Exploring the status of the Indonesian deep demersal fishery using length-based stock assessments

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Abstract

The deep demersal snapper-grouper fishery in Indonesia is a data-poor fisheries resource that provides food security and a source of income to millions globally. Owing to an ongoing crew-operated data recording system implemented in Indonesia since 2015, the stocks of this fishery can now be assessed using length-frequency data and updated life-history parameters. Here, we use two length-based methods, one that is fishery-specific and another that is more generalized, to assess the status of Indonesian stocks. Specifically, we develop a literature-based assessment method based on a patchwork of conventional approaches but tailored to the studied stocks, and compare it with a newly established and broadly applicable length-based Bayesian biomass estimation method (LBB). The methods were applied to 16 stocks from 4 Indonesian Fisheries Management Areas and were compared based on simulations, as well as the convergence of the resulting stock status classification and uncertainty of the results. Analyzing the effect of using the literature-based species/family-specific life-history parameter values for asymptotic length (L_{inf}) and relative natural mortality (M/K) in LBB showed that different values do affect the estimated biomass indicator. Nevertheless, in more than half the cases, the stock status classification did not differ between the two methods, while LBB results became more reliable with narrower confidence limits. Simulations, as well as similar status indicators between the two models support the value of the literature-based approach as an assessment methodology for the Indonesian deep demersal fisheries. Narrower confidence ranges highlight the importance of using fishery-specific information when applying generalized stock assessment methods. While most catches had few immature fish, half of the assessed stocks were consistently shown to have low biomass, indicating that important Indonesian stocks are at high risk of overfishing.

1. Introduction

The Indonesian multispecies deep demersal fishery is a highly productive yet data-poor fishery in the tropics that is characterized by highly diverse catch composition with hundreds of species being caught (Bailey et al. 1987). This species complex mainly consists of snappers (Lutjanidae) and groupers (Epinephelidae) which play a key role as predators in the ecosystem. The snappers and groupers are of high quality with global demand, which support the livelihoods and food security of numerous local, small-scale fishing communities (Cesar 1996). The multitude of species in such tropical fisheries, as well as the lack of historical or current species-specific catches and no information on fishing effort and baseline population abundances, make assessments quite challenging, often leaving them under-managed, as in this Indonesian case study (Stobutzki et al. 2006; Fenner 2012). The deep demersal snapper-grouper fishery is managed based on total allowable catches (TACs) per species, which limit the number of fishing licenses per fishery management area (FMA). However, the system faces considerable data and implementation challenges, hence the characterization of the fishery as under-managed (Wibisono et al. 2021).

The Generic Knowledge Indicator (GKI), that has been developed to evaluate the state of knowledge of snapper and grouper fisheries around the world, has shown that Indonesia presents a medium quality of biology/ecology information and fisheries data, while the knowledge level regarding stock assessments is very low (Amorim et al. 2018). A first step towards bridging this knowledge gap regarding Indonesian fisheries would be the regular collection of detailed data that can facilitate the application of stock assessment methods. To that end, a crew-operated data recording system (CODRS) has been developed and implemented by Yayasan Konservasi Alam Nusantara Indonesia for the past 6 years for extensive catch data collection (geo-referenced commercial catch data and length distributions for more than a hundred species of the snapper-grouper deep demersal fishery) that can support length-based stock assessments aiming to establish harvest control rules (Wibisono et al. 2019). Recording length-frequency (LF) data from commercial catches onboard, like in the CODRS, or at landing sites and markets is a cost-effective and straightforward methodology to attain the types of data required to estimate stock status, especially in data-poor fisheries (Pilling et al. 2008; Mildenberger et al. 2017). The CODRS datasets have so far been used to update life-history parameters of the top 50 species (Wibisono et al. 2019). Also, to identify factors that point towards particular locations and combinations of fishing gear and habitat characteristics linked to catches with immature fishes (Wibisono et al. 2021).

The majority of fish stocks, globally and locally, are data-poor and lack the comprehensive information required to assess biomass and fishing mortality relative to reference points (Costello et al. 2012; Osio et al. 2015). Thus, the need to assess the numerous data-poor stocks around the world has led to the development of various catch-based (Cope 2013; Froese et al. 2017), abundance-based (Froese et al. 2020), and length-based (Rudd & Thorson 2018) methods depending on the available datasets. In the case of Indonesia, the CODRS length data can be used in length-based models to assess the status of previously unassessed Indonesian stocks. The published analytical approaches aim to be simple and generically parameterized based on certain assumptions (e.g., Hordyk et al. 2015b; Ault et al. 2019). Nevertheless, the use of such generic assessment methods requires caution as their potential out-of-context blanket application may result in erroneous outputs and misinformed management advice (Dowling et al. 2019). Since each method has its own assumptions and limitations, local knowledge and expert guidance is required for the appropriate tailoring to individual stocks or fisheries based on the literature (Pilling et al. 2008; Carruthers et al. 2014).

Given that the different stock assessment models have varying data demands and levels of performance, they may produce alternative perspectives on reference points when applied to the same data (Bouch et al. 2020; Chong et al. 2020; Pons et al. 2020) and, as a result, a combination of methods to define a range of possible stock status estimates is encouraged for fisheries management (Chong et al. 2020). Regardless of whether the applied assessment methods are fishery-specific or more generalized, evaluating model performance can be challenging since the "true" stock status needs to be known (Cadrin & Dickey-Collas 2015), which is usually very rare for data-poor stocks (Froese et al. 2018a). In such cases, simulations show how well a method can reproduce known reference points. On simulated data, state-of-the-art models can correctly predict ~70% of mean lengths at infinite age and natural mortality relative to carrying capacity, within 95% confidence limits. Furthermore, they are over 90% accurate at predicting current stock biomass relative to unexploited stock biomass (Froese et al. 2018b). Relative biomass prediction can be accurate also on expert-assessed real-stock data (~76%). However, these models achieve lower performance at predicting other traits - e.g. fishing mortality relative to natural mortality (~50% accuracy) - also because of the larger discrepancy between expert estimations of these traits.

The present study provides species-specific assessments for 16 previously unassessed stocks of the Indonesian deep demersal snapper-grouper fishery using length-based life-history parameters in combination with catch length frequencies from the CODRS dataset. This particular fishery is used as the base to illustrate the implications of transitioning from generalized to fishery-specific assessment models. A highly customized length-based approach using literature studies that each highlight an aspect of the life-history of the studied fish populations is presented here. This fishery-specific method is then compared to a new more broadly applicable approach by Froese et al. (2018b) for estimating stock status using LF data from commercial catches: the length-based Bayesian biomass estimation method (LBB). In the case of LBB, a parameterization gradient and its effects on the model outcome are also examined, where we transition from running the model with the generalized default life-history settings (such as the asymptotic length L_{inf} and relative natural mortality M/K) to incorporating literature-based knowledge about the specific stocks analyzed. We ultimately aim to investigate whether these two approaches result in the same conclusions for management, and, if not, whether we can point to the most suitable approach based on simulations. The methods and assessment results presented here are expected to stimulate discussion among fisheries scientists on different modeling approaches, as well as among stakeholders in Indonesia regarding management options and decision-making.

2. Materials and methods

2.1 Study area and fisheries

Indonesia's demersal fishing grounds have high biodiversity, which is reflected in the multispecies nature of the catches (Pauly 1979; Wibisono et al. 2019). The Indonesian multispecies deep demersal fisheries operate in all of Indonesia's 11 fisheries management areas (FMAs 571, 572, 573, 711, 712, 713, 714, 715, 716, 717, 718) targeting more than a hundred species of snappers, groupers, emperors and other families at depths from about 50 to 500 m. The most common gear types used by the numerous smaller or larger fishing vessels (from less than 5 and up to 100 gross tonnage GT; Stobutzki et al. 2006) are droplines, bottom longlines, or a mix of both gears, while traps and gillnets are far less common and often used in combination with hook and line gears.

The Indonesian deep demersal fisheries are being monitored on a continuous basis since 2015 through the CODRS that collects data on species, catches, length composition, and fishing location of commercial vessels, aiming to address the existing data gap on the basic characteristics of the fishery (Wibisono et al. 2019). Approximately 4% (400 out of 10,000 boats) of the fishery is sampled by CODRS which covers all Indonesian FMAs and has produced over 3.5 million fish images so far (Mous et al. 2020). While this may seem like a small sample, in a huge archipelagic country like Indonesia, it is not realistic to reach a much higher sample through a privately funded project. Thus, even though we acknowledge the limitations of generalizing the results of this study, we maintain that this is an important first step to assess the status of previously unassessed Indonesian fish stocks.

In this study, commercial catch length frequencies collected through CODRS from 2016 to the end of 2020 for 11 of the most abundant species (16 stocks, 4 different FMAs) were used to assess stock status by applying and comparing two computational methods, i.e. a highly customized length-based approach to stock assessment and a new generally applied approach by Froese et al. (2018b) for estimating stock status using LF data from commercial catches. While the comparison cannot identify which method is best, convergence of findings may be interpreted as robustness and perhaps even accuracy of either method, whereas divergence may shed a light on the reasons why the same data sometimes lead to different interpretations. Nevertheless, simulations were also performed to test the consistency and potential biases of both methods.

2.2 Fishery-specific length-based approach to stock assessment

The customized approach is based on four length-based life-history parameters: maximum size L_{max} (the largest fish observed in the catches of each species measured through the over 3.5 million CODRS images), asymptotic size L_{inf} (the mean length in a cohort of infinite age), optimum harvest size L_{opt} (the length class with the highest biomass in an unexploited population) and size at maturity L_{mat} (the length class at which 50% of the individuals are mature). As documented in detail by Wibisono et al. (2019), the validated (checked for accuracy) L_{max} values in the CODRS dataset for each species were used as the starting point to calculate L_{inf}, L_{opt}, and L_{mat} from known relationships. For all families, we used $L_{inf} = 0.9 * L_{max}$ based on a recent simulation approach developed to estimate life-history parameters from a meta-analysis of published values and relationships between individual parameters (Nadon & Ault 2016). Size at maturity was different for each family, with L_{mat} = 0.59 * L_{inf} for deep water snappers (Lutjanidae) and L_{mat} = 0.46 * L_{inf} for deep water groupers (Epinephelidae: Newman et al. 2016). For emperors (Lethrinidae) and all other families, we used L_{mat} = 0.5 * L_{inf} based on the review of published ranges and meta-analyses (Binohlan & Froese 2009; Grandcourt et al. 2011; Younis et al. 2020). The values of the life-history parameters were compared with available data from other studies done in Indonesia and at comparable latitudes before being applied in the length-based assessments of the fisheries (Wibisono et al. 2019).

For the estimation of L_{opt}, we used the Beverton (1992) estimator:

$$L_{opt} = L_{\inf}(\frac{3}{3+\frac{M}{K}}) \quad [1]$$

To obtain family-specific estimates for M and K, we searched the literature for values of M, K, or M/K (some studies provided M/K as a ratio, without specifying the numerator and the denominator). We used publications with estimates for M and K values which were based on ageing studies, or on meta-analyses of such studies (e.g. Aldonov & Druzhinin 1979; Loubens 1980; Matthews & Samuel, 1991; Honebrink 2000; Newman 2002; Newman & Dunk 2003; Grandcourt et al. 2005; Grandcourt et al. 2006; Fry et al. 2006; Ebisawa & Ozawa 2009; Mehanna et al. 2012; Newman et al. 2016). The M/K values were compared with the accepted range as published for Type II Teleosts including tropical snappers (Prince et al. 2015) and with published values of M/K for specific tropical Indo Pacific species and families (Prince et al. 2019) that are important in the Indonesian deep demersal fisheries. All the life-history parameter values and invariants used in this study are presented in Table 1.

Stock status was assessed using an indicator for the Spawning Potential Ratio (SPR: Quinn & Deriso 1999), i.e. the estimated spawning stock biomass (SSB) as a fraction of the SSB of the pristine population [ratio between the modeled population biomass at estimated fishing mortality F and the modeled adult population biomass at F = 0 (pristine biomass)] (Meester et al. 2001). A standard, age-based population dynamics model (see Supplement) was applied to calculate the adult biomass starting from an arbitrary number of recruits. SPR was calculated on a per-recruit basis from the life-history parameters M (natural mortality), F, K, and L_{inf}, as well as from gear selectivity parameters. The instantaneous total mortality (Z = M + F) was estimated with the equilibrium Beverton-Holt estimator from length data using the Ehrhardt & Ault (1992) bias-correction. For this estimation, we used the length range of the catch length-frequency distribution starting with the length that is 5% higher than the modal length and ending with the 99^{th} percentile, as it is an accepted practice to disregard the right hand side of the LF that is too close to L_{inf} (Sparre & Venema 1998). F was calculated as the difference between Z and M, assuming full selectivity for the size range starting at modal length and ending with the largest fish in the catch. We assumed an S-shaped (logistic) selectivity curve, with 99% selectivity achieved at modal length, and with the length at 50% selectivity halfway between the first percentile and modal length of the catch length-frequency distribution.

To calculate the length-dependent M to be used in the SPR calculation, we used an empirical formula that relates M to length (from CODRS data) and growth (literature-derived K and L_{inf} calculated from the CODRS L_{max} based on published relationship) characteristics (Gislason et al. 2010):

$$M = \frac{1.733 * K * L_{\infty}^{1.44}}{L^{1.61}} \quad [2]$$

(reworked from its original notation as a log-transformed model)

Comparison with published values of natural mortality for the main families present in the tropical deep water demersal fisheries of the Indo-Pacific (Newman et al. 2016) showed that the relationship by Gislason et al. (2010) resulted in unrealistically high estimates of M for most families targeted here, except for Carangidae (jacks). Tropical deep-water snappers, groupers and emperors in the Indo-Pacific have low natural mortality rates, usually between 0.1 and 0.2

per year, and often below 0.15 per year (Newman 2002; Newman & Dunk 2003; Grandcourt et al. 2006; Newman et al. 2016). Therefore, to correct this, a family-dependent multiplicative correction factor (CF) was applied to the Gislason et al. (2010) relationship, as follows (L_{inf} and L are species-specific from CODRS data, while CF and K are family-specific):

$$M = \frac{CF * 1.733 * K * L_{\infty}^{1.44}}{L^{1.61}} \quad [3]$$

Most of the studies that we reviewed presented length-independent estimates for M that were valid for the larger, exploited size range of each species. For the estimation of CF for each family (Table 1), we assumed that these published estimates for M applied to L_{opt}. We support that this simplification is justifiable, since around L_{opt}, the Gislason et al. (2010) curve flattens out, meaning that the dependency between length and mortality is less strong in this size range. Under the assumption that published values of M apply to L_{opt}, and using published values for K together with the estimates for L_{inf} resulting from our CODRS data, we calculated the values for the CF (Table 1). It should be noted that the introduction of the Correction Factor did not put the modified Gislason et al. (2010) relation outside its original confidence limits. The CF values we found average 0.69, ranging between 0.5 and 0.97, whereas the lower confidence limit for the (back-transformed) confidence limit is 0.56. Hence, with one exception (grunts), the modified intercept remains within the 95% confidence interval presented by Gislason et al. (2010).

Another complication is that catch curve analysis assumes a constant total mortality (Z) over the size range that is used for its estimation, whereas Gislason et al. (2010) demonstrates that natural mortality varies with size. To work out this inconsistency, we applied the adjusted Gislason et al. (2010) empirical relationship to the length classes over which we estimated Z, then we calculated the average M over these size classes, and applied that average to the size range over which we estimated Z. Outside this size range, we assumed a varying M following the modified Gislason et al. (2010) relation.

A set of fishery indicators described below were derived from the literature-based method to facilitate management advice (Figure 1). A total population biomass B of half the pristine population biomass B_0 was considered to be the desired reference point for stock size, minimizing the impact of fishing (Froese et al. 2016). Using the SPR and B/B_0 estimates from our own data set, this target reference point correlates with an SPR of about 40%, agreeing with Harford et al. (2019) and not far from but slightly more conservative than the Wallace and Fletcher (2001) reference point. Therefore, we considered that when SPR is lower than the limit of 25% (0.313 B/B_0) then the stock is at high risk indicating overexploitation that may cause severe decline of the stock if fishing effort is not reduced. If SPR is equal to or greater than 25% (0.313 B/B_0) and lower than 40% (0.5 B/B_0) then the stock is considered to be at medium risk, while if SPR is equal to or greater than 40% (0.5 B/B_0) then the risk that the fishery will cause further stock decline is small. To facilitate comparison of the two methods' (see section 2.3) results, we turned SPR to B/B_0 assuming that B/B_0 = SPR/0.8 (Froese et al. 2019).

Apart from the SPR, the current status of stocks was expressed through the percentage of immature and a subset of large mature (mega-spawners: fish larger than 1.1 times the L_{opt}; Froese 2004) fish in the catch. With 0% immature fish in the catch as an ideal target (Froese 2004), a target of 10% or less is considered a reasonable indicator for sustainable (or safe) harvesting (Fujita et al. 2012; Vasilakopoulos et al. 2011). Zhang et al. (2009) consider 20% immature fish in the catch as an indicator for a fishery at risk, in their approach to an ecosystem based fisheries assessment. Results from meta-analyses of multiple fisheries showed stock status over a range of stocks to fall below precautionary limits at 30% or more immature fish in the catch (Vasilakopoulos et al. 2011). The fishery is considered at high risk when more than 50% of the fish in the catch are immature (Froese et al. 2016). Hence, if the percentage of immature fish in the catch is equal to or lower than 10%, then the stock is considered here to be at low risk since at least 90% of the fish in the catch are mature specimens that have spawned at least once before they were caught. If the immature fish in the catch are greater than 10% and up to 30%, the risk level is considered to be medium, while more than 30% of immature individuals indicate that the stock is at high risk of overharvesting of juveniles that have not had the chance to reproduce before capture. Regarding mega-spawners, if more than 30% of the catch consists of mega-spawners (and other fisheries do not catch the much smaller fish), it is indicated that this fish population is in good health (low risk). If more than 20% and less than or exactly 30% of the population consists of mega-spawners, then the risk level of recruitment overfishing through over harvesting of the mega spawners is medium, while the risk is high if 20% or less of the population are mega-spawners.

Another status indicator used was the “trade limit” length which was derived from the general buying behavior of processing companies as the minimum size of the fish accepted by the trade. Comparing the trade limit with L_{mat} may indicate incentives from traders for either unsustainable targeting of juveniles or more sustainable targeting of mature fish that have spawned at least once. We consider a trade limit at 10% below or above L_{mat} to be significantly different from it and we consider trade limits to provide incentives for targeting specific sizes of fish through price differentiation, as it has been shown that the larger individuals of a species attain higher market prices and are therefore selectively removed because they may yield higher profit (Tsikliras & Polymeros 2014). If the trade limit for a species is lower than $0.9 * L_{mat}$ it is indicated that the trade encourages the capture of immature fish impairing sustainability, and therefore the risk level is considered high. If the trade limit is above $1.1 * L_{mat}$ then there seems to be a low risk for recruitment overfishing. The risk is medium for intermediate values of trade limit.

While this literature-based method was specifically tailored to assess the status of Indonesian stocks of the deep demersal fishery, we do recognize that it may form a framework that could be customized to different fisheries and followed by other researchers when the only available data are length frequency distributions and L_{max}. The series of steps to be followed to apply the literature-based assessment framework are presented in Figure 1.

2.3 Length-based Bayesian biomass estimation method

The Length-based Bayesian biomass estimation method (LBB: Froese et al. 2018b) is an approach for estimating stock status in data-poor situations using LF data from commercial catches. The method is outlined below; for a more detailed description, the reader is referred to Froese et al. (2018b; 2019). The version of the code used (LBB_33a) can be found online at http://oceanrep.geomar.de/43182/, along with a simple but detailed user guide.

In LBB, it is assumed that the fish body grows in length according to the von Bertalanffy (1938) growth equation, as expressed by Beverton and Holt (1957),

$$L_t = L_{inf}[1 - e^{-K(t-t_0)}] \quad [4]$$

with L_t being the length at age t, L_{inf} the asymptotic length, K the growth rate by which L_{inf} is approached and t_0 the theoretical age at zero length.

The LBB model uses the annual LF data to simultaneously make an inference for four parameters over the age range represented in the LF sample with a Bayesian Monte Carlo Markov Chain approach: (i) L_{inf}, (ii) the length at first capture at which 50% of the individuals are retained by the gear (L_c), (iii) the mean relative natural mortality (M/K), and (iv) fishing mortality (F/K) over the past years. Priors for L_{inf}, relative total mortality (Z/K), and selectivity (S_L) are derived from the aggregated LF samples across years, while the prior for M/K is assumed to be around 1.5 (1.2-1.8) which is typical for adults of species that grow throughout their lives (Hordyk et al. 2015b; Froese et al. 2016). For species that have different life-history strategies with M/K ratios that diverge from the assumed range (Thorson et al. 2017), and if an appropriate L_{inf} estimate is available from an independent study, then these values can be introduced by the user to decrease uncertainty in the LBB results. To investigate the uncertainty in the output biomass indicators associated with the initial estimates of the life-history parameters, we ran the LBB model four times for each stock using: 1) no user-defined prior as input to the model, 2) user-defined prior as input for L_{inf} as presented above in Section 2.2, 3) user-defined prior as input for M/K that was estimated from the customized length-based approach presented above in Section 2.2, and 4) both L_{inf} and M/K priors set by the user.

When the above parameters are known, current stock status in the form of current stock biomass B relative to the unexploited stock size B_0 can be estimated from standard fisheries equations (Beverton & Holt 1957, 1966) and L_{c_opt} (i.e. the L_c value that would result in L_{opt} becoming the mean length in the catch, with the highest catch and biomass for the respective fishing mortality and a minimized impact on size structure; Froese et al. 2016) can also be calculated.

If the fish are fully selected by the gear, the curvature of the right side of the catch samples is a function of Z/K. This curve is expressed by the following equation (Quinn & Deriso 1999),

$$N_L = N_{Lstart}\left(\frac{L_{inf}-L}{L_{inf}-L_{start}}\right)^{Z/K} \qquad [5]$$

for L > L_{start} and L < L_{inf} in which N_L is the number of fish that survive to length L, N_{Lstart} is the number of individuals at length L_{start} with full selection, above which all individuals entering the gear are retained by the gear, and Z/K is the ratio of the total mortality rate Z to the somatic growth rate K.

The lengths that are partially selected by the gear are a function of gear selectivity (here assumed to be knife-edged selectivity, i.e. by a trawl or any gear with a trawl-like selection curve) for the species in question, as given by the following ogive (i.e., the curve that represents the proportion of individuals being caught by the gear at length) function,

$$S_L = \frac{1}{1+e^{-a(L-L_c)}} \qquad [6]$$

with S_L being the fraction of fish that are caught by the gear at length L, and a describing the steepness of the ogive (Sparre & Venema 1998; Quinn & Deriso 1999).

The difference equation below is fitted to the whole catch-in-numbers curve to estimate L_{inf}, L_c, a, M/K, and F/K at the same time,

$$N_{L_i} = N_{L_{i-1}} \left(\frac{L_{inf}-L_i}{L_{inf}-L_{i-1}}\right)^{\frac{M}{K}+\frac{F}{K}S_{L_i}} \qquad [7] \qquad \text{and } C_{L_i} = N_{L_i} S_{L_i} \qquad [8]$$

with L_i being the number of individual fish at length i, L_{i-1} being the number of fish at the previous length, and C referring to the number of individuals that are vulnerable to the gear and are proportionally represented in the catch (Froese et al. 2018b).

L_{opt} is calculated using Equation [1] and L_{c_opt} can be obtained from,

$$L_{c\_opt} = \frac{L_{inf}\left(2+3\frac{F}{M}\right)}{\left(1+\frac{F}{M}\right)\left(3+\frac{M}{K}\right)} \qquad [9]$$

and finally an index of relative biomass depletion for the exploited part of the population B/B_0 is then calculated from the following equation (Beverton & Holt 1966),

$$\frac{B}{B_0} = \frac{\frac{CPUE'}{R}}{\frac{B'_0>L_c}{R}} \qquad [10]$$

in which CPUE'/R is an index of catch per unit of effort that results from an index of yield-per-recruit expressed as a function of L_c/L_{inf}, F/K, M/K, and relative fishing mortality F/M and $B'_0 > L_c/R$ denotes the relative biomass in the exploited phase of the population if no fishing takes place (Froese et al. 2018b). B/B_0 from LBB was used as an indicator of stock status where, in line with SPR limits from the fishery-specific method, the stock is considered to be at high risk of overexploitation when $B/B_0 < 0.313$, at medium risk when $0.313 \leq B/B_0 < 0.5$, and at small risk when $B/B_0 > 0.5$ (see also section 2.2).

2.4 Simulations

For verification purposes in the absence of knowing "true" stock status, simulated LF data with known underlying parameter values were used to run both models and compare the results. Simulated data were used to assess model performance and validate the consistency between the two methods, following the practice reported in Froese et al. (2018b). These data were produced using equation [5] and assuming that the number of survivors per length followed a standard dynamic for full net selectivity (Quinn & Deriso 1999). Parameter values were set to simulate 3 hypothetical stocks representing full exploitation, with length at first capture ranging from 18 to 35 cm and with similar life histories to the Indonesian deep demersal stocks (L_{inf} from 35 to 120 cm and M/K from 1.33 to 1.6). The two stock assessment methods analyzed here, were checked to produce comparable results for the estimates of B/B_0 and SPR turned to B/B_0 (Table S1).

3. Results

In total, 16 stocks of the Indonesian deep demersal fisheries were analyzed with two different length-based assessment methods. The stocks belonged to 11 snapper, grouper, and croaker species of 4 fisheries management areas (FMAs) of the Indonesian waters: 573 Savu and Timor Sea, 712 Java Sea, 713 Makassar Strait, and 718 Arafura Sea. Figures 2-3 show the catch length frequency distributions for the CODRS samples collected in 2020 and life-history parameters (L_{mat}, L_{opt}, L_{inf}, L_{max}) as estimated with the customized length-based approach for the 16 analyzed Indonesian stocks. Table 2 shows the literature-based species/family-specific L_{inf} and M/K values that were used as input (priors) to the LBB model, as well as the resulting parameter values (median and ~95% confidence limits).

Based on the fishery-specific length-based approach presented here (Table 3), 9/16 (56%) stocks were in a poor state with spawning potential ratio (SPR) values below 0.25, while 4/16 (25%) stocks were in a medium state with SPR values between 0.25 and 0.39, and only 3/16 (19%) stocks were in a good state with SPR values at or over 0.40. A low percentage (≤10%) of immature individuals was found in the catch of 10/16 (63%) stocks, while for 3/16 (19%) stocks the percentage of immatures was 11-30% or over 30%. Most of the stocks (14/16, 88%) had a very low number of mega-spawners (≤20%), while the catches of only two stocks consisted of over 20 and 30% of very large mature fish. Based on the species-specific trade limit results, 5/11 (45%) species seemed to run a high risk of unsustainable exploitation of immature individuals, while 2/11 (18%) and 4/11 (36%) species ran a medium and low risk, respectively.

According to the LBB model run without user-defined priors (LBB B/B_0, Table 3), 10/16 (63%) stocks had poor relative biomass status with B/B_0 values below 0.313, 3/16 (19%) stocks were in moderate biomass state (between 0.313 and 0.49), and another 3/16 (19%) could be considered healthy with B/B_0 values at or over 0.5. Running the LBB model using a prior for L_{inf} as estimated from the customized length-based approach gave different results in some cases, with 8/16 (50%) stocks being in a poor state, 3/16 (19%) as medium status, and 5/16 (31%) in a healthy state. Informing the LBB model with an M/K prior that was estimated with the tailored length-based approach resulted in all of the analyzed stocks (100%) shown to have very low biomass levels compared to the pristine population biomass. Finally, when running LBB with both the L_{inf} and M/K priors from the customized length-based approach (Table 3; Figure 4), 12/16 (75%) stocks were shown to have unhealthy biomass levels, while 2/16 (13%) seemed to be in a medium (the snappers *Lutjanus russelli* and *Paracaesio gonzalesi*) and good (the grouper *Epinephelus areolatus* and the snapper *Lutjanus vitta*) biomass status. Based on the range of the confidence limits (Table 3), it was evident that the uncertainty in the LBB B/B_0 estimates was by far the highest when the model was run using the L_{inf} from the customized length-based approach as a user-defined prior, followed by running LBB with no set priors and then by using both L_{inf} and M/K priors. Uncertainty was reduced the most when running LBB with an M/K prior derived from the highly customized length-based approach. All results of the LBB analyses are given in the supplement (Figures S1-S136).

The four independent LBB runs resulted in the same poor status categorization for 7 out of the 16 (44%) analyzed stocks (LBB B/B_0, Table 3). For the remaining 9 stocks, the LBB runs resulted in two (4/16 stocks, 25%) or three (5/16 stocks, 31%) different status classifications for each stock. The highest agreement (but with quite high uncertainty) of the current method and the LBB model regarding biomass status, SPR, and B/B_0 respectively, was when LBB was run without any user-defined priors (11/16 stocks, 69%). Out of these 11 stocks whose biomass status were in agreement with both methods, 8/11 (73%) were shown to have low biomass, 2/11 (18%) had medium biomass levels, and only 1/11 (9% - the snapper *Paracaesio gonzalesi*) seemed to be healthy. Using the M/K prior and both L_{inf} and M/K resulted in the same status categorization for 9/16 (56%) stocks (with low and moderate uncertainty, respectively), while using only the L_{inf} prior showed an agreement of the two methods in 7/16 (44%) stocks (with the highest uncertainty).

Half of the studied stocks (8/16) were consistently categorized as having a poor biomass status, meaning that the current method and at least 3 out of the 4 LBB runs resulted in a low biomass indicators. These stocks were the orange croaker *Atrobucca brevis*, banded grouper *Epinephelus amblycephalus*, Malabar blood snapper *Lutjanus malabaricus* (in all three studied FMAs), emperor red snapper *L. sebae*, brownstripe, red snapper *L. vitta*, and pinjalo *Pinjalo pinjalo*. No stocks were consistently shown to have healthy biomass levels using the assessment methods tested here.

4. Discussion

In multispecies fisheries, like the deep demersal snapper-grouper fishery in Indonesia, the high diversity of species that share common morphological characteristics and life-history traits makes the identification and reporting at the species level challenging. This results in poor resolution of official catch statistics, hindering the application of stock assessment methods. Using the species-specific data collected through the CODRS over the past five years, as well as the estimated life-history characteristics for the main target species (Wibisono et al. 2019), it is now possible to apply length-based stock assessment methods to this fishery. This study explored the stock status results derived from two methods, a simple customized literature-based assessment framework based on conventional approaches (Figure 1), and a more generally applicable model (LBB: Froese et al. 2018b) for the analysis of length frequency distributions from commercial catches. The transition from a fishery-specific to a generalized method was examined and different parameterization levels of the latter method were tested, ranging from running LBB with the generalized default life-history settings to using literature-based values tailored to the analyzed stocks. The performance of both methods was tested with simulated stocks, showing that LBB gave biomass estimates close to the "true" simulation values and within the 95% confidence limits in all three simulated stocks (100%), while the fishery-specific method was accurate in two stocks (67%). In two out of the three simulated stocks, LBB overestimated biomass, whereas the fishery-specific method underestimated biomass in all three stocks which makes it a more precautionary approach. The results are expected to stimulate a focused discussion among stakeholders on the different methodologies, as well as the status of the fisheries.

The highly customized length-based assessment approach described here is the product of working with Indonesian species-specific CODRS datasets, cross-checking references to obtain family-specific life-history parameters that apply to Indo-Pacific species, and tweaking published methods (e.g., Gislason et al. 2010) to incorporate insights of others. The aim has been to develop a literature-based model that can be used specifically to assess the stock status of Indonesian deep demersal fisheries. Ultimately, as illustrated in Figure 1, this assessment framework can be followed by other researchers when the only available information is length data and L_{max}. For comparison and to discuss the transition from a fishery-specific to a generalized method and vice versa, we decided to also include LBB, i.e. the Length-based Bayesian biomass estimation method of Froese et al. (2018b). LBB is a more broadly applicable model that can nevertheless be tailored to the studied stocks when the user chooses to specify priors for known parameters, such as the asymptotic length L_{inf} and relative natural mortality M/K. It has been suggested, and it is confirmed here, that carefully tuning generic assessment approaches to the examined stocks using species-specific parameters may enhance their reliability (Dowling et al. 2019). LBB has been increasingly applied to Asian fisheries (Ju et al. 2020; Liang et al. 2020; Wang et al. 2020; Zhang et al. 2020; Kindong et al. 2020; Yue et al. 2021) and it has been gaining consideration as a plausible method in international commissions like the International Commission for the Conservation of Atlantic Tunas ICCAT. However, as it is a recently developed assessment method, this is among the first published comparisons of LBB with other length-based methods (Pons et al. 2020).

As observed in this study, it is to be anticipated that the performance of various compared methods may be different and often result in opposing status estimations based on the tested fishing intensity trends, depletion levels, data availability and resolution, and life-histories (Rosenberg et al. 2018; Pons et al. 2020; Bouch et al. 2020). The snapper and grouper stocks that are mostly included here (as well as a croaker species), cover a broad spectrum of depletion, and generally have small differences in their life-histories. As it has been previously shown, the biggest source of uncertainty in stock status estimates is the uncertainty in life-history parameters (Babcock et al. 2013; Mannini et al. 2020). Fundamental linkages between life-history parameters have long been identified in fishes (Beverton & Holt 1959; Beverton

1963). The ratio of natural mortality over growth rate (M/K) is one of these so called Beverton-Holt invariants (Charnov 1993). In species whose LF distributions contain only few individuals that survive to approximate L_{inf}, M/K is typically close to 1.5 as assumed by default for the M/K prior in the LBB model (Froese et al. 2018b; Froese et al. 2019). Nevertheless, this invariant, that has probably been conserved through natural selection (Beverton & Holt 1959), may in fact be quite different among taxonomic groups based on their life-history strategies and would be better defined on a taxon level as we have outlined here in the customized length-based approach (Prince et al. 2015; Thornson et al. 2017).

Users of the LBB approach are encouraged to replace the default setting of M/K with their own informed values when they have strong evidence that M/K lies outside the assumed default range of 1.2-1.8 for the analyzed stock (Froese et al. 2018b; Froese et al. 2019). Using default priors is understandable in truly data-poor situations when available data cannot support the implementation of data-rich assessment methods, but when some parameters specific to the analyzed stocks are known, then their use is highly encouraged (Bouch et al. 2020). In the present study, we followed this advice to use informed family-specific M/K values (~0.8) that were based on M and K information from various sources and reflected the low natural mortality and slow/modest growth rates of the deep-water tropical demersal snappers and groupers (e.g. Prince et al. 2015; Newman et al. 2016). We then tested the effect of this tweak on the results of the model and particularly the estimated relative biomass, which is the main target output of LBB (Table 1). Natural mortality (M) may affect stock assessment derived reference points and consequently management advice. Biased M values impact the information contained in the biomass index, since higher M for the same total mortality (Z) will correspond to lower fishing mortality (F) given the catch, and ultimately higher biomass (Punt et al. 2021). Indeed, based on model sensitivity, when the lower M/K values were used as priors, LBB estimated a higher relative fishing mortality and a lower stock status, albeit with considerably lower uncertainty, hence more reliable results, which is the goal of using informed user-defined priors. In more than half of the cases in our study that did not cause a change in the stock status classification. Thus, the use of literature-based species/family-specific life-history parameters is encouraged, as it is shown that when setting M/K within this range of values, the influence on the estimation of relative biomass, which is the main target output of LBB, is minor (Froese et al. 2018b), while the reliability of the results is greatly increased.

Asymptotic length is also a critical parameter for reliable estimates of fishing mortality and SPR (Hordyk et al. 2016), with higher values of it leading to an overestimation of exploitation rate and a subsequent underestimation of stock status, and vice versa. Indeed, based on model sensitivity, using lower L_{inf} priors from the customized length-based approach as an input to LBB consistently resulted in higher relative biomass for all stocks. The same pattern was also found by Nadon & Ault (2016). However, although L_{inf} is estimated from L_{max}, which is the most observable parameter in the set of life-history parameters, the LBB results with a literature-based L_{inf} prior were highly uncertain, mostly owing to the Malabar red snapper *Lutjanus malabaricus* (FMA 718), Russell's snapper *L. russelli* (FMA 718), and Vanuatu snapper *Paracaesio gonzalesi* (FMA 573). In these three cases, the literature-based L_{inf} prior that was inserted in LBB was so much lower than what LBB would have calculated using the default prior settings (Table 2), that the right hand side of the length distribution was truncated (Figures S58, S67, S113). This seems to be causing the high uncertainty or in some cases completely stopping the LBB calculations. L_{inf} is derived from L_{max} in both methods compared here as L_{max} has been shown to be a reasonable predictor of L_{inf} (Froese et al. 2019). However, the customized length-based approach calculates asymptotic length as L_{inf} = 0.9 * L_{max}, while LBB estimates L_{inf} from the available data, while considering a prior that, if not provided by the user, is derived from aggregated LF data within the range of 0.9 * median L_{max} – 1.2 * median L_{max} (Froese et al. 2018b; Froese et al. 2019). This might explain why running LBB with L_{inf} priors results in the lowest agreement between the two methods, as well as high uncertainty. For example, for the Malabar blood snapper *L. malabaricus* in FMA 712, the median L_{max} was 89 cm, so LBB picked a prior of 80.1-106.8 (that is 103; Figures S47, S48) when no user-defined prior was provided to the model, while for *L. malabaricus* in FMA 713, the median L_{max} was 90.5 cm, so LBB picked a prior of 81.45-108.6 (that is 104; Figures S56, S57). However, the literature-based L_{inf} value for this species was 85 cm, i.e. 0.9 * L_{max} (L_{max}=94 cm), and when this was inserted as a prior to LBB, the resulting B/B_0 estimates were more uncertain. Both lower (≤85 cm) and higher (up to 105.4 cm) L_{inf} estimates have been reported for this species in the west Pacific Ocean (Martinez-Andrade 2003).

On the other hand, running LBB with an M/K prior alone, or both L_{inf} and M/K priors estimated with the customized length-based approach, provided more reliable results with higher agreement between the two methods and low uncertainty. Inserting no priors into LBB had the highest agreement across assessment scores, but with quite high uncertainty, and therefore it would better be avoided when fishery-specific information is available like in this study. Consequently, when both agreement of the two methods and uncertainty of indicators are to be considered as performance criteria, and when species/family/stock-specific values are available, then the best approach is to run LBB using as priors the tailored and customized M/K values, or both L_{inf} and M/K. Communicating to managers the uncertainty in fisheries scientific advice that stems from uncertainty in the estimated parameters owing to measurement, process, or model errors, may allow them to evaluate trade-offs between different management strategies (Rosenberg & Restrepo 1994).

LBB simulation testing highlighted that the uncertainty in estimated B/B_0 values that are compatible with the LF pattern was considerably higher in lightly exploited stocks (Froese et al. 2018b), which was also the case with the Russell's snapper *Lutjanus russelli*, and brownstripe red snapper *L. vitta* (FMAs 712 and 718) in the present study (see Supplement). The biomass estimates of these stocks, along with the Vanuatu snapper *Paracaesio gonzalesi* and areolate grouper *Epinephelus areolatus*, were highly uncertain and thus presented the most contradicting results between the two methods and the different LBB runs. The observed discrepancies between the two methods could also be linked to the fact that B/B_0 was estimated for the exploited length range, while SPR used SSB. As pointed out by Froese et al. (2018b), "…*if L_c is significantly larger than mean length at first maturity, the depletion of biomass in the exploited length range may be much stronger than the depletion of spawning biomass*…". In any case, these stocks would benefit from further assessment possibly with longer time-series data and/or species- and area-specific life-history studies. Although longer time-series do not necessarily guarantee better estimates, it has been shown that ten years of length data may result in greater accuracy and precision of biomass estimates by length-based methods, especially for species that are medium or longer-lived (Rudd & Thorson 2018). The highest consensus between the methods and among LBB runs was reached in stocks that had low relative biomass. This could be related to the finding of Pons et al. (2020) who demonstrated that LBB performed better in cases of stocks that have relatively low to medium stock sizes.

Regarding stock status, various studies have investigated the levels of SPR to be used as target reference points, and it is generally accepted that an SPR value of approximately 40% is sustainable for most species (Hordyk et al. 2015a and references therein). Based on the biomass indicators (B/B_0 and SPR), half of the examined stocks were consistently shown to be fished at unsustainable levels, while none of the 16 stocks could be unanimously considered as healthy using both methods. Only the Vanuatu snapper *Paracaesio gonzalesi* was found to have a healthy biomass by the customized length-based approach and two of the four LBB runs. Babcock et al. (2013) also tested the sensitivity of length-based indicator results for the spear gun fishery of groupers and snappers in Belize and suggested that when stocks are shown to be overfished or experiencing overfishing across a range of plausible life-history parameters, then improved management with enforced size or catch limits would be recommended. This finding is worrying about the future of the most abundant stocks of the deep demersal fisheries in Indonesia and highlights the need for effective management, with potential enforcement of science-based harvest control rules that determine how much fishing can take place, based on indicators of the targeted stock status (Bellido et al. 2020). Such actions may contribute to ensuring the long-term sustainability of these vital resources of high commercial value which support the livelihoods and food security of numerous local communities. Although much like biomass estimations, the trade limit and mega-spawners indicators were not encouraging for the Indonesian deep demersal fisheries, the percentage of immature individuals in the catch was overall low, indicating that from this aspect the fishery seemed to be at lower risk (Froese et al. 2016). Nevertheless, attention should be paid to FMAs 712 and 713 where a high proportion of immature Malabar red snapper and pinjalo individuals seem to be getting caught. These areas, i.e. the Java Sea – Makassar Strait, have been identified by Wibisono et al. (2021) as juvenile hotspots and were therefore suggested to be prioritized in fisheries management plans as they overlap with common fishing grounds.

Tailoring assessment methods to the specific life-histories of the analyzed stocks and taking into account data quality and model assumptions is expected to increase the reliability of the results. To that end, a length-based approach to stock assessment that is especially tailored to the Indonesian deep demersal snapper-grouper fishery but can also be modified for other fisheries was presented here, along with the more broadly applicable LBB method of Froese et al. (2018b) for comparison. The results of the customized method agreed in most cases with LBB, while using the literature-based species/family-specific L_{inf} and M/K values in LBB improved the certainty of the stock status estimates, thus supporting the value of the customized method presented here as a tailored assessment framework especially for Indonesian fisheries. Both methods told the same story for at least half of the examined stocks pointing out that, in terms of biomass, important stocks of this fishery are at high risk and would need to be managed at more sustainable levels. It is important to continue collecting data through the CODRS to be able to monitor status and trends over time. After all, "[m]anaging a stock without knowing its condition might be like driving with a windshield blacked out; crashes can be expected" (Fenner 2012).

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Figure legends

Figure 1. Schematic of the different steps to be followed to apply the literature-based method to assess stock status with only available information the maximum length (L_{max}) and length-frequency distribution. L_{inf}: asymptotic size, L_{opt}: optimum harvest size, L_{mat}: size at maturity, SPR: spawning potential ratio.

Figure 2. Catch length frequency distributions, life-history parameters and reference points as estimated with the highly customized length-based approach presented here for orange croaker *Atrobucca brevis* (FMA 718), banded grouper *Epinephelus amblycephalus* (FMA 718), areolate grouper *E. areolatus* (FMAs 712 and 718), crimson snapper *Lutjanus erythropterus* (FMA 573), and Malabar red snapper *L. malabaricus* (FMAs 712, 713, 718). Fish photos are from the crew-operated data recording system (CODRS; Wibisono et al. 2019). SPR: spawning potential ratio. Lx-codrs = L_{max}, i.e. the largest specimen in the CODRS database.

Figure 3. Catch length frequency distributions, life-history parameters and reference points as estimated with the highly customized length-based approach presented here for Russell's snapper *Lutjanus russelli* (FMA 718), emperor red snapper *L. sebae* (FMA 718), brownstripe red snapper *L. vitta* (FMAs 712, 713, 718), Vanuatu snapper *Paracaesio gonzalesi* (FMA 573), slender pinjalo *Pinjalo lewisi* (FMA 573), and pinjalo *Pinjalo pinjalo* (FMA 712). Fish photos are from the crew-operated data recording system (CODRS; Wibisono et al. 2019). SPR: spawning potential ratio. Lx-codrs = L_{max}, i.e. the largest specimen in the CODRS database.

Figure 4. The relative biomass B/B_0 (black curve) with approximate 95% confidence limits (shaded grey area) for each of the 16 analyzed stocks (LBB runs using literature-based L_{inf} and M/K priors), with indication of a proxy for the biomass that can deliver the maximum sustainable yield B_{msy} (green dashed line) and a proxy for 0.5 B_{msy} (red dotted line). The number in the parenthesis indicates the Fisheries Management Area of the stock.

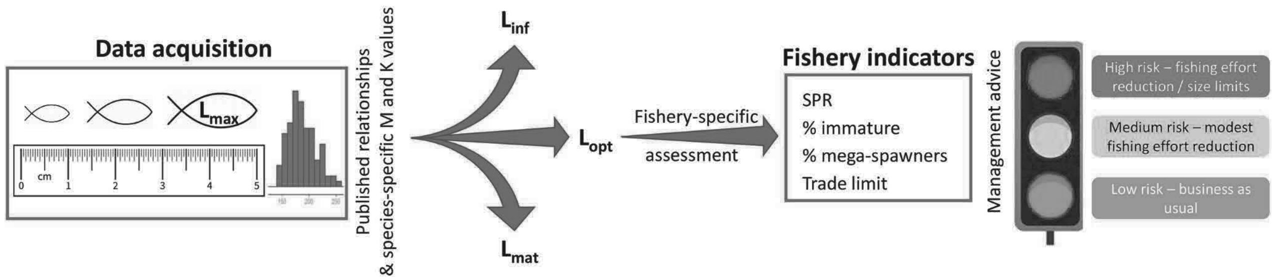

Figure 1. Dimarchopoulou et al.

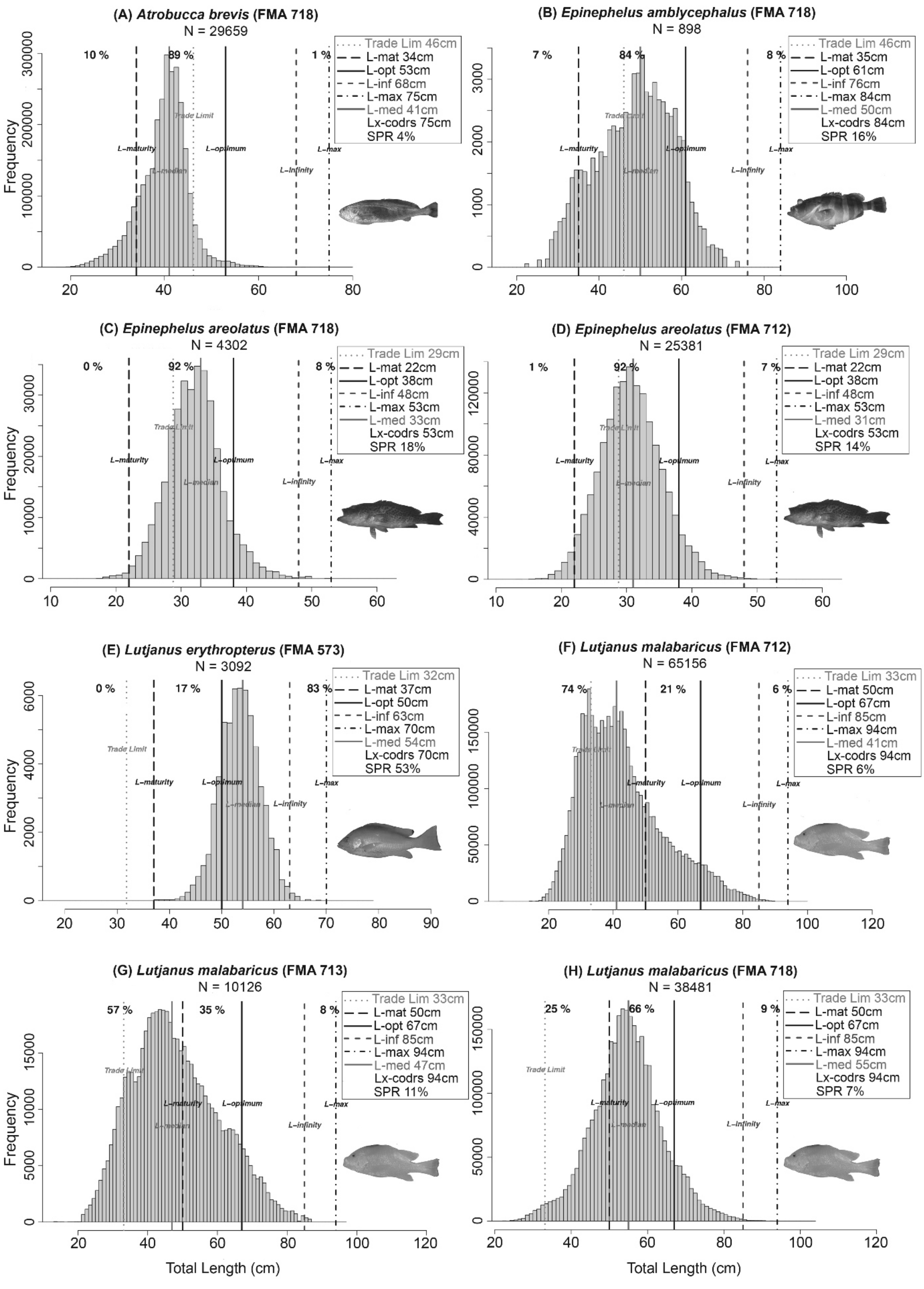

Figure 2. Dimarchopoulou et al.

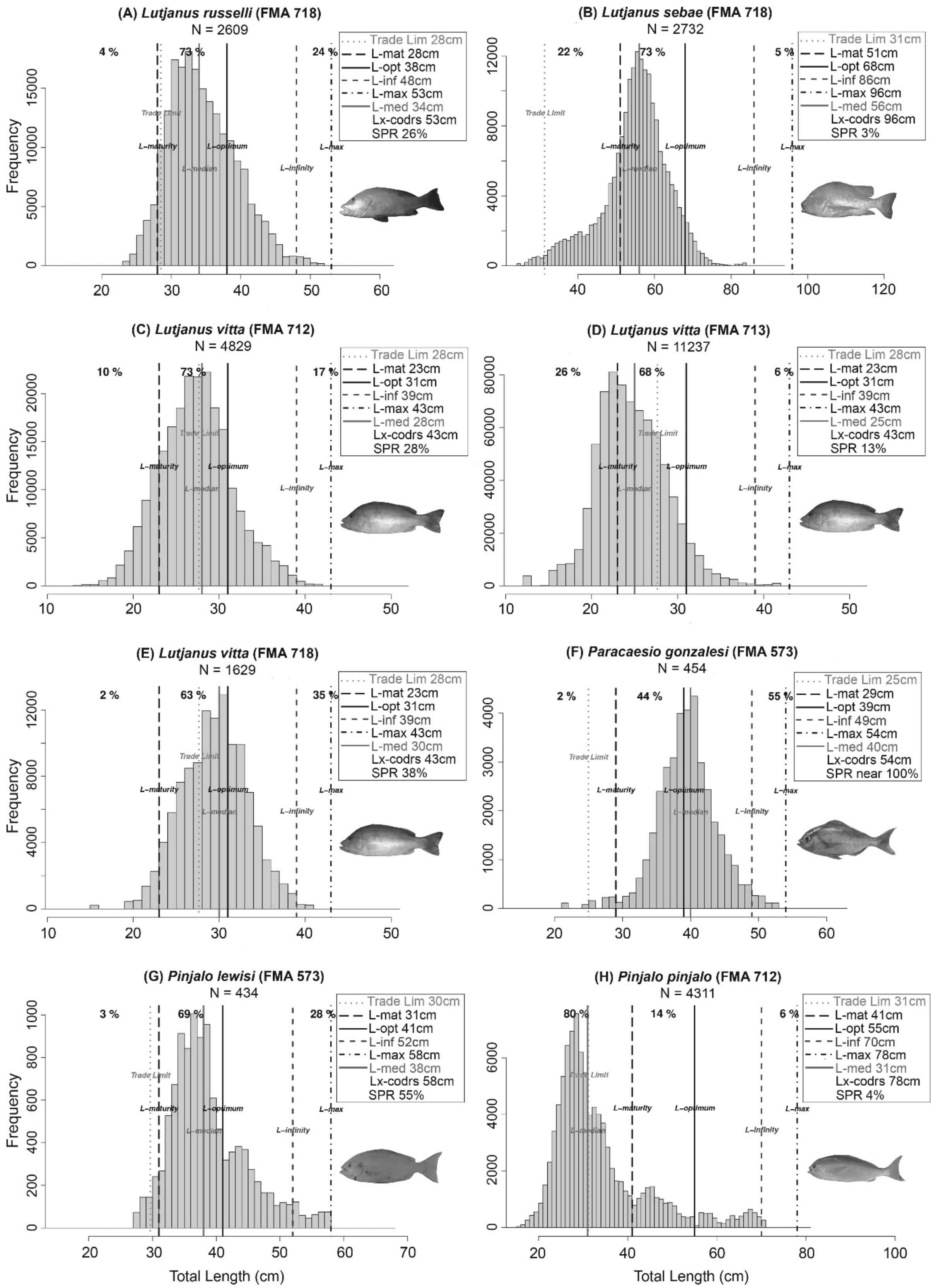

Figure 3. Dimarchopoulou et al.

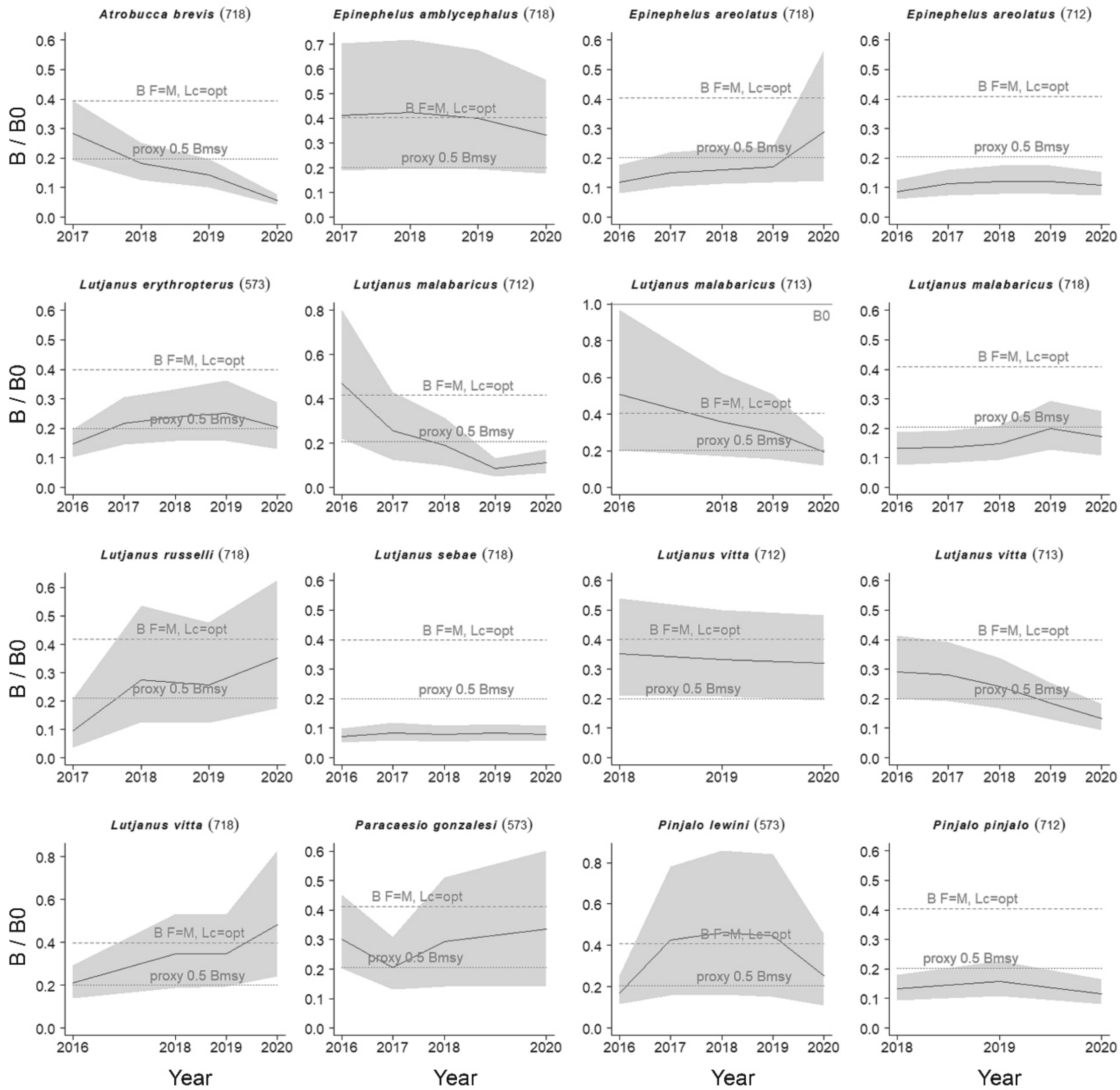

Figure 4. Dimarchopoulou et al.

Table 1. Life-history parameter values and invariables, and a correction factor (CF) to adjust length-dependent natural mortality M (Gislason et al. 2010) to estimated M at optimum harvest size L_{opt}.

Deep Demersal		**Mortality**		**Growth**		**Life-history Invariant values**		
Target Families	**L_{inf}/L_{max}**	**M (L_{opt})**	**CF**	**K**	**$(M/K)_{opt}$**	**L_{opt}/L_{inf}**	**L_{mat}/L_{opt}**	**L_{mat}/L_{inf}**
Snappers	0.90	0.18	0.67	0.23	0.79	0.79	0.75	0.59
Groupers	0.90	0.12	0.71	0.16	0.75	0.80	0.58	0.46
Emperors	0.90	0.15	0.60	0.21	0.70	0.81	0.62	0.50
Grunts	0.90	0.13	0.50	0.24	0.54	0.85	0.59	0.50
Jacks	0.90	0.35	0.97	0.22	1.61	0.65	0.77	0.50
Others	0.90	0.18	0.69	0.21	0.88	0.77	0.66	0.50

Table 2. Input and output life-history parameters for 16 species of the Indonesian deep demersal fisheries, analyzed with a highly customized length-based approach presented in this study (current method) and also with the LBB model (four independent runs: a. no user-defined priors set, b. an L_{inf} prior as estimated with the customized length-based approach was inserted into the model, c. an M/K prior as estimated with the customized length-based approach was inserted into the model, d. both informed priors were inserted into the model: Froese et al. 2018b). The literature-based L_{inf} and M/K values of the customized length-based approach were used an input (priors) to LBB runs b, c, and d. The resulting median estimated parameter values of the LBB model are presented along with their ~95% confidence limits of the Monte Carlo estimates in parentheses. FMA: Fisheries Management Area. L_{inf}: asymptotic length. M/K: natural mortality over growth rate.

			Customized length-based approach		LBB L_{inf}				LBB M/K			
Species	**Family**	**FMA**	**L_{inf}**	**M/K**	**No user-defined priors**	**L_{inf} prior**	**M/K prior**	**L_{inf} & M/K priors**	**No user-defined priors**	**L_{inf} prior**	**M/K prior**	**L_{inf} & M/K priors**
Atrobucca brevis	croaker	718	68	0.88	69.5 (68.5-70.6)	68.7 (67.6-69.8)	69.6 (68.6-70.7)	68.8 (67.9-70)	1.48 (1.2-1.73)	1.51 (1.26-1.72)	0.903 (0.73-1.02)	0.898 (0.75-1.02)
Epinephelus amblycephalus	grouper	718	76	0.75	73.5 (72.4-74.7)	75.6 (74.5-76.3)	72.7 (71.4-74)	74.4 (72.9-76.1)	1.41 (1.22-1.64)	1.85 (1.67-2.03)	0.772 (0.62-0.92)	0.778 (0.64-0.91)
Epinephelus areolatus	grouper	718	48		49.4 (48.9-50.1)	48.6 (48-49.3)	49.5 (49-50.2)	48.6 (48-49.3)	1.45 (1.18-1.72)	1.4 (1.11-1.69)	0.739 (0.6-0.89)	0.757 (0.6-0.89)
		712			48.7 (48.2-49.1)	47.7 (47.2-48.2)	48.7 (48.1-49.4)	47.7 (47.2-48.3)	1.18 (0.98-1.43)	1.13 (0.88-1.38)	0.682 (0.55-0.81)	0.686 (0.55-0.81)
Lutjanus erythropterus	snapper	573	70	0.79	65.6 (65.2-66)	68 (67.3-69.4)	65.4 (65.1-65.9)	68.6 (67.2-70.1)	1.61 (1.4-1.86)	1.76 (1.55-2.03)	0.877 (0.76-1)	0.855 (0.71-1.01)
Lutjanus malabaricus	snapper	712	85		103 (101-105)	86.4 (85.4-87.1)	103 (101-105)	86.4 (85.2-87.4)	1.07 (0.85-1.35)	0.71 (0.49-0.1)	0.704 (0.56-0.82)	0.613 (0.49-0.75)
		713			104 (102-106)	86.8 (85.8-87.8)	104 (102-106)	87 (85.8-88)	1.32 (1.05-1.63)	1.28 (1.1-1.47)	0.747 (0.62-0.91)	0.731 (0.6-0.86)

		718			95.2 (93.4-96.8)	88.2 *(87.3-89.3)	95.9 (94.3-97.4)	88.2 (87-89.1)	1.18 (0.83-1.4)	1.39 *(1.12-1.72)	0.734 (0.6-0.87)	0.695 (0.55-0.86)
Lutjanus russelli	snapper	718	48		52 (51.6-52.5)	48.8 (48.3-49.3)	52.3 (51.8-52.8)	48.7 (48.3-49.3)	1.33 (1.16-1.46)	1 (0.88-1.14)	0.626 (0.48-0.76)	0.592 (0.45-0.73)
Lutjanus sebae	snapper	718	86		87.7 (86.1-89.2)	87.6 (86.4-89.2)	87.9 (86.6-89.3)	88.3 (86.7-89.5)	1.75 (1.44-2.01)	1.75 (1.49-1.98)	0.842 (0.69-0.98)	0.852 (0.71-1.01)
Lutjanus vitta	snapper	712	39		42.7 (42.1-43.1)	40.2 (39.7-40.6)	42.7 (42.1-43.5)	40.1 (39.6-40.7)	1.59 (1.42-1.86)	1.48 (1.31-1.69)	0.811 (0.65-0.91)	0.814 (0.69-0.97)
		713			44.1 (43.4-44.8)	40.2 (39.7-40.8)	44.2 (43.5-44.9)	40.3 (39.7-40.8)	1.65 (1.44-1.96)	1.69 (1.42-1.93)	0.84 (0.71-0.79)	0.856 (0.72-0.99)
		718			45.9 (44.9-46.7)	40.3 (39.8-40.8)	45.9 (44.9-46.9)	40 (39.7-40.5)	1.61 (1.35-1.81)	1.45 (1.25-1.63)	0.804 (0.68-0.96)	0.841 (0.68-0.96)
Paracaesio gonzalesi	snapper	573	49		51.6 (50.9-52.3)	48 (47-48.6)	51.7 (50.8-52.6)	48.3 (47.4-49.1)	1.11 (0.87-1.37)	0.979 (0.7-1.11)	0.706 (0.58-0.87)	0.652 (0.5-0.76)
Pinjalo lewisi	snapper	573	52		59.9 (58.9-61.3)	53 (52.2-53.9)	60 (58.8-61.1)	52.7 (52-53.6)	1.68 (1.41-1.93)	1.6 (1.29-1.85)	0.802 (0.67-0.95)	0.719 (0.58-0.82)
Pinjalo pinjalo	snapper	712	70		70.9 (70.2-72.2)	71 (70.1-71.9)	71.1 (70.1-72)	71.1 (70.1-72)	1.52 (1.2-1.79)	1.4 (1.13-1.67)	0.76 (0.62-0.87)	0.756 (0.64-0.89)

Table 3. Results of the length-based assessments for 16 species of the Indonesian deep demersal fisheries. The data were analyzed with a highly customized length-based approach presented in this study (current method) and also with the LBB model (four independent runs: a. no user-defined priors set, b. an L_{inf} prior as estimated with the customized length-based approach was inserted into the model, c. an M/K prior as estimated with the customized length-based approach was inserted into the model, d. both informed priors were inserted into the model: Froese et al. 2018b). Presented values refer to the year 2020 (exceptions in which values are for 2019 are shown with an asterisk). Median estimated parameter values of the LBB model are presented along with their ~95% confidence limits of the Monte Carlo estimates in parentheses. FMA: Fisheries Management Area. B/B_0: current stock biomass relative to pristine population biomass. L_{max}: maximum recorded length in the dataset (cm). L_{inf}: asymptotic length. M/K: natural mortality over growth rate. SPR: Spawning Potential Ratio. Red values indicate poor stock status, orange values show medium status and green values represent good status. For details see the Materials and Methods section.

			Customized length-based approach						**LBB B/B_0**			
Species	**Family**	**FMA**	**Immatures (%)**	**Mega-spawners (%)**	**Trade limit (cm)**	**L_{max}**	**SPR**	**SPR to B/B_0**	**No user-defined priors**	**L_{inf} prior**	**M/K prior**	**L_{inf} & M/K priors**
Atrobucca brevis	croaker	718	10	0	46	75	0.04	0.05	0.06 (0.04-0.08)	0.06 (0.05-0.08)	0.02 (0.01-0.03)	0.02 (0.02-0.03)
Epinephelus amblycephalus	grouper	718	7	2	46	84	0.16	0.2	0.53 (0.1-1)	0.13 (0.02-0.51)	0.26 (0.12-0.4)	0.21 (0.13-0.35)
Epinephelus areolatus	grouper	718	0	3	29	53	0.18	0.23	0.28 (0.13-0.43)	0.49 (0.2-1.14)	0.19 (0.09-0.31)	0.53 (0.14-1.24)
		712	1	2			0.28	0.35	0.18 (0.14-0.24)	0.19 (0.12-0.29)	0.09 (0.06-0.13)	0.1 (0.07-0.13)
Lutjanus erythropterus	snapper	573	0	34	32	70	0.53	0.66	0.45 (0.25-0.71)	0.35 (0.22-0.5)	0.18 (0.11-0.24)	0.14 (0.1-0.19)
Lutjanus malabaricus	snapper	712	74	2	33	94	0.06	0.08	0.11 (0.06-0.19)	0.25 (0.12-0.41)	0.05 (0.03-0.07)	0.12 (0.07-0.18)
		713	57	3			0.11	0.14	0.13	0.39	0.06	0.18

									(0.07-0.24)	(0.1-0.8)	(0.04-0.1)	(0.1-0.26)
		718	25	3			0.07	0.09	0.01 (0-0.3)	0.9 *(0.09-3.1)	0.04 (0.02-0.08)	0.05 (0.03-0.09)
Lutjanus russelli	snapper	718	4	10	28	53	0.26	0.33	0.82 (0.23-1.72)	0.86 (0.24-2.28)	0.23 (0.15-0.34)	0.38 (0.19-0.65)
Lutjanus sebae	snapper	718	22	1	31	96	0.03	0.04	0.31 (0.19-0.44)	0.31 (0.21-0.42)	0.08 (0.06-0.11)	0.09 (0.06-0.12)
Lutjanus vitta	snapper	712	10	7			0.28	0.35	0.48 (0.23-0.78)	0.74 (0.1-1.75)	0.19 (0.14-0.27)	0.29 (0.17-0.45)
		713	26	2	28	43	0.13	0.16	0.17 (0.12-0.23)	0.3 (0.17-0.5)	0.07 (0.05-0.09)	0.12 (0.08-0.16)
		718	2	11			0.38	0.48	0.43 (0.21-0.63)	0.88 (0.29-1.88)	0.16 (0.11-0.23)	0.62 (0.27-1.19)
Paracaesio gonzalesi	snapper	573	1	23	25	54	~1	1.25	0.53 (0.16-1)	0.82 (0.002-4)	0.29 (0.18-0.49)	0.43 (0.2-0.72)
Pinjalo lewisi	snapper	573	3	15	30	58	0.55	0.69	0.12 (0.08-0.16)	0.26 (0.18-0.37)	0.04 (0.03-0.05)	0.11 (0.08-0.15)
Pinjalo pinjalo	snapper	712	80	4	31	78	0.04	0.05	0.09 (0.06-0.14)	0.09 (0.06-0.13)	0.03 (0.02-0.04)	0.03 (0.02-0.04)

Credit Author Statement

Donna Dimarchopoulou: Conceptualization, Methodology, Formal analysis, Writing – Original Draft, Writing – Review & Editing

Peter J. Mous: Conceptualization, Methodology, Writing – Original Draft, Funding acquisition, Project administration

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Elle Wibisono: Methodology, Data Curation, Writing – Review & Editing

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