Applying length-based assessment methods to fishery resources in the Bay of Biscay and Iberian Coast ecoregion: stock status and parameter sensitivity

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Abstract

Length-based methods have been widely applied to estimate biological parameters and understand the dynamics of marine resource populations within data-limited stocks. However, to date few studies have tested the sensitivity of parameters in length-based methods examining stocks with different traits and fishery contexts. In the Bay of Biscay and the Iberian Coast ecoregion, SE Europe (International Council for the Exploration of the Sea - ICES, Divisions 8 and 9a), many commercial resources are considered data-limited, and either little is known about their fisheries stock statuses or gaps remain in currently available assessments. Therefore, this study focuses on two of the most used length-based methods, which ICES considers to be the most appropriate to evaluate data-limited stocks, namely length-based indicators (LBI) and the length-based spawning potential ratio (LBSPR). Both methods have been applied to assess the stock statuses of various relevant species in the study area, such as: the small-spotted catshark (*Scyliorhinus canicula*), European anchovy (*Engraulis encrasicolus*), blackspot seabream (*Pagellus bogaraveo*), pouting (*Trisopterus luscus*), pollack (*Pollachius pollachius*), and Norway lobster (*Nephrops norvegicus*). For each stock, model results were compared with available knowledge on their current status. Furthermore, this paper discusses whether unexpected results are related to violations of the main model assumptions

(constant total mortality and recruitment, and logistic selectivity) or to a lack of representativeness of stock length composition. A sensitivity analysis was conducted on the two most important input parameters: L_{∞} (von Bertalanffy asymptotic average maximum body size) and M/k (ratio of natural mortality to von Bertalanffy growth rate). This analysis concluded that the variation/misspecification of both parameters (M/k and L_{∞}) had a considerable impact on the results given by both methods, and that this effect is more significant in the case of the L_{∞} parameter, thus highlighting the importance of its accuracy in a given assessment. Furthermore, the sensitivity analysis indicated that, among the LBI and LBSPR indicators, the least robust indicator was the LBI P_{mega} indicator. The remaining LBI method indicators can be considered more robust than the LBSPR indicators when there is uncertainty in the life history input parameters (M/k and L_{∞}). Among LBSPR indicators, SPR is more affected than F/M (relative fishing mortality) by the variation/misspecification of parameter L_{∞} , whereas under the variation of M/k both indicators perform similarly. However, it is important to consider that LBI indicators are very rough measures of stock statuses, whereas LBSPR measures describe stock statuses more explicitly. Thus, both measures can be used together to obtain more precision in estimating stock status. Nevertheless, when critical parameters are uncertain (e.g., L_{∞}) and the results of both methods contradict one another, LBI method indicators, with the exception of P_{mega} , are more trustworthy than LBSPR indicators.

Keywords: data-limited fisheries; stock assessment; LBI; LBSPR

1. Introduction

Landings from the North East Atlantic (FAO fishing area 27) accounted for 11% of total global marine capture in 2018 (FAO, 2020). To effectively manage exploited fish stocks biological and harvest information is needed to assess stock biomass (or abundance) and fishing mortality rates (or exploitation rates) and, thus, establish sustainable exploitation levels. Yet, this kind of information is usually deficient or inadequate and, when knowledge of stock biology is limited or exploitation data is lacking, such stocks are classified as data-limited stocks (Froese et al., 2012). Uncertainty inherent in data-limited stock assessments could compromise the ability to inform management, which is a concern considering that poorly studied stocks are generally in worse conditions than data-rich stocks (Costello et al., 2012; Hilborn et al., 2020). To overcome this deficiency, increasing research

75 has been dedicated to developing assessment methods for data-limited fisheries in recent years and
76 has resulted in a suite of assessment tools that can be applied in data-limited situations (Carruthers &
77 Hordyk, 2018; Chong et al., 2020). Nevertheless, many of these methods still require considerable
78 amounts of data either from fisheries or on the biology of the target species, including time-series
79 data on historical catches, catch-per-unit-effort (CPUE) or scientific survey yield trends and
80 information on the age structure of the stock or life cycle parameters, all of which are difficult to
81 obtain for many data-limited fisheries (Hordyk et al., 2015a).

82 Within this context, length-frequency data from catches are probably the most common source of
83 demographic information because they are relatively inexpensive and easy to record (Mildenberger
84 et al., 2017). As a result, a number of length-based methods have been developed and applied to
85 estimate biological parameters and understand the dynamics of stocks. This has prompted the
86 development of length-based techniques to estimate fish growth and mortality rates without age data
87 (Hordyk et al., 2015b). Froese (2004) proposed simple fishery indicators based on length
88 composition to provide insights into stock statuses and sustainable exploitation indicators. The mean
89 catch length of a stock has also been used to calculate the status of exploited stocks (Ault et al.,
90 2005) to estimate total mortality in fish stocks (Gedamke & Hoenig, 2006) and to estimate the
91 spawning potential ratio (SPR) in data-limited fisheries (Hordyk et al., 2015b).

92 Among the length-based methods applied to data-limited stocks, the International Council for the
93 Exploration of the Sea (ICES) Workshop on the “*Development of Quantitative Assessment*
94 *Methodologies based on Life-history Traits, Exploitation Characteristics and other Relevant*
95 *Parameters for Data-limited Stocks*” (WKLIFE V) (ICES, 2015) identified the length-based
96 indicator (LBI, methodology developed by ICES, 2015 although some indicators had been
97 introduced previously by Froese, 2004) and length-based spawning potential ratio (LBSPR; Hordyk

et al., 2015b) methods as the most appropriate to achieve reliable assessments. The LBI method provides a set of length-based indicators selected to analyze catch/landings–length composition and classify the stocks according to conservation, sustainability, yield optimization and maximum sustainable yield (MSY) objectives. On the other hand, the LBSPR method consists of a length-based model to assess stock status by the spawning potential ratio of a fish stock (spawning biomass per recruit (SBPR) in an exploited stock divide to the SBPR value in an unfished stock), measured through length composition data.

Both methods, i.e., LBI and LBSPR, are highly sensitive to biological information assumptions (Rudd et al., 2019). Therefore, it is critical to understand the sensitivity of these approaches to parameter inputs (ICES, 2018; Hordyk et al., 2015b). The truthfulness of the models' results is equally dependent on the total uncertainty of the required life history parameter estimates, the inputs in the methods, and the assumptions made (selectivity, recruitment, etc., see the next sections for more details). Although Chong et al. (2020) indicated that LBSPR was one of the most accurate length-based assessment methods, Hordyk et al. (2015b) showed that the model was extremely sensitive to the variation/misspecification of the L_{∞} (i.e., von Bertalanffy asymptotic average maximum body size) and M/k (ratio of natural mortality to von Bertalanffy growth rate) parameters. Most previous studies, such as Hordyk et al. (2015b), mainly focused on the sensitivity analysis of SPR estimates using simulation data rather than real exploited stocks data. Indeed, only a small number of studies have performed parameter sensitivity analyses for these methods with real case studies, among which are Sun et al. (2017) and Hordyk et al. (2015b), who applied it to yellow croaker fish (*Larimichthys polyactis*) in the Haizhou Bay in China and yellow fin whiting (*Sillago chomburgkii*) in the Shark Bay, Australia, respectively.

In the North East Atlantic, certain fishery resources, such as anglerfish, blue ling, blackspot

121 seabream, pollack, and skates, among others, are classified as data-limited stocks (ICES, 2012) and
122 have increasingly drawn the attention of ICES. Within this context our study has two objectives.
123 First, we sought to evaluate the status of 7 different fishery stocks in the Bay of Biscay and Iberian
124 Coast ecoregion (see Table 1 for details of ICES Divisions) using the LBI and LBSPR methods and
125 to compare whether these results concur with currently available knowledge surrounding the state of
126 these stocks. To that end, we checked whether disagreements between both sources of information
127 (i.e., current knowledge vs. our results) may have been related to the noncompliance of model
128 assumptions in each case. Second, we sought to analyze the robustness of these methods as applied
129 to the stocks studied under various scenarios by testing the sensitivity of life history input parameters
130 (M/k , and L_{∞}). For addressing above aims the following case studies were selected: the southern
131 range of the European anchovy (*Engraulis encrasicolus*) stock in ICES Division 9a, given that it is
132 one of the most important small pelagic species caught by purse seiners in Spanish waters; Norway
133 lobster (*Nephrops norvegicus*) Functional Units (FU 26-27 Western Galicia & Northern Portugal, 9a
134 and in FU 25 North Galicia, 8c), given that they are among the species with the highest economic
135 value caught by bottom trawl fleet in the area; the pouting (*Trisopterus luscus*), given that it is
136 among the species with high commercial importance caught by Portuguese and Spanish artisanal
137 fleet; the pollack (*Pollachius pollachius*), which is a bento-pelagic species mainly exploited by
138 France and Spain in a data-limited situation; the lesser spotted dogfish (or small-spotted catshark,
139 *Scyliorhinus canicula*), given that it is the most frequent and abundant shark species in Iberian
140 Waters; and the blackspot seabream (*Pagellus bogaraveo*), which, commercially, is one of the most
141 important demersal species in the Strait of Gibraltar area. These stocks all present differences in life-
142 traits and fishery exploitation levels and were, thus, chosen to ensure that a complete picture of the
143 performance of the methods be tested.

2. Material and methods

2.1 Stocks data

The LBI and LBSPR methods were applied to *E. encrasicolus*, *P. bogaraveo*, *T. luscus*, *S. canicula*, *P. pollachius*, and *N. norvegicus* FUs 25 and 26-27 (females) in ICES Divisions 8 and 9a. The selected stocks had not been previously assessed with LBI and LBSPR methods, although other assessments had been previously performed. Specifically, the *E. encrasicolus* Southern component is scientifically assessed every year by the ICES Working Group on Southern Horse Mackerel, Anchovy and Sardine (WGHANSA) using a GADGET (Globally applicable Area-Disaggregated General Ecosystem Toolbox) model and is considered to be at full reproductive capacity (ICES, 2020a). Since 2014, *S. canicula* has been assessed every two years by the ICES Working Group on Elasmobranch Fishes (WGEF) using stock indicator trends estimated from survey data and has shown increasing abundance indices since 2014 (ICES, 2020b). As for the *N. norvegicus* FU 25 and 26-27, the advice is triennial and is based on Landing Per Unit Effort (LPUE) trends. Given that biomass is extremely low in these stocks, the advice has been zero catch since 2003 (ICES, 2020c). On the other hand, *T. luscus* and *P. pollachius* have not been scientifically assessed, although recent studies have indicated signs of potential stock deterioration in specific areas, i.e., Galicia, Spain, based on catch rates and mean size trends (Alonso-Fernández et al., 2019; Alonso-Fernández et al., 2021). Finally, *P. bogaraveo* is assessed based on a biomass index trend and ICES provides catch advice following a precautionary approach. With the exception of *T. luscus* and *S. canicula*, a total allowable catch (TAC) is applied to these stocks in the study area.

The data required for LBI and LBSPR methods (annual length frequency distributions) for *S. canicula* and *N. norvegicus* FUs were provided from the Spanish bottom trawl fleet by the Spanish

167 Institute of Oceanography (IEO), and account for the majority of landings of these species. In
168 addition, the IEO provided data for *P. bogaraveo* from Spanish “Voracera” fleet that had targeted
169 species in the Strait of Gibraltar. Spanish Voracera fleet catch the vast majority of total *P. bogaraveo*
170 landings in this area. Data for *T. luscus* were registered by observers onboard the Galician coast
171 multigear artisanal fleet. Although it is difficult to determine the proportion of catches from each
172 type of fishing gear used to target *T. luscus*, for this study we selected the most representative fishing
173 gear (gillnet, called “VETAS”) used to catch this fish species (see Alonso-Fernández et al. 2019;
174 2021). *P. pollachius* data were obtained from the gillnet and longline fleets, neither of which are the
175 dominant fleet. We therefore had to combine the length compositions across fleets by using fleet-
176 specific catches to weight the proportions before aggregating them together. Data for *E. encrasicolus*
177 were provided by Spain (IEO) and Portugal (IPMA; Portuguese Institute of the Sea and Atmosphere)
178 from the purse-seine fleet (which is the dominant fleet). These data constitute official information
179 that countries share each year with both ICES and the respective working groups.
180 Note that all the mentioned length compositions represent landed fish. The life history parameters
181 (M/k , L_{∞} , L_{50} and L_{95} , length at 50% and 95% of maturity, respectively) of each stock are reported in
182 Table 1.

183 2.2. The length-based indicators (LBI) method

184 Length-based indicators are calculated from length frequency distributions obtained from catches or
185 landings and compared to reference levels based on life-history parameters. These indicators are
186 related to conservation, optimal yield, and length distributions relative to MSY expectations and can,
187 thus, provide descriptions of stock status. The LBI method requires the following data: length at
188 maturity (L_{50} the length at which the probability of having reached maturity is 50%), von Bertalanffy
189 asymptotic average maximum body size (L_{∞}), the ratio of natural mortality to von Bertalanffy

growth rate (M/k), and length compositions from catch/landings per year. The length-based indicator $L_{\max 5\%}$ (Table 2), which characterizes the upper portion of the length frequency distribution, analyzes the conservation of large individuals by comparing itself to the reference point L_{∞} . The corresponding ratio provides information on the degree of truncation of the stock length structure that may be caused by fishing, and according to a simulation study performed by Miethe & Dobby (2015), should be above 0.8. The P_{mega} indicator (Table 2) refers to the proportion of mega-spawners in the stock (fish larger than the optimum length $L_{\text{opt}} = 3L_{\infty} / (3 + (M/k))$ plus 10%) and follows the idea summarized by Froese (2004) as “Let the mega-spawners live”. Froese (2004) and ICES (2015) have suggested that values above 0.3 correspond to healthy stocks. *P_{mega} has been included in the analysis only to illustrate with evidences that this indicator should not be used.* Length indicators $L_{25\%}$ and L_c relate to the conservation of immature individuals and follow the “Let them spawn” principle (Froese, 2004). The ratio of both indicators to L_{50} is expected to be greater than 1 (Table 2). Finally, the $L_{\text{mean}}/L_{\text{opt}}$ ratio, whose value is expected to be approximately 1, relates to the optimal yield and follows the “Let them grow” principle (Froese, 2004). However, the $L_{\text{mean}}/L_{F=M}$ ratio, whose value is expected to be equal to or greater than 1, focuses on MSY considerations given that $L_{F=M}$ is a length-based proxy for MSY. To correctly interpret and discuss the results provided by the LBI method, it is crucial to consider that this method assumes that constant mortality and recruitment have created a new steady state, as reflected in the length compositions equilibrium conditions. When this assumption does not hold, results can be misinterpreted. *Furthermore, it should be noted that the reference values for each LBI indicator are sensitive to Froese (2004) selectivity assumptions.*

2.3. Length-based spawning potential ratio (LBSPR) method

The original LBSPR method described by Hordyk et al. (2015a, b) is based on a conventional age-structured equilibrium stock model. *The method uses maximum likelihood methods to find the*

213 values of relative fishing mortality (F/M) and selectivity-at-length that minimize the difference
214 between the observed and the expected length compositions of the catch and calculates the resulting
215 SPR. One drawback of the method is that selectivity is age-based rather than length-based, despite
216 the fact that fish selectivity is often length-dependent, and this leads to different fishing mortality
217 rates among fish of the same age; an effect known as “Lee’s Phenomenon” (Lee, 1912). Given that
218 the age-structured LBSPR method does not account for Lee’s Phenomenon it is assumed to over-
219 estimate fishing mortality when selectivity is length-dependent. Thus, in this study, we considered an
220 extension of this method, proposed by Hordyk et al. (2016), consisting of a length-structured version
221 of the LBSPR method that uses growth-type-groups (GTG) to account for length-based selectivity
222 (known as the GTG-LBSPR method).

223 The LBSPR method uses length composition data to estimate the spawning potential ratio (SPR) by
224 developing a computationally efficient length-per-recruit-structured model that splits the stock into
225 diverse sub-cohorts, or growth-type-groups, to account for length-dependent fish mortality rates.
226 Furthermore, this method can estimate both F/M and selectivity parameters (assuming logistic
227 selection).

228 The LBSPR method requires the following parameters: the M/k ratio, L_{∞} and knowledge of
229 maturity-at-size (L_{50} and L_{95} , length at 50% and 95% maturity, respectively). Furthermore, it applies
230 data on the length composition of the catch to estimate the SPR. Of note is that SPR estimates
231 ranging between 0.35-0.4 are generally associated with a stock at MSY level (Legault and Brooks,
232 2013), whereas SPR estimates ranging below 0.1-0.15 indicate that the stock is close to collapse
233 (such limits have been fixed on the basis of Goodyear, 1993, who pointed out that the risk of collapse
234 increases considerably for SPR values below 0.2). The LBSPR method assumes that length
235 composition data is representative of the exploited stock in a steady state, the selectivity curve is

236 logistic, and the method is equilibrium based (as with the LBI method). LBSPR also assumes that an
237 overall fishing mortality rate is the cause of the resultant length composition and, thus, assumes that
238 length composition data either come from the dominant fleet or that multiple fleets are combined into
239 one catch-weighted aggregate length composition.

240 **2.4. Sensitivity analysis**

241 To carry out the sensitivity analysis for this study, we first applied the LBI and LBSPR methods
242 using M/k and L_{∞} values defined after analyzing previous literature and other reliable information on
243 the stock/species (Table 1). In this study we refer to such values as M/k^{LIT} and L_{∞}^{LIT} and refer to the
244 corresponding setting as the reference setting. Hence, to analyze the underestimation and
245 overestimation effects of these parameters on the model outputs, we reapplied the LBI and LBSPR
246 methods using either a lower or upper bound of one of the two parameters instead of the M/k^{LIT} or
247 L_{∞}^{LIT} reference values. The different settings are summarized in Table 3.

248 The upper and lower bounds of the M/k^{LIT} and L_{∞}^{LIT} parameters in Table 3 were fixed following the
249 ideas put forth in a simulation study carried out by Hordyk et al. (2015b). In addition, $M/k=1.5$ was
250 considered following Jensen (1996), who suggested that such a value could be close to the optimal
251 value.

252 After applying each method with each of the parameter configurations/settings described in Table 3,
253 the results of the methods in settings 2-6 were compared with the results provided by the methods in
254 the reference setting to analyze the effect of either underestimation or overestimation of the M/k or
255 L_{∞} parameters. The metrics used to compare the methods in settings 2-6 are described below. The
256 first metric was defined for the LBI method. The reference model reports a certain stock status based

on each indicator series. Thus, given the change in the life history parameter (i.e., sensitivity analysis), any change in the stock status time series of an indicator is given as a percentage. More precisely, stock status time series are compared for each year and the number of years that a change is detected is divided by the total number of years in the time series to provide a percentage. Colors are used to distinguish between whether the status has changed to worse or better than the one derived from the reference model. Green percentages indicate that the status has changed to worse than the reference model, whereas red percentages indicate that it has improved. Henceforth, this metric is called the prediction percentage.

In addition to analyze the percentage of years that the reference stock status indicator changes, it is also necessary to know how much each indicator has changed in each setting in relation to the reference one. This change is the magnitude of the change regardless of whether the change leads to a change in the stock status or not. Therefore, for both methods, LBI and LBSPR, a second metric, i.e., the annual average of change ratio, is defined as the mean of the annual ratios of the indicator values in the corresponding setting (from 2 to 5; Table 3) over the indicator values in the reference. More precisely, if the time series of any given indicator in the reference setting is I_y^R , with y representing the year, $y = year1, \dots, yearL$, being $year1$ the first year for which the length distribution is available and $yearL$ the last year for which such information is provided, and the time series of the same indicator in any of the sensitivity analysis settings is I_y^S , then, the corresponding annual average of change ratio is equal to

$$\frac{\sum_{y=year1}^{yearL} \frac{I_y^S}{I_y^R}}{L}$$

with L representing the total number of years.

An analogous analysis of the one described above for M/k and L_∞ settings has been also carried out on the L_{50} parameter.

The methods were implemented using R software (R Core Team, 2019). The LBI method was computed using the *utilities.R* code available at *ICES Tools (development area)* Github (https://raw.githubusercontent.com/ices-tools-dev/LBIndicator_shiny/master/utilities.R). This code is a modification of the code used by ICES (2015). The LBSPR method, in turn, was adjusted using the LBSPR R package of Hordyk (2019). The code used in our study can be found at <https://github.com/IMPRESSPROJECT/Applying-length-based-methods-to-fisheries-resources-of-the-Bay-of-Biscay-and-Iberian-Coast.git>.

289

3. Results

3.1. LBI and LBSPR methods to assess stock status

Stock statuses were assessed from the results of the LBI and LBSPR methods in the reference parameter configurations. The corresponding LBI traffic light indicator tables can be found in the supplementary material, whereas Table 4 reports the outputs for the last year of each stock. Figures 1 and 2 report the results of the LBSPR method (SPR and F/M estimates and their smoother lines from Kalman filter and the Rauch-Tung-Striebel smoother; Rauch et al. 1965). LBSPR estimates are shown as a time series for each parameter configuration to simplify the reporting of results, however it is worth keeping in mind that the LBSPR method treats each year individually and under equilibrium conditions, so there are no links among estimates from different years.

The LBI model outputs suggest that for *N. norvegicus* FU 25 stock is not exploited at the MSY level, however it does come close in the last years with the optimal yield attained in the last years.

302 Furthermore, there is a lack of conservation status of large individuals. However, immature
 303 individuals would be correctly preserved. The LBSPR results suggest that the *N. norvegicus* FU 25
 304 stocks are below MSY levels, yet above collapse.

305 With respect to the *N. norvegicus* FU 26-27, although some LBI indicators reflected poor stock
 306 status at the beginning of the time series, it was shown to reach a healthy stock status. The LBSPR
 307 results also highlighted a healthy stock status (stock at the MSY level).

308 LBI findings highlighted that *S. canicula* stock is exploited close to MSY, optimal yield is obtained
 309 and the conservation status of large individuals is adequate. However, there is incorrect preservation
 310 of immature individuals for this stock. By contrast, LBSPR results suggested that *S. canicula* stock is
 311 not exploited at the MSY level and is close to collapse. Therefore, the conclusions of both
 312 assessments do not concur. It should be noted that the indicators for each method are not equivalent,
 313 e.g., an SPR greater than 40% does not mean the same as a $L_{\text{mean}}/L_{\text{opt}} \approx 1$ in terms of stock status.

314 LBI results showed that over the last years the *E. encrasicolus* stock was exploited at close to the
 315 MSY level and attained optimal yield. For this stock, immature individuals seem to be well
 316 preserved, unlike large individuals given that the proportion of mega-spawners is very low. The
 317 LBSPR results suggested that the stock is below the MSY level but above collapse.

318 As for the other stocks, *P. pollachius* was found to be exploited at the MSY level in the last years,
 319 the optimal yield came close to being attained in the last year, but the conservation of immature
 320 individuals and large individuals were both found to be below the reference points. LBSPR results
 321 suggested that stock is below the MSY level but above collapse.

322 Male *P. bogaraveo* are relatively well preserved, unlike the large proportion of mostly female
 323 individuals, given that the proportion of mega-spawners is very low. The stock is close to being
 324 exploited at the MSY level and optimal yield is close to being attained, but neither levels were

reached. LBSPR results suggested that the stock is below the MSY level but above collapse.

Finally, *T. luscus* was found to not be exploited at the MSY level. Furthermore, for this species the optimal yield was not attained and the conservation status of large individuals was found to be deficient. However, immature individuals were found to be correctly preserved. The LBSPR method suggested that the stock is not exploited at the MSY level and is close to collapse.

In addition to above results, LBSPR estimates of the selectivity parameters (assuming logistic selection) are reported in Figures 3 and 4 of the supplementary material. These figures show that for *T. luscus* and *P. pollachius*, there are limited changes in the selectivity estimates, which is the expected behaviour considering that fishing fleet selectivity has not evolved throughout the years. For *N. norvegicus* and *P. bogaraveo* the selectivity estimates values have increased throughout the years, whereas for *S. canicula* the selectivity estimates values have decreased throughout the years. However, that said, knowledge of the fleet selectivity leads us to assume that it is, in fact, constant.

Finally, for *E. encrasicolus* the estimates of the length at 50% selectivity are according to the change in the selectivity patterns of the fleet related to a minimum size regulation, however this change is not well represented by the length estimates at 95% selectivity.

Additionally, Table 5 summarizes the LBI and LBSPR results and provides previous knowledge information on stock status, thus enabling a verification of whether or not it matches the LBI and/or the LBSPR assessments. In summary, the LBI assessment is more or less in accordance with previous knowledge on *S. canicula*, *P. bogaraveo* and *T. luscus*, whereas the LBSPR assessment is approximately in accordance with previous knowledge on *P. bogaraveo*. Section 4 discusses the above summary in detail and the possible reasons for divergences between previous knowledge and LBI and LBSPR results.

3.2. Sensitivity analysis results: LBI and LBSPR

Results from the sensitivity analysis of the LBI approach on the basis of the metric [prediction percentage](#) (definition in Subsection 2.4) are summarized in Table 6 for *Nephrops*, *S. canicula*, and *E. encrasicolus* stocks, and in Table 7 for the remaining stocks. Each row reports the information on one of the 7 stocks addressed in the present study.

Based on the LBI indicators definition (Table 2), we can assert that, among all the indicators, the underestimation/overestimation of M/k can only affect indicators related to the optimal yield, MSY, and conservation of the properties of large individuals. Whereas overestimation and underestimation of L_{∞} can affect the $L_{\text{mean}}/L_{\text{opt}}$, $L_{\text{mean}}/L_{F=M}$, P_{mega} and $L_{\text{max}5\%}/L_{\infty}$ indicators. Note that indicators of the conservation of immatures are not affected by L_{∞} or M/k variation.

Tables 6 and 7 show that overestimation of M/k and underestimation of L_{∞} lead to more optimistic perceptions of stock statuses, and vice versa. Although misspecification of both parameters (M/k and L_{∞}) has an impact on the results in the LBI method, the effect is more significant in the case of the L_{∞} parameter. Thus, it can be concluded that this parameter is crucial to obtain an accurate assessment. In fact, for all stocks, the higher [prediction percentage](#) metric values were found be either overestimate or underestimate L_{∞} . Moreover, Tables 6 and 7 show that L_{∞} variation affects various indicators, i.e., for all stocks the greater number of affected length indicators were found to either underestimate or overestimate L_{∞} . Note that *T. luscus* was the only stock that did not change from the perception of the stock status when the different M/k were applied in the LBI method.

Additional conclusions can be derived if we focus on the values of the annual average of change ratios metric, defined on Subsection 2.4, and reported in Figure 3 for the LBI method. Among the

368 LBI indicators, P_{mega} was found to be the least robust indicator of the variation/misspecification of
 369 L_{∞} and M/k , whereas the most robust indicator was found to be $L_{\text{mean}}/L_{F=M}$. Note that the most robust
 370 indicator relates to the MSY property, whereas the least robust indicator corresponds to the
 371 conservation of large individuals, more precisely, to the proportion of mega-spawners.
 372 Results of the sensitivity analysis performed for the LBSPR method are summarized in Figures 1 and
 373 2 and show the SPR and F/M estimates and their smoother lines for the alternative
 374 configurations/settings (Table 3). These results indicate that either overestimation of M/k or
 375 underestimation of L_{∞} leads to more optimistic perceptions of stock statuses, and vice versa, and that
 376 the L_{∞} parameter is crucial to achieving accurate assessments given that it has a more significant
 377 effect on results. This conclusion is also supported by the annual average of change ratio values,
 378 which are also greater under L_{∞} variation than under M/k variation in both methods (Figures 3 and
 379 4).
 380 The annual average of change ratios, Figure 4 for the LBSPR method, suggest that among the
 381 LBSPR indicators, the variation/misspecification of M/k affects F/M and SPR similarly, whereas
 382 under L_{∞} variation SPR is more affected than F/M.
 383 By comparing the behaviour of the LBI and LBSPR indicators under M/k misspecification/variation
 384 with a focus on the values of the annual average of change ratio, we can derive conclusions on which
 385 method, either LBI or LBSPR, is best given uncertainty in M/k or L_{∞} . The indicator most affected by
 386 M/k variation is P_{mega} , followed by F/M and SPR, the latter of which perform similarly. By contrast,
 387 the indicator that is most affected by L_{∞} variation is also the P_{mega} indicator, followed by SPR and

388 F/M, thus, in this case the range of the annual average change ratio is clearly larger for SPR than
 389 F/M. Hence, we can conclude that the less robust indicator corresponds to the LBI method (P_{mega}
 390 indicator), yet that the remaining LBI method indicators are more robust than the LBSPR indicators
 391 when there is uncertainty in the life history input parameters (M/k and L_{∞}). However, it is important
 392 to consider that LBI indicators are very rough measures of stock statuses, whereas LBSPR measures
 393 describe stock statuses more explicitly. Thus, both LBI indicators (with the exception of P_{mega}) and
 394 LBSPR measures can be used together to obtain better precision of stock statuses. However, when
 395 the results of both methods contradict one another and the values of the life history input parameters
 396 are uncertain, although both sets of model assumptions are fulfilled the LBI method indicators (with
 397 the exception of P_{mega}) are more reliable than LBSPR indicators, especially when L_{∞} is uncertain.
 398 Nevertheless, when it comes to stock status, they are less specific. [Note that the reference points of](#)
 399 [LBI indicators depend on Froese \(2004\) selectivity assumptions whereas LBSPR, as long as logistic](#)
 400 [selectivity is correct, estimates selectivity and assures the interpretation matches the selectivity.](#)
 401 It is worth mentioning that SPR and P_{mega} values are restricted to 0 and 1, thus, if values are close to
 402 the extremes in the reference setting, slight changes in the values are possible when the method is
 403 applied to settings from 2 to 6 (Table 3). For example, if SPR is close to 0 in the reference setting,
 404 the values in settings 2 and 5 can only decrease to a minimum of 0. Thus, the reported change in the
 405 indicator will be small due to this lower bound, and not due to its performance. Despite this, it is
 406 possible to observe that the values of change in P_{mega} and SPR are higher than in other non-bounded
 407 indicators, such as $L_{\text{mean}}/L_{\text{opt}}$ and $L_{\text{mean}}/L_{F=M}$. This may be due to the fact that in our study P_{mega} is
 408 only 0 for *T. luscus* (in 13 years of the time series) and *N. norvegicus* FU 25 (for 2 years of the time
 409 series), and SPR is only 1 for two years in the *N. norvegicus* FU 26-27 time series. On the other

hand, it should be noted that small absolute changes in low values (values below approximately 0.5) can seem less relevant even though they lead to high ratio of change values. The absolute difference between both indicator values seem minor, but it is necessary to consider the magnitude of the reference indicator value given that, for example, a change from 0.01 to 0.03 does not have the same importance as a change from 1.01 to 1.03. This is the reason why larger annual average of change ratio values are observed for P_{mega} and SPR when the absolute difference between both values of the indicator appear to not be so distant from each other.

In addition, the results of an analogous sensitivity analysis of L_{50} parameter is reported on the supplementary material (Figures 5 and 6). Underestimation/overestimation of L_{50} parameter affects L_c/L_{50} and $L_{25\%}/L_{50}$ LBI indicators and SPR estimates (no effect over F/M estimates). The magnitude of the change on L_c/L_{50} and $L_{25\%}/L_{50}$ is similar to that observed in the L_{∞} scenario for indicators $L_{\text{mean}}/L_{\text{opt}}$ and $L_{\text{max}5\%}/L_{\infty}$. The effect of overestimation/underestimation of L_{50} over the SPR estimates is similar to the overestimation/underestimation effect of M/k and then less crucial than the L_{∞} variability.

Finally, the sensitivity of model outputs was found to vary among species. However, this variation cannot be explained by species life history traits, such as the L_{∞} (Figures 1 and 2 in the supplementary material).

4. Discussion

This is the first practical application of data-limited methods to various relevant commercial stocks in the Bay of Biscay and the Iberian Coast ecoregion waters. Results from the LBI and LBSPR

431 methods lead to the stock status perceptions described in Table 5. As previously mentioned, it is
432 important to compare whether these results are aligned with currently available knowledge on the
433 state of these stocks and with the compliance of model assumptions in each case. Table 5 also
434 summarizes this information, which is discussed in detail below.

435 Admittedly, unrealistic results may be related to, for example, non-representative length
436 compositions of the stock or violation of the theoretical assumptions of the model (constant mortality
437 and recruitment or logistic selectivity). Indeed, results from the simulations in Hordyk et al. (2015b)
438 showed that high recruitment variability is likely to cause considerable variation in estimates with the
439 LBSPR method. Hordyk et al. (2015b) also studied the effects violating the logistic selectivity
440 assumption and concluded that the model overestimates F/M and underestimates SPR when applied
441 to data from fisheries with dome-shaped selectivity. On the other hand, the expectation that $P_{\text{mega}} > 0.3$
442 (LBI method) assumes asymptotic selection. However, if the selection is dome-shaped, the true
443 proportion of mega spawners in the population is unknown.

444 With respect to *N. norvegicus* from FU 25, the LBI and LBSPR results are not consistent with
445 current knowledge on the stock, which is that catches have decreased by 98% and stock areas have
446 decreased by 63% throughout the time series and that total allowable catch (TAC) has been zero in
447 the FU since 2017 (ICES, in press; ICES, 2020c). The results of both methods lead to a more
448 optimistic stock status than true stock status, according to previous knowledge. For 2019, the LBI
449 method showed a fishery with low impact on immature individuals and attained optimum yield. This
450 is due to a lack of recruitment that increases the L_c vs. L_{50} and the L_{mean} vs. L_{opt} . The LBSPR method
451 shows increasing SPR estimates throughout the time series, which are proportional to decreases in
452 recruitment.

453 With respect to *N. norvegicus* FU 26-27, the healthy stock status derived from the LBI and LBSPR

models were not consistent with current perceptions of the status of this stock, given that ICES have advised zero catch for 2020, 2021 and 2022 based on the extremely low biomass of this stock (ICES, 2019). The abundance index from the bottom trawl survey has been decreasing since the 1990s and spatial analyses show a considerable reduction in the *N. norvegicus* distribution area in relation to their historical distribution (Vila et al., 2020).

The above disagreements between both sources of information can be attributed to the following reasons. With respect to *Nephrops*, life history parameters (M/k , L_{∞} , L_{50} , L_{95}) are highly uncertain. For example, in the case of FU 25, the L_{∞} was obtained with the maximum lengths observed in the length composition time series but previous knowledge of FU and others suggests that L_{∞} is clearly underestimated, whereas, for *N. norvegicus* in FU 26-27, biological parameters were estimated in the 1980s and they have not yet been updated. An additional limitation to these methods is that they do not take into account the spatial component that is clearly relevant in the case of *Nephrops*, which inhabits burrows and has a displacement capacity that is limited to 100 meters. Furthermore, fishing intensity has constrained the distribution area, which is now limited to a few spots where the length distribution provides a healthier view. Finally, the model assumptions (constant recruitment and total mortality) are not met for *Nephrops*.

Table 5 shows that for *S. canicula* different results were obtained from the two applied methods. LBSPR results are not consistent with previous knowledge of the stock status, whereas LBI results are consistent with previous knowledge, with the exception of the indicators of conservation of immature individuals, which are below the reference points. This exception may be related to the fact that the otter trawl fleet catches represent almost the whole stock length distribution yet most of the fish are discarded, particularly individuals smaller than 45 cm. Thus juvenile specimens are not well

476 represented. Finally, P_{mega} estimates may be affected by the fact that growth rates decrease as sexual
477 maturity is attained. This fact, although it can also be presented in other species, is especially
478 important in the elasmobranchs which have more complex reproduction procedures (oviparous,
479 ovoviviparous, viviparous), and even in the oviparous, such as *S. canicula*, as they have to produce
480 ovigerous capsules, which is an extra energy expenditure, see Araya & Cubillos (2006).

481 With respect to *E. encrasicolus*, the results of LBI and LBSPR are not consistent with previous
482 knowledge of the stock status (Table 5) and the possible reasons for this are explained below. The
483 low P_{mega} value may be related to the differences between catch and stock length distribution. In fact,
484 if we consider the most reliable estimates of stock distribution to be those estimated by the surveys
485 (corresponding to a particular quarter), then they differ from the catch distribution used in our model,
486 mainly because these length-based methods are not effective with a time step shorter than years and,
487 thus, quarterly distributions needed to be transformed into yearly distributions to be included in the
488 model. This transformation greatly increased the variability of catch length distributions. In addition,
489 most of the indicator thresholds were based on life history parameters that need to be updated. The
490 database used to calculate these indicator thresholds was based on data from before 2000 (Millán et
491 al., 1999, Bellido et al., 2000) and, therefore, did not consider the latest fluctuations in stock
492 dynamics. In addition, these outdated life history parameters did not consider a change in the
493 selectivity patterns of the fleet, including minimum size regulations that were effectively
494 implemented after 2001 (Rincón et al. 2019). The length estimates conducted at 50% selectivity
495 reproduce this change, however the length estimates at 95% selectivity do not (Figure 3 in the
496 supplementary material), the latter of which show a maximum around 2001 but then return to similar
497 levels to those at the beginning of the time series. For this to be consistent with the real selectivity,
498 these two periods should have different and marked estimates.

499 Results for *P. bogaraveo* derived from the LBI and LBSPR methods are consistent with current
500 stock status perceptions. Note that the reference biological parameters came from the Strait of
501 Gibraltar samplings and should be considered appropriate for this kind of exercise.

502 In the case of *T. luscus* the results derived from LBI are more or less consistent with previous
503 knowledge, whereas result from the LBSPR are not consistent with previous knowledge. Although
504 previous studies have indicated a negative trend in abundance indices for this species in southern
505 Galician small-scale fisheries (Alonso-Fernández et al., 2019), the high F/M ratio estimated by
506 LBSPR does not seem realistic, particularly taking into account the relatively stable pattern found on
507 the northern Galician coast, ICES Division 8c (Alonso-Fernández et al., 2021). In addition, SSF
508 (small-scale fishery) gears commonly used by this fleet, such as gillnets and trammel nets, tend to be
509 characterized by dome-shaped selectivity curves, which do not meet LBI and LBSPR assumptions
510 and actually affect SPR (underestimate) and F/M (overestimate) estimates (Hordyk et al. 2015b).
511 Moreover, dome-shaped selectivity usually has a lower impact on mean size trends than logistic
512 selectivity curves do (e.g., trawling in industrial fisheries) (Erzini et al., 2006), and this hampers the
513 detection of changes in stock statuses throughout the time series.

514 For *P. pollachius*, no assessment method had previously been applied to this stock, so it is not
515 possible to compare the results obtained using length-based methods from an official assessment.
516 Results must be interpreted with caution since the length distribution comes from different fleets
517 with different selectivity curves, even some dome-shaped ones. This fact implies that the mega-
518 spawners may not be fully caught and P_{mega} may be underestimated. Furthermore, dome-shaped
519 selectivity would lead to an underestimate of the SPR, as mentioned above in the discussion on *T.*
520 *luscus*.

521 The logistic selectivity assumption is usually violated in highly size-selective fisheries (for example

522 in *T. luscus* fisheries), and it could be problematic in multifleet fisheries, where stocks are caught in
523 different proportions by multiple gears with different selectivity patterns (for example in *P.*
524 *pollachius* fisheries). Pons et al. (2019) provide practical advice on how to combine the length
525 composition of a catch from different fleets with different selectivity patterns before applying the
526 LBSPR method. Their recommendation is that when there are multiple fleets with different
527 selectivity patterns targeting a single stock, the length-based models should be applied to the length
528 data from the fleets that target the broadest range of sizes, including juveniles and adults, when these
529 data are available.

530 Knowledge of the selectivity pattern is also required to correctly interpret LBI results. Cope and Punt
531 (2009) concluded that P_{mega} showed a wide range of possible values depending on fishery selectivity.
532 Their results challenge the notion that P_{mega} values between 0.3 and 0.4 indicate healthy stocks. They
533 illustrated that this assumption can encourage overfishing in certain circumstances (Froese, 2004).
534 Furthermore, our current study has shown that, P_{mega} should not be used because it either provides no
535 information or misleading conclusions.

536 Given these conclusions, Cope and Punt (2009) proposed a new measure to distinguish selectivity
537 patterns and construct a decision tree to develop stock status indicators, defined as the sum of the
538 three simple metrics: P_{mat} (which reflects exclusive take of mature individuals), P_{opt} (which consists
539 primarily of optimal size fish), and P_{mega} . Thus, a potential future direction for our analysis to take is
540 to apply Cope and Punt's (2009) approach to analyze the performance of their method for the stocks
541 we analyzed in this study and compare the results with those provided by the classic LBI approach.
542 This study illustrates the sensitivity of the LBI and LBSPR methods to the uncertainty of the life
543 history input parameters. Our sensitivity analysis was performed to examine the effects of the
544 misspecification/variation of two crucial parameters, M/k and L_{∞} , for almost all the Spanish stocks

545 assessed in the ICES Division covering different taxonomic groups and types of fisheries. Effects of
546 the misspecification/variation of M/k and L_{∞} must be considered when drawing conclusions on the
547 state of the stocks to prevent further failures in current management. Through our study, we conclude
548 that the influence of life history variation input parameters is very important in both methods. More
549 precisely, we conclude that diverging management decisions can be obtained when the crucial
550 parameter L_{∞} is either underestimated or overestimated (see Subsection 3.2 for the details leading to
551 this conclusion). In line with Shephard et al. (2018) we conclude that an unrealistically high L_{∞} may
552 lead to false negatives (a poor status result when the true state is good), whereas a low L_{∞} may lead
553 to false positives (a good status result when the true status is poor). Best practices to determine fixed
554 values for life history parameters in stock assessments would be to use estimates from stock-specific
555 studies (Rudd et al., 2019). However, when these studies are not available, our practical
556 recommendation is to carry out a sensitivity analysis on these parameters.

557 In our sensitivity analysis, we also compared the reference model results with the results obtained
558 using $M/k=1.5$ (suggestion from Jensen, 1996) of the Beverton–Holt life history invariant, BH-LHI.
559 Our results indicate that conclusions derived from the reference model can differ from those derived
560 from an $M/k=1.5$ based model. Although it is common to assume that this ratio does not vary, studies
561 have shown that this does not hold. For example, a study in the Kyphosid (*Scorpsiaequipinnis*), in
562 southwestern Australia, showed the M/k value for this species to be 0.33, which is very far from the
563 BH-LHI of 1.5 (Coulson et al., 2012). On the other hand, Prince et al. (2015) argued that a lack of
564 variation of $M/k=1.5$ is more commonly associated with marine mammals. Furthermore, Prince et al.
565 (2015) performed a meta-analysis of 123 marine species (teleosts, chondrichthyes, invertebrates and

566 marine mammals) and found that the M/k ratio ranged from 0.12 to 3.52, thus indicating that life
567 history ratios often vary considerably from the BH-LHI. Despite this, it should be noted that M/k is
568 less variable than L_{∞} , which is not always easy to estimate, especially for data limited species
569 (Charnov, 1993).

570 In our contribution, we applied the LBI and LBSPR methods to assess stocks in the Bay of Biscay
571 and the Iberian Coast ecoregion waters. Application of both methods increased our knowledge of
572 their performance, as we compared the results of both methods with previous knowledge. For some
573 stocks this comparison indicated the need to further study the reasons why these methods do not
574 provide realistic conclusions, i.e., the need to reviewed model assumptions, accuracy of input data,
575 etc. On the other hand, among our previously reported conclusions, our sensitivity analysis revealed
576 that L_{∞} is a crucial parameter and that the accuracy of its value is indispensable to obtain reliable
577 results from the methods, thus providing a practical recommendation (see Subsection 3.2 for the
578 details that lead to this conclusion). The sensitivity analysis also shows that L_{50} parameter is crucial
579 for a reliable conclusion over the immature individuals using LBI method, and equally important as
580 M/k for SPR estimates (no effect of the L_{50} variability is found over F/M). Furthermore, aligned with
581 conclusions previously derived in prior studies, we concluded that among the LBI and LBSPR
582 indicators the LBI method P_{mega} indicator was the least robust. However, the remaining LBI method
583 indicators were found to be more robust than the LBSPR indicators when uncertainty exists in the
584 life history input parameters (M/k , L_{50} and L_{∞}). Nevertheless, it is important to consider that LBI
585 indicators are very rough measures of stock statuses, whereas LBSPR measures describe stock
586 statuses based on a contrasted indicator, such as the Spawning Potential Ratio (SPR). Thus, both LBI
587 indicators (except P_{mega}) and LBSPR measures can be used together to obtain more precise stock

status estimates. Yet, if the results from both methods contradict one another and the life history input parameter values are known to be uncertain, and both sets of model assumptions are fulfilled, the LBI method indicators (except for P_{mega}) are more reliable than the LBSPR indicators under uncertain conditions, especially if L_{∞} is uncertain. When it comes to stock status, LBI indicators are less specific. Note that LBI indicators have the advantage of being able to be considered individually, i.e. a biased input parameter does not affect all indicators, unlike in LBSPR. On the other hand, when using the LBI method it is important to keep in mind that, as per our study, the most robust indicator corresponds to the MSY property. Among the LBSPR indicators, SPR was found to be more affected than F/M by the variation/misspecification of parameter L_{∞} , whereas under the variation of M/k both indicators performed quite similarly. Finally, it is important to note that neither the LBI method, nor the LBSPR method are not recommended for short-living species given that they cannot be applied with a shorter time step than years, for example, quarters (see the case of *E. encrasicolus* for more details). Furthermore, recruitment in short-living species represents a high proportion of the stock, hence high recruitment variability in short-living species affects the length composition more than in medium or long-term living species. Therefore, equilibrium based methods (LBI and LBSPR) are not recommended for short-living species.

605

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Tables

Table 1: Life history parameter values (M/k , L_{∞} , L_{50} and L_{95}) for each stock and the corresponding source of information. Stock codes, ICES divisions, and the time series of the length frequency distribution used for each stock are also reported. For *N. norvegicus* FUs 25 and 26-27 stocks, only females were considered. CL: Carapace length.

* $L_{95} = 1.15 \times L_{50}$ ** Strait of Gibraltar target fishery data *** Sexual change (males to females) length

Stocks	ICES Div.	Stock code	L_{∞}^{LIT}	M/k^{LIT}	$L_{50}; L_{95}$	Source	Length frequency distribution
<i>N. norvegicus</i>	8c	FU25	71 mm CL	1.9	28; 32.2* mm CL	Prince et al. (2015), Fariña (1984,1996)	1982-2019

<i>N. norvegicus</i>	9a	FU2627	65 mm CL	2.5	26; 29.9 mm CL	Fariña (1984)	1988-2019
<i>S. canicula</i>	8c 9a	syc.27.8c9a	75 cm	1.5	54.2; 58 cm	Rodriguez-Cabello et al.(1998) Rodriguez-Cabello (2008)	2014-2019
<i>E. encrasicolus</i>	9a	ane.27.9a	18.95 cm	1.44	11.2; 13.3 cm	Millán (1999), Bellido et al. (2000) ICES (2020a)	1988-2019
<i>P. bogaraveo</i>	9**	sbr.27.9	62 cm	1.42	33; 35 cm***	CopeMed II (2019)	1997-2019
<i>T. luscus</i>	8c 9a	-	46.7 cm	1.76	19.2; 21.43 cm	Labarta et al., (1982a, 1982b); Alonso-Fernández et al., (2008)	1999-2018
<i>P. pollachius</i>	8abd 9a	pol.27.89a	98.2 cm	1.65	42.3; 59 cm	Aleman, (2017); Alonso-Fernández et al., (2013); Léauté et al., (2017)	2010-2018

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866 Table 2: Set of length-based indicators, their references, the corresponding indicator ratios, and their
867 expected values grouped in terms of conservation/sustainability, optimal yield and MSY
868 considerations.

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Indicator	Calculation	Reference point	Indicator ratio	Expected value	Property
$L_{\max 5\%}$	Mean length of largest 5%	L_{∞}	$L_{\max 5\%}/L_{\infty}$	>0.8	Conservation (large individuals); CL
P_{mega}	Proportion of individuals above L_{opt} +	0.3-0.4	P_{mega}	>0.3	Conservation (large individuals);

	10%				CL
$L_{25\%}$	25th percentile of length distribution	L_{50}	$L_{25\%}/L_{50}$	>1	Conservation (immatures); CI
L_c	Length at first catch (length at 50% of mode)	L_{50}	L_c/L_{50}	>1	Conservation (immatures); CI
L_{mean}	Mean length of individuals $> L_c$	$L_{opt}=3L_{\infty}/(3+(M/k))$	L_{mean}/L_{opt}	≈ 1	Optimal yield; OY
L_{mean}	Mean length of individuals $> L_c$	$L_{F=M}=(1-a)L_c+aL_{\infty}$ $a=1/(2(M/k)+1)$	$L_{mean}/L_{F=M}$	≥ 1	MSY

Table 3: Description of the 6 different parameter configurations considered to assess the robustness/sensitivity of LBI and LBSPR methods to estimate the variation/misspecification of parameters M/k and L_{∞} .

Setting	L_{∞} value	M/k value
1: Reference setting	L_{∞}^{LIT}	M/k^{LIT}
2: Underestimated M/k	L_{∞}^{LIT}	$0.75 \cdot M/k^{LIT}$
3: Overestimated M/k	L_{∞}^{LIT}	$1.25 \cdot M/k^{LIT}$
4: Underestimated L_{∞}	$0.75 \cdot L_{\infty}^{LIT}$	M/k^{LIT}
5: Overestimated L_{∞}	$1.25 \cdot L_{\infty}^{LIT}$	M/k^{LIT}

6: M/k=1.5	L_{∞}^{LIT}	1.5
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Table 4: Traffic light indicator table for the last year of each stock. For *N. norvegicus* FUs 25 and 26-27 stocks, only females were considered.

		Conservation				Optimizing Yield	MSY
Stocks	Year	L_c/L_{50}	$L_{25\%}/L_{50}$	$L_{max5\%}/L_{\infty}$	P_{mega}	L_{mean}/L_{opt}	$L_{mean}/L_{F=M}$
<i>N. norvegicus</i> FU25	2019	1.23	1.30	0.70	0.04	0.91	0.94
<i>N. norvegicus</i> FU2627	2019	1.19	1.42	0.88	0.71	1.20	1.16
<i>S. canicula</i>	2019	0.90	0.90	0.82	0.30	1.06	0.96
<i>E. encrasicolus</i>	2019	0.98	0.98	0.79	0.05	0.95	0.93
<i>P. bogaraveo</i>	2019	1.00	1.00	0.79	0.05	0.89	0.92
<i>T. luscus</i>	2018	1.02	1.07	0.63	0.00	0.78	0.89
<i>P. pollachius</i>	2018	0.80	0.99	0.82	0.11	0.86	1.12

Table 5: Summary of the LBI and LBSPR results and previous knowledge information on stock status. Furthermore, the limitations of the application of LBI and LBSPR methods in each stock are briefly explained, with a focus on model assumption compliance. For *N. norvegicus* FUs 25 and 26-27 stocks, only females were considered. CL: conservation of large individuals; OY: optimal yield; MSY: maximum sustainable yield, and CI: conservation of immature individuals. ✓ indicated that the indicator ratios of the corresponding property are above their expected values whereas ✗ indicates the opposite, ≈ indicates that the indicator ratios of the corresponding property are below, but very close to, their expected values. More precisely, MSY, OY and CI indicators close to their expected

907 values indicate a value strictly larger than 0.9, 0.8 and 0.9, respectively. MSY_{ABOVE} and MSY_{BELOW}
 908 indicate that the stock is above or below the MSY level, and $Collapse_{ABOVE}$ and $Collapse_{CLOSE}$
 909 indicate that the stock is either above collapse or close to it, respectively.

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Stocks	LBI stock status	LBSPR stock status	Previous knowledge of stock status	Limitations of LBI and LBSPR
<i>N. norvegicus</i> FU25	$MSY \approx$ OY ✓ CI ✓ CL ✗	MSY_{BELOW} $Collapse_{ABOVE}$	catch trend and TAC=0 (ICES, in press; ICES, 2020c).	- No constant total mortality or recruitment. - Life history parameters are uncertain. - Need a spatial component.
<i>N. norvegicus</i> FU2627	MSY ✓ OY ✓ CI ✓ CL ✓	MSY_{ABOVE} $Collapse_{ABOVE}$	catch trend and TAC=0 (ICES, 2019).	
<i>S. canicula</i>	$MSY \approx$ OY ✓ CI ✗ CL ✓	MSY_{BELOW} $Collapse_{CLOSE}$	biomass trend (ICES, 2020b).	Length composition data does not represent juvenile specimens.
<i>E. encrasicolus</i>	$MSY \approx$ OY ✓ CI $\approx$ CL ✗	MSY_{BELOW} $Collapse_{ABOVE}$	Good stock status in terms of conservation and exploitation (ICES, 2020a).	- Variability of catch length distribution. - Not updated life history parameters.
<i>P. bogaraveo</i>	$MSY \approx$ OY $\approx$ CI ✓ CL ✗	MSY_{BELOW} $Collapse_{ABOVE}$	Overexploitation status below MSY levels (ICES, 2020d and GFCM, in press).	
<i>T. luscus</i>	MSY ✗	MSY_{BELOW}	abundance indices	No logistic selectivity.

	OY ✗ CI ✓ CL ✗	Collapse _{CLOSE}	trend (Alonso-Fernández et al., 2019).	
<i>P. pollachius</i>	MSY ✓ OY ≈ CI ✗ CL ✗	MSY _{BELOW} Collapse _{ABOVE}	No previous knowledge.	No logistic selectivity.

Table 6: Summary of the results derived from the sensitivity analysis for the whole time series and carried out for the LBI method applied to *Nephrops*, *S. canicula*, and *E. encrasicolus* stocks. For *N. norvegicus* FUs 25 and 26-27 stocks, only females were considered. CL: conservation of large individuals; OY: optimal yield; MSY: maximum sustainable yield. Green:(Red:) lower (higher) estimated indicator value relative to reference scenario. Percentage in brackets indicates the percentage of years that there was a change.

Stock	$0.75 \cdot M/k^{LIT}$	$1.25 \cdot M/k^{LIT}$	$0.75 \cdot L_{\infty}^{LIT}$	$1.25 \cdot L_{\infty}^{LIT}$	$M/k=1.5$
<i>N. norvegicus</i> FU25	OY: L_{mean}/L_{opt} (32%) MSY: $L_{mean}/L_{F=M}$ (8%)	CL: P_{mega} (3%) OY: L_{mean}/L_{opt} (47%) MSY: $L_{mean}/L_{F=M}$ (21%)	CL: $L_{max5\%}/L_{\infty}$ (100%) P_{mega} (89%) OY: L_{mean}/L_{opt} (68%) MSY:	OY: L_{mean}/L_{opt} (32%) MSY: $L_{mean}/L_{F=M}$ (8%)	OY: L_{mean}/L_{opt} (32%) MSY: $L_{mean}/L_{F=M}$ (8%)

			$L_{\text{mean}}/L_{F=M}$ (84%)		
<i>N. norvegicus</i> FU2627	CL: P_{mega} (38%) OY: $L_{\text{mean}}/L_{\text{opt}}$ (19%) MSY: $L_{\text{mean}}/L_{F=M}$ (31%)	CL: P_{mega} (9%) OY: $L_{\text{mean}}/L_{\text{opt}}$ (9%) MSY: $L_{\text{mean}}/L_{F=M}$ (9%)	CL: $L_{\text{max}5\%}/L_{\infty}$ (47%) P_{mega} (38%) OY: $L_{\text{mean}}/L_{\text{opt}}$ (16%) MSY: $L_{\text{mean}}/L_{F=M}$ (12%)	CL: $L_{\text{max}5\%}/L_{\infty}$ (47%) P_{mega} (53%) OY: $L_{\text{mean}}/L_{\text{opt}}$ (53%) MSY: $L_{\text{mean}}/L_{F=M}$ (50%)	CL: P_{mega} (53%) OY: $L_{\text{mean}}/L_{\text{opt}}$ (44%) MSY: $L_{\text{mean}}/L_{F=M}$ (50%)
<i>S. canicula</i>	CL: P_{mega} (50%)	CL: P_{mega} (50%)	CL: P_{mega} (50%) MSY: $L_{\text{mean}}/L_{F=M}$ (100%)	CL: P_{mega} (50%) $L_{\text{max}5\%}/L_{\infty}$ (100%) OY: $L_{\text{mean}}/L_{\text{opt}}$ (100%)	
<i>E. encrasicolus</i>	OY: $L_{\text{mean}}/L_{\text{opt}}$ (56%) MSY: $L_{\text{mean}}/L_{F=M}$ (6%)	OY: $L_{\text{mean}}/L_{\text{opt}}$ (22%) MSY: $L_{\text{mean}}/L_{F=M}$ (19%)	CL: $L_{\text{max}5\%}/L_{\infty}$ (81%) P_{mega} (97%) OY: $L_{\text{mean}}/L_{\text{opt}}$ (31%) MSY: $L_{\text{mean}}/L_{F=M}$ (75%)	CL: $L_{\text{max}5\%}/L_{\infty}$ (19%) OY: $L_{\text{mean}}/L_{\text{opt}}$ (66%) MSY: $L_{\text{mean}}/L_{F=M}$ (6%)	MSY: $L_{\text{mean}}/L_{F=M}$ (3%)

Table 7: Summary of the results derived from the sensitivity analysis for the whole time series and carried out for the LBI method applied to *P. bogaraveo*, *T. luscus*, and *P. pollachius*. CL: conservation of large individuals; OY: optimal yield; MSY: maximum sustainable yield. Green:(Red:) lower (higher) estimated indicator value relative to reference scenario. Percentage in brackets indicates the percentage of years that there was a change.

Stock	$0.75 \cdot M/k^{\text{LIT}}$	$1.25 \cdot M/k^{\text{LIT}}$	$0.75 \cdot L_{\infty}^{\text{LIT}}$	$1.25 \cdot L_{\infty}^{\text{LIT}}$	$M/k=1.5$
<i>P. bogaraveo</i>	OY: $L_{\text{mean}}/L_{\text{opt}}$ (17%) MSY: $L_{\text{mean}}/L_{F=M}$ (4%)	OY: $L_{\text{mean}}/L_{\text{opt}}$ (78%) MSY: $L_{\text{mean}}/L_{F=M}$ (22%)	CL: $L_{\text{max}5\%}/L_{\infty}$ (22%) P_{mega} (100%) OY: $L_{\text{mean}}/L_{\text{opt}}$ (83%) MSY: $L_{\text{mean}}/L_{F=M}$ (91%)	CL: $L_{\text{max}5\%}/L_{\infty}$ (74%) OY: $L_{\text{mean}}/L_{\text{opt}}$ (17%) MSY: $L_{\text{mean}}/L_{F=M}$ (4%)	OY: $L_{\text{mean}}/L_{\text{opt}}$ (35%) MSY: $L_{\text{mean}}/L_{F=M}$ (4%)
<i>T. luscus</i>			CL: $L_{\text{max}5\%}/L_{\infty}$ (80%)		

			P_{mega} (5%) OY: $L_{\text{mean}}/L_{\text{opt}}$ (100%) MSY: $L_{\text{mean}}/L_{F=M}$ (40%)		
<i>P. pollachius</i>	OY: $L_{\text{mean}}/L_{\text{opt}}$ (22%) MSY: $L_{\text{mean}}/L_{F=M}$ (11%)	OY: $L_{\text{mean}}/L_{\text{opt}}$ (33%) MSY: $L_{\text{mean}}/L_{F=M}$ (33%)	CL: $L_{\text{max}5\%}/L_{\infty}$ (89%) P_{mega} (56%) MSY: $L_{\text{mean}}/L_{F=M}$ (56%) OY: $L_{\text{mean}}/L_{\text{opt}}$ (67%)	OY: $L_{\text{mean}}/L_{\text{opt}}$ (22%) MSY: $L_{\text{mean}}/L_{F=M}$ (22%) CL: $L_{\text{max}5\%}/L_{\infty}$ (11%)	OY: $L_{\text{mean}}/L_{\text{opt}}$ (11%)

Figures

Figure 1: SPR and F/M estimate plots and their smoother lines derived from the sensitivity analysis performed for the LBSPR method applied to *N. norvegicus* FU25 and FU2627, *S. canicula* and *E. encrasicolus*. In the SPR plot, horizontal dotted lines delimit the range in which the stock is considered at the MSY level, whereas horizontal dashed lines represent the levels below which the stock is considered to be collapsed. In the F/M plot, the horizontal dotted line corresponds to the reference value of 1. For *S. canicula*, the dark blue line and points ($M/k=1.5$ setting) is missing as it overlaps with the black line and points (reference) given that M/k^{LIT} is 1.5. An unexpected high F/M estimate (≈ 150) for *E. encrasicolus* was observed yet was not plotted since the remaining lines and dots are compacted. Note that for *N. norvegicus* the plots refer to carapace length in mm.

Figure 2: Plots of the SPR and F/M estimates and their smoother lines derived from the sensitivity analysis carried out for the LBSPR method applied to *P. bogaraveo*, *T. luscus*, and *P. pollachius*. In the SPR plot, horizontal dotted lines delimit the range where the stock is considered at the MSY level, whereas horizontal dashed lines show the levels below which the stock is considered to be collapsed. In the F/M plot, the horizontal dotted line corresponds to the reference value of 1.

Figure 3: For each stock LBI indicator and setting, the annual average of change ratios (termed output change), defined as the mean of the annual ratios of the indicator values for the corresponding setting (from 2 to 5; Table 3) over the values of the indicator in the reference setting, are plotted as a dot for each stock. Furthermore, the associated standard deviation is represented by a vertical line whose extremes are the mean plus or minus the standard deviation. The left panel shows the results of the sensitivity analysis of the M/k parameter (overestimation in green and underestimation in red), whereas the right panel shows the results of the sensitivity analysis of the L_∞ parameter (overestimation in magenta and underestimation in blue). Note that no change of indicator $L_{\max 5\%}/L_\infty$ is derived from variation of M/k and, hence, the green and red dots overlap and are equal to 1.

Figure 4: For each stock, LBSPR indicator, and setting, the annual average of change ratios (termed output change), which is defined as the mean of the annual ratios of the indicator values in the corresponding setting (from 2 to 5; Table 3) over the values of the indicator in the reference setting, are plotted as a dot for each stock. Furthermore, the associated standard deviation is represented by a vertical line whose extremes are the mean plus or minus the standard deviation. The left panel shows the results of the sensitivity analysis of the M/k parameter (overestimation in green and underestimation in red), whereas the right panel shows the results of the sensitivity analysis of the L_∞ parameter (overestimation in magenta and underestimation in blue).