Length-based assessment and ecological review of skipjack tuna (*Katsuwonus pelamis*) in the Indian EEZ: insights from the Lakshadweep Sea

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Abstract

Skipjack tuna (*Katsuwonus pelamis*) constitutes an important component of tuna fisheries in the Indian Ocean, sustaining millions of livelihoods and feeding into the global tuna trade. This paper presents a length-based stock assessment of skipjack tuna in the Lakshadweep Sea of the Indian EEZ, based on length-frequency data analysed using TropFishR models. Fork length (FL) data (n=4,583) collected from the pole-and-line fishery indicated a broad size range of 28-94 cm, with multiple cohorts demonstrating continuous recruitment. Growth analysis (ELEFAN-SA) yielded an asymptotic length (L_∞) of 99.68 cm and growth coefficient (K) of 0.50 yr^{-1}. Mortality estimates showed natural mortality (M) of 0.55 yr^{-1}, fishing mortality (F) of 0.37 yr^{-1}, and exploitation rate (E_{cur}) of 0.40, below the threshold for overfishing. Thompson and Bell models confirmed F_{MSY} = 0.65 and E_{MSY} = 0.54, with current fishing pressure lower than sustainable reference points, indicating scope for increased harvests. Ecological review underscored skipjack's pivotal trophic role as a high level predator and prey for apex predators. The findings highlight the resilience of the Lakshadweep skipjack stock under current exploitation, while stressing the importance of continued monitoring, ecosystem-based management, and regional cooperation under the IOTC framework.

Keywords: Skipjack tuna, Lakshadweep Sea, TropFishR, Thompson and Bell analysis, pole-and-line, stock assessment, ecosystem approach

1. Introduction

Skipjack tuna (*Katsuwonus pelamis*) is a highly migratory, cosmopolitan species, widely distributed across tropical and subtropical oceans. Globally, it is the most abundant commercial tuna species, comprising over 57% of the world's tuna catch in 2023 (~2.96 million tonnes; ISSF, 2025). Its biological and ecological features - fast growth, early maturity, short lifespan contribute to resilience under fishing pressure compared to congeners like bigeye (*Thunnus obesus*). Economically, skipjack drives the global canned tuna industry, valued at USD 21.4 billion in 2025, with forecasts of sustained growth (Grand View Research, 2025).

Ecologically, skipjack occupies a trophic level around 4.0, preying on small pelagics, squids, and crustaceans (Varghese et al., 2019), while serving as a vital prey for sharks, billfishes, marine mammals, and larger tunas (Varghese et al., 2014). This dual role highlights its importance in maintaining pelagic food web balance. Its distribution and abundance respond to environmental drivers such as sea surface temperature and oxygen, making it a sentinel for climate variability, including ENSO, Arctic Oscillation Index (AOI), and Madden-Julian Oscillation Index (Liu et al., 2024).

The Lakshadweep Islands, situated in the eastern Arabian Sea about 200 to 400 km off the Kerala coast of mainland India, form a small but ecologically and economically significant

Union Territory of India. The archipelago comprises 36 islands, atolls, and reef systems, of which only a handful are inhabited. These islands represent one of the most traditional and community-based tuna fisheries in the Indian Ocean. The fishery here is centred around the pole-and-line method, an age-old practice that relies on the use of live bait, primarily small pelagic species such as *Spratelloides delicatulus*. Fishing operations are usually conducted close to the islands and surrounding reefs, reflecting both the nearshore distribution of skipjack and the logistical limitations of the local fleet.

What makes Lakshadweep pole and line fishery distinctive is not only the method itself, but also its socio-cultural and ecological attributes. The pole-and-line fishery is almost entirely small-scale in nature, operated by island communities whose livelihoods, food security, and cultural identity are closely tied to tuna fishing and its processing. The gear is highly selective, catching skipjack tuna with minimal bycatch, and it is widely recognised as one of the most sustainable tuna fishing practices globally. Unlike industrial purse seines, which often rely on drifting fish aggregating devices (FADs) and generate considerable bycatch of juvenile tunas and non-target species, pole-and-line fishing in Lakshadweep has a negligible ecological footprint. The fishery, therefore, not only sustains local communities, but also provides a model of responsible fishing practices that are increasingly valued in international tuna markets.

Length-based methods are particularly valuable in small-scale fisheries where age data are difficult to obtain due to the absence of otolith sampling facilities and routine biological monitoring. These approaches allow reliable estimation of growth, mortality, and exploitation parameters directly from length-frequency data, making them practical and cost-effective tools for assessing data-limited fisheries such as those in the Lakshadweep Islands.

Materials and Methods

To assess the status of skipjack tuna in the Lakshadweep Sea, systematic sampling was undertaken at key landing centre – Agatti island of Lakshadweep archipelago (Figure 1). This island was selected because they represent the core fishing grounds of the pole-and-line fleet and account for a significant proportion of tuna landings in the archipelago. Sampling was carried out during the period January to May and again from August to December 2024. The southwest monsoon months of June and July were excluded from sampling because fishing activity ceases during this season owing to rough seas and unfavourable weather conditions.

In total, fork length (FL) measurements of 4,583 specimens of skipjack tuna were recorded. Each fish was measured to the nearest centimetre, providing a robust dataset for length-based stock assessment. The data collection was stratified by month to ensure that seasonal patterns in the size structure of the catch could be captured. This design was particularly important for skipjack, which exhibits fast growth and multiple recruitment pulses throughout the year. The monthly stratification allowed us to examine the seasonal dynamics of the fishery, including the presence of juvenile cohorts and the availability of larger individuals during different periods. This structured sampling framework, combined with the strong traditional base of the pole-and-line fishery, provided an ideal foundation for assessing the biological and ecological status of skipjack tuna in the Lakshadweep Sea.

The analysis of skipjack tuna data was carried out using the R package TropFishR (Mildenberger et al., 2017), which is widely employed for length-based fisheries stock assessment in data-limited contexts. This tool allowed us to derive key growth and mortality parameters, assess the sustainability of current exploitation levels, and evaluate future yield potential under different management scenarios.

To examine the growth dynamics of skipjack tuna, the Electronic Length Frequency Analysis (ELEFAN) method was employed. Two optimisation algorithms were used to estimate the growth parameters: (i) ELEFAN with Simulated Annealing (ELEFAN S.A.) and (ii) ELEFAN with Genetic Algorithm (ELEFAN G.A.). Both approaches enable the simultaneous estimation of the von Bertalanffy parameters K and $L\infty$ using the same length-frequency data input. The performance of these two optimisation methods was compared based on results derived from the generated dataset.

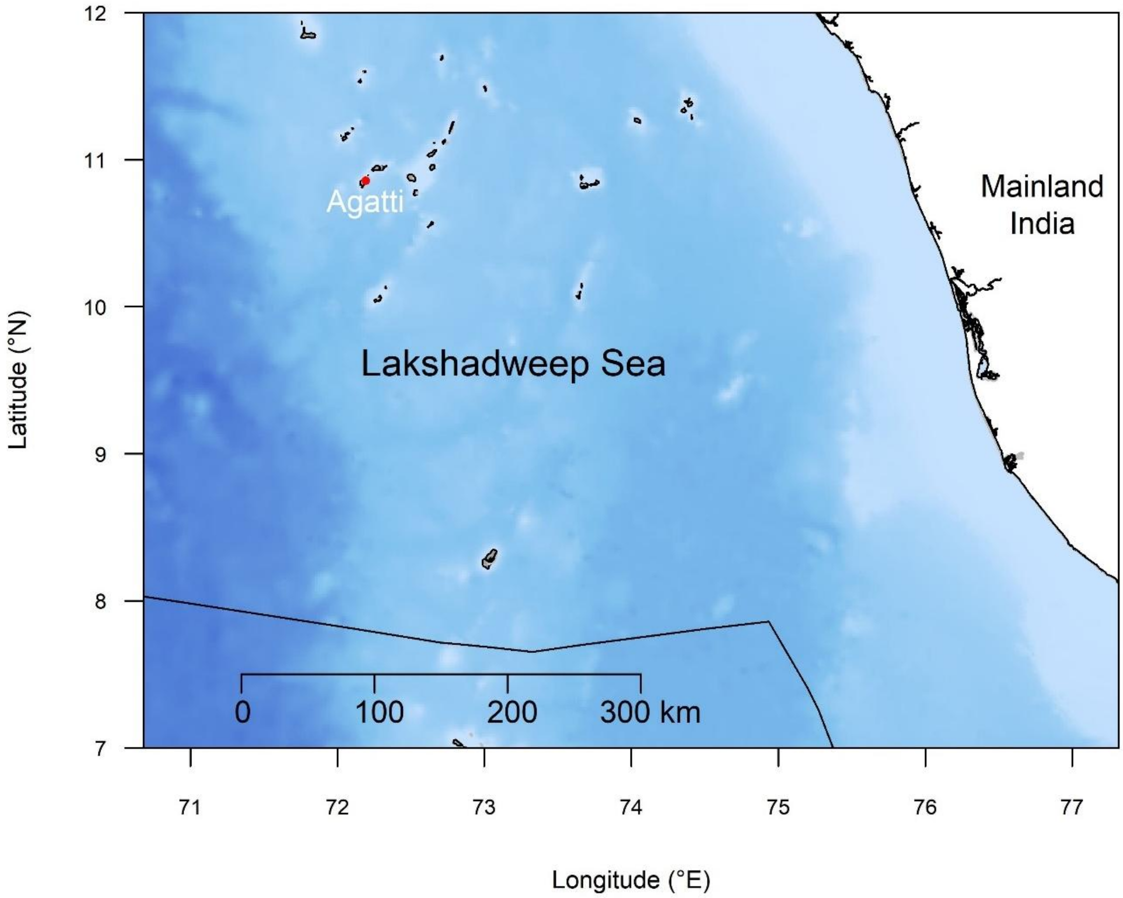

Figure 1. Map of Lakshadweep Sea showing sampling site: Agatti island

In the first approach, ELEFAN with Simulated Annealing (ELEFAN S.A.), the optimisation process progressively reduces the randomness of the search as the "temperature" parameter decreases, which controls the probability of accepting suboptimal solutions. The method requires specifying a maximum runtime (argument 'SA_time'), as variations in this setting can influence the final outcome. In the present study, a stable optimum of the objective function was achieved when 'SA_time' was set to four minutes.

The second optimisation routine, ELEFAN with Genetic Algorithm (ELEFAN G.A.), follows a similar principle in which the initial parameter values are randomly generated within predefined limits. As the iterations progress, parameter variability gradually narrows, allowing convergence toward local optima. The most critical parameter in this routine is the maximum number of generations, which was set to 100 for the present analysis. These methods optimise the fit of the von Bertalanffy growth function (VBGF) to the observed length-frequency data, yielding estimates of asymptotic length (L_∞), growth coefficient (K), and theoretical age at zero length (t_0). Confidence intervals around these parameters were generated through jackknife resampling, ensuring that the results reflected the variability inherent in the data. This step was essential for confirming that the estimated growth parameters were robust and consistent with known biological traits of skipjack.

Mortality and exploitation parameters were then estimated to evaluate the pressure of fishing on the stock. Total mortality (Z) was derived from length-converted catch curves, a method that relates the decline in abundance across size classes to natural and fishing-related losses. Natural mortality (M) was estimated using Pauly's widely applied empirical equation, which incorporates species growth parameters (L_∞ and K) and the mean environmental temperature of the fishing grounds. Fishing mortality (F) was subsequently calculated as the difference between Z and M, and the exploitation rate (E) was derived as the proportion of total mortality attributable to fishing ($E = F/Z$). These estimates provide insights into whether the fishery is operating within safe biological limits or exerting excessive pressure on the stock.

To further investigate long-term yield potential, we used the Thompson and Bell yield-per-recruit model (Thompson and Bell, 1934). This model simulates how changes in fishing mortality (F) and the length at first capture (Lc) influence yield, biomass, and spawning potential. By systematically altering these parameters, the analysis identifies reference points such as F_{MSY} and E_{MSY}, which indicate the fishing mortality and exploitation rate that would maximise sustainable yields. Comparing these reference points with the current fishing pressure help to determine whether the fishery is underexploited, fully exploited, or overexploited.

Finally, to complement the quantitative analyses, we undertook an ecological review of skipjack tuna. This involved synthesising published literature on its diet, trophic role, and migratory behaviour. Such a review was critical to place the stock assessment findings within a broader ecosystem perspective, recognising skipjack's dual role as both predator and prey in pelagic food webs and its sensitivity to environmental variability.

Results

The analysis of fork length data collected from 4,583 specimens revealed a wide size range, with individuals measuring from 28 cm to 94 cm. The mean fork length was 48.7 cm, suggesting that the fishery is exploiting a broad spectrum of size classes. A clear seasonal trend was evident when examining the data month by month (Figure 2). In January, the length distribution showed fish ranging between 28 and 74 cm, with a mean of 50 cm. February provided the largest sample size, with over 3,700 fish measured, revealing a broad spectrum from 29 to 93 cm. This wide spread suggested that both juvenile and sub-adult fish were present in the fishery at the same time. During March, the relatively smaller sample indicated larger mean sizes, peaking at around 74 cm, while April and May also displayed mean lengths above 58 cm, suggesting the availability of mature individuals during this period. The reappearance of large fish was also recorded in August and September, where mean lengths were around 65 cm, with maximum values reaching 94 cm. By contrast, November exhibited a dominance of smaller fish, with a mean length of only 46 cm and the smallest individuals of 28 cm recorded, pointing towards recruitment of juveniles into the fishery. In December, the mean size increased again to over 62 cm, and specimens up to 86 cm were documented. The seasonal presence of both juveniles and adults indicates that recruitment occurs throughout the year, with distinct pulses of juvenile entry followed by growth and availability of mature cohorts at later times.

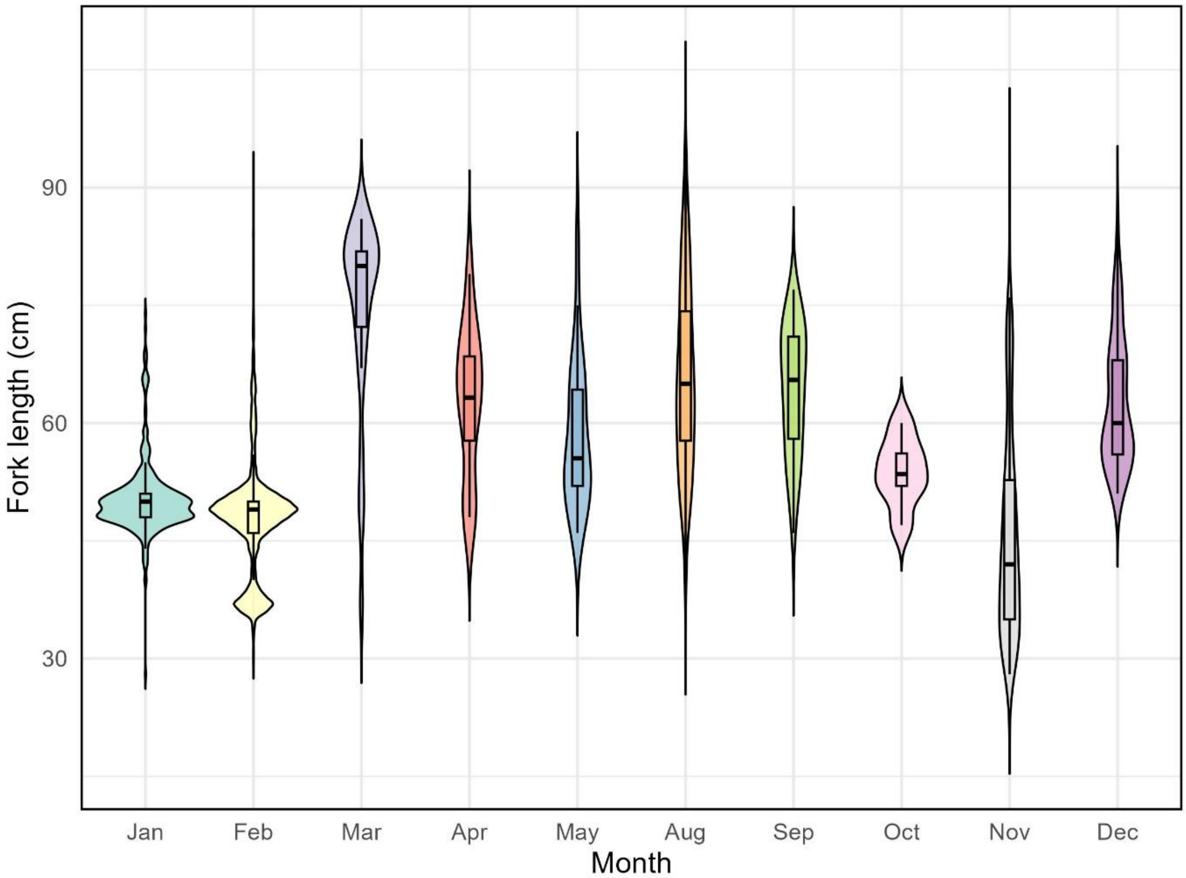

Figure 2. Monthly fork length distribution of skipjack tuna in Lakshadweep, India

Application of the ELEFAN method through simulated annealing (SA) and genetic algorithms (GA) provided growth parameter estimates. Although both methods produced broadly similar results, the ELEFAN-SA approach produced a slightly better fit to the data, with a maximum goodness-of-fit score of 0.297. The asymptotic fork length ($L\infty$) was estimated at 99.7 cm, the growth coefficient (K) at 0.50 yr^{-1}, and the theoretical age at zero length (t_0) at -0.23 yr (Table 1). These values are consistent with published estimates for skipjack in the Indian Ocean, and they underline the species' rapid growth and early maturity, which contribute to resilience against moderate levels of fishing pressure. Seasonal oscillations in growth were also evident, with parameters such as the amplitude of growth oscillation (C) and summer point of oscillation (ts) providing additional insights into seasonal growth patterns.

Table 1. Growth parameters and scores obtained from ELEFAN S.A. and ELEFAN G.A. along with Confidence intervals

Parameters	ELEFAN S.A.	ELEFAN G.A.	Confidence intervals
Asymptotic fork length L_∞ (cm)	99.67579	99.15744	93.0360-107.8525
Growth coefficient K (yr^{-1})	0.50276	0.518496	0.4933-0.5442
t_anchor	0.598228	0.62048	0.1664-0.8602
C	0.974614	0.748023	0.6296-0.9926
ts	0.514573	0.487841	0.2206-0.8090
phiL	3.69854	3.707396	3.6465-3.7725
Goodness of fit (Rn_max)	0.297015	0.292451	0.2630-0.3393

ts - summer point of oscillation, C - the amplitude of growth oscillation, t_anchor - the time point anchoring growth curves in year-length coordinate system.

The fit of the estimated growth parameters could as well be explored visually and the best fit seen through the peaks of the length-frequency data (Fig. 3).

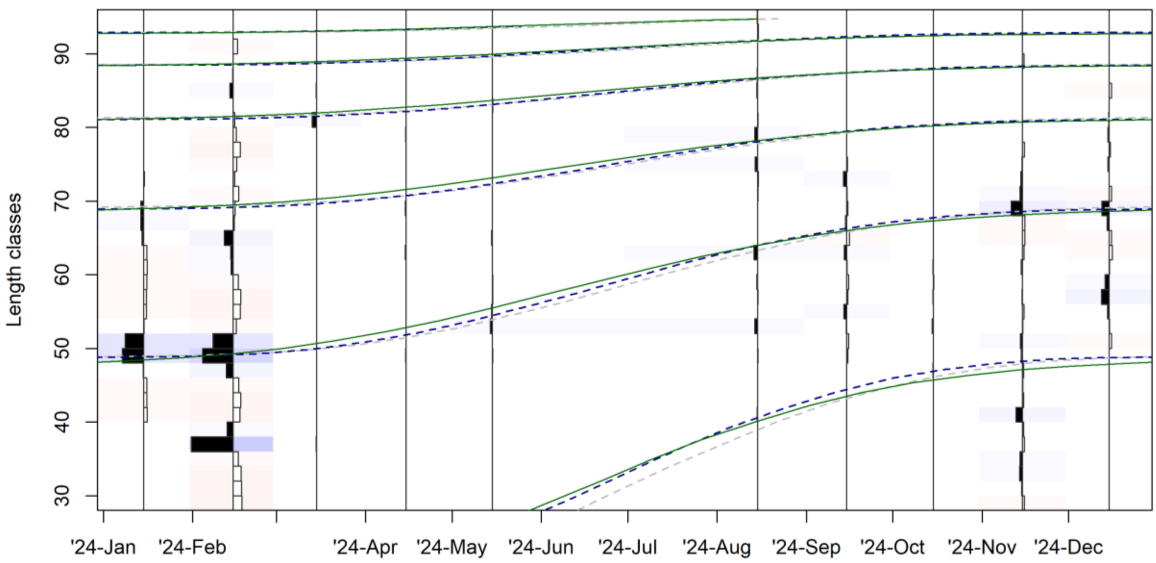

Figure 3. Graphical fit of estimated and true growth curves plotted through the length frequency data. The growth curves with the true values are displayed in grey, while the blue and green curves represent the curves of ELEFAN S.A. and ELEFAN G.A., respectively.

The von Bertalanffy growth curve estimated for skipjack tuna in the Lakshadweep waters revealed a rapid increase in length during the early life stages, followed by a gradual approach toward the asymptotic length ($L\infty$). The growth curve plotted (Figure 4) indicate that the species exhibits a relatively fast growth rate, attaining more than 80% of its maximum length within the first two years of life. Skipjack tuna of Agatti island attains forklength of 30.62 cm at the age of 0.5 years, 45.97 cm at 1 year, 67.19 cm at 2 years, and 80.03 cm at 3 years of age.

This growth pattern is consistent with the highly migratory and short-lived nature of skipjack tuna, reflecting its adaptation to a dynamic pelagic environment.

Table 2: Biological reference points of skipjack tuna of Lakshadweep estimated using Thompson and Bell yield-per-recruit model

BRP	F_value	E_value	YPR	SPR
Fmax	0.651303	0.713506	1660.33	0.246135
F0.1	0.410822	0.450057	1581.641	0.370608
F0.5	0.270541	0.296379	1391.782	0.493276
F0.4	0.370742	0.406149	1543.68	0.400504

The length-converted catch curve estimated the total mortality (*Z*) at 0.9128±0.2 yr-1, with natural mortality '*M*' obtained empirically using ELEFAN S.A. was 0.546 yr^{-1} using Pauly's empirical equation. Fishing mortality (*F*), calculated as the difference between *Z* and *M*, was 0.3668206 yr^{-1}. This corresponded to an exploitation rate (E_{cur}) of 0.401854, which is below the precautionary reference level of 0.5. The selectivity function derived from the catch curve estimated the length at 50% probability of capture (L_{50}) as 38.59624 cm, while the age at 50% probability of capture (t_{50}) was estimated as 0.9741153 yr (Figure 5). These values suggest that the stock is currently harvested below maximum sustainable levels, with exploitation focusing primarily on individuals above the size at first capture, thereby reducing the risk of recruitment overfishing.

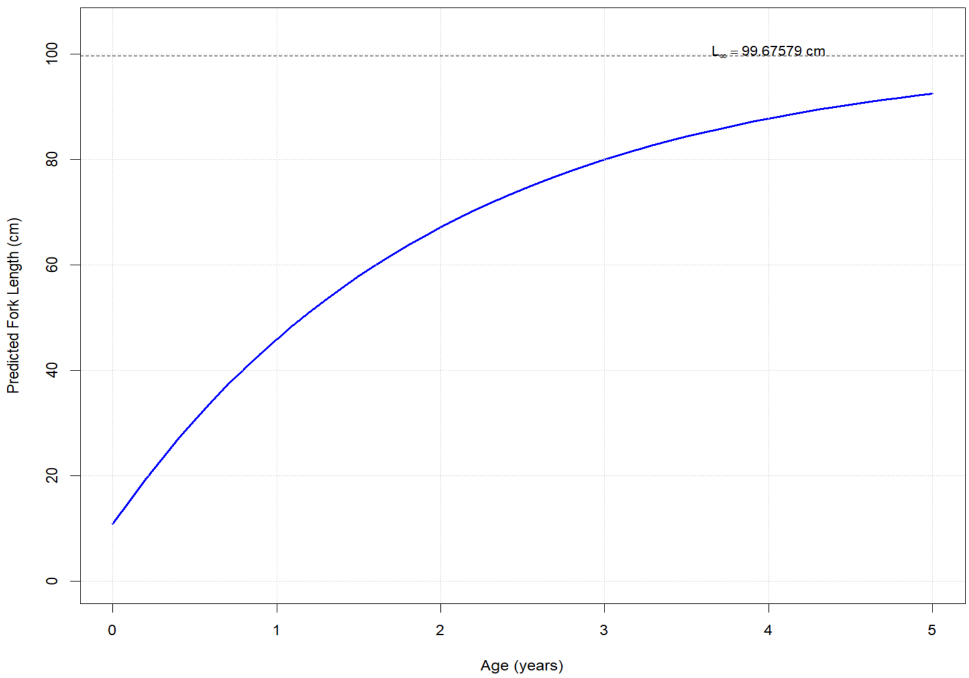

Figure 4. Von Bertalanffy growth curve of Skipjack tuna in Lakshadweep pole and line fishery

The Thompson and Bell yield-per-recruit model provided insights into long-term harvest potential under varying fishing mortalities and lengths at first capture. The analysis showed that maximum sustainable yield is achieved at a fishing mortality of 0.65 yr^{-1} (F_{MSY}), corresponding to an exploitation rate of 0.54 (E_{MSY}). The current fishing mortality (0.35) and exploitation rate (0.40) is well below this threshold, suggesting that the Lakshadweep stock is underexploited (Figure 6 and 7). The yield curve indicated that the present fishing mortality results in yields lower than what could potentially be achieved, and that moderate increases in fishing pressure could raise catches without threatening the stock. Importantly, however, such increases would need to be balanced with considerations of recruitment dynamics and ecosystem impacts. The prediction plot shows that the yield could be increased when fishing mortality is increased.

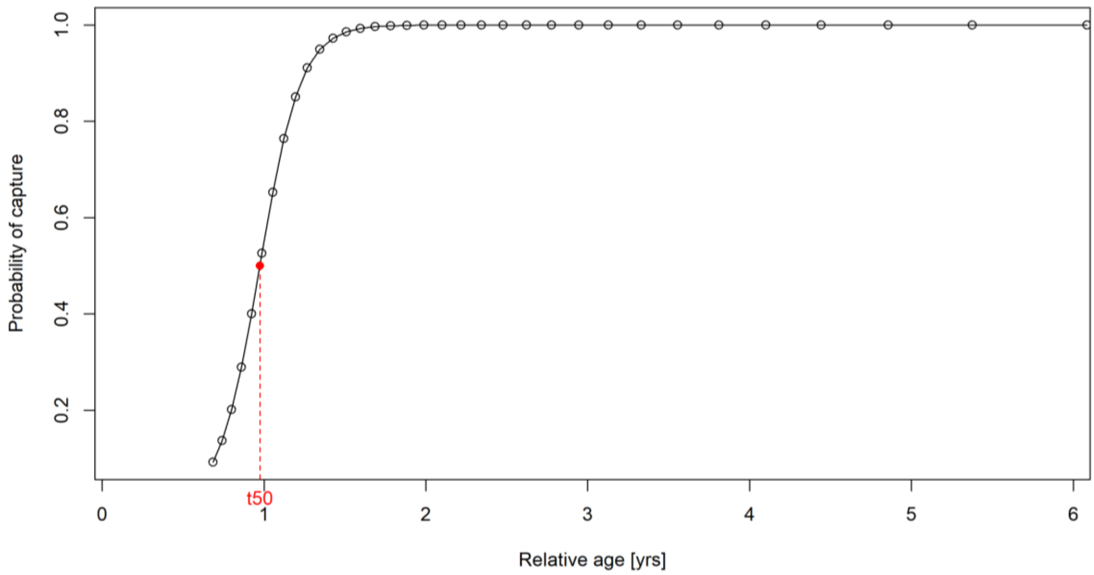

Figure 5. Probability of selectivity of skipjack of Lakshadweep showing the t_{50} - the age at which a fish has a 50% chance of being caught by the fishing gear.

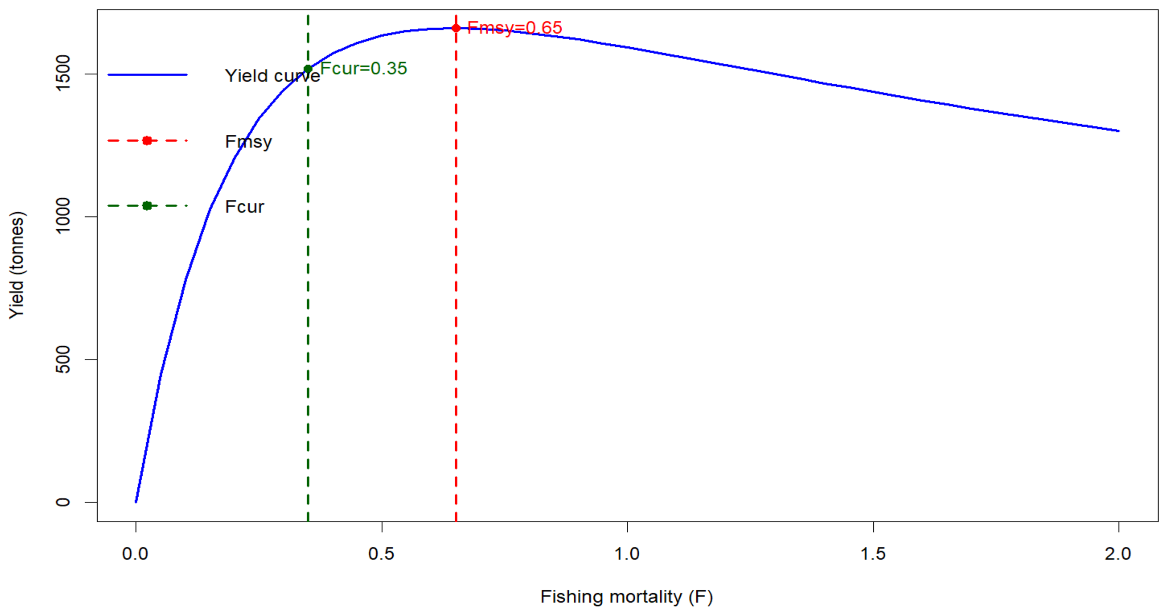

Figure 6: Thompson and Bell yield curve for skipjack tuna showing the relationship between fishing mortality (F) and predicted yield. The blue curve represents the yield-per-recruit response. The red dashed line marks the fishing mortality at maximum sustainable yield (F_{MSY} = 0.65), while the green dashed line denotes the current fishing mortality (F_{cur} = 0.35).

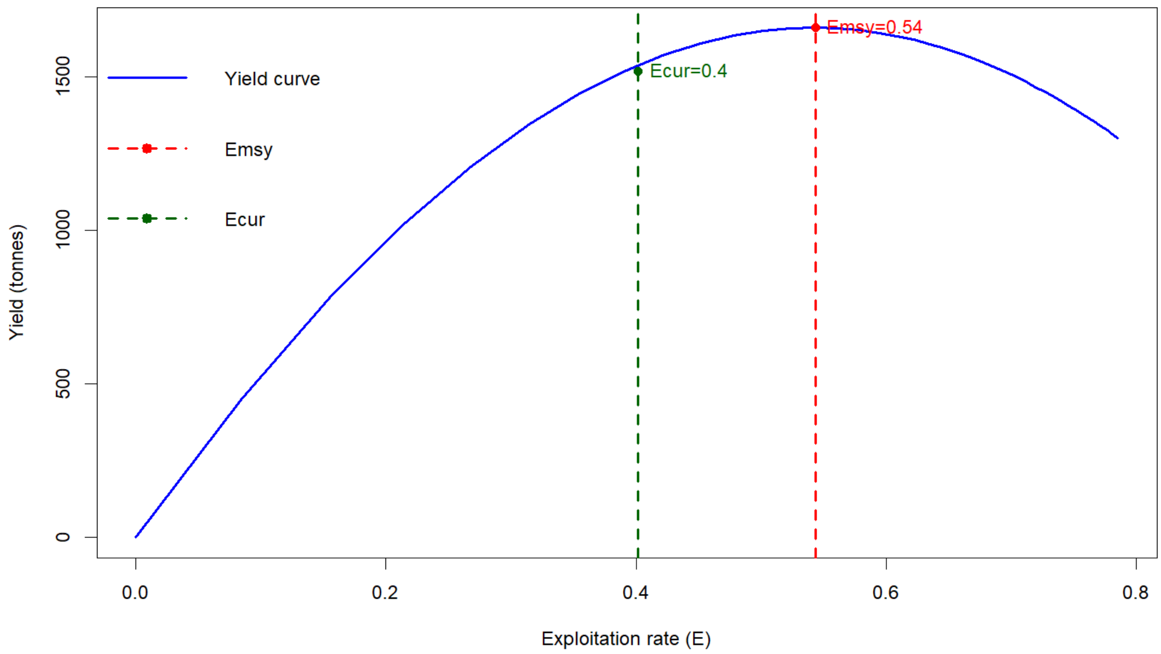

Figure 7: Thompson and Bell yield curve for skipjack tuna showing the relationship between Exploitation rate (E) and predicted yield. The blue curve represents the yield-per-recruit response. The red dashed line marks the exploitation rate at maximum sustainable yield (Emsy = 0.54), while the green dashed line denotes the current exploitation rate ($Ecur$ = 0.4).

Discussion

The present study provides a comprehensive assessment of skipjack tuna in the Agatti Island, combining length-based analyses with ecological context to evaluate stock status. The growth parameters estimated in the present study ($L\infty$ = 99.68 cm, K = 0.50 yr^{-1}, t_0 = -0.23 yr) indicate a relatively higher asymptotic length compared to earlier reports from Lakshadweep and the Indian EEZ. While the growth coefficient (K) remains comparable with the values reported by Sivadas et al. (2005), Koya et al. (2012) and Muhasin et al. (2020), the higher $L\infty$ suggests that skipjack tuna inhabiting the Agatti region may attain larger sizes, possibly reflecting regional differences in environmental conditions, prey availability, or fishing pressure. The slightly lower t_0 value in the present study also implies faster growth during the juvenile phase, consistent with the dynamic oceanic environment surrounding the Lakshadweep archipelago. Eveson et al. (2012), while analysing the tag-recapture and otolith data of Indian Ocean skipjacks also had reported very quick growth in the juvenile skipjacks followed by much slower growth in the second stage.

The results of present study indicate that the skipjack population of Agatti island is currently being fished at sustainable levels, with exploitation rates lower than the biological reference points of F_{MSY} and E_{MSY}. This finding is significant because it highlights that the traditional pole-and-line fishery, which dominates the Lakshadweep Islands, continues to operate within safe ecological limits.

When compared with broader Indian Ocean assessments, the Lakshadweep fishery appears to be in a relatively healthier condition. Regional analyses conducted under the IOTC framework have suggested that skipjack stocks in the wider Indian Ocean are not overfished, but are subject to increased fishing pressure, particularly from industrial purse seine fleets that rely heavily on fish aggregating devices (FADs) (IOTC, 2024). The present study reinforces that, within the Lakshadweep Sea, the exploitation pattern is distinct. Here, the pole-and-line fishery, with its reliance on live bait and its community-based operations, has inherently lower environmental impacts. The absence of bycatch and the selective nature of this gear ensure that exploitation is focused on the target species, avoiding many of the collateral impacts associated with more industrial methods.

From a socio-economic perspective, the Lakshadweep fishery provides much more than just landings of skipjack tuna. It is deeply intertwined with the culture, traditions, and livelihoods of island communities. The seasonal rhythm of fishing, the dependence on live bait species, and the use of traditional knowledge to locate tuna schools together contribute to a model of sustainable small-scale fisheries. The results of this study are therefore not only an indication of biological sustainability but also a validation of the resilience of a traditional fishery that continues to support local communities in the face of globalized fishing pressures.

Ecologically, skipjack tuna plays an important role as both predator and prey in pelagic ecosystems. By feeding on small pelagics, squids, and crustaceans, skipjack contributes to the transfer of energy from lower to higher trophic levels. At the same time, skipjack itself supports populations of large predators, including sharks, billfishes, and marine mammals.

Skipjack tuna in the eastern Arabian Sea are primarily piscivorous, with their diet dominated by teleost (bony) fishes (Varghese et al., 2019). Cephalopods were the second most significant prey group, while the contribution of crustaceans (e.g., crabs, shrimps) to the diet was marginal. This composition differs from earlier studies in the region (e.g., around Lakshadweep and Minicoy islands), which reported crustaceans as a dominant food item.

The most important single prey species for skipjack tuna was the purpleback flying squid, *Sthenoteuthis oualaniensis* (Varghese et al., 2019). This indicates that while teleosts as a group are dominant, *S. oualaniensis* is a crucial resource. Among teleosts, the principal species identified was the juvenile *Coryphaena hippurus*, while other significant teleost prey included: Bigeye cigarfish (*Cubiceps pauciradiatus*), Snake mackerel (*Gempylus serpens*), Flyingfish (*Hirundichthys coromandelensis*) etc. A notable finding was the prevalence of cannibalism, with juvenile skipjack tuna found in 7.14% of the nonempty stomachs. This aligns with observations from other ocean basins (Nakamura, 1965).

Based on the weight contribution of the different prey categories, the trophic level of skipjack tuna was estimated to be 4.28. This positions them as high level predators within the pelagic food web. Their feeding strategy is that of a generalist, capitalizing on the most densely available prey, which leads to spatial and temporal variations in their diet composition compared to other regions.

The presence of multiple cohorts throughout the year in Lakshadweep waters highlights the importance of these ecosystems as recruitment and feeding grounds for skipjack tuna (*Katsuwonus pelamis*) (Koya et al., 2012; Muhsin et al., 2020). However, the sensitivity of skipjack abundance to climatic oscillations, particularly ENSO-driven variability, indicates that long-term monitoring must include environmental indices to detect potential impacts of climate change on productivity (Lehodey et al., 1997; Briand et al., 2011). The growth and recruitment dynamics of skipjack tuna are strongly influenced by environmental factors such as sea surface temperature and chlorophyll-a concentration, which regulate the distribution and abundance of their prey (Andrade & Garcia, 1999; Langley et al., 2008). Variations in primary productivity and oceanographic conditions can cause pronounced interannual fluctuations in recruitment strength and size composition of the stock (Lehodey et al., 2014; IOTC, 2024). As the present study is based on data collected during a single year (2024), the results should be interpreted with caution, recognizing that they may not fully capture the natural variability in population dynamics. Long-term monitoring and the incorporation of environmental parameters are therefore essential before translating these findings into management or policy decisions (FAO, 2020).

The findings of the present study align well with the most recent assessment by the Indian Ocean Tuna Commission (IOTC, 2024), which indicates that the skipjack tuna stock in the Indian Ocean is not overfished and that overfishing is not occurring. The estimated growth and exploitation parameters from the Lakshadweep region are therefore consistent with the broader regional status, reinforcing that the current levels of fishing pressure in the traditional pole-and-line fishery remain sustainable within the context of the Indian Ocean population.

Length-based stock assessment models, such as those employed in this study, have proven particularly robust for data-limited fisheries where age-based analyses are not feasible (Sparre & Venema, 1998). These models facilitate the estimation of key biological reference points directly from length-frequency data, making them especially effective for small-scale tropical fisheries such as those of Lakshadweep (Mildenberger et al., 2017; Froese et al., 2018). However, since length-based assessments provide only temporal snapshots of population structure, their reliability increases substantially with multi-year datasets that account for environmental and recruitment variability (Taylor et al., 2019). Continued annual monitoring and integration of environmental parameters will enhance the robustness of parameter estimates and support adaptive, precautionary management approaches (FAO, 2020; Cochrane & Garcia, 2009).

The implications for management are therefore multifaceted. On one hand, the underexploited status of the skipjack stock suggests some potential for a controlled increase in harvests to enhance local food security and economic returns (IOTC, 2024). On the other hand, such expansion must proceed cautiously, as increased regional fishing effort—particularly from industrial purse-seine and longline fisheries—could offset the sustainability achieved by traditional pole-and-line operations (Hampton et al., 2021). Effective management must thus maintain a balance between optimising catches and ensuring the long-term sustainability of the resource through science-based decision-making, continuous data collection, and ecosystem-based management principles (FAO, 2021; Garcia & Cochrane, 2005).

In conclusion, the Lakshadweep skipjack fishery represents a unique example of sustainable exploitation, sustained by traditional methods and community-based practices. By maintaining current practices, strengthening monitoring frameworks, and engaging actively with regional management bodies such as the IOTC, India can safeguard both the biological health of skipjack tuna and the socio-economic security of the communities that depend on it.

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