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EVALUATION OF LENGTH-BASED STOCK ASSESSMENT APPROACHES: A PRELIMINARY ASSESSMENT OF THE STATUS OF *PAGELLUS BELLOTTI* AND *GALEOIDES DECADACTYLUS* IN SIERRA LEONE COASTAL WATERS

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ABSTRACT

The length-based spawning potential ratio (LBSPR) and mean length mortality estimator (MLZ) are widely used methods for assessing the status of data-poor fisheries management. The aim of this study was to conduct a preliminary assessment of the status of *Pagellus bellotti* and *Galeoides decadactylus* in Sierra Leone's coastal waters using LBSPR and MLZ. The length-frequency data were collected from the industrial fleets from 2018 to 2020. The estimated average spawning potential ratio (SPR) from the deterministic life-history parameters was 1.9% and 1.7% for *P. bellotti* and *G. decadactylus* respectively, while the average SPR from stochastic for *P. bellotti* and *G. decadactylus* were 1.7% and 2%, respectively. The SPR of both stocks was far below the limit reference point (SPR=20%), indicating that the recruitment of these stocks is threatened. The length at which 50% of the fish were selected was less than the length at which 50% of the stock had matured. This translates to high fishing pressure (F/M > 1) for both species. The MLZ average relative fishing mortality (F/M) obtained for *P. bellotti* and *G. decadactylus* were 3.56 and 3.26, respectively. These values are greater than one, indicating that the stocks are overfished. The LBSPR model captures the general trends in fishing mortality and spawning stock biomass of the Icelandic cod stock assessment model with slight variation. This shows that LBSPR is a cost-effective tool for analysing data-limited stocks.

Keywords: length-based stock assessment, SPR (spawning potential ratio), F/M (fishing mortality), overfishing, Sierra Leone.

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1 INTRODUCTION

1.1 Context

Although Sierra Leone is a small country on the African continent, it has a coastline of nearly 485 km, accounting for almost one-third of its national boundaries. Sierra Leone has an Exclusive Economic Zone (EEZ) of 200 nautical miles, covering approximately 159,300 km^2. The EEZ covers a continental shelf area of approximately 26,611 km^2 and is characterised by a broader scope in the north, at approximately 140 km, tapering to approximately 32 km in the south (Figure 1). The coastal fishing area within six nautical miles is approximately 18,302 km^2 (Heymans & Vakily, 2004). The annual offshore surface (0-5 m) water temperature variation is less than 4°C, with a range of 25-28°C. Salinity varies between 15 and 35 parts per thousand, and dissolved oxygen levels range from 4 mg/l to 4.5 mg/l (Zhuang et al., 2019). See Figure 1.

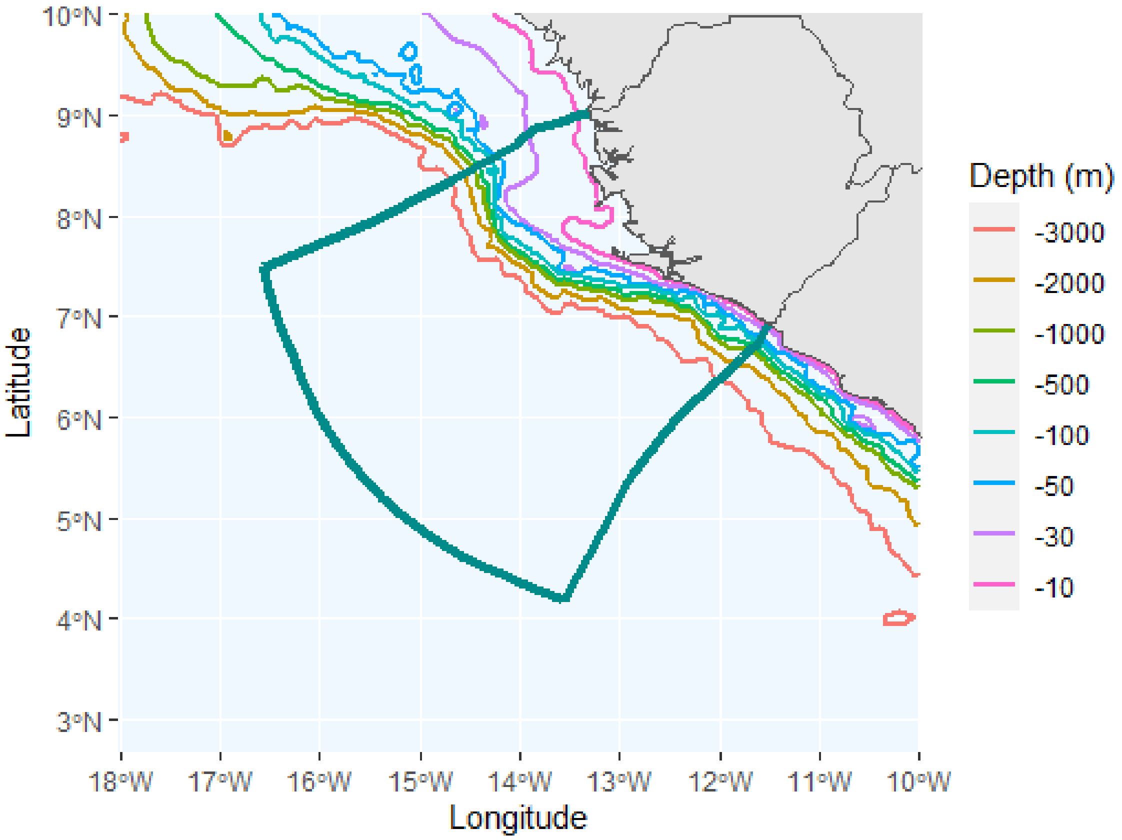

Figure 1. Map showing the Sierra Leone EEZ (green line) and depth contours in meters.

Similar to many other countries in West Africa, Sierra Leone contains a diverse and valuable array of fish stocks in both marine and freshwater environments. The fisheries sector is a significant economic branch of the country (Green et al., 2012). Sierra Leone's fisheries are worth an estimated harvestable value of over US$100 million annually, with a total biomass value of approximately US$500 million (MFMR, 2020). The fisheries industry is estimated to provide employment and a source of livelihood for over 500,000 people, mainly in coastal communities (Seisay, 2006). Fish is the most significant source of animal protein for most of the population in Sierra Leone (Neiland et al., 2016). The fisheries sector's contribution to

Sierra Leone's GDP is estimated to be 10.2% annually; however, this estimate is restricted only to fish-catching activities (Sheku & Andrew, 2019).

The management of fisheries resources in Sierra Leone is the responsibility of the Ministry of Fisheries and Marine Resources (MFMR). Various control measures, such as fishing gear types and mesh size restrictions, are used to manage fisheries. These are based on the 1994 Fisheries Management and Development Act and the 2020 fisheries regulations. They specify a minimum mesh size of 60 mm for demersal and pelagic trawl nets at the cod end. For the shrimp trawl net, a minimum mesh size of 45 mm is stipulated, and a 30 mm mesh size is specified for the seine. Additionally, licenced foreign trawlers must land 40% of their total catch for sale in local markets, while licenced foreign shrimp trawlers must land 70% of the bycatch and 5% of the shrimp captured during each fishing trip (Sheku & Andrew, 2019).

The fisheries resources of Sierra Leone have been subjected to continual exploitation for decades by commercial fishing vessels and artisanal fishing fleets (MFMR, 2020). Previous and current estimates indicate a decrease in the biomass of key commercially exploited fish species, with evidence of overfishing in 2020 (Johannessen, 2020). This is because of the weak implementation of management measures and inadequate enforcement capabilities to ensure compliance (MFMR, 2020).

1.2 Rationale

Sparidae *Pagellus bellotti* and Polynemidae *Galeoides decadactylus* are among the essential demersal species for both the industrial and artisanal fisheries of Sierra Leone. Despite their commercial value, few biological studies have been conducted on these species in the Sierra Leonean and West African sub-regions. Therefore, this study is important because it provides information on the status of these species for the present and future management of these resources.

1.3 Aim

This project aimed to conduct a preliminary assessment of two commercially important fish species in the territorial waters of Sierra Leone.

1.4 Specific Objectives

1. Use data-limited methods LBSPR and MLZ to assess the stocks status of *Pagellus bellotti* and *Galeoides decadactylus.*
2. Test how the uncertainty in the life-history parameters of each stock affects the stock status derived from data-limited methods.
3. Explore data-limited methods' abilities to accurately predict the status of data-rich stocks using Icelandic cod as an example.

2 LITERATURE REVIEW

2.1 Sierra Leone and neighbouring countries marine zone, catches and primary production

Figure 2 and Table 1 show comparisons of annual national catches (100s t) and factors relating to fisheries productivity in Sierra Leone and neighbouring West African countries for 2002-2011, respectively. Ivory Coast and Ghana have much smaller shelf areas but significantly larger EEZs than Sierra Leone. Primary productivity is comparable between Sierra Leone and Ghana, but fisheries catch for Ghana is much higher than for Sierra Leone. The higher catch rate could be related to the nature of the fishery, including the craft and fishing gear used.

Table 1. Comparison of factors relating to fishery productivity in Sierra Leone and neighbouring countries from 2002-2011. Source: (Vakiley et al, 2012)

Factor	Senegal	Guinea	Sierra Leone	Liberia	Ivory Coast	Ghana
EEZ (km^2)	157,550	109,456	159,300	246,152	174,545	224,908
Shelf area (km2)	21,835	48,122	26,611	17,962	11,824	22,501
Inshore Fishing Area (km^2)	16,943	17,761	18,302	14,176	8,332	16,699
Total catch for the year 2011	427 133	115 000	199 000	8 000	71 719	333 524
PP (mgC·m-^{2}·day-1)	1396	1002	686	613	774	691

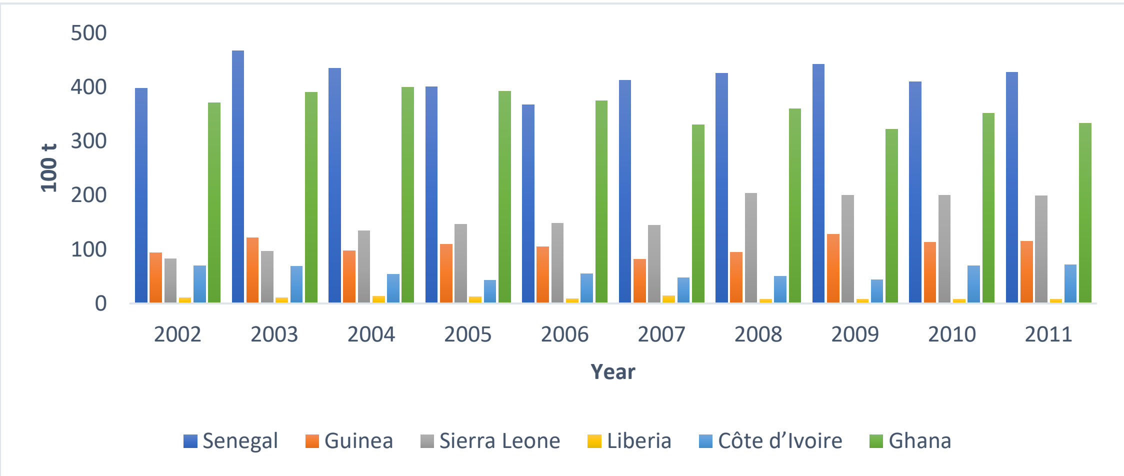

Figure 2. Comparison of annual national catches (100s t) from neighbouring West African countries from 2002-2011 (Vakily et al., 2012).

2.2 General status of *P. bellotti* and *G. decadactylus* in West Africa

2.2.1 Pagellus bellottii

Pagellus bellottii (Figure 3) is a tropical and subtropical demersal species that occupies hard sandy bottoms at depths of approximately 250 m (Johannessen, 2020). The species belongs to the family Sparidae and is commonly known as red pandora (Berg, 1958). It is found in schools, mainly in the upper 100 meters. Sporadic spawning occurs from the second year onwards between May and November and varies with latitude; it moves toward the coast for this reason (Koranteng & Pitcher, 1987). It is one of the most copious Sparidae species on the coast of West Africa. It is an essential element of multispecies coastal demersal fisheries in the Eastern Central Atlantic. The red pandora is one of the most valuable demersal fish landed at ports and beaches by the West African fleets (Koranteng & Pitcher, 1987).

Lazar (2017) and Amponsah et al. (2016) reported a maximum age of red pandora of 6.38 and 7 years, respectively, while Konoyima and Seisay (2021) reported a maximum age of the species as 5.5yr in the EEZ of Sierra Leone.

There have been considerable declines in biomass registered in Sierra Leone, Guinea, Senegal, and Ghana, and the stock is deemed to have been overharvested in these countries. Amponsah et al. (2017), Russell and Carpenter (2014), and Lazar (2017) reported overexploitation of the species on the coast off Ghana. In Sierra Leone, Konoyima and Seisay (2021) reported overfishing.

Red pandora was listed as the least concerned species on the International Union for Conservation of Nature (IUCN) Red List of Threatened Species in 2011 (Russell & Carpenter 2014).

Figure 3. *Pagellus bellottii*, red pandora

2.2.2 Galeoides decadactylus

Galeiodes dacadaylus (Figure 4) is very common and is likely the most common species of the family Polynemidae. It is distributed in the tropical and subtropical regions of the eastern Atlantic Ocean from Morocco to Angola on the west coast of Africa. It seldom occurs in Algeria, northern Africa, Namibia, or southern Africa (Motomura, 2004). It is commonly known as the African threadfin. Threadfin is a demersal species found at depths ranging from 10 m to 70 m over muddy bottoms, neighbouring sandy beaches, estuaries, and lagoons (Maigret & Ly, 1986). It consumes benthic invertebrates, small fish, detritus, and crustaceans. Mangrove communities serve as essential habitats for larvae and juveniles of this species (Moses, 2000). The dry season is the preferred breeding time for the African threadfin; however, it may reproduce throughout the year (De Sylva, 1990).

Overfishing of the threadfin was registered by Lazar (2017) and Wehye et al. (2017) on the coast off Ghana and Liberia, while Sossoupe et al. (2016) reported under fishing of the species on the coast off Benin.

Galeoides decadactylus was listed as near-threatened in 2014 on the IUCN Red List of Threatened Species (Russell & Carpenter, 2014).

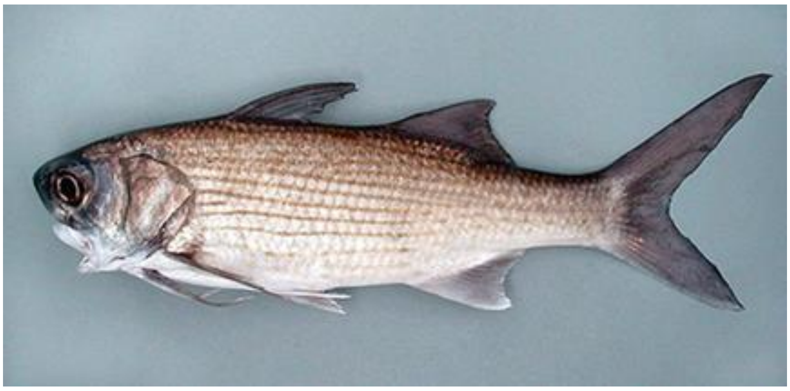

Figure 4. *Galeoides decadactylus*, African threadfin

2.2.3 Species Distribution

In terms of fishing operations and production, the Sierra Leone territorial waters are divided into three fishing grounds, including the southern ground (located between 11° W and 12° W) with target species including pelagic and demersal fish, shrimp, and crabs, the central fishing grounds (located between 07°14′N and 07°34′N), the most important shrimp fishing grounds, and the northern fishing grounds (latitude 07° 40′N and 09° 03′N) with target species including prawns and economical fish as bycatch (Zhuang et al., 2019).

Pagellus bellotti is present in large parts of Sierra Leone's EEZ; however, high abundances are found in the northern sea area with low temperature and higher salinity concentrations. Higher densities are located on the shelf at depths of 20-100m (Johannessen, 2020).

Galeoides decadactylus is widely distributed on the continental shelf of the country's territorial waters, and its distribution has no obvious correlation with the hydrological environment. High concentrations were found at depth of 20-50 m (Johannessen, 2020).

2.2.4 Catch estimate for the two selected species

In 2019, a Chinese research vessel conducted two demersal surveys: S01 (September 2019) and S02 (October 2019). The estimated biomass of *Pagellus bellotti* using the swept area method for the two surveys (S01 and S02) was 2,595 t and 5,927 t, respectively, whereas that of *Galeoides decadactylus was* 2,586 t and 6,236 t for S01 and S02, respectively (Zhuang et al., 2019) (Table 2).

Table 2. Biomass estimation from 2019 of two demersal surveys (S01 and S02) of commercially important fish species in Sierra Leone waters. Source: Zhuang et al. (2019).

Species	**Biomass (tonnes)**	
	Voyage S01	**Voyage S02**
Pseudupeneus prayensis	4,991.42	5,297.53
Pagrus caeruleostictus	3,412.90	5,723.63
Pseudotolithus senegalensis	2,166.31	2,566.05
Galeoides decadactylus	2,585.95	6,235.83
Pagellus bellottii	2,594.67	5,927.35
Brachydeuterus auritus	1,344.78	8,977.75
Eucinostomus melanopterus	538.860	5,56.740
Drepane africana	930.740	593.970
Trichiurus lepturus	1,084.68	1,106.53
Pteroscion peli	774.130	1,010.77

2.3 Icelandic Cod

Cod is abundant on continental shelves and banks of the North Atlantic Ocean and supports considerable fisheries (Brander, 1995). Owing to the extensive global spread of this species, the environments in which different cod populations reside vary greatly (Brander, 1995).

Cod (*Gadus morhua*) is the most significant marine resource in the Icelandic seas. It is the most important exploited groundfish species in Iceland. Its economic importance may have been momentarily overtaken by herring in the twentieth century and probably by Greenland sharks in the nineteenth century (Kurlanski, 1998). The demersal cod is extensively distributed in Icelandic waters, with a reasonably broad range of a few meters to 600 m (MFRI, 2020). Adult cod can be found in various habitats. However, most young cod stocks are protected in shallow kelp and grass settings. The optimal temperature for cod is 4-7ºC; however, the temperature restrictions for this species are somewhat greater. A substantial catch share is obtained when the temperature is less than 2°C (MFRI, 2020).

Cod spawns in smaller regional spawning components across Icelandic waters. Nonetheless, the most significant spawning regions are southwest and west of Iceland. Spawning begins early in spring (March-April) on the primary spawning grounds in the south's warmer waters. Spawning used to start later in the colder seas of the north; however, in recent years, spawning time has advanced dramatically in the north (MFRI, 2020).

2.4 Description of data-limited methods

High resource exploitation rates can lead to the overexploitation of stocks and, thus, reduced biomass, particularly for targeted species. In terms of fishery management, it is necessary to have the latest information on stock status as a reference for determining the management rules that promote sustainable fisheries (Patrick et al., 2010). The methods used to assess stock status are highly dependent on data availability. A stock is data-limited if a full stock assessment cannot be performed, because sufficient data are unavailable. In such cases, data available for an evaluation may be restricted, for example, due to a lack of sampling ability and the economic situation (Bentley, 2015). Simple methods are principally used to assess the status of such stocks based on available data.

Recently, scientists have attempted multiple approaches to find the best way to manage data-limited fisheries. Length-based methods (including Length-Based Spawning Potential Ratio and Mean Length-Based Mortality Estimators) have been developed, described, and tested with simulations by Hordyk et al. (2014) before their application to actual data by Prince et al. (2015). Assessments based on length data are cost-effective because length data are easily obtained. In contrast, obtaining estimates of other parameters, including, but not limited to, the aging process, can be expensive, time-consuming, and challenging. For instance, growth rings on otoliths and scales are difficult to determine in tropical species (Pauly, 1984).

2.4.1 Length-based Spawning Potential Ratio (LBSPR)

The LBSPR technique was built for data-limited fisheries, where little information about the fish stock is available other than a representative sample of the size structure of the population and an understanding of the species' life history (Hordyk, 2021). The LBSPR method does not require an estimation of the natural mortality rate (*M*). Instead, this method uses the ratio of natural mortality to the von Bertalanffy growth coefficient *K* (M/K). This ratio is assumed to vary less than natural mortality across fish populations and species (Prince et al., 2015). The LBSPR model assumes that the population is in equilibrium, and that the length composition is indicative of a stable state of the exploited population.

A Spawning Potential Ratio (SPR) is an index that describes the reproductive capacity of an exploited stock and is commonly used as an immediate management tool to establish reference points for fisheries (Hordyk, 2017). The SPR is the ratio of an exploited stock's current reproductive capacity (SPRx%) to the maximum potential reproductive capacity ($SPR_{100\%}$) when the stock is unfished. SPR is an established biological reference point that can be used to assess the status of stocks in data-limited fisheries (Brooks et al., 2010).

If the SPR of a stock is equal to one (SPR = 1), the stock is considered to be in an unfished state. Conversely, if the SPR of a stock equals zero (SPR = 0), all mature fish have been removed from the stock, or all female fish have been caught (Hordyk, 2017). General guidelines for SPR reference points state that a value of 40% (SPR = 0.4) can be used as a proxy for the maximum sustainable yield (MSY). By contrast, a value of 20% (SPR = 0.2) can be used as an indicative threshold below which recruitment rates are likely to be threatened (Prince et al., 2015; Walters & Martell, 2004). This method is a reliable tool for establishing biological reference points and can be used to regulate fishing mortality to maintain sustainable yields by developing management strategies for data-limited fisheries (Jatmiko et al., 2017).

2.4.2 Mean Length-Based Mortality Estimators (MLZ)

The Mean Length Mortality Estimator (MLZ) is a non-equilibrium-based method developed by Gedamek and Hoening (2006) to analyse the time-series of the mean length. This method expands upon the estimator of Beverton and Holt (1956), which estimates the total mortality (Z) from a single observation of mean length. The development of the MLZ method was motivated by the ability to relax the equilibrium assumptions of the Beverton–Holt method. The aim of developing this non-equilibrium method is to estimate the total mortality. A historical series of mortality rates are determined from a time series of mean length, and the timing of the changes in mortality is estimated using optimisation methods. The MLZ method has been used as a proxy reference point for MSY to determine the overfishing status, for instance, if $F/F_{MSY} > 1$ (Huynh, 2016).

3 METHODOLOGY

3.1 Study area

This study was conducted in the Exclusive Economic Zone (Figure 1) off the six nautical miles zone (Inshore Exclusion Zone) of Sierra Leone.

3.2 Data

3.2.1 Fisheries data

The artisanal sector in Sierra Leone operates in an open-access fishery, making it difficult for proper data collection in that sector. For this study, fish samples were taken randomly by various fisheries observers onboard different commercial bottom trawl fleets that used different fishing gear (including purse seines, gill nets, and hooks on lines) in the Sierra Leone territorial waters (Figure 5). A total of 2,067 and 7,892 *Pagellus bellottii* and *Galeoides decadactylus*, respectively, were length measured throughout the study period (2018-2020).

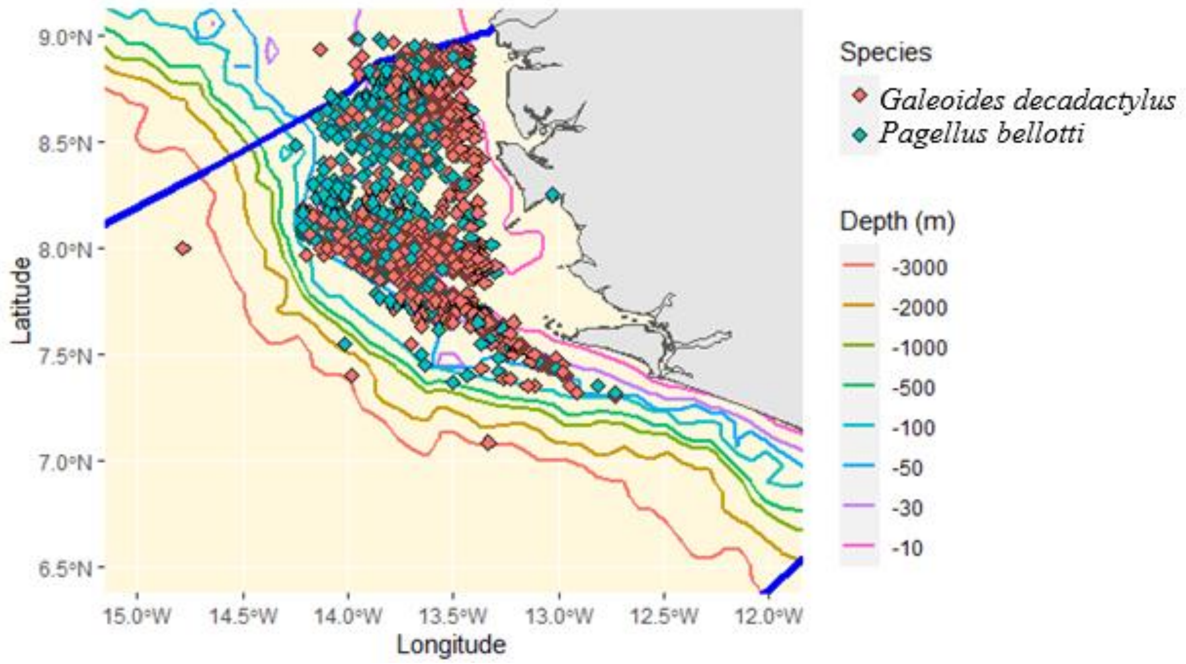

Figure 5. Map showing the Sierra Leone EEZ (blue line), catch position for each species, and depth contours in meters.

Data for the Icelandic cod assessment were obtained from a commercial bottom trawl fleet provided by the Iceland's Marine and Freshwater Research Institute (MFRI). A total of 2,680,016, with an annual average of 52,549 length measurements for 1970-2020 were used.

3.2.2 Biological parameters

The life history parameters (Table 3) related to stocks were obtained from several studies that used different methods to estimate these parameters. After several trials with other authors' life-history parameters, Lazar (2017) estimated life-history parameters (L_∞, M, K, L_{50}, and L_{95}) for both species were used. This is because Lazar's estimate provides better results than those of other authors.

Table 3. Life history parameter values (K, L∞, M, L50 and L95) for the two stocks (red pandora and threadfin) and the corresponding source of information.

	Parameters							
Species	K/yr	L_∞, (cm-TL)	M/yr	L_{50} (cm-TL)	L_{95} (cm-TL)	Country	Reference	Comment
P.bellottii	0.42	19.43	1.10**	9.9*	12.5	Ghana	Amponsah et al. (2016)	Growth overfishing reported
	0.53	34.20	1.12**	21.0	24.2***	Ghana	(Asabere-Ameyaw, 1999; 2000)	Overfishing is reported
	0.42	31.7	0.96**	14.4*	16.5*	Ivory coast	Kouame et al. (2020)	Fork length (cm) was used as a unit of measurement.
	0.28	34.8	0.60	16.5	18.9***	-	(Thorson et al., 2017)	Estimate from FishLife R package
	0.51	46.5	1.11**	27.0*	31.5*	Ghana	Lazar (2017)	Overexploitation reported
G. decadactylus	0.18	54.1	0.49**	13.8*	25.2*	Liberia	Wehye & Amponsah, (2017)	Growth overfishing observed
	0.19	39.6	0.36**	17.2*	21.1*	Ghana	Amponsah et al. (2021)	Overexploitation reported
	0.80	26.3	1.64**	15.4*	20.0*	Benin	Sossoukpe et al. (2016)	under-fishing reported
	0.47	47.8	0.93**	27.5*	36.0*	Ghana	Lazar (2017)	Overexploitation reported

**Empirical estimation; * logistic curve; K &L∞ are obtained from von Bertalanffy growth function; ***L95 = 1.15 x L50 (Cousido-Rocha et al., 2022).

3.3 Data-limited models

3.3.1 LBSPR

The open-source statistical software R (version 4.1.1) with the LBSPR (version 0.1.6) package was used to estimate the selectivity lengths (SL_{50} and SL_{95}), relative fishing mortality (F/M), and spawning potential ratio (SPR).

The model was fitted to length-frequency data of catch composition from 2018-2020. The input parameters for the model included: natural mortality (M), the von Bertalanffy growth parameters (asymptotic length-L_{∞}, growth coefficient-K), and size-at-maturity (L_{50} and L_{95}). The L_{50} and L_{95} parameters correspond to the lengths at which 50% and 95% of the stock is expected to mature, respectively. The estimates for these parameters were obtained from the literature (see Table *3*). The target reference point spawning potential ratio (SPR) was set at 40% or 0.4; this is the value that serves as a proxy for MSY. The SPR limit reference point was set at 20% or 0.2, which is the minimum threshold at which recruitment rates are likely to be threatened. These values are based on the recommendations of Hordyk et al. (2017). The model output was visualised using the LBSPR R package.

The uncertainty in SPR was calculated using Monte Carlo simulations with 1000 bootstrapped iterations. The iterations were generated by assuming covariance values for CV-L_{∞} and CV-M/K of 0.1 and 0.2, respectively, and these values were fixed. The model was subsequently run using each iteration of the input parameters, resulting in 1000 estimates of SPR. The distribution of SPRs was plotted using boxplots for each year and compared with the deterministic values resulting from the model using the fixed parameters from Table 4. Uncertainty analysis was performed using functions modified from the stochastic LBSPR R repository developed by Cope (2020).

3.3.2 MLZ

The open-source statistical software R (version 4.1.1) with MLZ (version 0.1.3) package was used to estimate a historical series of total mortality rates for both species over a three-year period (2018-2020).

The model was fitted to length-frequency data of catch composition from to 2018-2020. The input parameters included the length at first capture (the length at which animals are fully vulnerable to the fishery and gear) and Von Bertalanffy growth parameters (L_{∞}, k). The estimates for these parameters were obtained from Lazar (2017) (see Table *3*). The model output was converted to relative fishing mortality (F/M) using Gulland’s (1969) formula: total mortality (Z) = fishing mortality (F) + natural mortality (M).

3.4 Comparison of LBSPR and the Icelandic cod assessment model

To assess the usefulness of the LBSPR method and evaluate its potential to provide a tool for the cost-effective assessment of data-poor fisheries, such as Sierra Leone, an empirical test was conducted by comparing the cod LBSPR model (data-poor assessment) against the analytical stock assessment model utilised by the Marine and Freshwater Research Institute (rich-data assessment), Iceland (MFRI, 2020). For the LBSPR model, length-frequency data for commercial bottom trawls from 1970-2020 were used as inputs for the model. All input parameters were either obtained from the literature or estimated from the data. Growth parameters were estimated from data by fitting a von Bertalanffy model using the FSA R package (Ogle et al., 2022). The L_{50} parameter was taken from Marteinsdottir and Begg (2002), and L_{95} was estimated from the maturity data collected by the MFRI. The Icelandic cod stock assessment used a natural mortality coefficient of 0.2. Therefore, this value was used to convert the resulting F/M ratios to F ratios for comparison with the official stock assessment.

4 RESULTS

4.1 Stocks status

4.1.1 Pagellusbellotti-LBSPR

The spawning potential ratio, relative fishing mortality (F/M), and selectivity (SL_{50} and SL_{95}) were estimated with 95% confidence intervals for the period 2018–2020 (Figure *6*). The results showed a very low spawning potential ratio with an average of 1.9% throughout the study period. The lengths at 50% selection (SL_{50}) from 2018 to 2020 were 14.51, 19.54, and 20.58, respectively (Figure *7*). The average relative fishing mortality obtained was 6.66 (Table *4*).

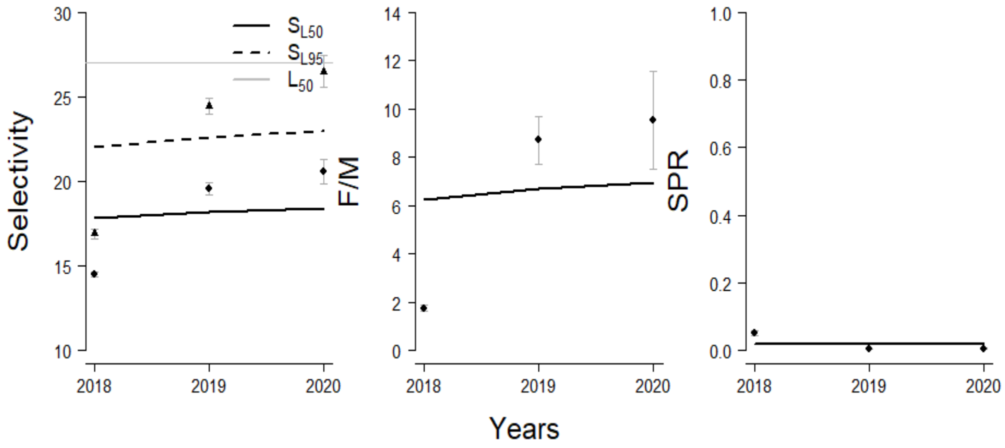

Figure 6. Estimated selectivity at maturity (left), relative fishing mortality (middle), and deterministic SPR (right) of *P. bellotti*. In each graph, the estimates and variances for each year are shown. The solid lines show the smoothed estimates.

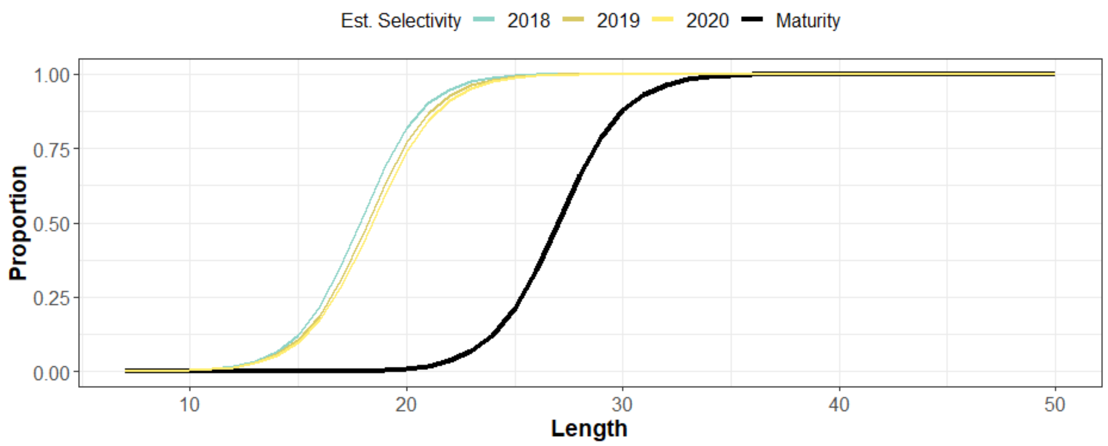

Figure 7. The yearly estimated selectivity curve (coloured lines) and the specified maturity size (black line) of P. bellotti.

Table 4. Estimated length selectivity (SL50, SL95), relative fishing mortality (F/M), and spawning potential ratio (SPR) of P. bellotti.

Year	SPR	SL50	SL95	F/M
2018	0.050±0.0000160	14.51±0.007	16.91±0.02	1.74±0.004
2019	0.003±0.0000002	19.54±0.032	24.44±0.06	8.70±0.265
2020	0.004±0.0000011	20.58±0.137	26.49±0.23	9.55±1.077

When considering the uncertainty in the growth parameters, the median SPR was similar to the deterministic SPR values (Figure *8* and Table *4*). In 2018, the median SPR was 1% lower than the deterministic value, whereas in 2019 and 2020, the median SPR was 0.7% and 0.6% higher than the deterministic values for *P. bellotti (*Figure 8 and Table *4*), respectively. The variation in growth parameters had a greater impact on the resulting SPR in 2018 than in 2019 and 2020. Here, the distribution of SPRs ranged from 0-12%, whereas in 2019 and 2020, the distribution was generally smaller than 3%.

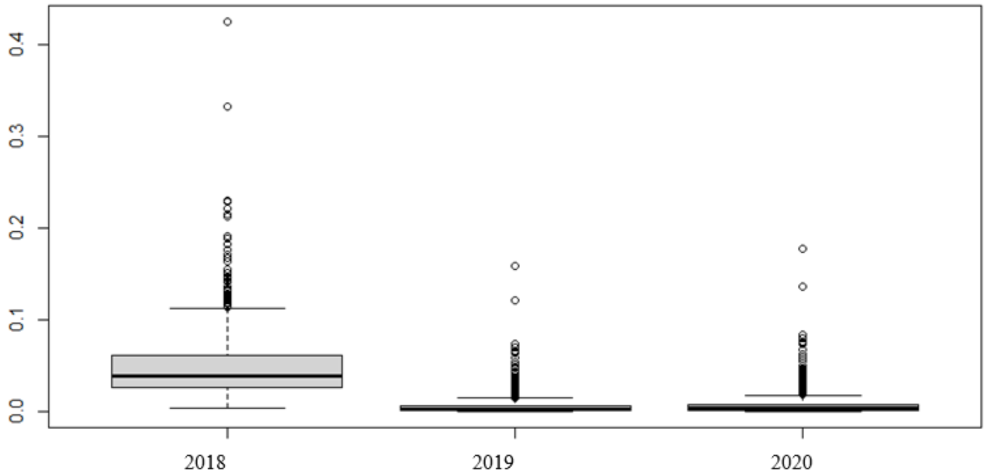

Figure 8. The SPR stochastic boxplot of *Pagellus bellotti* from 2018-2020.

4.1.2 Galeoides decadactylus-LBSPR

The spawning potential ratio, relative fishing (F/M), and selectivity length (SL_{50} and SL_{95}) were estimated with 95% confidence intervals for each year from 2018 to 2020 (Figure 9). The average relative fishing mortality (F/M) obtained for *G. decadactylus* was 4.2. An average of 1.7% was found for the SPR, and the average length at which 50% of the fish were caught (SL_{50}) was 15.8 cm (Figure 10 and Table 5).

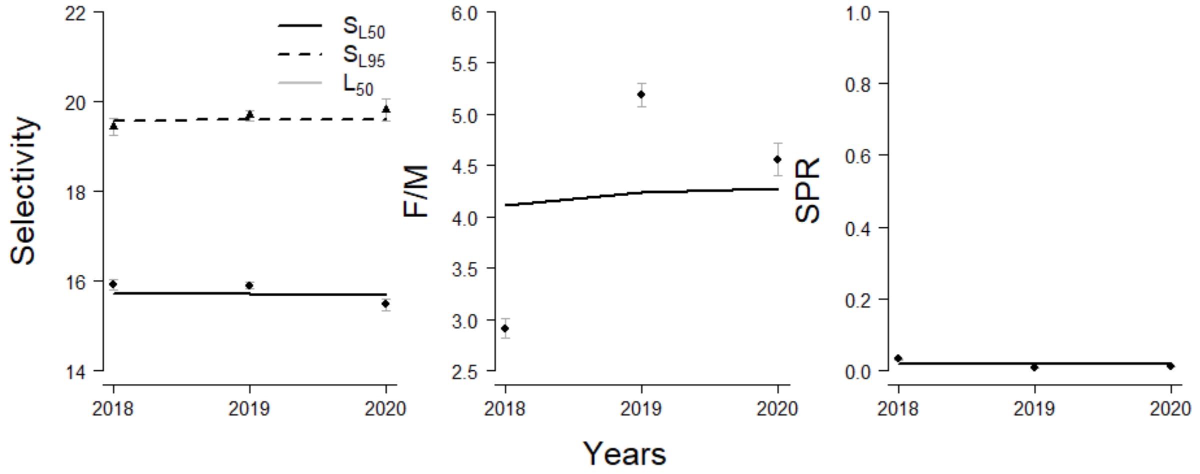

Figure 9. Estimates by year (with 95% confidence interval): estimated size selectivity at maturity (left), relative fishing mortality (middle), and deterministic SPR (right) of G. decadactylus. Estimates and variances for each year, solid lines smoothed estimates.

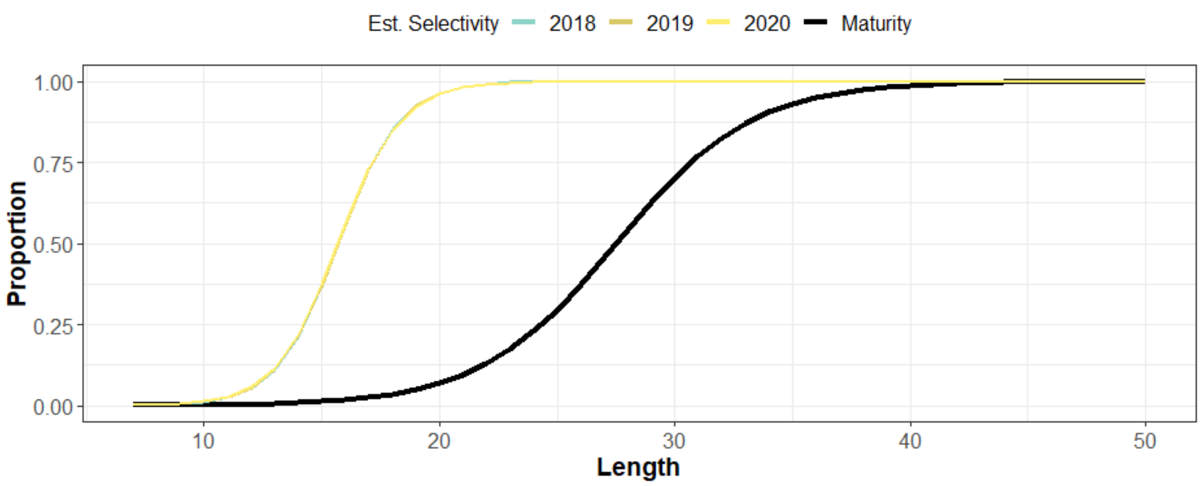

Figure 10. Maturity-at-length: the yearly estimated selectivity curve (coloured lines) and the specified size of maturity (black line) of G. decadactylus.

Table 5. The estimated length selectivity (SL50, SL95), relative fishing (F/M), and spawning potential ratio (SPR) of G. decadctylus.

Year	SPR	SL50	SL95	F/M
2018	0.03±0.00000116	15.91±0.0030	19.44±0.0098	2.91±0.0022
2019	0.01±0.00000004	15.89±0.0013	19.68±0.0039	5.19±0.0035
2020	0.01±0.00000017	15.47±0.0049	19.81±0.0144	4.56±0.0065

The results of the uncertainty analysis showed that the stochastic median SPR is the same as the deterministic SPR values in each year (Figure 11 and Table 6). The variation in growth parameters observed in 2018 had a greater impact on the resulting SPR. Here, the distribution of SPRs ranged from 0-10%, whereas in 2019 and 2020, the distribution was generally smaller than 3% (Figure 11).

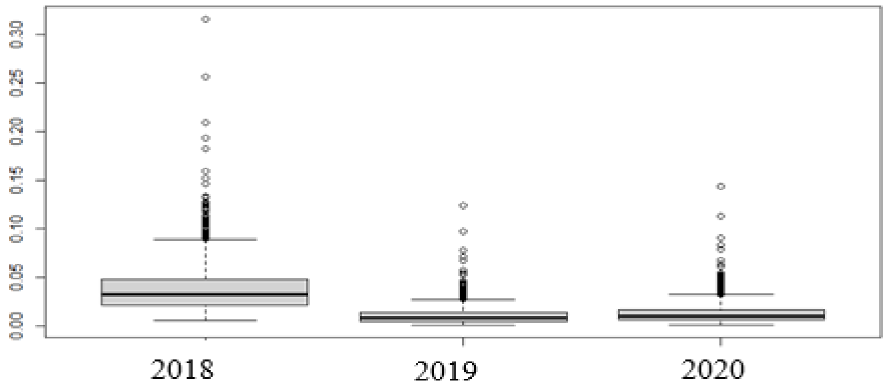

Figure 11. SPR stochastic boxplot estimate of *G. decadactylus* from 2018-2020.

Table 6. Summary of LBSPR static and LBSPR stochastic values for both species (*P.bellotti* and *G.decadactylus*) from 2018-2020.

Year	Deterministic/Static SPR		Median stochastic SPR	
	Species		Species	
	P. bellotti	*G. decadactylus*	*P. bellotti*	*G. decadactylus*
2018	0.050	0.03	0.04	0.03
2019	0.003	0.01	0.01	0.01
2020	0.004	0.01	0.01	0.01

4.2 MLZ Relative fishing mortality and length at first capture

MLZ average relative fishing mortality values obtained were 3.56 and 3.26 for *P. bellotti* and *G. decadactylus,* while the average length at first capture were 18.75 and 16.80 for the two species, respectively (Table 7 and Figure 12).

Table 7. Average relative fishing mortality (F/M) and the length at first capture (SL50) estimates for the two models (LBSPR and MLZ) from 2018 to 2020.

Model	**Parameter**	**Species**	
		P. bellotti	*G. decadactylus*
MLZ	F/M	3.56	3.26
	SL50	18.75	16.8

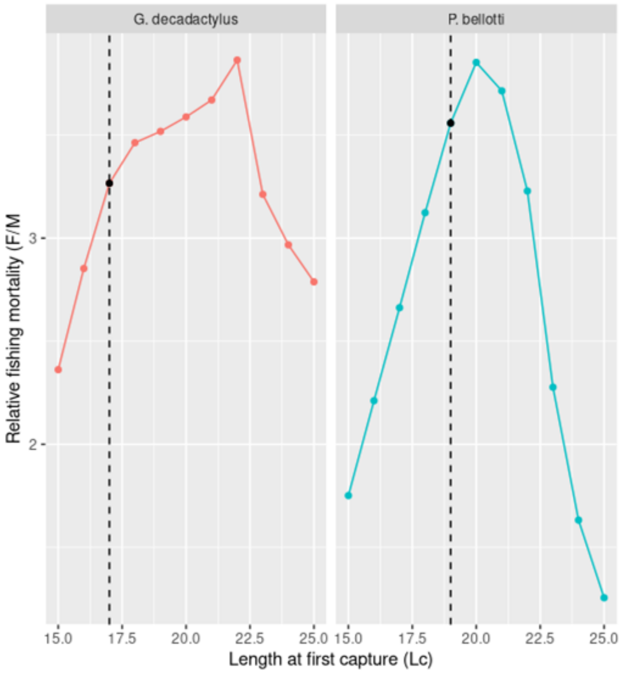

Figure 12. The change in relative mortality (solid lines) as length at first capture (Lc) varied between *G. decadactylus* and *P. Bellotti*. The vertical dotted lines are aligned with the estimate of Lc used in the model.

4.3 Comparison of LBSPR and the Icelandic cod assessment model

The LBSPR model captured the general trends in fishing mortality of the Icelandic cod stock assessment model. However, its ability to match the stock assessment model varies significantly on a year-to-year basis. For instance, the general increase from 1980 to 1990 and the subsequent decline until the present are captured; however, fishing mortality is overestimated in the '70s and 2000s, and some peaks, for instance in 1978, were missed (Figure *13*).

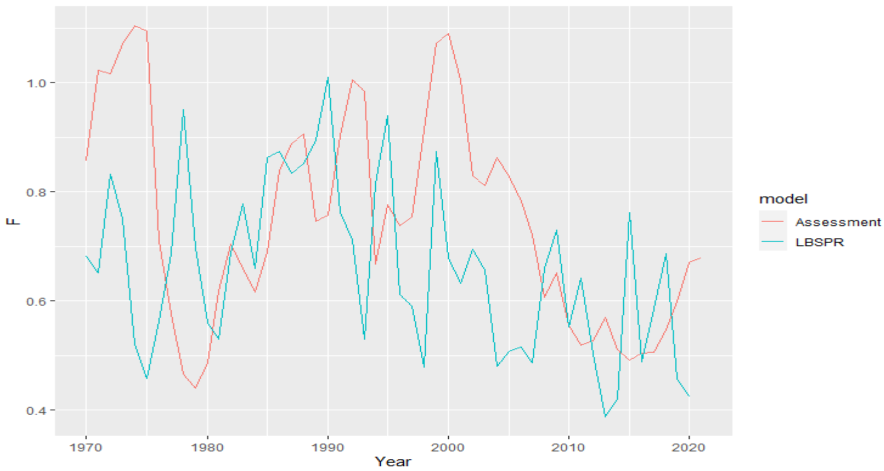

Figure 13. Comparison of the fishing mortality of the LBSPR model (red line) and Icelandic assessment (blue line) of Iceland cod.

The general trends in the Icelandic cod spawning stock biomass (SSB) are reflected in the SPR (Figure *14*). For instance, the increase in SSB from the early 1990s to the present is also seen in the SPR. However, similar to the fishing mortality results, the correlation between SSB and SPR varied significantly between the years (Figure 14).

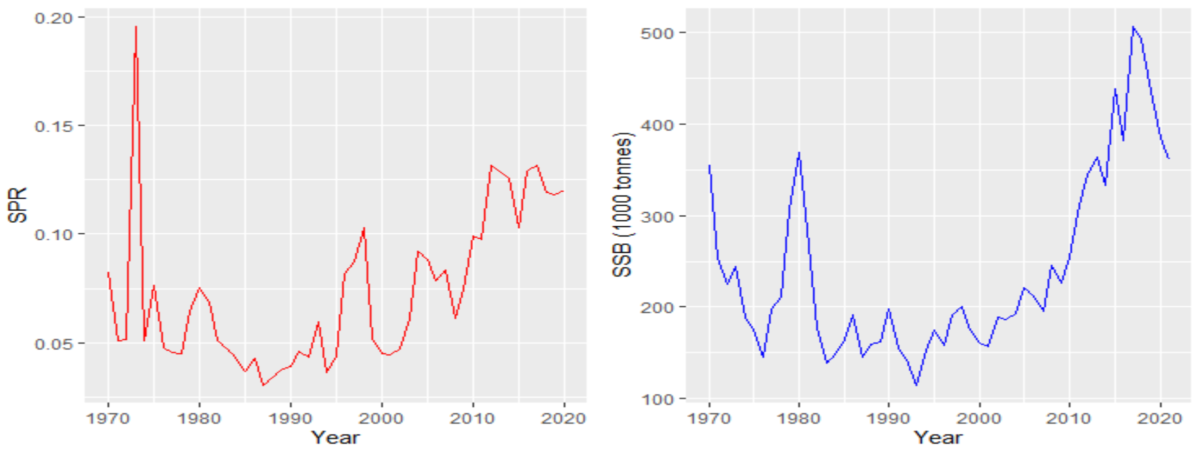

Figure 14 Comparison of LBSPR model SPR (red line) and the Icelandic assessment SSB (blue line)

5 DISCUSSION

5.1 Stocks status

In this study, two data-limited methods were applied to assess the status of the two stocks in the EEZ of Sierra Leone. The results show that both types of stocks are heavily overfished. When using Monte Carlo simulations to calculate SPR, the result shows a low SPR, which indicates that the stock's recruitment status is threatened.

This project provides information on the first application of LBSPR and MLZ approaches to assess fish stocks in the Sierra Leone EEZ. The LBSPR and MLZ approaches, advanced by Hordyk et al. (2014) and Gedamek & Hoening (2006), were developed to estimate data-limited stocks' SPR and total mortality, respectively. These techniques were not created to replace more precise, age-structured assessment techniques; instead, they were designed to provide broad applicability and cost-effective starting points for longer-term data collection, assessment, and management procedures where there are few, if any, pre-existing data and few alternative possibilities.

Accounting for variations in growth parameters and M/K in the LBSPR model resulted in median SPR values that were similar to the deterministic SPR values for both species. However, in 2018, the median SPR for *P. Bellotti* was 1% lower than the deterministic value, whereas the median SPR obtained for *G. decadactylus* was the same as the deterministic value for each year. In 2019 and 2020, no SPR variation was observed for either species. The variation in growth parameters observed in 2018 had a greater impact on the resulting SPR. In 2018, the distribution of SPRs ranged from 0-12% and 0-10%, whereas in 2019 and 2020, the distribution was generally less than 3% for both *P. Bellotti* and *G. decadactylus*. The low SPRs values (< 20%) obtained in this study indicate that the recruitment rate is threatened and the collapse of stocks is likely (Goodyear, 1993). Similar low SPR value was recorded by Yonvitner et al. (2021), who obtained an average SPR of 2% of the *Upeneus sp* stocks studied in the Sunda Strait, Indonesia. Ba (2019) also reported an SPR below 2% for *Merluccius polli* and *M. senegalensis* on the coast off Morocco, Mauritania, and Senegal.

The length at which 50% of the stock was caught (SL_{50}) was found to be lower than the length at which 50% of the stock matured (L_{50}). This translated to highly high fishing pressure (F/M > 1) for both *P. Bellotti* and *G. decadactylus*, with an average of 6.66 and 4.22, for the LBSPR model; 3.56 and 3.26 for the MLZ model, respectively. The slight differences in fishing pressure between the two stocks could be attributed to the differences in their distribution and body shape. A high concentration of *P. bellotti* was found slightly offshore (20-50 metres depth) and it had a compressiform body shape. This could be a disadvantage for the species in fishing nets. *G. decadactylus* with the slightly lower fishing pressure was found to be highly concentrated at (10-30 metres depth) (prohibited area for the industrial fleet). It has a fusiform body shape, which could serve as an advantage to the species because it has a high chance of escaping the fishing net. Johannessen (2020) also observed a similar distribution of the species during the *Dr. Fridtjof Nansen* 2020 survey on the coast off Sierra Leone.

To be more precise in the assessment of the status for each stock, MLZ was used to estimate the total mortality, which was converted to relative fishing mortality (F/M) using stock-specific estimates of natural mortality. A high relative fishing mortality was detected by both models, with slightly lower results from the MLZ model. The higher value of relative fishing mortality (F/M > 1) indicates that the stocks are receiving high fishing pressure, indicating that the stocks are overfished. Lazar (2017) also reported the overfishing of this stock on the coast off Ghana. Amponsah et al. (2016) and Asabere-Ameyaw (1999; 2000) also reported overexploitation of the red pandora on the coast off Ghana, whereas Amponsah et al. (2021) and Wehye and Amponsah (2017) reported growth overfishing of the threadfin on the coast off Ghana and Liberia, respectively.

Despite the variability and the inability of the LBSPR to significantly match the year-to-year output of the Icelandic cod stock assessment model, the LBSPR model captured the general trends in fishing mortality and the spawning stock biomass of the Icelandic cod stock assessment model. A similar study was conducted by Huynh et al. (2020), who compared mortality estimates from three methodologically related mean length-based methods to those from age-structured models in six stocks in the south-eastern United States. Huynh et al. (2020) noticed that three of the length-based mortality estimators performed less well for low M/K stocks but concluded that the length-based mortality estimators are attractive as alternatives to age-structured models due to the simpler data requirements and ease of use.

6 CONCLUSION

The SPRs estimated for the two local stocks are below the limit reference point (SPR=20%), which is the threshold for the minimum reproduction of fish stocks for a sustainable fishery. The average SPR estimated for both species was 2%, indicating that the sustainability of *Pagellous bellotti* and *Galeoides decadactylus* is questionable, because recruitment is threatened. The length at which 50% of the stock was caught (SL_{50}) was found to be lower than the length at which 50% of the stock matured (L_{50}); this created an extremely high fishing pressure (F/M>1) as fish are caught before allowing them to spawn at least one time. The MLZ total mortality estimates were also high, confirming the results of LBSPR. The comparison between models shows that the LBSPR model captured the general trends of a data-rich analytical stock assessment, suggesting that the LBSPR model can provide a better tool for cost-effective evaluation of data-poor fisheries such as Sierra Leone.

The LBSPR model is highly sensitive to life history parameters (Prince et al., 2015). This means that we expect the variation in SPR to result from variations in the growth parameters. Therefore, we have high confidence in the conclusions of this study because when uncertainty in growth parameters was considered, the conclusion that each stock was below its critical SPR threshold did not change.

7 RECOMMENDATION

If stocks are to be sustainably managed, the current fishing gear needs to be adjusted to allow a higher proportion of stocks to reach their length at first maturity (L50) before being caught, which can reduce the high fishing pressure found during this study. However, this should be accompanied by proper monitoring of industrial fleets.

Detailed studies of the maturity status and growth of these species are recommended to obtain stock-specific input parameters for data-limited models.

Continuous collection of length-frequency data is also recommended to obtain high-quality data for use in future data-limited stock assessments and before drawing solid conclusions on the status of stocks.

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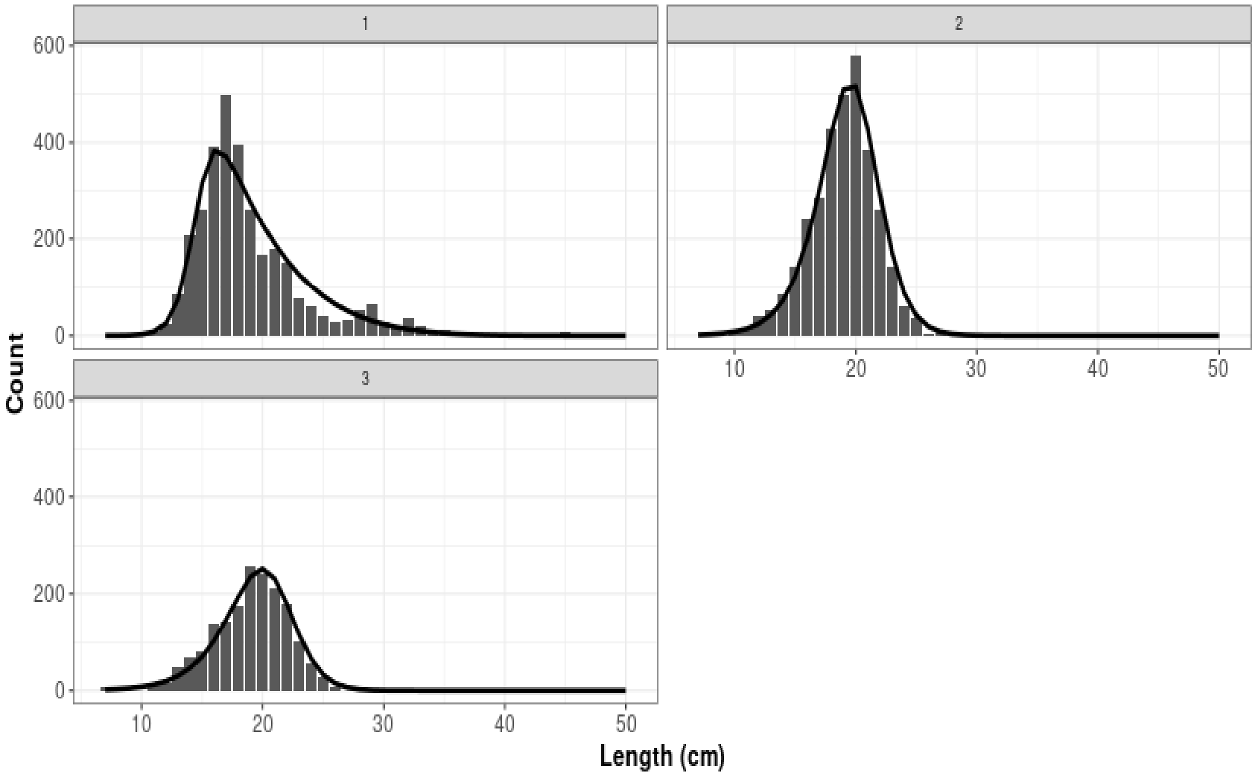
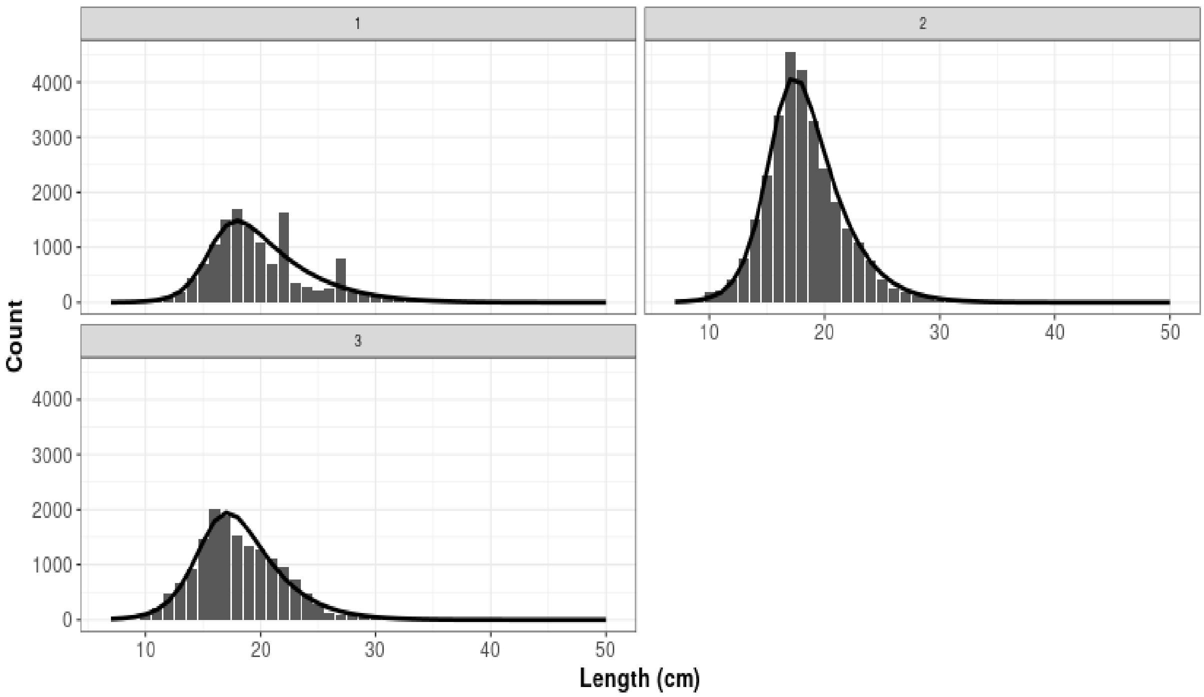
APPENDIX



Data: Histogram of Length Data: Size distribution (bar) and curve fitting (solid line) of P. bellotti.



Data: Histogram of Length Data: size distribution (bar) and curve fitting (solid line) of G. decadactylus.

Pagellus bellotti data used

Length	2018	2019	2020
7	1	0	9
8	0	0	0
9	1	0	0
10	0	13	0
11	8	16	12
12	25	40	16
13	87	54	47
14	206	86	70
15	259	143	79
16	390	241	138
17	496	284	140
18	397	429	173
19	259	498	258
20	167	578	239
21	179	384	212
22	151	260	180
23	77	141	101
24	62	59	56
25	40	37	27
26	29	4	9
27	31	9	1
28	54	8	0
29	66	4	1
30	26	0	2
31	21	1	0
32	36	0	0
33	20	0	1
34	8	0	0
35	10	0	0
36	1	0	0
37	0	0	0
38	2	0	0
39	1	0	0
40	0	0	1
41	0	0	0
42	0	0	0
43	0	0	0
44	0	0	1
45	6	0	0
46	0	0	0
47	0	0	0
48	0	0	0
49	0	0	0
50	0	0	0

Galeoides decadactylus data used

Length	2018	2019	2020
7	6	0	0
8	6	13	2
9	11	32	2
10	28	195	132
11	38	233	227
12	98	403	473
13	180	801	664
14	454	1501	914
15	703	2318	1466
16	1062	3386	2011
17	1488	4535	1884
18	1690	4235	1533
19	1370	3281	1325
20	1069	2422	1284
21	686	1820	1125
22	1616	1354	963
23	352	1080	744
24	286	760	466
25	216	411	270
26	263	250	129
27	797	184	91
28	198	121	78
29	161	104	55
30	111	42	47
31	62	58	16
32	64	30	6
33	67	40	14
34	46	14	4
35	24	29	8
36	10	15	0
37	3	13	0
38	3	3	0
39	5	5	0
40	2	3	0
41	1	2	0
42	0	1	0
43	0	3	0
44	1	4	0
45	0	0	0
46	1	0	0
47	1	0	0
48	0	0	0
49	0	1	0
50	0	0	0