefficients of variation in recruitment magnitudes estimate because of better evaluation of second order properties of the log-likelihood function about the maximum.

The studies that provided recent evidence that the Mediterranean dolphinfish is a single genetic population also considered locations in the eastern Mediterranean Basin. However, fisheries data from countries in the eastern Mediterranean were not available for this study. In any case, this species does not represent a significant fraction of official statistics of countries from the eastern Mediterranean, so we consider our five-fleet model a reasonably complete account of the status of the stock for the whole Mediterranean. This species is further targeted by recreational and game fisheries, given its social relevance and tradition in most Mediterranean countries (Moltó *et al.*, 2020). The magnitude of the recreational harvesting is also unknown, but it can be considerable, as demonstrated by several studies analysing recreational harvesting and uncertainties regarding the recreational fishery in the Mediterranean Sea (Morales-Nin *et al.*, 2005b; Cabanellas-Reboredo *et al.*, 2017; Michailidis *et al.*, 2020). Therefore, pending confirmation that the recreational fisheries for dolphinfish are a small part of total catch in the Mediterranean (say, <5%), our results should be considered as tentatively complete, potentially needing a sixth fleet for a full account of the stock biomass and exploitation rates.

In the near future, the results of this multiannual five-fleet stock assessment could be further exploited to go beyond the use of exploitation rates as a variable to be considered for management. Biomass estimates could be used to fit surplus production models (Roa-Ureta *et al.*, 2019). These models would provide biological reference points derived from maximum sustainable yield and latent productivity to inform sustainable-oriented management. In addition, recruitment magnitude estimates from the depletion model can be used to fit a spawning stock-recruitment model (Roa-Ureta *et al.*, 2021). The spawning abundance could be obtained considering the maturity ogive, length–frequency data, and the abundance estimates from depletion models during the spawning season. Thus, the spawning abundance could be related to total recruitment the following year and better capture the population dynamics of this stock. These models would result in further biological reference points, in addition to exploitation rates, to better inform the management of the Mediterranean dolphinfish fishery, an issue that the GFCM has recently demanded.

Supplementary Data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Data availability statement

The data underlying this article will be shared on reasonable request to the corresponding author.

Author contributions

VM: Conceptualization, data curation, and writing—original draft; PH: Conceptualization, supervision, project administration, data curation, and writing—review & editing; AO-Á: Conceptualization, data curation, and writing—review & editing; IAC: Conceptualization, data curation, and writing—review & editing; RHR-U: Conceptualization, methodology, formal analysis, software, and writing—review & editing.

Conflicts of Interest

The authors have no conflicts of interest to declare.

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