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RESEARCH ARTICLE

Assessment of *Sardinella lemuru* Bleeker 1853 in Southeast and Northeast Sulu Seas within FMA-4 using TropFishR

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ABSTRACT

The study was conducted to assess the exploitation status, mortality rates, and growth parameters of sardines (*Sardinella lemuru*) in Fishery Management Area 4 (FMA-4) from 2018 to 2023, a region responsible for about 50% to 70% of the country's sardine production (FFTC, 2017). Using consistent monitoring from the National Stock Assessment Program (NSAP) and statistical analysis tools such as TropFishR (R), key indicators such as exploitation rate (E), fishing mortality (F), natural mortality (M), and growth parameters (L_{inf}, K) were estimated annually. The exploitation rates ranged from 0.60 to 0.68, nearing the limit reference point of 0.70, while fishing pressure also ranged from 1.53 to 2.15, suggesting that *S. lemuru* stocks are under high fishing pressure or are highly exploited. The fishing mortality consistently exceeded natural mortality over the years, further emphasizing the elevated pressure exerted by commercial fisheries. Growth analysis exhibited moderately fast-growing stocks, with variations in capture probability across years influenced by fishing gears and management practices, notably closed fishing seasons. Parameter estimation methods such as Powell-Wetherall plots, K-Scan, Response Surface Analysis (RSA), Simulated Annealing (SA), and Genetic Algorithm (GA) were applied to optimize the growth models and evaluate key values for L_{inf} and K, ensuring reliable and accurate results. These results highlight the immediate need for management or harvest strategies to improve sardine stocks in FMA-4. Trends showed temporal variability in the probability of capture, reflecting the effects of policy interventions like seasonal closures. Despite such measures, the continued high exploitation rates and mortality suggest existing strategies may be insufficient. Without decisive action, *S. lemuru* stocks face heightened risks of decline. The findings provide essential guidance for policymakers to avert potential fishery collapse and promote sustainable sardine management in the Philippines.

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1. INTRODUCTION

The Zamboanga Peninsula (also known as Region IX) is a prominent landform located in the western part of Mindanao, Philippines. It extends southwestward toward the Sulu Archipelago and is bordered by the Sulu Sea to the west and the Moro Gulf to the south. It has an estimated area of 6,526.68 square miles (16,904.03 square km) (PhilAtlas 2013). The peninsula comprises three provinces: Zamboanga del Norte, Zamboanga del Sur, and Zamboanga Sibugay, along with the highly urbanized Zamboanga City. This region is also responsible for about 50% to 70% of the country's sardine production (Fernandez et al. 2017).

The region consists of three major provinces and two highly urbanized cities. The region's coastline totals about 1,416.65 kilometers, encompassing at least 54 coastal municipalities and cities, with 589 fish landing areas, according to the Philippine Statistics Authority (Philippine Statistics Authority 2018).

Zamboanga Peninsula consists of four (4) major fishing grounds: South and East Sulu Sea, Celebes Sea, and Moro Gulf, and also covers three (3) Fishery Management Areas: FMAs 4, 3, and 9. These fishing grounds are among the most productive in the country. Apart from these major fishing grounds, the peninsula also has at least thirteen (13) marine fishing grounds; Dapitan Bay, Dipolog Bay, Sindangan Bay, Siocon Bay, Coronado Point, Sibuco Bay, Pagadian

Bay, Illana Bay, Dumanquillas Bay, Paguil Bay, Murceillagos Bay, Sibuguey Bay, and Basilan Strait.

The National Stock Assessment Program (NSAP) of Region IX assesses and monitors at least 25 major and minor fish landing areas across the entire peninsula that are part of FMA-4. This study was conducted to assess the status of *Sardinella lemuru* in FMA-4, using TropFishR as the main statistical model to determine the exploitation level of this stock. This analysis will be further useful in informing management measures and interventions that require a scientific basis to support informed decision-making.

The region that registered the largest volume in 2023, at least 343,687.21 metric tons (MT), was Region IX, followed by Region XII with 237,033.26 MT and BARMM with 205,353.37 MT in fisheries production for both commercial and municipal fishing (Philippine Statistics Authority 2024).

This study aims to assess the status of *S. lemuru* in FMA-4 through: (1) assessment of catch production and length frequency data through the use of TropFishR; (2) determination of fishing gears capable of catching sardines; and (3) determination of levels of exploitation and fishing pressure.

2. METHODOLOGY

2.1 Study site

The study was conducted at selected fish landing sites in FMA-4, Southeast and Northeast Sulu Sea. Figure 1 shows the map of the selected fish landing sites in Zamboanga Peninsula, Philippines. It shows that NSAP assesses and monitors at least 25 major and minor fish landing areas in the entire peninsula, which is part of FMA-4, including two (2) major fishing grounds: the South Sulu Sea and the East Sulu Sea, including the northeastern portion of the Sulu Sea. However, two (2) municipal landing areas, namely Roxas and Pitogo, and one (1) commercial landing site in Pagadian are excluded from the FMA 4 assessment coverage as they are associated with FMA 3 and FMA 9, respectively. Thus, the NSAP Region IX assessment coverage for FMA 4 comprises a total of 22 fish landing areas, consisting of 13 municipal and 9 commercial landing areas.

Table 1 shows the Zamboanga Peninsula landing site composition for *S. lemuru* with its accompanying coordinates.

2.2 Data collection

Data on catch and length frequency are obtained using a sampling methodology in which a representative subset of a population or group is selected for observation and analysis to infer the characteristics of the entire population. This approach is employed to optimize data collection efforts by reducing both time and cost, while maintaining statistical reliability and accuracy. One common approach is simple random sampling, in which each unit within the population has an equal probability of being selected, ensuring unbiased representation. However, at large-scale fish landing sites where complete enumeration of all arriving fishing vessels is not feasible due to logistical constraints, a stratified random sampling method is often utilized. This involves dividing the entire population or area into distinct strata (e.g., by time, boat type, or landing zone), followed by the random selection of units within each stratum. This ensures that each stratum is proportionally represented and that the probability of selection remains consistent within each segment of the population.

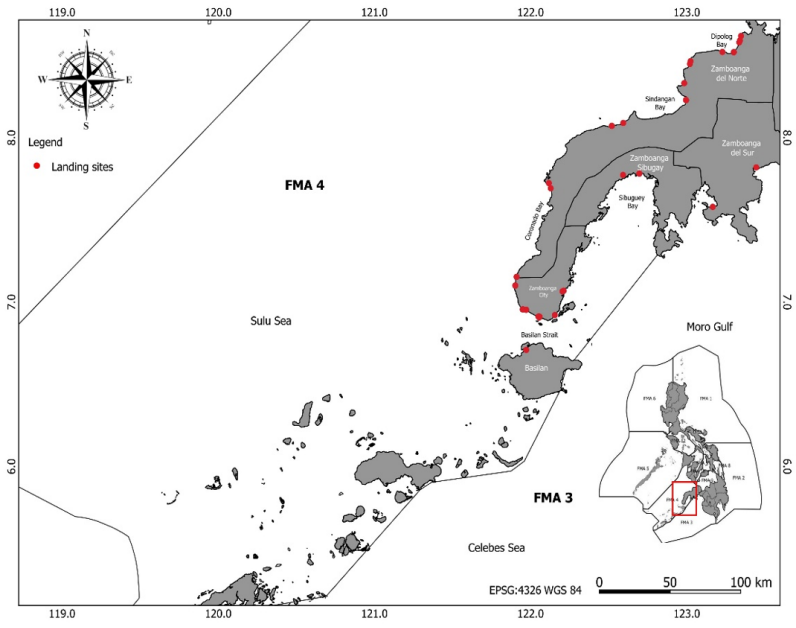

Figure 1. Geological position of NSAP landing areas in FMA 4.

Table 1. NSAP IX landing site composition for *Sardinella lemuru.*

Landing Site Name	Location (Coordinates)	Accessibility	Landing Type	Main Gear Landed (For sardines)	Estimated Volume of Catch Landed from 2018 to 2023 (MT)
PFDA Sangali	7.069516° 122.213099°	By Land/By Boat	Commercial	Purse Seine	53.01
Jordan Wharf	6.954464° 121.951702°	By Land/By Boat	Commercial	Purse Seine	47,973.71
Universal Wharf	6.954858° 121.950916°	By Land/By Boat	Commercial	Purse Seine	161,906.19
Universal Canning	6.954787° 121.951041°	By Land/By Boat	Commercial	Purse Seine	138,790.18
Arena Blanco	6.921022° 122.154971°	By Land/By Boat	Municipal	DGN	26.04
Tres Marias	6.910681° 122.055115°	By Land/By Boat	Municipal	MHL, MJ, J	313.18
Mega Wharf	6.953237° 121.968253°	By Land/By Boat	Commercial	Purse Seine	337,600.97
Labuan, Lawingan	7.102656° 121.901700°	By Land/By Boat	Municipal	SN, RN, DGN	11,827.95
Labuan, Bato Rampoon		By Land/By Boat	Municipal	SN, RN, DGN,	11,819.83
AMR Wharf	6.952830° 121.974405°	By Land/By Boat	Commercial	Purse Seine	107,755.97
YL/NANCY	6.970017° 121.933961°	By Land/By Boat	Commercial	Purse Seine	417,417.94
Cosak (Basilan)	6.708534° 121.970688°	By Land/By Boat	Municipal	RN, SGN, SN	1,695.28
Naga Wharf (Sibugay)	7.788509° 122.693009°	By Land/By Boat	Municipal	RN, SLN,	83.06
Buluan (Sibugay)	7.710571° 122.532587°	By Land/By Boat	Municipal	BSGN, BN, TN, BTN, SSGN, GN	3.44
Bangkerohan (Sibugay)	7.774021° 122.591541°	By Land/By Boat	Municipal	FC, RN	94.99
Katipunan (ZDN)	8.521169° 123.301467°	By Land/By Boat	Municipal	BRN, BSGN, DGN, RN,	498.77
Margosatubig (ZDS)	7.579547° 123.167285°	By Land/By Boat	Municipal	BG, BSGN, DGN, FC, GN, RN, SLN.	437.37

Figure 2 illustrates the different forms used in NSAP data collection. These forms were designed to ensure efficient data encoding, collection, and processing. All essential data variables are recorded using the standardized NSAP data forms. These forms serve as the primary instruments for systematic data collection and are designed to be compatible with the NSAP relational database system.

Table 2 shows the monthly sampling schedule of NSAP data enumerators.

Table 3 shows the definitions of terms embedded in the data collection forms and their descriptions. These terms are significant for categorizing data groups or sets of information, enabling easier distinction during encoding and analysis.

Table 4 shows the specific types of data collected during the sampling period.

2.2.1 Catch and effort data collection

This component quantifies total fish landings and associated fishing operations within the defined sampling area. Data are acquired through structured interviews with fishers or vessel operators. The core variables collected include; (1) total catch volume, disaggregated by individual fishing vessel and type of fishing gear used; (3) fishing gear classification, including, but not limited to, ring net, purse seine, surface gillnet, and handline; and (3) fishing effort parameters, such as the number of hauls per trip, duration of fishing operations (in hours), and other effort-related metrics. These parameters are essential for estimating catch per unit effort (CPUE) and evaluating gear efficiency.

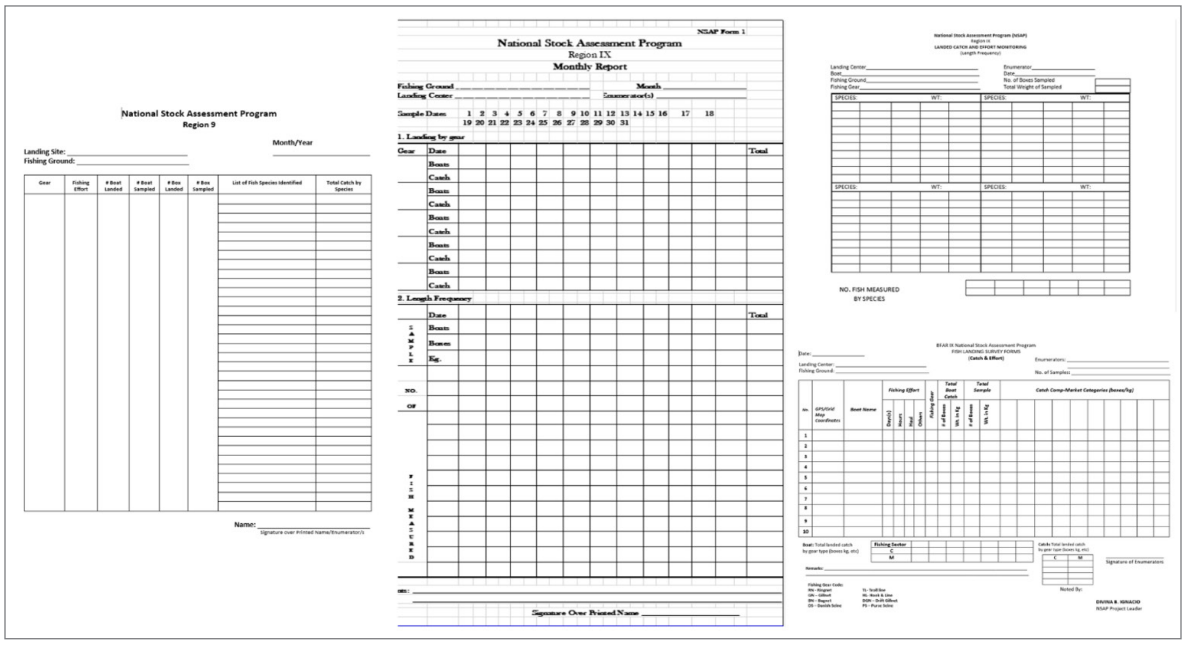

Figure 2. NSAP data collection forms.

Table 2. Monthly sampling schedules.

SUN	MON	TUE	WED	THU	FRI	SAT
		1	2	3	4	5
6	7	8	9	10	11	12
13	14	15	16	17	18	19
20	21	22	23	24	25	26
27	28	29	30			

Legend:

- **Sampling Day (Major Landing Sites)**
- **Sampling Day (Minor Landing Sites)**
- **Data Consolidation and Review**

Table 3. Terms used in data collection forms and their description.

TERMINOLOGIES	DESCRIPTION
Date	Indicates the specific sampling date during which the data collection activity was conducted.
Landing Center	Refers to the designated fish landing site covered during the sampling activity. Landing centers are categorized as commercial, municipal, major, or minor, depending on the volume and type of boat landings.
Fishing Ground	Denotes the marine or inland water area where the fishing operation occurred and where the catch was harvested.
Enumerators	The authorized personnel or data collectors assigned to conduct field data gathering at the specified landing site.
Number of Samples	The total count of fishing vessels for which length and weight measurements were taken on the sampling day.
Sample Serial Number	A unique identifier assigned to each fishing boat sampled during the survey, used to track individual records within the dataset.
Boat Name	The registered name of the fishing vessel. For unnamed or non-motorized vessels, the name of the fishing operator or fisherman may be used as a proxy, provided it is consistently associated with the same vessel. Boat classification should be based on the type of fishing gear used.
Fishing Gear	Specifies the gear type employed during the fishing operation (e.g., gillnet, purse seine, longline), which determines the selectivity and catch composition.

Table 4. Specific types of data collected during sampling period.

Unit of Catch (Weight)	Represents the total landed catch of each fishing vessel recorded in kilograms (kg) or metric tons (MT). For biological sampling purposes, subsample weights are recorded in grams (g) to ensure finer measurement resolution.
Total Boat Catch (Number of Boxes)	Denotes the total count of fish storage containers used by the vessel upon landing. These containers may include boxes, "bañeras", or insulated foam boxes, which are typically standardized but may vary in volume.
Total Boat Catch (Weight in Kilograms)	Refers to the estimated total weight of the landed catch per boat and per gear type, expressed in kilograms. For catches stored in containers, estimates may be derived by inquiring about the standard weights used or by physical validation (e.g., displacing fish within the container to assess actual fish mass while discounting the volume of water and ice).
Total Sample (Number of Boxes)	Indicates the number of containers from which fish were drawn for sub-sampling activities, including species composition and biometric assessments (length and weight measurements). These samples are typically extracted randomly and represent a fraction of the total catch.
Total Sample (Weight in Kilograms)	The aggregated weight of the subsampled fish specimens taken from the selected containers, recorded in kilograms. This value contributes to estimates of length-frequency distributions and species composition.
Catch Composition (Species and Volume)	Represents the taxonomic breakdown of the landed catch per fishing gear, expressed by number of containers or estimated weight per species. If available, scientific names should be used to identify species. The sum of species weights must reconcile with the Total Boat Catch to maintain data integrity and consistency across all reporting fields.
Length Data (Per Species and Gear Type)	Describes the measured total length (in centimeters) of individual fish specimens obtained from subsamples, categorized by species and corresponding fishing gear. These measurements provide data for length-frequency analysis, growth parameter estimation, and stock assessment models. Random sampling must be applied to avoid bias, and measurements should follow standardized length definitions (e.g., total length, fork length, or standard length) depending on the species' morphological characteristics.
Landing Center (Landing Area)	Refers to the designated fish landing site covered during the sampling activity. These sites are classified based on the volume and type of landings as either commercial, municipal, major, or minor landing centers. This classification helps assess the scale of fishing operations and guide data collection priorities. The geographic coordinates or administrative barangay/municipality names should also be recorded where applicable.
Fishing Ground	Denotes the marine or inland water area where fishing activity was conducted. This is the location where the fishing vessel deployed its gear and harvested fish. Fishing grounds are identified based on local geographic names or mapped regions and are crucial for spatial analysis of fishing effort and resource distribution. This information helps in tracking fishing pressure and stock dynamics within defined ecological zones.
Fishing Effort	Refers to the quantified fishing activity or input, such as the duration, frequency, and intensity of gear use, aimed at harvesting fish in a specified fishing ground. This is a key variable in assessing catch-per-unit-effort (CPUE) and overall fishing pressure.

Figure 3 shows that there are at least five (5) main fishing gears used in catching sardines both in municipal and commercial fishing operations. The gear with the largest number of catches in terms of volume originates from the purse seine gear, amounting to at least 97.4%, and ring net (2.04%), while other gears such as bag net (0.22%), drift gillnet (0.19%), and scoopnet (0.14%) amount to less than 1%.

2.2.2 Subsample weight and species composition

This involves extracting and analyzing a representative subsample of the catch, typically stratified by gear type: (1) determine total weight of the subsample, measured using calibrated weighing scales; (2) species identification and sorting, subsamples are sorted into species or species groups, and each is identified to the taxonomic level of species, using scientific nomenclature (e.g., *Nemipterus japonicus, Decapterus macrosoma, S. lemuru*); and (3) quantification of species group weights, the biomass of each identified species or species group is measured and documented.

2.2.3 Measurement of length frequency by species and gear

Length data are obtained from individuals within the subsample and may be applied to all species present or selectively to commercially significant or dominant species, depending on the sampling protocol or the project leader's directives. Length measurements are stratified by gear type to account for gear-specific selectivity patterns and are essential for stock assessment models, such as length-based cohort analysis.

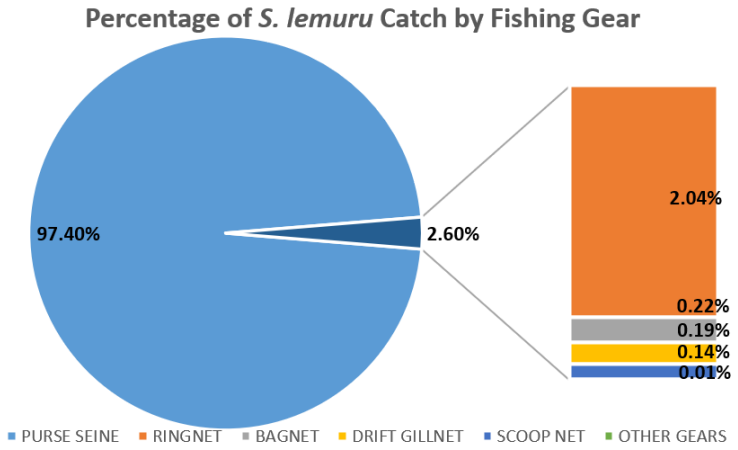

Figure 3. Composition of gears targeting and catching sardines in FMA-4.

2.2.4 Sources of catch and effort data

Table 5 exhibits the most commonly used fishing gears along with their codes and how effort is measured for each gear type. Other fishing efforts may be added as needed and deemed significant.

2.2.4.1 Landing site interviews

Catch and effort data are primarily gathered through on-site surveys conducted by trained Data Enumerators at designated fish landing centers. Information is obtained through direct interviews with fishers and includes key variables such as the date and location of fishing activity, total catch volume, type of fishing gear used, and fishing effort (e.g., number of hours fished, number of crew members). This method is most applicable to small-scale or coastal fisheries, where fishing trips are typically short (e.g., day trips or a few days at sea). Due to its reliance on self-reported data, this method is limited by the accuracy of fishers' recall.

2.2.4.2 Logbook-based surveys

For large-scale commercial fisheries, particularly those operating for extended periods at sea (e.g., purse seiners), catch and effort data are obtained through a logbook recording system. Vessel operators or captains document fishing operations, including catch volume, effort metrics, and fishing location, in standardized logbooks. Most commercial vessels maintain their own navigational and fishing logs, which provide a more systematic and continuous data source compared to recall-based interviews.

Table 5. Commonly used gear type in FMA-4 and effort measurement.

Gear Type	Measurement of Effort (CPUE)
Trawl (T)	Number and Duration of hauls, Duration of Dragging hours, Time at Sea
Purse Seine (PS), Ringnet (RN), Bagnet (BN); Beach Seine (BS)	Number and Duration of hauls, Duration of Fishing hours, Time at Sea
Danish Seine (DS)	Number and Duration of hauls, Time at Sea
Bottom Gill Net (BGN), Drift Gill Net (DGN), Surface Gill Net (SGN)	Length of net in meters (Number of "banata"), Duration of setting
Lift Net (LN)	Number of hauls, Gear Soak time
Multiple Hook & Line (MHL), Hook & Line (H&L), Longline (LL)	Number of hooks, Number of sets, Gear Soak Time
Handline (H)	Duration of fishing hours, Number of lines, Number of days fishing, Time at Sea
Troll Line (TL)	Number of lines, Duration of fishing hours
Jigger (J)	Number of jigs, Duration of hours jigging
Spear Gun (SG)	Number of spears used, Diving Duration
Fish Pot (FP), Fish Corral (FC)	Duration of hours during which the gear was submerged underwater, Number of hauls per day, Number of units

2.2.4.3 Scope and limitations

This study encompasses sardine catches from FMA-4, including the South and East Sulu Sea, and the northeastern portion of the Sulu Sea. The only model used in this study to establish the findings is the Tropical Fish R (TropFishR). The species of focus in this study is *S. lemuru* (Bleeker, 1853), also known as the Bali Sardine. The gears that were accounted for originate from both the commercial and municipal sectors and are recorded as capable of catching sardines. Twenty-five (25) landing sites were accounted for and sampled. In addition to catch volume and length data, boat information and particulars, such as but not limited to boat name, boat type, and main gear used, are recorded. Other pieces of information such as gross tonnage (GT) and boat length are also recorded. The data used in this study range from 2018 to 2023 and cover two major fishing grounds in FMA 4 (see Table 6).

The entire data collection protocol for this study was adopted from the methods of NSAP in the Philippine Capture Fisheries Atlas (Santos et al. 2017).

Table 6. Data specification.

Year Covered:	2018–2023
Statistical Tool Used:	FISAT and TropfishR (R)
Management Area:	FMA-4
Fishing Ground/s:	South Sulu Sea and East Sulu Sea
Landing Areas:	NSAP Landing Areas
Species:	*Sardinella lemuru*

3. RESULTS

The Fishery Management Area 4 (FMA-4) generates the major production of sardines in the entire country, amassing an average volume of 1,198,623.39 Metric Tons (MT) or at least 80% of the entire fishery production of FMA-4 within the last 6 years from 2018–2023. Throughout the years, the value of sardines holds significance in terms of economic value and importance due to its incremental demand. As a result, the growing sardine manufacturing industry on the peninsula postulated and instigated an increase in its fishing effort, placing even greater pressure on a highly exploited stock.

Over the years, the NSAP has continuously monitored the landed catch volume of *S. lemuru* from the South and East Sulu Sea. Through constant data gathering and the use of various statistical tools such as but not limited to TropFishR (R), the initiative was able to produce reliable results and estimates with regard to the exploitation status of the sardine fishery within the region annually.

3.1 2018–2020 Lump data analysis

3.1.1 Powell-Wetherall

The following analyses were done to assess and evaluate the fitness of the selected values of growth parameters that will be used for the yearly analysis of *S. lemuru.* The following results were obtained using various length-based methods of analysis (e.g., Powell-Wetherall, Response Surface analysis, Simulated Annealing, and Genetic Algorithm) to search for values that show statistical evidence of being the best fit among the other values for the other parameters.

Figures 4 and 5 show the Powell-Wetherall and VBGF plots. The Powell-Wetherall method is generally used to estimate the infinite length (L_{inf}) and the ratio of total mortality to growth rate (Z/K) in fish populations from length-frequency data. It is a widely

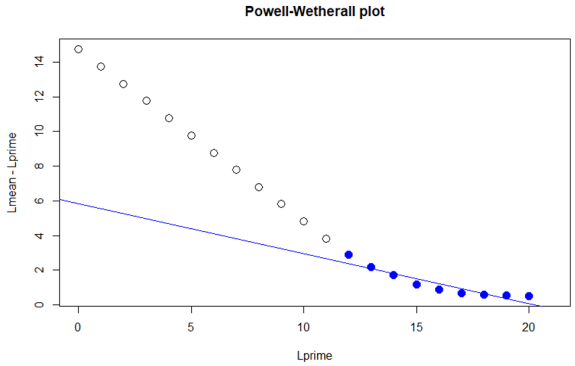

Figure 4. Powell-Wetherall Plot for 2018–2020 (14, 20).

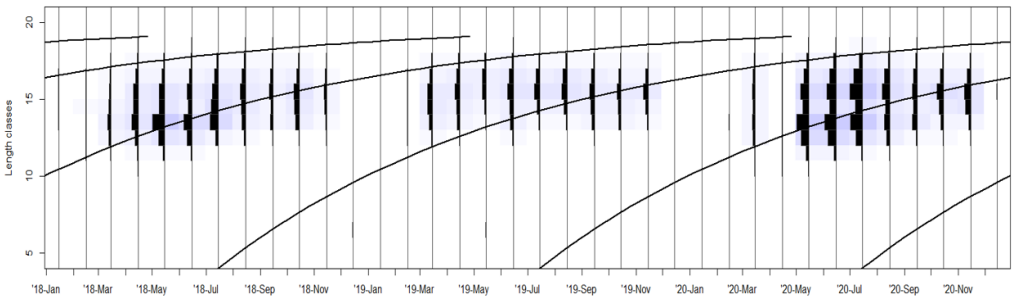

Figure 5. VBGF Plot based on Powell-Wetherall selected values for 2018–2020 (14, 20)

used method in stock assessment, particularly in data-limited contexts. This method assumes that the stock or population of a given species is in a steady state, that growth follows the von Bertalanffy Growth Function (see Figure 5), and that selection patterns remain unchanged. The selected values in this case were 14 and 20. The selection (see Figure 4) also provided the following values: L_{inf} = 20.03 + -5.71 (14, 20), K = 1.02, t_anchor = 0.3160637, C = 0, ts = 0, phiL = 2.612, and Ø = 0.199.

3.1.2 Response surface analysis

Response Surface Analysis (see Figure 6) is a statistical model that uses growth parameters such as K, L_{inf}, and M to assess variables (e.g., fish mortality or length at first capture) and their effects on yield or biomass. This was used to evaluate and possibly identify more suitable K and L_{inf} values, in addition to the K scan and Powell-Wetherall used prior to RSA. Further iterations yielded a value considered the best and most suitable fit among the other values based on the Standard Reference points (see Table 8). The values provided were; L_{inf} = 20, K = 1.09, t_anchor = 0.3440526, C = 0, ts = 0, phiL = 2.63948 and Ø = 0.199.

3.1.3 Simulated annealing

Simulated Annealing (see Figure 7) is an optimization method used to estimate key parameters such as growth rates, mortality, and selectivity by minimizing the difference between observed and predicted values (e.g., length-frequency data). It is particularly effective in avoiding local minima, making it suitable for complex, non-linear models in stock assessments (Mildenberger et al., 2017). This was used to evaluate and identify a more suitable K and Linf, in addition to the K scan and Powell-Wetherall

Table 7. Trigger Reference Points.

Species	Parameters	Limit Reference Point
Sardinella lemuru	Exploitation Rate (E)	0.70
	FM	2.5
	L_{m50}	15.1

Table 8. Summary of results for 2018–2020.

Parameters	Values
L_{max}	20.75
L_{inf}	20.0
K	1.09
Z	3.89
M	1.55
F	2.33
E	0.60
F/M	1.50
L_{50}	14.56
L_{75}	15.14
L_{95}	15.98
phiL	2.612006
Ø	0.199

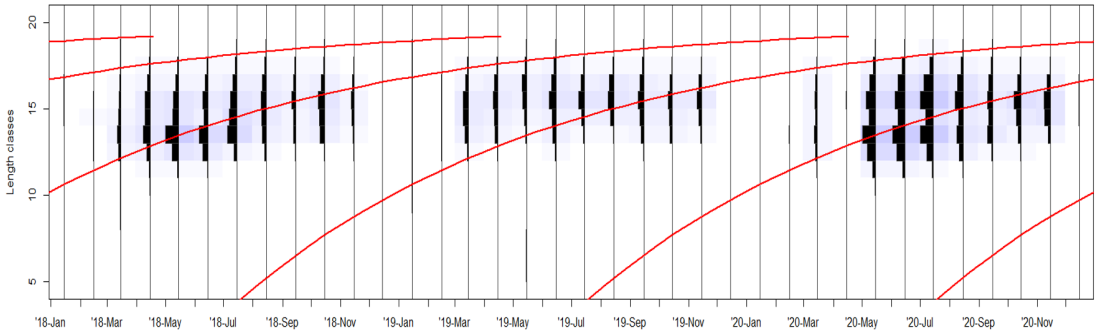

Figure 6. VBGF plot based on RSA selected values (L_{∞} = 20.0, K = 1.09) for 2018–2020.

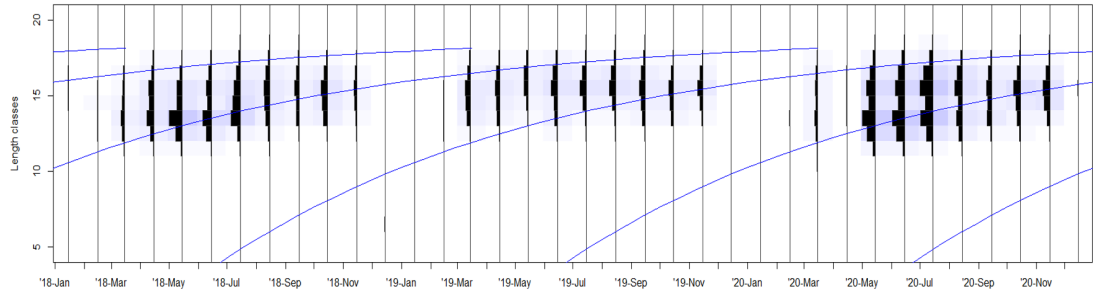

Figure 7. VBGF plot based on Simulated Annealing selected values (L_{∞} = 19.03, K = 1.03) for 2018–2020.

used prior to SA. The analysis provided the following values; (3) L_{inf} = 19.03804, K = 1.03, t_anchor = 0.2530141, phiL = 2.572857 and Ø = 0.3129173.

3.1.4 Genetic algorithm

Genetic Algorithm (see Figures 8 and 9) is a population-based search technique used to optimize biological and fishery parameters such as growth (L_{inf}, K), fishing mortality (F), and selectivity by simulating natural evolutionary processes. GAs work by generating a population of possible solutions, selecting the best fits, and using genetic operations (selection, crossover, mutation) to evolve better solutions over generations. This method was used to assess further and evaluate a more suitable K and L_{inf} aside from the K scan and Powell-Wetherall that was used prior to SA. The analysis provided the following values (3) L_{inf} = 19.13, K = 1.043539, t_anchor = 0.2666911, phiL = 2.582035 and Ø = 0.313

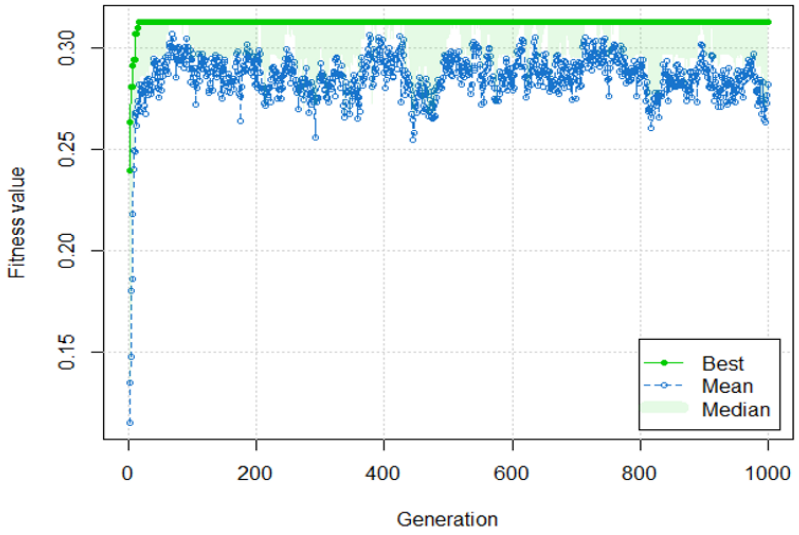

Figure 8. GA plot third iteration based on selected values from Powell-Wetherall for 2018–2020.

3.1.5 Selectivity and mortality estimation

Selectivity values and probability of capture (see Figures 10 and 11) were selected based on the provided results from Powell-Wetherall, RSA, SA and GA. The following results were based on the L_{inf} and K values that were analyzed using the Response Surface Analysis (RSA). The following values shown (see Table 8) were determined using the mortality estimation

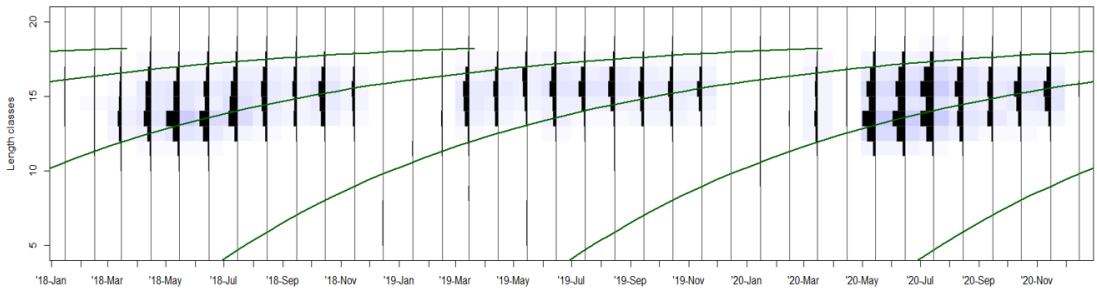

Figure 9. VBGF plot based on Genetic Algorithm Iteration for 2018–2020.

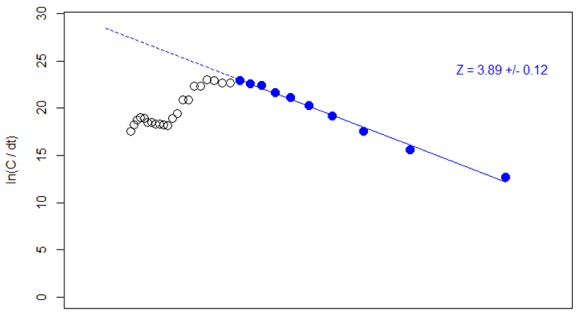

Figure 10. Catch curve and selectivity for 2018–2020.

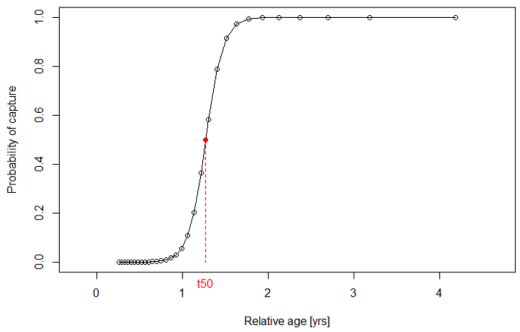

Figure 11. Probability of capture relative to age for 2018–2020.

analysis; Total mortality (Z) = 3.89, Natural mortality (M) = 1.55, Fishing mortality (F) = 2.33, Exploitation rate (E) = 0.60, Fishing pressure (F/M) = 1.50, L_{50} = 14.56, L_{75} = 15.14 L_{95} = 15.98, phiL = 2.612006 and Ø = 0.199.

3.2 2021-2023 Lump data analysis

3.2.1 Powell-Wetherall

Figures 12 and 13 show the Powell-Wetherall and VBGF Plots for the years 2021-2023. The 3-year lump analysis allows for a broader standpoint in terms of observing the growth curve shown in the VBGF plot. This allows for an extended view of the increment growth, which was determined using the aforementioned parameters. The values provided by these parameters are as follows: L_{inf} = 20.16 +- 7.22, K = 1.07, phiL = 2.638566, and Ø = 0.178.

3.2.2 Response surface analysis

Figure 14 shows the VBGF Plot based on the following values from the response surface analysis, which was based on the Powell-Wetherall-selected

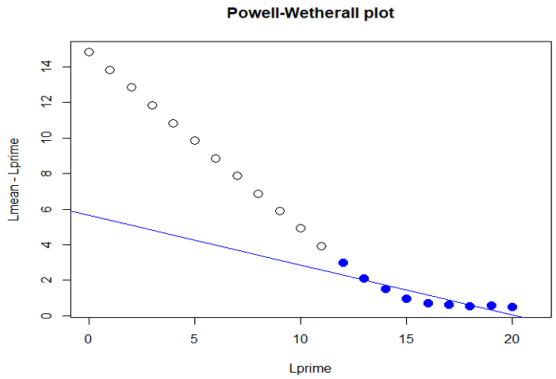

Figure 12. Shows the Powell-Wetherall plot for 2021–2023 (13, 22).

values. The values are as follows; L_{inf} = 20.1, K = 1.1, t_anchor = 0.2593369, C = 0, ts = 0, phiL = 2.647785 and Ø = 0.193.

3.2.3 Simulated annealing

Figure 15 illustrates the VBGF Plot based on the values provided by the Simulated Annealing analysis that was based on the Powell-Wetherall selected values. The values are as follows; L_{inf} =17.78, K = 1.09, t_anchor = 0.1613683, phiL = 2.539864 and Ø = 0.4714136.

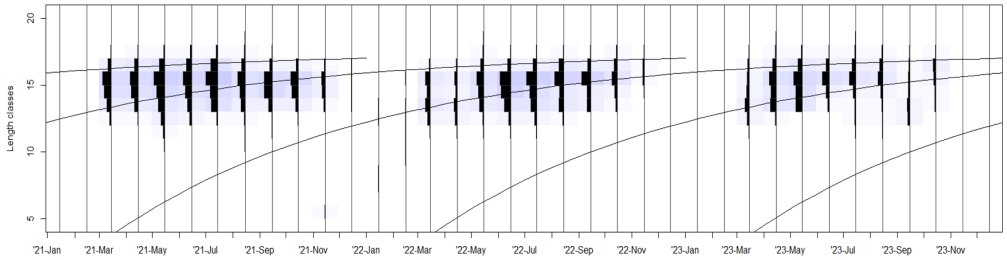

Figure 13. VBGF plot based on the Powell-Wetherall selection for 2021–2023 (13, 22).

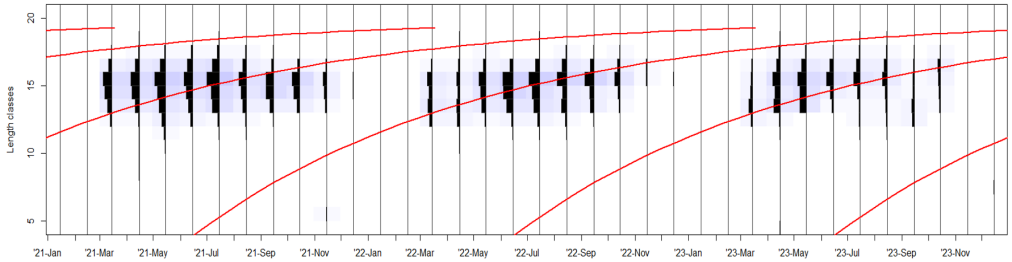

Figure 14. RSA VBGF plot based on the Powell-Wetherall selected values for 2021–2023 (13, 22).

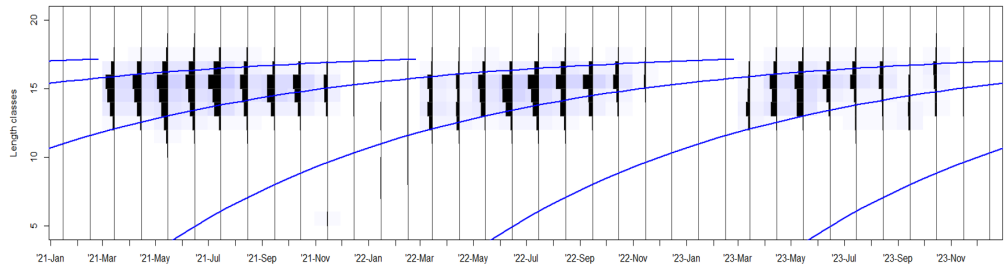

Figure 15. Simulated Annealing VBGF plot based on Powell-Wetherall selected values for 2021–2023 (13, 22).

3.2.4 Genetic algorithm

Figures 16 and 17 show the VBGF Plot from the Genetic Algorithm analysis, which yielded the following values using the Powell-Wetherall-selected values. The iterations were run multiple times to compare the fitness scores of each value and select the best and most suitable fit among the values. The values that were deemed to be the best fit are as follows: L_{inf} = 17.58503, K = 1.0598, t_anchor = 0.1747753, phiL = 2.51551 and Ø = 0.4699124 with a fitness score of above 0.45 (see Figure 16), indicating statistical accuracy in terms of estimates.

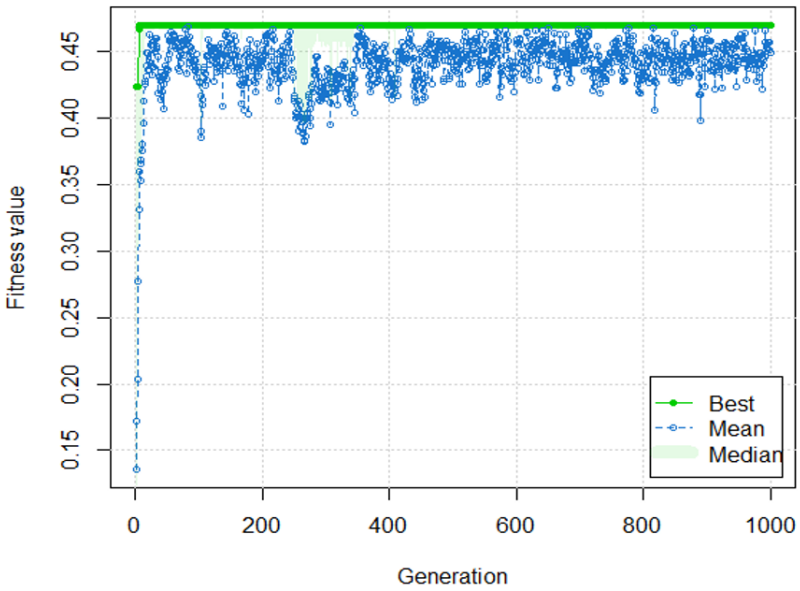

Figure 16. Genetic Algorithm based on Powell-Wetherall selected values for 2021–2023. (13, 22).

3.3 Selectivity and mortality estimation

Figures 18 and 19 show the selectivity and probability of capture by age, based on the values provided by Powell-Wetherall and Response surface analysis (see Table 9). These values were assessed to determine whether they align with real-time values, as depicted in the figures above. The values are as follows; L_{inf} = 20.1, K = 1.1, Z = 5.08, M = 1.60, F = 3.48, E = 0.68, F/M = 2.17, L_{50} = 14.76, L_{75} = 15.29, L_{95} = 16.06, phiL = 2.58 and Ø = 0.178.

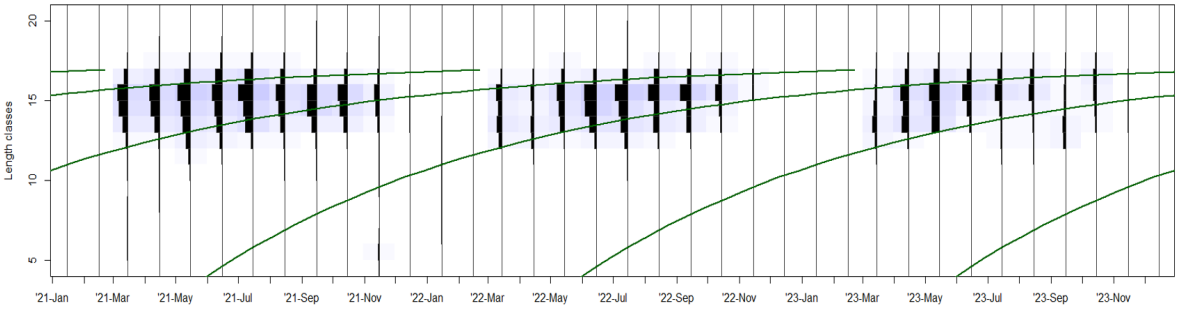

Figure 17. GA VBGF plot based on Powell-Wetherall selection for 2021–2023 (13, 22).

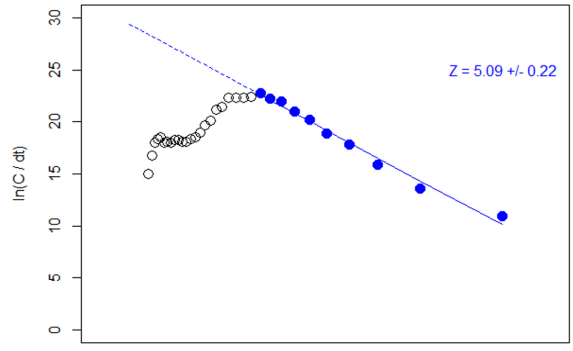

Figure 18. Catch curve and selectivity for 2021–2023.

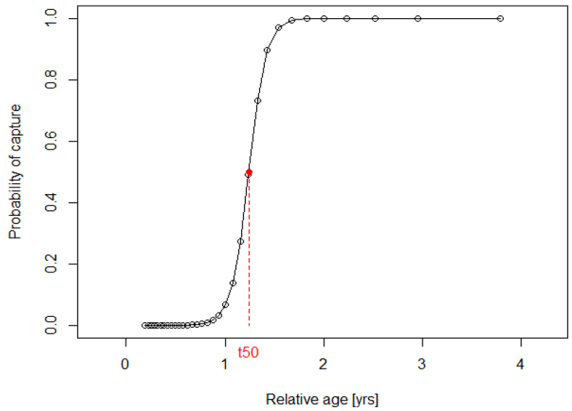

Figure 19. Probability of capture relative to age for 2021–2023.

Table 9. Summary of results (2021–2023).

Parameters	Values
L_{max}	20.75
L_{inf}	20.1
K	1.1
Z	5.08
M	1.60
F	3.48
E	0.68
F/M	2.17
L_{50}	14.76
L_{75}	15.29
L_{95}	16.06
phiL	2.58
Ø	0.178

The following results of the parameter estimation methods and statistical models shown in Tables 8 and 9 above were used to estimate the Exploitation (E) values and Fishing Pressure (F/M) from 2018 to 2023. The average length of *S. lemuru* throughout these years ranges from 13.25 to 16.75 cm. The status of the sardine fishery of FMA-4 was observed to be approaching its trigger limit of 0.70 (see Table 7), with the highest recorded exploitation value of 0.68 in years 2021–2023, and at the same time, the highest fishing pressure (2.17) recorded within a 6-year time frame. The increase in both E and F/M values is primarily due to the inclusion of municipal sardine catches. Municipal gears, though incomparable to commercial gears in terms of volume, still contribute significantly to the entire catch make-up of FMA-4. Sardine fishers take advantage of sardines' economic significance by catching more, and this annual increase in fishing pressure takes a toll. The sardine cannery industry in the Philippines has produced an average of 355,000 metric tons of canned sardines annually since 2014 (BFAR 2020). The demand for sardines, not only in markets but also in the mass production of canned products, drives more fishers to actively target *S. lemuru*.

3.4 Summary of results

Table 10 summarizes results analyzed annually using TropFishR, pertinent to the 3-year lump analysis. The L_{inf} and K values used in this analysis were derived from the 3-year lump analysis to assess differences in the yearly values of exploitation, mortality, fishing pressure, and length at first capture. As observed in the results, there is a subtle difference in the E ratio and F/M values when analyzed annually and in a 3-year lump manner. However, it is also important to note that these results do not differ significantly. The 3-year lump analysis was conducted to assess the continuous incremental growth of *S. lemuru*, while the annual analysis was conducted to examine differences in exploitation rate and mortality, which are significant for yearly estimates. These results portray a dire state of the sardine fishery, driven by continuous exploitation and a steady, incremental annual increase in fishing pressure.

3.5 Length distribution of *S. lemuru*

Figure 20 exhibits the length distribution of *S. lemuru* from 2018 to 2023. The most dominant length observed from year 2018 ranges from (13.25–15.57 cm), while in 2019, the most length observed ranges from (14.75–16.75 cm), in 2020 the length ranged from (13.25–16.25 cm), for 2021 from (14.25–16.25 cm), 2022 from (13.75–16.25 cm) and 2023 the length with the most observed frequency ranged from (14.75–16.25 cm).

The reason for the presence of juvenile catches is due to the inclusion of length data from municipal gears. Municipal fishers are known to use fishing gears that have smaller mesh sizes compared

Table 10. Summary of annual results.

Parameters	2018	2019	2020	2021	2022	2023
L_{inf}	20.0	20.0	20.0	20.1	20.1	20.1
K	1.09	1.09	1.09	1.1	1.1	1.1
Z	4.14	4.47	4.44	5.18	4.41	5.009
M	1.63	1.63	1.63	1.64	1.64	1.64
F	2.51	2.84	2.81	3.54	2.77	3.36
E	0.60	0.63	0.63	0.68	0.62	0.67
F/M	1.53	1.74	1.72	2.15	1.68	2.04
(Φ')	2.63	2.63	2.64	2.64	2.648	2.648
L_{50}	14.55	15.46	14.25	14.83	13.24	14.70
L_{75}	15.13	16.05	14.69	15.37	14.27	15.19
L_{95}	15.97	16.87	15.35	16.16	15.65	15.91

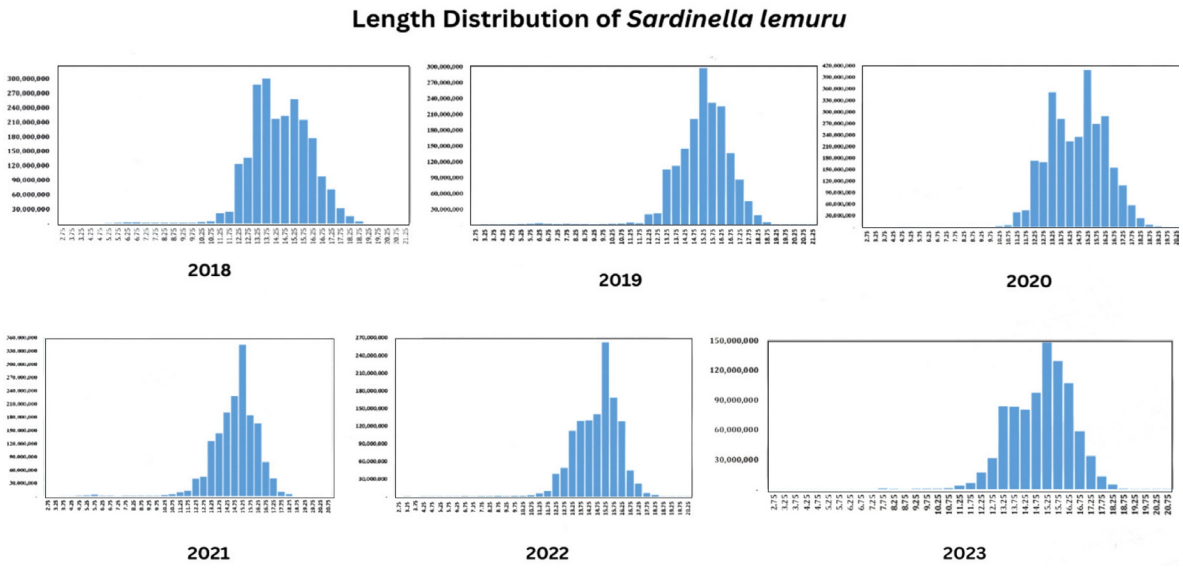

Figure 20. Sardinella lemuru length distribution.

to commercial gears. Some gears, including scoopnet, ringnet, and even bagnet, are selective in their catches, specifically sardines. In the case of scoopnet, the catch make-up is composed primarily of sardines. Although most catches appear to be from independent fishing operations, in some cases their catch originates from purse seine. This is because purse seine gear enters municipal waters (less than 15 km), attracting more sardines due to its light having greater luminance than that of municipal fishers. This compels municipal fishers to scoop out some of the purse seine catch to keep up with the catch.

Ringnet and bagnet are among the main contributors to juvenile catches due to their smaller mesh sizes compared to purse seines; the minimum length at which these gears catch is observed to be below 13 cm, with most catches comprising juveniles alone.

4. DISCUSSION

One of the main reasons fish stocks are declining in FMA 4 is the increasing number of juvenile fish being caught before they even have the chance to grow and reproduce (BFAR 2014; BFAR 2012; BFAR 2015). Harvesting young fish too early prevents them from reaching their full size and reduces the overall number of fish that would have been available if they were allowed to mature (Beverton and Holt 1957). This places the stocks in a vulnerable state. This problem is especially common in tropical fisheries that use different types of gear and often do not strictly enforce rules about net mesh sizes. Declining fish stocks are often linked to inadequate fisheries management rather than the unavoidable consequences of fishing itself, highlighting the need for effective governance and enforcement (Mora et al. 2011). Studies have shown that catching juveniles not only hurts future fish populations, but also threatens the livelihoods of people who depend on fishing (Najmudeen and Sathiadhas 2008). That is why it is so important to use fishing methods that target adult fish, giving younger ones a chance to grow and help sustain the fishery for the long term.

Assessing fish stocks can be challenging when detailed data are limited, as is often the case in the Philippines. That is why length-based assessment methods have become essential tools for understanding the health of these fisheries (Prince et al. 2015). For example, the Length-Based Bayesian Biomass (LBB) approach uses information on the sizes of caught fish to estimate the status of a fish population. This method, which has been widely used in small pelagic fisheries, relies on indicators such as the average fish length relative to the optimal length (L_{mean}/L_{opt}) and the balance between fishing and natural mortality rates to provide insights into how heavily a stock is being fished (Froese et al. 2018). These models are especially helpful for spotting problems like growth overfishing when fishes are caught before they have had a chance to grow or even replenish the stock that was lost due to exploitation and recruitment overfishing, which happens when too few young fish survive to adulthood (Taylor and Mildenberger 2017). Even without traditional age data, length-based methods give researchers a practical way to monitor

and manage fisheries. On top of that, new tools like TropFishR make it easier for scientists to analyze fish size data, allowing for more accurate estimates of growth and survival rates through advanced modeling techniques (Mildenberger et al. 2017).

Based on the results shown, the status of the sardine fishery in FMA-4 appears to be highly exploited due to excessive fishing operations, resulting in continuous fishing pressure within its waters. Every year, the levels of fishing pressure were observed to fluctuate at higher levels, with no indication of returning to a healthy level. A stock assessment of *Sardinella fimbriata* in Bangladesh using LBB, along with 10 years' worth of data from 2008 to 2017, indicated overfishing, with 74% of the stock exploited. The reference point for sardine stocks in Bangladesh ranges from 0.4 to 0.5. The stocks were further classified based on the B/BMSY values (Fanning et al., 2019) and explained as healthy stock (B/BMSY > 1.1); slightly overfished (0.8 < B/BMSY ≤ 1.1); overfished (0.8 ≤ B/BMSY ≤ 0.5); grossly overfished (0.5 < B/BMSY ≤ 0.2); and collapsed (B/BMSY < 0.2). The B/BMSY was calculated to be lower than the reference point (0.26), indicating a grossly overfished stock (Barman et al. 2021). The LBB-derived parameter results from L_{mean}/L_{opt} and L_c/L_{c_opt} indicated the shortened length structure and capture of very young individuals for S. fimbriata, likely due to smaller mesh sizes (Barman et al. 2021)

These results are comparable to the sardine stock status in FMA-4 with respect to exploitation and juvenile catch. The causality of fishing pressure to exploitation and the excessive juvenile fishing leads to the depletion of stocks due to prolonged overfishing. Other studies on sardine stock assessment show that sardine sustainability depends on whether fishing pressure is regulated (Arendse et al. 2007). Excessive and continuous fishing activities show massive depletion of stocks within 10 years, as evidenced by the stock assessment by Barman et al. (2021).

Juvenile catching plays a vital role in the case of an overexploited population. Fishing gear that catches juveniles, such as ring nets, contributes significantly to the declining status of sardine stocks. By catching juveniles, it becomes difficult for the remaining population to replenish the number exploited (Dar et al. 2015). In open-access marine fisheries, the intentional and unintentional capture of juvenile fish is dire, as it can lead to a major reduction in future yields and obstruct recruitment into the fishery. This problem is severe in cases of multi-gear and multi-species fisheries. Growth overfishing occurs when fish are harvested before reaching their optimal size for capture (Najmudeen and Sathiadhas 2008). Sustainable fisheries management should involve only gear that targets larger fish while allowing juveniles to escape.

On a much broader scale, a study by Guanco et al. (2014) shows that many marine fish stocks are already overfished or being exploited in unsustainable ways. The Food and Agriculture Organization (2022) reports that rising demand for fish, combined with weak regulations, has played a big role in the ongoing decline of fish populations. For sardines and other small pelagic species, changes in the environment can cause stock numbers to go up and down, but the main culprit behind their long-term decline is still too much fishing (Checkley et al. 2009). Additionally, relying too heavily on the concept of maximum sustainable yield (MSY) without applying careful, precautionary management has been blamed for causing stock collapses in some fisheries (Pauly and Froese 2021).

In addition, the current fisheries status of sardines appears to be different from that in the early 2000s. According to a fisheries assessment conducted between 2004 and 2008, encompassing the Western and Central Visayan Sea, Sorsogon Bay, Lagonoy Bay, and Honda Bay, the status of sardine stocks in the Philippines as a whole was observed to be healthy. However, certain fishing grounds have exhibited signs of depletion. Based on NSAP data, sardines in the western and central Visayas have been reported to be under heavy fishing pressure in particular, with stocks of *S. gibbosa* and *S. fimbriata* being overexploited (Guanco et al. 2009). The basis of evidence for overexploitation was based on the standard length (SL) data from captured fish, which were less than the standard length at first maturity for these particular species. Furthermore, in Sorsogon Bay, located in Southeast Luzon, the *Escualosa thoracata* (white sardine), which was considered the dominant species captured, was reportedly overfished, based on an analysis showing a declining catch size with progressively increasing effort (Olano et al. 2009a). Assessments of Lagonoy Gulf fisheries indicate that small and large pelagic species dominate the catch at 43.83% and 42.18%, respectively, while high fishing pressure has caused exploitation rates to exceed sustainable levels. Furthermore, 89% to 98% of small pelagic fish are harvested before reaching maturity, largely due to juvenile targeting by commercial gear in municipal waters (Olano et al. 2009b) For Honda Bay, Palawan, *A. sirm* was considered overexploited, as data show it was harvested above optimal levels (Ramos et al. 2009).

The stock status and exploitation patterns observed in sardine fisheries, particularly in FMA-4, can also be better understood in the context of stock structure and population connectivity. A study on *S. lemuru* in the Philippines demonstrated that this species exhibits genetic structuring across geographic regions, suggesting that populations may not be fully mixed and could function as separate sub-stocks (Willette et al. 2011). The significance of the multiple iterations of parameters, as shown in Figures 4–20 under the Lump Data Analysis, which allowed the TropFishR to analyze 6 years' worth of length frequency data subdivided into two pairs (e.g., 2018–2020 and 2021–2023), was to stress the method of selecting values that reflects the current situation and status of fisheries. The multiple trials have provided a broader perspective and selected values through various analytical methods. This is because selecting the L_{inf} and K values provided by the model on a yearly basis occasionally does not reflect the current fishery situation; this is the importance of multiple iterations using different values from different methods of analysis, since statistical models of analysis, as such, adheres to the empirical relationships in terms of estimating asymptotic length, length at first maturity (Froese and Binohlan 2000). It creates room for options while depicting real-time probabilities based on various reference points.

Often, iterated values provide an indication of a healthy stock when, in reality, the opposite is true. Multiple trials allow further assessment and evaluation and eliminate bias by determining the "best fit" or most suitable values – that reflects real-time information regarding the status of fishery stocks, particularly *S. lemuru* – without settling on the first result that was provided during the first trial.

Furthermore, the data used in this analysis were improved by excluding length frequencies that rarely appear in a year. These length frequencies were considered outliers and do not necessarily represent any length in the data set due to their lower occurrence. Some of the factors considered during the exclusion of what was deemed as outliers were: (1) They are likely to be data entry errors or misidentification; (2) They do not represent a biologically meaningful portion of the population; (3) Their inclusion would likely distort model fitting (e.g., cause unrealistic estimates of L_{inf}, K, or Z/K in VBGF).

5. CONCLUSION AND RECOMMENDATIONS

The sardine stocks in FMA-4, encompassing the South and East Sulu Sea, based on the results provided, have consistently exhibited high exploitation and fishing pressure levels throughout 2018 up until 2023, with exploitation rates (E) ranging between 0.60 and 0.68, which are alarmingly close to the critical trigger reference point of 0.70. Fishing mortality (F) consistently remained high across the years, while fishing pressure (FM) plummeted above the threshold limit of 2.0, indicating that the sardine population is experiencing sustained and continuous heavy fishing activities.

During this period, growth parameters and mortality estimates indicate that, while *S. lemuru* are moderately fast-growing, the stocks are under high levels of pressure, particularly due to increased fishing effort driven by rising economic demand. The data also show that a significant portion of the catch comprises individuals below the standard length at first maturity (L_m = 15.1 cm), particularly in years when early capture of juveniles was observed and due to the participation of municipal fishing gears, potentially compromising the rate of stock replenishment and directly affecting sustainability. Moreover, the selectivity differences between commercial and municipal gears also subsequently impact the catch composition, with municipal gears contributing more to juvenile captures due to smaller mesh sizes. Although some years (like 2019) exhibited signs of significantly mature catches and which can be seen as possibly better stock conditions, the overall trend, based on analysis, reflects that sardine stocks are heavily exploited and are approaching the established limit reference point, especially if no changes in fishing efforts are made.

In light of the findings that *S.lemuru* stocks in FMA-4 are currently experiencing sustained high fishing pressure and are approaching near the limit reference point, the following management recommendations are proposed to prevent further stock depletion and ensure the long-term sustainability of the sardine fishery:

5.1 Immediate regulation of fishing effort

The consistent exploitation rates (E = 0.60–0.68) near the trigger point of 0.70 and fishing mortality values above the sustainable threshold necessitate immediate interventions to reduce fishing pressure. This can be achieved through a combination of seasonal closures, spatial restrictions in critical

habitats, and strict enforcement of allowable fishing days and vessel quotas, particularly during peak spawning periods.

5.2 Implementation of size-based management measures

A significant proportion of the catch comprises individuals below the length at first maturity (L_m = 15.1 cm), indicating widespread juvenile fishing. Mandating the use of appropriate mesh sizes in both commercial and municipal fisheries, particularly enforcing minimum mesh size regulations, will allow juvenile fish to escape and reach reproductive maturity, thereby supporting recruitment and stock regeneration.

5.3 Gear-specific regulations

Municipal fishing gears are observed to have lower selectivity and higher juvenile catch rates. Regulatory differentiation between gear types must be implemented, including the phasing out of non-selective or destructive gear types and incentivizing the adoption of selective and sustainable gear technologies.

5.4 Data-driven adaptive management

The use of multiple iterations and parameter estimations through TropFishR demonstrates the importance of robust, real-time monitoring. It is recommended that regular length-based assessments continue, ideally integrated with biological sampling (e.g., gonadal maturity), to inform adaptive fisheries management. An annual update of growth and mortality parameters should be institutionalized to track stock changes more accurately.

5.5 Establishment of a harvest control rule (HCR)

Introduce a Harvest Control Rule framework incorporating Target, Trigger, and Limit reference points for fishing mortality (F) and exploitation (E), aligned with international standards. This will serve as a proactive mechanism to adjust fishing efforts based on real-time stock assessments.

5.6 Capacity building and stakeholder engagement

Engage local fisher folks and municipal fisheries management units in education campaigns and co-management initiatives. Emphasis should be placed on the ecological and economic risks of overfishing, the importance of protecting juvenile fish, and the benefits of long-term sustainability.

5.7 Exploration of alternative livelihoods

To reduce dependence on sardine fishing and ease fishing pressure, support programs should be implemented to provide alternative income sources for coastal communities, including aquaculture, ecotourism, and other sustainable marine-related enterprises.

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AUTHOR CONTRIBUTIONS

Ignacio DB: Supervision, Conceptualization and Design of the Study, Analysis and Interpretation of Data, and Revision. **Lague VM**: Acquisition of Data, Analysis and Interpretation of Data, Writing-original draft, and Revision. **Revillas CB**: Acquisition of data, Analysis and/or interpretation of data, and Revision. **Kunting AK:** Project Supervision. **Flores NAL:** Analysis and/or interpretation of data, and Revision

CONFLICTS OF INTEREST

The authors declare no actual, potential, or perceived conflict of interest for this study.

ETHICS STATEMENT

The authors affirm that all international, national, and institutional guidelines for the care and use of laboratory animals have been diligently followed and adhered to throughout this study

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