grocentre.is/ftp Final Project 2021

EVALUATION OF LENGTH-BASED STOCK ASSESSMENT APPROACHES A PRELIMINARYASSESSMENT 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 status for data-poor fisheries management. The aim of this study is to conduct a preliminary assessment of the statuses of *Pagellus bellotti* and *Galeoides decadactylus* in Sierra Leone's coastal waters using LBSPR and MLZ. The length-frequency data were collected from industrial fleets from 2018 to 2020. The estimated average spawning potential ratio (SPR) from the deterministic life-history parameters were 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. Both stocks' SPR were found to be far below the limit reference point (SPR=20%), indicating that 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 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 the spawning stock biomass of the Icelandic cod stock assessment model with slight variation. This shows that the LBSPR can provide a cost-effective tool for analyzing data-limited stocks.

This paper should be cited as:
Mansaray, A. 2022. *Evaluation of Length-Based Stock Assessment Approaches: A preliminary assessment of the status of Pagellus bellotti (Steindachner,1882) and Galeoides decadactylus (Bloch, 1795) in Sierra Leone EEZ.* GRÓ Fisheries Training Programme under the auspices of UNESCO, Iceland. Final project.
https://www.grocentre.is/static/gro/publication/1728/document/Mansaray21prf.pdf

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1 INTRODUCTION

1.1 Context

Although Sierra Leone is a small country on the African continent, it has nearly 485 kilometres of coastline, 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 roughly 26,611 km^2, characterized by a broader scope in the north, at about 140 km, tapering to approximately 32 km in the south (Figure 1). The coastal fishing area within the six nautical mile limit is approximately 18,302 km^2 (Heymans & Vakily, 2004). The yearly offshore surface (0-5 m) water temperature variation is less than 4 degrees Celsius with a range of 25-28°C. The 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).

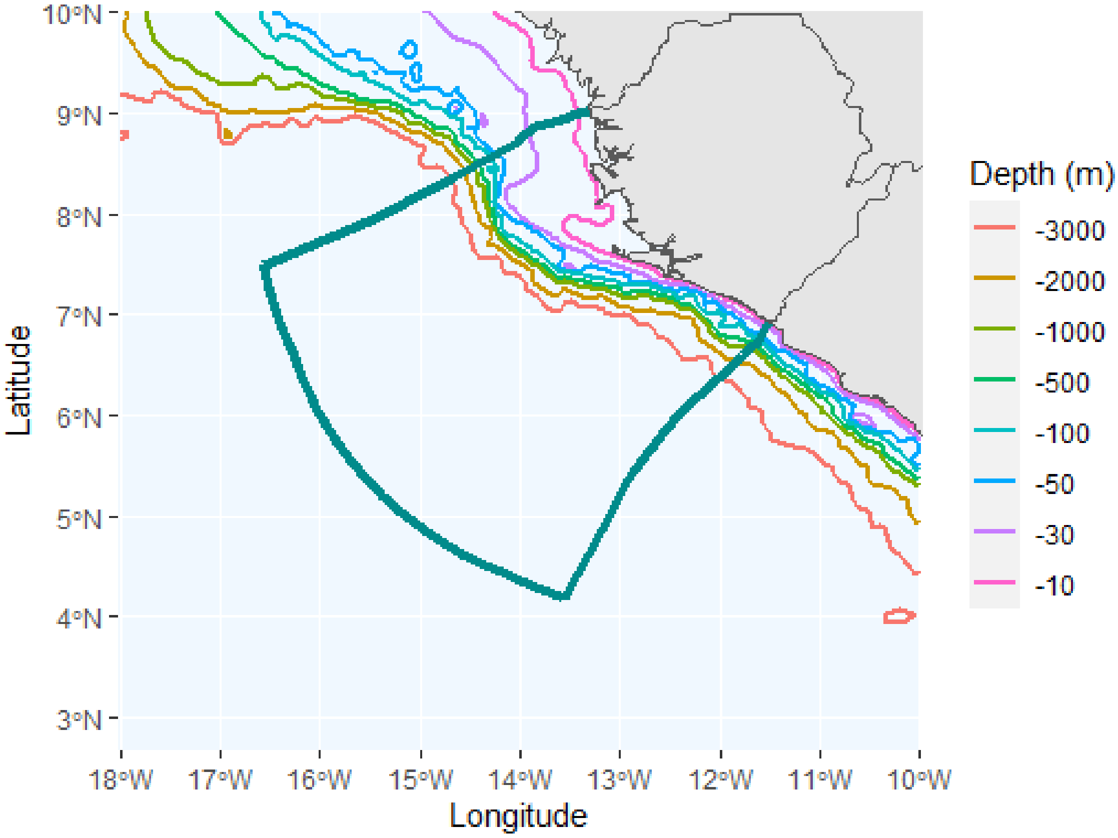

Figure 8: Map showing the Sierra Leone EEZ (green line) and depth contours in meters.

Like 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 one of the significant economic branches in 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 the fisheries resources in Sierra Leone is the responsibility of the Ministry of Fisheries and Marine Resources (MFMR). Various control measures are used to manage the fisheries, such as fishing gear types and mesh size restrictions. These are based on the 1994 Fisheries Management and Development Act and the fisheries regulations of 2020. They specify a minimum mesh size of 60 mm for demersal and pelagic trawl nets at the cod-end. As for the shrimp trawl net, a minimum mesh size of 45 mm is stipulated, and a 30 mm mesh size is specified for seine. Additionally, licensed foreign trawlers must land 40% of their total catch for sale in local markets, whilst licensed foreign shrimp trawlers must land 70% of bycatch and 5% of shrimps 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 biomass of key commercially exploited fish species with evidence of overfishing in 2020 (Johannessen, 2020). This is due to the weak implementation of management measures and inadequate enforcement capabilities to ensure compliance (MFMR, 2020).

1.2 Rationale

The Sparidae *Pagellus bellotti* and the 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 Sierra Leone or the West African subregion. Therefore, this study is important because it will provide information on the statuses of these species for present and future management of the resources.

1.3 Aim

This project aim to conduct a preliminary assessment of two commercially important fish species in Sierra Leone's territorial waters.

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 uncertainty in the life-history parameters of each stock affects the stocks status derived from the data-limited methods.
3. Explore the 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 could be related to the nature of the fishery, including craft and fishing gear used.

Table 9: Comparison of factors relating to fisheries productivity in Sierra Leone and neighbouring countries from 2002-2011.

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

Source: (Vakily *et al.*, 2012)

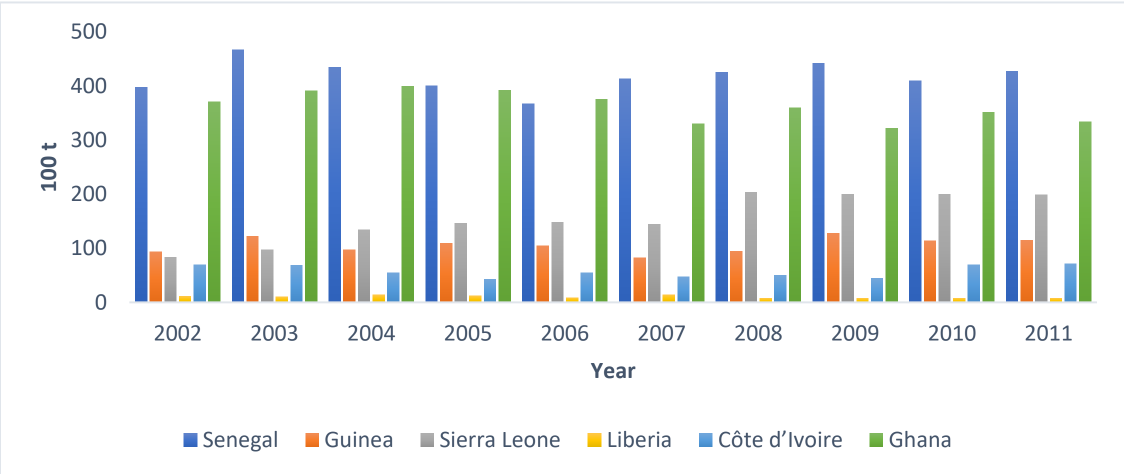

Figure 2: Comparison of annual national catches (100s t) from neighbouring West African countries from 2002-2011 (Vakily *et al.*, 2012).

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 occupying hard and sandy bottoms to depths of about 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 m. 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 West African coast. It is an essential element of the multi-species coastal demersal fisheries in the Eastern Central

Atlantic. The red pandora is one of the most valuable demersal fishes that landed at ports and beaches from West African fleets (Koranteng & Pitcher, 1987).

Lazar (2017) and Amponsah *et al.* (2016) reported a maximum age of red pandora as 6.38yr and 7yr 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 from Sierra Leone, Guinea, Senegal, and Ghana, and the stock is deemed to have been overharvested in these countries. Amponsah *et al*. (2017), Russell & Carpenter (2014) and Lazar (2017) all reported overexploitation of the species on the coast off Ghana. In Sierra Leone, overfishing is reported by Konoyima and Seisay (2021).

Red pandora was listed as least concerned 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 sub-tropical regions of the eastern Atlantic oceans from Morocco to Angola on the west coast of Africa. It seldom occurs in Algeria, northern Africa, Namibia, southern Africa (Motomura, 2004). It is commonly known as African threadfin. The threadfin is a demersal species found at depths ranging from 10 to 70 m over muddy bottoms neighbouring sandy beaches, in estuaries, and lagoons (Maigret & Ly, 1986). It consumes benthic invertebrates, small fish, detritus, and small crustaceans. Mangroves communities serve as essential habitats for the larva and juvenile of the 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).

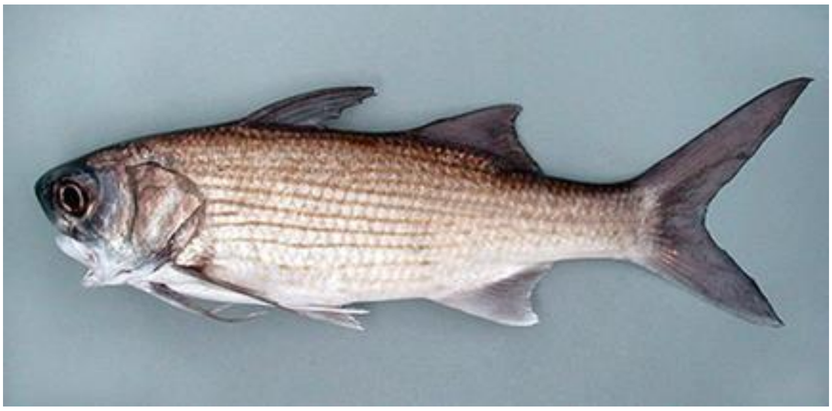

Figure 4. *Galeoides decadactylus*, African threadfin

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 11^0 W and 12 W)—target species include pelagic and demersal fish, shrimp, and crabs; the central fishing ground (located between 07°14′N and 07°34′N)—most important shrimp fishing ground; and the northern fishing grounds (latitude 07 ° 40′N and 09 ° 03′N)—target species include 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 20-100m (Johannessen, 2020).

Galeoides decadactylus is widely distributed in the continental shelf of the country's territorial waters, and its distribution has no obvious correlation with the hydrological environment. High concentration is found at depth 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). Estimated biomass of *Pagellus bellotti* using the swept area methods for the two surveys (S01 and S02) were 2,595 t and 5,927 t, respectively, while *Galeoides decadactylus* biomass ware 2,586 t and 6,236 t for S01 and S02, respectively (Zhuang *et a*l., 2019) (Table 2).

Table 10: 2019 biomass estimation of two demersal surveys (S01 and S02) of commercially important fish species in Sierra Leone waters.

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

Source: Zhuang *et al.* (2019)

2.3 Icelandic Cod

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

Icelandic seas' most significant marine resource is the cod (*Gadus morhua*). 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 Greenland sharks in the nineteenth century (Kurlanski, 1998). The demersal cod is extensively distributed in Icelandic water, with a reasonably broad range of a few meters to 600 meters (MFRI, 2020). Adult cod can be found in a variety of habitats. On the other hand, most young cod stock is protected in shallow kelp and grass settings. The optimal temperature for cod is 4-7^{o}C; however, the temperature restrictions for this species are somewhat greater. A substantial catch share is taken when the temperature is less than 2^{o}C (MFRI, 2020).

Cod spawn in smaller regional spawning components across Icelandic waters. Nonetheless, the most significant spawning regions are southwest and west of Iceland. Spawning begins early in the 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, but 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 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 management rules that promote sustainable fisheries (Patrick *et al.*, 2010). The methods used to assess the status of stock are highly dependent on data availability. A stock is data-limited if a full stock assessment cannot be performed because sufficient data is 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). Simpler methods are principally used to assess their status for such stocks based on the available data.

Recently, scientists tried multi-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 simulation by Hordyk *et al*. (2014) before the application to actual data by Prince *et al*. (2015). Assessment based on length data is cost-effective because length data is easily obtained. In contrast, obtaining estimates of other parameters, including but not limited to the ageing process, can be expensive, time-consuming, and challenging. For instance, growth rings on otoliths and scales are hard 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 estimate of the natural mortality rate (*M*). Instead, the method uses the ratio of natural mortality to the von Bertalanffy growth coefficient *K* (M/K). This ratio is assumed to vary less across fish populations and species than natural mortality (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. The SPR is an established biological reference point that can be applied 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 said to be in an unfished state. Conversely, if the SPR of a stock equals zero (SPR = 0), all the mature fish have been removed from the stock, or all the 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 maximum sustainable yield (MSY). In 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)

Mean Length Mortality Estimator (MLZ) is a non-equilibrium-based method developed by Gedamek & Hoening (2006) to analyse time-series of mean length. This method expands upon the estimator of Beverton and Holt (1956), which estimates 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 the development of this non-equilibrium method is for the estimation of 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 optimization methods. The MLZ method has been used as proxy reference points for MSY to determine 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 is operating in an open access fishery, making it difficult for proper data collection to be done 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 gears (including purse seines, gill nets, and hooks on lines) in Sierra Leone territorial waters (Figure 5). A total of 2067 and 7892 of *Pagellus bellottii* and *Galeoides decadactylus*, respectively, were length measured throughout the study period (2018-2020).

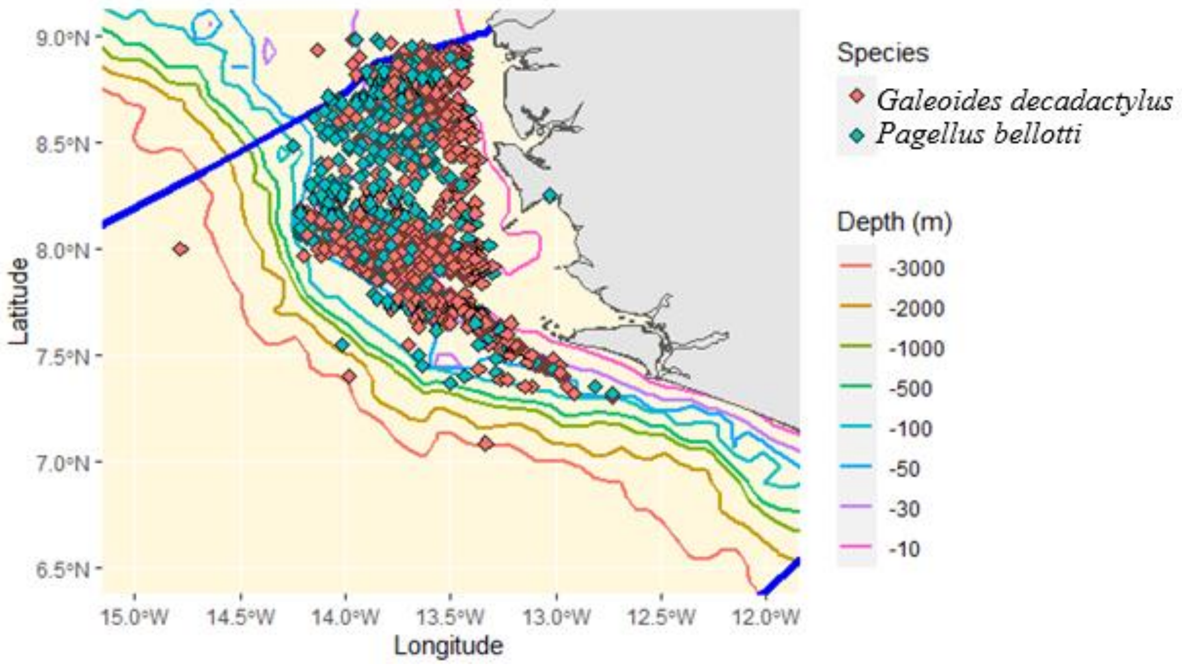

Figure 5. Map showing the Sierra Leone EEZ (Blue line), the catch position for each species, and the depth contours in meters.

Data for the Icelandic cod assessment came from a commercial bottom trawl fleet provided by 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 4) related to the stocks were taken 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 a better result than the other authors.

Table 11. Life history parameter values (K, L_∞, M, L_{50} and L_{95}) 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 LBSPR (version 0.1.6) package was used for the estimation of the selectivity lengths (SL_{50} and SL_{95}), relative fishing mortality (F/M) and the spawning potential ratio (SPR).

The model was fit to length-frequency data of the 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 are expected to be matured. Estimates for these parameters were taken from the literature (see Table 4). 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 limit reference point SPR was set at 20% or 0.2; this is the minimum threshold at which recruitment rates are likely to be threatened. These values were based on recommendations by Hordyk *et al.* (2017). 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 input parameters, resulting in 1000 estimates of SPR. The distribution of SPRs was plotted using boxplots for each year and compared to the deterministic values resulting from the model using the fixed parameters from Table 4. The uncertainty analysis was carried out 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 for the estimation of a historical series of total mortality rates for both species for three years period (2018-2020).

The model was fit to length-frequency data of the catch composition from 2018-2020. The input parameters included the length at first capture (the length at which animals are fully vulnerable to the fishery and the gear) and the Von Bertalanffy growth parameters (L_∞, k). Estimates for these parameters were taken from Lazar (2017) (see Table 4). Model output was converted to relative fishing mortality (F/M) using the Gulland (1969) formula: Total mortality (Z) = Fishing mortality (F) + Natural mortality (M).

3.4 Comparison of LBSPR and the Icelandic cod assessment model

In assessing the usefulness of the LBSPR method and evaluating its potential to provide a tool for the cost-effective assessment of data-poor fisheries like 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 taken from the literature or estimated from 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 & Begg (2002), and L_{95} was estimated from maturity data collected by MFRI. The Icelandic cod stock assessment uses a natural mortality coefficient of 0.2. Therefore, this value was used to convert the resulting F/M ratios to F 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 from 2018 to 2020 (Figure 6). The results showed a very low spawning potential ratio with an average of 1.9% throughout the period. The lengths at 50% selection (SL_{50}) were 14.51, 19.54 and 20.58 for 2018 to 2020, respectively (Figure 6). The average relative fishing mortality obtained was 6.66 (Table 5).

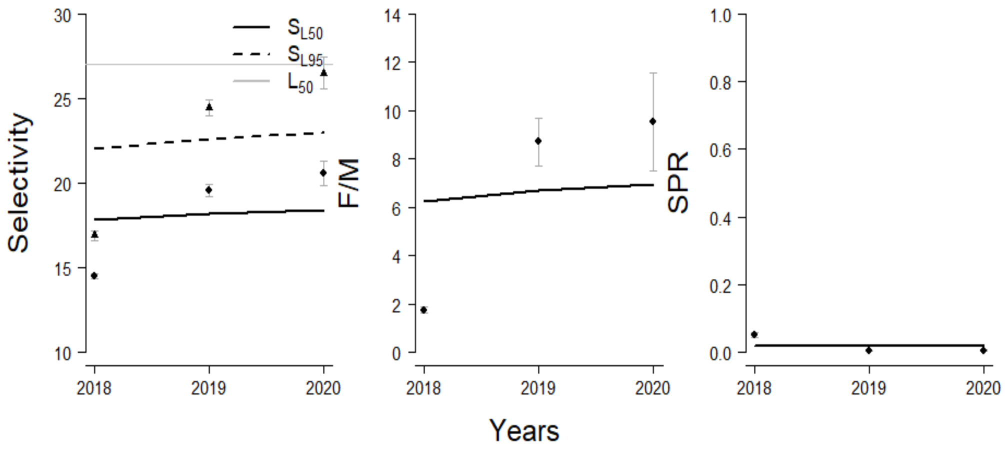

Figure 6. The estimated size of selectivity at maturity (left), relative fishing mortality (middle), and deterministic SPR (right) of *P. bellotti*. In each graph the estimates and variances are shown for each year. The solid lines show smoothed estimates.

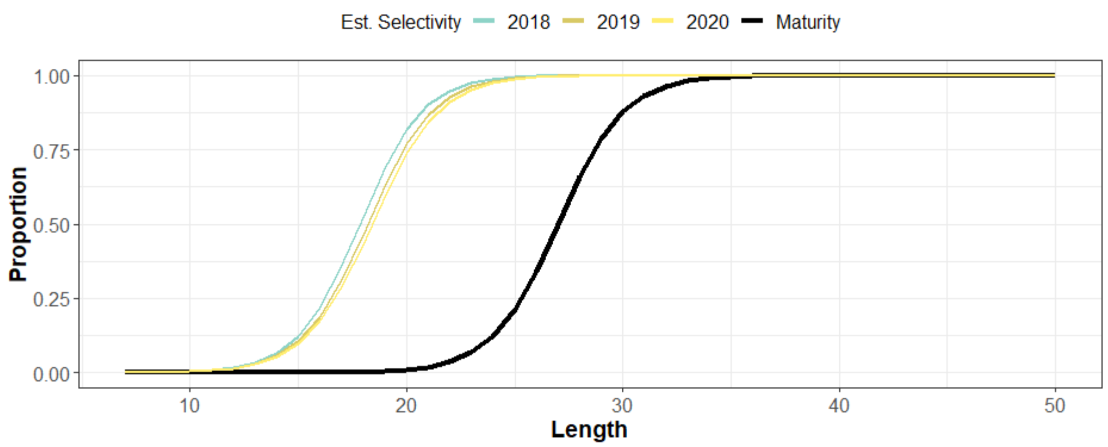

Figure 7. The yearly estimated selectivity curve (coloured lines) and the specified maturity size (black line) of *P. bellotti.*

Table 12: The estimated length selectivity (SL_{50}, SL_{95}), 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 uncertainty in the growth parameters, the median SPR was very similar to the deterministic SPR values (Figure 8 and Table 7). In 2018, the median SPR was 1% lower than the deterministic value, whilst in 2019 and 2020, the median SPR were 0.7% and 0.6% higher than the deterministic values for *P. bellotti* respectively (Figure 8 and Table 7); 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%, whilst in 2019 and 2020, the distribution was generally smaller than 3%.

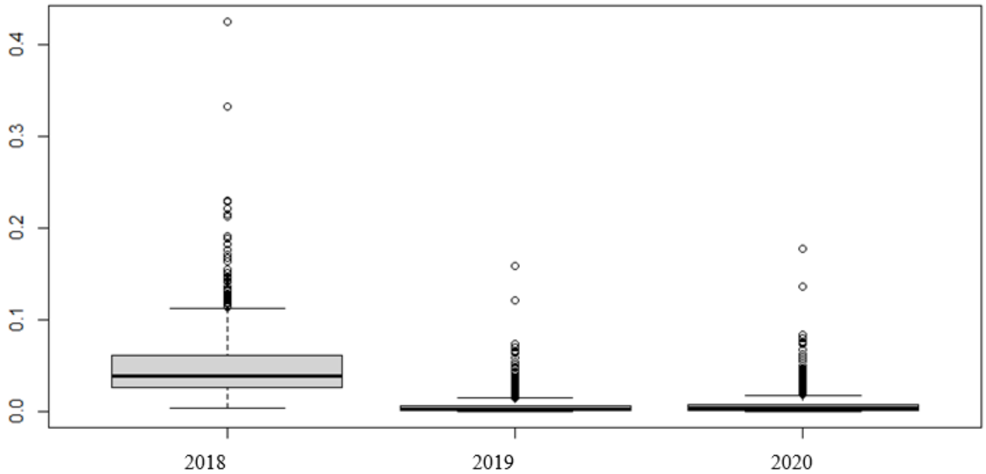

Figure 8. The SPR stochastic boxplot of *Pagellus bellotti* from 2018-2020.

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 fish were caught (SL_{50}) was 15.8 cm (Figure 9 and Table 6).

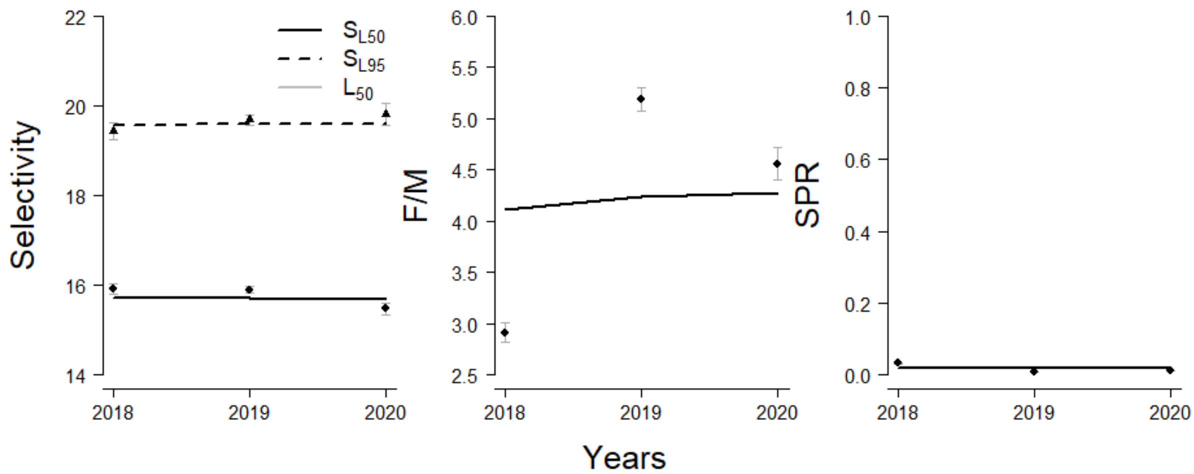

Figure 9. Estimates by year (with 95% confidence intervals)- the estimated size of selectivity at maturity (left), relative fishing mortality (middle), and deterministic SPR (right) of *G. decadactylus*. In each graph the estimates and variances are shown for each year. The solid lines show smoothed estimates.

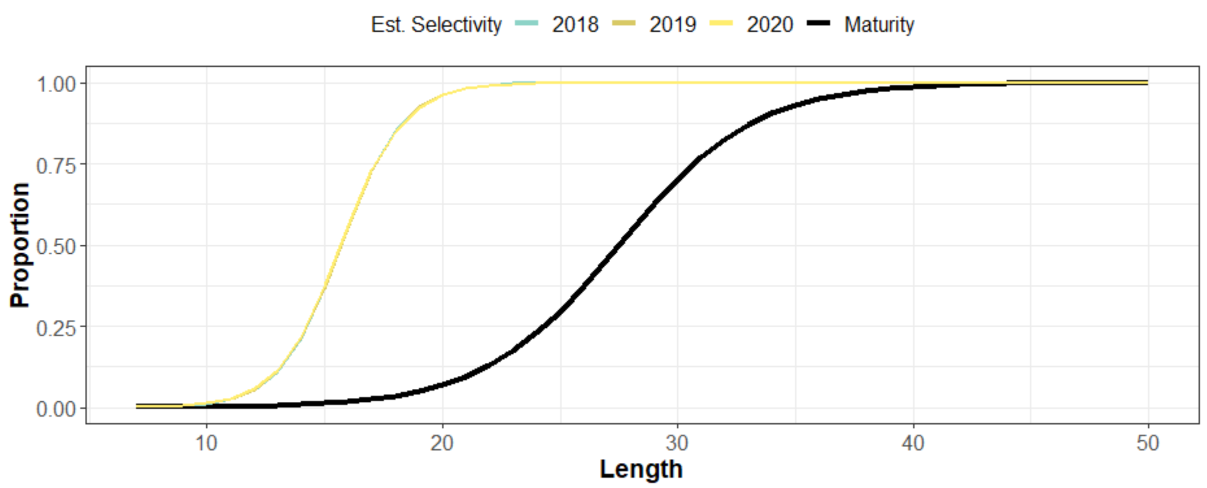

Figure 10. Maturity-at-Length- the yearly estimated selectivity curve (coloured lines) and the specified size of maturity (black line) of *G. decadactylus*.

Table 13. The estimated length selectivity (SL_{50}, SL_{95}), 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 7). 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%, whilst in 2019 and 2020, the distribution was generally smaller than 3% (Figure 11).

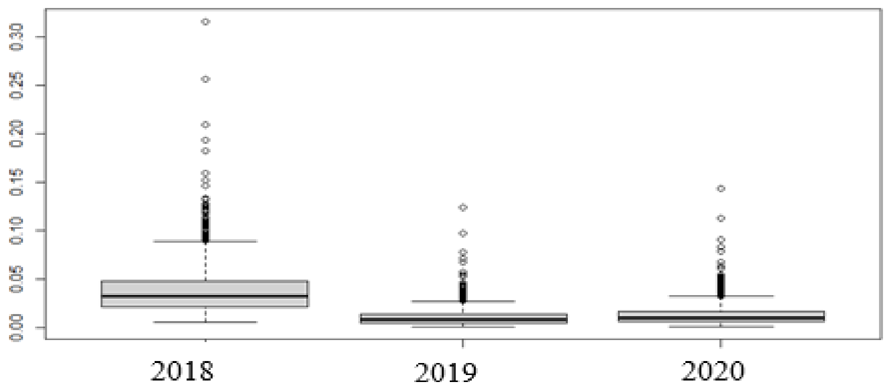

Figure 11. The SPR stochastic boxplot estimate of *G. decadactylus* from 2018-2020.

Table 14. 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 8 and Figure 13).

Table 15. Average relative fishing mortality(F/M) and the length at first capture (SL_{50}) 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

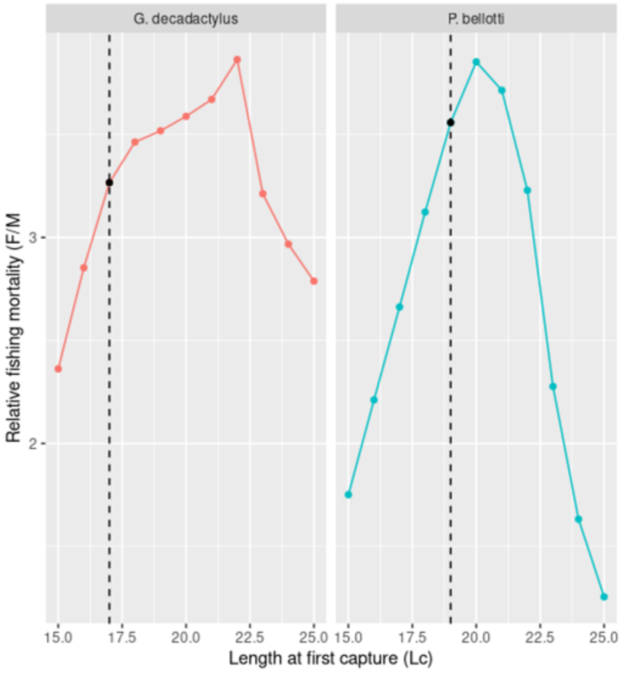

Figure 13. Change in relative mortality (solid lines) as length at first capture (Lc) is varied for *G. decadactylus* and *P. Bellotti*. The vertical dotted lines are aligned with the estimate of Lc used in the model.

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 varied greatly on a year-to-year basis. For instance, the general increase from 1980 to 1990 and the subsequent decline until present are captured; however, fishing mortality is overestimated in the ‘70s and 2000's and some peaks, for instance in 1978, are missed (Figure 14).

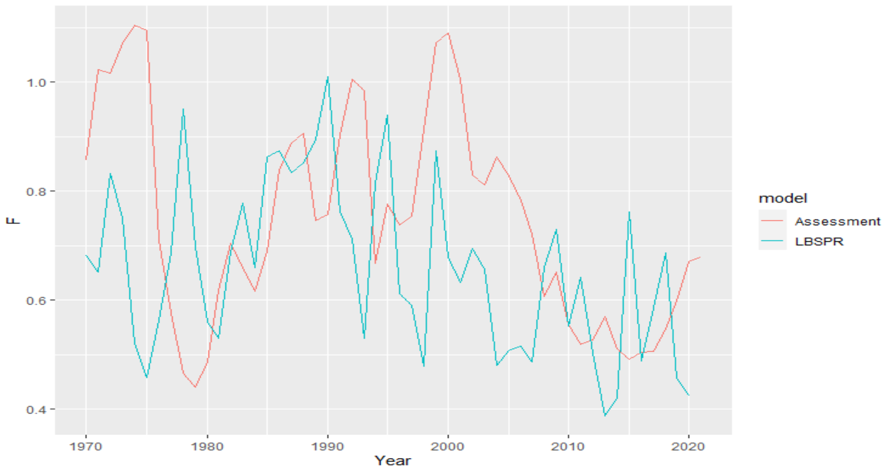

Figure 14. Comparison of the fishing mortality of the LBSPR model (red line) and the Icelandic assessment (blue line) of the Iceland cod

The general trends in the Icelandic cod spawning stock biomass (SSB) are reflected in the SPR (Figure 15). 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 varies significantly between years (Figure 15).

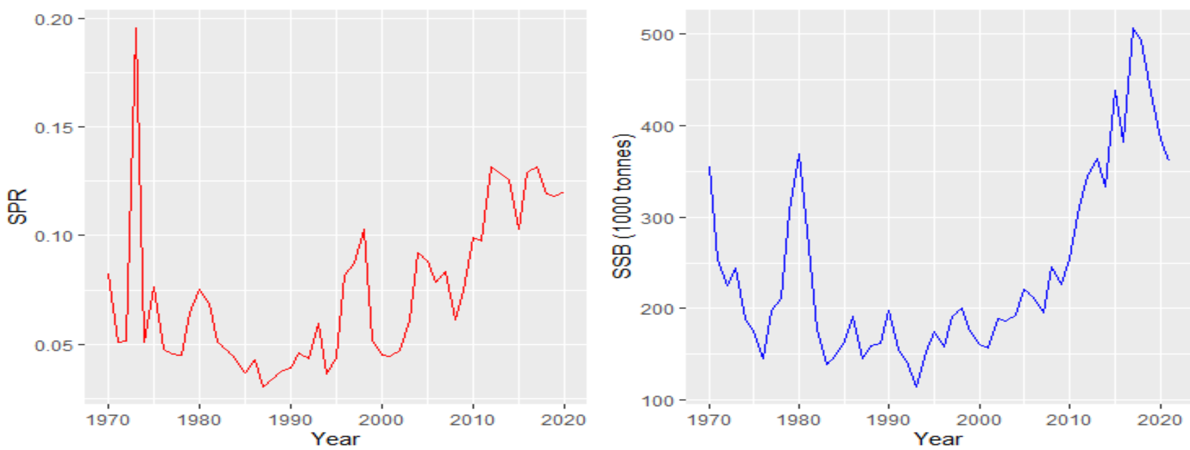

Figure 15. Comparison of LBSPR model SPR (red line) and the Icelandic assessment SSB (blue line)

5 DISCUSSION

5.1 Stocks status

In this study, two data-limited methods were applied to assess the status of two stocks in the EEZ of Sierra Leone. The result showed that both stocks are heavily overfished. When using Monte Carlo simulations to calculate the 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 the LBSPR and MLZ approaches to assess fish stocks in the Sierra Leone EEZ. The LBSPR and MLZ approaches, advanced by Hordyk *et al.* (2014a) 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 collecting, assessment, and management procedures where there are few, if any, pre-existing data, and few alternative possibilities.

Accounting for variation 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, whilst the median SPR obtained for *G. decadactylus* was the same as the deterministic value in each year. In 2019 and 2020, no variation in SPR was observed for both 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%, whilst in 2019 and 2020, the distribution was generally smaller than 3% for both *P. bellotti* and *G. decadactylus*. The low SPRs values (< 20%) obtained in this study is an indication of recruitment rate being threatened and that collapse of the 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% of *Merluccius polli* and *M. senegalensis* study done 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 differences in their distribution and body shapes. A high concentration of *P. bellotti* was found slightly offshore (20-50 metres depth), and it has a compressiform body shape. This could serve as a disadvantage for the species to the fishing net. *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; this could serve as an advantage to the species as it has a high chance of escaping the fishing net. A similar distribution of the species was also observed by Johannessen (2020) during the *Dr Fridtjof Nansen* 2020 survey on the coast off Sierra Leone.

To be more precise in the assessment of 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. 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 a high fishing pressure, indicating that the stocks are overfished. Lazar (2017) also reported overfished 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, whiles Amponsah *et al*. (2021) and Wehye & 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 done 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 southeastern 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 of 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 as 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, which confirmed the result of the 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 a cost-effective evaluation of data-poor fisheries like Sierra Leone.

The LBSPR model is highly sensitive to life-history parameters (Prince *et al*., 2015). This means we expect variation in SPR to result from variation in growth parameters. Therefore, we can 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 the stocks are to be sustainably managed, the current fishing gears need to be adjusted to allow a higher proportion of the stocks to reach their length at first maturity (L50) before being caught; this measure can reduce the high fishing pressure found during this study. However, this should be accompanied by proper monitoring of the industrial fleets.

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

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

ACKNOWLEDGMENT

In successfully accomplishing this project, many heads have helped me. Therefore, I would like to thank all those who are connected to making this project a reality.

Principally, I would thank the Almighty God for allowing me to complete this project with success.

Then, I would like to thank my supervisors, Jónas Páll Jónasson and Will Butler, under whose guidance I learnt a lot about this project, especially R software. Their suggestions and directions have helped me in the completion of this project. Special thanks to my HOD, Dr. MD. Kpundeh, and the dean, Prof. Olufemi Olapade, School of Natural Resources Management, Njala University, Sierra Leone, for allowing me to take part in this vital programme. I would also like to thank the director, Ministry of Fisheries and Marine Resources, Mrs. Kadijatu Jalloh, and team for providing me with the data.

Finally, I would like to express my sincere appreciation to the GRO. FTP team for selecting me as one of the beneficiaries for such an essential programme in my life. Thank you, Mary Frances, Stefán Úlfarsson, Julie Ingham, Tumi Tómasson, Agnes Eydal, and Thor Asgeirsson, for your hospitality throughout my six months of staying in Iceland.

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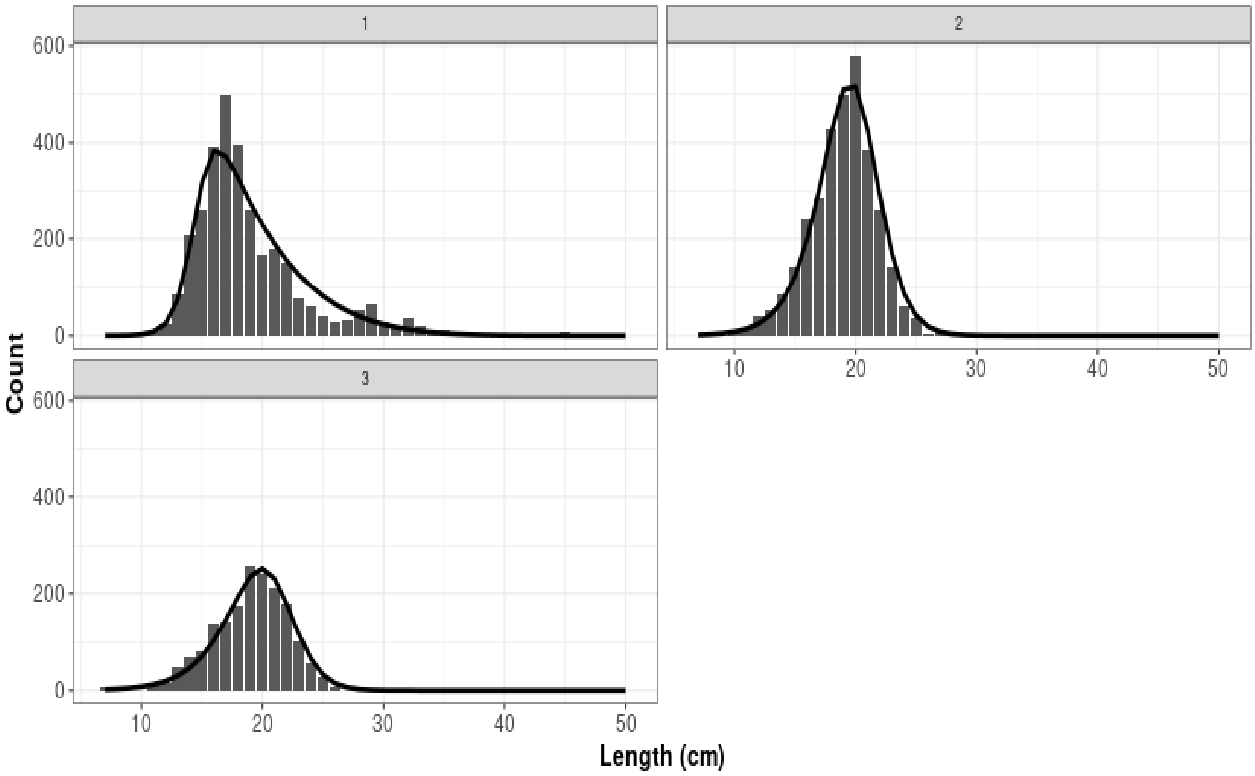
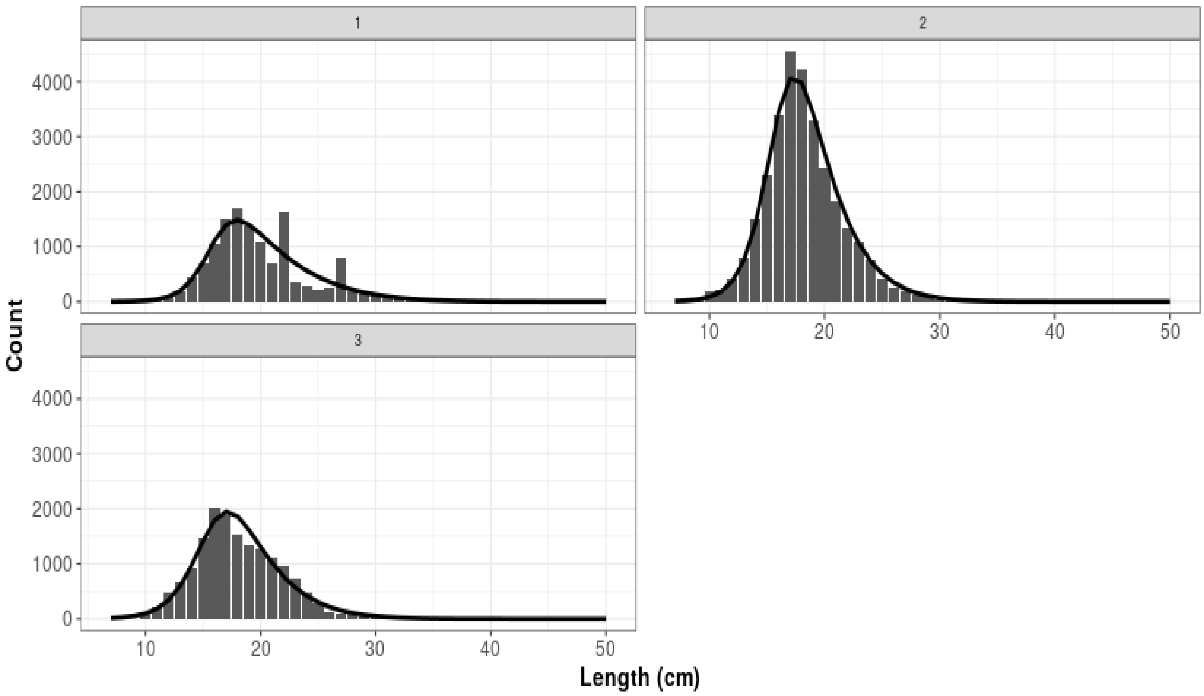
APPENDIX



Data- Histogram of Length Data- the size distribution (bar) and curve fitting (solid line) of *P. bellotti*.



Data- Histogram of Length Data- the 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