Unveiling The Invisible Fishery: Advancing Bycatch Management and Sustainability in Papua New Guinea's Tuna Fisheries

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Abstract

Papua New Guinea's (PNG) purse seine tuna fishery is a major part of the Western and Central Pacific Ocean (WCPO) tuna industry, supporting regional food security, employment, and economic development. Yet bycatch—the incidental capture of non-target organisms—receives considerably less attention than target tuna landings. This study examined bycatch dynamics in PNG's purse seine fishery using observer data from 2014 to 2024. The research quantified dominant bycatch species, tracked temporal trends, compared species composition between Drifting Fish Aggregating Device (Drifting FAD) and Free-School sets, and assessed retention and discard patterns to identify opportunities for sustainable utilization.

Bycatch composition in the fishery is highly uneven. Silky shark (*Carcharhinus falciformis*) contributed the highest biomass, followed by whale shark (*Rhincodon typus*), rainbow runner (*Elagatis bipinnulata*), Bryde's whale (*Balaenoptera edeni*), false killer whale (*Pseudorca crassidens*), sei whale (*Balaenoptera borealis*), and mackerel scad (*Decapterus macarellus*). Biomass for these species varied considerably across the study period. Several species exhibited peaks in recorded biomass during the late 2010s, followed by lower or relatively stable recorded totals in subsequent years. Annual fluctuations may reflect changes in fishing effort, observer coverage, reporting practices, the spatial distribution of fishing operations, or environmental conditions; these influences were not separately tested.

Recorded bycatch composition differed between the two fishing modes analyzed. Within the two-mode analysis subset, free-school sets accounted for most of the silky shark, whale shark, Bryde's whale, and blue marlin biomass. Rainbow runner and mackerel scad, by contrast, were closely associated with Drifting FAD operations. Retention patterns followed a similar split: Recorded whale shark and cetacean biomass was entirely discarded, whereas nearly all silky shark biomass was discarded (99.76%).

Separate Kruskal–Wallis tests detected differences in the distributions of recorded biomass among years, fishing set categories and species identities. Species identity produced the largest Kruskal–Wallis statistic among three separate group comparisons; this result does not identify a causal driver.

This study points to an "invisible fishery" within PNG's offshore sector. Teleost bycatch species like rainbow runner and mackerel scad hold under-recognized potential for food security, local consumption, processing, and aquaculture feed. Most of the recorded biomass for rainbow runner and mackerel scad was discarded in the dataset; the feasibility and safeguards of potential utilization require further assessment.

The findings point to the need for stronger observer monitoring, targeted mitigation strategies, and species-specific data in fisheries policy. The teleost bycatch that makes up this "invisible fishery" deserves more scientific and policy attention. Properly managed, it could support fisheries diversification and long-term resilience in PNG's offshore sector.

Table of Contents

Abstract 2
List of Figures 5
List of Tables 6
Attestation of Authorship 7
Artificial Intelligence Declaration 8
Acknowledgements 17
1. Introduction and Literature Review 18
1.1 Bycatch in Global Fisheries 20
1.2 Purse Seine Bycatch in the Western Central Pacific Ocean. 22
1.3 Bycatch in PNG's Purse Seine Fisheries 25
1.4 Governance and Management Approaches 25
1.5 Research question 28
1.6 Objectives 28
2. Methods 29
2.1 Description of Data 29
2.2 Purse seine sampling of bycatch species data collection 29
2.3 Data set 30
2.4 Analysis 31
2.4.1 Dominant Bycatch Species 31
2.4.2 Temporal Trends of Dominant Bycatch Species 31
2.4.3 Comparison of Species Composition Between Drifting FAD and Free School 31
2.4.4 Catch Composition by Retention and Discard Proportions 31
2.4.5 Non-Parametric Analysis 32
3. Results 32
3.1 Dominant Bycatch Species 32
3.2 Temporal Trends of Dominant Bycatch species 33
3.3 Comparison of Species Composition Between Drifting FAD and Free-School 35
3.4 Catch Composition by Retention and Discard Proportions 36
3.5 Non-Parametric Analysis 36
3.5.1 Bycatch versus Year 37
3.5.2 Bycatch versus Set Type 38
3.5.3 Bycatch versus Species Composition 38
3.5.4 Visualizing the patterns 39
4. Discussion 42
4.1 Species Composition and Dominance Patterns of Bycatch Species 42
4.2 Temporal Variability in Dominant Patterns of Bycatch Species 45

4.3 Comparative Analysis of Bycatch Composition Between Drifting FAD 49
4.4 Retention and Discard Patterns in Bycatch Composition 52
4.5 Drivers of Bycatch Variability in PNG's Purse Seine Fishery 54
4.5.1 Temporal Drivers of Bycatch Variability 54
4.5.2 Operational Drivers: Influence of Fishing set type 55
4.5.3 Species Composition as the Dominant Ecological Driver 56
4.5.4 Ecological and Management Implications 57
4.6 Rethinking Bycatch: From Waste to Resource 60
4.7 Study limitations and uncertainty 62
4.8 Future research and practical management priorities 63
5. Conclusion 65
References 67

List of Figures

Figure 1: Historical distribution and proportions of tuna purse-seine 23
Figure 2: Recorded total biomass (metric tonnes, mt) of the seven specie..... 33
Figure 3: Annual recorded bycatch biomass (metric tonnes, mt)..... 34
Figure 4: Recorded bycatch biomass (metric tonnes, mt) of the seven. 35
Figure 5: Percentage of recorded species-specific bycatch biomass..... 36
Figure 6: Distributions of log-transformed observation-level recorded. 41

List of Tables

Table 1: Seven highest-biomass species with taxonomic classification 33
Table 2: Results showing Kruskal – Wallis analysis of explanatory variables. 37
Table 3: Summary statistics for recorded biomass (mt) per species-level. 37
Table 4: Results showing median Bycatch by Set Type. 38
Table 5: Results showing Post-hoc Pairwise comparison. 38
Table 6: Results showing median Bycatch by Species. 39

Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor used artificial intelligence tools or generative artificial intelligence tools (unless it is clearly stated, and referenced, along with the purpose of use), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Artificial Intelligence Declaration

Specify the chapter number(s) in your research proposal/research component where AI was used.
Chapter number(s): Chapter 1, 3, 4
Briefly explain why the AI tool was used (e.g., idea generation, summarization, data analysis, image creation, etc.).
Purpose of AI Use: AI was used for idea generation, data analysis, grammar correction, re-structuring of original sentences for flow and synthesis.
Clearly state the AI tools used.
AI Tool(s) Used: Julius AI was used for data analysis, and ChatGPT was used for grammar checks and corrections, idea generation, and reference checks.
Prompts or queries entered into the AI tool (only the instructive portion of the prompt is required). Include all relevant variations.
Prompts Used: Refer to Appendix
A summary or description of the AI-generated output. (Optional: attach output in an appendix.)
Output Received: Refer to Appendix
Describe how the AI output was used, edited, or transformed.
Post-AI Processing Methods: the outputs in the form of images (plots, charts, tables) were used in the results section. Where there was no table, an original table was generated with values from the output.

You may use this free text box to explain the intent for the use of the AI generated content. *For example, rather than stating what prompt(s) were used, you may articulate the purpose for which the prompt was used (supported by examples) here:*

STUDENT DECLARATION
By signing you are confirming that the AI use stated in the table(s) above are accurate and follow AUT's recommended guidelines detailed in the AI Hub and Postgraduate Handbook.
Student Name: **Angela Kwapena** **Signature:** **Date:** **02/06/2026**

Appendix:

Prompts or queries entered into the AI tool (only the instructive portion of the prompt is required). Include all relevant variations.
Prompts Used: Julius AI Using the uploaded PNG purse seine bycatch dataset, perform a Kruskal-Wallis analysis to investigate the operational drivers of bycatch variability. Objective: Determine whether bycatch weight differs significantly across years, fishing set types, and species composition (top 7 most dominant species). Response Variable: * Total bycatch weight (combine retained and discarded bycatch weights to create total bycatch biomass).

Explanatory Variables:

1. Year (yr)

   * Represents temporal variation in bycatch patterns over time.

2. Set Type

   * Drifting FAD (dFAD)
   * Unassociated / Free-school sets
   * Represents operational fishing mode differences.

3. Species Composition (only top 7 dominant species)

   * Species/common_name/sp_code
   * Represents ecological variation in dominant bycatch species.

Data Preparation:

1. Create total bycatch weight:
   total_bycatch = retained_weight + discarded_weight

2. Remove missing values.

3. Filter dataset to include only:

   * Drifting FAD sets
   * Free-school sets

4. Convert:

   * Year into factor variable if necessary
   * Set type into categorical factor
   * Species composition into categorical factor

Statistical Analysis:
Perform separate Kruskal-Wallis tests using bycatch weight as the response variable:

1. Bycatch vs Year
2. Bycatch vs Set Type
3. Bycatch vs Species Composition

Use the Kruskal-Wallis test because bycatch data is likely non-normal and highly skewed.

Use this model conceptually:

Bycatch \sim Year + SetType + Species

Required R functions:

* kruskal.test()
* dunnTest() or pairwise.wilcox.test() for post-hoc comparisons if significant

Required Outputs:

1. Kruskal-Wallis test statistics
2. Chi-square values
3. Degrees of freedom
4. p-values
5. Post-hoc pairwise comparisons if significant
6. Boxplots for:

   * bycatch by year

* bycatch by set type
* bycatch by species

7. Summary tables of median bycatch values.

Dominant Bycatch species:

I uploaded the file: `PNG - Angela Kwapena - Obs summary bycatch.csv`

I uploaded bycatch dataset from tuna purse seine in Papua New Guinea. Can you plot the top seven(7) species by weight. Have the title to read as, "Top Bycatch Species by Weight". Species to be at the x-axis.

Temporal trends:

I have uploaded the following files for you to use: PNG - Angela Kwapena - Obs summary bycatch.csv

I uploaded the file: `PNG - Angela Kwapena - Obs summary bycatch.csv`

Using the data uploaded, can you plot a chart showing temporal trends of the seven(7)dominant species using species weight over time(year). Title of chart must read,"Temporal Trends of Dominant Bycatch Species. Time(year) to be on the x-axis and weight to be on the y-axis.

Drifting FAD vs Free-School plots:

I uploaded the file: `PNG - Angela Kwapena - Obs summary bycatch.csv`

Using the dataset uploaded, can you filter the School type_id column and remove "other", 'whale', 'whale shark', 'log'. Using Drifting FAD vs Unassociated(Free-School) data, plot the 7 top most dominant species against their catch(weight). I want to see how each species is caught. Whether, it's via Drifting FADs or Unassociated (Free-School). Title of the chart to read, 'Comparison of Species Composition Between 'Drifting FAD and Free-School'. Remove labels on the bars. Leave the labels on the x-axis of the species names. Remove "species" on the x-axis. Put the legend on the right. Resize the Title to fit the chart area.

Retention Plots:
I uploaded the file: PNG - Angela Kwapena - Obs summary bycatch.csv
Using the uploaded data, Can you plot a chart titled "Catch Composition by Retention and Discard Proportions". I want to see how much of each species is caught and retained and how much discarded by weight. Plot top 7 dominant species only. Use the Ret_MT_est column and Disc_MT. Label all the bars on the x-axis. Display the legend on the right

A summary or description of the AI-generated output. (Optional: attach output in an appendix.)

Output Received:

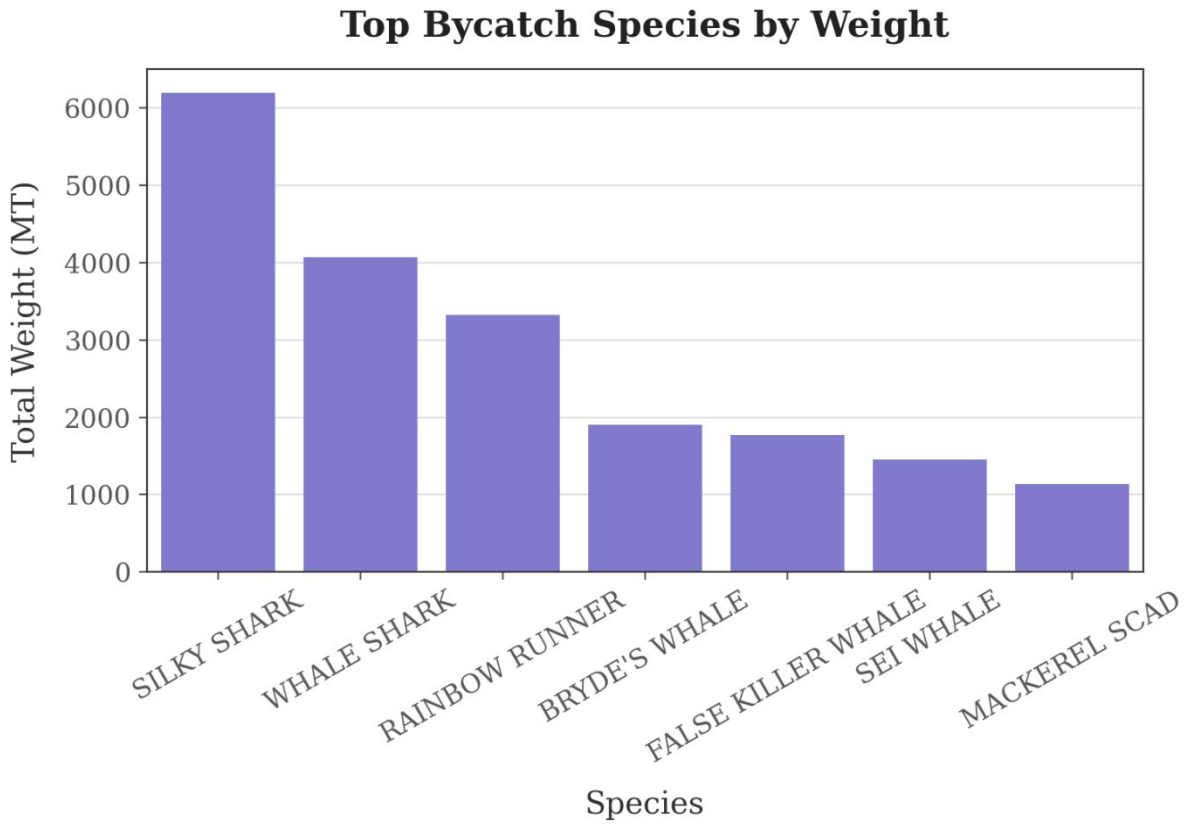
I plotted the **top seven bycatch species by total weight** with **species on the x-axis** and the title:

“Top Bycatch Species by Weight”

I calculated total weight as:

- `Ret_MT_est + Disc

Common Name	Scientific name	Genus	Family	Total Weight (MT)
Silky shark	*Carcharhinus falciformis*	*Carcharhinus*	Carcharhinidae	6194.492
Whale shark	*Rhincodon typus*	*Rhincodon*	Rhincodontidae	4075.956
Rainbow runner	*Elagatis bipinnulata*	*Elagatis*	Carangidae	3320.102
Bryde's whale	*Balaenoptera edeni*	*Balaenoptera*	Balaenopteridae	1900.266
False killer whale	*Pseudorca crassidens*	*Pseudorca*	Delphinidae	1766.064
Sei whale	*Balaenoptera borealis*	*Balaenoptera*	Balaenopteridae	1453.577
Mackerel scad	*Decapterus macarellus*	*Decapterus*	Carangidae	1136.325



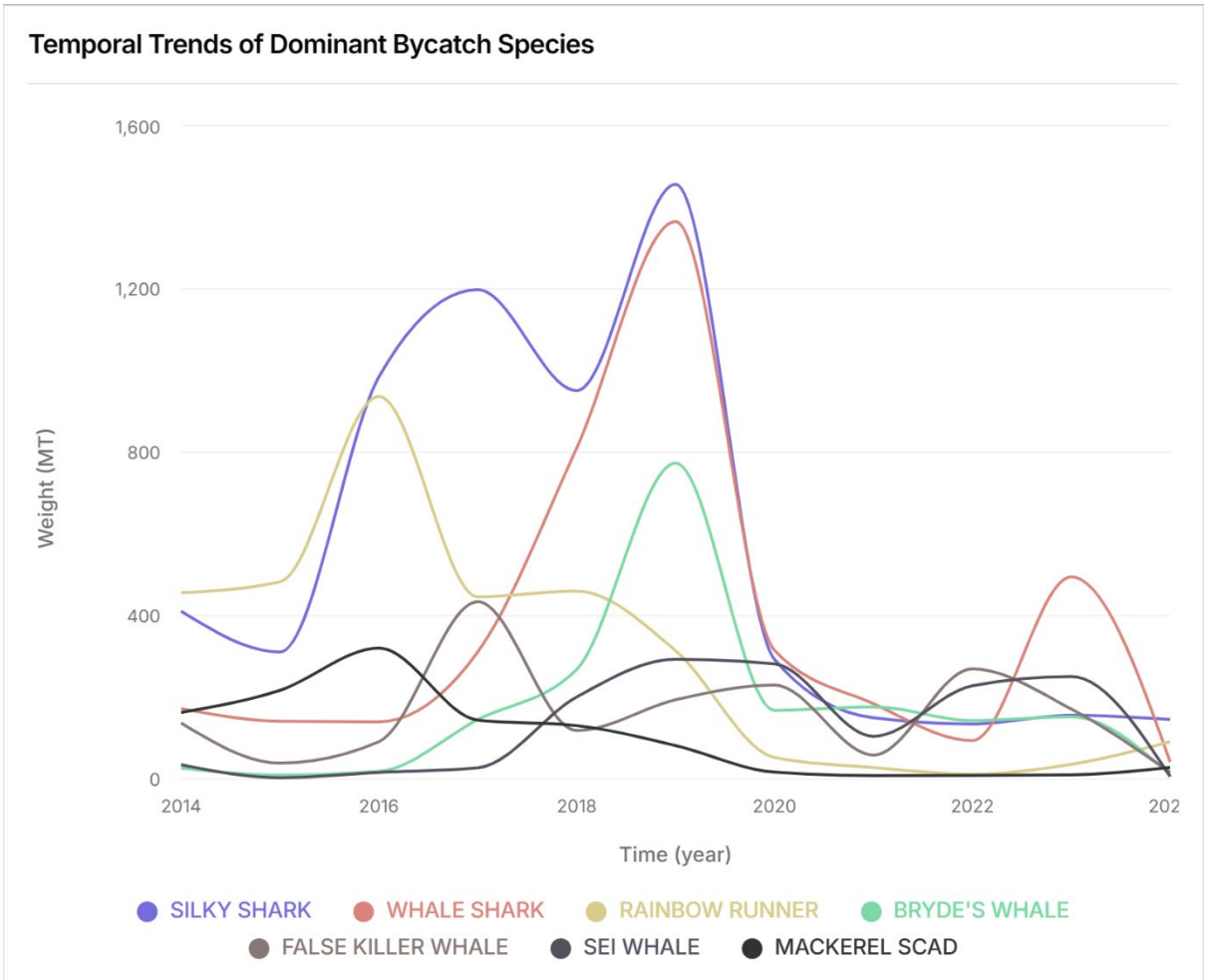
Temporal trend chart created

I aggregated the dataset by **year** and **species**, using total species weight as:

Ret_MT_est + Disc_MT

Then I plotted the seven dominant bycatch species over time with:

Title - *Temporal Trends of Dominant Bycatch Species* **X-axis** - *Time year* **Y-axis** - *Weight MT*



I filtered the **schtype_id** column to compare only:

- **Drifting FAD**
- **Unassociated**, labelled as **Free-school**

I removed:

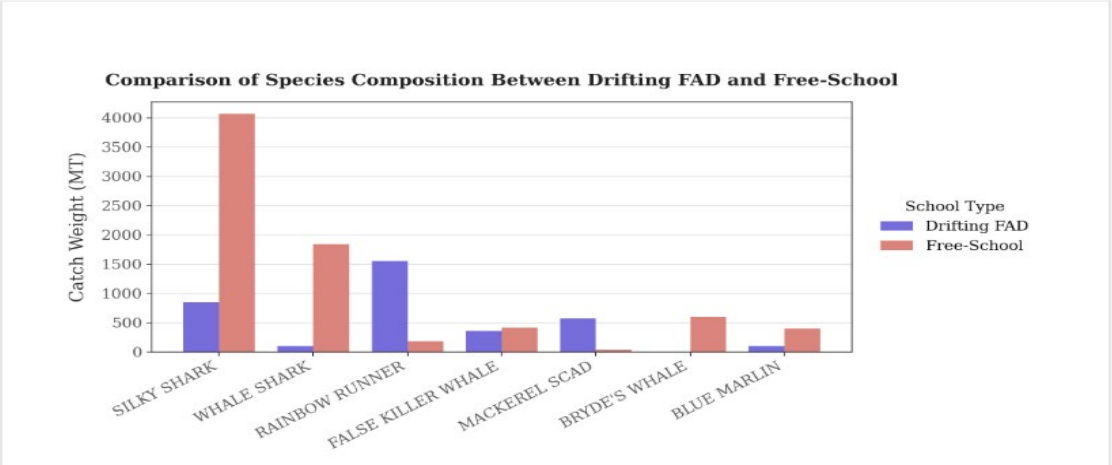
- **OTHER**
- **WHALE**
- **WHALE SHARK**
- **LOG**

Then I plotted the **top 7 dominant species by catch weight** using total weight:

Ret_MT_est + Disc_MT

The chart title was set to:

Comparison of Species Composition Between 'Drifting FAD and Free-School'



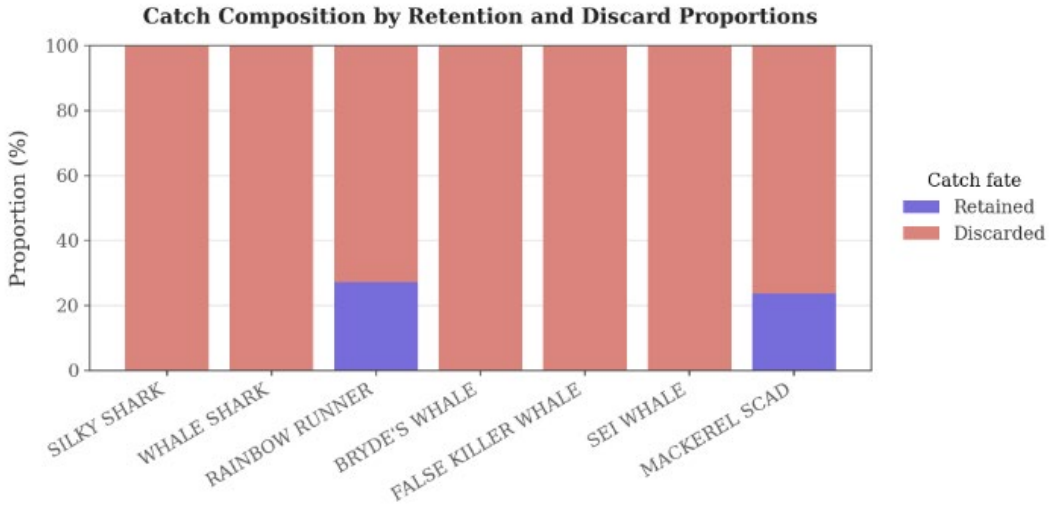
I plotted **Catch Composition by Retention and Discard Proportions** for the **top 7 dominant species**.

I used:

- **Ret_MT_est** for retained catch weight
- **Disc_MT** for discarded catch weight
- Total dominance calculated as **Ret_MT_est + Disc_MT**

The chart is a **stacked bar chart**, with:

- All species labelled on the x-axis
- Retained and discarded weights shown separately
- Legend displayed on the right



I analysed the uploaded PNG purse seine bycatch dataset using a non-parametric Kruskal-Wallis approach, as requested. The response variable was:

total_bycatch = retained_weight + discarded_weight

where:

- **retained_weight** = **Ret_MT_est**
- **discarded_weight** = **Disc_MT**
- total bycatch biomass is in metric tonnes, MT

The dataset was filtered to include only:

- **Drifting FAD sets**
- **Unassociated / Free-school sets**
- **Top 7 dominant bycatch species by total biomass**

After cleaning and filtering, the final analysis dataset contained **49,628 observations**

Explanatory variable	Chi-square	df	p-value	Interpretation
Year	1016.941	10	4.19×10^{-212}	Significant temporal differences
Set type	2825.960	1	< 0.001	Significant operational differences
Species composition	5417.651	6	< 0.001	Significant species-level differences

Bycatch vs Year

Year	n	Total (mt)	Median (mt)	Mean (mt)	q1 (mt)	q3 (mt)	Max (mt)
2014	4,308	769.301	0.050	0.178574977	0.020	0.100	26
2015	3,609	604.342	0.050	0.167454142	0.020	0.140	15
2016	7,613	1,713.551	0.060	0.225082228	0.028	0.150	40
2017	8,927	1,918.099	0.050	0.214864904	0.020	0.120	60
2018	7,982	1,735.734	0.050	0.217456026	0.020	0.120	156
2019	7,460	2276.49	0.070	0.305159517	0.025	0.200	70
2020	2,600	536.658	0.050	0.206406923	0.020	0.100	20
2021	1,566	287.928	0.040	0.183862069	0.010	0.100	20
2022	1,647	289.414	0.033	0.175721919	0.010	0.080	20
2023	2,449	721.633	0.030	0.294664353	0.010	0.080	100
2024	1,467	260.503	0.050	0.177575324	0.020	0.100	15

Bycatch vs set type

Set_type	n	Total (mt)	Median (mt)	Mean (mt)	q1 (mt)	q3 (mt)	Max (mt)
Free-School	23,277	7,567.665	0.08	0.325113417	0.030	0.2	156
Drifting FAD	26,351	3,545.988	0.04	0.134567493	0.015	0.1	75

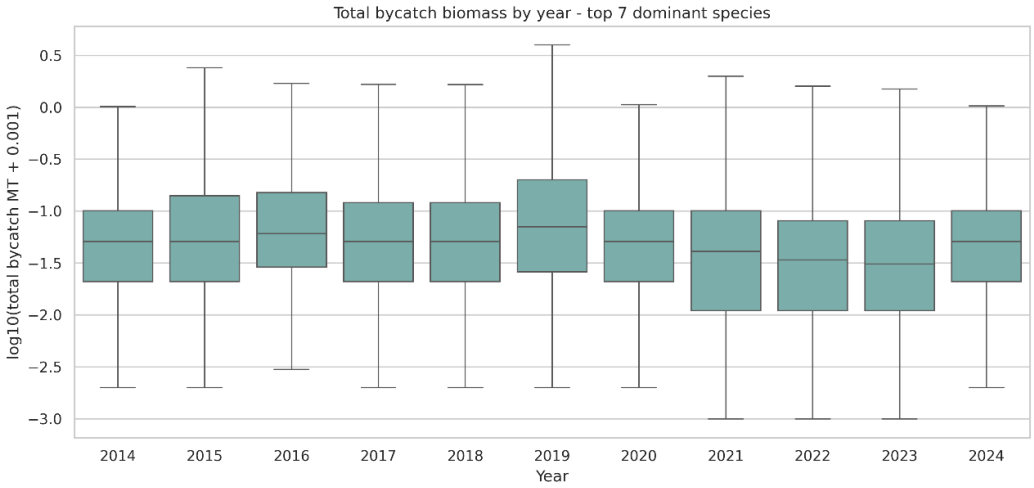
Pairwise

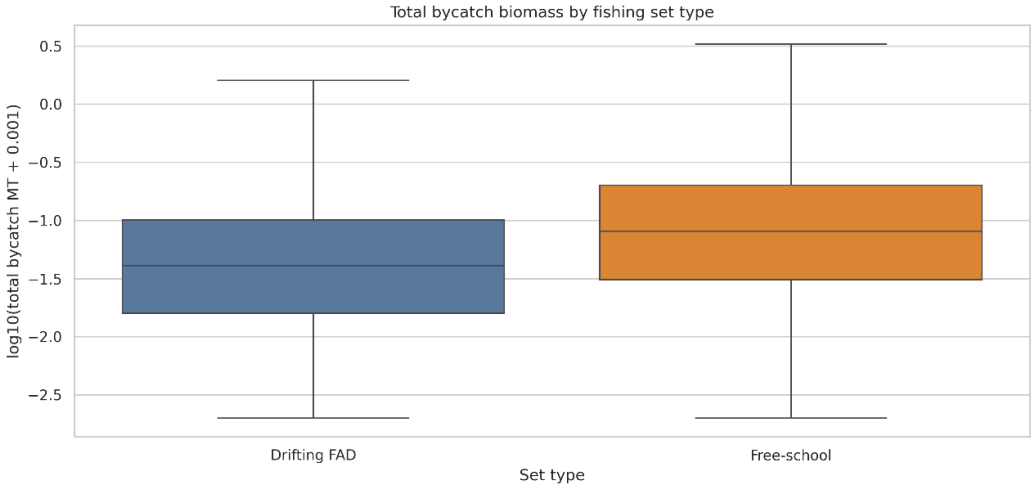
Comparison	Median 1	Median 2	Holm-adjusted p-value	Significant
Drifting FAD vs Free-School	0.040	0.080	<0.001	Yes

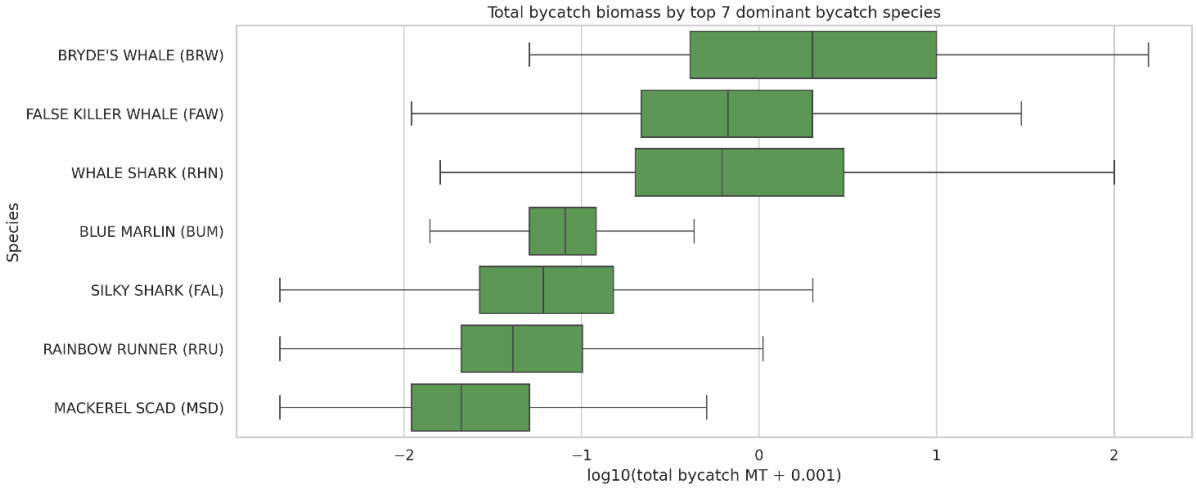
Bycatch vs Species Composition

species	n	Total (mt)	Median (mt)	Mean (mt)	q1 (mt)	q3 (mt)	Max (mt)
Bryde's Whale (BRW)	79	605.964	2.0000	7.67043	0.40950	10.00000	156.0
False Killer Whale (FAW)	390	781.404	0.6675	2.00360	0.21575	2.00000	75.0
Whale Shark (RHN)	693	1,941.937	0.6170	2.802218	0.20000	3.00000	100.0
Blue Marlin (BUM)	4,571	511.940	0.0800	0.111997	0.05000	0.12000	3.1
Silky Shark (FAL)	25,184	4,914.742	0.0600	0.195153	0.02575	0.15000	24.0
Rainbow Runner (RRU)	11,937	1,739.504	0.0400	0.145724	0.02000	0.10000	40.0
Mackerel Scad (MSD)	6,774	618.162	0.0200	0.091255	0.01000	0.05000	26.0

Patterns plotted using Boxplots







Acknowledgements

I would like to express my sincere gratitude to my supervisors, Dr Armagan Sabetian and Professor Sebastian Leuzinger, for their invaluable guidance, patience, encouragement, and constructive feedback throughout this study. I also acknowledge the support provided by the School at Auckland University of Technology for providing the academic environment and resources necessary for this research. Special appreciation is extended to the National Fisheries Authority of Papua New Guinea and the Parties to the Nauru Agreement Office (PNAO) for their financial and institutional support throughout my postgraduate studies. To my family, thank you for your unwavering support, sacrifices, encouragement, and belief in me throughout this journey. This thesis represents not only an academic milestone, but also a reflection of collective support, encouragement and contributions of many individuals and institutions to whom I remain deeply grateful to.

1. Introduction and Literature Review

Fisheries are fundamental to ensuring food security, supporting livelihoods, and contributing significantly to national economies throughout the Pacific region. Papua New Guinea (PNG), the largest nation among the Pacific Islands, possesses one of the most expansive and biologically productive Exclusive Economic Zones (EEZs) globally covering an estimated 2.4 million square kilometres of oceanic territory (Nicol et al., 2009).

A significant portion of the tuna captures in the Western and Central Pacific Ocean (WCPO) come from purse seine tuna fisheries which predominate in this EEZ (Fei et al., 2025). While the socioeconomic value of tuna fisheries is widely recognised, comparatively less attention has been paid to bycatch, defined here as the incidental capture of non-target organisms. The term varies across taxa and contextual applications. In many cases, bycatch refers primarily to fish and sharks that become hooked or entangled during fishing operations. For marine mammals, however, the term interaction is more commonly used to describe a range of lethal and sublethal entanglements. In contrast, the scope of interactions for seabirds is broader, encompassing not only entanglement or hooking but also physical contact with fishing gear, such as when birds collide with trawl warp lines or other equipment without becoming ensnared (Roberson & Wilcox, 2025). Although overshadowed by the primary tuna harvest, bycatch is a hidden or ‘invisible’ fishery, yet one that exerts far-reaching ecological, economic and management effects across the broader marine ecosystem (Hall et al., 2017).

Historically, bycatch was either not reported or reported with low accuracy, resulting in significant data gaps (Brouwer et al., 2024). Addressing bycatch has become an increasingly urgent priority as global fisheries governance shifts toward a more holistic approach. Within the WCPO, the Western and Central Pacific Fisheries Commission (WCPFC), along with subregional and national bodies such as the Parties to the Nauru Agreement (PNA), the Forum Fisheries Agency (FFA), underscore the importance of incorporating bycatch considerations into sustainability assessments and harvest strategies (Gilman, 2011).

For example, the WCPFC maintains the Bycatch Mitigation Information System (BMIS), a comprehensive online platform designed to support fisheries managers, scientists, fishers, and the public. The BMIS functions as a centralized repository of information on bycatch mitigation and management practices across the WCPO. Of particular concern are species of special interest, including seabirds, sharks, and marine turtles which are incidentally captured in fisheries targeting highly migratory species such as tuna and billfish. Guided by WCPFC Conservation and Management Measures (CMMs), fishing operations within the Convention Area are obligated to minimize the incidental capture of both fish and non-fish species. The BMIS plays a vital role in supporting these objectives by improving access to bycatch related knowledge and facilitating the adoption of best practices within tuna and billfish fisheries (WCPFC, 2025).

Despite the existence of such institutional frameworks, however, the documentation of purse-seine bycatch in Papua New Guinea remains insufficient and its integration into management decision-making is still limited. According to Gillett (2011), in developing countries, documentation and management systems are often inadequate or absent. In the context of PNG, fisheries data are often accessible, yet the capacity to conduct in-depth research remains constrained by limited manpower and the competing responsibilities of public servants. Many officers with access to relevant data are unable to dedicate sufficient time to research activities due to their official duties. Consequently, most local researchers tend to produce or publish scientific papers only when they are on study leave or training abroad, where they have the opportunity and resources to focus on academic writing. Over the past decade, existing studies have primarily concentrated on sharks, particularly within the Gulf of Papua region. To date, PNG–specific bycatch research has been limited to a few key studies. These include investigations into the sustainable management of shark resources of PNG and the socioeconomic and biological characteristics of the fishery (White et al., 2018); analyses of elasmobranch bycatch in the demersal prawn fishery in the Gulf of Papua (White et al., 2019); and an ecological risk assessment of elasmobranchs caught in the Gulf of Papua prawn trawl fishery (Baje et al., 2021).

Additionally, Kandu & Saevalsson, (2021) examined bycatch in the PNG purse seine fishery, emphasizing policy frameworks and comparing national measures with those of the WCPFC. More recently, (Baje et al., 2022) explored the dietary overlap of carcharhinid sharks from the Gulf of Papua, providing insights into species interactions but leaving offshore bycatch dynamics largely unexplored. Why is it essential to undertake continuous research on bycatch data or, more broadly, on any type of fisheries data? The answer lies in its fundamental role in informing and guiding the fisheries sector. Utilizing locally generated data, analysing it, and translating the findings into meaningful insights should form the foundation for sustainable fisheries development. Through this process, the sector not only strengthens its evidence-based decision making but also enhances knowledge generation and capacity building which is the essential pathway through which informed management and progress can occur. Therefore, developing a comprehensive understanding of bycatch dynamics, species composition, and utilization options is vital both for mitigating ecological impacts and for advancing the sustainable exploitation of fisheries resources (Clucas, 1997).

In this study, historical purse-seine observer records were analysed to (i) describe recorded bycatch composition and identify the highest-biomass species; (ii) summarise annual variation in recorded biomass; (iii) compare recorded biomass between Drifting FAD and Free-School observations; and (iv) assess retained and discarded proportions for selected species.

1.1 Bycatch in Global Fisheries

At the global level, bycatch remains a major challenge affecting both industrial and small-scale fisheries. The Food and Agriculture Organization (FAO) estimates that roughly 9.1 million tonnes of fish are discarded annually, reflecting substantial inefficiencies within fishing practices and emphasizing the ecological pressures such waste places on marine ecosystems (FAO, 2020). Within tuna fisheries, bycatch consists of a broad array of species, including small pelagic fishes, elasmobranchs, marine turtles and seabirds (Gilman, 2011). Although purse-seine fishing is often regarded as more selective compared to methods such as trawling, it still produces considerable amounts of bycatch, especially during sets around Drifting FADs (Dagorn et al., 2013).

Drifting Fish Aggregating Devices are artificial floating platforms widely utilized in tropical tuna purse seine fisheries to increase fishing efficiency and facilitate the capture of target species. However, their extensive use has raised several ecological and management concerns, including the heightened risk of overfishing, greater capture of juvenile tunas, and higher bycatch levels compared to Free-School sets (Pons et al., 2023).

Additional issues such as ghost fishing and the accumulation of marine debris further compound these impacts. In response to these challenges, environmental organizations and representatives from alternative fishing sectors have called for a total ban on Drifting FAD use. Yet, enforcing such a prohibition could have far-reaching implications, potentially disrupting global tuna supply chains, reducing tuna availability for consumption, and resulting in significant revenue losses for small island developing states, particularly within the Pacific region (Pons et al., 2023). Given the environmental concerns associated with Drifting FADs, a critical question emerges: how can their impacts be effectively mitigated? According to Pons et al. (2023), the sustainable use of Drifting FADs requires robust management frameworks designed to mitigate their ecological impacts. Pons et al. (2023) further highlight that with advances in technology and management, Drifting FAD use can be made more responsible, for instance, through the implementation of temporal and spatial deployment restrictions, organized recovery programs, and improved data transparency. These measures collectively offer practical solutions to reduce bycatch and minimize broader environmental harm.

Moreover, Pons et al., (2023) emphasize that all management decisions must be guided by sound scientific evidence to effectively address the legitimate concerns associated with Drifting FAD use, ensuring the sustainability of pelagic and coastal ecosystems and long-term viability of tropical tuna fisheries. This view is further supported by Torres-Irineo et al., (2014) highlighting that FAD-associated sets tend to exhibit higher species richness than free-school sets, underscoring the need for continued attention to the ecological dynamics of FAD use within tropical tuna fisheries. Therefore, a well-balanced strategy for managing FADs is vital to sustain ecological integrity while supporting economic resilience.

Considering that Drifting FADs substantially contribute to bycatch, a critical question arises: how extensively does bycatch affect the ecological balance of marine ecosystems? According to Komoroske & Lewison, (2015), the ecological effects of bycatch are complex and multifaceted. At the population level, studies reveal that bycatch can exacerbate declines in vulnerable species groups, including sharks, rays, and marine turtles, many of which are already recognized as being of high conservation concern. Furthermore, (Derocher, 2013), outline that the removal of non-target species can disrupt trophic relationships and energy flows within marine ecosystems, potentially triggering cascading effects that undermine long-term ecosystem productivity.

Since fishing is the most significant human-induced force that alters the structure and function of marine environments (Derocher, 2013; Jackson et al., 2001), perhaps there is a potential approach to better manage this issue. (Derocher, 2013) and (Jackson et al., 2001) highlight that contemporary management is increasingly shifting from traditional single species approaches toward ecosystem-based management (EBM). This transition represents a positive shift in fisheries management. However, it raises an important question: What exactly is ecosystem-based management (EBM) or ecosystem-based fisheries management (EBFM), and how does it relate to bycatch? According to (Pikitch et al., 2004), traditional fisheries management has been ineffective, largely because it focuses on maximizing catches of individual target species while overlooking the broader ecosystem context which includes habitats, prey, predators and the complex interactions among species. To address this limitation, the authors advocate for a more comprehensive and integrated management framework, known as ecosystem-based fisheries management. This approach essentially reverses conventional management priorities, emphasizing the protection and sustainability of entire ecosystems as the foundation upon which the management of target species should be built.

Moreover, EBM or EBFM must consider not only the direct and indirect effects of commercial fishing but also the broader influences of bycatch, recreational and artisanal fisheries, as well as environmental changes, which can often be substantial and unforeseen. The combined, or synergistic impacts of fishing pressure, environmental variability, and climate change pose escalating threats to marine ecosystems and add further complexity to effective fisheries management (Crowder et al., 2008; Myers & Worm, 2003).

As a result, contemporary global policy discourse increasingly recognizes bycatch not merely as a waste management concern but as a critical factor influencing ecosystem integrity and the long-term sustainability of fisheries. Given that fisheries bycatch poses a significant threat to numerous marine megafauna species across the world’s oceans, extensive research over recent decades has enhanced our understanding of species impacted, as well as the magnitude and spatial distribution of bycatch. During this period, notable progress has also been achieved in developing effective mitigation measures and implementing best practices aimed at minimizing bycatch and its ecological consequences (Komoroske & Lewison, 2015).

Ultimately, avoiding bycatch remains a major challenge, as many non-target species are found in close association with target species, making it difficult to prevent their capture during fishing operations. Nonetheless, Roberson & Wilcox, (2025) observe that within purse seine fisheries, there is considerable variation in fishing behaviour and performance among individual vessel operators indicating that operator-specific practices can significantly affect both the magnitude and species composition of bycatch.

Roberson and Wilcox, (2025) emphasize that the observed patterns of variation highlight the potential to reduce bycatch through targeted measures focusing on specific performance groups of individuals, presenting an alternative strategy that complements fleet-wide management controls. This approach may prove advantageous, as many vessel operators possess extensive fishing experience and a deep understanding of species distribution and behaviour. Their knowledge of optimal fishing grounds, seasonal abundance, and the likelihood of encountering both target and non-target species provide valuable insight. Harnessing this experiential knowledge could therefore contribute to minimizing bycatch through more selective and informed fishing practices.

1.2 Purse Seine Bycatch in the Western Central Pacific Ocean.

More than half of the world's tuna catch comes from the largest tuna fishery in the world, which is found in the WCPO (Hampton et al., 2017). From small scale, artisanal operations in Pacific states' coastal waters to large scale industrial purse seine, pole and line operations in Pacific states' EEZs and international waters which is also known as the high seas, the tuna fisheries in the WCPO Convention Area is diverse (Hare et al., 2021). This area, where FAD use is prevalent is dominated by purse seine fleets (Figure 1), which specifically target bigeye (Thunnus obesus), yellowfin (Thunnus albacares), and skipjack (Katsuwonus pelamis) tuna. Fishing on FADs known as 'Associated' and fishing on Free-Schools known as 'Unassociated' are the two types of purse seine fishing that take place. The two fishing techniques have different catch and size compositions and multiple WCPFC Cooperating Commission Members (CCMs) control the usage of FADs (Hare et al., 2021).

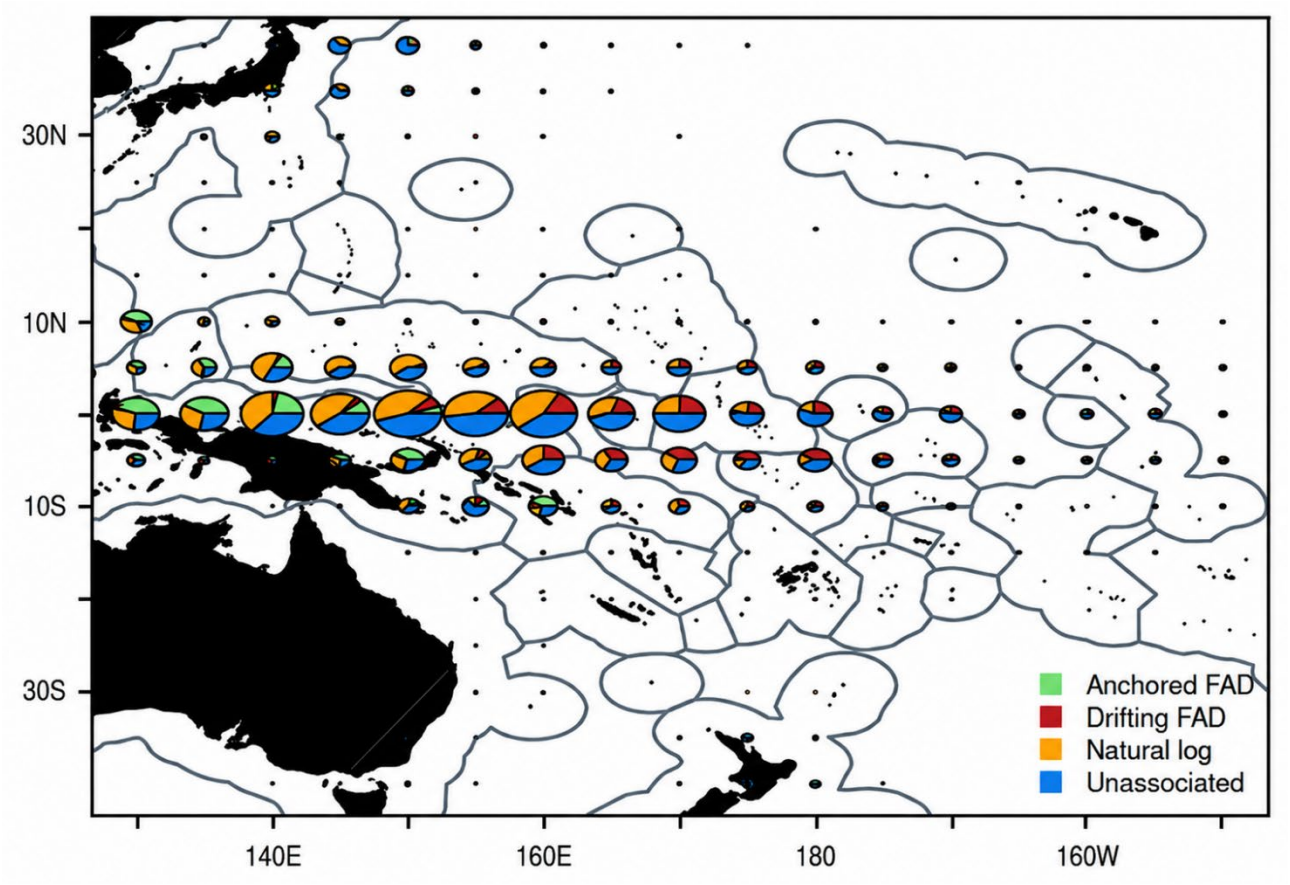


Figure 1: Historical distribution and proportions of tuna purse-seine catch by fishing association category across the Western and Central Pacific Ocean, 1980–2010. This contextual literature figure predates the 2014–2024 bycatch observation period examined in the present thesis. Adapted from: (Leroy et al., 2013)

It is the WCPFC's duty to evaluate how fishing affects non-target species. Most of this bycatch originates from large-scale purse seine fisheries that are mostly found in tropical waters. In recent years, almost 85% of the purse seine harvest of tropical tunas which has fluctuated between 1.7 and 2.2 million tonnes yearly since 2001 has come from these enormous vessels which typically have a carrying capacity of more than 500 tonnes (Peatman & Nicol, 2021). However, concerns over elevated bycatch rates have intensified due to the heavy reliance on FAD-associated fishing. As we have seen previously, studies indicate that, in comparison to free-school sets, FAD-associated sets generate greater volumes of bycatch and a higher proportion of juvenile bigeye and yellowfin (Dagorn et al., 2013; Harley et al., 2015). Reducing the incidental capture of fish, marine mammals, reptiles, seabirds and other marine organisms represents a critical aspect of responsible fisheries management. It plays a vital role in halting population declines and supporting the recovery of species that are threatened or vulnerable to fishing pressure (Peatman et al., 2023).

How, then, can this objective be achieved? Within the framework of the WCPFC, observer programs coordinated by the Pacific Community (SPC) have played a crucial role in enhancing bycatch monitoring across the WCPO. According to (Williams & Terawasi, 2016), using regional observer

datasets, bycatch in purse seine fisheries is mostly made up of non-target finfish species such as rainbow runner (*Elagatis bipinnulata*), mahi-mahi (*Coryphaena hippurus*), triggerfishes and several species of mackerel along with incidental captures of sharks and rays. Williams & Terawasi (2016), further emphasize that, although these species make up only a small proportion of the total catch compared to tuna, they possess notable ecological and socio-economic importance.

At a recent working group meeting of the WCPFC, updated bycatch estimates were presented for more than 45 non-target species groups, derived from the extensive equatorial purse seine catch data (Peatman & Nicol, 2021). The accompanying observer data reported results with 95% confidence intervals, indicating a measure of uncertainty around the estimates. The authors highlighted that bycatch levels in the WCPO purse seine fishery are highly variable, fluctuating across fishing trips and regions. While observer data provide a means of quantifying this variability, the broad confidence intervals highlight persistent uncertainties in bycatch estimation. Collectively, these findings emphasize that bycatch within the WCPO purse seine fishery remains both substantial and unpredictable, underscoring the need for enhanced monitoring and refined analytical methods.

Additionally, (Peatman & Nicol, 2021) further highlighted that the management framework overseeing purse seine bycatch in this region has evolved gradually in response to emerging ecological and operational challenges. The WCPFC has adopted a range of Conservation Management Measures (CMMs) designed to improve FAD management, ensure sufficient observer coverage, and strengthen reporting obligations. These measures encompass gear modifications, the establishment of minimum mesh size standards, and the application of temporal and spatial restrictions on FAD associated sets, all aimed at reducing bycatch risk and promoting sustainable fishing practices.

The authors emphasised that successful bycatch mitigation depends on understanding both the operational characteristics of purse-seine fisheries and the aggregation behaviour of non-target species around FADs. However, despite notable progress, several challenges remain, particularly in relation to data completeness and compliance. In many fleets, observer coverage continues to be inadequate, and the extrapolation of bycatch estimates across different fleets still carries a high degree of uncertainty.

Furthermore, monitoring bycatch mortality and post-release survival is complicated by high seas operations and transhipment activities, which often occur beyond the reach of direct observation. The spatial variability of fishing sets and the uneven distribution of FADs add further complexity, introducing heterogeneity in bycatch risk and hindering the standardisation of bycatch per unit effort metrics. Additionally, the occurrence of ‘cryptic mortality’—unreported or delayed deaths of non-target species—remains a significant source of uncertainty in purse seine bycatch assessments (Hall & Roman, 2013).

1.3 Bycatch in PNG's Purse Seine Fisheries

The offshore purse seine fishery operating within the Papua New Guinea EEZ forms a central pillar of the country's tuna sector (Nicol et al., 2009). Catches in this zone have averaged about 250,000 tonnes/year over the past decade, peaking at approximately 466,000 tonnes in 2007 (Kumoru, 2008). As discussed earlier in this paper, research on bycatch in PNG remains limited, despite the availability of data that could support such studies. This issue is particularly important because PNG's tuna purse seine fishery accounts for approximately 20% of total WCPO purse seine catch in some years (Nicol et al., 2009). This means that even relatively low bycatch rates can translate into substantial volumes of non-target catch. Consequently, the systematic recognition and monitoring of bycatch composition in PNG's offshore purse seine fisheries are crucial to ensuring that national fisheries management is effectively aligned with regional EBM principles.

According to Williams & Terawasi, (2014), existing data suggest that the bycatch composition of PNG's purse seine fishery generally reflects regional trends, catches dominated by small pelagic fishes, juvenile tunas and the occasional retention of species such as dolphinfish (*Coryphaena hippurus*), rainbow runner (*Elagatis bipinnulata*), silky sharks (*Carcharhinus falciformis*), and other finfish and billfish. Although interactions with vulnerable and protected species including marine turtles and whale sharks occur infrequently, they remain a significant conservation concern, necessitating the implementation of mitigation measures such as safe-release protocols and spatial management measures (WCPFC, 2018).

The socio-economic value of bycatch in PNG remains largely underexplored. However, anecdotal observations suggest that certain bycatch species such as mackerel and rainbow runner could have potential for local market development, provided they are harvested and managed sustainably (Gillett, 2011). However, the development of such opportunities is constrained by inadequate infrastructure, weak cold-chain networks, and insufficient policy support. This reflects what may be described as an "invisible fishery": an under-recognised component of PNG's fisheries sector that could contribute to food security and economic benefits, provided any utilisation is legal, feasible and ecologically sustainable.

1.4 Governance and Management Approaches

The governance and management of bycatch within the WCPO are shaped by a multifaceted interplay of institutional, ecological, and political factors. As the region encompassing the world's most extensive tuna fisheries, the WCPO contributes more than 55% of global tuna production (Williams & Ruaia, 2022). These fisheries hold substantial economic importance for island nations including Papua New Guinea. According to WCPFC, (2025), at the regional scale, the Commission serves as the principal legal and institutional framework governing fisheries management.

Established under the 2000 Convention for the Conservation and Management of Highly Migratory Fish Stocks in the WCPO, the Commission oversees the coordination of conservation and management measures across both the high seas and EEZs. Its CMMs are legally binding on member states and outline regulatory standards for observer coverage, catch documentation, bycatch mitigation and the deployment and management of FADs .

Moreover, WCPFC, (2025) emphasized that the Convention draws extensively on the principles and provisions outlined in the United Nations Fish Stocks Agreement (UNFSA), while simultaneously accommodating the unique political, socio-economic, geographic, and environmental conditions of the WCPO region. Its primary objective is to address persistent challenges in the governance of high seas fisheries, including unregulated fishing practices, overcapitalization, excessive fleet capacity, re-flagging of vessels to circumvent management controls, the use of non-selective fishing gear, deficiencies in data reliability and inadequate multilateral cooperation in the conservation and management of highly migratory fish stocks.

Furthermore, the authors highlight that the Convention establishes a framework that enables the participation of fishing entities in the Commission, thereby legally binding them to its provisions, while also allowing for the inclusion of territories and possessions in its activities. In addition, the Convention acknowledges the specific needs and developmental priorities of developing States and promotes collaboration with other Regional Fisheries Management Organisations (RFMOs) jurisdictions that may intersect with that of the Commission. These elements collectively reflect the distinctive geopolitical context within which the Commission operates.

Several CMMs implemented under the WCPFC directly address bycatch mitigation. For instance, CMM 2024-05: Conservation Measure for Sharks acknowledges the ecological, biological, cultural, and economic significance of sharks as apex predators in marine ecosystems, while recognising the vulnerability of many species to fishing pressure. The measure aims to promote the long-term conservation, sustainable management and responsible use of shark populations and associated fisheries through the application of precautionary and ecosystem-based approaches to fisheries management. This CMM applies across both the high seas and the EEZs within the Convention Area (CA) (WCPFC, 2025). Similarly, the Tropical Tuna Measure (CMM 2023-01) was designed to support the sustainable management of skipjack (*Katsuwonus pelamis*), bigeye (*Thunnus obesus*), and yellowfin (*Thunnus albacares*) tuna fisheries in a manner that equitably benefits commission members, cooperating non-members and participating territories, while addressing the specific needs of developing states. Among its provisions, the measure establishes seasonal closures for FAD use and imposes limits on FAD deployment, both of which are critical for reducing the incidental capture of juvenile tunas and other non-target species (WCPFC, 2025). Together, these frameworks represent a transition toward ecosystem-based fisheries management, emphasizing the preservation of ecological integrity within pelagic ecosystems rather than focusing solely on individual species conservation (Pikitch et al., 2004).

The Pacific Islands Forum Fisheries Agency (FFA) complements the functions of the WCPFC by delivering both technical and policy support to its seventeen member states, including Papua New Guinea. Through its Regional Monitoring, Control Surveillance (MCS) Strategy 2024 -2029, the FFA promotes an integrated framework for surveillance and enforcement that strengthens compliance and data integrity. This approach places particular emphasis on electronic monitoring (EM), vessel monitoring systems (VMS) and observer programmes, all of which enhance the reliability of bycatch information (FFA, 2025b). Similarly, the Pacific Community (SPC) provides scientific and analytical support to the region, administering observer data through the BMIS – a centralized repository that compiles species profiles, mitigation measures and safe-release protocols (SPC, 2025a).

At the subregional scale, the Parties to the Nauru Agreement (PNA) of which Papua New Guinea is a member, manages the Vessel Day Scheme (VDS); a market-oriented mechanism for controlling fishing effort that enables the allocation and trading of fishing days among participating countries (Havice & Campling, 2010). Although the VDS was initially developed to regulate tuna fishing effort and enhance economic returns, it also contributes indirectly to bycatch management by placing an upper limit on the total purse seine fishing effort within the region. In addition, the PNA have implemented a FAD Management Scheme that imposes restrictions on the number of FADs deployed, requires their tracking and identification and promotes the adoption of non-entangling and environmentally responsible designs (PNA, 2025).

In PNG, the National Tuna Management Plan established under the mandate of the Fisheries Management Act 1998 (as amended) serves as the cornerstone of offshore fisheries governance. The National Fisheries Authority (NFA) administers the national tuna management plan that is consistent with both WCPFC and PNA regulatory frameworks. In recent years, PNG has increasingly emphasized diversification in fishing operations and resource utilization. This strategy involves expanding into complementary fishing activities, including the adoption of alternative fishing methods, the enhancement and introduction of improved gear technologies, and the development of value chains for non-target species such as small pelagics and mackerel, with the goal of strengthening local food security. One of the key approaches undertaken by PNG through the NFA to achieve this vision is the implementation of the Fisheries Strategic Plan 2021-2030. This plan serves as the comprehensive roadmap, providing clarity and direction for strategic decision-making within PNG's fisheries sector.

Through this framework, the NFA has been actively working to modernize its regulatory and management systems, ensuring that all existing management plans and measures are reviewed, updated, and aligned with contemporary fisheries concepts and sustainable development goals. The objective is to establish pathways that foster economic growth, sectoral stability, and resource sustainability.

The impact of this vision is already evident. Over the past few months, the organization has successfully developed and updated several key management and development plans, including the Bech der mer (Sea cucumber) Management Plan, Tuna Management Plan, Mud Crab Management Plan, Gulf of Papua Prawn Fishery Management Plan, and the Western Province and Torres Strait Tropical Rock Lobster Fishery Management Plan, all of which demonstrate significant progress within PNG's coastal fisheries management space.

Furthermore, a notable recent advancement in the offshore fisheries management sector, echoing objectives of the National Tuna Domestication strategy is the establishment of the East New Britain Initiative (ENBi), which is currently taking shape as an emerging framework in the region with PNG serving as its current chair. Its primary objective is to maximize economic returns from tuna fisheries through the establishment of regional fisheries hubs and other value-adding initiatives designed to strengthen members by giving them the leverage in their shared tuna resources and finding collective and inclusive investment pathways (FFA, 2025a). Nonetheless, such diversification initiatives must remain within ecologically sustainable limits and avoid creating incentives that could lead to the targeting of bycatch species (Teh et al., 2014). PNG faces the challenge of balancing economic diversification with ecological sustainability to ensure that the utilization of bycatch does not compromise conservation goals.

1.5 Research question

What are the key drivers of bycatch variability in Papua New Guinea's tuna purse seine fisheries, and how can species-specific bycatch trends inform ecosystem-based management and fisheries diversification strategies?

1.6 Objectives

The objectives of this study are as follows:

1. Quantify and characterise bycatch species composition and diversity in Papua New Guinea's purse seine tuna fishery, with emphasis on identifying the dominant bycatch species.
2. Analyse temporal trends in bycatch for key species to determine changes in catch magnitude and composition over time.
3. Evaluate the influence of operational factors (e.g., set type: FAD-associated versus free-school) on bycatch variability and species-specific recorded biomass.
4. Identify key drivers of bycatch patterns and assess their implications for management, including the potential for developing utilisation strategies for high-volume bycatch species within an ecosystem-based fisheries management framework.

2. Methods

2.1 Description of Data

To conduct this study, Purse Seine Bycatch data from the PNG Offshore Tuna Fisheries was used. Data for years 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023 and 2024 were analysed. This data frame consisted of year, observer program code, vessel name, flag name, trip number, departure date, set date, set number, type of gear, type of school identification, RMFO area, EEZ code, species category code, species code, common name, scientific name, fate code, life status, retained catch in metric tonnes, and discarded catch in metric tonnes.

The supplied observer extract contains 112,585 records from 2014 to 2024. The rows include year, vessel/trip and set identifiers, school type, species code and name, and estimated retained and discarded biomass. Because an observation is a species-level row and multiple rows can originate from the same set, record counts should not be interpreted as counts of unique fishing events. This extract does not provide a complete denominator of all purse-seine trips or sets undertaken by the fleet; therefore, the actual coverage percentage of the observer programme cannot be inferred from these records alone. The results are reported as biomass within the observed dataset, rather than fleet-wide expanded biomass estimates or standardised bycatch rates.

2.2 Purse seine sampling of bycatch species data collection

Bycatch data are collected by trained observers deployed aboard purse-seine vessels. These observers receive training through the Pacific Islands Regional Fisheries Observer (PIRFO) training Framework, a competency-based program typically delivered by trainers from the Pacific Community (SPC) and freelance PIRFO-certified trainers across the region. Fisheries observers are specifically trained to monitor fishing operations and record data using standardized tools such as the SPC/FFA Regional Observer Workbook and Deck Sampling Forms. These forms are designed to capture detailed information from a range of fishing vessel types including purse seiners, long liners, pole-and-line vessels, and carrier vessels.

Fisheries observers collect length-frequency data on both target species and bycatch using a standardized Deck Form, known as the PS-4 form. This form provides three sampling options (see Annex), which observers must select to indicate the sampling protocol applied when catches are brailed onboard and transferred into the wells.

1. Grab Sampling – This method is primarily applied to target tuna species such as yellowfin (YFT), bigeye (BET), and skipjack (SKJ) during brailing operations.

2. Spill Sampling – Introduced by the SPC, this protocol involves sampling an entire brail, including both target and non-target species. However, recent reports indicate that this method is no longer commonly practiced (Itano et al., 2019).
3. Other Sampling – This option applies to additional or supplementary sampling activities undertaken by observers, often conducted after grab sampling. It typically focuses on bycatch species landed in large quantities.

Bycatch sampling under these protocols allows observers to record length-frequency data for a range of species, including mackerel scads, triggerfish, frigate and kawakawa tunas, mahimahi, rainbow runner, silky sharks, and in rare instances cetaceans such as dolphins if caught in large groups. Although seabird bycatch is uncommon in tropical purse seine fisheries, it may occur further south and is more prevalent in longline operations. Certain bycatch species such as marlins, sailfish, moonfish, sunfish, turtles, and oceanic whitetip sharks are occasionally landed, typically in small numbers ranging from one to five individuals. In most cases, observers do not collect length measurements for these species; however, such data may be recorded opportunistically when feasible. All bycatch landings, whether sampled or unsampled, are documented in the Catch Reconciliation Form (PS-3). This form is used to generate approximate estimates of bycatch quantities, which can then be categorized as discarded or retained (e.g., for consumption or other uses) based on their whole weight.

2.3 Data set

The Oceanic Fisheries Program (OFP) of the Pacific Community (SPC) provides scientific and technical advice on the status of fish stocks, management strategies, and impacts of fishing and environmental factors, including climate change, on both target and non-target species within the pelagic ecosystem. OFP supports member countries by delivering this work at both national and regional levels and through various sub-regional fisheries organisations of which they are members, including WCPFC, FFA, PNA and the South Pacific Group (SPG). Structurally, the Programme operates through three key divisions: the Fisheries & Ecosystem Monitoring Assessment (FEMA) section, the Data Management (DM) section and the Stock Assessment & Modelling (SAM) section, each contributing to the overall goal of supporting sustainable fisheries management in the region (SPC, 2025b).

The purse seine dataset utilized in this study was obtained with authorization from the Offshore Fisheries Sub-division under the Fisheries Management Business Group of the National Fisheries Authority (NFA) of PNG. Data was accessed from the Data Management Team of the Oceanic Fisheries Programme. PNG maintains ownership rights to the dataset through its membership in the Pacific Community (SPC). Access to the dataset was provided under strict data confidentiality protocols and through institutional collaboration between the NFA and SPC to ensure the responsible use of fisheries information for scientific and management purposes.

2.4 Analysis

2.4.1 Dominant Bycatch Species

To examine the dominant key bycatch species, the total biomass (metric tonnes) of all recorded bycatch was quantified by combining the retained and the discarded weights (Total weight = retained weight + discard weight). These values were then calculated and plotted against the species recorded. The seven species with the greatest summed recorded biomass were selected, and their relative contributions were visualised using a comparative plot.

2.4.2 Temporal Trends of Dominant Bycatch Species

To assess temporal trends among the most dominant bycatch species, retained and discarded weights were combined to determine the total biomass (metric tonnes) for each species (Total weight = retained weight + discard weight). The resulting plots describe annual variation in recorded biomass during 2014–2024; annual totals were not standardised by observer coverage or fishing effort.

2.4.3 Comparison of Species Composition Between Drifting FAD and Free School

For the comparison between fishing modes, records were restricted to the DRIFTING FAD and UNASSOCIATED categories, with the latter termed free-school sets throughout this thesis. Other recorded set categories were excluded to define an operationally comparable two-mode subset, not because their observations were necessarily statistical outliers. Species were ranked by total recorded biomass after this filtering step, and the seven highest-ranked species were selected for Figure 4 and the statistical analyses. This subset comprised silky shark, whale shark, rainbow runner, Bryde's whale, false killer whale, mackerel scad and blue marlin. It differs from the overall seven-species list (Table 1 and Figures 2–3), where sei whale ranks among the highest total biomasses across all set types. Biomass was calculated for each record as estimated retained weight plus recorded discarded weight in metric tonnes (mt).

2.4.4 Catch Composition by Retention and Discard Proportions

For each of the seven dominant species identified from the full dataset, total recorded biomass was calculated as retained biomass plus discarded biomass. The retained proportion was calculated as 100 × retained biomass / total biomass, and the discarded proportion as 100 × discarded biomass / total biomass.

The analysis focused on dominant bycatch species, enabling a clearer evaluation of overall retention and discard proportions within the fishery.

2.4.5 Non-Parametric Analysis

Following exclusion of records outside DRIFTING FAD and UNASSOCIATED sets and selection of the seven dominant species within that subset, 49,628 species-level records remained for analysis. Three separate Kruskal–Wallis tests were used to evaluate differences in the distributions of observation-level total recorded bycatch biomass among years (2014–2024), fishing set categories, and species identities. Post-hoc pairwise comparisons across years were assessed using two-sided rank-based tests with Holm adjustment for multiple comparisons. The response variable was recorded biomass per data row; thus, group comparisons should not be equated with vessel- or set-standardised encounter risks. Species records may originate from the same fishing set, so within-set and within-vessel dependence could affect conventional significance tests; a multilevel model with a verified set identifier should be considered in future analyses. These univariate comparisons demonstrate distributional differences but do not identify independent causal effects.

3. Results

3.1 Dominant Bycatch Species

Table 1 shows that the bycatch composition is dominated by a small number of species, with silky shark (*Carcharhinus falciformis*) contributing the highest biomass (> 6,000 mt). This is followed by the whale shark (*Rhincodon typus*) (> 4000 mt), rainbow runner (*Elagatis bipinnulata*) (> 3000 mt), Bryde's whale (*Balaenoptera edeni*) (~ 2000 mt), false killer whale (*Pseudorca crassidens*) (~1800 mt), sei whale (*Balaenoptera borealis*) (> 1,400 mt). Mackerel scad (Decapterus macarellus), the second teleost in the top-seven list after rainbow runner, contributed just over 1,000 mt. These seven species contributed the highest summed recorded biomass among taxa represented in the analysed observer extract over 2014–2024.

The composition is notably skewed, with a limited number of species accounting for the majority of total bycatch biomass. This pattern is further illustrated in Figure 2, which shows a highly uneven distribution of catch across species in Papua New Guinea's purse seine fishery during the study period. Within this distribution, the prominence of large-bodied marine taxa, including cetaceans and elasmobranchs, is evident in the recorded biomass totals.

Furthermore, from a taxonomic perspective, the dominant bycatch species are distributed across five families. These are: Carcharhinidae, Rhincodontidae, Carangidae, Balaenopteridae and Delphinidae.

This diversity reflects the broad representation of pelagic elasmobranchs, teleost fishes, and marine mammals within the fishery (Table 1).

Table 1: Seven highest-biomass species with taxonomic classification and summed recorded biomass (mt).

Common Name	Scientific name	Genus	Family	Total Weight (mt)
Silky shark	*Carcharhinus falciformis*	*Carcharhinus*	Carcharhinidae	6,194.492
Whale shark	*Rhincodon typus*	*Rhincodon*	Rhincodontidae	4,075.956
Rainbow runner	*Elagatis bipinnulata*	*Elagatis*	Carangidae	3,320.102
Bryde's whale	*Balaenoptera edeni*	*Balaenoptera*	Balaenopteridae	1,900.266
False killer whale	*Pseudorca crassidens*	*Pseudorca*	Delphinidae	1,766.064
Sei whale	*Balaenoptera borealis*	*Balaenoptera*	Balaenopteridae	1,453.577
Mackerel scad	*Decapterus macarellus*	*Decapterus*	Carangidae	1,136.325

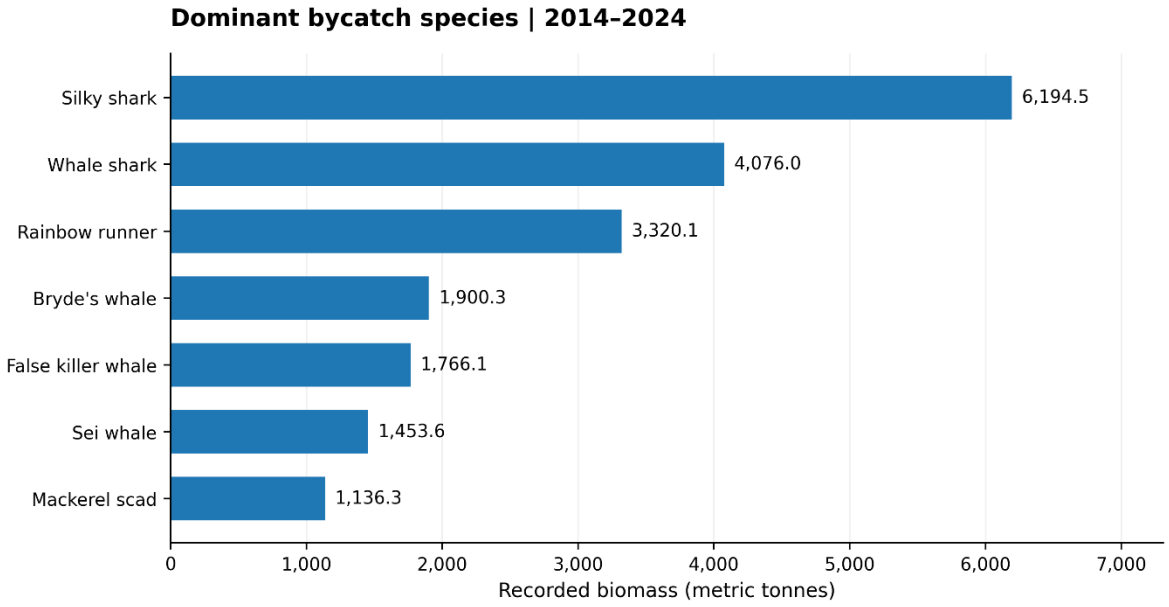


Figure 2: Recorded total biomass (metric tonnes, mt) of the seven species contributing the greatest biomass to the purse-seine observer dataset, 2014–2024. Each value is the sum of estimated retained biomass (Ret_MT_est) and discarded biomass (Disc_MT) across all recorded fishing set categories. The analysis is based on recorded observer observations and has not been adjusted for fishing effort or observer coverage.

3.2 Temporal Trends of Dominant Bycatch species

Figure 3 presents the temporal trends in bycatch biomass for the dominant species over the study period 2014 – 2024, revealing distinct patterns in species-specific variability through time.

The silky shark (*Carcharhinus falciformis*) exhibits a progressive increase in biomass from 2015 – 2019, reaching its peak between 2018 and 2019, followed by a steady decline thereafter. Similarly, the whale shark (*Rhincodon typus*) shows a marked increase beginning in 2016, with its highest

biomass recorded in 2019. Post – 2019, whale shark bycatch declines consistently until 2022, with a minor resurgence in 2023, before decreasing again in 2024.

In contrast, rainbow runner (*Elagatis bipinnulata*) demonstrates an early increase between 2014 and 2015, reaching its maximum biomass in 2016, after which catches decline but slowly pick up again in 2024. The Bryde's whale (*Balaenoptera edeni*) displays a gradual increase from 2016, peaking in 2019, followed by a declining trend in subsequent years.

The false killer whale (*Pseudorca crassidens*) shows an initial decline up to 2016, after which biomass increases to a peak in 2017, followed by a general downward trend, with minor fluctuations observed between 2020 and 2022. For sei whale (*Balaenoptera borealis*), biomass increases steadily from 2015 – 2020, after which a decline is evident, interrupted by a slight increase in 2023.

Finally, mackerel scad (*Decapterus macarellus*) demonstrates a gradual and consistent increase up to its peak in 2016, followed by a steady decline from 2017 onwards but slightly picks up again in 2023 and 2024.

Overall, several species exhibited peaks in recorded biomass during the late 2010s, followed by lower recorded totals in subsequent years. Patterns differed among species and cannot be interpreted as trends in abundance because the values were not standardised by fishing effort or observer coverage.

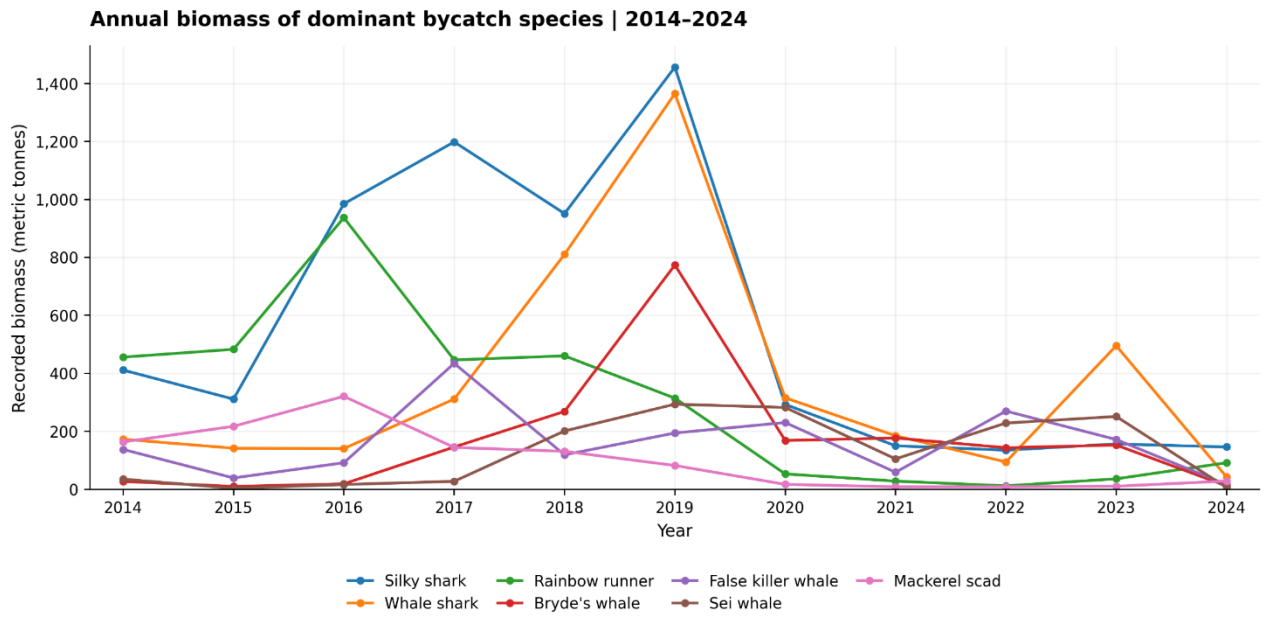


Figure 3: Annual recorded bycatch biomass (metric tonnes, mt) of the seven highest-biomass species in the full purse-seine observer dataset, 2014–2024. Annual totals were obtained by summing estimated retained and recorded discarded biomass across all observed set categories. Lines connect the observed annual totals without interpolation; annual differences have not been standardised by fishing effort or observation coverage.

3.3 Comparison of Species Composition Between Drifting FAD and Free-School

Figure 4 below illustrates a comparison of species composition between Drifting FAD sets and free-school sets, focusing on the dominant contributing species.

The silky shark (*Carcharhinus falciformis*) accounts for the largest proportion of bycatch, with most of its biomass derived from free-school sets (exceeding 4,100 mt), compared to approximately 750 mt from Drifting FAD. A similar pattern is observed for the whale shark (*Rhincodon typus*), where free-school sets dominate (~1,800 mt), while Drifting FAD sets contribute less than 200 mt.

In contrast, rainbow runner (*Elagatis bipinnulata*) exhibits a strong association with Drifting FAD sets, with nearly all recorded biomass (~1,600 mt) originating from these sets, and only about 300 mt from free-school sets. The false killer whale (*Pseudorca crassidens*) shows relatively comparable contributions from both set types, each accounting for just under 500 mt, indicating minimal variation between fishing modes.

Mackerel scad (*Decapterus macarellus*) is predominantly captured in Drifting FAD (~ 600 mt), with only a minor contribution (~100 mt) from Free-School sets. Nearly all recorded Bryde's whale biomass in this two-mode subset occurred in free-school sets; a small amount was also recorded for drifting-FAD sets (approximately 0.350 mt). Similarly, blue marlin (*Makaira nigricans*) displays higher catches in Free-School sets (~400 mt) compared to just over 100 mt from Drifting FAD sets.

Overall, the distributions of recorded biomass differed among the seven selected species and the two fishing set categories. In particular, rainbow runner and mackerel scad contributed greater recorded biomass in drifting-FAD sets. These comparisons were not standardised for fishing effort or observer coverage and should not be interpreted as relative encounter risks.

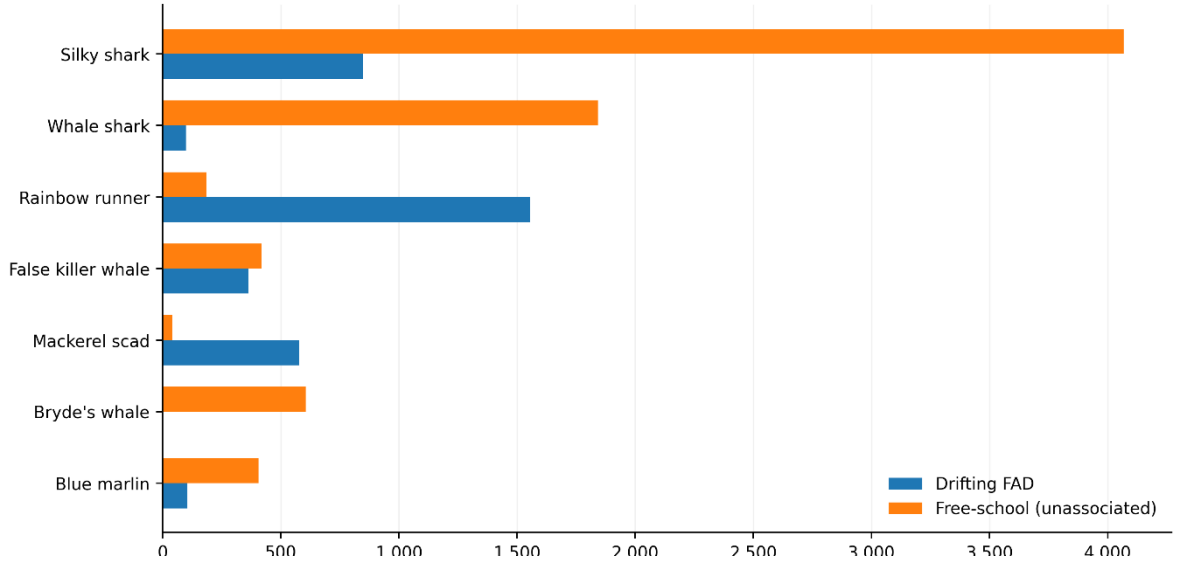


Figure 4: Recorded bycatch biomass (metric tonnes, mt) of the seven highest-biomass species identified after restricting the observer dataset to Drifting FAD-associated and unassociated (free-school) purse-seine sets, 2014–2024. Biomass is the sum of the Ret_MT_est and Disc_MT fields; other set categories were excluded. This subset includes blue marlin in place of sei whale, which is present in the unfiltered top-seven ranking in Figure 2. Values have not been standardised by the total number of fishing sets of each type.

3.4 Catch Composition by Retention and Discard Proportions

Figure 5 below shows the proportional composition of retained and discarded catches for the dominant bycatch species.

Retention and discard proportions varied by taxon. In the full observer dataset (2014–2024, all recorded set types), the retained biomass share was approximately 27.1% for rainbow runner and 23.7% for mackerel scad. All recorded whale shark, Bryde's whale, false killer whale and sei whale biomass was classified as discarded. Silky shark biomass was almost entirely recorded as discarded; nevertheless, a small retained component (14.931 mt, or 0.24% of the species total) was present. These are recorded mass fractions, not estimates of post-release survival or explanations of why a specimen was retained or discarded.

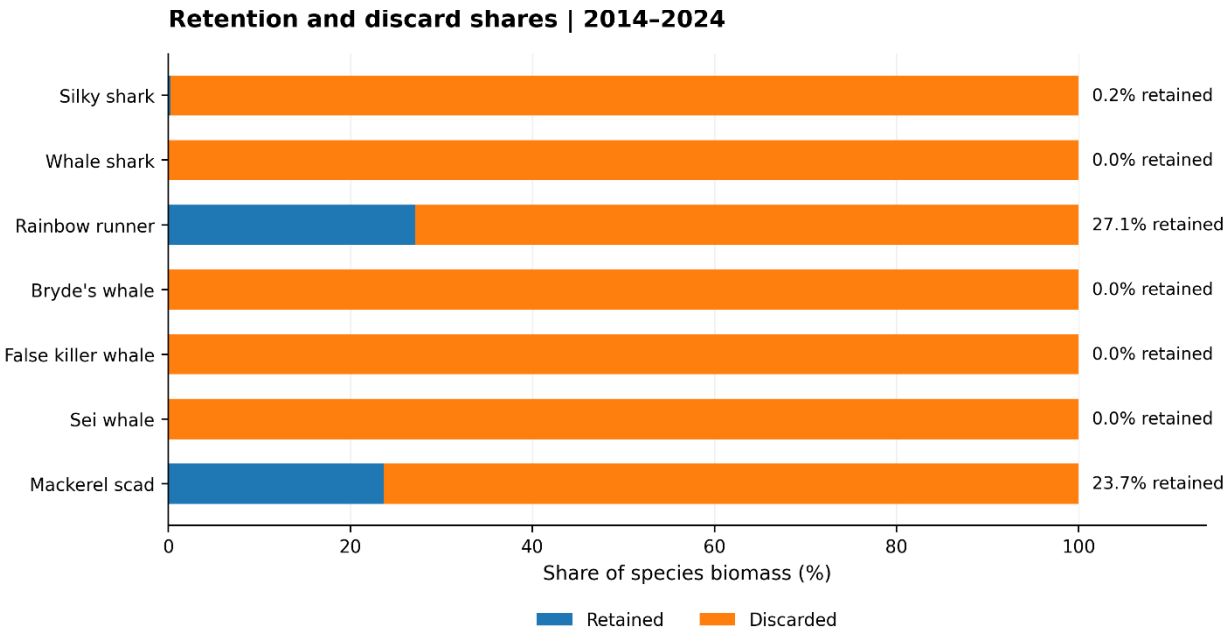


Figure 5: Percentage of recorded species-specific bycatch biomass classified as retained or discarded for the seven overall dominant species, 2014–2024. For each species, retained share was calculated as 100 × ΣRet_MT_est/[ΣRet_MT_est + ΣDisc_MT], with discarded share as the remainder. All recorded fishing set categories were included. The recorded silky shark retention fraction was small but nonzero (0.24%). These catch-fate proportions do not measure post-release survival.

3.5 Non-Parametric Analysis

The Kruskal -Wallis test evaluates whether the distribution of total bycatch differs among groups. It is appropriate here because bycatch biomass is strongly skewed (as seen earlier), includes many small values, and contains occasional very large bycatch events.

Table 2 shows Total bycatch biomass differed significantly across Years, Fishing set types and Dominant bycatch species with P-values of 4.19×10^{-212}, <0.001 and < 0.001 respectively. All three Kruskal–Wallis tests returned $p < .05$, indicating differences in the observed biomass distributions among levels of the respective grouping variables. These comparisons do not establish causation or independence among records. The tests identify statistically detectable distributional differences

among the specified groups in the analysed records. They do not establish independence among species-level records or the ecological and operational mechanisms responsible for those differences.

Table 2: Results showing Kruskal – Wallis analysis of explanatory variables on bycatch biomass as the response variable.

Explanatory variable	Chi-square	df	p-value	Interpretation
Year	1,016.941	10	4.19 x10 $^{-212}$	Significant temporal differences
Set type	2,825.960	1	< 0.001	Significant operational differences
Species composition	5,417.651	6	< 0.001	Significant species-level differences

3.5.1 Bycatch versus Year

It was seen that there was a statistically significant difference in total bycatch biomass among years (Table 2).

Table 3: Summary statistics for recorded biomass (mt) per species-level observation by year in the two-set-type, seven-species subset (2014–2024). Note. n = species-level observations; Q1 and Q3 = first and third quartiles.

Year	n	Total (mt)	Median (mt)	Mean (mt)	q1 (mt)	q3 (mt)	Max (mt)
2014	4,308	769.301	0.050	0.178574977	0.020	0.100	26
2015	3,609	604.342	0.050	0.167454142	0.020	0.140	15
2016	7,613	1,713.551	0.060	0.225082228	0.028	0.150	40
2017	8,927	1,918.099	0.050	0.214864904	0.020	0.120	60
2018	7,982	1,735.734	0.050	0.217456026	0.020	0.120	156
2019	7,460	2276.49	0.070	0.305159517	0.025	0.200	70
2020	2,600	536.658	0.050	0.206406923	0.020	0.100	20
2021	1,566	287.928	0.040	0.183862069	0.010	0.100	20
2022	1,647	289.414	0.033	0.175721919	0.010	0.080	20
2023	2,449	721.633	0.030	0.294664353	0.010	0.080	100
2024	1,467	260.503	0.050	0.177575324	0.020	0.100	15

Because the Kruskal-Wallis test for explanatory variable 'Year' was significant, pairwise Wilcoxon rank-sum comparisons with Holm adjustment for multiple testing were performed. It was seen that 42 out of 55 year to year comparisons were significant. Years with relatively high median bycatch included 2019 and 2016. Years with relatively low median bycatch included 2023, 2022, and 2021. Some years were not significantly different from each other, especially years with the same or very similar medians, such as 2014 versus 2020, 2015 versus 2017, 2017 versus 2018, and 2021 versus 2022 (Table 3).

3.5.2 Bycatch versus Set Type

It was seen that there was a highly significant difference in total bycatch biomass between Drifting FAD and Free-school sets (Table 2). Free-School sets had higher median total bycatch biomass than Drifting FAD sets among the top dominant bycatch species. Table 4 shows Free-School median to be 0.080 mt while Drifting FAD median was 0.040 mt. The pairwise comparison between drifting-FAD and free-school observations was statistically significant after Holm adjustment (Table 5; adjusted $p < .001$).

Table 4: Results showing median Bycatch by Set Type.

Set Type	n	Total (mt)	Median (mt)	Mean (mt)	q1 (mt)	q3 (mt)	Max (mt)
Free-School	23,277	7,567.665	0.080	0.325	0.030	0.2	156
Drifting FAD	26,351	3,545.988	0.040	0.135	0.015	0.1	75

Table 5: Results showing Post-hoc Pairwise comparison.

Comparison	Median 1	Median 2	Holm-adjusted p-value	Significant
Drifting FAD vs Free-School	0.040	0.080	<0.001	Yes

3.5.3 Bycatch versus Species Composition

Kruskal-Wallis results revealed a highly significant difference in total bycatch biomass among the dominant species (Table 2). The analysis further indicated that the most pronounced contrasts occurred between large-bodied species and smaller schooling pelagic species. In particular, the species exhibiting the highest median bycatch biomass per observation were identified as follows (Table 6):

1. Bryde's whale – median 2.000 mt
2. False killer whale – median 0.668 mt

3. Whale shark – median 0.617 mt

Species with lower median bycatch per observation included:

- Blue marlin – 0.080 mt
- Silky shark – 0.060 mt
- Rainbow runner – 0.040 mt
- Mackerel scad – 0.020 mt

Table 6: Results showing median Bycatch by Species.

Species	n	Total (mt)	Median (mt)	Mean (mt)	q1 (mt)	q3 (mt)	Max (mt)
Bryde's Whale	79	605.964	2.000	7.670	0.410	10.000	156.000
False Killer Whale	390	781.404	0.668	2.004	0.216	2.000	75.000
Whale Shark	693	1,941.937	0.617	2.802	0.200	3.000	100.000
Blue Marlin	4,571	511.940	0.080	0.112	0.050	0.120	3.100
Silky Shark	25,184	4,914.742	0.060	0.195	0.026	0.150	24.000
Rainbow Runner	11,937	1,739.504	0.040	0.146	0.020	0.100	40.000
Mackerel Scad	6,774	618.162	0.020	0.091	0.010	0.050	26.000

3.5.4 Visualizing the patterns

Figure 6 shows boxplots summarizing distributional variation among year, set-type and species groups. The upper panel shows the distribution of total bycatch biomass by year from 2014 to 2024. Generally, it was seen that bycatch biomass displayed considerable interannual variability, although median values remained relatively consistent throughout the study period. However, some years particularly 2019, exhibited higher upper ranges and greater variability in bycatch biomass compared to other years. The broader spread observed in certain years indicates that bycatch events were more variable and potentially more intense during those periods. As a result, ‘Year’ appears to function as an important temporal driver of variability in bycatch. Furthermore, the year panel shows a gradual decline in typical bycatch over recent years.

The middle panel compares bycatch biomass between the two fishing set types: Drifting Fish Aggregating Devices (dFADs) and free-school sets. According to Figure 6, clear differences are evident between the two operational fishing modes. Free-School sets generally displayed higher median bycatch biomass and a wider upper range compared to Drifting FAD sets. In contrast, Drifting

FAD-associated fishing operations appeared to produce comparatively lower median bycatch biomass. Furthermore, the set-type panel makes free-school versus Drifting FAD gap visible.

The lower panel shows bycatch biomass across the most dominant bycatch species. Significant differences in biomass distribution were observed among species, indicating strong species-specific variability in occurrence of bycatch. Bryde's whale (BRW), false killer whale (FAW), and whale shark (RHN) displayed the highest biomass distributions and upper ranges among the recorded species. On the other hand, rainbow runner (RRU), mackerel scad (MSD), silky shark (FAL), and blue marlin (BUM) generally displayed lower median biomass values, although variability remained evident within each species group. Furthermore, the species panel highlights the order of magnitude separation between megafauna and smaller pelagic species.

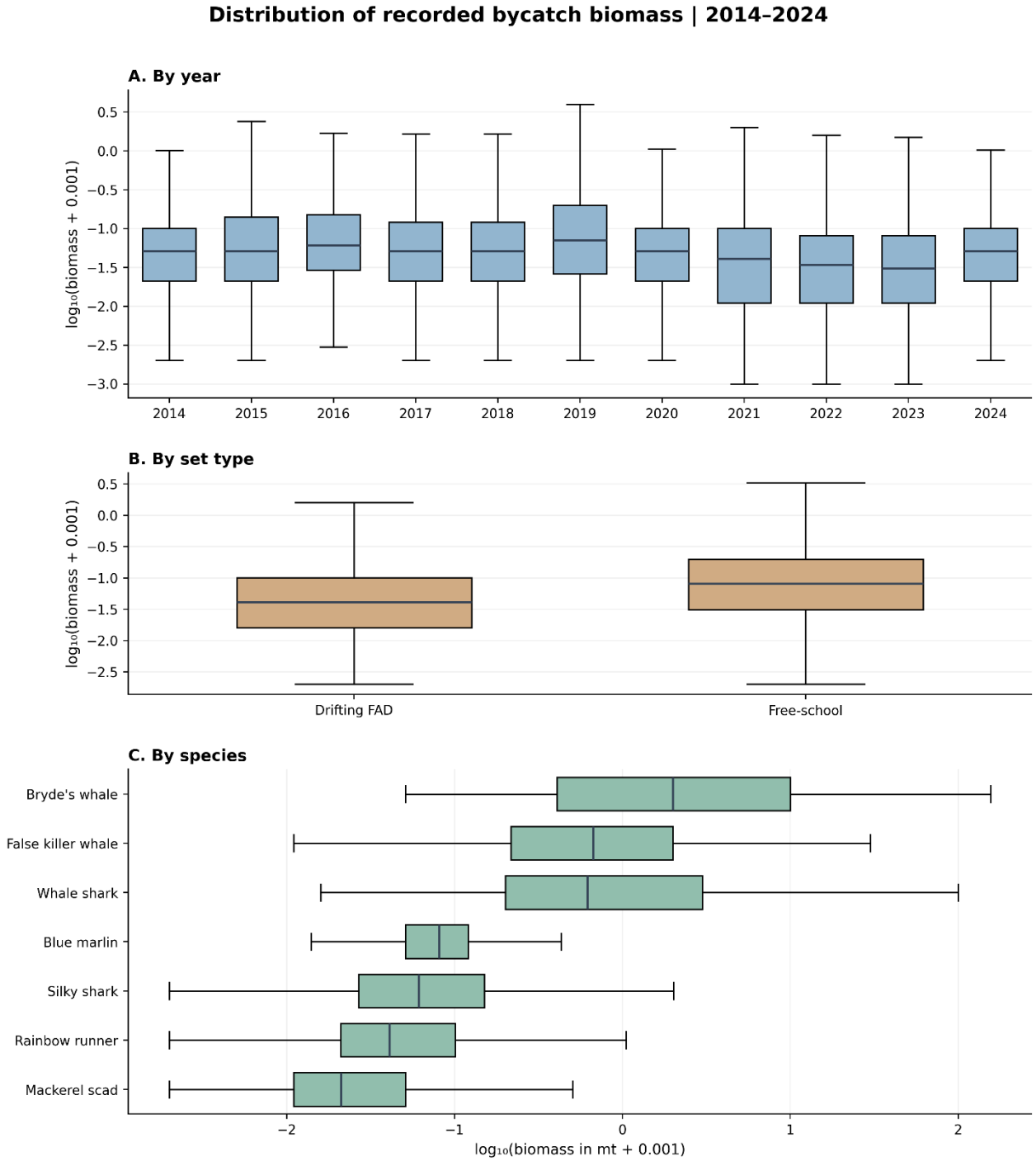


Figure 6: Distributions of log-transformed observation-level recorded total bycatch biomass by (A) year, (B) purse-seine set category, and (C) species in the two-mode seven-species analysis subset, 2014–2024 (n = 49,628 species-level records). Biomass (mt) was transformed using $\log_{10}$(total biomass + 0.001). Boxes represent the interquartile range (25th–75th percentiles), horizontal lines denote medians, and whiskers extend to the most extreme observations within 1.5 times the interquartile range. Outlier markers are suppressed to preserve legibility. Species-level records are not necessarily independent purse-seine sets.

4. Discussion

At a global scale, fisheries bycatch is widely recognized as a significant source of mortality for marine mammals, cetaceans, teleost fishes, and other marine fauna (Berkenbusch et al., 2013; Elliot et al., 2023; Roberson & Wilcox, 2025). Consequently, the systematic monitoring and effective management of bycatch have become integral to strengthening fisheries governance, as well as to promoting ecological integrity and socio-economic sustainability within marine resource systems (Gilman. et al., 2017; Hall. et al., 2017). Therefore, from the perspective of a developing country, critical questions surrounding fisheries bycatch secure careful consideration: To what extent do we understand the nature and scale of bycatch within our fisheries? Do we possess adequate knowledge of the species diversity and composition associated with bycatch? Furthermore, are sufficient data available to effectively inform fisheries management and conservation decisions? These questions highlight the existence of a significant knowledge gap and emphasize the urgent need to improve research, monitoring, and information collection on bycatch dynamics.

To address this gap, the present study provides an assessment of bycatch dynamics within Papua New Guinea's (PNG) purse seine tuna fishery, with particular focus on species composition, temporal variability, operational influences, and the potential for bycatch utilisation.

4.1 Species Composition and Dominance Patterns of Bycatch Species

The results showed (Figure 2) that the bycatch composition within Papua New Guinea's (PNG) purse seine tuna fishery was highly uneven and dominated by a relatively small quantity of species. Among the dominant taxa recorded, silky shark contributed the highest biomass (>6,000 metric tonnes), followed by whale shark (>4,000 metric tonnes), rainbow runner (>3,000 metric tonnes), Bryde's whale (~2,000 metric tonnes), false killer whale (~1,800 metric tonnes), sei whale (>1,400 metric tonnes), and mackerel scad (>1000 metric tonnes). This demonstrates a markedly skewed bycatch structure in which only a few species account for most of the total bycatch biomass within the purse seine fishery (Figure 2). According to Amande et al., (2010) and Hall & Roman, (2013) such patterns are frequently observed in tropical tuna purse seine fisheries, where certain pelagic species display strong ecological associations with tuna schools and fishing operations.

The dominance of silky shark within the bycatch assemblage is particularly significant and consistent with findings reported across global tuna fisheries (Amandè et al., 2008). Silky sharks are widely regarded as one of the most vulnerable and commonly captured shark species in tropical tuna purse fisheries due to their strong behavioural association with Drifting Fish Aggregating Devices (dFADs) and pelagic tuna schools (Amandè et al., 2008; Clarke et al., 2013; Filmalter et al., 2013). Their high representation in the present study suggests that purse seine fishing operations within PNG waters overlap substantially with habitats occupied by this species. This finding is ecologically important because silky sharks are characterised by relatively slow growth, low productive output, and late

maturity, making them highly susceptible to fishing mortality (Bonfil, 2008). Consequently, persistent high bycatch levels may have important implications for regional shark population sustainability.

Furthermore, the observed dominance of silky shark may also reflect operational characteristics of the fishery itself. Previous studies have shown that shark interactions are often elevated in fisheries utilising Drifting FADs because these floating structures aggregate a wide range of pelagic organisms, including elasmobranchs (Dagorn et al., 2013). Although the present study observed stronger associations of silky shark biomass with free-school sets compared to Drifting FAD sets, the species remained consistently across both fishing modes. This suggests a broad distribution of silky sharks within the fishery and reflects the species' ecological adaptability and widespread occurrence throughout tropical pelagic ecosystems (Talwar et al., 2025).

A recent study by Talwar et al., (2025) examining the spatial management of Silky Shark in the Eastern Pacific Ocean, using genetic, movement, life history, and fisheries-dependent data collected across much of the species' Pacific range found that silky sharks utilise both shelf-edge and offshore habitats as pupping and nursery grounds. The study further identified a female-biased sex ratio within oceanic and equatorial regions, which overlapped with areas experiencing high levels of silky shark bycatch in large-scale fisheries.

The second most dominant species observed in the present study was the Whale shark (*Rhincodon typus*) (Figure 2) noting its substantial contribution. Although whale shark interactions are relatively infrequent compared to smaller pelagic species, their exceptionally large body size results in disproportionately high biomass contributions when captures occur (Capietto et al., 2014). The presence of whale sharks among the dominant bycatch species therefore reflects the ecological overlap between tuna purse seine operations and productive pelagic habitats utilised by these large filter – feeding megafauna (Escalle et al., 2019; Martin & Shahid, 2021). Whale sharks are known to associate with tuna schools and productive oceanographic features such as frontal systems and areas of high plankton abundance, which may explain their occurrence within purse seine fishing grounds (Sequeira. et al., 2014).

From a management perspective, the presence of Whale Shark within the dominant bycatch assemblage is of considerable significance, given that the species is internationally protected and currently classified as Endangered on the International Union for Conservation of Nature Red List (Pierce & Norman, 2016). The species is also protected under various regional and international conservation management measures, including provisions implemented by the Western Central Pacific Fisheries Commission (WCPFC) (WCPFC, 2018). For example, section twenty-five (25) of the Conservation Management Measure 2025-06 (CMM 2025-06), emphasizes that Commission Cooperating Members (CCMs) shall prohibit their flagged vessels from setting a purse seine on a school of tuna associated with a whale shark if the animal is sighted prior to the commencement of the set (WCPFC, 2025). Given the large size of the whale Shark, its emergence as the second most

dominant species within the bycatch composition is particularly noteworthy, especially considering ongoing advancements in fishing technology and mitigation measures. This raises important questions regarding why whale sharks continue to be incidentally captured during purse seine operations. As whale shark biomass contributed substantially to the overall bycatch profile, its occurrence primarily highlights significant conservation and mitigation concerns. These findings further emphasize the importance of strengthening safe handling and release procedures, while also improving avoidance strategies within purse seine fisheries.

The third most dominant bycatch species observed was the Rainbow runner (*Elagatis bipinnulata*). Rainbow runners are known fast-swimming pelagic teleost that are commonly associated with Drifting FAD fishing operations (Forget et al., 2020), a pattern also observed in the present study. The high biomass contribution of rainbow runner identified in this study reflects an ecological pattern distinct from that of the megafauna species recorded. This observation is consistent with previous research showing that small pelagic fishes commonly aggregate around floating structures, attracted by increased feeding opportunities, shelter, and schooling behaviour (Castro et al., 2002). Furthermore, in a study investigating the associative behaviour of oceanic Rainbow runner and triggerfish around floating objects, Forget et al., (2020), used acoustic transmitters to examine species movement patterns. The study found that rainbow runners remained associated with floating objects for prolonged periods, with a mean residence time of approximately 94 days. Additionally, it was also seen that during the daytime hours, individuals expanded their home range and typically undertook short excursions away from the floating object, usually lasting less than two hours. Therefore, the strong association between rainbow runner and Drifting FAD sets reflects the ecological influence of artificial aggregation devices on pelagic community structure within tuna fisheries.

The presence of large cetaceans, including Bryde's whale (Balaenoptera edeni), False killer whale (Pseudorca crassidens) and sei whale (Balaenoptera borealis), within the dominant bycatch assemblage is of considerable ecological significance. Interactions between cetaceans and purse seine fisheries are commonly linked to spatial overlap between fishing activities and highly productive pelagic ecosystems where marine mammals aggregate for fer feeding (Romanov, 2002). Thus indicating, that purse seine operations in PNG waters may occur within habitats that support a broad diversity of higher trophic - level predators.

Moreover, the results also displayed (Table 1) that Bryde's whale exhibited notably high biomass contributions among the cetacean species recorded in this study. This pattern may be associated with the species' preference for productive tropical and subtropical waters where prey availability and feeding opportunities are abundant (Constantine et al., 2018). Similarly, False killer whales are highly mobile apex predators that are known to interact with tuna fisheries through feeding associations with target tuna schools (Baird, 2009). Sei whales, although less frequently encountered, are also associated with offshore productive waters and may occasionally overlap

spatially with industrial tuna fishing activities (Prieto et al., 2012). The presence of these marine mammals within the bycatch records raises important conservation concerns. Marine mammals as discussed earlier are generally characterised by slow reproductive rates and long life spans, traits that increase their vulnerability to anthropogenic sources of mortality (Read, 2008). Therefore, their occurrence within the fishery highlights the importance of effective mitigation measures, observer monitoring, and safe-release protocols.

Furthermore, the skewed distribution (Figure 2) of bycatch biomass observed in this study is consistent with patterns reported in other purse seine fisheries globally, where a limited number of species dominate total bycatch composition (Amandè. et al., 2010). Such skewness may arise from behavioural, ecological and operational factors influencing species susceptibility to capture (Roberson & Wilcox, 2025). Species that exhibit schooling behaviour, strong associations with floating objects, or spatial overlap with tuna schools are generally more vulnerable to purse seine interactions (Dagorn et al., 2013). Consequently, the dominance patterns observed in PNG's fishery likely reflect both ecological characteristics of pelagic species and fishing practices within the region.

What do these findings imply from a fisheries management perspective? They underscore the importance of understanding species composition and dominance patterns in supporting the development of effective ecosystem-based fisheries management approaches. Identifying dominant bycatch species enables fisheries managers to better prioritise mitigation measures and conservation strategies for species that are particularly vulnerable to fishing interactions. For example, the dominance of Silky shark indicates that shark mitigation measures should remain a key management priority within Papua new Guinea's purse seine fishery especially when there are current discussions on re-opening the shark fishery which was shelved more than a decade ago. In the same way, the occurrence of protected megafauna including Whale shark and cetacean species, highlights the ongoing need for safety release protocols and strengthened observer-based monitoring systems for the offshore tuna fishery.

4.2 Temporal Variability in Dominant Patterns of Bycatch Species

The temporal trends identified in this study (Figure 3) revealed considerable interannual variability in the biomass of dominant bycatch species recorded within Papua New Guinea's purse seine tuna fishery between 2014 and 2024.

Results indicated that several species experienced pronounced increases during the late 2010s, particularly between 2018-2019, before exhibiting declining or stabilising trends in subsequent years. These findings suggest that bycatch dynamics within Papua New Guinea's offshore tuna fishery are highly variable rather than constant, fluctuating over time in response, to interactions among environmental variability, species ecology, fishing effort, and operational fishing practices as highlighted by Komoroske & Lewis (2015). The authors further emphasized that, fisheries bycatch

should be examined within the context of a changing ocean and evolving socio-cultural environment, where species, ecosystem, and human communities are simultaneously responding to multiple stressors and dynamic conditions. Consequently, the development of adaptive and responsive management strategies capable of addressing the changing ecological, social, cultural, and economic dimensions of the global bycatch landscape remains critically important.

Additionally, understanding these temporal trends is essential, as long as long-term shifts in bycatch patterns can offer valuable insights into ecosystem dynamics, species vulnerability, and the broader ecological impacts associated with industrial tuna fisheries (Hall & Roman, 2013).

Among the dominant species, silky shark displayed the highest increase in bycatch biomass between 2015 and 2019, before declining markedly in the years that followed. This pattern is ecologically significant, silky sharks are commonly recognised as one of the most frequently captured shark species in tropical tuna purse seine fisheries globally (Clarke et al., 2013). Similar increases in silky shark interactions have been documented across the Atlantic, Indian, and Pacific Oceans, particularly within fisheries associated with Drifting Fish Aggregating Devices (dFADs) (Amandè. et al., 2010; Filmalter et al., 2013). The increase in catch observed within PNG waters during the late 2010s may therefore reflect intensified interactions between purse seine fishing activities and pelagic shark habitats throughout that period. The subsequent decline in silky shark biomass after 2019 may be attributed to several factors. One possible explanation is the implementation of improved regional mitigation and management measures by the Western and Central Pacific Fisheries Commission, including enhanced shark handling requirements and increased awareness surrounding shark conservation, which may have contributed to reduced shark interactions and mortality over time (Haas et al., 2024).

However, according to Bonfil, (2008) declining bycatch trends could indicate broader population declines associated with cumulative fishing pressure, given the species' low reproductive capacity and high vulnerability to exploitation. Why is this concerning? The author, explained that silky shark is regarded as one of the most vulnerable pelagic shark species due to their slow growth and low reproductive capacity. Consequently, although declining bycatch levels may appear positive from a fisheries interaction perspective, they may also indicate reductions in population abundance within the broader ecosystem.

The temporal trend observed for whale shark followed a broadly similar pattern, characterised by a marked increase from 2016 to a peak in 2019, before declining in subsequent years. Whale sharks are highly migratory filter- feeding species whose distribution is strongly influenced by ocean productivity, plankton availability, and thermal conditions (Sequeira et al., 2014). Their increased occurrence during the late 2010s may therefore indicate favourable environmental conditions that promoted the aggregation of both tuna and whale sharks within PNG waters during this period.

Globally, interactions between Whale shark purse seine fisheries have been closely linked to tuna schools and highly productive pelagic habitats (Capietto et al., 2014). Purse seine sets conducted in proximity near whale sharks have historically occurred because tuna schools often aggregate beneath these large animals. Consequently, the elevated whale shark biomass observed around 2018 -2019 (Figure 3) may reflect increased spatial overlap between tuna fishing activities and ecologically productive zones within PNG's EEZ. However, as whale sharks are classified as Endangered under IUCN Red List and are protected under regional conservation frameworks, continued interactions remain a significant conservation concern (Pierce & Norman, 2016). Furthermore, the decline in whale shark bycatch after 2019 may therefore reflect improved awareness and avoidance measures by fishing fleets, although environmental changes affecting species distribution cannot be excluded.

The temporal variability observed for rainbow runner differed markedly from that of the large megafaunal species. Rainbow runner displayed an initial peak around 2016, followed by a decline and a slight resurgence towards 2024. This trend likely reflects the species' ecological association with floating objects such as Drifting FADs. As a schooling pelagic teleost, known to aggregate around floating structures feeding where opportunities and shelter are available (Castro et al., 2002). Consequently, temporal fluctuations in rainbow runner bycatch may be strongly influenced by changes in Drifting FAD deployment patterns, fishing effort, and oceanographic conditions (Dagorn et al., 2013; Pons et al., 2023).

The early peak observed in 2016 (Figure 3) may reflect periods of intensified Drifting FAD-associated fishing activity or enhanced aggregation behaviour among pelagic teleost species. Similar relationships between rainbow runner abundance and Drifting FAD fisheries have been reported in tropical tuna fisheries worldwide (Dagorn et al., 2013). Importantly, unlike many of the megafaunal species recorded in this study, rainbow runner exhibited a degree of retention within the fishery. This may indicate potential economic or subsistence importance and further suggests that temporal variations in rainbow runner biomass could influence opportunities for fisheries diversification and bycatch utilisation strategies within Papua New Guinea.

The temporal trend observed for Bryde's whale displayed a gradual increase leading up to a peak around 2019, followed by a subsequent decline in biomass. Bryde's whale are known to inhabit productive tropical and subtropical waters characterised by high prey availability and feeding opportunities (Best, 2001). Their increasing biomass during the late 2010s may therefore reflect enhanced prey productivity or increased spatial overlap between fishing activities and cetacean feeding grounds during that period.

Interactions Marine mammals and fisheries are increasingly recognised as indicators of ecological overlap between industrial fishing operations and marine predator habitats (Read, 2008). Therefore, the occurrence of Bryde's whales within the bycatch trends is ecologically significant, as it indicates

that tuna fisheries operate within broader pelagic ecosystems that support diverse megafaunal assemblages. The decline in Brydes whale biomass after 2019 may reflect shifts in species distribution, changes in prey availability, or variations in fishing effort allocation (Félix et al., 2025; Tremblay-Boyer & Berkenbusch, 2020) within the PNG waters.

Similarly, false killer whale showed fluctuating temporal trends, characterised by an initial decline, followed by a peak around 2017 and subsequent reductions in later years. False killer whales are highly mobile apex predators that commonly associate with tuna schools and offshore pelagic habitats. Their fluctuating biomass trends may have therefore reflect shifting prey distributions, changes in fishing locations, or broader ecosystem variability (Baird, 2009).

Globally, interactions between false killer whale and industrial fisheries have raised significant conservation concerns due to the species' high susceptibility to fisheries -related mortality and behavioural disturbance (Read, 2008). Although the biomass recorded in this study was lower than that of silky shark and whale shark, the repeated temporal fluctuations observed highlight the persistent overlap between tuna fishing activities and cetacean habitats within PNG waters. This suggests that mitigation and monitoring efforts should continue to prioritise marine mammal interactions within the fishery (Silva et al., 2002).

The trend observed for sei whale demonstrated relatively consistent increases between 2015 and 2020, followed by a decline in subsequent years and a slight resurgence in 2023. According to Konishi et al., (2024), Sei whales are highly migratory baleen whales whose distribution and movements are strongly influenced by prey availability and oceanographic conditions. As a result, the temporal variability may reflect broader environmental fluctuations occurring within the Western Central Pacific Ocean region.

Furthermore, results showed mackerel scad exhibited an early peak around 2016 followed by declining biomass, although slight increases were observed again between 2023 and 2024. Mackerel scad is a small pelagic schooling species commonly associated with floating structures and productive pelagic environments (Xu et al., 2023). Similar to, rainbow runner, its temporal fluctuations may reflect variations in Drifting FAD-associated fishing activity and environmental conditions influencing pelagic fish distributions (Dagorn et al., 2013).

According to (Hazen et al., 2018), the decline observed after 2016 (Figure 3) may have occurred due to changes in species aggregation behaviour, shifts in fishing operations, or variability in regional oceanographic conditions. Ultimately, the temporal variability identified in this study underscores the importance of adopting adaptive fisheries management approaches that can respond to changing ecosystem conditions and evolving species interactions over time (Hall. et al., 2017). Therefore, as previously highlighted, an improved understanding of interannual fluctuations among dominant bycatch species can enhance Papua New Guinea's capacity to strengthen conservation outcomes,

support ecosystem-based fisheries management, and promote sustainable governance within the offshore tuna sector.

4.3 Comparative Analysis of Bycatch Composition Between Drifting FAD and Free-School sets

This section presents the results of the comparative analysis between Drifting Fish Aggregating Device (dFAD) sets and free-school sets.

Figure 4 demonstrated distinct differences in species composition and biomass contribution among dominant bycatch species within Papua New Guinea's (PNG) purse seine tuna fishery. Generally, the results showed that free-school sets accounted for the majority of bycatch biomass among several large pelagic and megafaunal species, whereas certain teleost species, particularly rainbow runner and mackerel scad, demonstrated strong associations with Drifting FAD-associated fishing operations. According to (Dagorn et al., 2013), these results show that fishing mode plays a significant role in shaping bycatch composition and further highlight the ecological influence of Drifting FADs on pelagic community structure within tropical tuna fisheries.

The most prominent pattern observed was the substantial dominance of silky shark biomass within free-school sets, which exceeded 4,100 metric tonnes compared to approximately 750 metric tonnes recorded in Drifting FAD-associated sets. This finding contrasts with many global studies, given the species' well documented behavioural attraction to floating objects (Dagorn et al., 2013; Filmalter et al., 2013). This is further supported by (Clarke et al., 2013), highlighting silky sharks are frequently identified as one of the dominant shark species associated with Drifting FAD sets because these structures aggregate tuna, forage species, and predators within the pelagic environment.

However, the predominance of silky shark biomass within free-school sets observed in this study suggests that silky shark interactions within PNG waters may not be exclusively driven by Drifting FAD-associated aggregation behaviour. Instead, these findings may exhibit substantial ecological overlap between free-school tuna aggregations and habitats occupied by silky shark. Free-school tuna sets are typically associated with naturally occurring schools of tuna rather than artificial floating structures, and these schools are commonly found in productive oceanographic regions such as thermal fronts, convergence zones, and upwelling systems, where pelagic predator species are also known to concentrate (Hall & Roman, 2013). Therefore, the high silky shark biomass observed in free- school sets may reflect the broader ecological productivity of PNG's offshore pelagic ecosystem.

Similarly, whale shark biomass was considerably higher in free-school sets (~1,800 metric tonnes) compared to Drifting FAD sets (<200 metric tonnes). This finding is particularly significant as whale sharks are globally recognised for their frequent association with tuna schools targeted by purse

seine fishing vessels (Capietto et al., 2014). Historically in order to locate schools of tuna, purse seine operators use whale sharks as guides because tuna schools are known to commonly aggregate beneath these large filter-feeding megafauna (Hall & Roman, 2013). Therefore, the strong free-schooling association observed in PNG waters likely reflects tuna fishing practices occurring around naturally aggregated tuna schools associated with whale sharks rather than Drifting FAD structures (Ketchum et al., 2013).

Furthermore, their elevated biomass contribution within free-school sets depicts continued overlap between industrial tuna fisheries and whale shark habitats within the fishing waters in PNG. However, this raises concerns especially with accidental entanglement, injury, and stress during purse seine fishing activities. Thus, despite whale shark interactions are relatively uncommon in terms of occurrence, their exceptionally large body size results in significant biomass contributions when captured or encircled (Capietto et al., 2014). As a result, the findings underscore the need for continued implementation of whale shark release protocols and mitigation measures within PNG's purse seine fishery.

Rainbow runner on the other hand, displayed a strong association with Drifting FAD sets, with almost all recorded (~1,600 metric tonnes) originating from Drifting FAD fishing operations in contrast to the large pelagic megafauna. This findings are closely associated with global studies exhibiting that rainbow runner and other small pelagic teleosts demonstrate strong behavioural attraction to floating objects (Castro et al., 2002). Moreover, Dargorn et al., (2013), further explained, that drifting Drifting FADs create artificial habitats that attract forage species and small schooling fishes seeking shelter, feeding opportunities and social aggregation. The authors further note that the ecological role of Drifting FADs as fish aggregating structures altering pelagic species distributions is reflected by the strong Drifting FAD association observed for rainbow runner. According to Amande et al., (2010) similar results have been documented in tuna fisheries across the Atlantic, Indian, and Pacific Oceans, where Drifting FAD-associated catches are often characterised by higher abundances of non-target pelagic fishes compared to free-school sets. The ecological consequence of this aggregation effect is that Drifting FAD fisheries may increase interactions with certain species that would otherwise occur less frequently within open-ocean environments (Hampton et al., 2017).

A similar pattern was observed for mackerel scad, which was predominantly captured in Drifting FAD sets (~600 metric tonnes) with minimal contribution from free-school sets. As a small pelagic schooling species commonly associated with floating structures, this result further supports the broader understanding that Drifting FADs significantly influence pelagic species assemblages by attracting forage fishes and associated predators (Dagorn et al., 2013).

Furthermore, according to (Davies et al., 2014), the aggregation of species such as rainbow runner and mackerel scad around Drifting FAD carries important ecological implications as these species constitute part of the broader pelagic food web that supports larger predators, including tuna, sharks,

and marine mammals. Consequently, extensive Drifting FAD deployment may modify natural species distribution patterns and ecological interactions within offshore ecosystems (Maufroy et al., 2017). Such ecological alterations have become an increasing global concern as the use of Drifting FADs continues to expand across tropical tuna fisheries, raising questions regarding their long-term impacts on pelagic biodiversity, ecosystem functioning, and fisheries sustainability (Dagorn et al., 2013; Maufroy et al., 2017).

In contrast, Bryde's whale was observed exclusively in free-school sets, with no recorded biomass observed in Drifting FAD operations. According to IWC, (2026), this pattern indicates that interactions involving Bryde's whales are more closely linked to naturally occurring tuna aggregations and biologically productive pelagic environments rather than artificial aggregation devices. Because, Bryde's whales are known to inhibit warm productive waters where prey densities are elevated (IWC, 2026), their exclusive occurrence within free-school sets likely reflects the spatial overlap between natural tuna schools and cetacean feeding grounds.

Similarly, blue marlin displayed significant higher biomass in free-school sets (~400 metric tonnes). Blue marlin are large apex predators associated with open-ocean pelagic ecosystems and highly mobile tuna schools (Rooker et al., 2019). According to (Hall & Roman, 2013), past studies have reported that billfish species are more frequently encountered in free-school tuna fisheries because these operations target naturally occurring tuna aggregations within productive offshore environments. Therefore, the higher blue marlin biomass observed in free-school sets is consistent with broader ecological patterns reported globally.

Interestingly, false killer whale demonstrated relatively similar biomass contributions between Drifting FAD and free-school sets suggesting that this species interacts broadly across both fishing modes rather than exhibiting strong association with either operational type (Clavareau et al., 2020). Additionally, according to Baird (2009), False killer whales are highly mobile apex predators that regularly interact with tuna schools and pelagic fisheries. Their relatively even distribution across set types may therefore reflect their wide-ranging movement behaviour and broad ecological overlap with tuna fishing operations.

The findings of this study are particularly significant as they demonstrate substantial differences in bycatch composition between Drifting FAD-associated and free-school fishing operations. These variations provide valuable insights into the ecological processes influencing species interactions within tropical tuna fisheries (Davies et al., 2014). More importantly, the results indicate that different fishing modes may expose specific species groups to varying levels of bycatch risks.

Ultimately, an important consideration regarding the fishing methods employed within Papua New Guinea's tuna fishery relates to the country's ongoing implementation of Marine Stewardship Council certification (MSC) standards for its fishery products. What are the implications of this? According to a study by Ponte, (2008), the Food and Agriculture Organization (FAO) and various conservation

organizations have, over recent decades, consistently highlighted global concerns surrounding the overexploitation of fish stocks and the broader ecological impacts of intensive fishing activities on aquatic environments.

To address these challenges Ponte, (2008), outlined that several fisheries management responses have been developed internationally. These include: 1) legal instruments, such as global agreements and national or local fisheries legislation, 2) voluntary or 'soft' instruments, including the FAO Code of Conduct for Responsible Fisheries; and 3) market - civil society- driven initiatives particularly ecolabelling schemes such as Marine Stewardship Council certification. What, then, is the role of MSC certification? Ponte, (2008) explained that ecolabels function as seals of approval that transmit environmental information to consumers. These certifications assess the environmental impact of a product throughout its production and supply chain and are awarded to products considered to have reduced environmental impacts. In essence, MSC certification signifies that a fishery is operating in accordance with recognised standards of environmental sustainability and responsible fisheries management.

Furthermore, Ponte, (2008) outlined that, beyond their environmental significance, ecolabelling schemes also provide important economic advantages. Increased competitiveness within retail markets, improved market access, enhanced consumer confidence, and greater profitability are among the key benefits associated with ecolabelled fisheries products. Consequently, achieving MSC certification may strengthen both the economic value and market credibility of Papua New Guinea's tuna fishery products. This may explain why the results showed higher biomass contributions from free-school sets compared to Drifting FAD-associated sets.

4.4 Retention and Discard Patterns in Bycatch Composition

According to Figure 5, the retention and discard analysis revealed clear species - specific differences in the treatment dominant bycatch species within Papua New Guinea's purse seine tuna fishery. The results demonstrated that majority of dominant bycatch species were entirely discarded, whereas only two species, rainbow runner (*Elagatis bipinnulata*) and mackerel scad (*Decapterus macarellus*), exhibited measurable levels of retention. Specifically, silky shark (*Carcharhinus falciformis*), whale shark (Rhincodon typus), Bryde's whale (*Balaenoptera edeni*), false killer whale (*Pseudorca crassidens*), and sei whale (*Balaenoptera borealis*) were recorded as fully discarded, with no observed retention throughout the study period. In contrast, rainbow runner demonstrated approximately 29% retention, while mackerel scad exhibited approximately 22% retention, with the remaining proportion discarded. These findings suggests that bycatch utilisation within the fishery is highly selective and largely confined to teleost species possessing potential food, bait or commercial value.

The complete discard of silky shark, whale shark, and cetacean species is both ecologically and legally significant. These species are generally unsuitable for economic utilisation due to their protected status, ecological vulnerability, and high conservation concern. For example, Whale sharks and cetaceans, are characterised by long life spans, slow growth, and low reproductive rates, meaning that even relatively low levels of fisheries interaction may result in significant population-level impacts over time (Capietto et al., 2014; Read, 2008). Furthermore, their complete discard status therefore likely reflects existing regulatory requirements, conservation obligations, and the absence of legal commercial markets for these species (Kelleher, 2005). According to Cook et al., (2019), discarding does not necessarily imply minimal ecological impact. The authors further emphasize that if individuals are injured or deceased prior to release, discarding still constitutes fisheries-related mortality. This is ecologically important because the primary concern extends beyond whether a species is retained or discarded, to whether the organism ultimately survives the fishing interaction (Cook et al., 2019).

Furthermore, the retention of rainbow runner and mackerel scad presents a different interpretation. According to (Pilling et al., 2013), these species are pelagic teleosts and are generally considered more suitable for utilisation than sharks, whale sharks and marine mammals. Pilling et al., (2013), further noted that the partial retention of rainbow runner and mackerel scad suggests that they already have some level of economic or subsistence value within the fishery, potentially for crew consumption, local markets, bait, or small-scale processing. This finding is important because it demonstrates that bycatch species are not managed uniformly within the fishery. Certain species are discarded due to conservation concerns, regulatory protections, or limited suitability for utilisation, whereas others are retained because of their edibility and potential economic value.

Similar studies on tropical tuna purse seine fisheries have reported that non-target catches frequently include small pelagic fishes that may be utilised for local consumption or secondary markets. However, the extent of utilisation often depends on factors such as handling practices, storage capacity, market accessibility, and vessel conditions (Amandè. et al., 2010; Hall & Roman, 2013).

The relatively low retention rates observed for rainbow runner and mackerel scad further suggest that the utilisation of these species remains underdeveloped within the fishery. Although retention levels for these species were higher compared to other dominant bycatch species, the majority of the catch was still discarded. This may indicate missed opportunities for value addition, particularly where the fish are of suitable quality for human consumption or secondary processing. Rainbow runner is a food fish in many tropical regions, while mackerel scad is widely consumed in Pacific Island countries and other coastal communities (Andrew et al., 2025; Bell et al., 2019; Charlton et al., 2016; Pilling et al., 2015).

In a study by (Tacon & Metian, 2015), the authors highlighted that the potential utilisation pathways for retained bycatch species must warrant careful consideration. Tacon & Metian, (2015) outlined

that first, rainbow runner and mackerel scad could be further promoted for direct human consumption through local fresh fish markets, as well as through processed products as smoked fish, dried fish, canned products, or frozen packs. Such processing approaches may extend product shelf life and improve distribution to inland and urban markets. Second, lower-quality fish that is unsuitable for direct consumption could be processed into fishmeal or fish oil for livestock, poultry, or aquaculture feed. This would support a more circular fisheries economy by reducing waste and converting unused biomass into productive inputs. Third, where infrastructure and technical capacity allow, fish by-products could be used for value-added products such as fish silage, fertiliser, pet food, or nutraceutical products. However, these options must be carefully assessed to ensure they are economically viable and do not create incentives to increase bycatch (Tacon & Metian, 2015).

4.5 Drivers of Bycatch Variability in PNG's Purse Seine Fishery

In this section, the non-parametric Kruskal-Wallis analysis was performed to assess what drives Bycatch in the fishery. The analysis showed that total bycatch biomass differed significantly across all explanatory variables examined which were, 'Year' (χ^2 = 1016.941, df = 10, p = 4.19 x 10^{-212}), 'Type of fishing set' (χ^2 = 2825.960, df = 1, p < 0.001), and species composition (χ^2 = 5417.651, df = 6, p < .001) (Table 2). These results highlight that bycatch variability within Papua New Guinea's purse seine tuna fishery is not random but is structured by a combination of temporal, operational, and ecological processes (Pikitch et al., 2004). The significance of all three explanatory variables highlights the complexity of bycatch dynamics and reinforces the importance of adopting ecosystem-based approaches to fisheries management.

4.5.1 Temporal Drivers of Bycatch Variability

The significant differences observed among years indicate that temporal variability plays an important role in shaping bycatch patterns. Median bycatch biomass was highest in 2019 (0.07 mt) and relatively elevated in 2016, whereas lower median values were recorded during 2021 -2023 (Table 3). The substantial number of significant pairwise comparisons between years suggests that bycatch patterns shifted meaningfully over the study period. Temporal variation in bycatch has been widely reported in tropical tuna fisheries and is often linked to interannual changes in environmental conditions, fishing effort and spatial distribution of target and non-target species (Gilman. et al., 2017; Hall & Roman, 2013). In the western and central Pacific Ocean, oceanographic variability such as El Nino – Southern Oscillation (ENSO) events can alter sea surface temperature, primary productivity, and prey aggregation patterns, thereby influencing the distribution of tuna and associated bycatch species (Lehodey et al., 2011). These shifts may partially explain the elevated bycatch observed in certain years, particularly 2019 (Table 3).

The apparent decline in median bycatch during more recent years may reflect changes in operational practices, improved compliance with bycatch mitigation measures, or broader shifts in ecosystem

structure (Komoroske & Lewison, 2015). The implementation of increasingly stringent regional conservation and management measures by the WCPFC may have contributed to reduction in bycatch interactions through improved monitoring, release protocols and enhanced controls (Cooper & Bigelow, 2024; Haas et al., 2024).

From a management perspective, the strong temporal signal suggests that bycatch mitigation should not rely solely on static measures. Instead, adaptive management approaches that account for interannual environmental variability may improve mitigation effectiveness. Dynamic management frameworks that integrate environmental indicators and annual bycatch risk assessments could provide more responsive basis for managing bycatch interactions (Hall & Roman, 2013; Peatman et al., 2023).

According to Maxwell et al, (2015), conventional spatial marine management approaches often rely on fixed boundaries to regulate activities around marine resources, despite the fact that many oceanographic features, marine species, and resource users are highly mobile. They argued that for marine management to be truly effective, it must be as dynamic and adaptive as the ocean systems it seeks to govern. By refining management measures to match the temporal and spatial variability of marine ecosystems, dynamic ocean management provides a more effective means of balancing ecological conservation with economic activities.

Furthermore, Crespo et al., (2024), highlighted that seasonal and adaptive spatial management measures can play an important role in reducing fisheries impacts on non-target catches. The authors emphasized that identifying persistently high-risk areas in the open ocean, where dynamic environmental conditions influence shifts in species distributions, is critical for evaluating the effectiveness of fisheries closures. This is particularly relevant in the context of the Western and Central Pacific Ocean (WCPO) management measures, where over time, periodic high seas closures have been implemented as part of broader ocean management strategies aimed at aligning fisheries activities with temporal ecological variability and conservation objectives.

4.5.2 Operational Drivers: Influence of Fishing set type

Fishing set type emerged as a particularly strong operational driver of bycatch variability, with free-school sets exhibiting significantly higher median bycatch biomass (0.080 mt) than Drifting FAD sets (0.040 mt) (Table 4). This result suggests that operational fishing mode substantially influences bycatch outcomes (Duffy et al., 2019).

The higher bycatch biomass associated with free-school sets likely reflects the ecological characteristics of naturally aggregated tuna schools. Free-School tuna aggregations often occur in productive pelagic habitats that are also frequented by large marine megafauna, including whale sharks, cetaceans and sharks (Dagorn et al., 2013). Consequently, purse seine operations targeting these naturally occurring aggregations may increase the likelihood of interactions with large-bodied non-target species (Tolotti et al., 2020). By contrast, Drifting FAD-associated fishing tends to

aggregate species that exhibit affinity for floating structures, particularly smaller teleosts such as rainbow runner and mackerel scad (Maufroy et al., 2017).

These findings suggest that different fishing modes generate distinct ecological footprints (Romanov, 2002). Free-School operations appear to pose greater interaction risks for large pelagic megafauna, whereas Drifting FAD-associated operations may influence ecological processes through altered aggregation dynamics. According to Castro et al., (2002), several hypotheses have been proposed to explain this behaviour of pelagic fish, around floating objects, with the most widely accepted explanation being that these structures provide refuge from predation. However, the authors suggested that this association may also represent an evolved behavioural adaptation that enhances the survival of eggs, larvae, and juvenile life stages during dispersal to new habitats. They explained that natural floating materials, including algae and drifting tree branches, are often transported by ocean currents originating from rivers, estuaries, and coastal zones where such objects are commonly generated. These currents also transport planktonic productivity from nutrient-rich coastal systems into otherwise oligotrophic pelagic waters. As a result, fish associated with drifting floating structures may benefit not only by feeding on invertebrates attached to these substrates but also by exploiting the concentrated plankton resources that accumulate in convergent waters. Castro et al., (2002), further emphasized that the associative behaviour observed around floating devices likely arises from multiple convergent ecological drivers rather than a single causal mechanism. More broadly, they argued that drifting objects function as ecological pathways to relatively productive habitats, thereby increasing the likelihood of survival for larval and juvenile fish during critical developmental stages. This operational contrast has direct implications for management. Species-specific mitigation strategies may therefore be more effective than uniform bycatch regulations across all fishing modes (Swimmer et al., 2020).

4.5.3 Species Composition as the Dominant Ecological Driver

Among the three grouping variables assessed separately, species identity yielded the largest Kruskal–Wallis statistic (H = 5,417.651), indicating substantial differences in the distributions of recorded biomass among the selected taxa. Because these tests were univariate and not designed to estimate independent effects or mechanisms, the statistic should not be interpreted as showing that species identity is the strongest ecological cause of variation. Differences in body size, recording procedures, and capture circumstances may also contribute, and disentangling those factors will require a model that incorporates fishing effort, observation structure and relevant covariates.

Bryde's whale exhibited the highest median bycatch biomass (2.000 mt), followed by false killer whale (0.668 mt) and whale shark (0.617 mt), whereas lower median values were observed for blue marlin, silky shark, rainbow runner, and mackerel scad. These patterns likely reflect differences in body size, ecological behaviour, habitat overlap with purse seine operations and species – specific susceptibility to capture (Hall & Roman, 2013). The elevated biomass associated with large marine megafauna is ecologically significant. Species such as whale sharks and cetaceans are highly

vulnerable to fishing interactions due to their life-history traits, including slow growth, delayed maturity, and low reproductive rates (Lewison et al., 2014). According to Read, (2008), even relatively infrequent interactions between fisheries and marine megafauna can result in disproportionate conservation consequences for these taxa. This highlights the significance of such interactions, as their impacts may extend far beyond the immediate mortality of individual organisms. Furthermore, the authors emphasized that understanding fisheries interactions with marine mammals requires consideration of the broader ecological transformations driven by global fishing activities. These impacts have contributed to substantial alterations in marine ecosystem structure and function, including shifts in trophic dynamics, changes in species assemblages, and disruptions to natural pathway of energy flow. Such ecosystem-level consequences underscore the potential for even low-frequency bycatch events to generate significant and long-term ecological effects. Additionally, the presence of large - bodied megafauna within bycatch records suggest substantial ecological overlap between purse seine fishing operations and biologically important pelagic habitats highlighting the need for continued monitoring of ecosystem interactions beyond target tuna species (Scales et al., 2018). Conversely, the comparatively lower median biomass observed for rainbow runner and mackerel scad is noteworthy from a fisheries diversification perspective.

4.5.4 Ecological and Management Implications

Collectively, the results demonstrate that bycatch variability in PNG's purse seine fishery is shaped by interacting temporal, operational, and ecological drivers. Species identity and set category showed substantial differences in recorded biomass distributions; the analyses do not rank their independent causal influence. From an ecological perspective, these findings suggest that purse seine operations interact with a highly dynamic pelagic ecosystem, where species–specific susceptibility is shaped by fluctuating environmental conditions (Duffy et al., 2019). These findings reinforce the need to move beyond conventional target-species management towards broader ecosystem-based management frameworks. This perspective is strongly supported by Pikitch et al., (2004), who argued that traditional fisheries management has often proven inadequate because of its narrow focus on maximizing the harvest of individual target species while frequently overlooking critical ecosystem components, including habitats, predator-prey relationships, species interactions, and broader ecological processes. In response to these limitations Pikitch et al., (2004), proposed ecosystem-based fisheries management (EBFM) as a more effective and holistic approach. At its core, EBFM reverses conventional management priorities by placing ecosystem integrity at the centre of decision-making, rather than focusing solely on target stock productivity. The significance of this approach lies in its overarching objective of sustaining healthy marine ecosystems alongside the fisheries they support. Furthermore, EBFM seeks to prevent ecosystem degradation, minimise the risk of irreversible changes to species assemblages and ecological processes, and secure long-term socio-economic benefits without compromising ecosystem resilience. It also emphasizes the importance of developing sufficient ecological knowledge to better understand the consequences of human activities on marine systems. Where scientific uncertainty persists, the framework advocates

for precautionary and robust management measures that prioritize ecosystem protection. Therefore, in the context of these findings, the observed bycatch interactions highlight the interconnectedness of PNG's pelagic ecosystem and demonstrate why management approaches must account for ecological complexity, species-specific vulnerabilities and ecosystem functioning if fisheries sustainability is to be achieved over the long term.

To add further, from a management perspective, several important implications emerge from these findings. First, the temporal variability observed in bycatch patterns highlights the need for adaptive monitoring systems capable of responding to shifting ecological conditions. According to Maxwell et al., (2015), regular bycatch assessments combined with environmental forecasting tools can enhance the responsiveness of fisheries management.

Maxwell et al., (2015), further emphasized that marine resource management has historically been shaped by approaches adapted from terrestrial systems. Management tools such as marine protected areas, marine spatial planning, and quota-based frameworks, including individual transferable quotas and bag limits are largely grounded in terrestrial management principles. However, the authors argued that open ocean differs fundamentally from terrestrial environments. In terrestrial and nearshore marine systems, habitat structure is typically created by stationary or long-lived primary producers such as forests, grasslands, seagrass beds, kelp forests, and coral reefs. In contrast, pelagic marine ecosystems are structured by highly dynamic oceanographic processes, where microscopic and short-lived autotrophs underpin food webs that are organised around transient physical features such as fronts, eddies, and convergence zones. Because of this unmatched spatial and temporal variability, Maxwell et al., (2015) contended that static management approaches are often poorly suited to highly dynamic marine environments. They noted that while the ocean itself, along with many human activities such as fishing and shipping, is inherently dynamic, most existing marine management frameworks remain relatively fixed in space and time. To address this mismatch, Maxwell et al., (2015) proposed that management must become as fluid as the system it seeks to regulate. They defined dynamic ocean management as a management approach that changes rapidly across space and time in response to shifting oceanographic conditions and patterns of resource use through the integration of near real-time biological, oceanographic, social, and economic data.

The authors identified three key components required to operationalise this approach: the use of existing datasets such as remote sensing products, animal tracking information, and fisheries observer data like the one used in this study; the application of advanced analytical and predictive modelling techniques to forecast species distributions and ecological conditions; and the adoption of rapid data-sharing technologies capable of delivering management information at spatial and temporal scales fine enough to support real-time decision-making. In the context of this study, these principles are particularly relevant as they provide a practical framework for improving bycatch management within PNG's purse seine fishery.

Second, the operational differences between free-school and Drifting FAD sets support the development of fishing mode-specific mitigation measures rather than broad, uniform regulatory approaches. Swimmer et al., (2020), emphasized that the complexity of Drifting FAD fishing strategies presents unique management challenges. The authors explained that because Drifting FADs are deployed to drift freely while being tracked by geo-locating buoys, a substantial proportion are estimated to become lost, abandoned, or otherwise unaccounted for each year. This raises significant ecological concerns, particularly through ghost fishing, whereby derelict or abandoned Drifting FADs continue to entangle and contribute directly to the mortality of non-target species.

Swimmer et al., (2020) further highlighted that these ecosystem-level impacts have prompted ongoing research aimed at redesigning Drifting FADs using non-entangling and biodegradable materials to reduce their ecological footprint. The authors noted that findings from such research have increasingly informed the conservation and management measures adopted by Regional Fisheries Management Organizations (RFMOs). In response, most RFMOs have implemented management measures specifically tailored to different fishing modes, with many regulations focusing on limiting Drifting FAD deployments and promoting the use of biodegradable and non-entangling Drifting FAD designs. These developments underscore the importance of operationally targeted mitigation strategies, particularly within ecosystem-based fisheries management frameworks, where management interventions must account for the distinct ecological risks associated with different fishing practices.

Third, species–level differences observed in this study suggest that management interventions should be tailored according to both ecological vulnerability and species-specific utilisation potential. This aligns with the broader objectives of ecosystem-based fisheries management, which seeks to achieve long term ecological sustainability through management approaches that move beyond traditional single-species frameworks. Duffy et al., (2019) emphasized that ecosystem- based fisheries management is increasingly being adopted globally as a more holistic approach to fisheries governance, completing or replacing conventional target-species management strategies.

In evaluating bycatch vulnerability within the tuna purse seine fisheries of the eastern Pacific Ocean, Duffy et al., (2019) highlighted the growing application of ecological risk assessment (ERA), particularly Productivity-Susceptibility (PSA), as a practical tool for assessing the relative vulnerability of data-limited non-target species to fishing impacts. The authors developed a PSA framework for the eastern Pacific purse seine fishery to evaluate vulnerability across three operational set types: dolphin associated sets, unassociated (Free-School), and floating object sets. Recognising the operational differences among these fishing modes, susceptibility estimates for each species were integrated across set types to generate fleet-wide vulnerability assessments.

Their findings demonstrated clear species-level differences in ecological risk. Vulnerability was highest among elasmobranchs species, including giant manta rays, big eye tuna and pelagic

thresher sharks, smooth and scalloped hammerhead sharks and silky sharks. Billfishes, dolphins, other rays, ocean sunfish, and certain tuna species were classified as moderately vulnerable, while most teleost species exhibited the lowest vulnerability scores. Duffy et al., (2019) argued that these distinctions are highly significant for fisheries management because they allow managers to identify priority species for targeted research, monitoring and mitigation.

The significance of this approach lies in its capacity to support more strategic and evidence-based management interventions. By distinguishing between highly vulnerable conservation-sensitive species and lower risk species with greater utilisation potential, ecological risk assessments provide a pathway for balancing biodiversity conservation with sustainable resource use. In the context of this study, such species-specific differentiation is particularly important for informing management responses within PNG's purse seine fishery. Conservation measures for vulnerable megafauna must be strengthened. At the same time, opportunities for the sustainable utilisation of lower-vulnerability teleost bycatch can be explored within an ecosystem-based fisheries management framework.

4.6 Rethinking Bycatch: From Waste to Resource

Historically, fisheries bycatch has been widely regarded as an unavoidable outcome of fishing operations and, in many instances, as biological waste with minimal economic value (Kelleher, 2005). A study by Hall & Roman, (2013), highlighted that with industrial tuna fisheries, non-target species captured during fishing activities are frequently discarded at sea due to regulatory restrictions, low market demand, poor onboard storage capacity, or the absence of established value chains.

However, according to (FAO, 2020), growing concerns surrounding food security, resource efficiency, and sustainable fisheries development have increasingly challenged this traditional perception of bycatch. Thus, as global fisheries move toward ecosystem-based fisheries management (EBFM) and circular economy approaches, the authors highlight that, there is increasing recognition that certain bycatch species, particularly teleost species, may represent underutilised biological resources rather than simple waste products.

The findings from this study demonstrate that although large marine megafauna such as sharks, cetaceans, and whale sharks dominate portions of the bycatch biomass, several teleost species are also captured and partially retained within PNG's purse seine tuna fishery. Species such as rainbow runner and mackerel scad were observed among the dominant bycatch taxa and showed evidence of retention rather than complete discard.

As outlined by Tacon & Metian, (2015) the utilisation of bycatch species globally has become increasingly important in efforts to reduce waste and maximise fisheries productivity. Tacon & Metian, further stated, in many developing coastal nations, retained bycatch contributes directly to

local food systems through domestic fish markets, crew consumption, artisanal processing, and small-scale trade networks. In PNG, similar utilisation pathways may already exist informally within parts of the offshore fisheries sector. Retained fish from industrial purse seine operations may enter domestic markets through transhipment ports or via informal distribution networks involving vessel crews and surrounding local communities. For example, the port of Rabaul (one of the busiest ports) located in East New Britain province serves as a major transhipment hub for purse seiners, carrier vessels and motherships operating within the region. On average, approximately 10 to 15 vessels call into the port each week for compulsory inspection by relevant authorities, particularly during peak licensing periods. During these visits, informal exchanges commonly occur, whereby vessel crews trade frozen fish with local residents for fresh produce such as fruits and vegetables. Such practices may provide an important supplementary source of affordable protein, particularly in urban and coastal areas where fish demand continues to increase.

According to (Gillett, 2009), the potential economic value of teleost bycatch extends beyond direct human consumption. The author further explained that species such as rainbow runner and mackerel scad may also be suitable for value-added processing industries. These species could potentially be processed into smoked, dried, canned, frozen, or vacuum-packed products for domestic and regional markets. Furthermore, Gillet (2009) noted, that the development of such products could generate opportunities for small and medium enterprises (SME), particularly within coastal provinces that already have existing fisheries infrastructure. Similar utilisation strategies have been explored in other Pacific Island countries where fisheries diversification is increasingly viewed as a mechanism for improving food security, employment, and rural economic development (Bell et al., 2015).

Furthermore, retained teleost bycatch may also provide opportunities for fishmeal and aquaculture feed production. Globally, fishmeal industries frequently utilise low-value pelagic species and fish processing waste as inputs for aquaculture feeds, livestock feeds, and agriculture supplements (Olsen & Hasan, 2012). According to (Sammut et al., 2024) the development of local fishmeal could contribute to the emerging aquaculture sector while simultaneously reducing post-harvest waste from industrial fisheries, within Papua New Guinea. Sammut et al., (2024) noted that this may be significantly relevant given the increasing interest in aquaculture development and coastal fisheries diversification within the country. Therefore, by converting retained bycatch into secondary products, fisheries operations may generate additional economic returns while improving overall resource efficiency.

In a report by (FAO, 2020), teleost bycatch may also support other value-adding industries in addition to fishmeal production. For example, fish oils extracted from pelagic species may potentially be refined for use in nutritional supplements, while fish skin, bones, and collagen-rich tissues could contribute to cosmetic, pharmaceutical, or agricultural products (Espinales et al., 2023). FAO, (2020) further emphasized that although such industries require substantial technological investment, infrastructure, and regulatory oversight, they demonstrate the broader economic possibilities

associated with fisheries by-products. Internationally, the concept of fully-utilising harvested marine resources has become increasingly central to sustainable fisheries development and blue economy initiatives (Keen et al., 2018).

Nevertheless, (Hall et al., 2000) notes that the utilisation of bycatch species must be approached cautiously and within appropriate management frameworks. The author argued that the objectives of bycatch utilisation should not be to encourage the deliberate targeting of unavoidable catches that already occur within the fishery. Effective governance is essential to ensure that any bycatch-utilisation initiative remains consistent with conservation obligations.

Importantly, species-specific approaches are required because not all bycatch species possess equal ecological vulnerability or economic value (Hall et al., 2000). The authors emphasized that teleost species with relatively higher productivity and lower conservation concern may provide the most appropriate candidates for pilot utilisation programmes. Such programmes could be integrated within PNG's broader ecosystem-based fisheries management framework while supporting national objectives related to food security, employment generation, and fisheries diversification (Gillett, 2009).

This study suggests that, for Papua New Guinea, reconceptualising bycatch as a potential resource rather than solely as waste presents an important opportunity for the offshore fisheries sector. Industrial tuna fisheries already contribute substantially to the national economy through access fees, employment, and export revenue. Additionally, for PNG, where offshore fisheries are a major economic driver and where there is growing interest in domestic value-adding initiatives, the utilisation of bycatch represents a strategic opportunity. However, such utilisation must be carefully evaluated to ensure it does not create perverse incentives that increase bycatch or undermine conservation objectives.

4.7 Study limitations and uncertainty

The interpretation of this study is constrained by the structure, coverage and reporting characteristics of the underlying observer data. Although trained observers provide an important source of species-level fisheries information, the analysed extract does not include a verified denominator for all fishing trips and sets conducted in the fishery during 2014–2024. Consequently, the temporal and operational representativeness of the observations cannot be quantified, and a change in annual recorded biomass cannot be interpreted unambiguously as a change in true bycatch incidence or population abundance. Interannual differences may arise from changes in fishing effort, observer coverage, the set types sampled, fishing location, vessel practices, or broader ecological conditions. Those effects were not partitioned in the present analysis.

Measurement and reporting uncertainty are additional limitations. Retained and discarded weights may be estimated from catch reconciliation procedures rather than direct measurement of every organism, and species identification, handling, detection and reporting can vary among events. Large-bodied species may contribute disproportionate biomass from relatively few interactions, making totals particularly sensitive to single observations and estimated body mass. Conversely, small organisms, rapid releases, and difficult-to-identify taxa may be under-recorded. The present descriptive figures do not display confidence intervals for the underlying biomass estimates; therefore, the apparent precision of displayed totals should not be mistaken for known statistical accuracy or completeness of fleet-wide recording.

Statistical interpretation also requires caution. The Kruskal–Wallis tests compare ranks across selected groups but are performed separately and do not control jointly for year, set type, species, spatial conditions or vessel characteristics. Multiple species records may come from the same fishing set and are therefore not necessarily independent. Statistical significance in such a large dataset does not by itself establish management-scale effect sizes, relative causal importance, or mechanisms of ecological association. A further limitation is that the analysis does not measure post-release survival, cryptic mortality, or species population trajectories. As a result, high recorded biomass signals the importance of monitoring an interaction but cannot alone be converted into mortality rates or population-level impacts.

Finally, the study examines a two-mode subset for some comparisons. The DRIFTING FAD and UNASSOCIATED filters exclude other school-type codes, and the species list is reselected within the subset. This difference must be considered when comparing figures. The findings are therefore best treated as a transparent description of recorded bycatch composition and distributional differences within the observer extract, accompanied by hypotheses for future causal testing.

4.8 Future research and practical management priorities

A first research priority is to quantify observer coverage by year, vessel, fishing area, season and set type using the total set and trip denominators recorded by fishery authorities. Combining verified denominators with the observer extract would allow bycatch-per-set or bycatch-per-unit-effort estimates and uncertainty intervals, rather than relying on unstandardised annual totals alone. Future analyses should consider mixed-effects or hierarchical models that account for shared vessel and set identities, zero-inflated catch distributions, and environmental covariates such as sea surface temperature, location, season and fish aggregating device characteristics. This would enable hypotheses concerning operational and environmental contributions to be tested directly.

A second priority is species-specific validation. Recording biological measurements, species identification confidence, handling outcomes, fate and release condition would improve estimation for rare large-bodied interactions and less conspicuous taxa. Targeted studies of post-release

survival for sharks and other vulnerable megafauna, ideally combined with onboard electronic monitoring where appropriate, could help distinguish observed capture and discard from actual mortality. Monitoring should be designed to support transparent quality assurance, comparable records across years and systematic reporting of measurement uncertainty.

For management, the results justify a precautionary, staged approach rather than immediate conclusions about causal drivers. Authorities could use the descriptive species and set-type patterns to identify where focused assessment is warranted, followed by testing of risk-reduction and safe-release interventions with clearly defined performance indicators. Fishing-mode-specific mitigation should be evaluated using effort-standardised measures and compliance data, not biomass totals alone. Collaboration between PNG's National Fisheries Authority, Pacific regional science bodies and relevant industry stakeholders would help ensure that resulting measures align with existing conservation obligations.

These findings should be interpreted within the limits of observer-derived and unstandardised biomass totals. The observed differences across years, set categories and species were statistically detectable, but the analysis did not establish their causal mechanisms or produce fleet-wide bycatch rates with uncertainty estimates. Future monitoring, effort-standardised analyses and independently evaluated mitigation measures are therefore essential to translate the descriptive patterns into robust management decisions.

The potential utilisation of selected teleost bycatch, particularly rainbow runner and mackerel scad, should be evaluated only through bounded feasibility studies. Pilot work should assess the reliably available volume of legal, low-vulnerability incidental catch, preservation and food-safety standards, cold-chain feasibility, local demand, economic value, traceability, and the risk of creating incentives to target non-target species. Conservation-sensitive taxa must remain subject to appropriate avoidance, handling and release measures. A successful pilot would be one that reduces waste without increasing incidental catch or weakening ecosystem protection.

5. Conclusion

This study provides one of the first comprehensive assessments of bycatch in Papua New Guinea's (PNG) purse seine tuna fishery. Using observer data from 2014 to 2024, it examined species composition, temporal trends, differences between Drifting Fish Aggregating Device and free-school sets, and retention patterns. The findings contribute to our understanding of the ecological footprint of PNG's offshore tuna fishery and support ecosystem-based fisheries management (EBFM) approaches aligned with regional governance.

Bycatch in the fishery is highly uneven. Silky shark (*Carcharhinus falciformis*) contributed the most biomass, followed by whale shark (*Rhincodon typus*), rainbow runner (*Elagatis bipinnulata*), Bryde's whale (*Balaenoptera edeni*), false killer whale (*Pseudorca crassidens*), sei whale (*Balaenoptera borealis*), and mackerel scad (*Decapterus macarellus*). The dominance of sharks, cetaceans, and large pelagic megafauna shows that purse seine operations overlap heavily with productive pelagic habitats in PNG waters. This reinforces global concerns about industrial tuna fisheries interacting with vulnerable marine species (Gilman, 2011; Hall. et al., 2017).

Biomass for dominant species varied considerably over time. Silky shark and whale shark catches increased through the late 2010s before declining or stabilizing in the recent years. These shifts suggest that a combination of environmental variability, fishing effort, species ecology, and vessel practices drive bycatch dynamics. Bycatch in PNG's tuna fishery is not static. It fluctuates with broader ecosystem processes and fishing behaviour. Understanding these patterns aids in providing insights to the changing species distributions, ecosystem productivity, and emerging conservation risks in the Western and Central Pacific Ocean (WCPO).

The comparative analysis showed that fishing mode strongly influence bycatch composition. The results revealed that free-school sets accounted for most of the silky shark, whale shark, Bryde's whale, and blue marlin biomass. In contrast, rainbow runner and mackerel scad, were closely associated to Drifting FAD operations. Both fishing modes pose ecological risks, although the impacts differ across components or different parts of the pelagic ecosystem. Management strategies that focus only on Drifting FAD impacts will miss the substantial bycatch interactions happening in free-school fisheries. Mitigation in PNG needs to cover all operational modes.

Retention patterns followed a similar distinction. Recorded whale-shark and cetacean biomass was entirely discarded, while 99.76% of silky-shark biomass was discarded; small retained fractions were observed for some teleost taxa. Rainbow runner and mackerel scad showed limited retention. These patterns reflect conservation regulations, market value, handling capacity, and species suitability for utilization. Furthermore, discarding protected species is necessary, but it doesn't erase ecological impact because post-release mortality still occurs. The partial retention of rainbow runner and mackerel scad, however, shows that some teleost bycatch species possess economic value.

The analysis of bycatch drivers further strengthens the conclusions of this study by demonstrating that bycatch variability is shaped by interacting temporal, operational and ecological processes rather than occurring randomly. The significant influence of year, fishing set type, and species composition confirm that bycatch dynamics reflect broader ecosystem variability and fishing behaviour, reinforcing the need for ecosystem-based management approaches that account for ecological complexity.

The findings answer the core research question: bycatch variability in PNG's purse seine fishery is driven by time, fishing mode and species composition. Species-specific trends provide clear insights for ecosystem-based management and diversification. Bycatch data should not just feed into mitigation and conservation; it should inform broader fisheries planning and sustainable development.

At a broader level, this study reinforces that effective fisheries management must look beyond target tuna species. The presence of sharks, cetaceans, whale sharks, billfish, and teleost fishes in PNG's bycatch highlights the interconnected nature of oceanic ecosystems. It supports the EBFM principles pushed by the WCPFC and other regional bodies (Pikitch et al., 2004; WCPFC, 2025). Continued investment in observer programs, data collection, and species-level monitoring remains essential for evidence-based governance.

One of the most important contributions of this study is the recognition that certain teleost bycatch species represent what may be described as the "invisible fishery" within PNG's offshore sector. Species like rainbow runner and mackerel scad are overshadowed by the tuna harvest, but they hold potential for utilization, value addition, and fisheries diversification. Much of this biomass is currently discarded despite its potential for food security and local markets. PNG could treat this bycatch not just as waste, but as a secondary resource that supports local development and nutritional security.

From a development outlook selected teleost bycatch could support direct human consumption, smoked and dried products, fishmeal, livestock and aquaculture feed, and other processing. Any utilization strategy needs strict or fitted regulation to avoid creating incentives to target non-target species or undermine conservation. Sustainable use must sit within an EBFM framework that balances ecological protection with economic opportunity.

Bycatch in PNG's purse seine tuna fishery is both a conservation challenge and a development opportunity. Vulnerable megafauna needs continued protection and mitigation. Certain teleost species, however, represent an under-recognized resource that could support fisheries diversification and food security. This "invisible fishery" deserves more scientific and policy attention. With improved monitoring and carefully evaluated utilisation initiatives, PNG may advance conservation, food-security and economic-resilience objectives, subject to appropriate feasibility assessments and safeguards.

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