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Original Article

Population structure, stock status, and management implications of longtail tuna (*Thunnus tonggol*) in the Natuna Sea, Indonesia

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Abstract: The Natuna Sea, a strategic and biodiverse marine area, supports significant fishery resources. This study investigated the population dynamics of longtail tuna (*Thunnus tonggol*), a species of considerable ecological and economic importance, to provide a scientific basis for sustainable fisheries management in the region. Monthly fork length data were collected throughout 2021 from drift gillnet catches landed at Pemangkat Fishing Port, West Kalimantan, and were analyzed using the FiSAT II software package. Key population parameters were estimated as: asymptotic length (L_∞) = 114.45 cm, growth coefficient (K) = 0.36 year^{-1}, and theoretical age at zero length (t_0) = - 0.2865 years. Natural mortality (M) was 0.65 year^{-1}, fishing mortality (F) was 0.58 year^{-1}, and total mortality (Z) was 1.23 year^{-1}. These values yielded a current exploitation rate (E) of 0.43. Recruitment was bimodal, occurring in March–April and August–September. The length at first capture (L_c) was estimated at 54.33 cm. The spawning potential ratio (SPR) was estimated to be 30%, a level considered above the minimum biological limit reference point for sustainability. The yield-per-recruit analysis demonstrates that the existing exploitation rate (E = 0.43) falls short of the rates necessary to attain maximum yield per recruit (E_{max} = 0.598) and the optimal yield per recruit ($E_{0.1}$ = 0.507). These findings suggest that the *T. tonggol* stock in the Natuna Sea is currently in a developing exploitation phase, with potential for carefully managed increases in fishing effort while ensuring long-term sustainability.

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Introduction

The Natuna Sea, a marine region in northern Indonesia, borders the South China Sea on both sides. In the north, it borders Vietnam and Malaysia, and the South China Sea, where Indonesia's EEZ overlaps with China's claim under the Nine-Dash Line (Isak et al., 2020). Abundant fishery resources and high biodiversity characterize this strategic marine region. However, due to their rich fishery potential and open geographic location, these waters are susceptible to access by foreign fishing vessels, which frequently results in illegal, unreported, and unregulated (IUU) fishing (Muhamad, 2012). Wijayanti et al. (2021) reported that the prevalence of illegal fishing in the Natuna Sea is attributable to inadequate surveillance and law enforcement capabilities. Geographically, these are neritic waters with an average depth of approximately 70 meters (Hidayat and Noegroho, 2018), which constitute a significant marine fishing ground and provide a highly suitable habitat for various pelagic fish species.

One such pelagic fish species of considerable economic and ecological importance in the Natuna Sea is the longtail tuna, *Thunnus tonggol*, found in shallow coastal and island-associated waters (Griffiths et al., 2007). The global distribution of *T. tonggol* is extensive, ranging from Japan, Australia, the Indonesian archipelago, Papua New Guinea, and the Philippines, to the Java Sea to the Somali Coast, the Red Sea, the Persian Gulf, the Arabian Peninsula, Indian waters, and the Malacca Strait (Collete and Nauen, 1983; Eagderi et al., 2019). The Java Sea, Natuna Sea, and Strait of Malacca are frequent habitats for longtail tuna in Indonesian waters

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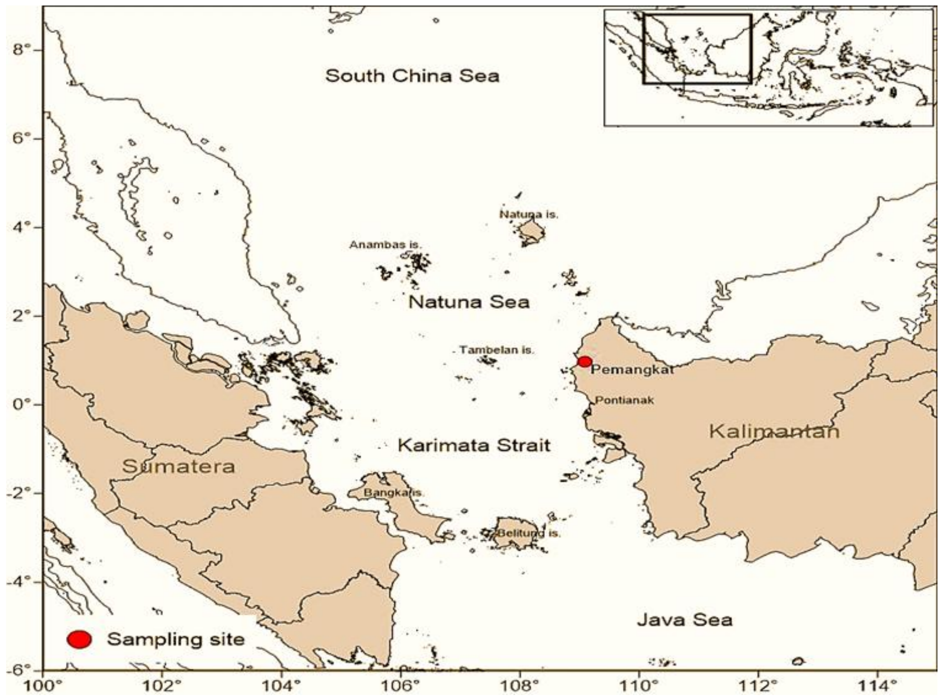

Figure 1. Sampling Site for longtail tuna data collection, Natuna Sea.

(Hidayat et al., 2020). In the Natuna Sea, longtail tuna is exploited using gill nets and is frequently caught alongside other neritic tuna species, such as kawakawa (*Euthynnus affinis*) and Spanish mackerel (*Scomberomorus commerson*).

The escalating intensity of fishing activities has, however, led to increasing pressure on *T. tonggol* resources within the Natuna Sea. Continuous and inadequately controlled fishing efforts can drive fisheries toward overexploitation, potentially culminating in stock collapse, a risk well-documented in fisheries science (Hilborn and Walters, 1992). To ensure the long-term sustainability of *T. tonggol* resources, it is imperative to conduct comprehensive studies of this species' population dynamics in the Natuna Sea. Such research provides a critical overview of the current stock condition and the status of its utilization. Information on fish population dynamics, including parameters such as exploitation rates, mortality, and growth, is fundamental to the formulation and support of effective, sustainable fisheries management strategies (Allen and Hightower, 2010). Furthermore, understanding the biological characteristics and population dynamics of *T. tonggol* in specific fishing grounds, such as the Natuna Sea, is essential for region-based fisheries management. Given the Natuna Sea's importance as a vital fishing ground and critical ecosystem, periodic assessments are necessary to monitor population dynamics and productivity. Therefore, this study aims to analyze key population dynamic parameters, specifically the growth rate, mortality rate, and exploitation rate of longtail tuna in the Natuna Sea. The findings are expected to provide scientific recommendations to support the sustainable management of this valuable resource.

Materials and Methods

The data were collected monthly over one year, from January to December 2021. The primary data consisted of fork length (FL, cm) measurements of longtail tuna obtained from the commercial catches of drift gillnet fishers. These catches were landed at the Pemangkat Fishing Port in West Kalimantan, Indonesia, a major landing site for fisheries operating in the Natuna Sea. Fish were measured for fork length, and these data were subsequently grouped into length classes each month to compile length-frequency distributions. The data collection process was facilitated by trained enumerators stationed at the fish sampling locations (Fig. 1).

Data analysis

Length at first capture (Lc): By fitting a logistic selection curve to the length-frequency data, we were able to estimate the mean length at first capture (Lc), which is the length at which half of the fish that contact the gear are held. To simulate the likelihood of capture at a specific length, the formula outlined by Sparre and Venema (1998): S_{Lest}= 1/(1+exp(S1-S2*L)) was utilized, where S1 and S2 are constants of the logistic curve, and L is the fish length. The initial length of capture (Lc) was then calculated as Lc = S1/ S2.

Growth parameters: The growth coefficient (K), asymptotic length (L∞), and von Bertalanffy growth parameters were analyzed by the Electronic Length Frequency Analysis (ELEFAN I) routine within the FiSAT II software (Gayanilo et al., 2005). ELEFAN I identifies growth curves by tracing modes through sequentially arranged monthly length-frequency data. The von Bertalanffy Growth Formula (VBGF) is expressed as (Sparre and Venema, 1998): $L_t=L_\infty(1-e^{-K(t-t_0)})$, where Lt = the length at age t, L∞ = the asymptotic length (cm), K = the coefficient of growth (year^{-1}), and t_0 = The age at which fish might theoretically be completely lengthless (years). The parameter t_0 was estimated using Pauly's (1980) empirical formula: $\log(-t_0) = -0.3922-0.2752\log(L_\infty)-1.038\log(K)$.

Mortality rates: The instantaneous rate of natural mortality (M) was estimated using Pauly's empirical formula (Pauly, 1980), which relates M to L∞, K, and the mean annual sea surface water temperature (T°C) of the environment: $\log(M) = -0.0066-0.279\log(L_\infty) + 0.654 \log(K) + 0.4634 \log(T)$. The instantaneous rate of total mortality (Z, year^{-1}) was estimated using the Beverton and Holt (1956) in (Sparre and Venema, 1998) length-converted catch curve method, as implemented in FiSAT II: $Z=K(L_\infty-\bar{L})/(\bar{L}-L')$, where $\bar{L}$ is the mean length of fish fully recruited to the gear, and L′ is the lowest length of fish fully recruited to the gear, the instantaneous rate of fishing mortality (F) was subsequently calculated as the difference between total and natural mortality: F=Z−M.

Exploitation rate: The exploitation rate (E) was calculated using the formula (Sparre and Venema, 1998) of E = F/Z or E = F/(F+M).

Yield per recruit: Yield-per-recruit (Y/R) was analyzed using the Beverton and Holt (1957) length-based model (Sparre and Venema, 1998) incorporated into FiSAT II, which accounts for the selection ogive and incomplete recruitment. The general form of the yield per recruit equation used is:

$$Y/R = F * A * W\infty * \left\{\frac{1}{Z} - \left(\frac{3U}{Z+K}\right) + \left(\frac{3U^2}{Z+2K}\right) - \left(\frac{U^3}{Z+3K}\right)\right\}$$

Where W∞ is the asymptotic weight (gr), tc is the mean age at first capture, and tr is the mean age at recruitment. The term U is defined as 1−(Lc/L∞).

Spawning potential ratio: The spawning potential ratio (SPR) was assessed using a length-based SPR model (LB-SPR) developed by Hordyk et al. (2014). This model utilizes estimates of the ratio M/K, L∞, and the length at first maturity (Lm) as key input parameters. For this study, Lm was defined as the length at which 50% of the population is mature (Lm50). The SPR calculation is based on the following formula (Prince et al., 2015):

$$SPR_t = \frac{\sum_{t=0}^{t} EP_t}{\sum_{t=0}^{tmax} EP_t}$$

Where EPt is the reproductive output at age t. Originally, EPt is defined as: $EP_t = (N_{t-1}e - M)f_t$, where Nt is the number of individuals at age t (with N_0 often standardized to 1000), and ft is the average fecundity at age t. Due to the unavailability of direct fecundity data (ft) for *T. tonggol* in this study, EPt was computed using an alternative proxy for reproductive output: EPt= Nt·Wt·mt, where Wt is the weight of the fish at age t, and mt is the proportion of mature fish at age t.

Results

Fisheries characteristics: The longtail tuna fishery in the Natuna Sea was predominantly exploited by drift gillnetters, which accounted for 94% of the recorded catches, while purse seiners contributed the remaining 6%. The drift gillnet vessels operating from Pemangkat are typically constructed of wood, with gross tonnage ranging from 16 to 47 GT. These

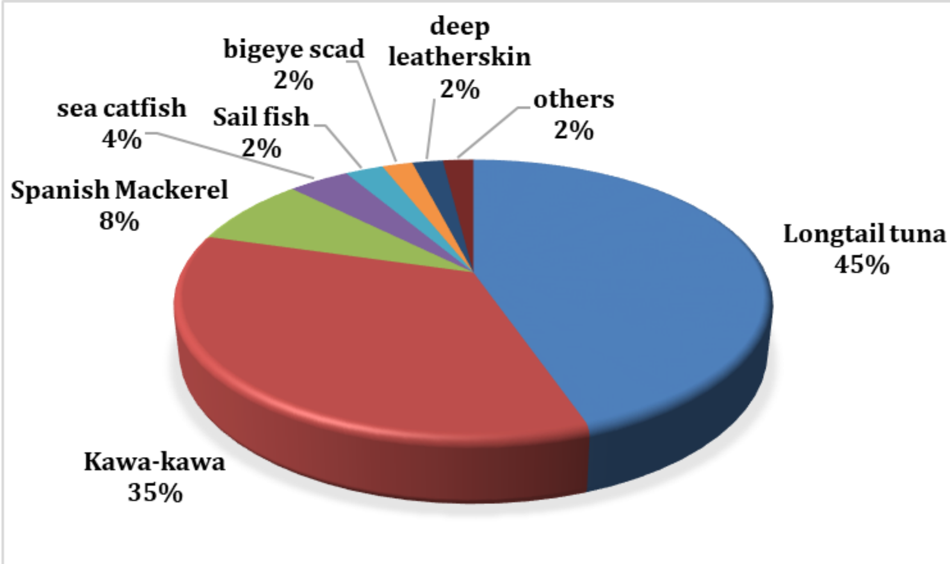

Figure 2. Catch composition of the drift gillnet fishery landing at Pemangkat fishing port, Natuna Sea.

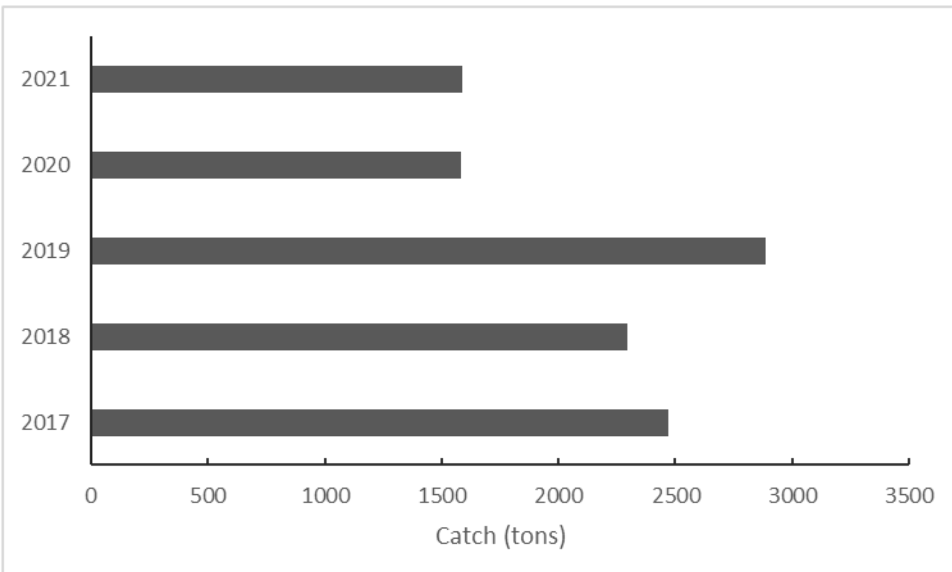

Figure 3. Annual catch trend (2017–2021) longtail tuna, Natuna Sea.

vessels undertake fishing trips averaging 9-10 days. The standard mesh size utilized in these drift gillnets is 4 inches (approximately 10.16 cm).

The species composition of catches from the drift gillnet fishery indicated that longtail tuna constituted the largest proportion at 44.7%. Other significant species included kawakawa at 34.8%, Spanish mackerel at 7%, sea catfish (Ariidae) at 4%, sailfish (*Istiophorus platypterus*) at 2.5%, deep leatherskin (*Chorinemus tala*) and bigeye trevally (*Caranx sexfasciatus*) at 2% (Fig. 2). These data confirm the drift gillnet as the primary fishing gear targeting longtail tuna in the study area. The annual catch of longtail tuna in the Natuna Sea exhibited a fluctuating trend over the five years from 2017 to 2021. The catch reportedly peaked in 2019 at 2,886 tons, decreased to 1,584 tons in 2020, and increased slightly to 1,586 tons in 2021 (Fig. 3).

Monthly observations of longtail tuna landings at PPN Pemangkat throughout 2021 revealed distinct seasonal patterns (Fig. 4). The primary peak in catches occurred during January-February. A secondary, smaller peak was observed later in the year, spanning October, November, and December. The highest

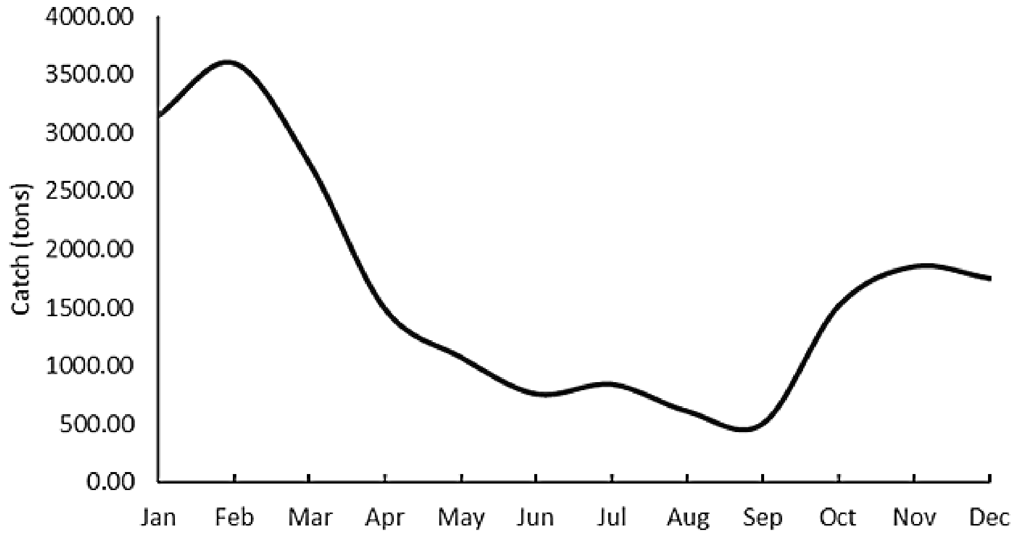

Figure 4. The monthly catch of longtail tuna landed at the Pemangkat fishing port.

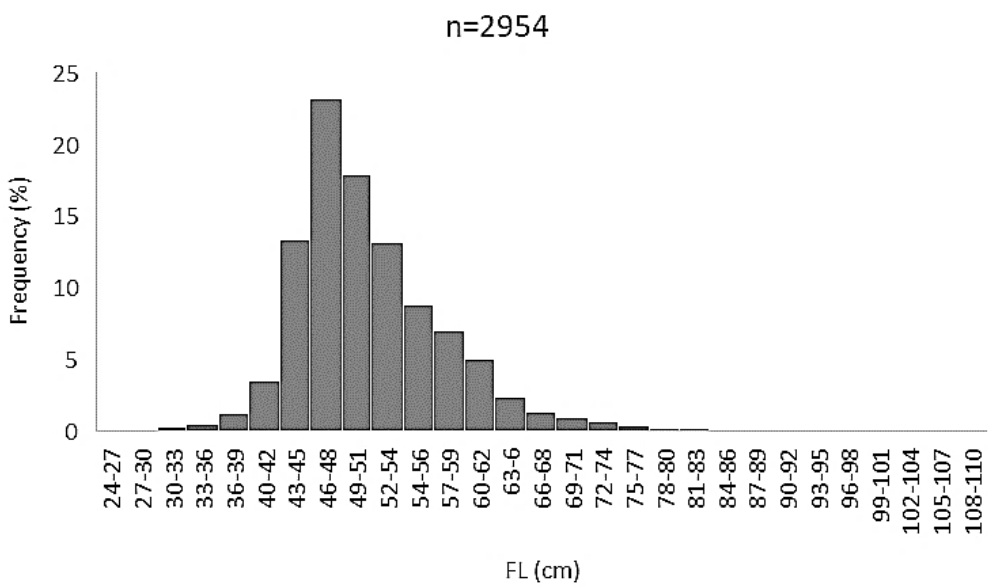

Figure 5. Length frequency distribution of longtail tuna landed at the Pemangkat fishing port.

average monthly catch of longtail tuna was recorded in February (3601 tons), followed by January (3150 tons) and November (1855 tons).

Size structure of longtail tuna: The length-frequency distribution of *T. tonggol* sampled from the Natuna Sea over the 12-month study period was found to be unimodal and normally distributed (Fig. 5). The modal fork length class was 46-48 cm. The smallest individual recorded measured 24 cm FL, while the largest was 110 cm FL.

Length at first capture: The analysis of the probability of capture by the drift gillnet gear as a function of fish length yielded a Lc value for *T. tonggol* in the Natuna Sea of 54.33 cm FL (Fig. 6).

Growth parameters: The L∞ value was estimated to be 114.45 cm FL, and the K was 0.36 year^{-1}. Incorporating the estimated L∞, K, and the calculated t_0 of -0.2865, the Von Bertalanffy growth equation for *T. tonggol* in the Natuna Sea was formulated as: Lt $=114.45(1-e^{-0.36(t+0.29)})$). The growth curve illustrating the relationship between age and fork length is presented in Figure 7. Based on this model, *T. tonggol* are estimated to reach lengths of approximately 41.7 cm, 61.9 cm, 75.3 cm, 84.2 cm, and 90.2 cm at ages 1, 2, 3, 4, and 5 years, respectively. The most rapid growth phase occurs between 0 and 1 year of age, with

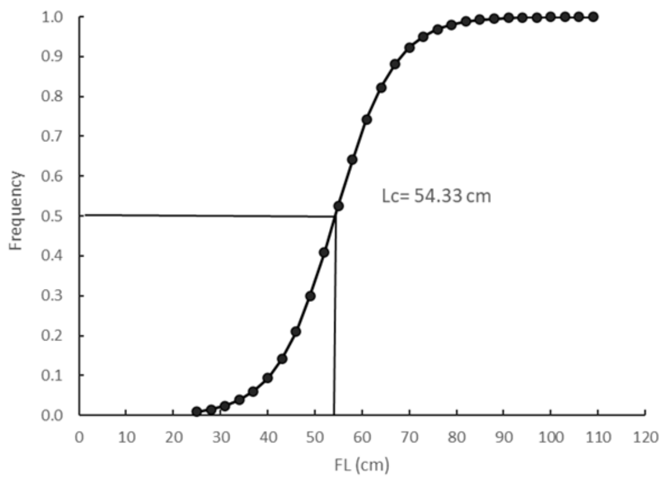

Figure 6. Lc value of longtail tuna from drift gillnets at Natuna Sea.

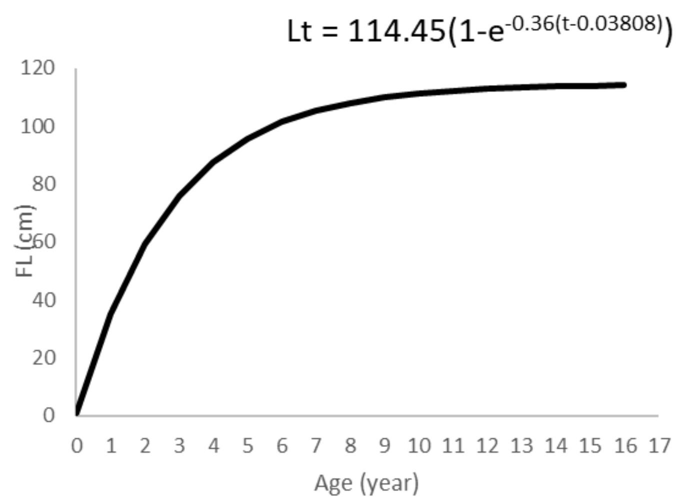

Figure 7. Von Bertalanffy growth curve by age of longtail tuna landed at Natuna Sea.

an average monthly length increment of 2.94 cm. This species may achieve its maximum length in 8 years.

Mortality and exploitation rate: The Z-value is 1.23 year^{-1} as a result of the length-converted catch curve analysis (Fig. 8). The F-value was determined to be 0.58 year-1, with a M value of 0.65 year^{-1} (based on Pauly's empirical formula with T = 29°C). In the Natuna Sea, the E-value for *T. tonggol* was 0.43.

Recruitment: The annual recruitment pattern of *T. tonggol* into the Natuna Sea fishery, as derived from the length-frequency data, exhibited a bimodal distribution (Fig. 9). Two distinct recruitment pulses were identified: a major peak occurring in March–April, and a smaller, secondary peak observed in August–September.

Yield per recruit: The yield per recruit (Y/R) analysis indicated that under current fishing patterns, Y/R increases with fishing mortality until reaching a maximum (E_{max}) at an exploitation rate of 0.598 (Fig. 10). The exploitation rate corresponding to 10% of the marginal yield ($E_{0.1}$) was estimated at 0.507. The $E_{current}$ is 0.43, below both Emax and $E_{0.1}$, suggesting that the fishery is currently in a developing phase with potential for increased yield under higher exploitation.

Spawning potential ratio: The SPR analysis estimated the spawning potential ratio for *T. tonggol* in the Natuna Sea to be 30%. This estimation utilized a length at 50% maturity (Lm_{50}) of 42.3 cm FL, based on previous work by Hidayat et al. (2020). An SPR of 30% indicates that the current spawning stock biomass is approximately 30% of the estimated unexploited spawning stock biomass.

Discussions

The present study revealed that the longtail tuna fishery in the Natuna Sea is primarily dominated by drift gillnet vessels, accounting for approximately 94% of total landings. This dominance indicates that drift gillnets are the most efficient and most widely adopted fishing gear for targeting *T. tonggol* in the region. The vessel size and trip duration characterize a semi-industrial fishery in Indonesia. The catch composition shows *T. tonggol* as the main target species (44.7%), followed by kawakawa and Spanish mackerel. This species mix reflects a multispecies fishery, typical of tropical pelagic ecosystems (Collete and Nauen, 1983). Such multispecies characteristics pose challenges for management, as gear regulations for one species may inadvertently affect others. Annual catch trends from 2017 to 2021 exhibit fluctuations, with a peak in 2019 and a significant decline in 2020-2021. This decline may be associated with reduced fishing activity due to the COVID-19 pandemic (Sari et al., 2021; Muntaha et al., 2023).

The length-frequency distribution was unimodal, a normal distribution extending from 24 to 110 cm. The Lc in this study was 54.33 cm FL, which is considerably larger than the reported Lm for

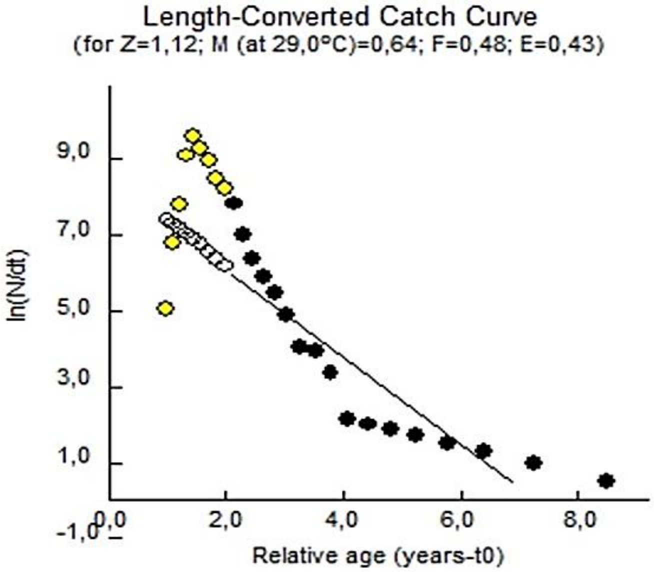

Figure 8. Length converted catch curve of longtail tuna landed at Natuna Sea.

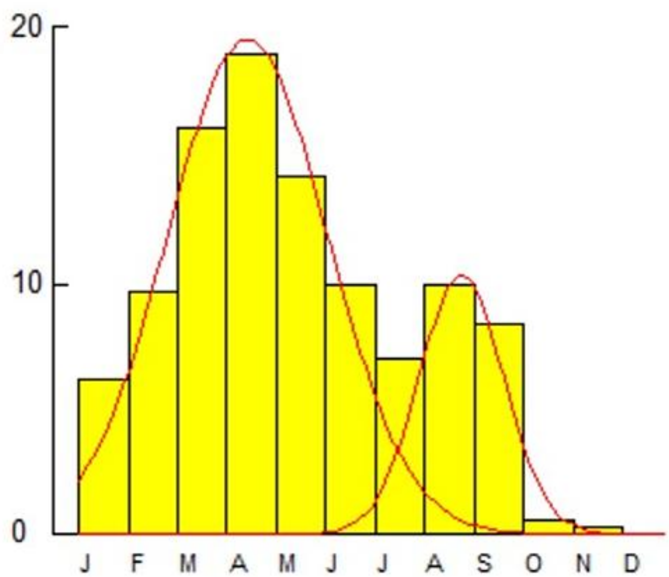

Figure 9. Recruitment pattern of longtail tuna landed at Natuna Sea.

T. tonggol in the Natuna Sea and Java Sea, which ranges from 41.1 to 42.3 cm FL (Hidayat and Noegroho, 2018; Hidayat et al., 2020). This implies that the current fishing practices, particularly the 4-inch mesh size of the drift gillnets in Pemangkat, allow a significant portion of the longtail tuna population to spawn at least once before becoming vulnerable to capture. This is a positive indicator of stock sustainability, as it supports successful recruitment by ensuring replenishment from mature individuals.

The estimated von Bertalanffy growth parameters

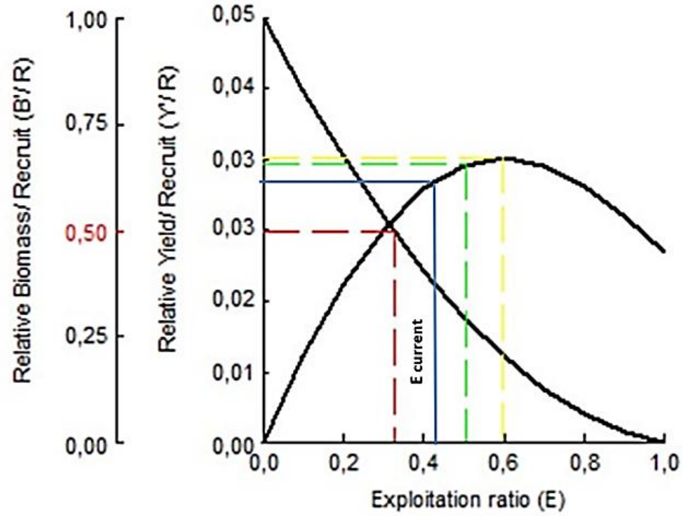

Figure 10. Yield per recruit (y/r) of longtail tuna landed at Natuna Sea.

for longtail tuna in the Natuna Sea indicate a relatively slow growth rate and a moderately large maximum size. The K-value, in particular, aligns with the general understanding that larger tuna species exhibit lower growth coefficients (Sparre and Venema, 1998). These findings can be contextualized by comparing them with estimates from other regions and studies, as summarized in Table 1. Many environmental factors, such as species population, water temperature, and prey availability, contribute to the common occurrence of differing L∞ and K values in different studies (Ju et al., 2016; Ghosh et al., 2016; Çiloğlu and Ateş, 2022).

This study found a higher estimated natural mortality rate (M) for *T. tonggol* 0.65 year^{-1} compared to the Persian Gulf and Iranian coasts—0.43, 0.49, and 0.44, respectively (Kaymaram et al., 2013; Darvishi M et al., 2016; Yasemi et al., 2017), but lower than in the Indian coast and Java Sea with 0.77 per year (Abdussamad et al., 2012; Hidayat et al., 2020). Several variables affect variations in natural mortality rates, including fishing pressure, seawater temperature at the time of sampling, disease, predation, stress, and age (Sparre and Venema, 1998; Chen et al., 2018; Bergström et al., 2022; Levangie et al., 2022).

The current exploitation rate is 0.43. According to Gulland (1971), an optimally exploited stock is often characterized by an exploitation rate in which fishing mortality equals natural mortality (F = M),

Table 1. Comparison of growth parameter for longtail tuna from various studies.

Area	L_∞ (cm)	K(yr^{-1})	Method	Author
India	93	0.49	LF	Silas et al. (1986)
Thailand	108	0.55	LF	Yesaki (1994)
Japan	55	1.7	Otoliths	Itoh et al. (1999)
Australia	135.4	0.23	Otoliths	Griffiths et al. (2010)
India	123.5	0.51	LF	Abdussamad et al. (2012)
Iran	133.8	0.35	LF	Kaymaram et al. (2013)
Pakistan	55.7	1.049	LF	Quratulan et al. (2016)
Iran	129.6	0.39	LF	Darvishi et al. (2016)
Iran	111.23	0.3	LF	Yasemi et al. (2017)
Natuna sea	114.45	0.36	LF	This study

Note: K: Growth rate; L_∞: Asymptotic length; LF: length frequency

corresponding to $E = 0.5$. The E value of 0.43 suggests that the *T. tonggol* stock in the Natuna Sea is currently exploited at a level below the commonly cited optimum, indicating that the stock is likely not overfished with respect to growth overfishing and is in a developing phase of exploitation.

The bimodal recruitment pattern observed, with peaks in March–April and August–September, and a recruitment size of approximately 24 cm FL, is consistent with findings for *T. tonggol* in other regions, such as Indian waters (Abdussamad et al., 2012). Such bimodal recruitment in tropical species is often linked to biannual monsoon cycles, which influence oceanographic conditions, primary productivity, and consequently, spawning and larval (Abesamis and Russ, 2010; Rabbaniha and Mousavi Golsefid, 2014). The major recruitment peak in April likely corresponds to spawning events that occurred during the August–September period of the previous year (the eastern monsoon season), given the species' growth rate (Hidayat and Noegroho, 2018b).

The yield-per-recruit analysis further supports the notion that *T. tonggol* stock is not currently overexploited. The current exploitation rate (E = 0.43) is below both the $E_{0.1}$ (0.507) and E_{max} (0.598) reference points. This suggests that, theoretically, there is scope to increase exploitation from current levels. An increase in exploitation by approximately 15.2% could achieve the $E_{0.1}$ target (often considered a more conservative and economically sound target than E_{max}), while an increase of up to 28.1% could reach E_{max}. However, any such increase must be approached with caution.

The estimated spawning potential ratio (SPR) of 30% for longtail tuna in the Natuna Sea provides another important indicator of stock status. Fishery management guidelines often consider an SPR of 20% as a minimum biological limit reference point (LRP), below which the risk of recruitment impairment is high, and an SPR of 30-40% or higher as a target reference point (TRP) for sustainable fisheries (Prince et al., 2015). The current SPR of 30% places the stock above the LRP, suggesting that the population currently maintains sufficient reproductive capacity for self-replenishment. This aligns with the classification of the stock as being sustainably utilized, although it also indicates that the stock is not at the more conservative target levels that some management frameworks aim for, warranting continued monitoring and a precautionary management stance (Mace and Sissenwine, 1993).

Management implications: Based on the collective evidence from growth, mortality, exploitation, and reproductive parameters, the *T. tonggol* stock in the Natuna Sea appears to be in a state of sustainable, moderate utilization. The current fishing pressure does not seem to have pushed the stock into an overexploited state. The observation that most fish are caught after reaching maturity is a positive sign for recruitment sustainability. Given this assessment, implementation of stringent input controls (e.g., reductions in fishing effort) or output controls (e.g., total allowable catches) may not be necessary at this juncture. Furthermore, while a minimum legal catch size (e.g., ≥ 42 cm FL, corresponding to Lm) is a common management tool, its practical enforcement in a diffuse, multi-gear fishery can be challenging. The current regulation on the 4-inch mesh size for drift gillnets appears reasonably effective in allowing fish to mature before capture and should therefore be maintained and enforced. However, a precautionary approach is always warranted, especially for a developing fishery. While the Y/R analysis suggests potential for increased exploitation, this should be pursued cautiously to avoid future overfishing. One proactive management measure that could be considered is implementing a seasonal closure during the peak spawning period. Based on the recruitment patterns and inferred spawning times, a closure during August and September could provide additional protection to spawning aggregations, thereby enhancing spawning success and bolstering recruitment to the fishery. Continuous monitoring of catch, effort, and biological parameters will be essential to adapt management measures as the fishery evolves.

Conclusion

Research on longtail tuna in the Natuna Sea has shown that their average length is 46-48 centimeters, with a range of 24-110 centimeters. Because the length at first capture is longer than the length at first maturity, this suggests that most individuals had the opportunity to reproduce before capture. This quality is indicative of robust and healthy stock. The estimated growth parameters ($L\infty$ = 114.45 cm, K = 0.36 year^{-1}) indicate that *T. tonggol* in this area exhibits moderate growth, consistent with characteristics of similar tuna species. Mortality rates (M = 0.65 year^{-1}, F = 0.58 year^{-1}, Z = 1.23 year^{-1}) and an exploitation rate (E) of 0.43 suggest that the stock is currently subject to a level of fishing pressure that is below overexploitation. This is further supported by the current Spawning Potential Ratio (SPR) of 30%, which exceeds the minimum biological limit, indicating healthy reproductive capacity in the stock. Yield-per-recruit analysis, showing that the current exploitation rate (E = 0.43) is below both the maximum yield (Emax = 0.598) and optimal yield ($E_{0.1}$ = 0.507) levels. This suggests that the *T. tonggol* stock in the Natuna Sea is currently in a developing exploitation phase, with some potential for a carefully managed increase in fishing effort without immediately jeopardizing sustainability. Overall, the utilization status of *T. tonggol* in the Natuna Sea can be classified as moderate, with current fishing pressure within sustainable limits. While there is potential for an increase of up to 15.2%, any such increase must be implemented within a precautionary management framework to mitigate the risk of future overfishing. A primary management recommendation arising from this study is to consider a seasonal closure during the peak spawning months of August and September. This measure would aim to protect spawning adults, thereby enhancing reproductive success and contributing to the long-term sustainability of this valuable fishery resource. Continued monitoring and periodic reassessment of stock status are crucial for adaptive management.

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