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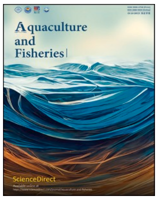

Original research article

Target reference points and implications for *Sardinella maderensis* in Liberia’s coastal waters

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ABSTRACT

Small-scale fisheries, particularly those targeting small pelagic fish, are a vital sector in Liberia, providing essential food for the local population and generating income for livelihoods. Sardinella maderensis, predominantly caught by motorized canoes using gill nets and seine nets, is the primary species in these fisheries. To establish management target reference points for the S. maderensis fishery, this study applied the Schaefer production model to aggregated and disaggregated catch and effort data collected by Liberia’s National Fisheries and Aquaculture Authority (NaFAA) from 2018 to 2022. The findings indicate that, in both the aggregated and disaggregated models, the current (2022) fishing effort exceeds the MEY level, leading to diminishing economic returns and approaching economic overfishing thresholds. The economic reference points, MEY and E_{MEY}, were estimated to be 3% and 19% lower in the aggregated model, and 30% and 44% lower in the disaggregated model, compared to the current (2022) catch and relative fishing effort. This situation arises when the cost of fishing exceeds the price of fish, driven by inefficient and ineffective fishing boats, which leads to high unit costs of effort compared to unit revenue. To fully realize the potential of the S. maderensis fishery, this study recommends a combination of input and output control management strategies, the adoption of more efficient fishing technologies, and the provision of alternative livelihoods for coastal communities.

1. Introduction

Liberia is a low-income nation where fisheries have the potential to contribute significantly to both national economic development and sustainable livelihoods for the most vulnerable. Fisheries contribute approximately 10% of Liberia’s gross domestic product (GDP), and the small-scale fisheries sector is estimated to employ around 33,000 people in the country (Wuor & Mabon, 2022). Fisheries in Liberia can broadly be divided into two categories: small-scale fisheries (SSF), including artisanal and semi-artisanal coastal fisheries, which make up around 86% of the country’s fisheries, and industrial fisheries (Wuor & Mabon, 2022). Small-scale fisheries in Liberia use canoes powered by sails and paddles, as well as open boats under 60 feet with engines not exceeding 40 horsepower, with common fishing gear including cast nets, beach seines, gill nets, longlines, hooks and lines, and traps (Jueseah et al., 2020). The Sardinella species are mostly caught in larger quantities than other pelagic species in SSF. In 2016 the sardinella species constituted 25% of the artisanal fishery production (NaFAA, 2017). *Sardinella maderensis*, commonly 25 cm long with a maximum length of 30 cm, is found in the Mediterranean and eastern Atlantic Ocean, adapted to water temperatures of 24 °C or higher and a depth range of 0–80 m (Ba et al., 2016; Braham et al., 2024; Corten et al., 2017; Rainer & Daniel, 2024). Recent studies have provided updated insights into the environmental preferences, feeding habits, and spawning behavior of *Sardinella maderensis*, complementing earlier findings by Whitehead (1985). This species is highly adaptable to estuarine environments characterized by low salinity and temperatures ranging from 24 to 28 °C, which are prevalent along the West African coast (Thiaw et al., 2017). Regarding spawning, investigations have highlighted that S. maderensis exhibits spawning peaks during warm seasons, aligning with increased plankton productivity driven by seasonal upwelling (Ettahiri et al., 2003).

Few studies (Wehye & Amponsah, 2017; Yokie, 2020) have assessed the stock of *Sardinella maderensis* in the coastal waters of Liberia using various methods and reported high fishing pressure on the stock. However, these studies did not take into consideration the target reference points and management implications of the species. Baldé et al. (2019) suggest that the length-based Bayesian biomass (LBB) model could be a tool to assess data-poor fisheries, allowing the inclusion of several years of length–frequency data with minimal

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prerequisites. Diogoul et al. (2021) show that despite strong annual variability and the presence of major stressors (overfishing, climate change), the Canary Current Large Marine Ecosystem (CCLME) remained relatively stable and is of major economic and social importance in providing sustainable livelihoods, fish-protein supplies, and revenue for the coastal populations and states of West African countries.

Globally, the percentage of overfished fish stock has increased from 10% in the 1970s to over 35% in 2019 (FAO, 2022). Overfishing is harvesting the fish stock above the limit that it can no longer produce and creating adverse effects on ecosystems functions, biodiversity, and extreme reduction in fish landings that lead to negative impact on livelihood and unproductive economic activities (FAO, 2020). The maximum sustainable yield (MSY) is the highest yearly catch that can be sustained of an indefinite period while the stock can produce more (Per Sparre and Siebren C. Venema, 1998). According to Spare and Venema (1998), the MSY can be derived if the data of catch and effort over time are available. Management reference points for fisheries, such as maximum sustainable yield (MSY), are often estimated using bio-economic models originally proposed by Gordon (1954) and further developed by Schaefer (1957). Recent adaptations of these models (Brito et al., 2024; Nguyen, 2011; Nguyen et al., 2016, 2018; Nguyen & Hoang, 2024; Nguyen & Tran, 2023; Thanh, 2013) have proven particularly useful for estimating reference points for data-limited stocks by utilizing catch data, resilience, and qualitative stock status information.

Based on these considerations and the need to sustainably manage Liberia's fisheries resources in accordance with United Nations Sustainable Development Goal 14.4, this research aims to derive management reference points for *Sardinella maderensis*, an important coastal pelagic commercial species in Liberia. The benefits of this research to Liberia's fisheries sector include sustainable management practices, optimal productivity based on the derived reference points, and the provision of information on the stock of S. *maderensis*. Additionally, the research will offer alternative management strategies to aid in the sustainable management of the S. *maderensis* fishery in Liberia's coastal waters. This study is not only significant for local and regional fisheries management but also provides valuable insights for the global scientific community. Researchers outside Liberia and West Africa can benefit from this study by applying its methodologies and findings for comparative analysis, utilizing the Schaefer production model in different contexts, gaining insights into sustainable fishing practices, and drawing policy implications to enhance fisheries management worldwide.

2. Materials and methods

2.1. Research location

Small-scale fisheries in Liberia are conducted on the continental shelf, close to the shore, within 6–10 nautical miles (NM) inshore. The production of fish for local consumption and income generation for livelihoods are two key factors that make small-scale fisheries a vital sector in Liberia. Approximately 11,000 full-time fishers and 22,000 fish processors and traders rely on small-scale fisheries for their livelihood (Chu et al., 2017). There are nine coastal counties or regions that contain 114 landing sites for small-scale fishers to land their catches. The nine coastal counties are Montserrado, Grand Capemount, Bomi, Margibi, Grand Bassa, Rivercess, Grand Kru, Sinoe, and Maryland. These counties are shown in colors on the map of Liberia (Fig. 1). Within these counties, there are fisheries enumerators that are assigned to various landing sites to gather information on the catches of small-scale fisheries. These information are sent to the National Fisheries and Aquaculture Authority for research and decision making on best management practices. S. *maderensis* is a schooling pelagic species that is landed in the nine coastal counties of Liberia. Each region is made up of three counties. Grand Kru, Maryland and Sinoe counties made up the Southeastern region, Grand Bassa, Margibi and Rivercess counties made up the Westeastern region, while the Western region contain Bomi, Grand Capemount and Montserrado counties.

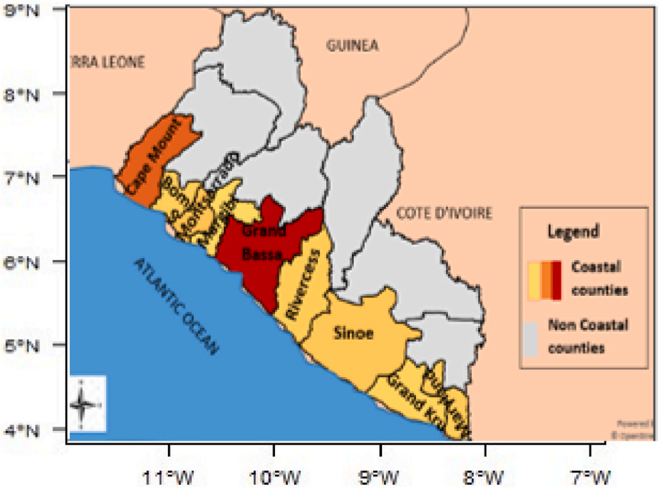

Fig. 1. Map of Liberia showing the nine coastal counties where small-scale fisheries catch data are collected. Source: Author's contribution-based on *S. maderensis* catch data.

2.2. Method

2.2.1. Harvest function

In the analysis, an appropriate bio-economic model was applied. The model includes natural growth function, harvest function and cost function which are three cardinal functions of Fisheries bio-economic model. Using the harvest function for an exploited stock, a general growth model can be given as:

$$\frac{dx}{dt} = F(x) - H(E, X) \tag{1}$$

where *F(x)* is the function of the stock's biological expansion, and *H(E, X)* which is the harvest function, that is influenced by stock biomass *(X)* and fishing effort *(E)*. A Belgium mathematician, Pierre-Francois Vehulst initially suggested the use of biological growth of stock as a model of Population

$$F(X) = rX\left(1 - \frac{X}{K}\right) \tag{2}$$

In the equation, K represents the carrying capacity of the environment and r represents the rate at which growth occurs.

At equilibrium, $\frac{dx}{dt} = 0$, the stock doesn't change. In other terms, the sustainable yield that may be obtained while maintaining a fixed stock level (X) is equal to the natural growth *F(X)*. Consequently, at equilibrium or steady state circumstances, the sustainable yield is calculated from the equation:

$$F(x) = H(E, X) \tag{3}$$

Many times, it is considered that a fishery's harvest function is expressed as

$$H = (E, X) = qE^{\alpha}X^{\beta} \tag{4}$$

where, E is effort, X is the stock biomass, q is the catchabiity coefficient and α and β are parameters. If $\alpha = \beta = 1$, then,

$$H(E, X) = qEX. \tag{5}$$

2.2.2. Schaefer Model

This model presupposes that biological growth adheres to the logistic growth function. It is assumed that the fishing effort (*E*) is the aggregation of motorized canoes and the biomass (*X*) consits of a single species that is harvested by diferent gears and measured in tons. Formulas (2), (3) and (4) can be used to obtain

$$qEX = rX\left(1 - \frac{X}{K}\right), qE = r - \frac{rX}{K}, X = K - \frac{KqE}{R} \tag{6}$$

The yield that can be sustained at a particular level of effort is determined by

$$H(E) = qKE - \frac{q^{2K}}{r}E^2 \tag{7}$$

Where $\alpha = qk, \beta = q^2K$ and the relationship between Catch Per Unit Effort (*CPUE*) and Effort (*E*) are linear, the equation written as

$$H = CPUE = \frac{H(E)}{E} = qk - \frac{q^2K}{r}E = a + bE.$$

$$H = aE + bE^2\ . \tag{8}$$

2.2.3. *The economic function*

A fishery's total cost (*TC*) and the total revenue (*TR*) to be given as:

$$TRt = \mathscr{P}^*H(t);\ TC = c^*Et, \tag{9}$$

where, $\mathscr{P}$ is the constant price per unit of biomass harvested and c is the constant cost of effort per unit. The sustainable economic rent offered by the fishing resource at any given level of effort is the difference between total sustainable revenue (*TR*) and total cost (*TC*). It can be expressed as

$$\pi t = TR(t) - TC(t). \tag{10}$$

When equation (9) is substituted in equation (10), it can be written as

$$\pi t = \mathscr{P}^*H(t) - c^*Et \tag{11}$$

The sustainable economic rent offered by the fishing resource at any given level of effort can be obtained by substituting equation (8) into equation (11):

$$\pi t = \mathscr{P}H - CE = (\mathscr{P}\alpha - c)E + \mathscr{P}\beta E^2. \tag{12}$$

2.2.4. *Refernce points*

2.2.4.1. Open access yield (YOA). Under an open-access scenario, fishermen will participate in the fishery until the marginal cost (MC) equals average revenue (AR). Cost per unit effort, price, and catchability coefficient are used in this instance to define the open access stock biomass (X_{OA}):

$$MC = AR \leftrightarrow c = \frac{\mathscr{P}H}{E} = \mathscr{P}qXoA \leftrightarrow XoA = \frac{c}{\mathscr{P}q} \tag{13}$$

The function that is used to estimate the effort and yield at open access conditions is given in Table 1.

2.2.4.2. Maximum sustainable yield (MSY). By differentiating equation (8) the efforts that generate the highest yield (E_{MSY}), and the Maximum Sustainable Yield (MSY) can be determined by these expressions Table 2.

2.2.4.3. Maximum economic yield (MEY). At the equilibrium point where the fishing effort generates the largest economic rent (E_{MEY}) and the maximum economic rent (*MEY*) is obtained by differentiating equation (12) with regard to Effort (*E*). The results are given in Table 3.

Table 1
Function of effort and yield in open access.

Model	Effort at Open Access (E_{OA})	Yield at open access (Y_{OA})
Schaefer	$EoA = c - \frac{\mathscr{P}\alpha}{\mathscr{P}\beta}$	$y_{OA} = \frac{C^2 - \mathscr{P}C\alpha}{P^2\beta}$

Table 2
E_{MSY} and MSY for schaefer models.

Model	Effort at MSY (E_{MSY})	MSY
Schaefer	$E_{MSY} = -\frac{\alpha}{2\beta} = \frac{r}{2q}$	$MSY = -\frac{\alpha^2}{4\beta} = \frac{rK}{4}$

Table 3
Function of effort and maximum economic yield.

Model	Effort at MSY (E_{MEY})	MEY
Schaefer	$E_{MEY} = \frac{c - \mathscr{P}\alpha}{2\mathscr{P}\beta} = \frac{r(\mathscr{P}\alpha k - c)}{2\mathscr{P}^2\beta}$	$MEY = \frac{C^2 - \mathscr{P}^2\alpha^2}{4\mathscr{P}^2\beta} = \frac{r\left(\mathscr{P}^2q^2k^2 - c^2\right)}{4\mathscr{P}^2q^2k}$

2.2.5. *Catch per unit effort (CPUE)*

To quantify fishing effort, the total number of active motorized canoes that were engaged in the harvest of *S. maderensis* in each year from the research and statistics division of the National Fisheries and Aquaculture Authority (NaFAA) for the period of 2018–2022 were considered. Metric tonnes were used as the unit of measurement for harvested *S. maderensis* (biomass). *S. maderensis* is mainly caught by using gill nets, and seine nets. For fishing effort of different gears, there is a need to standardize the harvest and convert it to relative catch per unit effort (Nguyen & Tran, 2023). The method of Spare and Venema (1998) was used to standardized *CPUE*:

$$CPUE_{it} = \frac{y_it}{fit}, \overline{CPUE} = \frac{\sum_{t=1}^{T} CPUE_{it}}{T}, R_{it} = \frac{CPUE_{it}}{\overline{CPUE}}, R_t = \frac{\sum_{i=1}^{n} R_{i^t}{}^* y_{it}}{\sum_{i=1}^{n} y_{it}} \tag{14}$$

Where:

y_{it} represents yield of gear *i* in year *t*,
f_{it} is the effort of gear *i* in year *t*,
$CPUE_{it}$ is the catch per unit effort of gear *i* effort in year *t*,
$\overline{CPUE}$ is the average catch per unit of gear *i* effort from the period of the first year to year *T*,
R_{it} is the relative catch per unit of gear *i* effort in year *t*, and.
R_t represents the sum of relative CPUE weighed by the yields of *n* gears in year *t*. Tables 4 and 5

2.3. *Data and parameters for estimating the model*

Due to gaps in the data caused by inaccurate sampling, the research employed two approaches to analyze the data using the Schaefer Model: Aggregated and Disaggregated. In the Aggregated approach, the total annual landings of *Sardinella maderensis* were used, with missing values treated as zeros. This approach resulted in five observations of catch per unit effort (CPUE) over five years, with CPUE fluctuating based on changes in fishing effort. In the Disaggregated approach, the five years of data were structured as a panel dataset across three geographical regions—southeastern, westeastern, and western—while accounting for the missing values. Over the analysis period, the CPUE showed inconsistent behavior without a clear trend. Unlike the aggregated method, the disaggregated approach highlighted more obvious fluctuations in both CPUE and effort. These variations in CPUE can be partially explained by the differing qualities of boats in operation. Additionally, the fluctuations in the number of operational boats help to further explain the observed behavior of CPUE. Fig. 2 shows the catch and effort data for the two major gears, gill nets and seine nets, which were aggregated into relative effort to represent fishing effort. Between 2018

Table 4

Aggregated data summary statistics of Catch, Relative effort and CPUE of *S. maderensis* fishery on the coast of Liberia.

Parameter	Number of observations	Mean	Standard deviation	Minimum value	Maximum value
Catch (t)	5	7334.26	2493.77	4954.1	11360.17
Effort (Relative effort)	5	6549.82	1837.10	3464.71	8417.07
CPUE	5	1.23	0.38	0.75	1.76

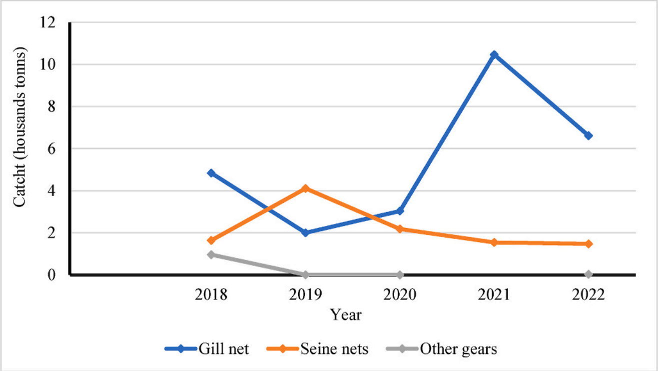

Fig. 2. Harvest of *S. maderensis* by gill nets and Seine nets on the coast of Liberia from 2018 to 2022. Data source: NaFAA.

and 2022, 69% of *Sardinella maderensis* landings were harvested using gill nets, 28% using seine nets, and 3% using other gears (Fig. 2).

The catch data for *Sardinella maderensis* from gill nets and purse seine nets were combined to generate management target reference points. Since *S. maderensis* is predominantly caught using these two gears, the catches and efforts from gill net and purse seine boats were normalized and converted into relative aggregated effort and relative aggregated CPUE. Tables 5 and 6 present the statistical summaries of the catch, effort, and CPUE time series data for both the aggregated and disaggregated approaches for the S. *maderensis* fishery in Liberia's artisanal fisheries from 2018 to 2022. The aggregated approach includes five observations, while the disaggregated approach contains 13 observations. The disaggregated technique shows standard deviations for catch and effort that are 17% and 3% higher, respectively, compared to the aggregated approach (Tables 5 and 6). However, the standard deviation for CPUE in the disaggregated data is 35% higher than that of the aggregated data (Tables 4 and 5). The study used 2022 as the base year, and Table 6 provides the aggregated and disaggregated catch and effort data for the S. maderensis fishery in 2022.

The basic economic data needed for the model were unit price (landed value of 1 kg of *S. maderensis*) and the unit cost (the cost for landing one 1 kg of *S. madernsis*). This reasech determined the unit price of *S. maderensis* based on the landed value provided in the annual report of the research and statistic division of the National Fisheries and Aquaculture Authority (NaFAA, 2021). The price was determined using equation (9) and converted to United States dollars (USD) at the Central Bank of Liberia's exchange rate of 150 Liberian dollars (LRD) to one USD. The total annual cost of a motorized Fanti small-scale fisheries canoe, including typical expenses such as the costs of the vessel, fishing gear, fishing license, labor (crew), outboard engine and fuel/gasoline, repairs and maintenance, as well as food and bait, was found to total thirteen thousand two hundred and ninety United States dollars (USD13,290) (Jueseah et al., 2020). Based on the yearly cost for each boat and the yearly landed catch data, the cost per unit effort was estimated. See Table 7 for detail economic data.

Table 5

A summary statistics of Catch, Effort, and CPUE disaggregated data of *S. maderensis* fishery on the coast of Liberia from 2018 to 2022.

Parameter	Number of observations	Mean	Standard deviation	Minimum value	Maximum value
Catch (t)	13	2820.87	2068.96	508.92	7347.13
Effort (Relative effort)	13	3100	1789.96	486	5724
CPUE	13	1.054	0.586	0.235	2.12

Table 6

Current (2022) aggregated and disaggregated catch and effort data of *S. maderensis* fishery.

Approach	Relative Effort	Catch (t)
Aggregated	6 946	7 910.92
Disaggregated	13 076	7 910.92

3. Results

3.1. Parameters

The Schaefer model's α and β parameters for equation (8) were determined via linear regression analysis of the catch and effort data (Table 8). The two approaches aggregated and disaggregated analysis confirm that there is a negative correlation between CPUE and effort. The slope coefficients were −1.11E-04 and -1.39E-04 for aggregated and disaggregated respectively. The P-values showed that the coefficients were different from zero at a 95% significant level. The R^2 values, 0.30 and 0.21, indicate that about 30% and 21% of the CPUE variations in the aggregated and disaggregated approaches, respectively, are explained by the Schaefer model. These R^2 values are relatively low, which could be due to several reasons. One possible reason is that the Schaefer model, being relatively simplistic, may not fully capture the complex dynamics of the fisheries, including environmental variability, multi-species interactions, or other socio-economic factors. Additionally, limited data availability and potential measurement errors could further contribute to the lower explanatory power of the model.

3.2. Aggregated model

The equilibrium yield graph, total revenue (TR), and total cost (TC) derived from the aggregated model against effort are shown in Figs. 3 and 4. Essential reference points, including MSY, the effort at which maximum sustainable yield was obtained (E_{MSY}), MEY, and the effort at which maximum economic yield was achieved (E_{MEY}) for *S. maderensis*, were estimated. The blue triangle and the black dots in Fig. 3 show the MSY point and the annual catch statistics of *S. maderensis* that were used to determine the sustainable yield for the aggregated data. Fig. 3 illustrates the relationship between sustainable yield and relative fishing effort, with the Maximum Sustainable Yield (MSY) shown at the peak of the curve. The observed catches, represented by black dots, are mostly below or near the MSY, indicating that fishing efforts have generally

Table 7

Economic parameters.

S. maderensis Fleet	Total Cost Per unit effort (US $1000/t)	Price wet-whole fish (US $1000/t)
Fanti boat (Motorized)	1.2255	1.6

Table 8
Regression analysis output and calculated parameters of the Schaefer model.

Approach	Variable	Coefficients	Standard Error	*t*-Stat	*P*-value	
Aggregated	Alpha (α)	1.99E+00	0.805	2.47	0.13	R^2: 0.30
	Beta (β)	−1.11E-04	0.00012	−0.92	0.45	*F statistic*: 0.848
Disaggregated	Alpha (α)	1.42E+00	0.303	4.70	0.00085	R^2: 0.21
	Beta (β)	−1.39E-04	8.45E-05	−1.65	0.131	*F statistic*: 2.711

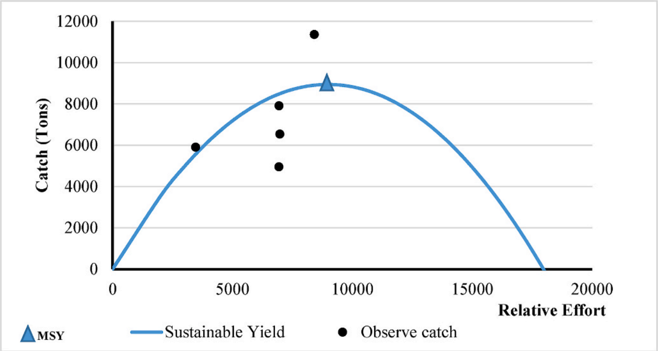

Fig. 3. Aggregated Sustainable yield modelled and catch of *S. maderensis*.

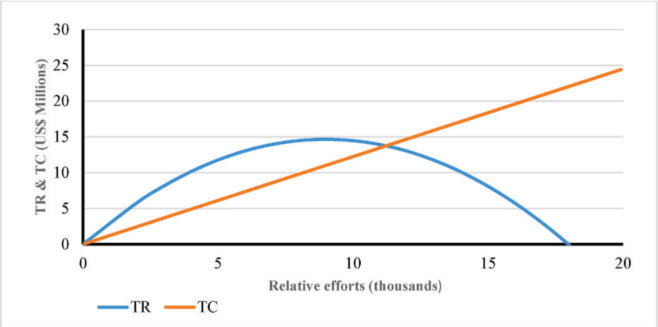

Fig. 4. TR and TC against aggregated relative effort.

remained below the level required to reach the maximum sustainable yield. This suggests that the fishery is not overfished and is operating within sustainable limits. However, the observed catches are also not fully utilizing the fishery's potential, indicating room for increased effort to achieve MSY. Only one data point slightly exceeds the MSY, but this is not a significant concern for overfishing based on the aggregated model. Fig. 4 shows that the intersection of TR and TC marks the breakeven point, indicating that fishing efforts beyond this point lead to economic losses. Effort levels should remain below the point where costs begin to outweigh revenues to avoid economic inefficiency and ensure sustainable profits. Balancing the maximization of catches with the optimization of economic returns is crucial for long-term sustainability.

The estimation results of the reference points (OA/current situation, MSY, MEY) for the aggregated model are shown in Table 9 below.

Table 9
Aggregated reference points.

Reference points	OA/Current (2022)	MSY	MEY
Catch (t)	8388.58/7910.92	8943.61	7682.95
Relative Effort	11223/6946	8985	5611
Total Cost Year^{-1} (USD Millions)	1348.05/8.51	11.011	6.88
Total Revenue Year^{-1} (USD Millions)	1348.05/12.970	14.66	12.60
Resource Rent Year^{-1} (USD Millions)	0/4.46	3.65	5.72

Table 9 indicates that the current (2022) fishing effort is 12% lower than the fishing effort level at MSY, but 19% higher than the fishing effort level at MEY. This situation leads to diminishing economic returns and brings the fishery closer to economic overfishing thresholds. To maximize economic efficiency and ensure long-term sustainability, reducing fishing effort toward the MEY level would minimize costs, maximize resource rent, and maintain sustainable catch levels, as suggested by the aggregated model.

3.3. *Disaggregated model*

The equilibrium yield graph, total revenue (TR), and total cost (TC) derived from the disagregated model against effort are shown in Figs. 5 and 6. Essential reference points, including MSY, the effort at which maximum sustainable yield was obtained (E_{MSY}), MEY, and the effort at which maximum economic yield was achieved (E_{MEY}) for *S. maderensis*, were estimated. The blue triangle and the black dots in Fig. 5 show the MSY point and the annual catch statistics of *S. maderensis* that were used to determine the sustainable yield for the aggregated data. Fig. 5 suggests that the fishery is experiencing both under- and overexploitation at different points in time. Some observed catches exceed the MSY, indicating that fishing efforts in these instances are unsustainable and could lead to overfishing. Conversely, other observations indicate underutilization, where fishing efforts are below optimal levels. To ensure long-term sustainability, fishing efforts should aim to stay close to the MSY, optimizing catch without overexploiting the resource.

The estimation results of the reference points (OA/current situation, MSY, MEY) for the disaggregated model are shown in Table 10 below. Table 10 shows that the fishery is currently (2022) biologically sustainable but economically overexploited, with fishing efforts far exceeding the MEY level. As a result, the fishery is operating at a significant loss, as indicated by the negative resource rent. Reducing fishing effort toward the MEY level would significantly lower costs, increase economic efficiency, and allow the fishery to break even or become slightly profitable. To ensure long-term sustainability and profitability, fishing effort must be adjusted downward toward MEY levels, where both ecological and economic factors are optimized according to the disaggregated model.

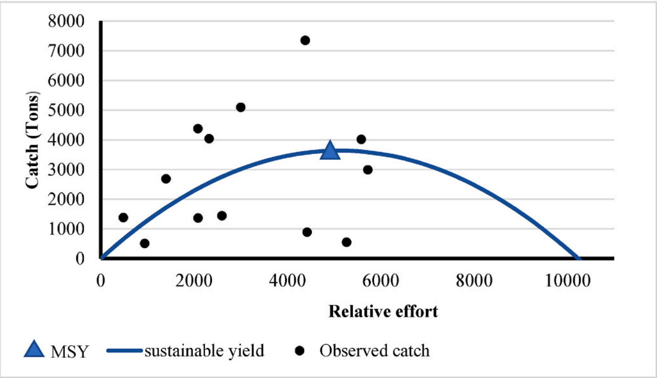

Fig. 5. Disaggregated (regional) Sustainable yield modelled and catch of *S. maderensis*.

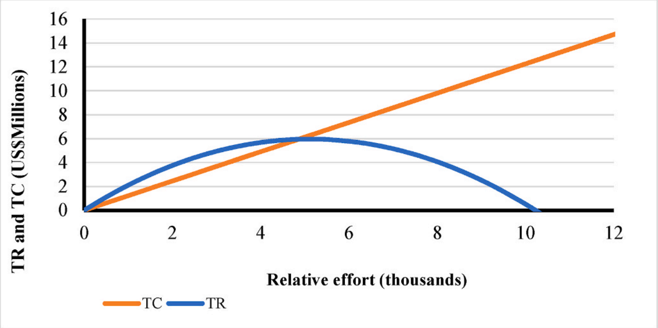

Fig. 6. TR and TC against disaggregated (regional) relative effort.

Table 10
Disaggregated reference points.

Reference points	OA/Current (2022)	MSY	MEY
Catch (t)	10880.85/ 7910.92	10909.39	5515.65
Relative Effort	14557/13076	15342	7279
Total Cost Year^{-1} (USD Millions)	18031.96/16.02	18.80	9.043
Total Revenue Year^{-1} (USD Millions)	18031.96/12.97	17.89	8.92
Resource Rent Year^{-1} (USD Millions)	0/-3.05	−0.91	0.123

3.4. Robust checks

To ensure reliable results, a CMSY and Bayesian Schaefer Model (BSM) analysis was conducted to assess the stock status of *S. maderensis* (stock: SDL) using catch data from 2018 to 2022 and abundance indices (CPUE). The analysis incorporated expert-informed priors for initial, intermediate (2021), and final relative biomass levels, along with ranges for intrinsic growth rate (*r*) and carrying capacity (*k*). A total of 2181 viable trajectories for 2040 *r-k* pairs were identified, providing robust estimates of population parameters.

The CMSY analysis estimated an intrinsic growth rate (r) of 0.621 (95% CI: 0.463–0.833) and a carrying capacity (k) of 53.4 thousand tons (95% CI: 31.9–89.3). The maximum sustainable yield (MSY) was 8.76 thousand tons (95% CI: 5.69–12.7), with relative biomass in the last year (2022) at 0.514 k (95% CI: 0.501–0.57). Exploitation levels (F/(r/2)) in the last year were estimated at 0.928 (95% CI: 0.838–0.953), suggesting fishing pressure was close to sustainable limits.

The Bayesian Schaefer Model produced consistent estimates, with *r* at 0.422 (95% CI: 0.306–0.582), *k* at 81.7 × 10^3 t (95% CI: 53.6–125), and MSY at 8.62 × 10^3 t (95% CI: 6.22–12). Relative biomass in 2022 was estimated at 0.492 *k* (95% CI: 0.422–0.588), while exploitation levels (F/(r/2)) were 0.995 (95% CI: 0.65–1.47). The biomass-to-B_{msy} ratio (B/B_{msy}) was 0.983 (95% CI: 0.843–1.18), and fishing mortality (F/F_{msy}) was near unity (0.995, 95% CI: 0.65–1.47), indicating that the fishery is operating at or slightly above sustainable exploitation thresholds.

The management reference points based on the BSM analysis suggested an F_{msy} of 0.211 (95% CI: 0.153–0.291), with a B_{msy} of 40.9 × 10^3 t (95% CI: 26.8–62.3). The biomass in 2022 was estimated at 40.2 × 10^3 t (95% CI: 34.5–48.1), indicating that the stock is near its B_{msy}. These findings highlight that while the fishery is close to sustainable levels, any increase in exploitation could risk overfishing, emphasizing the need for cautious management to maintain stock sustainability (Fig. 7)

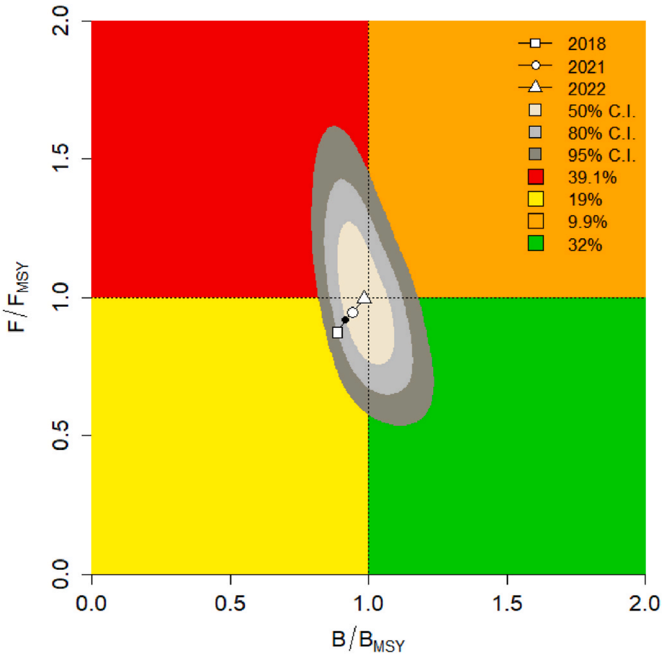

Fig. 7. Results from Bayesian Schaefer model (BSM) using catch & CPUE.

4. Discussion

4.1. Model estimation

The Schaefer model seemed to predict appropriate economic outcomes and valid biological parameters for the *S. maderensis* fishery in the Coastal waters of Liberia using aggregated and disaggregated data approaches. Also, the model had statistically significant coefficients that made the results credible. Data limitations for catch and effort were short, which makes it difficult for model accuracy. The results from both the aggregated and disaggregated models indicate that the current (2022) fishing effort exceeds the fishing effort level at MEY, leading to diminishing economic returns and approaching economic overfishing thresholds. Our findings are consistent with a study indicating that the pelagic fisheries of Liberia are underutilized (Jueseah, Dadi, Tómasson, & Knutsson, 2020). Other studies, such as Wehye and Amponsah (2017), reported that *S. maderensis* was being harvested closed to the maximum sustainable yield, while Yokie (2020) concluded that recruitment overfishing was occurring in the stock of *S. maderensis* in the coastal waters of Liberia. We acknowledge that the inputs used for our models were derived from a short period. Therefore, the findings may not fully capture global changes in the fishery. The reference points generated by the models reflect only local conditions. The catch and effort reference points in this study were determined by the models to account for practice-based uncertainty. This study found that the unit cost of effort is considerably higher than the unit price of catch for *S. maderensis* in Liberia, due to inefficient and ineffective fishing boats, as well as the social responsibilities of the fishery. Furthermore, the study findings revealed that direct input controls are the sole management strategy for the fishery. The implications of these findings extend beyond the West African context, providing validation for the use of the Schaefer production model in small-scale fisheries globally. The study offers valuable lessons on achieving sustainable fisheries management by balancing biological and economic objectives, emphasizing the importance of economic considerations in fisheries management, and presenting adaptable policy recommendations and methodological frameworks to enhancing sustainability and research comparability in diverse fishing communities worldwide.

4.2. Reference points

The output from the models revealed that the fishery's open access yield (Y_{OA}), and MSY of both the aggregated and disaggregated data were 6%, 12% and 27% higher than the current (2022) catch, 7910.92 tons. The estimated relative efforts corresponding with the Open access yield and the MSY for the aggregated data were 38% and 23% larger than the current (2022) relative effort, 6946. As for the disaggregated data, the estimated efforts corresponding with the Open access yield and MSY were 10% and 15% higher than the current (2022) effort, 13076 (Table 11). When the amount of fishing efforts exceeds what is necessary to harvest a fish stock at its MSY, the fish stock is biologically unsustainable. The annual catch data for all gears combined reveals significant variability over recent years, with a noticeable peak in 2021 followed by a decline in 2022. Comparing this trend with the estimated reference points highlights key differences. The aggregated maximum sustainable yield (MSY) is estimated at 8943.61 tons, which is 12% higher than the current 2022 catch of 7910.92 t, suggesting that the fishery is operating slightly below its sustainable capacity. The disaggregated MSY, at 10,909.39 tons, indicates an even larger potential for a 27% increase in catch if optimal conditions are met.

S. maderensis is one of the pelagic fish species that is popular and highly valued on the local market of Liberia. The study examined its possible economic profitability by determining the economic target reference points. The targeted economic reference points, MEY and E_{MEY} were estimated for the aggregated and disaggregated data as 7 682.95 t and 5 611 relative efforts and 5 515 t and 7279 relative efforts respectively. In addition, the estimated MEY and E_{MEY} for the aggregated data were 3% and 19% lower than the current (2022) catch, 7 910.92 t and 6 946 relative efforts. As for the disaggregated data, the MEY and E_{MEY} were 30% and 44% lower than the current catch and relative effort (Table 11). The results indicate the current Total Revenue (TR) and resource rent for the aggregated data to be 12.970 and 4.46 million United States dollars respectively. The total revenue for the disaggregated data was 12.9705 million United States dollars and there was negative resource rent. However, the cost at MSY was higher than the total revenue at MSY for the disaggregated data. From the two approaches, aggregated and disaggregated, results, the aggregated analysis presents a profitable S. maderensis fishery while the disaggregated do not. Our results indicate that while the fishery is operating close to biologically sustainable levels, current effort and catch levels may exceed the maximum economic yield (MEY), suggesting that expenses associated with fishing effort might outweigh the economic benefits in some scenarios. Specifically, the current catch exceeds the MEY by 3% in the aggregated scenario and by 30% in the disaggregated scenario, with effort levels surpassing economically optimal thresholds by 19% and 44%, respectively. This highlights a potential trade-off between maximizing biological yield and maintaining economic profitability. To address this, we recommend adjusting fishing effort closer to levels that achieve MEY, which would enhance economic efficiency while ensuring the sustainability of the stock. These findings underscore the importance of integrating both biological and economic reference points into fisheries management to achieve balanced and optimal outcomes. To strengthen the discussion, we have compared our findings with previous research on Sardinella maderensis and related fisheries in West Africa. The estimated maximum sustainable yield (MSY) in this study is consistent with the findings of Thiaw et al., 2017, who highlighted the sensitivity of Sardinella stocks to environmental fluctuations and fishing pressure.

The *S. maderensis* fishery is less profitable because the cost of unit effort is relatively higher the price of unit catch which shrinks the profit margin in the disaggregated analysis. The high cost of unit effort in the *S. maderensis* fishery is associated with the ineffectiveness and inefficiency of artisanal Fanti boats that are used to harvest the species in the coastal waters of Liberia. The results confirmed previous report that the artisanal Fanti fleets were inefficient and needed to be improved technically (Jueseah et al., 2020). Another reason for the high cost can be linked to the social responsibility of the fishery to provide jobs for fishing community dwellers. The lack of alternative employment activities caused the overcapacity of artisanal Fanti boats thus increasing cost. Despite measuring only 10–15 m in length, each artisanal Fanti boat typically has a crew of 12–20 people (Chu et al., 2017).

Length, weight, and condition factor are usually crucial factors to consider when determining the price of landed fish (Sjöberg, 2015). The unit price of *S. maderensis* might be relatively low due to the size of the landed fish. The length at first capture for *S. maderensis* is approximately 10 inches (Baldé et al., 2019). Wehye and Amponsah (2017) and Yokie (2020) reported growth overfishing and recruitment overfishing of *S. maderensis* stock in the coastal waters of Liberia respectively. Growth overfishing occurs when fish are harvested at a smaller size, below the size that would yield higher returns per recruit. Recruitment overfishing happens when fish are caught before reaching maturity. According to Yokie (2020), the maximum size of fish captured was 42 cm, with 82.22% of the sampled catch being juveniles and only 8.25% being mature.

S. maderensis, like other marine species in Liberia's artisanal fisheries, is managed under Liberia's fisheries regulations and the Fisheries and Aquaculture Policy. These policies aim to sustainably manage fishing resources, restore key fish species to MSY levels, and ensure that fisheries contribute to local economies while balancing social, economic, and environmental benefits. The fisheries regulations prohibit the use of monofilament nets. However, to catch *S. maderensis*, fishers predominantly use monofilament gill nets and purse seine nets in various sizes. The use of illegal monofilament gill nets has been reported as the main issue hindering the sustainability of artisanal fisheries in Liberia (Dunbar et al., 2021).

The measures mentioned in the Fisheries regulations are directed to input control fisheries management. However, these controls are more strictly enforced in the marine industrial fisheries than in the marine artisanal fisheries (Jueseah et al., 2020).

The two approaches of data analysis, aggregated and disaggregated, were used to account for missing values within the data set and show similarities and differences the outcome will provide. Depending on the way the missing values in the data are treated can determine how large or small the estimated Maximum Sustainable Yield (MSY) will be. In this study, the missing values were treated in the aggregated data as zeros and treated in the disaggregated data to meet conditional expectations or average.

The study discovered that technological development of efforts and improvement in management methods are required for the achievement

Table 11
Comparison of estimated target reference points to current (2022) catch and effort data of *S. maderensis* fishery.

Estimated Variable	Aggregated	Difference	Catch &Effort	Disaggregated	Difference	Catch & Effort
MSY (t)	8943.61	12%>	7910.92	10909.39	27%>	7910.92
E_{MSY} (Relative effort)	8985	23%>	6946	15342	15%>	13076
Y_{OA} (t)	8388.58	6%>	7910.92	10880.85	27%>	7910.92
E_{OA} (Relative effort)	11223	38%>	6946	14557	10%>	13076
MEY (t)	7682.95	3%<	7910.92	5515.65	30%<	7910.92
E_{MEY} (Relative effort)	5611	19%<	6946	7279	44%<	13076

of the target reference points, however the results obtained imply increase of current efforts to achieve MSY and MEY. The *S. maderensis* fishery is exploited close to MEY because the cost of unit effort is relatively high in comparison to the cost of unit catch, which reduces the profit margin. The high cost per unit effort in the *S. maderensis* fishery is attributed to the ineffectiveness and inefficiency of the artisanal Fanti boats that are employed to harvest the species in the coastal waters of Liberia.

5. Conclusion

In conclusion, the results from both the aggregated and disaggregated models indicate that the current (2022) fishing effort exceeds the fishing effort level at MEY, leading to diminishing economic returns and approaching economic overfishing thresholds. The economic reference points, MEY and E_{MEY}, were estimated for the aggregated data at 7682.95 t and 5611 relative efforts, and for the disaggregated data at 5 515 t and 7 279 relative efforts, respectively. Additionally, the estimated MEY and E_{MEY} for the aggregated data were 3% and 19% lower than the current (2022) catch, which was 7 910.92 t and 6 946 relative efforts. For the disaggregated data, MEY and E_{MEY} were 30% and 44% lower than the current catch and relative effort, respectively. Several recommendations can be made to enhance fishing management strategies based on the study evaluations. First, combining input and output controls management techniques, such as close season and effort restrictions, is advised to create sustainable fishing practices. Secondly, by implementing efficient and productive fishing technology, the fishing process can be made more effective while reducing unfavourable effects on the marine ecosystem. Thirdly, reducing the burden on marine resources can be accomplished by giving coastal residents alternatives to fishing as a source of income. Furthermore, the current gear mesh size standards must be strengthened and enforced to guarantee the sustainable usage of fishing gear. Finally, boosting data gathering programs can help to increase the precision and dependability of the information gathered for decision-making processes. In general, following these suggestions can promote sustainable fishing methods, guarantee the long-term survival of marine ecosystems, and sustainably manage the fisheries resources of Liberia in accordance with the United Nations sustainable development goals number 14.4.

CRediT authorship contribution statement

Isaac Patrick Johns: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Thanh Viet Nguyen:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Daði Már Kristó-fers-son:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Statement on ethics approval and consent

The authors confirm that the ethical policies of the journal, as noted in the author guidelines page for *Aquaculture and Fisheries*, have been adhered to. No ethical approval was required for this study as the dataset used for this article consisted of field samples that were collected following a commercial fishing practice in accordance with the local legislation and institutional requirements. No other authorization or ethics board approval was required to conduct this study. The captured animals were not exposed to any additional stress other than that involved in commercial fishing practices, and no further direct or indirect manipulation with the fish or other animals were conducted during the trials. Therefore, no information on animal welfare or on steps taken to mitigate fish suffering and methods of sacrifice is provided. This study did not involve endangered or protected species.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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