This is what we know: assessing the stock status of the data-poor common sole on the Iberian coast

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Abstract

In the Iberian Coast region, the common sole (*Solea solea*) is considered a very relevant species due to its high commercial value. Despite its importance, the current status of this stock is still poorly known due to the scarcity of available data to apply formal assessment methods. In data-poor situations length-based methods have been widely applied to estimate biological parameters and to understand the dynamics of marine stocks. In this study we evaluate the status of common sole in the Iberian Coast region using the following three different length-based methods: (1) the length-based indicators, (2) the length-based spawning potential ratio and (3) the mean length-based mortality estimators. Overall, the three methods agree that this stock appears to be exploited at the maximum sustainable yield level, the immatures are well preserved whereas the proportion of large mature individuals is relatively low, although it has been increased in the last years. Assessing the status of this valuable stock through data-limited methods is the first step towards designing and implementing effective management measures.

Keywords: data-limited fisheries; stock assessment; LBI; LBSPR; Mean length Z; *Solea solea*

Introduction

Sustainability refers to the ability of an exploited population to produce goods and services, including yields at adequate levels in the short term, while maintaining sufficient reproductive capacity to continue providing these goods and services in the indefinite future (Walters and Martell, 2004). Intensive exploitation and overfishing are perhaps the main threats to marine living resources. The sustainability of artisanal multi-species fisheries is a key conservation concern given its socio-economic (Chuenpagdee and Pauly, 2008; Weeratunge et al., 2014) and ecological importance, due to the significant dependence of artisanal fishers and the considerable and growing threats to coastal habitats (i.e. pollution and climate change, loss of habitats, etc.) (Halpern et al., 2015). However, insufficient and poor-quality data (i.e., lack of life-history traits, historical time series of catches structured by age, stock length distributions, fishing effort by gear and sector), prevent the application of assessment models used for many of the stocks exploited by small scale fisheries (Costello et al., 2012). Nevertheless, even with limited data, some aspects of the stock status can be inferred. In fact, data-limited assessment methods are increasingly used to assess the status of data-limited populations and provide scientific advice for their management (Carruthers et al., 2014; Dowling et al., 2019; Chrysafi and Kuparinen, 2016).

Length frequency data from commercial catches are often the most common type of data and the unique source of demographic information collected in data-limited fisheries, as they are relatively cheap and easy to collect (Pilling et al., 2009; Hordyk et al., 2015a; Mildenerger et al., 2017; Cousido-Rocha et al., submitted). As a result, numerous length-based methodologies have been developed, of which the most widely used are the Length-Based Indicators (LBI; Froese, 2004; ICES, 2015), the Length-Based Spawning Potential Ratio (LBSPR; Hordyk et al., 2015a) and the mean length-based mortality estimators (MLZ; Then et al., 2018).

The LBI method ranks stocks according to conservation, sustainability, yield optimization and maximum sustainable yield (MSY) objectives by calculating a set of indicators based on the length composition of the catches/landings (Babcock et al., 2013; Shephard et al., 2018). LBSPR assesses stock status by the Spawning Potential ratio (SPR) defined as the proportion of Spawning Biomass per recruit (SBPR) in an exploited stock with regards to SBPR in an unfished (virgin) stock (Prince et al., 2015, 2020). MLZ estimates the year-specific total mortality rates from the annual mean lengths of fish whose lengths are larger than L_c (i.e. the length at which fish are fully vulnerable to the fishery) (Gedamke and Honenig, 2006). That is, the MLZ model requires a time series of length frequency data to define the annual mean lengths of fish fully vulnerable to the sampling gear, as well as the von Bertalanffy growth parameters. M can be obtained externally or estimated inside the model.

In the Iberian Coast region, common sole (*Solea solea*, Linnaeus, 1758) is targeted mainly by multi-species fleets using as main fishing gears trammel nets (Pennino et al., submitted). As mentioned above, this species has traditionally been considered of great importance due to its elevated commercial value (Teixeira et al., 2009; Teixeira and Cabral, 2010). Despite that in the North Sea the common sole stock is historically assessed and managed. In the Iberian Coast region the stock status was poorly known until recently (Tanner et al., 2017).

The management unit of the common sole stock in Iberian Atlantic waters includes both the Portuguese and Spanish fleets that operate in the International Council for the Exploration of the Sea (ICES) divisions 8c and 9a. Before 2021, this stock was classified as ICES category 5 that includes stocks for which only landings or a short series of catches are available (ICES 2021). In 2021 this stock was benchmarked, new data and models (*i.e.* the ones presented in this study) were presented and for this reason was upgraded to ICES category 3 that includes stocks for which survey, trends-based assessments, or other indices are available that provide reliable indications of trends in stock metrics, such as total mortality, recruitment, and biomass

(ICES, 2021). Management of all sole species are made under a combined TAC which could prevent effective control of the single-species exploitation rates. For the period 2011-2019, the common sole represented on average almost 60% of the total catches of sole species (ICES, 2021).

Catches of common sole of all gears and mesh sizes are under the Landing Obligation (LO), although discards for this species are considered negligible in the area (ICES 2019a). Overall, although some previous studies on the Portuguese flatfish fleet exist (Teixeira et al., 2009; Teixeira and Cabral, 2010), scientific studies to support an improvement of management measures are required for this stock.

Within this context, our study used length frequency data to evaluate the status of the common sole in the Iberian Coast region based on LBI, LBSPR and MLZ methods, which are the ones recommended by ICES to assess data-limited stocks (ICES, 2018). Assessing the status of this valuable data-limited stock is the first step towards the design and implementation of effective management measures.

Material and methods

Common sole data

Common sole length frequency distribution of commercial catches for the period 2011-2019 were collected by the Instituto Español de Oceanografía (IEO-CSIC) and the Instituto Português do Mar e da Atmosfera (IPMA), as part of their national fishery sampling programs under the European Data Collection Framework (DCF), designed to provide evidential support for scientific advice regarding the Common Fisheries Policy.

Length frequency distribution collection in landing ports follows a stratified multistage design in which the primary sampling unit is [auction*day]. The sampling design is stratified by fleet, auction and quarter and sampling effort is based on the number of trips funded by the DCF

national sampling plan. From each selected trip, length frequency distributions of every landed species and commercial category are collected in a concurrent sampling scenario (Silva et al., 2017). To obtain the length frequency distribution for each fishing fleet, numbers obtained at each length class in the sampled trips are raised to the total landed weight by quarter (See Table S1 of supplementary material for more details on the sampling network).

The two main fleets that catch this species in the area are (1) the Portuguese polyvalent fleet, which includes coastal and local vessels with overall length ranging from 5 to 23 m, usually licensed to operate with more than one passive fishing gear (most commonly gill and trammel nets, longlines and traps) that can be deployed in the same trip and target a high diversity of species (Duarte et al., 2009); and (2) the Spanish artisanal fleet that catches sole mainly using bottom gill and trammel nets. Both Spanish metiers are discriminated within the Spanish sampling plan and data are also reported separately to the ICES assessment working groups. Overall length frequency data used in the analyzes were derived from these two fleets from trammel nets (98%) and trawls (2%) (ICES, 2021).

Life-history parameters required for applying length-based methods include: length at maturity (L_{mat} , also known as L_{50} , and L_{95} which are the lengths at which the probability of having reached the maturity is 50% and 95%, respectively), parameters of the von Bertalanffy growth equation (K and L_{∞}), ratio of natural mortality to von Bertalanffy growth rate (M/K), and length–weight relationship parameters (a and b parameters). Length-weight relationships were built using individual total length and total weight measured by observers onboard the small-scale fishing fleet off NW Spain (Alonso-Fernández et al., 2021). Most of these population parameters were extracted from published studies for the common sole in Portuguese waters (Table 1).

Length based indicators (LBI) method

143 The LBI method consists of several length-based indicators describing the length frequency
144 data from commercial catches, which are compared to appropriate reference points related to
145 conservation/sustainability, optimal yield and maximum sustainable yield (MSY)
146 considerations providing a description of the stock status. The indicators related to
147 conservation/sustainability can be classified in two groups: (i) conservation of large individuals
148 and (ii) conservation of immatures.

149 LBI method considers the following indicators related to (i) conservation of large individuals:
150 $L_{\max 5\%}$, which is the mean length of the largest 5% of the fish, and P_{mega} , which is the proportion
151 of large fish in the catch (“mega-spawners”), i.e. fish of a size larger than the optimum length
152 ($L_{\text{opt}}=3L_{\infty}/(3+M/K)$) plus 10%. $L_{\max 5\%}$ indicator is compared to the reference point L_{∞} defining
153 the corresponding indicator ratio $L_{\max 5\%}/L_{\infty}$, which provides information about the degree of
154 truncation of the population length structure that may be caused by fishing and whose expected
155 value in healthy stocks is above 0.8 (Miethe and Dobby, 2015). P_{mega} follows the idea
156 summarized by Froese (2004) as “Let the mega-spawners live” and in healthy stocks P_{mega}
157 must be above 0.3 (see Froese, 2004 and ICES, 2015).

158 The indicators related to (ii) conservation of immatures are: L_c , which is the length at first
159 catch, and $L_{25\%}$, which is the 25th percentile of length distribution. Both indicators are compared
160 to the reference point L_{mat} defining the indicator ratios $L_{25\%}/L_{\text{mat}}$ and L_c/L_{mat} that follow the
161 principle “Let them spawn” (Froese, 2004) and are expected to be higher than 1 in healthy
162 stocks.

163 Finally, LBI method considers the indicator L_{mean} (mean length of individuals above L_c) and
164 compares it to the reference points L_{opt} and $L_{F=M}=(1-a)L_c+aL_{\infty}$, $a=1/(2(M/K)+1)$, which is a
165 length-based proxy for MSY, defining the indicator ratios, $L_{\text{mean}}/L_{\text{opt}}$ and $L_{\text{mean}}/L_{F=M}$, for
166 optimal yield and MSY considerations, respectively. Their values in healthy stocks are

expected to be approximately 1, for $L_{\text{mean}}/L_{\text{opt}}$, and equal or larger than 1, for $L_{\text{mean}}/L_{\text{F=M}}$. Note that the indicator ratio $L_{\text{mean}}/L_{\text{opt}}$ follows the principle “Let them grow” (Froese, 2004). As mentioned above, the LBI indicators require the length frequency data from catches/landings and the life-history parameters described in Table 1. The results derived from the application of the LBI method must be analyzed and interpreted taking into account that it assumes equilibrium conditions (constant total mortality and recruitment along the entire data time series), logistic selectivity, and that the catch length distribution is representative of the population length distribution.

Length-based spawning potential ratio (LBSPR) method

This approach focuses on the effect of fishing on the spawning biomass per recruit (SBPR) of the stock. It is based on the concept that without fishing, the population can reach 100% of its natural potential for spawning, but that fishing reduces the population’s SBPR.

The SPR index ranges between 0 and 1, with a value of 1 representing an unexploited stock. It is frequently assumed that stocks with a SPR range between 0.35-0.4 could be considered exploited at MSY level (Legault and Brooks, 2013), although this is a quite variable parameter (Hordyk et al., 2015b). Stocks with a SPR below 0.1-0.15 are considered close to collapse (such limits have been fixed on basis on Goodyear, 1993, who pointed out that for SPR values below 0.2 the risk of collapse increases considerably).

Unlike fishing mortality-based approaches, which directly relate to part of the population removed each year by fishing, SPR method reflects the cumulative effect of fishing and ecological impacts on the spawning potential of exploited stocks from a few previous years (a life span period approximately). SPR can be used to set targets and limit reference points for monitoring of population status.

The LBSPR method estimates the SPR using the life-history parameters included in Table 1 and the catch length composition data. To correctly discuss the results of the LBSPR method it must be taken into account that it provides a SPR value assuming that the population is in equilibrium (as the LBI method). Furthermore, it assumes that the length frequency data is representative of the exploited population at steady state, and that the selectivity is well represented by a logistic curve. LBSPR also assumes that an overall fishing mortality rate has caused the resultant length composition, and thus it requires that length composition data comes from the dominant fleet, or that multiple fleets are combined into one composite, and a catch-weighted aggregate length composition is derived.

Mean length-based mortality estimators (MLZ)

The mean length of fish that are fully vulnerable to the sampling gear can be used to estimate year-specific total mortality from basic growth parameters, a known length at first capture (L_c ; length of full selectivity), and a time series of fishing effort. If natural mortality is known (or estimated, as described later), fishing mortality rates can also be calculated. This approach may in some cases represent the best opportunity to reconstruct the mortality history of a stock.

Then et al., (2018), henceforth referred to as the Then method, parameterized the annual total mortality rate as the sum of the annual fishing mortality and time and age-invariant natural mortality rate. Assuming that the fishing mortality is proportional to the fishing effort by the catchability coefficient, the catchability coefficient and the natural mortality rate are estimated based on the goodness-of-fit to the mean length data through maximum likelihood estimation. An important advantage of Then et al. (2018) method over previous proposals, as Beverton and Holt (1956, 1957) or Gedamke and Hoenig (2006), is that the use of fishing effort allows annual estimates of total and fishing mortality instead of the full period of the total mortality

rate (Beverton and Holt, 1956, 1957) or time-blocks total mortality rates (Gedamke and Hoenig, 2006).

The Then et al. (2018) method requires the life-history parameters in Table 1, and the so-called length of first capture L_c , corresponding to the age t_c , at which animals are fully vulnerable to the fishery and to the sampling gear (Gedamke and Hoenig, 2006; Then et al., 2018). Note that L_c in MLZ and LBI are calculated differently. This method also uses the annual mean lengths of fish larger than L_c as input data, which are computed from the length frequency data. L_c has been calculated as the length corresponding to the peak in the histogram of the general length frequency distribution, obtaining $L_c = 30.5$. Finally, as mentioned above, the method needs a time series of fishing effort, usually derived as the ratio of the catches and an index of biomass, as catch per unit effort (CPUE) or landings per unit of effort (LPUE) indices. Here, the effective effort of the fleet from 2011 to 2019 was calculated as the ratio of commercial landings and LPUE from the Portuguese polyvalent fleet (see details in supplementary materials).

Additionally to the above data and input parameters, guesses for the maximum age, catchability coefficient and natural mortality rate must be specified. We set the maximum age guess at 15 years and the catchability coefficient guess to 0.15 divided by the mean of the time series of effort, being 0.15 a guess for time invariant fishing mortality, while the guess for M is 0.3, according to the value in Table 1. The model also requires a specification of the fishing effort prior to the first year of the mean length data which has been set equal to the fishing effort at the first year of our time series.

The Then et al. (2018) method is based on several assumptions that must be taken into account when discussing the obtained results. Such assumptions are: constant recruitment over time, deterministic and time-invariant growth following a von Bertalanffy growth equation, knife-

edge and time-invariant selectivity above the length of full selectivity (L_c), and known fishing effort proportional to fishing mortality.

Implementation and sensitivity analysis

As mentioned above, the three methods were applied using the life-history parameters listed in Table 1, in addition to the length frequency composition of the common sole catches. This scenario was considered as the base one used to assess the stock status of sole. However, it is important to analyze the effect of underestimation and overestimation (misspecification) of the relatively uncertain life-history parameters on the model outputs for each one of the methods. For this reason the following sensitivity analysis has been carried out:

1. LBI method has been reapplied using underestimate and overestimate values of L_∞ , M/K and L_{50} parameters,
2. For the LBSPR method the same analysis has been carried out considering the parameters L_∞ , M/K and L_{50} , L_{95} ,
3. For the MLZ method the sensitivity to the misspecification of L_∞ , K and L_c parameters has been analyzed. Additionally, the sensitivity of the model outputs to the guesses of maximum age (max A) and catchability coefficient (q) has also been addressed.

The lower and upper bounds for each of the mentioned parameters was a reduction and an increase by 10 and 20% on the base value in Table 1, except for L_c where the percentage of change has been reduced to 5% as the increase of 10 or 20% on the base value of $L_c=30.5$ is too high according to the annual mean lengths values. The MLZ method has been adjusted, both in the base setting and in the sensitivity analysis scenarios, without fixing a natural mortality rate obtained from external sources. Therefore, for comparative purposes the MLZ method has been reapplied in the base setting fixing M equal to the value given in Table 1.

All the statistical analyses were performed using R programming language (R Development Core Team, 2021). The LBI method was fitted using the R code available at ICES Tools (development area) Github (https://raw.githubusercontent.com/ices-tools-dev/LBIndicator_shiny/master/utilities.R); LBSPR method was implemented using the LBSPR package (Hordyk, 2019) and MLZ method was implemented using the Then et al. (2018) method, whose R code is available at https://github.com/ices-tools-dev/ICES_MS/tree/master/R.

All the R code implemented in this study can be found as open-access source in the GitHub repository (<https://github.com/IMPRESSPROJECT/assessing-the-stock-status-of-the-data-poor-common-sole-8c9a>).

Results

The length frequency distribution was consistent along the entire time series, with a mode around 30 cm (Figure 1), showing overall an unimodal distribution.

Length based indicators (LBI) method

Time-series of LBI derived from the base model suggest that the common sole showed a generally improving state (Table 2 and Figure 2). Most indicators received a consistently good evaluation, except for P_{mega} , which represents the proportion of the mega-spawners with 0.3 as a target. Indeed, from the base model we can conclude that the stock is exploited at MSY level and the optimal yield is attained. The conservation of immature individuals is achieved whereas the proportion of mega-spawners is low, although it has increased in the last few years. Note that although the values of MSY and of the maturity conservation indicators (i.e., L_c/L_{mat} ,

293 $L_{25\%}/L_{mat}$) are below the expected value of 1 for some years, these values are very close to this
294 reference value.

295 The sensitivity analysis shows that the overestimation of M/K and the underestimation of L_{∞}
296 and L_{50} leads to a more optimistic perception of the state of stock, and vice versa (Figure 3 and
297 Figure S4). As we expected, by definition, there is no impact of underestimation or
298 overestimation of L_{∞} on the L_c/L_{mat} and $L_{25\%}/L_{mat}$ indicators in both scenarios (10 and 20%).
299 Among the indicator ratios for which misspecification of parameter L_{∞} has an effect (L_{mean}/L_{opt} ,
300 $L_{mean}/L_{F=M}$, P_{mega} and $L_{max5\%}/L_{\infty}$), P_{mega} reports the highest mean ratios change for
301 underestimation and overestimation of L_{∞} . For both scenarios (10 and 20%), Figure 3 and
302 Figure S4, combined with Table 2, shows that the magnitude of the annual average of changes
303 in ratios are not large enough to lead to different final conclusions on the stock status, with the
304 exception of P_{mega} which increases attaining values above the threshold of 0.3 for
305 underestimation of L_{∞} giving the perception that mega-spawners would be well preserved. In
306 the sensitive analysis of the M/K parameter, the magnitude of the annual average of the ratio
307 change is lower than the corresponding one in the L_{∞} study, suggesting that the L_{∞} parameter
308 is more relevant in the method computation than M/K (Figure 3 and Figure S4). The
309 misspecification of M/K affects P_{mega} , optimal yield and MSY indicators. The greatest mean
310 ratio change corresponds to P_{mega} with overestimation of M/K where values were increased
311 being larger or close to the threshold of 0.3, whereas the small differences among 1 and the
312 mean ratios change of the remaining indicators lead to the conclusions about the stock status
313 derived from the base model.

314 Finally, the sensitivity analysis of the L_{50} shows that the underestimation or overestimation of
315 this parameter only affects the indicator ratios related to the conservation of immature
316 individuals, L_c/L_{mat} and $L_{25\%}/L_{mat}$. The decreasing of such indicator ratios under overestimation

L_{50} is not disturbing since the differences among 1 and the annual average of ratios change are slight.

Summarizing, the sensitive analysis supports the conclusion of a generally improving state of common sole derived from the base LBI application.

Length-based spawning potential ratio (LBSPR) method

The results of the LBSPR method in the base parameter configuration suggested that the common sole has been exploited at MSY level (Figure 4), agreeing with the LBI indicators. Along the time series, SPR values vary between 0.28 and 0.41, which is around the expected range for a healthy stock. Moreover, it is worth noting that the SPR shows an increasing trend over time, with the higher values of 0.38 and 0.41 occurring in the last two years of the time series. According to that, a decreasing trend can be observed on the F/M values. Changes in the selectivity estimates are minimal, which is the expected behaviour taking into account that there were no reasons to think that the fishing fleet selectivity has evolved significantly along the study period.

The main conclusions match those exposed previously for the LBI method. That is, the overestimation of M/K and the underestimation of L_{∞} and L_{50} and L_{95} leads to a more optimistic perception of the stock status, and vice versa (Figure 4, 5, S5 and S6). Furthermore, the results show that the accuracy of the L_{∞} parameter is crucial in the LBSPR method since its underestimation and overestimation leads to very different results. In spite of this, it is worth mentioning that with the 10% scenario even under the overestimation of the L_{∞} (the most pessimistic setting) the corresponding SPR values are above the thresholds associated with a collapsed stock. On the contrary in the 20% scenario, values are close to the thresholds of a collapsed stock for some years, but not in the most recent ones (Figure S5 and S6).

The parameters M/K , L_{50} and L_{95} also have an effect on the results but in a softer manner, leading to a similar perception of the stock status as in the base setting.

Mean length-based mortality estimators (MLZ)

The effective effort showed a sharp increase in 2012 followed by a strong decrease in the following year (Figure 6). In the base model, the fishing mortality estimates range from 0.20 to 0.15 showing a decreasing pattern (Figure 7). The year 2012 was the year with the highest fishing mortality estimate ($F = 0.22$), while 2013 was the one with the lowest value ($F = 0.14$). Furthermore, Figure 7 also includes horizontal lines representing $F_{\max}$, the value of fishing mortality that produces maximum YPR (Yield-per-Recruit), and $F_{0.1}$, the value of fishing mortality at which the slope of the YPR curve is reduced to 0.1 of the slope estimated at the origin. Both reference points have been computed using the YPR analysis implemented in https://github.com/ices-tools-dev/ICES_MSU/tree/master/R and the values of K , L_{∞} , L_c , a and b in Table 1, $t_0 = -0.15$ (hypothetical age at which the species has zero length) and $M=0.31$. The F estimates for all the scenarios are below $F_{\max}$, and furthermore only for the overestimation of L_c parameter in both scenarios (10 and 20%) the F estimates are above the reference of $F_{0.1}$.

The fits to the mean length data were similar regardless of whether M was estimated or fixed (Figures 7, 8, S7 and S8). With M fixed at 0.31, the estimated values of F were lower, reaching 0.20 in 2012 and decreasing to 0.12 in 2013.

Figures 7, 8 and S7 and S8 show that the MLZ outputs are not sensitive to the guesses of maximum age ($\max A$) and catchability coefficient (q). A slight reduction and increase in the F and q estimates was predicted by the model runs during the time series concurrent with the increase and decrease in the K , nevertheless the differences among 1 and the annual average of

change ratios are soft as well (Figure 8 and S8). On the contrary, M estimates are almost not affected by the K variation.

As in previous methods, the crucial parameters are L_c and L_∞ leading to a more pessimistic perception of the stock when they are overestimated. Although the estimates of fishing mortality undergo significant changes when L_c or L_∞ values are modified, it is important to stand out that the temporal decreasing trends of the F is maintained in all the settings. Therefore, the conclusion of a reduction in the fishing mortality rates is consistent over all the settings in spite of the fact that the values of F can change substantially under overestimation or underestimation of L_c or L_∞ .

Discussion

This study shows that, across the most plausible range of life history parameters, the common sole stock of the ICES divisions 8c and 9a seems to be exploited at MSY level. Using a 9-year time series of catch data, reference points for length-based assessment were obtained. LBI estimated indicator values are reasonable and traffic light assessment outcomes reflect that the conservation of immatures is achieved in this stock whereas the proportion of large mature individuals is low, although it has been increased in the last years. This result could also reflect the selectivity pattern of the artisanal fleet that operates in shallower waters where larger individuals are scarce. Indeed, the expectation of $P_{\text{mega}} > 0.3$ (LBI method) assumes asymptotic selection; if the selection is dome-shaped, we must take into account that lower values of P_{mega} are desirable following the fishing strategy that no mega-spawners are caught (Shepard et al., 2018). This could be the case of the common sole fisheries which are mainly conducted with gillnets with dome-shaped selectivity. Cope and Punt (2009), also conclude that P_{mega} showed a wide range of possible values depending on fishery selectivity.

SPR is defined as the proportion (or rate) of the unfished reproductive population left after exploitation by a fishery and is generally used to set target and limit reference points for fisheries management in data-limited fisheries (Hordyk, 2019). Based on the definition of spawning potential ratio (SPR), unfished stocks have an SPR of 100% (SPR100%). Fishing mortality reduces SPR100% from the unfished level to SPRX% (Suryandari, 2018). Scenarios analysed in this study resulted in a mean SPR value of 35%. The reference limit of SPR 35-40% is generally considered a conventional substitution for MSY (Legault and Brooks, 2013). This indicates that the common sole stock is in a healthy status, with a good proportion of individuals remaining to spawn. However it is worth to be mentioned that the deviation from certain assumptions can lead to a bias in the final estimates. For instance, according to Hordyk et al., (2015b), the LBSPR slightly underestimates the SPR for populations caught with gill nets (their selectivity curve is dome-shaped) as in the case of the Portuguese polyvalent fleet. The MLZ showed that the fishing mortality is decreasing for this stock in recent years. This trend could also be related to the fact that a precautionary TAC reduction of 20% was applied to fishing opportunities in 2013 and again in 2018. This catch reduction was suggested because this stock was classified as category 5 within the ICES framework, which means that no information on abundance or exploitation was available (ICES, 2012). In these cases ICES considers that a precautionary approach should be implemented. Indeed, scientific studies to underpin an improvement of management measures for this stock are scarce and do not reflect the importance of this resource. Although some regulations exist concerning Total Allowable Catches (TAC) based on the landings trend, fishing quotas and MCRS (Minimum Conservation Reference Size) the common sole stock has not been quantitatively assessed until the moment. Various authors have found that estimates of the parameters q and M are highly negatively correlated when estimated within a common model framework (e.g. Megrey, 1988; Wang, 1999; Fu and Quinn II, 2000). These parameters are also difficult to estimate reliably when

417 there is little contrast in the catch or effort data. Here, due to the data-limited situation of this
418 stock where the time series is very short (only 9-years were available to perform the study), a
419 lack of contrast in both catch and effort could be possible.

420 In the absence of direct fishing effort data, one could estimate effort from total commercial
421 catch. In practice, it may be difficult to obtain a time series of standardized fishing effort
422 because of multiple and changing fishing gears. Indeed, in our case only one LPUE time series
423 was available from Portugal and no effort was introduced for Spain. However, the Portuguese
424 polyvalent fleet from which the LPUE was derived is the main fleet that catches this stock and
425 for this reason was considered representative.

426 A comparison of our results to those of other studies is hampered by the limited amount of
427 research that has been conducted on the dynamics of common sole populations in the Iberian
428 Coast region. Nevertheless, recent studies on the relative abundance indices and body size
429 trends of coastal species in the Northwestern of the Iberian peninsula suggest a relatively stable
430 scenario (without sign of undesirable patterns) of the status of the *S. solea* stock exploited by
431 small-scale fisheries (Alonso-Fernández et al., 2019; 2021).

432 The other stocks of *S. solea* in the surrounding areas, as those from the ICES divisions 7.e
433 (western English Channel), 7.f and 7.g (Bristol Channel, Celtic Sea) and 8.a and 8.b (northern
434 and central Bay of Biscay), showed healthy stock status in all the reference points relative
435 to the fishing pressure (i.e., F_{msy} , F_{pa} , F_{lim} and F_{mgt}) and stock size (i.e., $B_{trigger}$, B_{pa} , B_{lim} and
436 B_{mgt}) (ICES, 2019b; ICES, 2019c; ICES, 2020).

437 Our sensitivity analysis has been performed examining the effects of misspecification/variation
438 of the crucial parameters of the three implemented methods. The effects of inaccuracy in input
439 parameters should be taken into account when drawing conclusions about stock status to avoid
440 further failures in actual management. Through our study we came to the conclusion that the
441 influence of the variation in the parameters of the input life history is of great importance in all

the methods. More precisely, we state that different management decisions can be drawn when the crucial parameter L_{∞} is underestimated or overestimated by 10%. According to Shephard et al., (2018) we concluded that an unrealistically high L_{∞} could generate false negatives (a poor state result when the true state is good), while a low L_{∞} could generate false positives (a good state result when the true state is bad). Best practices for determining fixed values for life cycle parameters in stock assessment would use estimates from specific stock studies (Rudd et al., 2019). However, when such studies are not available, our practical recommendation is to perform a sensitive analysis on these parameters.

Although there is some variability and uncertainty in the results of our study, the pattern of exploitation appears to be clear and consistent. Given the data available, the 3 methods analyzed show a general agreement in the results on stock and exploitation status strengthening our conclusions. More and better data are required to conduct a proper assessment (Dowling et al., 2019); nevertheless, the present study shows no evidence that the common sole population in the Iberian Coast region is experiencing high levels of mortality or is currently under any threat. It should be noted, however, that the results of our study apply only to the specific studied area and that the time series available is considerably short. Thus, further research will be needed to complement our study and improve our understanding of this stock.

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Tables

Table 1: Life history parameters (L_{∞} , L_{50} , L_{95} , M/K , K and a and b) for the common sole (*Solea solea*) stock and the corresponding source of information. For each of the length based methods (LBI, LBSPR and MLZ) we specify which of the life history parameters are required.

Parameters	Value	Source	Methods		
			LBI	LBSPR	MLZ
L_{∞}	48.9 cm	ICES stock annex <i>S. solea</i> divisions 8c9a	✓	✓	✓
L_{50}	26 cm	Jardim et al., (2011)	✓	✓	
L_{95}	27.5 cm	ICES stock annex <i>S. solea</i> divisions 8ab		✓	
M/K	1.41	Cerim et al. (2020) and Teixeira and Cabral (2010)	✓	✓	
K	0.22	Teixeira and Cabral (2010)			✓
a and b	$a=0.009476898$; $b=3.018329$	Alonso-Fernández et al., 2021		✓	

Table 2: Traffic light indicator table for the LBI analysis.

	Conservation				Optimizing Yield	MSY
Year	L_c/L_{mat}	$L_{25\%}/L_{mat}$	$L_{max5\%}/L_{\infty}$	P_{mega}	L_{mean}/L_{opt}	$L_{mean}/L_{F=M}$
Expected value	>1	>1	>0.8	>0.3	≈ 1	≥ 1
2011	1.10	1.10	0.94	0.13	1.00	0.99
2012	0.83	1.02	0.90	0.17	0.96	1.12
2013	1.02	1.10	0.89	0.14	0.99	1.01
2014	1.02	1.10	0.91	0.15	0.99	1.02
2015	1.06	1.10	0.88	0.12	0.98	0.98
2016	0.87	0.98	0.93	0.17	0.95	1.08
2017	1.10	1.13	0.91	0.15	1.02	1.00
2018	1.02	1.10	0.93	0.18	1.00	1.03
2019	1.13	1.17	0.94	0.23	1.05	1.01

Figures

Figure 1: Length frequency composition of the common sole catches from 2011-2019.

Figure 2: Temporal trends of the LBI indicator ratios estimates derived from the base model. Horizontal lines at reference values of 0.3, 0.8 and 1 are included. Note that P_{mega} must be above 0.3, the expected value of $L_{max5\%}/L_{\infty}$ is above 0.8, and L_c/L_{mat} , $L_{25\%}/L_{mat}$, L_{mean}/L_{opt} , and $L_{mean}/L_{F=M}$ are expected to be higher than 1 or closed to it.

Figure 3: LBI sensitive analysis using underestimation and overestimation of L_{∞} , M/K and L_{50} parameters at the 10% of the reference model values. For each setting, the annual average of ratios change, defined as the mean of the annual vector of ratios of the values of the indicator in the corresponding setting over such values in the reference setting, is plotted as a point. Furthermore, the associated standard deviation is represented through a horizontal line whose extremes are the mean minus the standard deviation and plus such quantity.

Figure 4: LBSPR results (F/M, SPR, L_{50} and L_{95}) for the base model and sensitive analysis scenarios of the common sole stock. LBSPR sensitive analysis was performed using the underestimation and overestimation of L_{∞} , M/K, L_{50} and L_{95} parameters at the 10% of the reference model values. In the F/M plot the results of the overestimation and underestimation of L_{50} and L_{95} overlap the reference scenarios. In SPR plot horizontal dashed lines delimit the range where the stock is considered at MSY level, whereas horizontal dotted lines show the levels below which the stock is considered collapsed.

Figure 5: LBSPR sensitive analysis using underestimation and overestimation of L_{∞} , M/K , L_{50} and L_{95} , parameters at the 10% of the reference model values. For each setting, the annual average of the ratios change, defined as the mean of the annual vector of ratios of the values of SPR (or F/M) estimates in the corresponding setting over such values in the reference setting, is plotted as a dot. Furthermore, the associated standard deviation is represented through a vertical line whose extremes are the mean minus the standard deviation and plus such quantity.

Figure 6. Catches and effective effort index used in the MLZ model for the common sole from 2011 to 2019 in the Portuguese waters (Division 9a).

Figure 7: F estimates derived from MLZ method in the base setting and sensitive analysis scenarios for the common sole stock. MLZ sensitive analysis was performed using the underestimation and overestimation of L_{∞} and K parameters and maximum age ($\max A$) and q guesses at the 10% of the base model values, whereas such percentage was 5% for the sensitive analysis of the L_c parameter. In all settings, in the base one and in the sensitivity analysis settings mentioned above, the natural mortality rate (M) was estimated, for comparative purposes, the graph also includes the F estimates corresponding to the reference model but fixing M equal to 0.31. F_{max} , the value of fishing mortality that produces maximum YPR (Yield-per-Recruit), is represented by a dotted horizontal line. $F_{0.1}$, the value of fishing mortality at which the slope of the YPR curve is reduced to 0.1 of that estimated at the origin, is represented by a horizontal dashed line.

Figure 8: MLZ sensitive analysis using underestimation and overestimation of L_{∞} and K parameters, and maximum age (max A) and q guesses at the 10% of the base model values, whereas such percentage was 5% for the sensitive analysis of the L_c parameter. In all settings, the natural mortality rate (M) was estimated, for comparative purposes, the graph also includes the setting corresponding to fix M equal to 0.31. For each setting, the annual average of ratios change, defined as the mean of the annual vector of ratios among the F values in the corresponding setting and such values in the reference setting, is plotted as a dot. Furthermore, the associated standard deviation is represented through a horizontal line whose extremes are the mean minus the standard deviation and plus such quantity. For M and q , the ratios among

847 their values in the corresponding setting and such values in the reference setting are plotted as
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