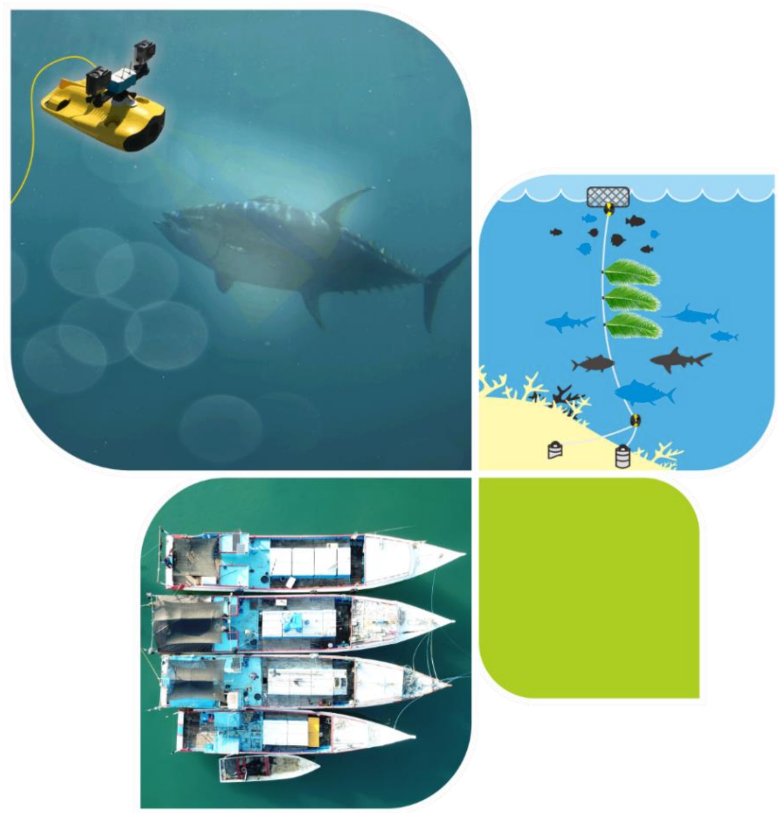
Human and Fish Behaviour Around Fish Aggregating Devices (FADs) in Indonesia



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Submitted in fulfilment of the requirement for the
Degree of Doctor of Philosophy

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October 2024

Abstract

Deep-water anchored Fish Aggregating Devices (FADs) are utilized to attract fish and support tuna fishing operations in the Indonesian Indian Ocean. Various demersal/reef and pelagic fish species at different developmental stages naturally aggregate around these devices, creating artificial resource patches in the pelagic habitat. These artificial patches are advantageous to fishers because they can be located more easily and quickly than free-swimming schools, thus minimizing search time and operating costs. Introduced in the late 1990s, this method has grown rapidly and become the dominant practice in artisanal, medium, and large-scale industrial tuna fisheries.

The medium-scale tuna handline fishery off the South Coast of Java (Indian Ocean) employs FADs to support their fishing operations in offshore waters. Fishers can easily switch between fishing gears during a single trip, adapting to sea conditions, catch success, and the behaviour of the fish. The weak management system of this fishery results in limited information about their fishing behaviour and the spatial distribution of fishing effort. Additionally, collecting scientific data on fish behaviour associated with FADs in the pelagic ecosystem is challenging due to the difficulties in accessing their natural environment, particularly in locations where FADs are usually distributed far from coastlines and over broad offshore areas.

This thesis combines quantitative and qualitative research techniques to investigate the behaviour of fishers and fish associated with FADs. Low-cost satellite GPS trackers were used to monitor the movements of individual tuna handline fishing vessels. This approach effectively identified fishers' actual fishing grounds, fishing activities, and the distribution of FADs. Additionally, interview techniques were employed to identify the variability of fishing behaviours and to explore the decision-making processes and motivations behind them. Both methods also allowed for the identification of illegal fishing activities.

Fishers' knowledge of tuna behaviour around FADs, acquired through their extensive practical experience, provides crucial information that complements scientific observations of FADs. A novel technique integrating acoustic surveys and a remotely operated vehicle (ROV) equipped with a stereo-camera system allows for the characterization of fish communities, behaviours, and densities around FADs. This approach provides valuable data to mitigate the impact on non-target species associated with FADs.

This study demonstrates the importance of integrating diverse knowledge sources, including scientific knowledge and local knowledge, to obtain reliable information on fisher and fish behaviours.

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Acknowledgement

First and foremost, I would like to express my gratitude and appreciation to my supervisors Dr. David Bailey, Professor Shaun Killen, Dr. Chris Wilcox, and Dr. Charlotte Hopkins, for their guidance, encouragement and great effort to make this thesis possible. I am very much thankful for great patience in assistance and consultancy. My gratitude also extends to Dr. Dorothy McKeegan and Professor Colin Selman, thanks for help and guidance during these four years of my study.

Further, I am very grateful to the Indonesia Endowment Fund for Education, The Indonesian Ministry of Finance for financial support during my study at the University of Glasgow. Ministry of Marine Affairs and Fisheries, Dr. Toni Ruchimat and Prof. Wudianto for giving me support, motivation and the opportunity to obtain PhD study. I am also indebted to my friend Agung Wahyudi who helping me with the data collection in the Sendangbiru fishing port. I would like to express my very sincere gratitude to Kathryn Elmer and Davina Hill.

Thank you to my beloved wife Erieska Nuryanti for her understanding and support. Similar thanks go to my son and daughter Anzio Athalla Hoved and Sienna Ellisif Aerilyn for love and inspiration.

Last but not least, I wish to thank Killen Lab and Indonesian student association for making my years as a student in Glasgow so enjoyable. Thank you for the help and share good moments.

This thesis is dedicated to my parents, Anwar Hasyim and Sri Sularsih.

Author’s Declaration

I declare that, except where explicit reference is made to the contribution of others, that this thesis is the result of my own work and has not been submitted for any other degree at the University of Glasgow or any other institution.

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Chapter 1: Introduction

1.1 Indonesian Tuna Fishery

Indonesia is the largest archipelagic country in the world, consisting of approximately 17,508 islands with a coastline of over 91,000 km, and located between the Pacific and Indian Oceans (Sui et al., 2020). The fishery sector is essential, providing employment for 7 million people and more than 50 percent of Indonesia's animal protein needs (Bank, 2021). Indonesia's marine capture fishery production reached more than 6.7 million tonnes in 2018, as the second largest such fishery in the world after China (Fao, 2018, Fao, 2020).

Tuna species dominate the country's production with more than 1.3 million metric tonnes in 2020, contributing 20.79% of all marine capture commodities. This is an increase of 1818% since 1973. As a result, Indonesia is the largest tuna-producing country in the world (Mmaf, 2019, Dgf, 1983). Tuna products have a high economic value worldwide, especially in the export market where greater profits can be made (Fao, 2022). The export value of tuna products from Indonesia reached approximately US$ 724 million in 2020 and represented 5.3% of the global tuna market (US$ 26.1 billion). By species, skipjack (SKJ, *Katsuwonus pelamis*), yellowfin tuna (YFT, *Thunnus albacares*), bigeye tuna (BET, *Thunnus obesus*), albacore tuna (ALB, *Thunnus alalunga*) and bluefin tuna (SBT, *Thunnus maccoyii*) are the priority species for export as fresh, frozen, prepared, and preserved products. Neritic tuna species, i.e. eastern little tuna (*Euthynnus affinis*), longtail tuna (*Thunnus tonggol*), frigate tuna (*Auxis thazard*), and bullet tuna (*Auxis rochei*) are consumed as fresh and prepared products by the domestic market (Sunoko and Huang, 2014).

The Indonesian tuna fishery is a diversified and complex fishing fleet, encompassing industrial, medium and small-scale vessels operating in archipelagic, Exclusive Economic Zone (EEZ), territorial, and high seas waters (Proctor et al., 2018). A large-scale fishing vessel is a large-sized vessel of more than 30 GT (gross tonnage), typically designed to operate with long lines, purse seines, and pole-and-line methods. Meanwhile, medium-scale vessels range from 10 to 30 GT, and small-scale vessels are less than 10 GT; both typically operate using handlines/troll lines and gillnets. Indonesia's EEZ is subdivided into 11 Fishery Management Areas (FMAs), each distinguished by its unique ecological attributes, natural resources, infrastructure, human resource capabilities, and industrial landscape. Indonesia tuna fishing fleets dispersed across the FMAs within three distinct regional zones: Indonesia's Indian

Ocean (IIO), Indonesia's Archipelagic Waters (IAW), and Indonesia's Pacific Ocean (IPO) (Figure 1).

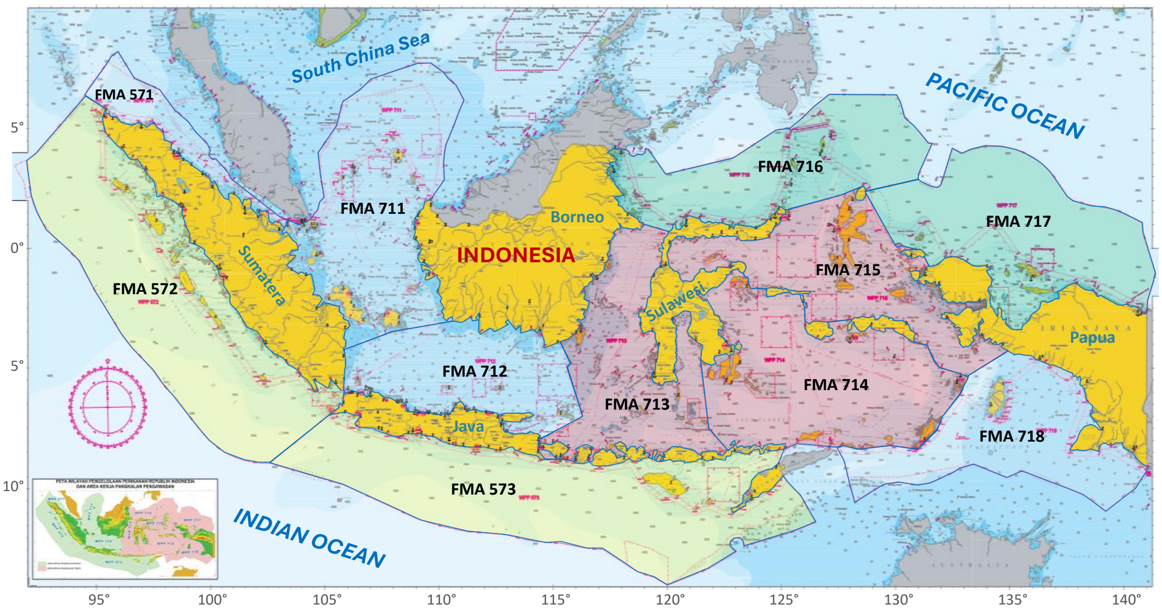


Figure 1. Indonesia's Fisheries Management Areas (FMAs) are subdivided into eleven distinct management areas.

Situated between two main tuna fishing grounds, the Pacific Ocean and the Indian Ocean, Indonesia has become a member of Regional Fisheries Management Organizations (RFMOs): the Indian Ocean Tuna Commission (IOTC) and the Western and Central Pacific Fisheries Commission (WCPFC). In 2022, 1,730 active fishing vessels were reported to the IOTC, and 33 active fishing vessels were reported to the WCPFC in 2024. Moreover, Pet et al. (2022) reported that 12,979 vessels fishing for tuna operated within IAW (FMA 713, 714 and 715). A recent statistics report published by the Indonesian Ministry for Marine Affairs and Fisheries (MMAF) estimated that there are 64,897 units of tuna fishing gears, comprising 80% of handlines/troll lines, 11.7% purse seines and 8.3% longlines.

In the Indian Ocean (FMA 572 and 573), it is estimated that up to 90% of tuna fishing vessels are small-scale (Proctor et al., 2019). However, the catch volume from small-scale gears like handline, trollline, and pole and line represent less than 40% of the total catch. In contrast, more than 60% of the catch is dominated by industrial-scale tuna vessels using purse-seine and longline gear (Ruchimat et al., 2017). Tuna fishery sectors in the Indian Ocean rely heavily on the use of deep-water anchored Fish Aggregation Devices (FADs) to capture tropical tuna species. The use of FADs to attract fish and support tuna fishing operations has grown rapidly since the early 1990s globally, and it has become the dominant practice in tuna purse seine and handline/ trollline fishing (Fonteneau et al., 2013, Guillotreau et al., 2011, Davies et al., 2014). By using FADs, fishers create their own fishing grounds and can reduce the time spent searching for fish. FADs make catching tuna much more effective and efficient compared to targeting free-swimming schools. FAD use greatly reduces the uncertainty in defining fishing grounds because of the higher probability of finding tuna, improves the catch rate and reduces the financial and carbon cost of fishing (Girard et al., 2004). Fishing more efficiently also reduces the time which must be spent at sea, reducing risk to fishers.

1.2 Handline Tuna Fishery Associated with FADs

1.2.1 The Development of Tuna FAD Fishery

It is unclear when FADs were first used in the Indonesian Fishery. According to Rusman (1954), shallow water FADs known locally as ‘unjan’ were already used by North-Sumatran fishers in 1921 for catching the small pelagic fish yellowstripe scad. They were deployed 10 to 30 nautical miles (nmi) from shore (depth 15-30 m). More than six decades later, due to growing tuna demand abroad and following the success of the Philippines and other countries in using deep-water anchored FADs, one of the Indonesian fishery state enterprises (PT. Usaha Mina) started using deep-water anchored FADs (2000-5000 m depth) to support their fishing operation (Table 1) (Hardjono, 1991, Macusi et al., 2015, Widodo et al., 2017). The rapid development of the Indonesian tuna fishery in the 1980s was also influenced by the extension of maritime jurisdiction under the new EEZ declaration prescribed by UNCLOS. With this extended jurisdiction, Indonesia has exclusive control over the living and non-living resources out to 200 nmi from shore. The UNCLOS regulations also allowed new alternative strategies in terms of tuna resources management, such as licensing for foreign vessels and joint venture programmes.

The development of the tuna FAD fishery in Indonesia’s Indian Ocean region began in two distinct areas: East Java and West Sumatra. In the late 1990s, Bugis migrant fishers from South Sulawesi, known as ‘andon’ fishers, introduced a novel fishing technique using handline gear to catch fish around deep-water anchored FADs off the South Coast of Java. They transported small fishing boats, called ‘sekoci’ boats, from South Sulawesi and deployed deep-water anchored FADs constructed from local materials. As local fishers adopted this new technique, a significant number transitioned to handline fishing. According to Budiono (2005), this practice led to improved catch levels, driving the rapid growth of the handline fishery on the South Coast of Java between 2002 and 2005, particularly in the Sendang Biru, Prigi, and Sadeng fishing ports (Budiono, 2005, Mardlijah, 2008, Salim and Rahmat, 2016). Meanwhile, purse seiners from Sibolga introduced deep-water anchored FADs to the Mentawai waters in West Sumatra around 2003. (Atmaja et al., 2016). By 2006, approximately 46 deep-water anchored FADs had been deployed in the Sibolga purse seine fishing grounds (Widodo, 2006). Furthermore, numerous purse seiners from Northern Java ventured into new fishing grounds in the Indian Ocean, specifically in West Sumatra and South Java, utilizing deep-water anchored FADs to enhance their fishing operations. Since then, FADs have proliferated throughout the Indian Ocean.

Fishing pressure from commercial FAD fisheries has become a significant issue for the management of tuna in the Indian and Pacific Oceans. The stocks of yellowfin and bigeye tuna are particularly affected, with increased juvenile and adult fishing mortalities attributed to distant-water purse seiners associated with FADs (Bailey and Sumaila, 2010, Hoyle et al., 2023, Williams and Ruaia, 2021). Declining stocks of yellowfin and bigeye tuna have been observed in the Pacific Ocean, and these species are considered overfished in the Indian Ocean (Williams and Ruaia, 2021, Iotc, 2024). On the other hand, compliance with regulations related to synchronization licensing among municipalities remains a challenge for small-scale tuna fisheries in the Philippines and other Pacific countries. This lack of compliance also results in difficulties in estimating the number of FADs in the area (Lennert-Cody et al., 2018).

Table 1. History of Indonesian tuna and FAD development.

Year	Milestone	References
1905	Pole and line introduced by Japanese in Maluku	(Mcelroy, 1989)
1918	Pole and line introduced in by Japanese in Sulawesi	
1921	FADs used for catching yellowstripe scad in Serdang – North Sumatra	(Rusman, 1954)
1950s	Pole and line introduced in North Sulawesi	(Mathews et al., 1996)
1962	Introduction of commercial tuna long line by Japanese followed by Taiwanese and Korean vessels	(Mcelroy, 1989)
1971	Pole and line introduced by Japanese in Irian Jaya	(Mcelroy, 1989)
1974	Tuna purse seiner was introduced in north Irian Jaya	(Mcelroy, 1989)
1975	First exported tuna from Indonesia	
1983-1986	Research about tuna FADs used for purse seine conducted by MFRI in Prigi – East Java	(Hardjono, 1991, Widodo et al., 2017)
1985	Research about FADs used for tuna fishing conducted by MFRI in Mamuju – South Sulawesi	(Hardjono, 1991)
1985	FADs for tuna fishing trials conducted by Fishing Technology Development Centre in Tomini Bay – North Sulawesi	(Hardjono, 1991)
1985	Indonesian fishery state enterprises (PT. Usaha Mina) started using deep-water anchored for pole and line in Maluku and Sorong	(Hardjono, 1991, Nugroho and Atmaja, 2013, Widodo et al., 2017)
1990	Philippine introduced 200 FADs in Sulawesi Sea for purse seine operation	(Butcher, 2004, Mathews et al., 1996)

1992	Research of tuna FADs used for purse seine conducted by MFRI in Cempi Bay – West Nusa Tenggara	(Widodo et al., 2017)
1992	Research of tuna FADs used for handline/ trollline by MFRI in Binuangen Cape – West Java, Semangka Bay – Lampung, South Coast – West Sumatra	(Widodo et al., 2017)
2000	The massive use of FADs in the Indian Ocean – West Sumatra, South of Java, and East Nusa Tenggara	(Widodo et al., 2017)

1.2.2 Handline Fishery in the Indian Ocean

Fishery management authority in Indonesia is divided between the central and provincial levels, according to fishery scales and jurisdictions, as stated in the Decentralization Law 23/2014. The provincial government is tasked with managing fishery and marine resources within 12 miles of the coast and for all fishing vessels ≤ 30 GT (medium and small-scale fishery). Meanwhile, the central government manages fishery and marine resources between 12 and 200 nautical miles from the coastline, or from the outer provincial limit to the outer limit of Indonesia's exclusive economic zone, and for all fishing vessels > 30 GT (Industrial-scale fishery) (Pet et al., 2022).

The handline fishery in the Indian Ocean (FMA 713) along the South Coast of Java is distinguished into small and medium-scale fishing fleets. The medium-scale handline fishery utilises larger vessels and undertakes longer trips. Medium-scale tuna handline vessels vary between 10 – 30 GT with average dimensions of 14 m in length, 2.9 m in width and 1.1 m in depth (Proctor et al., 2019) (Figure 2). Catches are preserved with ice in the vessels' insulated storage due to lack of onboard freezers. Vessels typically have a crew of four to five, including the captain. The fishing bases are concentrated at six fishing ports in Southern Java, spread across four distinct provincial jurisdictions: Palabuhanratu in West Java, Cilacap in Central Java, Sadeng in Yogyakarta, and Tamperan, Prigi, as well as Pondok Dadap – Sendangbiru, all in East Java (Nurani et al., 2018).

Although their registration and licenses are issued by the provincial government, these fishing operations frequently extend beyond the 12-mile provincial limit. Wiadnya et al. (2018), handline fishery operates in offshore waters typically extending more than 60 nmi. Most fishers are also unaware of the regulation requiring them to report every deployment of FADs to the fishing authority. This situation presents significant challenges for monitoring the fishery to accurately determine the actual fishing grounds and fishing activities.

Handline fishing is the simplest form of line fishing, consisting of a line, a sinker, a cast snood, and at least one hook (Gabriel et al., 2008). Medium-scale tuna fishing employs various handlining techniques, ranging from using small multiple feathered hooks to target small tunas at the surface to using a single large hook with natural bait for catching large tuna at depths of up to 200 meters (Pet et al., 2022, Anggawangsa et al., 2021). Individual vessels combine all these techniques in a single trip, adapting to switch between target species according to the season, sea conditions, and catch success (Proctor, 2019).

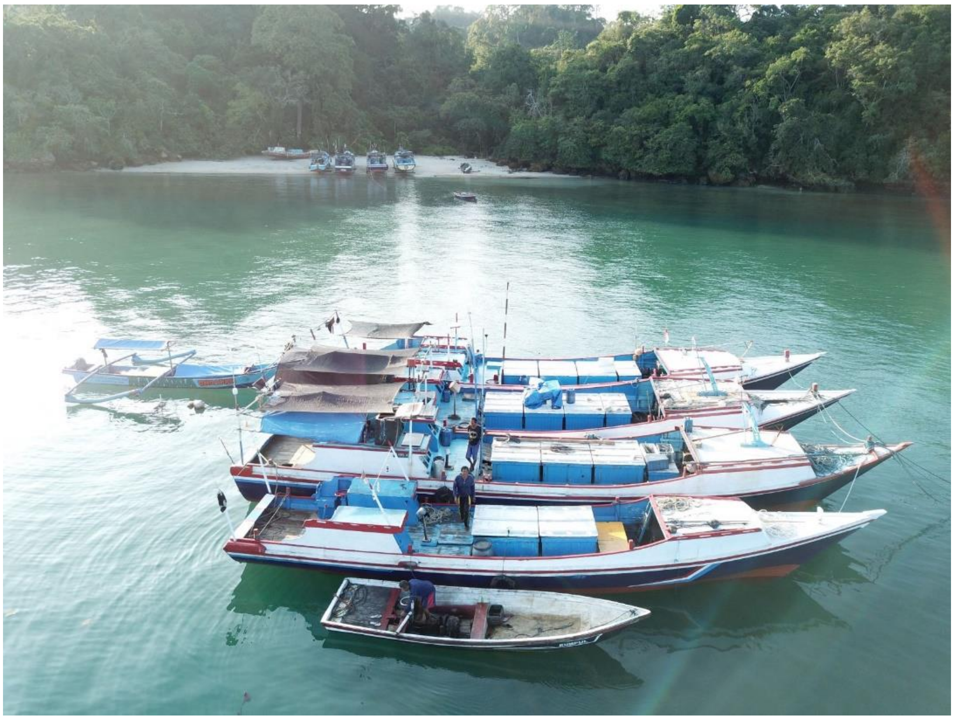


Figure 2. Typical medium-scale tuna handline fishing vessels.

Handline fishing fleets share fishing grounds with other fisheries, such as mini purse seine fishing fleets and outrigger fishing fleets, based along the south coast of Java, and Jakarta industrial purse seine fishing fleets based in North Java. Mini purse seine and outrigger fishing fleets deploy their FADs closer to the coast compared to Jakarta industrial purse seine fleets. Jakarta industrial purse seine fleets also share their FADs with handline fishing fleets (Widodo et al., 2023, Anggawangsa et al., 2023).

1.3 FADs as Marine Artificial Structure

Man-made structures covered more than 32,000 km^2 of the ocean's seabed worldwide in 2018, with projections suggesting an expansion to approximately 39,400 km^2 by 2028 (Bugnot et al., 2021). FADs and artificial reefs (ARs) are both types of marine artificial structures (Ceccarelli and Hurley, 2022). FADs are deployed in pelagic environments primarily used by fishers to enhance fishing operations by attracting fish to a specific location, thus facilitating their capture and are almost always fisheries oriented. However, they can also serve as valuable platforms for scientific objectives (Brehmer et al., 2019). Moreno et al. (2016)

investigated the potential use of FADs for deploying scientific instruments, such as electronic tag receivers, cameras, and hydrophones to observe pelagic ecosystems: monitoring the movements of pelagic animals, deriving fishery-independent indices of abundance, and monitoring the fish diversity. Meanwhile, ARs serve a broader range of functions, mainly focused on ecological conservation and restoration, habitat creation, recreational opportunities, and enhancement of fish stocks. Designed to mimic the ecological functions of natural reefs, artificial reefs are structures deliberately situated on the seabed to protect, regenerate, aggregate, and enhance marine species populations (Hunter and Sayer, 2009, Walles et al., 2016). There are several types of ARs constructed both intentionally and unintentionally with over 200 different kinds of materials, (Baine, 2001, Schweitzer and Stevens, 2019, Hylkema et al., 2021). Artificial reefs include a variety of structures, from concrete modules, and disposable objects (tyres and porcelain toilets) to decommissioned ships, trains, and airplanes, each varying in dimension and deployment configuration (Gilliland et al., 2023).

There are two general types of FAD: anchored/permanently moored (aFADs) and drifting (dFADs). dFADs are widely used across the world's oceans, primarily in industrial tuna purse seine fisheries. Unlike anchored FADs, which are fixed to the ocean floor, dFADs are allowed to drift with ocean currents for weeks or months and are often equipped with GPS tracking devices to monitor their movement. The distribution of dFADs reflects the migratory patterns of tuna as target species and are used predominantly in open ocean areas far from coastal regions (Moreno et al., 2016). The annual deployment of dFADs across the globe is challenging to quantify precisely but is believed to exceed 100,000, reflecting a trend of increasing reliance on these devices in the fishing industry (Gershman et al., 2015). Meanwhile, aFADs are primarily utilized by small-scale tuna fisheries off the coast around the islands and in the oceanic zones of the Indian Ocean, Pacific Ocean and Mediterranean Sea (Jaquemet et al., 2011, De Domenico et al., 2023).

Regardless of the potential benefits of FADs, their increasing frequency worldwide has given rise to concerns regarding their possible negative impacts, including overexploitation of tuna stocks, high catches of juvenile tunas, bycatch, marine pollution, and ecosystem disruption (Amandè et al., 2010). The widespread use of FADs by industrial fishing operations negatively affects small-scale fishers and coastal communities. These communities often rely on traditional, sustainable fishing methods and may find struggle to compete with industrial fishing operations (Pollnac, 2007).

1.3.1 Why Do Fish Gather Around FADs?

The aggregation of many species of pelagic fish in great numbers around floating objects is a common and natural behaviour in the world's tropical and subtropical oceans. This phenomenon has been observed since Ancient Greek and Roman times. A painted vase from the Greek Geometric period (8th century B.C.) was found in Ischia Island depicting aggregations of fish under the floating corpses of shipwreck victims (Castro et al., 2002). Moreover, in the 2nd century a young Greek poet Oppian wrote Halieutica (On Fishing) dedicated to the emperor Marcus Aurelius consist of five lesson poetry book about the behaviour of fish and other marine species (books 1-2) and the art of fishing (books 3-5) (Bekker-Nielsen, 2005, Taquet, 2013). He described the behaviour of pelagic fish in the Mediterranean Sea and the use of floating objects to catch dolphinfish. The floating objects known as "logs" by fishers and fishery biologists, refers to any natural or artificial object or residue floating at the sea surface like algae, jellyfish, kelp, whale corpses, branches of trees originating in rivers, vegetal debris, boards, destroyed fishing gear, housing, and including man-made objects built and deployed by fishers for fishing purposes (FADs) (Fréon and Dagorn, 2000, Castro et al., 2002).

A total of 333 species belonging to 96 families in tropical and subtropical oceans of the world have been found attracted to floating objects (Castro et al., 2002). The first scientific study to categorise animal aggregations under and around floating objects was carried out by Kojima (1960) off Hamada, Japan. He observed that dolphinfish were one of the common species attracted to bamboo rafts. Furthermore, Parin and Fedoryako (1999) classified the assemblage under floating objects into three categories of spatial distribution: Intranatant species (<50 cm from the object), extranatant species (50 cm – 2 m from the object) and circumnatant species (>2 m from the object) Fréon and Dagorn (2000) adopted a similar classification with different distance categories: within 2 m for the intranatant species, 10 to 50 m for extranatant species, and within 50 m to several nautical miles of a FAD for circumnatant species. However, some species were found in more than one of these assemblages, species-specific details could not be determined (Fréon and Dagorn, 2000, Moreno et al., 2007c). Castro et al. (2002) categorized fish behaviour based on the distance from floating objects and their dependency on these objects. Fish were classified as "aggregated" when they lived close to the floating structure and were highly dependent on it. Conversely, fish were considered "associated" if they were found relatively far from the structure, with unclear dependency on the object.

Different species of fish at various development stages are aggregated or associated around floating objects (Capello et al., 2012). Several theories have been advanced to explain this aggregative and associative behaviour, but for most of the species it remains poorly understood (Table 2). The most likely motivations are a combination of predator avoidance, social interaction, and feeding (Filmalter, 2015).

Table 2. The reasons for fish to aggregate or associate around floating objects, according to Castro et al. (2002) and Fréon and Dagorn (2000).

Motivation for the relationship	Hypotheses
Aggregated	Protection from predators
	Availability of food
	Reference point for fish
	Visual stimulus in an optical void
	Schooling companion
	Substitute of the sea-bed species not adapted to a pelagic life
	Negative phototropic response of fish to shadows
	Spawning substrates
	Cleaning stations
	Resting areas
	Seeking shade
	Comfortability stipulation
Associated	Meeting point
	Indicator-log
	Availability of food
	Resting areas
	Geographical references
	School recomposition
	Comfortability stipulation
	Predator avoidance

Almost all ontogenetic stages of fish have been recorded aggregated or associated around floating objects, however a review by Castro et al. (2002) concludes that 80% of the species are juveniles and less than 20% are adults (Parin and Fedoryako, 1999). Robert et al. (2012) found that juveniles stayed longer at FADs compared adult fish. It was assumed that floating objects serve as important habitat in the pelagic environment for the early developmental stages of many coastal as well as pelagic species (Sinopoli et al., 2023). Fish use floating structures as vehicles for the dispersion of eggs, larvae, and juveniles to other areas and to increase survival rate in the pelagic environment which is characterized with highly limited food availability and lack of refuges (Castro et al., 2002, Hunter, 1968, Parker and Tunnicliffe, 1994). The larvae and juveniles of non-pelagic fish are recruited beneath floating objects when these objects are located in coastal waters, including using the float as a substitute for a reef or seabed/ substratum (Castro et al., 2002, Hunter and Mitchell, 1967). During their most vulnerable stages of development, fish may benefit from the direct and indirect role of floating objects as a food provider and have an increased chance of survival (Sinopoli et al., 2023). Fouling organisms, through a process known as rafting, utilize floating objects as habitat for colonisation, and many fish have been observed preying intensively on these rafting flora and fauna. Common rafting fauna include isopod, amphipod, and decapod crustaceans (Ida, 1967, Safran and Omori, 1990, Shaffer et al., 1995). According to an experimental study by Nelson (2003), the presence of a fouling community on a floating object significantly increased the number of the fish assemblages compared to those lacking fouling organisms. A total of 387 taxa have been found rafting on floating structures in all major oceanic regions, and predator-prey interactions are very common between aggregated/ associated species and those rafting organisms (Kiessling et al., 2015, Thiel and Gutow, 2005). Fish drifting along with natural floating objects may also obtain advantages by being passively transported to convergence zones where planktonic food accumulates (Pattrick et al., 2021, Whitney et al., 2021). Thus, a drifting FAD may represent a means of reaching relatively rich areas or act as a good indicator of productive environments (Bakun, 2006). Ibrahim et al. (1996) and Vassilopoulou et al. (2004) found that the stomach contents of fish caught at FADs revealed various phytoplankton and zooplankton from the epipelagic layer and the absence of any rafting organisms.

Floating objects have a function for protection from predators in several different ways: the structure provides direct shelter for aggregated fish, making the silhouette of the fish difficult to see by predators below, protecting a school’s blind zone from approach by predators, through camouflage and mimicry, and other unexplained mechanisms of interference with a predator’s ability to capture prey (Breder, 1942, Dooley, 1972, Gooding and Magnuson, 1967, Hastings et al., 1976, Hunter and Mitchell, 1967, Mitchell, 1970, Mortensen, 1917, Murray et al., 1985, Randall and Randall, 1960, Soemarto, 1960, Wickham and Russel, 1974, Wickham et al., 1973)

Unlike the aggregative and associative behaviour of small (demersal/reef or pelagic) and juvenile fish that are largely driven by protection from predators, adult large fish such as tuna and dolphinfish are associated with floating objects for foraging (Arenas et al., 1992, Gooding and Magnuson, 1967, Hunter, 1968, Wickham et al., 1973). Another hypothesis proposed by Fréon and Dagorn (2000) suggests that schooling pelagic species like tuna use floating objects as spatial reference points to facilitate schooling behaviour and form larger schools (the meeting-point hypothesis). Girard et al. (2004) found that tuna wander in the ocean until they detect a FAD and, when within a radius of about 10 km, orient themselves toward it, attracted by the sound produced by the FADs.

1.3.2 Characteristic of FADs in Indonesia

Similar to anchored FADs used by fisheries in other countries, Indonesian aFADs consist of four essential components: the surface float, the mainline connecting to the seafloor, the subsurface attractor, and the anchor (Widodo et al., 2016). aFADs used in Indonesia, particularly in the Indian Ocean, are adapted to local conditions, availability of materials, and sustainability considerations. The float is composed of a cylinder of expanded polystyrene (EPS), approximately 1.5 m^3 in size, and is typically wrapped in pieces of nets or old motorcycle tyres. EPS replaced steel pontoons in earlier designs due to cheapness and the greater buoyancy possible for the same weight of float (Bearzi et al., 2023). The float is tethered to large concrete blocks that are dropped to the sea floor at depths of approximately 1,500 to 3,000 meters (Figure 3). Each block (60-80 kg) includes embedded ropes or motorcycle tyres serving as attachment points, with 25 to 40 blocks connected to create an anchor weighing a total of 2 to 3 tonnes (Proctor et al., 2019). To attract fish and encourage tuna to aggregate, coconut leaves are attached beneath the float as a subsurface attractor. The use of natural attractors, such as coconut leaves (*Cocos nucifera*) and palm fronds (*Nypa fruticans*), offers an environmentally sustainable alternative to synthetic materials like plastic, which have been banned. The main expense in deploying an aFAD arises from the mooring line; typically making up at least 70% of total costs, and a greater percentage in deeper water (Natsir and Agnarsson, 2018). The ownership of FADs can be broadly categorised into three main types: FADs provided by local government (Province, Regency), FADs owned by a local fishing association or fishers group, and private FADs (Proctor et al., 2019).

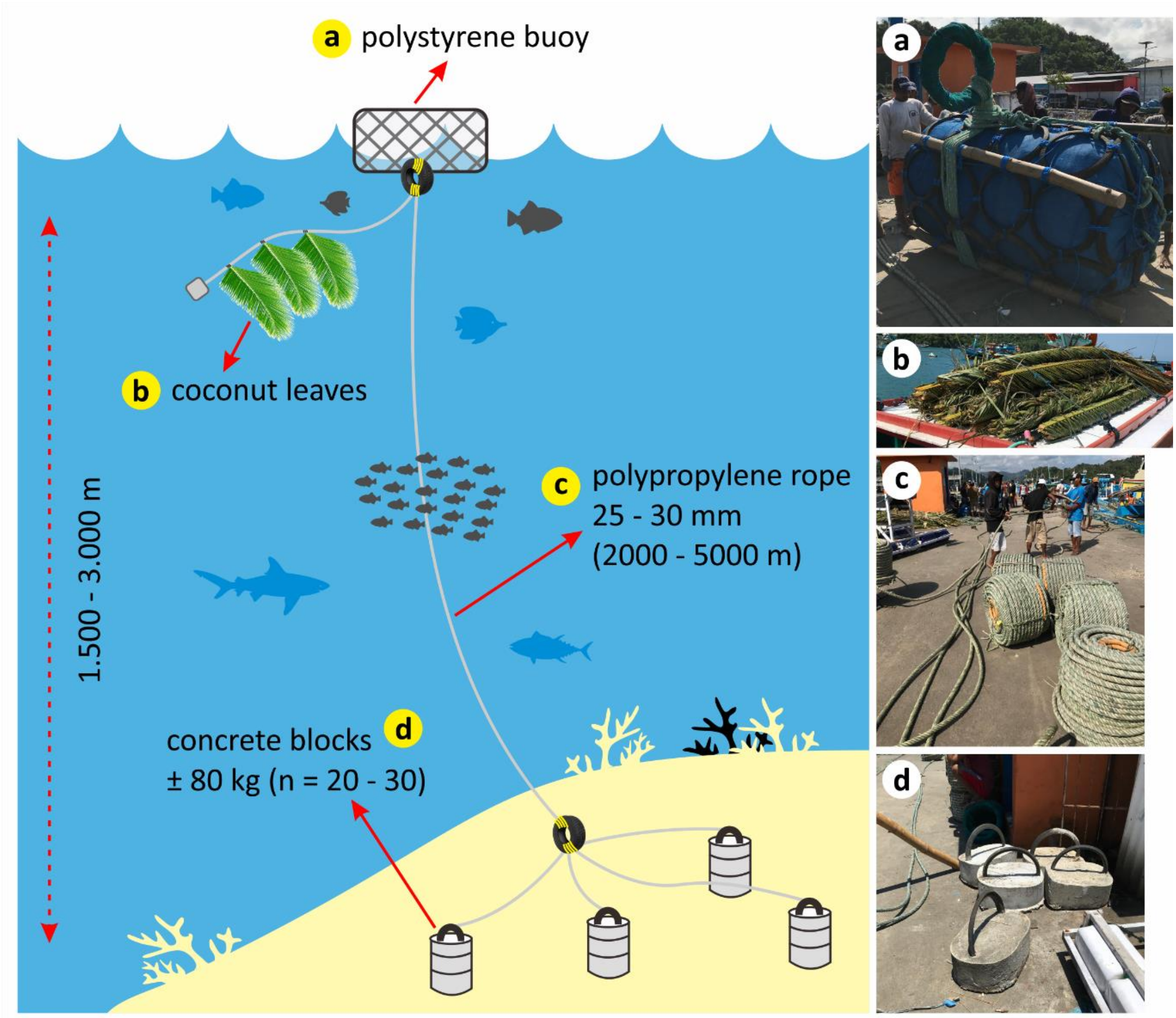


Figure 3. Construction of Indonesian deep-water anchored FAD.

1.4 Fishers' Behaviour and Fish Behaviour Associated with FADs

1.4.1 A Mixed-Methods Approach for a Complex Fishery

Managing fisheries essentially means managing people, making the understanding of fisher behaviour and fishing fleet dynamics crucial for sustainable fisheries management and to prevent the collapse of fisheries (Hilborn, 1985). However, budget and human resource constraints often restrict efforts to monitor fisher behaviour, particularly in developing countries. Moreover, obtaining reliable information on fisher behaviour and accurately identifying the spatiotemporal distribution of their efforts has become increasingly challenging due to the diversity of fishing techniques and the highly varied catch composition (Mendoza-Carranza et al., 2018). Therefore, integrating a diverse range of knowledge sources, including Indigenous, local, and scientific knowledge, is essential. Knowledge integration enhances the evidence-base for policy advice, decision-making, and environmental management (Alexander et al., 2019). Methods to integrate diverse knowledge systems include: (i) community-based participatory research; (ii) mixed-method research; (iii) ethnographic studies; and (iv) simulation modelling (Alexander et al., 2019).

Mixed-methods research aims to integrate diverse perspectives by consistently incorporating both qualitative and quantitative approaches to enrich understanding in both theory and practice (Johnson et al., 2007, Creswell and Creswell, 2005). Integration of quantitative and qualitative data at the design level can be achieved through three fundamental approaches: (i) exploratory sequential; (ii) explanatory sequential; and (iii) convergent designs (Creswell and Creswell, 2005, Fetters et al., 2013). In an exploratory design, qualitative data are collected and analysed first, which then leads to a second quantitative phase where the preliminary findings can be tested. Conversely, in an explanatory design, the process begins with collecting and analysing quantitative data, followed by qualitative methods to further explain the initial quantitative results. Both designs involve a two-phase data collection process, which differs from the convergent design, where quantitative and qualitative data are collected and analysed separately but in parallel within a similar timeframe and then evaluates the results to see if the findings confirm or conflict with each other (Creswell and Creswell, 2005, Creswell et al., 2008, Fetters et al., 2013).

Free et al. (2015) demonstrated that a mixed-method approach can effectively evaluate fisher behaviour in Lake Hövsgöl National Park, Mongolia. By combining surveys of derelict fishing gear with interviews, illegal fishing and its impacts can be assessed effectively and inexpensively. Metcalfe et al. (2017) showed how the combination of cost-effective trackers and community engagement can provide detailed information about the behaviour and fishing grounds of small-scale fisheries in the Republic of Congo. The recent development of low-cost tracking systems facilitates the collection of data on small-scale fishing vessels (Mendo et al., 2019). The tracking data can be analysed to reveal movement patterns, such as speed and turning angle, efficiently generating information on variations in fishing behaviour and the spatial distribution of fishing effort (Mendo et al., 2019, Mills et al., 2007). However, it is difficult to understand fisher motivations or underlying decision-making processes from movement data alone (Foley and Timonen, 2015, Rapp, 2007). Therefore, qualitative methods help to further investigate and understand quantitative data (Tenny et al., 2022). A mixed methods approach provides new insights and understanding that are unattainable with only one method. Mixed methods approaches allow us to answer a broader range of research questions and strengthens the resulting evidence through the corroboration and integration of findings (Dencer-Brown et al., 2022).

1.4.2 Scientific Fish Observation around FADs based on Fisher Ecological Knowledge (FEK) of Fish Behaviour

FEK represents the cumulative knowledge, practices, experiences, and beliefs of local fishers regarding ecological relationships, obtained through extensive personal empirical observation and interaction with local ecosystems (Charnley et al., 2007, Hamilton et al., 2011). Fishers can offer prompt and precise insights into fish behaviour, including spatial patterns, schooling, swimming, and escape behaviour (Moreno et al., 2007b). Because fishers spend the majority of their lives at sea, they have developed a vast body of knowledge through observing, understanding, and accumulating information on fish behaviour to ensure their success (Moreno et al., 2007a).

FEK can offer an alternative, cost-effective source of ecological data for evidence-based decision-making when other data are scarce (Alexander et al., 2019, Archer et al., 2020). Several studies have applied the FEK to identify fish behaviour around FADs in various fishing fleets, including tuna pole-and-line in the Maldives, tuna purse seine and ring net in the Southern Philippines, and Spanish and French tuna purse seine operations in the western Indian Ocean (Jauharee et al., 2021, Moreno et al., 2007b). FEK has also been demonstrated as an effective complement to scientific knowledge, enhancing both confidence and depth of understanding (Moller et al., 2004, Ponton-Cevallos et al., 2022). FEK can be used simultaneously with conventional scientific research in a convergent mixed-methods design and can also serve as a baseline for developing conventional scientific research and monitoring in an exploratory sequential mixed-method design (Bizri et al., 2016, Braga-Pereira et al., 2022).

A sufficient understanding of fish behaviour and distribution is essential for supporting stock assessment and effective fisheries management (Fréon and Misund, 1999, Capello et al., 2016). These research areas have become top priorities for RFMOs (Ehrhardt et al., 2017). There are two main types of data used to assess fish behaviour and stock abundance indices: fishery-dependent and fishery-independent data (Claytor, 2001). Data derived from fishery-independent methods are considered to have fewer biases compared to those from traditional fishery-dependent methods (Claytor, 2001, Rago, 2005, Gimona and Fernandes, 2003).

Fishery-dependent methods, such as FEK and the Catch Per Unit Effort (CPUE) index, are frequently used in FAD studies to analyse fish behaviour and identify trends in abundance. These methods are favoured for their relative cost-effectiveness and ease of data collection (Jauharee et al., 2021, Moreno et al., 2007b, Baidai, 2020, Branch et al., 2006). While fishery-independent approaches may just be modified versions of commercial practices, they can also use active acoustics, passive acoustics (tags), satellite tags, commercial echo-sounder buoys and camera systems (Capello et al., 2016, Jauharee et al., 2021, Santiago et al., 2016, Brehmer et al., 2006, Doray et al., 2006, Josse et al., 2000, Moreno et al., 2007c).

In the vast and remote habitats of pelagic species, where collecting information on behaviour and abundance is challenging, integrating active acoustics and optical camera systems offers more advantages compared to other techniques such as fishing experiments (Boldt et al., 2018). Both methods are non-destructive and can complement each other (Scoulding et al., 2023, Ernst et al., 2017). Acoustic echo integration and echo counting enable both absolute and relative abundance estimates over large sampling volumes (Conners and Schwager, 2002, Godø, 2009). However, acoustic methods face limitations in identifying acoustic targets and rely on species and length distribution data to convert acoustic backscatter into fish density (Simmonds and Maclennan, 2008). The stereo-video camera systems have proven effective for verifying acoustic targets of fish species and measuring their lengths (Santana-Garcon et al., 2014, Boldt et al., 2018, Ernst et al., 2017).

The first attempt at fish abundance estimation using acoustic methods was reported in 1950. Subsequently, since the 1970s, many countries have developed acoustic survey programmes for their main pelagic stocks and have used the acoustic data to correct fishery-dependent data (Simmonds and Maclennan, 2006, Fernandes et al., 2002, Massé and Gerlotto, 2003). Acoustic approaches have been adopted by many research and management organisations to the estimate fish populations and assess their behaviour in the sea and fresh waters (Appenzeller and Leggett, 1992, Simmonds and Maclennan, 2006). Moreover, the applications of video-based methods in fisheries research vary from conducting basic biodiversity assessments to employing of calibrated multi-camera systems (videogrammetry) for analysing complex fish behaviour: swimming, schooling, feeding and territorial actions (Neuswanger et al., 2016). Understanding fish behaviour is crucial for mitigating the impact of fishing on fish populations and ecosystems (Diaz Pauli and Sih, 2017).

The calibration process of multi-camera systems plays an important role in achieving a high degree of measurement accuracy and precision. It involves identifying both intrinsic and extrinsic parameters: intrinsic parameters relate to lens distortion, while extrinsic parameters define the cameras' relative position and orientation. With these parameters determined, the system can accurately triangulate the position of objects within the scene (Real-Moreno et al., 2024, Harvey et al., 2001). The recent development of affordable high-definition waterproof cameras and the availability of open-sources videogrammetry software have made these technologies more applicable and user-friendly (Struthers et al., 2015, Neuswanger et al., 2016).

1.5 Thesis Aims and Objectives

Despite numerous studies on the behaviour of fish and fishers using FADs worldwide, most of these studies have focused on the large-scale industrial fishery and employed a single scientific method, such as visual or acoustic methods alone (Brehmer et al., 2019, Sinopoli et al., 2012, Macusi et al., 2017, Lennert-Cody et al., 2018, Jauharee et al., 2021, Forget et al., 2015, Trygonis et al., 2016). There is a notable scarcity of detailed scientific literature about small and medium-scale tuna fisheries, particularly regarding their behaviour and the spatiotemporal distribution of their efforts. On the other hand, FEK has underused potential benefits when combined with scientific knowledge to understand fish behaviour around FADs (Vilalta-Navas et al., 2023, Alexander et al., 2019). This study aimed to bridge this gap by employing an explanatory sequential mixed-methods design that combined low-cost satellite trackers (chapter 2) supported with fishers' perspectives (chapter 3) to gain a comprehensive understanding of fishing behaviour in medium-scale tuna hand line fishery in the North-Eastern Indian Ocean, Indonesia. Additionally, studies about fish behaviour around FADs were also conducted through FEK (chapter 3) as baseline for developing scientific research and monitoring of FADs (chapter 4) by integrating acoustic and optical camera systems. The information generated from this study will be valuable in formulating policies and management plans, particularly concerning the regulation of hand line fishery in Indonesia.

The objectives were to:

(i) determine the effectiveness of satellite tracking technologies in identifying actual fishing grounds, fishing activities and the distribution of FADs

(ii) identify fishing tactics and fishing strategies (fishing behaviour), including decision-making processes and motivations behind them.

(iii) test a novel technique that combines acoustics and an ROV stereo-camera system for observing behaviour and estimating the relative abundance estimation of fish around FADs.

(iv) compare FEK of fish behaviour with scientific knowledge derived from acoustic and stereo-camera system.

Chapter 2: Vessel Behaviour Identification

2.1 Abstract

The medium-scale handline fishery on the South Coast of Java is unique, employing multiple fishing gears and techniques with relatively small boats to fish for tuna species in offshore waters. Deep-water anchored Fish Aggregating Devices (FADs) are used to attract tuna, supporting their fishing operations. Fish schools aggregate around the FADs, creating artificial resource patches in the pelagic habitat of the oceans. These artificial patches can be located more easily and quickly than free-swimming schools, thus minimizing search time and operating costs. However, the weak management system of this fishery results in limited information about their fishing behavior and the spatial distribution of fishing effort. In this study, we use low-cost satellite tracking technologies verified with observer data to identify actual fishing grounds, fishing activities, and the distribution of FADs in the handline fishery. Our findings reveal heterogeneity in the fishing behavior of the handline fishery. This variation includes differences in the duration of fishing trips, inter-FAD distances, distances of FADs from the fishing port, traveling time between FADs, and residence times at FADs. An estimated 73 FADs were identified by analyzing tracking data using the optimality model as the theoretical basis. The residence time of fishers increased with patch quality, influenced by multiple variables: fishing coordinates, day of the year, distance of FADs from the fishing port, and the series of fishing days. Our results show that low-cost satellite tracking is a potential tool for providing information on fishing behavior and the spatial distribution of fishing effort, especially for small and medium-scale fisheries in areas lacking conventional cellular networks. A high-resolution position recording time interval is recommended to capture the entire range of fishing activities. Furthermore, understanding fisher behavior is essential for effective management.

2.2 Introduction

Anchored FADs are used extensively in the Indian Ocean by Indonesian tuna fishing fleets. These fisheries span a broad geographical range in the eastern and north-eastern Indian Ocean, covering the high seas, Indonesia's territorial waters, and its Exclusive Economic Zone (EEZ). The main challenge of FAD fishery management in Indonesia, particularly for medium and small-scale fisheries, is the lack of information regarding how and where anchored FADs are used. Understanding harvesting behaviour around FADs and its dynamic factors: regulations, technology, weather, cost, and fish abundance, plays a critical role in supporting effective fishery management (Wilen, 2002).

According to existing regulations (Ministry of Marine Affairs and Fishery (MMAF) Ministerial Decree No 18/2021), FADs cannot be deployed and utilized without a FAD license issued by the Director General of Capture Fishery (DGCF - MMAF). Despite this regulation, most FADs in Indonesian waters remain unregistered. One of the main issues is that fishers intentionally do not report their FAD locations for reasons of commercial confidentiality. Monitoring and enforcement of offshore FAD fishing are difficult, time-consuming, and costly. (Bailey et al., 2012). In addition, medium and small-scale fishing fleets are not required to participate in the Vessel Monitoring System (VMS) program issued by MMAF, making the identification of fishing grounds more challenging due to limited information about the spatial distribution and dynamics of fishing activities. Catch reports and statistics data provided by fishers are subject of inaccuracy (Bailey et al., 2012). Port-based sampling and observer programs have been conducted annually by MMAF for medium and small-scale fisheries, but only with limited sample sizes.

VMS is an important instrument in Monitoring, Control, and Surveillance (MCS) systems and has been used worldwide to monitor fishing vessel locations and movements, evaluate fishing fleet behaviour, and provide an overview of the distribution of fishing activity for fishery control and enforcement (Chang, 2011, Watson et al., 2018). However, VMS systems require expensive onboard equipment and are often considered unsuitable for medium- and small-scale fishers (Suhendar and Kristófersson, 2012). The low technological capacity of medium- and small-scale fishing fleets, characterized by a lack of permanent energy supply and limited space onboard, also poses a major challenge for VMS system implementation (Tassetti et al., 2021, Tassetti et al., 2022).

Conventional terrestrial tracking technology is also inapplicable for offshore FAD fishery due to its coverage limitations. The cellular network (GSM or 2G/3G/4G/5G) is the most commonly used terrestrial network-based technology for positioning and navigation (Dardari et al., 2012).

It relies on a set of base stations with a maximum coverage range of 10-20 km from the coastline with good GSM coverage These GPS trackers require a SIM card to use the network to send location data (Dardari et al., 2012, Tavares et al., 2023). An example of this tracking system was developed by Tassetti et al. (2021) and Tilley et al. (2020) for monitoring inshore small-scale fishing vessels in the port of Ancona, Italy, and Timor-Leste using Tetronika FMM640 and Pelagic Data Systems (PDS) v1.25c GPS trackers (Hoenner et al., 2022).

The development of satellite-based GPS trackers has enabled practical and affordable vessel tracking in offshore areas not covered by terrestrial tracking technologies. Several satellite trackers are currently available on the market, including the Globalstar Spot Trace®, YB3i YB Tracking, and Garmin inReach®. Among these, the Spot Trace® tracker is the most cost-effective option, with a device price of USD 80 and an annual airtime service cost of USD 143 per device (Tavares et al., 2023, Osat, 2024, Globalstar, 2024). Spot Trace® trackers utilize the Globalstar satellite communication system, which consists of a constellation of 48 low Earth orbit satellites that provide coverage between 70 degrees North and South latitudes (Dietrich, 1997). However, a significant limitation of the Spot Trace® tracker is its short battery life, which lasts approximately up to two months. This presents a challenge for long-term vessel tracking, as the battery replacement process requires minor training (Hoenner et al., 2022, Natsir et al., 2019).

The medium-scale tuna handline fishery on the South Coast of Java is based in six fishing ports (Nurani et al. 2018). This fishery employs FADs, which attract numerous pelagic fish, including both tuna and non-tuna species. Schools of fish aggregate around the FADs, artificially creating resource patches in the pelagic habitat of the oceans. These artificial patches can be located more easily and quickly than free-swimming schools, thus minimizing search time and operating costs, as highlighted by Fonteneau, Pallares, and Pianet (2000). Even though FAD technology reduces the uncertainty for fishers regarding where to fish, the patches created by FADs vary in quality, influencing the decision-making process of fishers on how to select patches, target species, when to leave a patch, and how to move or change location within and between patches, as discussed by Aswani (1998) and Wolfe (2013). Christensen and Raakjær (2006) classify these short-term fishing patterns as fishing tactics. Behavioural ecologists refer to these fishing tactics as foraging decisions (Kramer 2001).

Fishers are assumed to behave as optimal foragers, aiming to maximize the exploitation of resources while minimizing time and cost (Richard et al., 2018). Scientists have been using and testing optimal foraging theory as the theoretical basis for assessing the foraging behaviour of animals, including humans. The Area-restricted Search (ARS) and Marginal Value Theorem (MVT) are optimality models widely applied to study human foraging behaviour in patchy environments. Examples include Nahua mushroom gatherers in Mexico (Pacheco-Cobos et al., 2019), artisanal fishers in the Commonwealth of Dominica (Alvard et al., 2015), Colombian blowgun hunters (Ross and Winterhalder, 2018) and human visual search in berry picking (Wolfe, 2013).

A forager should adopt search strategies to optimize the search efficiency (Humphries et al., 2010). In environments with patchily distributed resources, where resource locations are spatially autocorrelated like FADs in the pelagic ocean, ARS strategies are optimal (Hills et al., 2013). In contrast, Levy flights and Brownian search strategy are efficient for encountering sparse, randomly distributed, and abundant resources, respectively (Humphries et al., 2010, Ross and Winterhalder, 2018). The ARS search strategy is characterized by intensive and extensive search patterns performed by foragers as an adaptive response to resource patches. Active search for resources is energetically costly. Allocating a more intensive or detailed search to cover a small area (localized) with slower speed and increased sinuosity of movement following the discovery of a resource patch (intrapatch search) will improve search efficacy. Additionally, performing a less detailed search to cover a large area with more rapid and linear movement after failing to encounter resource patches over a sufficient period of time (interpatch search) will minimize search time and increase encounter rates. (Benhamou, 1992, Knell and Codling, 2012, Pacheco-Cobos et al., 2019, Ross and Winterhalder, 2018).

After efficient foragers encounter a resource patch and spend more time performing interpatch searches, they face a declining rate of return as they continue to exploit the patch. They need to balance the benefits of remaining at the current patch against the prospect of performing an interpatch search to identify a better-quality resource patch if they leave (Busch and Olofsson, 2012). MVT predicts the optimal foraging time within a patch. A forager leaves a patch when the marginal rate of return for foraging in that patch equals the mean return for a set of visited patches. Thus, patch quality should affect patch-leaving decisions (Figure 4) (Charnov, 1976).

Alvard, Carlson, and McGaffey (2015) implemented the partial sum method and the max-min algorithm to generate ARS and travel segments of the artisanal FAD fishery in the Commonwealth of Dominica. They used movement data extracted from GPS loggers mounted on fishers' boats to correctly identify FAD patches through a methodological framework consisting of four steps: collection of GPS data, calculation of the cumulative sum (CumSum) of speed deviations, segmentation with the max-min algorithm, and ground truthing (Alvard and Carlson, 2020).

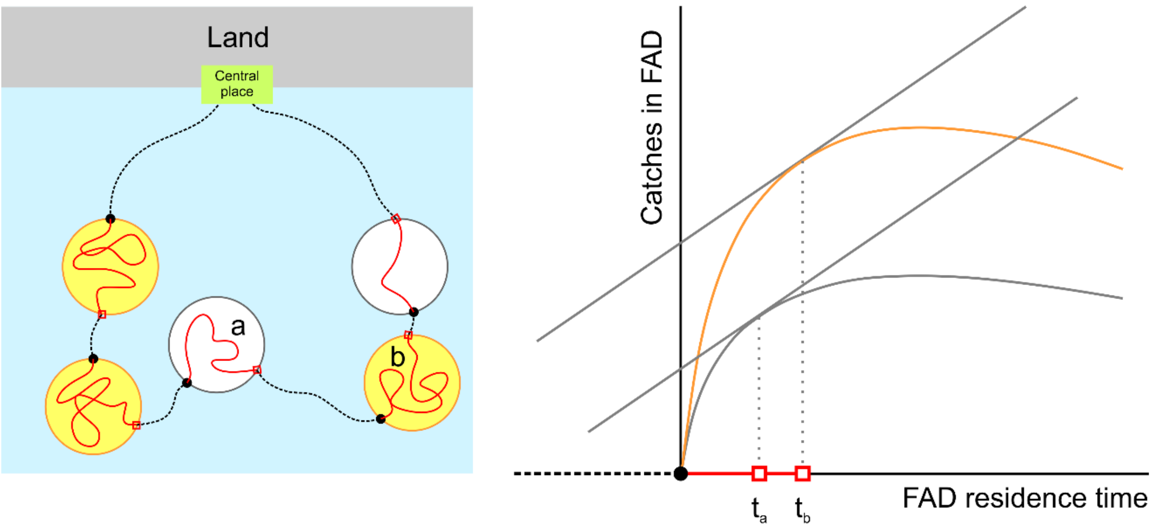


Figure 4. Marginal Value Theorem applied in handline tuna fishery. Left: A fisher leaves the fishing base (central place) and performs interpatch search (dashed black line), entering a patch (black circles) and spending some time exploiting it (red line) or conducting intrapatch search before deciding to leave in search another patches (red square). There are heterogeneous qualities of FADs, good quality FADs (Yellow) and bad quality FADs (white), with interpatch search (dashed black line) and intrapatch search (red line). Right: fishers should spend more time on good FADs ($t_b > t_a$). Modified from Charnov, E.L, 1976 and Calcagno, 2019.

This chapter aimed to determine effectiveness of satellite tracking technologies in identifying actual fishing grounds, fishing activities and the distribution FADs guided by the following three objectives: (i) test ARS to distinct search pattern, (ii) define factors affecting residence time in FADs and (iii) test the MVT model.

2.3 Methods

2.3.1 Data Collection

Permission to use satellite-based GPS trackers (Spot Trace®) on selected hand line vessels was granted by the Research Centre for Fishery (RCF) under the Ministry of Marine Affairs and Fishery (MMAF), Republic of Indonesia. RCF – MMAF installed the tracking devices after thoroughly informing the fishers about the purpose of the data collection and obtaining their oral consent to participate in the study. Subjects were also made aware that they had the option to decline participation and were free withdraw at any time. All data gathered from the vessel tracking devices were kept confidential and made anonymized.

Tracking Data

A total of seven satellite-based GPS trackers (Spot Trace®) were used and distributed across three fishing ports rotationally on fourteen vessels: 2 boats in Palabuhanratu (West Java), 2 boats in Sadeng (Yogyakarta), and 10 boats in Pondok Dadap (East Java) (Figure 5). Non-probabilistic convenience sampling was carried out by distributing tracking devices to vessels that were available in the fishing port. Tracking data were collected from December 2017 to August 2021.

Satellite-based GPS trackers were used to detect the movements of tuna handline vessels due to their ability to be used almost everywhere, without the coverage limitations associated with terrestrial GSM tracking technology, which relies on a cellular network (Figure 5). Spot Trace® is a satellite tracking device developed by SPOT, LLC, a subsidiary of Globalstar, Inc. This device is designed primarily to track assets and provide near real-time position information. It is the only device on the market that uses a Low Earth Orbit (LEO) satellite communication system at an affordable cost. It has been utilized in a wide range of studies for coastal and open-ocean applications, including tracking positions and monitoring ocean surface drifters, riverine litter, oil spills, fishing vessels, and air balloons (Page et al., 2019, González-Rocha et al., 2021, Carlson et al., 2017, Hoenner et al., 2022, Ruiz et al., 2022, Gemignani and Marcuccio, 2021, Hough, 2023, Jacob et al., 2022).

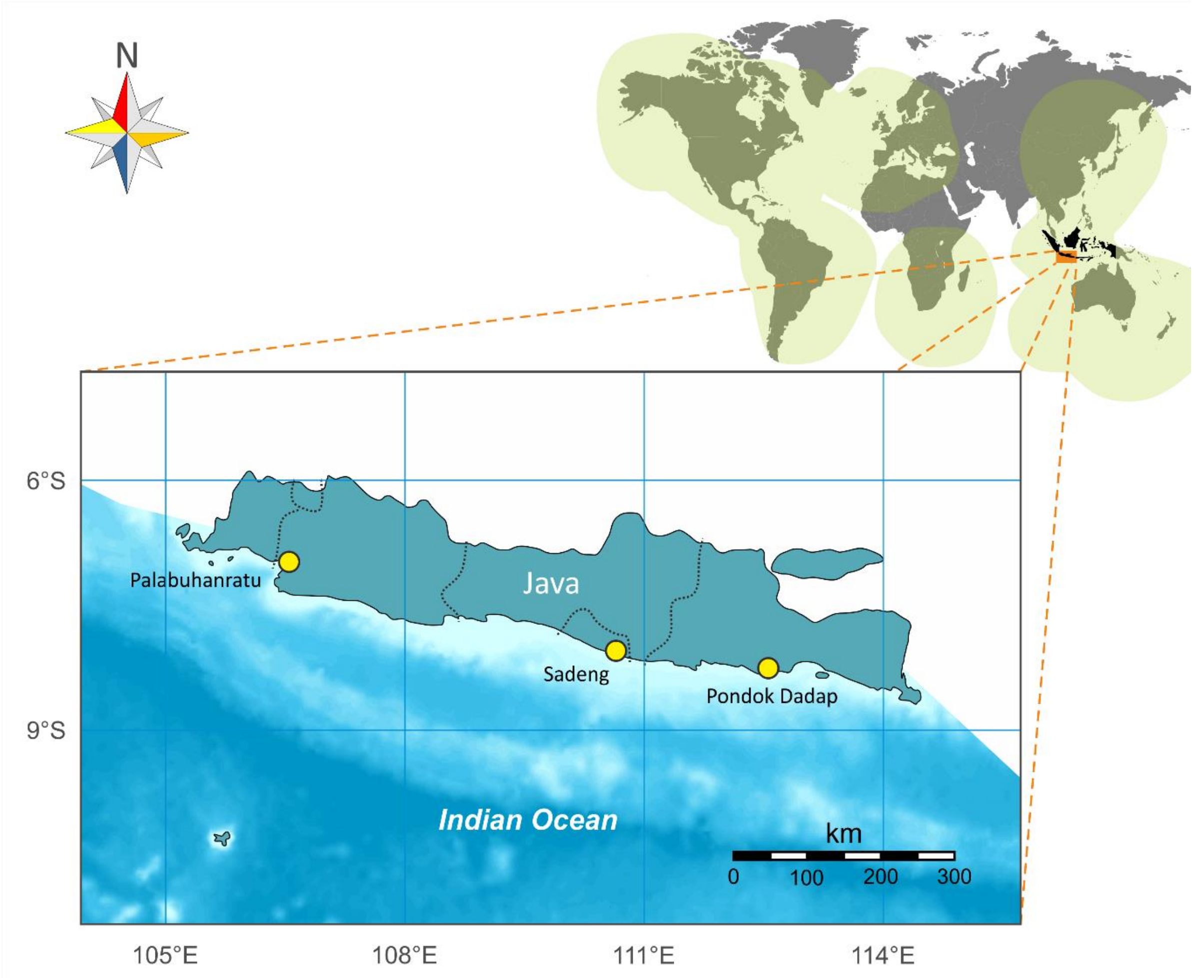


Figure 5. Fishing port locations where the tracking devices distributed (yellow circles) and Spot Trace® covering areas (transparent green).

Spot Trace devices transmit GPS position and time via the Globalstar communication satellite system, which operates worldwide between 70° North and South latitudes (Dietrich, 1997). The system consists LEO satellite constellation (48 satellites at a height of 1,410 km) combined with cellular Code Division Multiple Access (CDMA) technology (Richharia and Westbrook, 2011). It offers reliable tracking capabilities and is cost-effective, easy to use, robust, and small (6.83 cm x 5.13 cm x 2.14 cm; 87.9 g) (Figure 6). The tracker devices were mounted onboard the boats with no cover and pointed towards the sky for optimal signal reception. The units have an immersion protection rating of IP67, meaning they can be immersed in water depths between 15 centimetres and 1 meter for up to 30 minutes. This level of protection allows them to be left unhoused without being damaged by waves or spray. The tracking intervals can be set to 2.5, 5, 10, 30, or 60 minutes. However, to maximize battery life, a 60-minute interval was used, allowing for continuous tracking for up to two months. Using a shorter time interval would result in a trade-off with shorter battery life, which was not feasible due to technical issues related to battery replacement. Fishers cannot replace the batteries themselves, and the local fishery officers responsible for distributing the tracking devices have limited time for battery replacement.

Figure 6. Dimension of SPOT trace device used during study.

On-board Observer Data

Observer sampling onboard tuna handline vessels was conducted between July and November 2019 on six tuna handline vessels based in Pondok Dadap - Sendangbiru fishing port (Table 3). Data were collected on paper log sheets documenting the times and positions of all setting and hauling activities. The total weight and number of catches were recorded for all hauls, along with length and weight frequency data from representative samples of each species caught. These data were compared with and verified against the tracking data.

Table 3. Detail information about six tuna handline vessels sampled during observer sampling data.

Vessel	Length (m)	GT (tonnes)	Crew number	Trip length (day)	Capacity (tonnes)
HLS1	18.8	24	5	8	8
HLS2	15.1	13	6	13	6
HLS3	15.4	12	5	14	5
HLS4	16.5	17	5	14	4.5
HLS5	17.5	18	5	17	6
HLS6	16.6	15	5	13	3

2.3.2 Data analysis

Patch Identification and FAD Distribution

The tracking data consisted of coordinate ping positions (where φ is latitude, λ is longitude) and time (date and hour). All individual trips were identified, and only completed trips with both departure and return positions were used for analysis. GPS satellite receivers rely on signals from a certain number of satellites. Consequently, multiple factors can result in signal failures where no position data are transferred (Bertiger and Yunck, 1990). The distance D_t between two coordinate ping positions was obtained using the spherical law of cosines:

$$D_t = \text{acos}\,(\sin\varphi 1.\sin\varphi 2 + \cos\varphi 1.\cos\varphi 2.\,cos\Delta\lambda).\,R \qquad (1)$$

where R is the Earth's radius (mean radius = 3,440 nmi). Furthermore, vessel speed S_t is then simply calculated by dividing distance (D_t) by elapsed time Δt. The partial sum method is used to identify the Area-restricted Search (ARS) as an indicator of resource patches, or spaces within which foraging occurs, in every fishing trip.

$$C_\tau = \sum_{t=2}^{\tau} (S_t - \bar{S}) \qquad (2)$$

where C_τ denotes the cumulative sum of information at time τ.

Knell and Codling (2012) introduced the partial sum method to identify extensive and intensive search movements exhibited by foragers. Alvard et al. (2015), along with Schreier and Grove (2021), demonstrated the effectiveness of this method in differentiating between two modes of movement patterns in artisanal fishing vessels and primates. Intensive search movements are characterized by negative deviations from the mean travel speed and high sinuosity. The partial sum method has been shown to have better accuracy and reliability compared to other methods, such as Moving Average (MA), First-passage Time (FPT), Residence Time (RT), and Fractal Landscape (FL).

Turning points between two different movements in an observation sequence, generated by the cumulative sum equation, can be visually inferred or identified using the max-min (MM) algorithm. This algorithm separates two movement patterns based on speed changes, with the rising cumulative sum curve above the average indicating travel and the falling curve indicating ARS.

The max-min algorithm developed by Knell and Codling (2012) operates as follows:
The current maximum value $C_{\tau max}$ is equal to the cumulative sum at time τ or C_τ. When $C_{\tau+1} > C_{\tau max}$ for step $\tau + 1$, then $C_{\tau max}$ is updated from $C_{\tau+1}$. The $C_{\tau max}$ remains

unchanged if $C_{\tau+1} < C_{\tau max}$ or is classified as a turning point within the time series. The local minimum values are determined by a similar procedure.

The tuna hand line tracking data were analysed using the partial sum method and the max-min algorithm developed by Knell and Codling (2012), focusing solely on speed as the movement path property and the sinuosity of the tracking path, following Alvard and Carlson (2020). Additionally, the distribution of FADs is estimated based on the intrapatch and interpatch search behaviour of tuna handline vessels using density-based spatial cluster analysis (Figure 7).

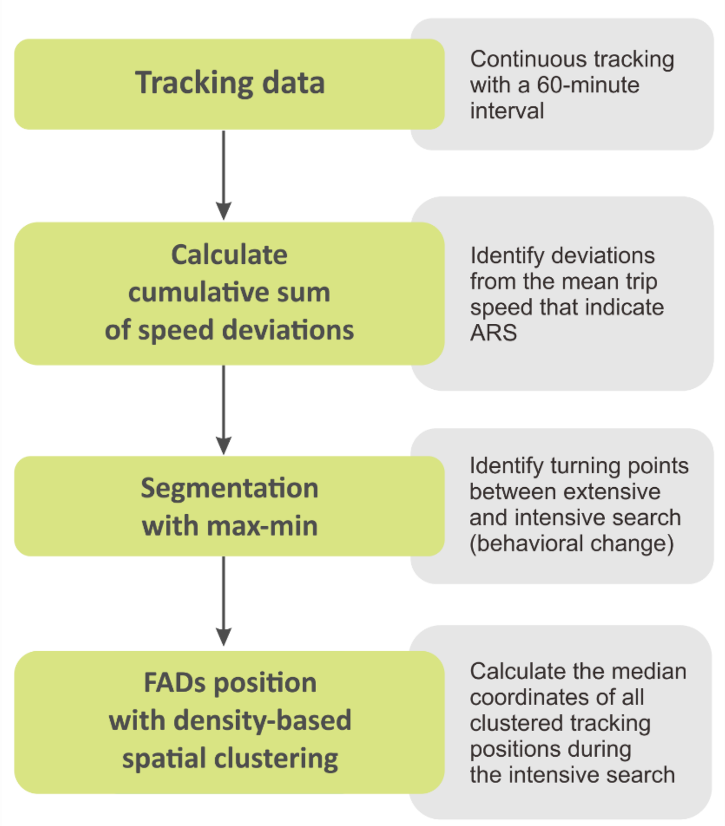


Figure 7. Methodological framework of patch identification and FAD distribution estimates. Modified from Alvard and Carlson (2020).

The density-based spatial clustering algorithm detects the coordinate ping positions within patches that overlap spatially and then organize those positions into clusters by identifying dense regions separated by low-density regions (Liu et al., 2012). Moreover, FAD positions can be obtained by the calculating the median of all coordinate ping positions in one cluster. Density-based spatial clustering analysis was performed using the *dbscan* package in R. Two input parameters are used to define the spatial threshold to form a cluster: the minimum number of points (MinPts) to form a cluster or a dense region and the radius of the neighbourhood *epsilon* (Eps) of a point (Ester et al., 1996, Galán, 2019, Gialampoukidis et al., 2019, Kumar and Reddy, 2016). The MinPts parameter is set to two, meaning that at least two coordinate ping positions are needed to form a cluster, while Eps is defined as the radius of a circular area, assuming that an anchored buoy drifts around within a roughly circular area from the centre (Figure 8) influenced by winds and currents (Imano et al., 2019).

Fishers adopt a slackly anchored buoy system for FAD deployment to cope with the Indian Ocean currents and maintain the buoy at the surface (Fishers, pers. Comm., June 2021). The radius of the circular area (r) was estimated by calculating a simple Pythagorean theorem equation if we know the depth of the water and length of a FAD's rope (assuming the rope is a straight line):

$$r = \sqrt{rope\ length^2 - depth^2} \quad (3)$$

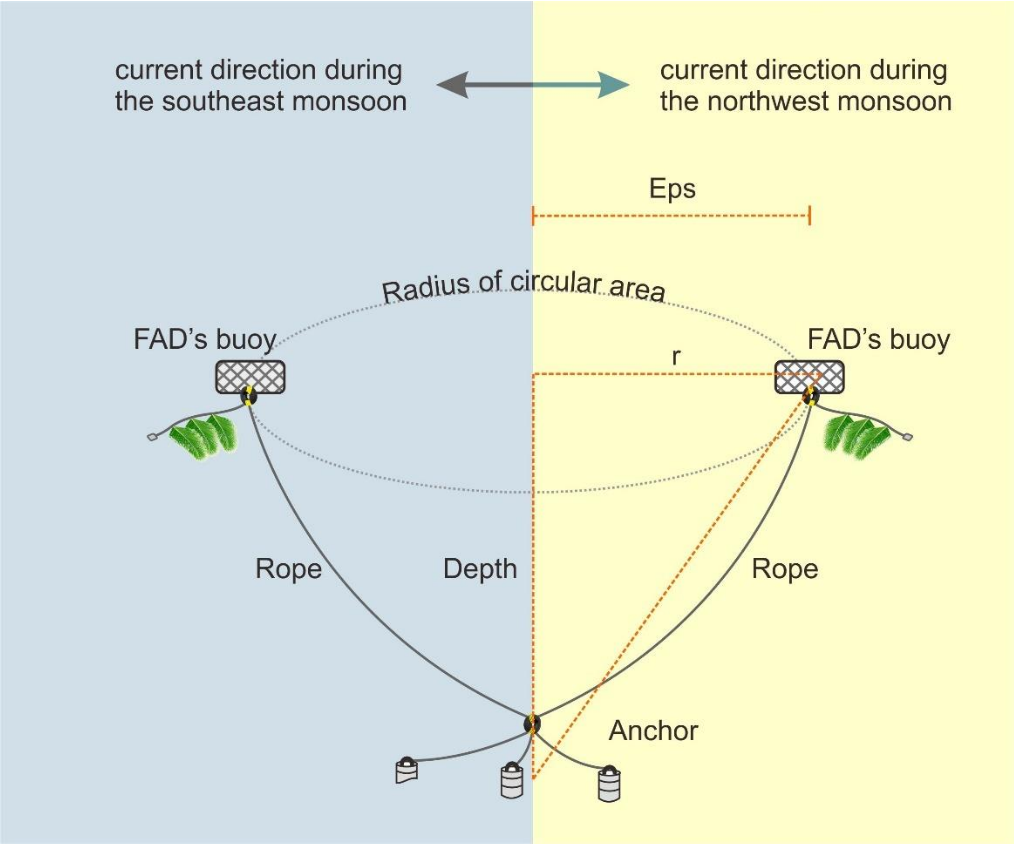


Figure 8. The illustration of the radius of the circular area (r) as the main input parameter for density-based spatial clustering analysis.

Spatial-temporal and Primary Resources GAM Analysis

FADs serving as resource patches in the pelagic habitat of the oceans vary in quality (good and poor). According to MVT, fishers should spend more time on good quality FADs. To predict and understand the factors that may influence the residence time of fishers at these patches, analysis of tracking data and observer data was performed using a generalized additive model (GAM) with the mgcv library in R (version 4.1.1) available at CRAN R-Project (Larsen, 2015).

Five explanatory variables were extracted from the tracking data: coordinates (longitude and latitude), the day of the year (a cyclic feature), distance of patches from the fishing port, the series of fishing days, and the region of the fishing base. These variables were included in the model. The term 'te(Longitude, Latitude),' representing a tensor product smooth, was fitted over a two-dimensional spatial surface, while other smoothing functions utilized spline-based smooths as thin-plate regression splines. The region, as a categorical variable, was included as a linear function. The Restricted Maximum Likelihood (REML) was chosen for the estimation of variance parameters, and the best-fitting distribution was selected from among the Poisson, Tweedie, binomial, and negative binomial distributions based on the fit to the full model. The best-performing model was identified by multi-model inference according to the lowest Akaike's Information Criterion (AIC) value and was compared with null model (intercept only). The model equation is thus defined as:

tw(Patch_Time) = te(Longitude, Latitude) + s(Days, bs = "cc") +
s(Dist_OfPatchesFromPort) + s(DayOfTrip) + Region (4)

Furthermore, single-factor models of total catches (£) as a function of species price and weight gained in patches obtained from observer sampling data were fitted on the patch's residence time:

tw(PatchMinutes) = s(GainMoney) (5)

This model aims to analyse the relationship between the financial gain from catches and the time spent at each patch.

2.4 Results

A total of 2,403 tracking points (pings) were collected from 14 tuna handline boats: 2 boats in Palabuhanratu, West Java; 2 boats in Sadeng, Yogyakarta; and 10 boats in Pondok Dadap, Sendangbiru, East Java (Figure 9). These tracking points are from 42 fishing trips and resulted in 27 complete tracks suitable for analysis. Fifteen incomplete tracks were excluded from the analysis. Of the fishing trips, 47.5% were based in Sadeng, 40% in Pondok Dadap, and 12.5% in Palabuhanratu.

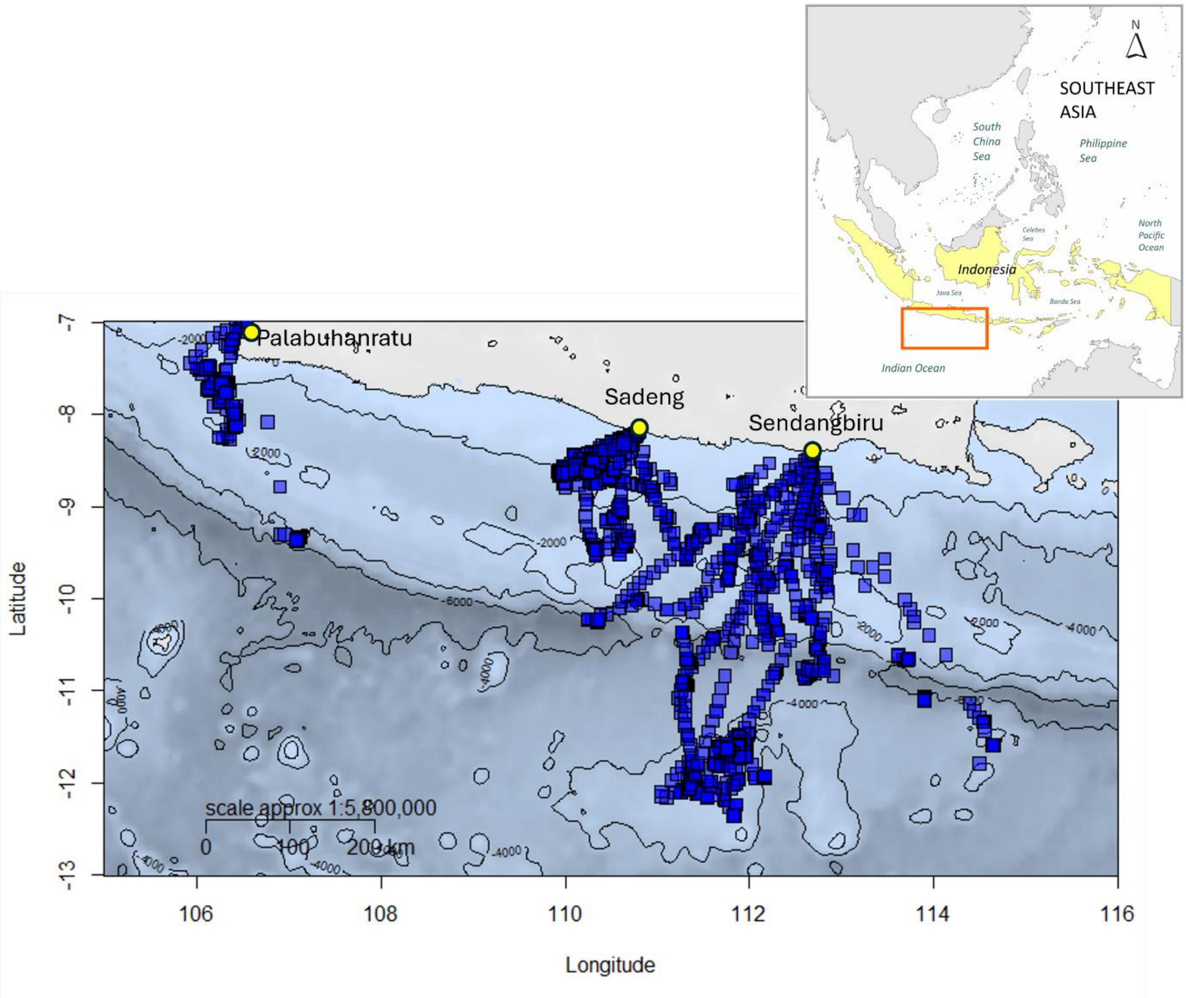


Figure 9. GPS tracking patterns of handline vessels during their fishing operations (blue squares) off the South Coast of Java, Indonesia, illustrate the spatial distribution and movement of the vessels in this region.

2.4.1 Patch Segmentation Based on Extensive and Intensive Searches

The plot of cumulative sums, based on Equation 2, shows a distinct pattern of turning points between two search strategies: extensive and intensive (Figure 10). A positive slope indicates consistent travel at speeds greater than the mean, representing the extensive search period, while a negative slope indicates persistent movement at speeds below the mean, characterizing the intensive search period. The frequency of intensive searches corresponds to the number of patches visited by fishing vessels. The number of intensive searches corresponds to the number of patches visited by fishing vessels. According to ARS theory, intensive search is marked by slower speeds and increased sinuosity of movement, typically occurring after the discovery of a resource patch as the vessel covers a smaller area.

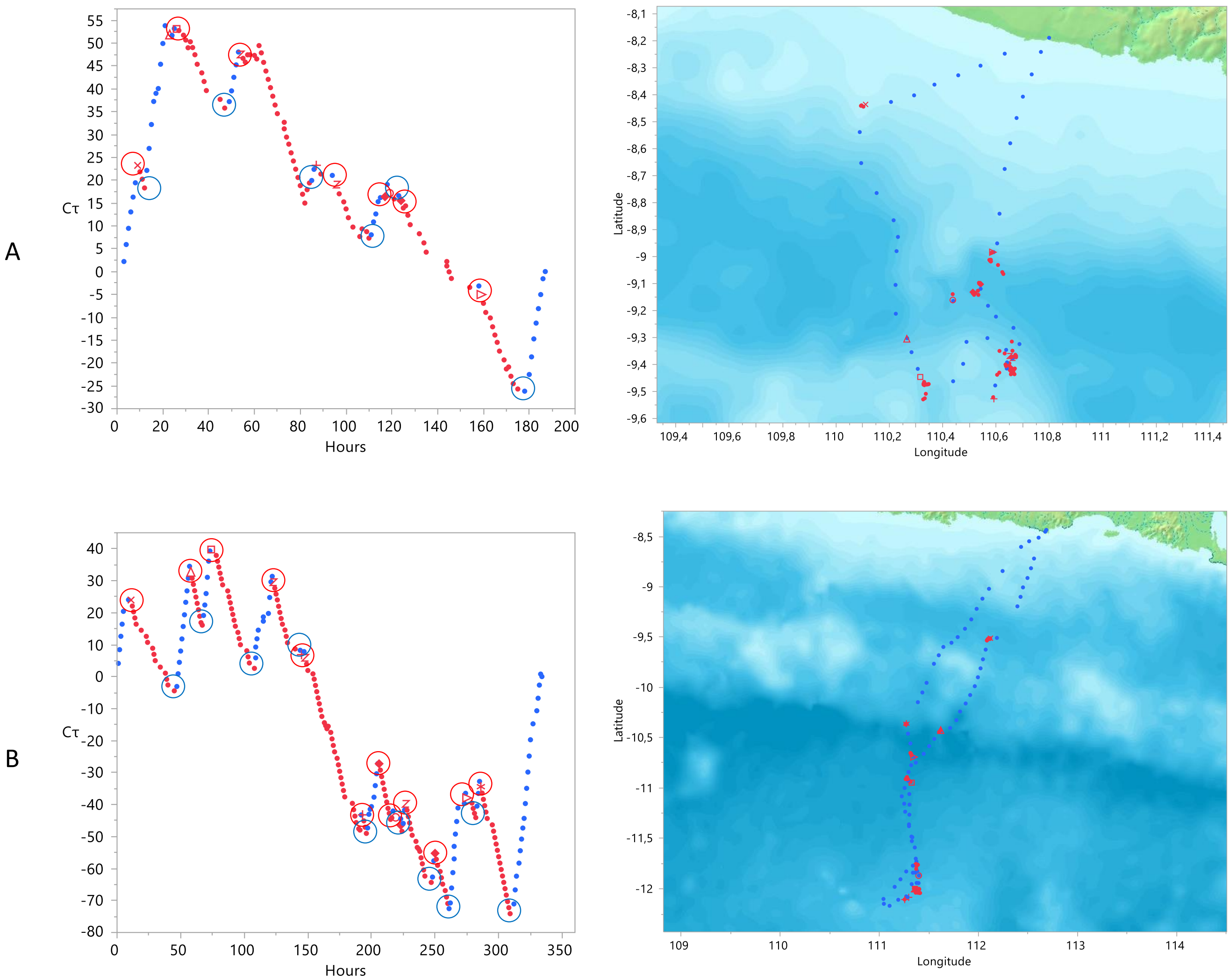


Figure 10. Two examples of track segmentation: extensive search (red dot) and intensive search (blue dot). Turning points between two different movements: the turning point to intensive search/ARS (large red circle) and the turning point to extensive search (large blue circle).

2.4.2 FAD Distribution of Handline

The number of FADs can be estimated by calculating the median of all coordinate positions within a cluster. Each cluster comprises coordinate positions of patches. Approximately 73 FADs were visited by tuna handline fishing fleets: 9 FADs by vessels based in Palabuhanratu, 14 FADs by vessels based in Jogja, and 50 FADs by vessels based in Pondok Dadap (Figure

11). The average distance of all estimated locations of handline FADs was 166.36 ± 119.6 nautical miles (nmi), with inter-FAD distances ranging from 4.27 to 562 nmi. Additionally, 35 FADs (47.95% of the total number) had inter-FAD distances of less than 10 nmi from each other.

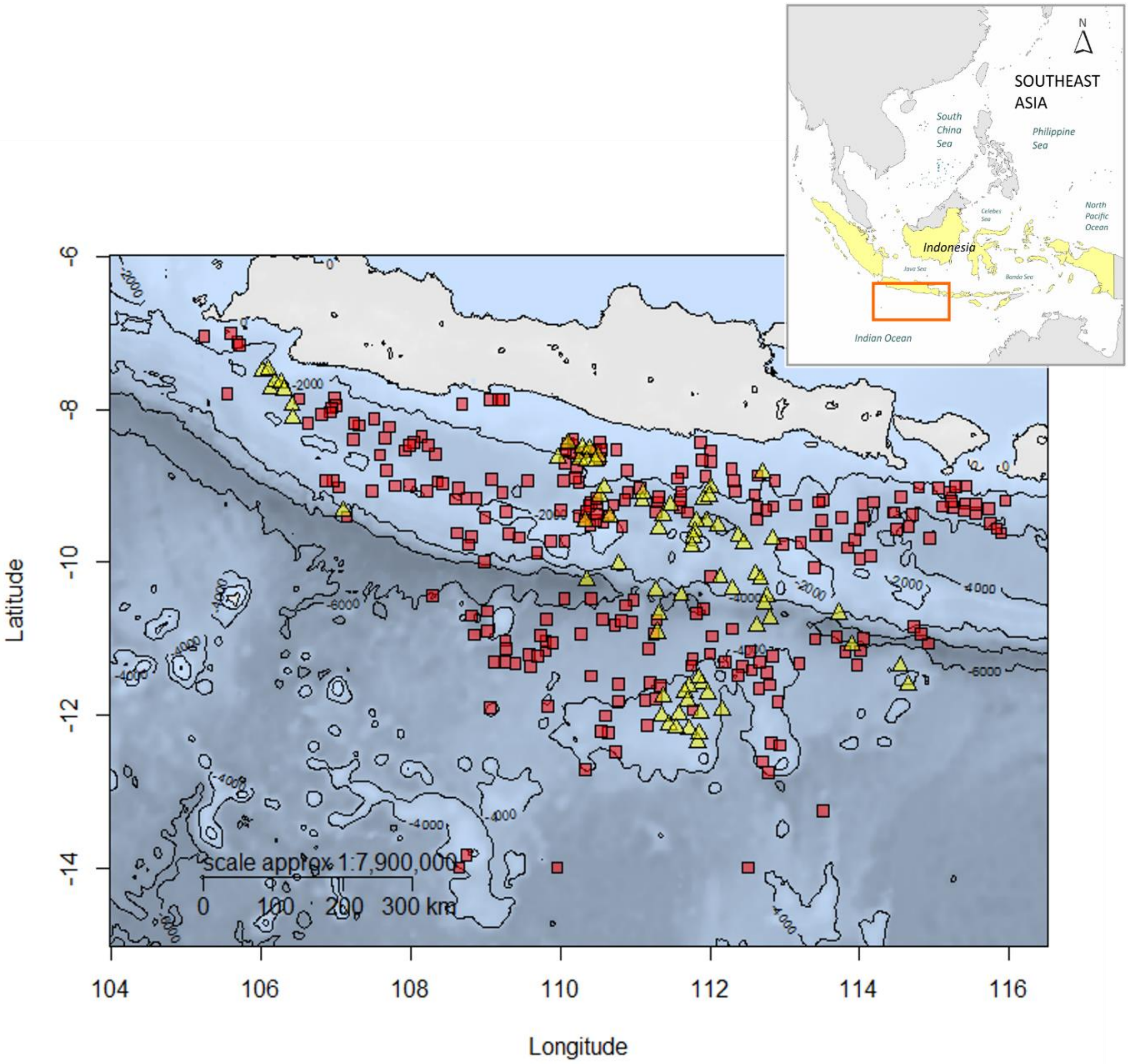


Figure 11. Estimated distribution of FADs utilized by medium-scale tuna handline (yellow) tracked in this study, overlaid with industrial-scale tuna purse seine FADs (red).

2.4.3 Behaviour of Vessels Between Patches

A total of 163 resource patches were visited by tuna handline vessels. Vessels based in Palabuhanratu visited 21 patches, those from Yogyakarta visited 48 patches, and those from Pondok Dadap visited 94 patches (Figure 12). The duration of fishing trips for all vessels ranged from 2.4 to 13.9 days, with an average of 7.3 days (± 2.7 SD). The mean distance from fishing ports to the patches was 109.9 nmi (± 71.1 SD), with distances ranging from 18.7 to

240.1 nmi. On average, vessels spent 5.1 hours (± 4.8 hours) traveling between patches, with times ranging from 0.3 to 22.5 hours. Additionally, the residence time at patches varied from 0.7 hours to 8.6 days, with an average of 0.8 days (± 1.1 SD).

Comparing the patch residence times of vessels from the three different fishing ports, vessels from Palabuhanratu had residence times ranging from 1 hour to 8.6 days (average 1.1 days ± 1.8 SD), vessels from Yogyakarta had residence times ranging from 1 hour to 4.8 days (average 1.1 days ± 1.3 SD), and vessels from Pondok Dadap had residence times ranging from 0.7 hours to 4.8 days (average 0.6 days ± 0.8 SD).

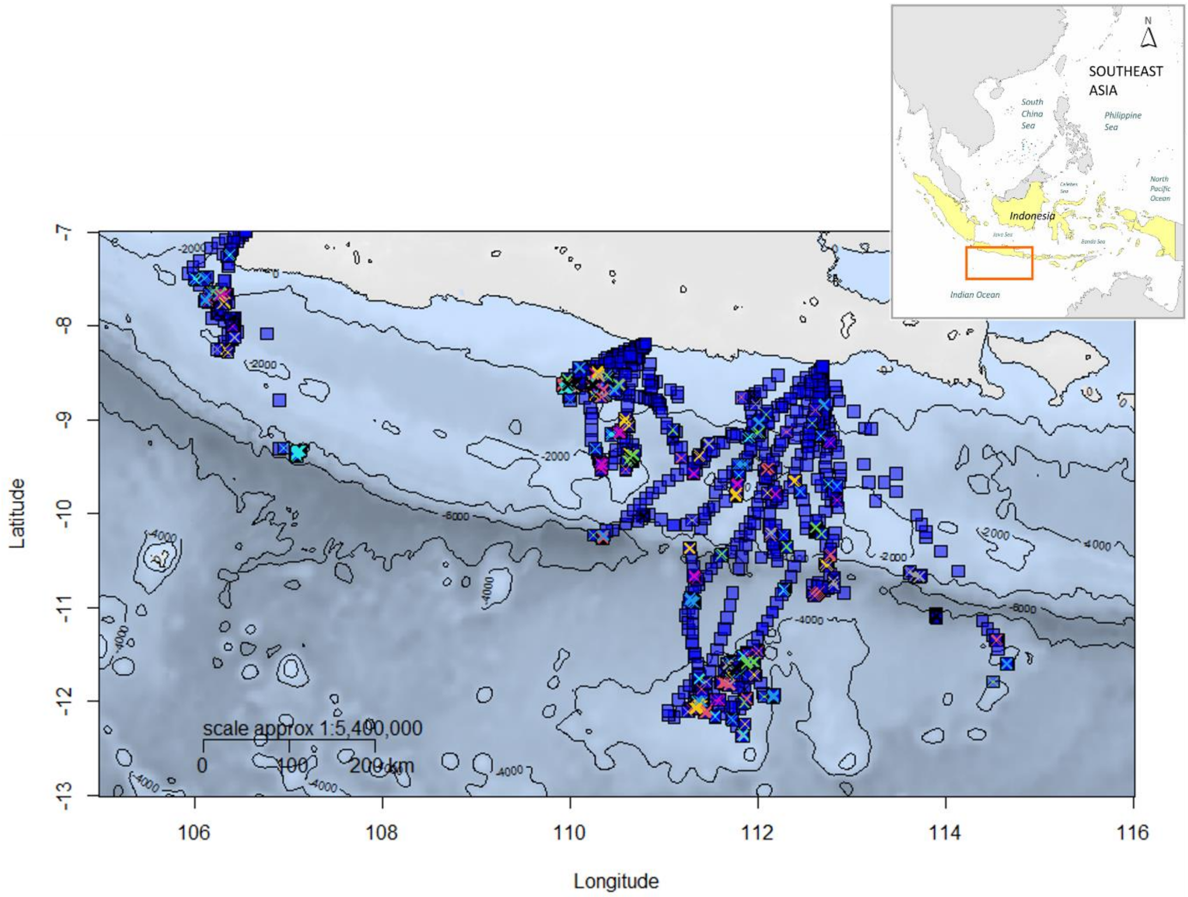


Figure 12. Tracking positions of handline vessels during fishing operations (transparent blue square). The number of clusters indicating the aggregation of intensive search in one area was segmented from the complete tracks and indicated by "x" in multiple colours.

According to observer sampling data, the patch residence time varied from 4 minutes to 21 hours, with an average of 4.7 hours (± 5 SD). Additionally, catches per patch ranged from 0 to 1020 kg, with an average of 120 kg (± 198.6 SD). A total of 13 fish species were captured across all fishing operations, predominantly tuna species: skipjack (*Katsuwonus pelamis)*, bigeye (*Thunnus obesus*), yellowfin (*Thunnus albacares*), and albacore (*Thunnus alalunga)*, respectively.

Spatial-temporal Analysis

No significant collinearity was found among the variables considered in this study. The results of the GAM indicate that the full model, which included the effects of all explanatory variables: longitude, latitude, day of the year (cyclic feature), distance of patches from the fishing port, series of fishing days, and region provided the best fit, with the lowest AIC (1297.96) and the highest deviance explained (28.6%). All variables were significant, except for two levels of the region categorical variable: Palabuhanratu and Yogyakarta (Table 4). The null model had an AIC value of 1340.32.

Table 4. Parameter estimates and significance of the spatial-temporal GAM model for residence time in patches. SE = standard error, df = degree of freedom.

Parameter	Coefficient	SE	t-value	Df	p-value
Parametric terms					
Intercept	3.153	0.225	14.017	1	< 0.001
RegionSendangbiru	-0.928	0.437	-2.123	1	< 0.05
Smoothing terms					
Longitude, latitude				3	< 0.05
Day of year				8	< 0.05
Dist_OfPatchesFromPort				1	< 0.01
DayOfTrip				4	< 0.001

Longitude positively influenced fishers' residence time in patches, with relatively longer residence times observed further east from 106° to 114° E. A dome-shaped relationship was found between fishers' residence time in patches and latitude, with longer residence times occurring further north from 12° to 8.5° S (Figure 13a). The residence time in patches was significantly driven by the day of the year, with monthly trends peaking approximately in August (Figure 13b), whereas the lowest residence times occurred in April. Moreover, the relationship between patch residence time and the distance of patches from the fishing port was linear (df = 1) (Figure 13c), indicating that residence time increased with greater distances from the fishing port. The GAM results also demonstrated a dome-shaped functional relationship between fishers' residence time in patches and the series of fishing days. The number of fishing trips had a positive effect on residence times, peaking at about six days, but showed a negative relationship beyond six days (Figure 13d). Regionally, the shortest residence time was recorded in Sendangbiru, indicated by a lower mean residence time compared to other regions.

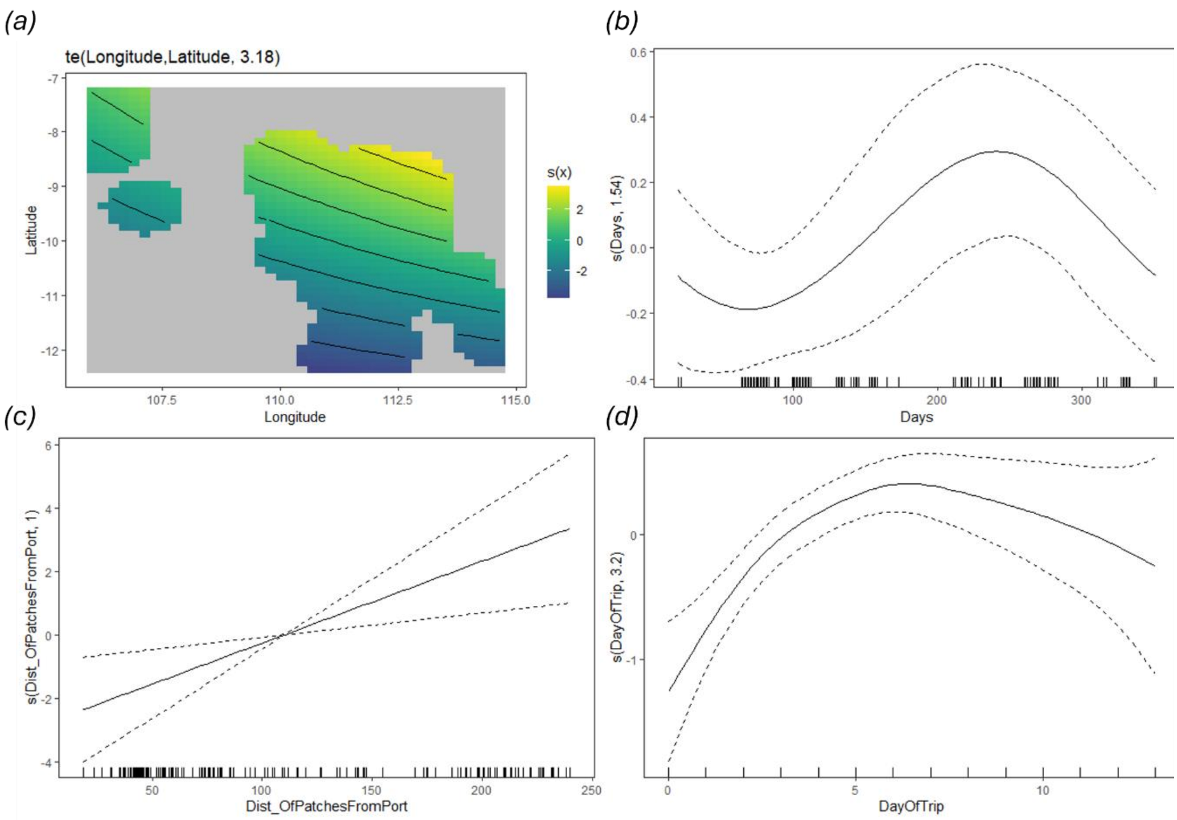


Figure 13. The term plots for each of the predictor variables retained in the best-fitting GAM for the patch residence time response variable: Longitude latitude (a), day of the year (b), distance of patches from fishing port (c), and day number of fishing trip (d).

Patch Quality Analysis

Based on the single-factor models, the GAM fitted for the gainmoney variable in relation to the patch residence time of fishers returned a power of 1.77, with an AIC of 1169.67. The variation in patch residence time explained approximately 51.3% of the deviance observed in the model (Table 5). Gainmoney or total value of catches (£), as a function of species weight multiplied by species price and weight gained in patches, were positively correlated with fishers' residence time ($p < 0.001$). The residence time of handline fishers in patches increased with more productive patches, as indicated by the greater monetary gain from the patches rather than being directly related to an increase in catch weight (Figure 14).

Table 5. Parameter estimates and significance of single-factor total catches (£) GAM model for residence time in patches. SE = standard error, df = degree of freedom.

Parameter	Coefficient	SE	t-value	df	p-value
Parametric terms					
Intercept	5.352	0.076	70.3	1	< 0.001
Smoothing terms					
GainMoney				5	< 0.001

The interaction effect of the catches (£) gained in the patches as a smoothed variable and the patch's residence time was bimodal and exhibited non-linear relationships, as indicated by df = 5. From the plot, it appears reasonable to assume that fishers tend to stay longer in patches as catches (£) gained in the patches increase up to £250, while showing relatively small variations in gain between £250 - £500 and £1050 - £1500.

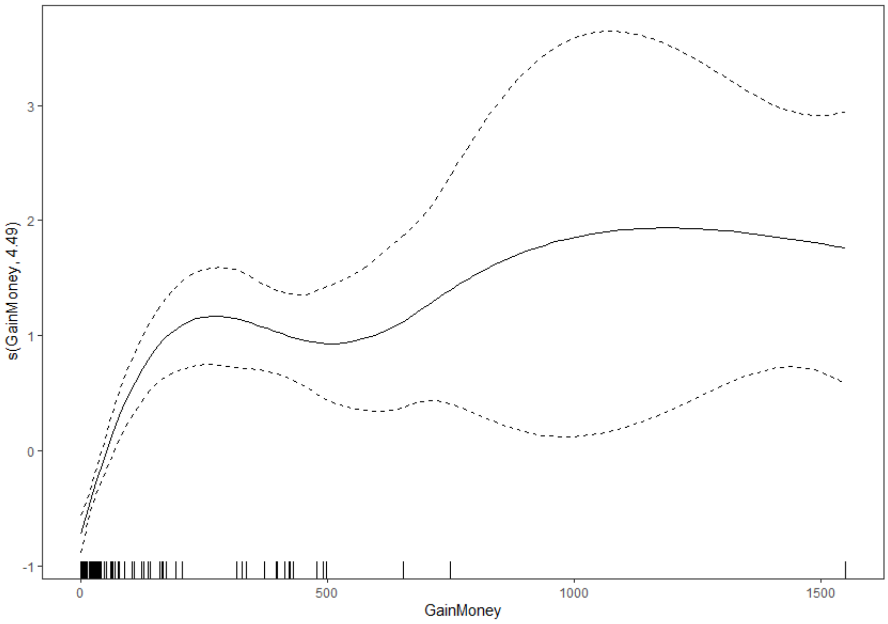


Figure 14. The relationship of catches £ to the patch's residence.

2.5 Discussion

2.5.1 Patch and FAD Identification

Satellite tracking provides reliable data for describing the movements and activities of handline fishing fleets along the south coast of Java. By applying the ARS optimality model, we can differentiate between intensive and extensive search patterns within the tracking data. These patterns, once clearly identified, allow for the determination of patches that indicate the locations of FADs. After defining these patches or FAD locations, we analyze the short-term and long-term fishing patterns of handline vessels around these areas. Key metrics in this analysis include the distance between FADs, the number of FADs visited, and the residence time within FADs.

We observed discrepancies in residence time between satellite tracking data and observer data, particularly concerning the minimum residence time. According to tracking data, the minimum residence time was 40 minutes. In contrast, observer data showed that fishers often conducted 'short' intensive searches lasting less than five minutes when encountering a FAD, departing if no fish were visually observed. Fishers likely use their past foraging experiences and accumulated skills to estimate the optimal patch-departure time. The absence of tuna prey can indicate non productive FAD (Jauharee et al., 2021, Marshall et al., 2013). Consequently, this may lead to a certain number of FADs being undetected and potentially underestimating their number, as the satellite tracking device in this study was set to record positional data at 1-hour intervals, as per the default setting provided by MMAF. To capture the entire movement pattern of handline vessels more accurately, the SPOT Trace satellite tracking device should be configured to record positional data every 2.5 minutes. Tracking intervals can be set to 2.5, 5, 10, 30, or 60 minutes (Globalstar, 2024).

To achieve the necessary higher resolution for accurately capturing vessel movements, a trade-off with shorter battery life is implied. With a 2.5-minute tracking interval and constant movement, the expected battery life is approximately 6 days under clear sky conditions and at room temperature. Alvard and Carlson (2020) used a 1-second tracking interval with their GPS logger device to examine the one-day fishing activities of artisanal fishers in the Commonwealth of Dominica, resulting in a battery life of only 41 hours. In the central Gulf of California, Frawley et al. (2021) used a solar-powered cellular tracking device set to 10-second intervals to monitor small-scale fisheries without experiencing battery issues. The use of external battery packs and solar power for the SPOT trackers could mitigate this problem but would require at least basic waterproof housing.

Although ARS can be discerned from travel movement indicated by negative deviations from the mean speed, uncertainties typically arise from slower movements unrelated to ARS, such as those caused by rough weather, engine failure, and overnight stays at FADs. For example, when engine failure occurs away from FADs, vessel drift at slower speeds for more than one hour can be mistakenly identified as patches. Although rough weather and overnight stays at FADs are unrelated to ARS, these activities associated with FADs still provide true patch locations. During rough weather, captains often anchor their vessels at FADs. The risk of misidentifying patches at higher resolution tracking intervals is likely to increase due to the slower movement of vessels for activities such as urinating, recovering from rough waves, or encountering other vessels, leading to potential false positive errors (Alvard et al., 2015).

According to the Ministry Decree No. PER.18/MEN/2021 regarding fishing gear and auxiliary gear deployment in Indonesian territory, FADs must be deployed 10 nmi apart. However, we observed that 47.95% of the total estimated number of FADs (73) did not adhere to this spacing requirement. The distances between FADs and FAD density have significant implications for tuna movement and their ecological impact. When the distances between

FADs decrease, tuna tend to visit more FADs, resulting in higher connectivity. Consequently, they spend less time traveling and more time staying around FADs (Pérez et al., 2020).

2.5.2 Should I stay or should I go?

The MVT model was tested under the assumption that fishers must balance the benefits of remaining at their current FAD against the potential advantages of conducting an inter-FAD search to identify a site with a higher catch rate (Busch and Olofsson, 2012). Fishers are likely to remain longer at productive FADs, where the catch rate remains high, and move more quickly away from less productive FADs, where the catch rate declines rapidly.

Variability in handline fishing behaviour is reflected in differences in the duration of fishing trips, distances between FADs, the distance of FADs from the fishing port, travel time between FADs, and residence times at FADs. The MVT optimality model provides a theoretical framework that considers patch quality as a factor influencing the residence time of handline fishers, which is affected by multiple variables. Residence time within patches appears to be primarily driven by the seasonality of tuna as the primary resource. The fishing season for the three dominant tuna species (yellowfin, skipjack, and bigeye) on the South Coast of Java occurs during the southeast monsoon, between June and October (Hargiyatno et al., 2021). This seasonal pattern may explain why monthly residence time trends peak around day 240 of the year (August). As the fishing season progresses, the quality of FADs (patches) improves, resulting in higher catch rates and, consequently, an increase in patch residence time (Charnov, 1976, Mella et al., 2018).

Fishers also spent more time foraging in patches located further from the port, which served as the central place. It is assumed that distant foraging patches are utilized only if the net catch gain is higher than that at nearby patches. The depletion of nearshore resources and competition may be the reasons why fishers are moving further offshore in search of "better quality" patches. Artisanal tuna vessels (<10 GT) and mini purse seiners typically operate in nearby patches. Fishers select fishing sites according to the Ideal Free Distribution (IFD), moving further to maximize success while avoiding competition and conflict in the areas they leave behind (Abernethy et al., 2007, Mcelroy et al., 2023, Girardin et al., 2015).

Results from the analysis of single-factor models of total catches (£) as a function of species price and weight gained in patches, obtained from observer sampling data, also support the MVT hypothesis. The residence time of fishers in patches increased with patch quality, as indicated by positive non-linear relationships between total catches (£) and fishers' residence time. Fishers tend to stay longer in patches as catches (£) increase, up to £250, while showing relatively small variations in gain between £250–£500 and £1050–£1500. Residence time may be influenced by economic motives, with fishers prioritizing the value of the catch over its volume, spending more time on high-quality FADs with high-value species or sizes (Joshi et al., 2021, Branch et al., 2006). Fishers gather information about fish prices prior to their fishing trips (Salas et al., 2004).

2.5.3 The Movement Dynamic of Tuna and Fishers

A notable distinction exists between the movement dynamics of tuna and fishers in relation to their foraging behaviour. Previous studies have demonstrated that tuna exhibit correlated random walk behaviour between FAD associations, influenced by their encounters with prey or inter-individual interactions (Girard et al., 2004, Pérez et al., 2020, Pérez et al., 2022, Kadota et al., 2011). In contrast, our findings reveal that fishers employ an area-restricted search strategy, alternating between intensive and extensive search modes when targeting tuna. Fishers decrease inter-FAD distances and increase FAD density to enhance connectivity between them, which in turn encourages tuna to spend longer periods around patches (Pérez et al., 2020).

We assume that the movement patterns of handline fishing fleets observed during this study were highly variable in response to the dynamic random walk behaviour of tuna. The movement of handline fishing fleets may reflect the movements of tuna (Kaplan et al., 2014). This highly variable movement pattern likely represents a strategy employed by fishers to increase the probability of encountering tuna, their primary resource. This adaptability allows fishers to make rapid decisions about which potential patches to visit, providing a significant advantage. (Mella et al., 2018).

2.6 Conclusion

The results of this study indicate that low-cost satellite-based GPS trackers provide reliable data for describing the movements of handline vessels operating in offshore waters. The tracking data can be utilized to estimate the distribution of FADs and the variability that contributes to the residence time of fishers at these FADs. In addition, these portable satellite-based GPS trackers are applicable for small- and medium-scale fishing fleets with low technological capacity, characterized by a lack of permanent energy supply and limited space onboard. However, in this study, the trackers were set to record positional data at 1-hour intervals, which was insufficient to capture fishing activities that occur within minutes. Higher resolution in the interval of recorded positional data is needed to capture the entire movement pattern of vessels more accurately.

Chapter 3: Vessel Behaviour Interpretation

3.1 Abstract

The handline fishery on the South Coast of Java utilizes deep-water anchored Fish Aggregating Devices (FADs) to attract tuna in offshore waters. Satellite tracking technologies effectively provide information on fishing behaviour and the spatial distribution of their fishing effort. Heterogeneity in fishing behaviour among handline fishers was observed from the tracking data. However, it is difficult to identify the decision-making processes and motivations behind these behaviours relying solely on a single quantitative method. Here, we show that qualitative methods can help to further investigate and understand the quantitative data obtained from satellite tracking, explaining the variability in fishing behaviour and the motivations behind it. Additionally, Fisher Ecological Knowledge (FEK) can offer an alternative, cost-effective source of fish behaviour data. We found a complex combination of three strategies in the handline fishery: (i) targeting large tuna, (ii) working as auxiliary boats for Jakarta purse seiners, and (iii) targeting hairtail fish. The tactical decisions of handline fishers regarding the allocation of fishing effort between FADs vary according to their strategy and are influenced by three variables: FAD ownership, technology used, fishing group, and fishing experience. The impact of COVID-19 was observed to affect the fishery and alter their fishing behaviour. We found that moderate current conditions were the most favourable for fishing operations, and large tuna tend to distribute on the up-current side of the FADs. Our results demonstrate that incorporating both qualitative and quantitative research enriches understanding in both theory and practice. Integration of these knowledge sources enhances the evidence base for policy advice, decision-making, and environmental management, especially in contexts of data scarcity and limited reliable information.

3.2 Introduction

Successful fisheries management requires good knowledge of fish populations in their ecosystems and the behaviour of the humans involved (Branch et al., 2006, Hilborn, 1985). Christensen and Raakjær (2006) divided fisher behaviour into short-term (fishing tactic) and long-term (fishing strategy). How and why fishers behave influenced by interrelated of environmental, social, and economic conditions in the fishery (Hart and Pitcher, 1998, Yletyinen et al., 2018). Their ability to adjust short-term tactic and long-term strategy to the changing condition and optimize their catching rates may affect to the health of fish resources.

Assessing the behaviour of small and medium scale fishery is challenging due to the complexity arising from diverse of fishing techniques and highly varied catch species. In developing countries with limited budgets and human resources, data scarcity and reliable information about fisher behaviour become additional issues. Medium-scale tuna handline fishery on the South Coast of Java utilized Fish Aggregating Device (FADs) to support their operations in offshore waters. Monitoring and enforcing offshore fisheries is difficult, time consuming and costly (Bailey et al., 2012). The lack of information regarding fishing behaviour and diverse factors influencing fishers' decisions pose significant obstacles to effective management of the fishery. In the previous chapter, we used low-cost satellite tracking devices verified with observer data to identify actual fishing grounds, fishing activities and the distribution of FADs. Despite these quantitative methods proving effective in assessing fishers' behaviour in terms of fishing locations and movement pattern, understanding the motivations underlying movement heterogeneity between FADs remain challenging. Qualitative methods help to further investigate and understand quantitative data addressing this limitation (Tenny, Brannan, and Brannan 2017). This method focus on the aspects that cannot be quantified using quantitative approaches, answering questions about particular moments, events, meaning, experience, and perspective (Hammarberg et al., 2016, Queirós et al., 2017, Jackman et al., 2022). In addition, catch and effort data issued by the fishing port authority provide insight into trends in abundance, changes of catchability and seasonal pattern of fishing (Curran et al., 1996, Pascoe et al., 2024). Integrating a diverse range of knowledge sources, including indigenous, local, and scientific knowledge, is essential. Knowledge integration enhances the evidence-base for policy advice, decision-making, and environmental management (Alexander et al., 2019).

The aim of this study was to identify and interpret heterogeneity in fishing behaviour of the handline fishery in the North-Eastern Indian Ocean, Indonesia based on preliminary tracking data, to gain a comprehensive understanding of their fishing behaviour. The study had three key objectives: (i) identify the variability of fishing tactics and fishing strategies (fishing behaviour), (ii) explore decision-making processes and motivations behind them and (iii) provide insights into Fishers' Ecological Knowledge (FEK) of fish behaviour.

3.3 Materials and Methods

3.3.1 Case Study Area

The study area is located on the South Coast of Malang Regency, East Java, Indonesia, situated within Fishery Management Areas (FMA) 713 and part of the Eastern Indian Ocean FAO area 57 (Figure 15). Pondok Dadap fishing port is an important fishing port and the largest base for medium-scale handline fishing on the south coast of Java. Approximately 463 vessels were registered at this port in 2021, 30% of which are migrant vessels (Anonymous, 2022). In 2022, the total tuna landed at Pondok Dadap fishing port reached 5.8 thousand tons, dominating the total catches (Anonymous, 2023).

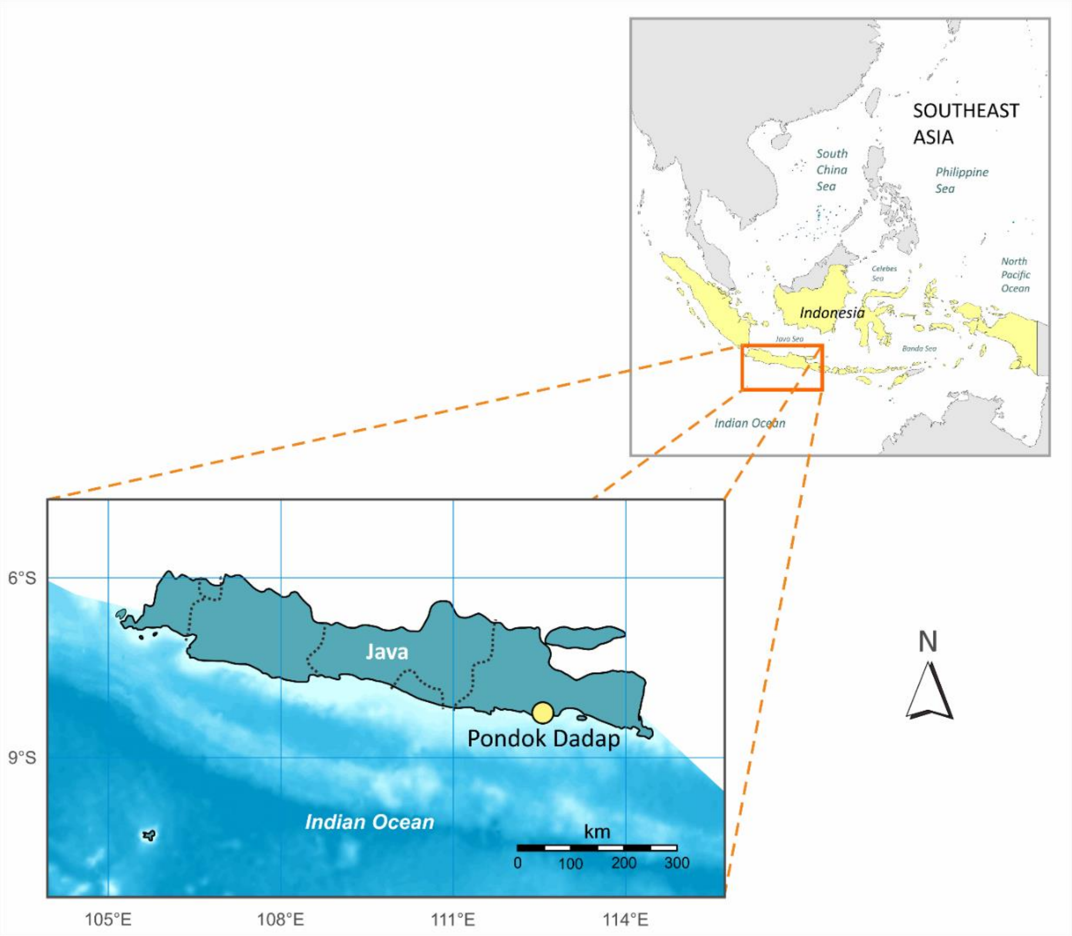


Figure 15. Pondok Dadap Coastal Fishing Port in the South Coast of Malang Regency, East Java.

There are four types of fishing ports based on their technical and operational aspects: Oceanic Fishing Port (OFP - class A), Archipelago Fishing Port (AFP - class B), Coastal Fishing Port (CFP - class C) and Fishing Landing Place (FLP - class D). The Pondok Dadap fishing port is classified as a Coastal Fishing Port (CFP- class C) according to criteria outlined in Ministry Decree No. PER.08/MEN/2012 (Table 6).

Table 6. Technical and operational criteria of Class C fishing port from Ministry Decree No. PER.08/MEN/2012

Technical criteria	Operational criteria
- Operational/fishery activities in territorial waters. - Have mooring/docking facilities for fishing vessels of at least 10 GT. - Have a pier with a minimum length of 100 meters and a minimum depth of 2 meters. - Accommodate at least 30 fishing vessels, totalling a minimum of 300 GT. - Utilize and manage a minimum area of 5 hectares.	- Have an average 5 tons of fish loading and unloading activities per day. - Have fish processing and supporting industries.

3.3.2 Semi Structured Interviews

Between March 17th to April 2nd 2021, semi structured fisher interviews were conducted at Pondok Dadap fishing port with the aim of understanding fishing behaviour and decision making around the use of FADs. The study population was defined according to the following inclusion criteria: vessel type ('sekoci' vessel), size of vessels from 10 to 30 gross tonnage (GT) and handline fishing gear (Robinson, 2014). Vessel registration data obtained from fishing port authority comprised of id, name, size, fishing gear, captain, origin, and owner of the vessels facilitated the selection based on these criteria.

A total of 30 active captains of handline vessels were recruited as participants using a 'convenience' sampling strategy (Young et al., 2018). Among these captains, six had been previously tracked using Spot Trace® satellite trackers. The logbook officer at the fishing port pier provided information on the number of handline vessels that had landed fish that day, with vessels typically landing their catches from morning until before lunchtime (6.00 – 11.30 am). Fishing captains were approached on their vessels after they finish unloading their catch. The interview location, date and time were arranged based on what was feasible for participants. Most preferred to have the interview conducted directly during the first approach on their vessels, while the rest requested to meet later that day in a coffee shop or around the pier area. It is important to create an ideal situation for participants to prevent them from feeling restricted or uncomfortable, thereby encouraging them to share information openly and honestly during the interview (Cresswell, 2013). Face-to-face interviews were conducted in 'Bahasa' Indonesia with each participant. The interviews lasted between 50 and 100 minutes. The "Voice Memos app" on an iPhone 7 plus was used to record all interviews after permission for recording had been given.

An interview guide was used as a basis for discussion with active handline captains, comprised of four broad topic areas (Figure 16) These topics were developed based on information obtained from a preliminary quantitative study of handline fishers' behaviour, which utilized satellite tracking and observer data, as detailed in Chapter 2. Topic guide 1-3 were used for all participants, while topic 4 was only applicable to the five participants who had previously installed satellite tracking devices on their vessels (Chapter 2). A printed map of vessel tracking points was provided to help these five participants recall moments during fishing trips and to make the questions more concrete and understandable (Rosenthal, 2016).

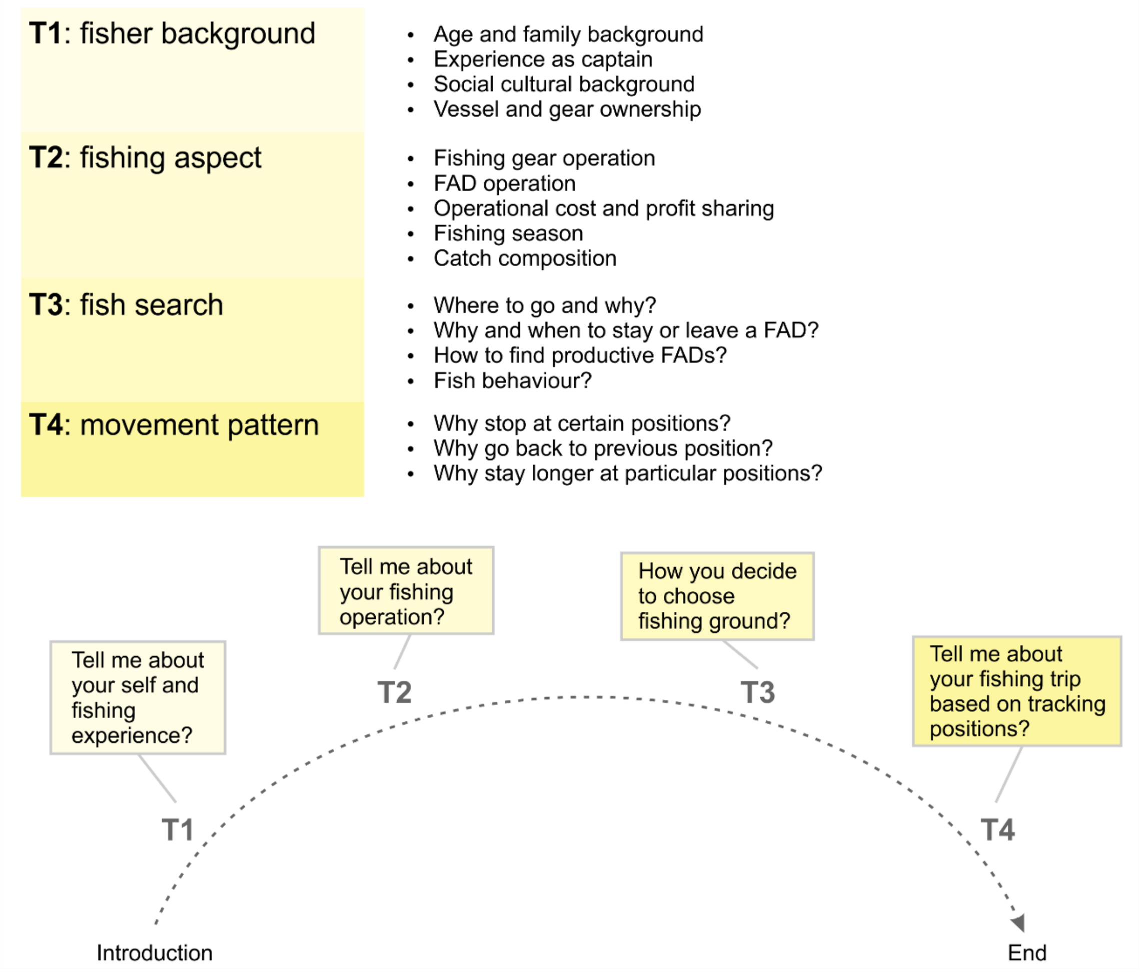


Figure 16. List of topics and follow-up questions (top) with the main question for each topic, arranged in an arc to determine the best order of topics. Modified from Knott et al. 2022.

The interview guide approach provides a systematic and comprehensive technique for interviewing diverse individuals by defining the issues to be explored in advance. Therefore, it maintains focus during interactions while still allowing individual perspectives and experiences to emerge (Patton, 2002). Open-ended questions were preferably to gaining an elaborated response and extended reflection from participants (Patton, 2002, Rosenthal, 2016, Knott et al., 2022).

This study was guided and approved by the ethical principles on non-clinical research using human participants set out by the Research Centre for Fishery (RCF) under the Ministry of Marine Affairs and Fishery (MMAF), Republic of Indonesia. All participants received written information regarding their participation, outlining the nature of the project, how the data was to be used and details of an independent contact within the RCF. All participants were given the option of confidentiality and anonymity in written reports and all participants provided informed consent for this study. All participation was voluntary, and participants were informed that they could withdraw at any time for any reason and have their contributions removed from the project if they so wished.

3.3.3 Catch Data

Catch and effort data were obtained from the fishing port authority through an official letter from RCF to the head of Pondok Dadap Coastal Fishing Port. The fishing port authorities are responsible for recording logbook data for all vessels greater than 5 GT. This data includes fishing gear, coordinates of fishing ground, season, hook rate, Catch Per Unit Effort (CPUE), information of bycatch and Ecological Related Species (ERS) (Utama et al., 2021). However, the catch and effort data are subject to uncertainty with particularly due to problems with underreported catches, a well-known issue identified in global fisheries statistics (Yuniarta et al., 2017, Pauly and Zeller, 2016). Since 2018, the Pondok Dadap fishing port authority has been updating their logbook data collection protocol. Completed logbooks provided by landing vessels must be validated in real time by on-duty officers at the landing pier, who then make corrections to any unrealistic logbook reports.

3.3.4 Data Analysis

Thematic analysis has been widely used as an approach to analysing interview material in both in qualitative social and life sciences (Knott et al., 2022, Hennessey and Barnett, 2023, Osborne and Grant-Smith, 2021). This approach enables the identification, analysis, and reporting of patterns (themes) within a qualitative data set, based on commonalities and differences in a systematic manner (Figure 17) (Braun and Clarke, 2006, Gale et al., 2013).

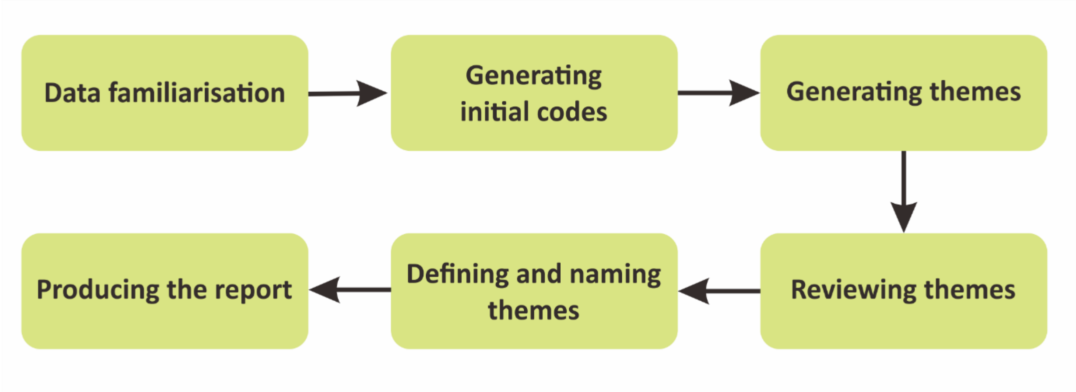


Figure 17. Six-phase analytical process of thematic analysis according Braun and Clarke (2006).

The audio recordings from the interviews were replayed and transcribed manually verbatim. This transcription included the addition of observational and graphic notes, as some participants preferred to draw illustrations during the interview such as fishing gear construction or fish positions around FADs. The complete transcription was then translated from Bahasa into English and each transcript was read numerous times to familiarize with the data. This familiarisation is essential for identifying information that may be relevant to the research questions (Byrne, 2022). The entire dataset was then coded using qualitative data analysis software NVivo (version 14.23.24). Coding involves assigning codes to individual words, phrases, sentences, or entire paragraphs within each transcript to facilitate the interpretation of their meanings (Young et al., 2018, Braun and Clarke, 2019). All coded relevant data items were then categorized into identifiable potential themes according to shared meanings (Wæraas, 2022, Creswell and Creswell, 2017). A theme represents a significant aspect of the data relevant to the research question and reflects a patterned response or meaning within the dataset (Braun and Clarke, 2006, Braun and Clarke, 2019).These themes were then reviewed and refined into the final set of themes. Descriptive statistics of the catch and effort data were used in conjunction with the interviews to provide insight into changes of catchability and seasonal pattern of fishing (Curran et al., 1996, Pascoe et al., 2024).

3.4 Result

3.4.1 Participant Characteristic

A total of 30 active captains of handline vessels were interviewed at the Pondok Dadap fishing port (Table 7). Two captains declined interviews because they did not have time. Respondents were predominately local residents (27 captains) to subdistrict of Sumbermanjing Wetan where the fishing port located, with only three captains being migrants from Sinjai, Sulawesi. Local residents can be further categorized as originally from Sulawesi (60%), from Java (20%) who have been domiciled for years and from local village (10%). The respondents had an average of 12.3 years of experience working as handline captains, with experience ranging from 1 to 23 years. Eighteen captains were also the owner of the vessels. Most of the vessels were equipped with GPS and radio telecommunication (86.7%), while only 6.7% had GPS alone. There were two vessels (6.7%) equipped with fish finders to support their fishing operation. Eighteen captains reported they had not deployed FADs, while the rest remain deployed their own FADs. Migrant fishers worked seasonally during the southeast monsoon March-September also referred to as the tuna season, bringing their fishing vessel from Sinjai to Pondok Dapap fishing port (Figure 18).

Table 7. Demographics of interview respondents at the Pondok Dadap fishing port (19 March – 27 July 2021).

Participant	Ethnicity	Fishing experience (year)	Vessel equipment	Vessel ownership	FAD ownership	Satellite tracker
Respondent 1	Local (Javanese)	18	Radio, GPS	Owner	No FAD	Yes
Respondent 2	Local (Javanese)	20	Radio, GPS	Owner	No FAD	No
Respondent 3	Migrant	2	GPS	No	1 FAD	No
Respondent 4	Migrant	16	Radio, GPS	Owner	No FAD	No
Respondent 5	Local (Celebes)	23	Radio, GPS	Owner	2 FADs	No
Respondent 6	Local (Celebes)	3	Radio, GPS	No	No FAD	No
Respondent 7	Local (Celebes)	8	Radio, GPS	No	No FAD	No
Respondent 8	Local (Javanese)	19	Radio, GPS	No	No FAD	No
Respondent 9	Local (Celebes)	15	GPS	Owner	2 FADs	No
Respondent 10	Local (Javanese)	14	Radio, GPS	Owner	2 FADs	No
Respondent 11	Local (Celebes)	1	Radio, GPS	No	No FAD	No
Respondent 12	Local (Celebes)	16	Radio, GPS	Owner	No FAD	Yes
Respondent 13	Local (Celebes)	22	Radio, GPS, fish finder	Owner	No FAD	Yes
Respondent 14	Local (Celebes)	17	Radio, GPS	Owner	No FAD	No
Respondent 15	Local (Celebes)	3	Radio, GPS	No	2 FADs	No
Respondent 16	Migrant	16	Radio, GPS	No	No FAD	No
Respondent 17	Local (Javanese)	5	Radio, GPS	Owner	1 FAD	No
Respondent 18	Local (Villager)	23	Radio, GPS	Owner	No FAD	Yes
Respondent 19	Local (Celebes)	6	Radio, GPS	Owner	1 FAD	Yes
Respondent 20	Local (Villager)	13	Radio, GPS	Owner	1 FAD	No
Respondent 21	Local (Celebes)	1	Radio, GPS	Owner	No FAD	Yes
Respondent 22	Local (Celebes)	16	Radio, GPS	Owner	1 FAD	No
Respondent 23	Local (Villager)	12	Radio, GPS	No	No FAD	No
Respondent 24	Local (Celebes)	18	Radio, GPS	Owner	No FAD	No
Respondent 25	Local (Javanese)	2	Radio, GPS	No	No FAD	No
Respondent 26	Local (Celebes)	23	Radio, GPS	Owner	No FAD	No
Respondent 27	Local (Celebes)	12	Radio, GPS	Owner	No FAD	No
Respondent 28	Local (Celebes)	7	Radio, GPS	No	2 FADs	No
Respondent 29	Local (Celebes)	10	Radio, GPS, fish finder	No	2 FADs	No
Respondent 30	Local (Celebes)	8	Radio, GPS	No	2 FADs	No

Fishing Ground

According to the interviews, handline fishing fleets at Pondok Dadap fishing port operate alongside other fisheries, outrigger fishing fleets targeting large tuna and mini purse seine fleets targeting small pelagic fish. These two fisheries also rely on FADs to support their fishing operation, with their distribution limited to the southernmost latitude of 9° S, about 60 miles from the fishing port (Figure 18). The Jakarta purse seine FADs are spread between latitude of 9° S and 14° S overlapping with handline FADs between latitude 9° S and 12° S. The distance from Pondok Dadap fishing port to the Jakarta purse seine and handline FADs is approximately 90-350 miles.

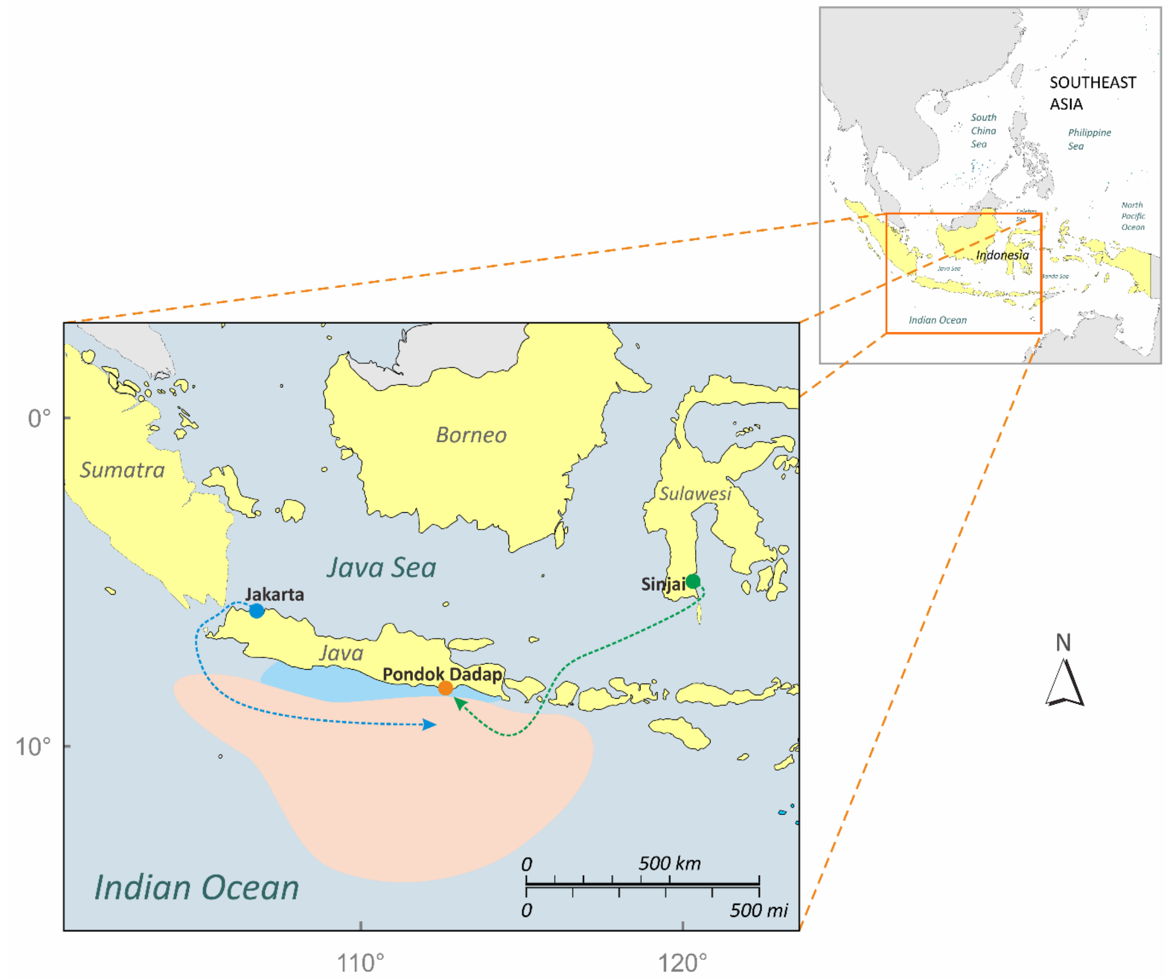


Figure 18. Fishing ground of outrigger fishing boats and mini purse seines (light blue) and industrial purse seine and handline (pink). Route of migrant fishers from Sinjai to Pondok Dadap fishing port (dashed green) and route of industrial purse seine from Jakarta as fishing base (dashed blue).

Fishing Technique

All the captains operated various handlining and trolling techniques: seven types of fishing gear were identified during the interviews: surface handlining (‘coping’), drop-stone handlining (‘batuan’), mid-water handlining (‘pelamba’), float lining (‘tomba’), multiple handlining (‘taber/oncoran’), trolling (‘tonda’) and kite lining (‘layangan’) (Figure 19). They easily switched between fishing gears in a single trip, adapting to sea conditions, catch success and the behaviour of the fish. The fishing gear can be distinguished into two different depth layer operations: surface fishing gear and mid-layer fishing gear. Hook sizes 2/0 – 5/0 were used with artificial lures to catch juvenile yellowfin tuna (j-YFT), juvenile big eye tuna (j-BET), skipjack (SKJ) and small pelagic fish (Table 8). The freshly-caught small pelagic fish and juvenile tuna were then directly rigged on the larger hook sizes 7/0 – 9/0 of float lines and kite lines as live bait to catch large tuna over 20 kg. They also operated squid jig (‘egi’) at night to catch squid and use it as live bait on mid-water handline to catch large bigeye tuna. Chopped squid including ink were used later as bait for drop-stone handlining during day fishing operations.

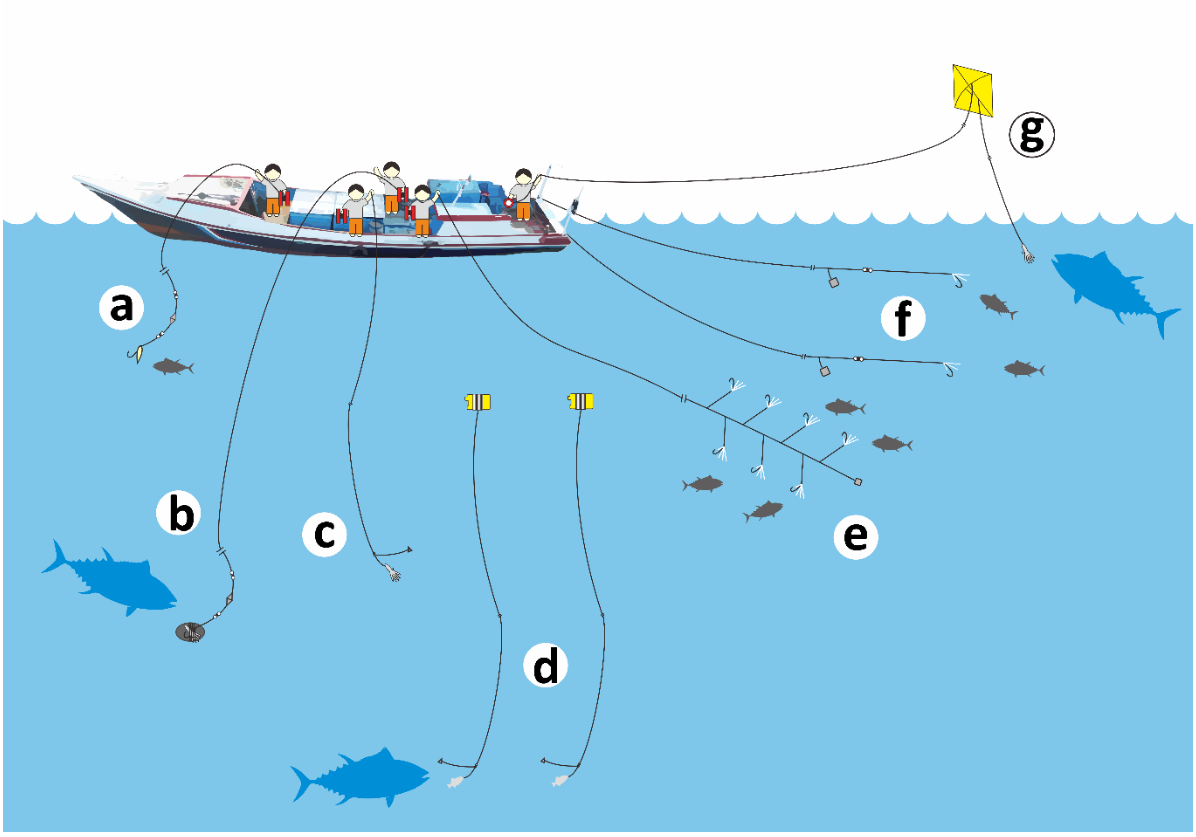


Figure 19. Seven types of handlining and trolling techniques operated by handline fishers: surface handline (a), drop-stone handline (b), mid-water handline (c), float line (d), multiple handline (e), troll line (f) and kite line (g).

Table 8. Technical information of fishing gears operated by handline fishers.

Techniques	Description	Bait	Depth	Target
Surface handline	Hook size no. 3/0-4/0	Lures	15-20 m	Small pelagic, SKJ, j-YFT, j-BET
Drop-stone handline	Hook size no. 6/0-9/0	Pieces of squid	60-135 m	Large ALB
Mid-water handline	Hook size no. 8/0-9/0	Live squid	75-105 m	Large YFT, BET
Float line	Hook size no. 7/0-9/0	Live fish	30-80 m	Large YFT, BET
Multiple handline	Hook size no. 2/0-5/0 - Day: 30-45 branches - Night: 5-25 branches	Lures	15-20 m	Small pelagic, SKJ, j-YFT, j-BET
Troll line	Treble hooks size no. 3/0-4/0, single and multiple line (7 branches)	Lures	15-20 m	Small pelagic, SKJ, j-YFT, j-BET
Kite line	Treble hooks size no. 8/0-9/0 for large tuna and size 4/0-5/0 for small pelagic or juvenile tuna	Rubber squid lure	Surface water	Small pelagic, SKJ, j-YFT, j-BET or Large YFT, BET

Catch Composition

The catch compositions of handline at Pondok Dadap during period 2018 – 2021 collected from official landing report showed skipjack contributing almost half of the total catches (47.6%) (Figure 20). The other tuna species: albacore, mix of juvenile tuna (j-YFT and j-BFT), and large yellowfin tuna contributed to 43% of the total catches followed by the other six species that only made up less than 10%.

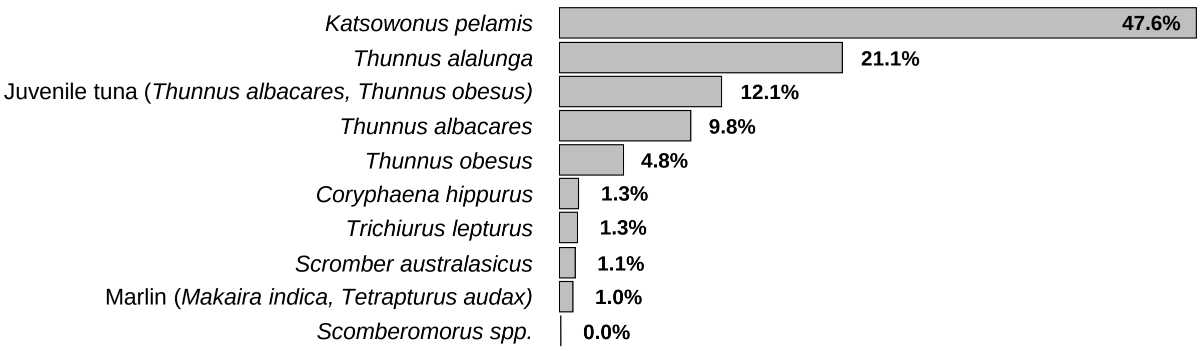


Figure 20. Catch composition of handline fleets in Pondok Dadap 2018-2021

Sources: (Anonymous, 2022)

Fishing Seasonality

Most respondents mentioned that the peak abundance of large yellowfin (YFT, *Thunnus albacares*) and bigeye tuna (BET, *Thunnus obesus*) occurs from May to September, and albacore tuna peaks from July to September. Small pelagic fish, skipjack, and juvenile tuna can be found throughout most months. This respondents' statements were supported by CPUE data, which showed a shifting catch/trip (kg) between large yellowfin and big eye tuna (March – July) with large albacore (May – September) indicating a shifting season (Figure 21).

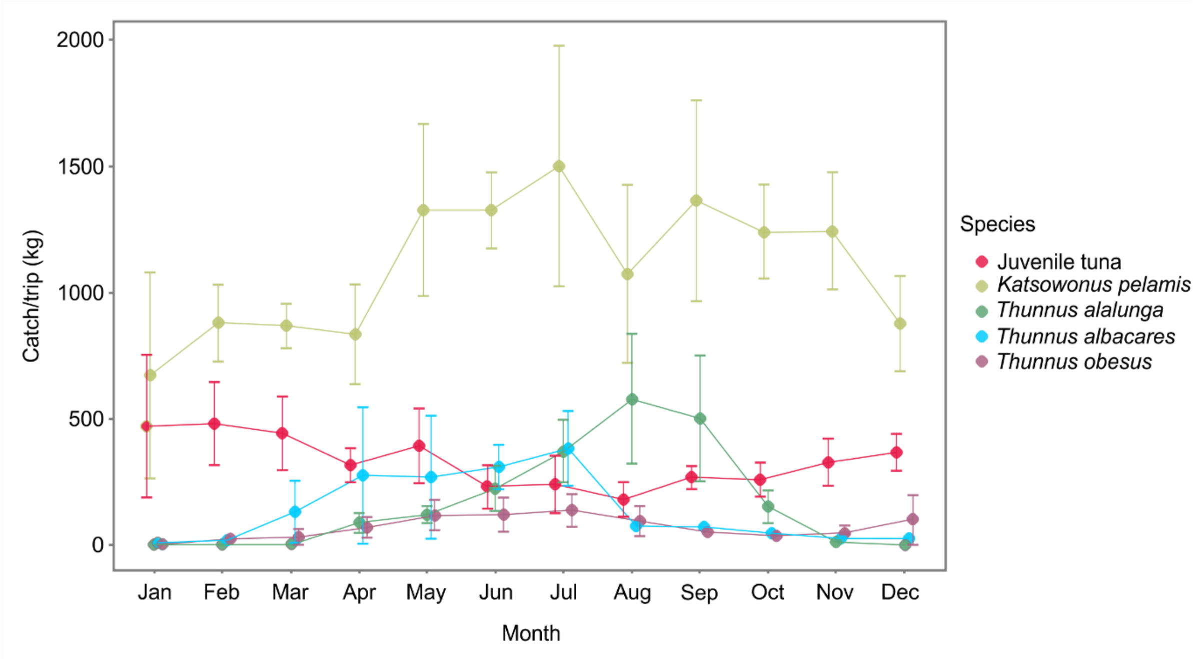


Figure 21. CPUE of handline fisheries 2018-2021.

Sources: (Anonymous, 2022)

3.4.2 Fishing Strategy

The interviews revealed fishing strategies of the handline fishery were a complex combination of three strategies: (i) targeting large tuna, (ii) working as auxiliary boat for Jakarta purse seiners and (iii) targeting hairtail fish (Figure 22). Introduced by Sinjai fishers in 1996, the handline fishery was initially considered as specialist fishery, targeting large tuna as the only strategy. Participants stated that they diversified their fishing strategies to become generalists in response to changing conditions and developments in the fishery. Three distinct key events were identified as leading to an increase in the available number of fishing strategies: the operation of Jakarta purse seine fleets, the introduction radio telecommunication and the increased demand for hairtail fish (*Trichiurus spp*) exported to China.

In 2009, Jakarta purse seine began fishing activity on the south coast of Java, overlapping with handline fishing grounds and triggering conflicts between the two fisheries. However, the introduction of radio telecommunication in 2011 facilitated communication between handline and purse seine captains, leading to fishing collaboration. Twenty-eight respondents established a mutualistic relationship with Jakarta purse seiners. The relationship occurred on different levels of collaboration, from simply helping to fulfil the logistics needs of purse seiners, maintaining their FADs, and assisting in fishing operation to sharing cost of FAD deployment and building handline boats together. In return, purse seiners shared their catches with hardliners.

"*We prefer to collaborate with purse seiners as main strategy and have an unwritten agreement to support their fishing operations. We monitor the aggregation of small pelagic fish, skipjack and juvenile tuna around their FADs and inform them of harvestable locations".* Respondents 12, 24, 27

They were permitted to fish for large tuna while fulfilling their role as fish "hunters." During the large tuna season, they could temporarily abandon their designated role and freely switch strategies to target large tuna. The respondents argued that purse seiners benefited from this collaboration because they could save fuel and effort and receive more accurate information about fish locations. The "hunters" were responsible for maintaining the FADs by regularly replacing the attractants and protecting the FADs from being harvested by other purse seine groups. In contrast, fishers whose main strategy targeted large tuna would collaborate with purse seiners as an option.

"*Our main objective is targeting large tuna, and collaboration with purse seiners is the last option to cover the travel costs*". Respondents 8, 18, and 20

They usually voluntarily help supply logistic for purse seiners and replace FAD's attractants when asked to maintain good collaboration. Two respondents had no collaboration with Jakarta purse seiners typically had no radio onboard, and owned their private FADs shared with 5-7 vessels knowns as a 'FAD group'.

"*We believe in our instinct and knowledge and do not rely on radio because it makes captains unfocused and confused about where to go".* Respondents 9 and 21

The northwest monsoon lasting from November to March, is known as the off season and is associated with heavy rainfall and rough waves. During this period, local captains switch strategies to one-day fishing trips targeting valuable hairtail fish found close to the shore. distributed along the coast not far from land. Hairtail fishing is favourable because high demand of the commodity surged the price up to £2.5/kg. Migrant fishers return to their hometown in Sinjai, Sulawesi, and travel back to the Pondok Dadap around March mostly after celebrating Eid al-Fitr.

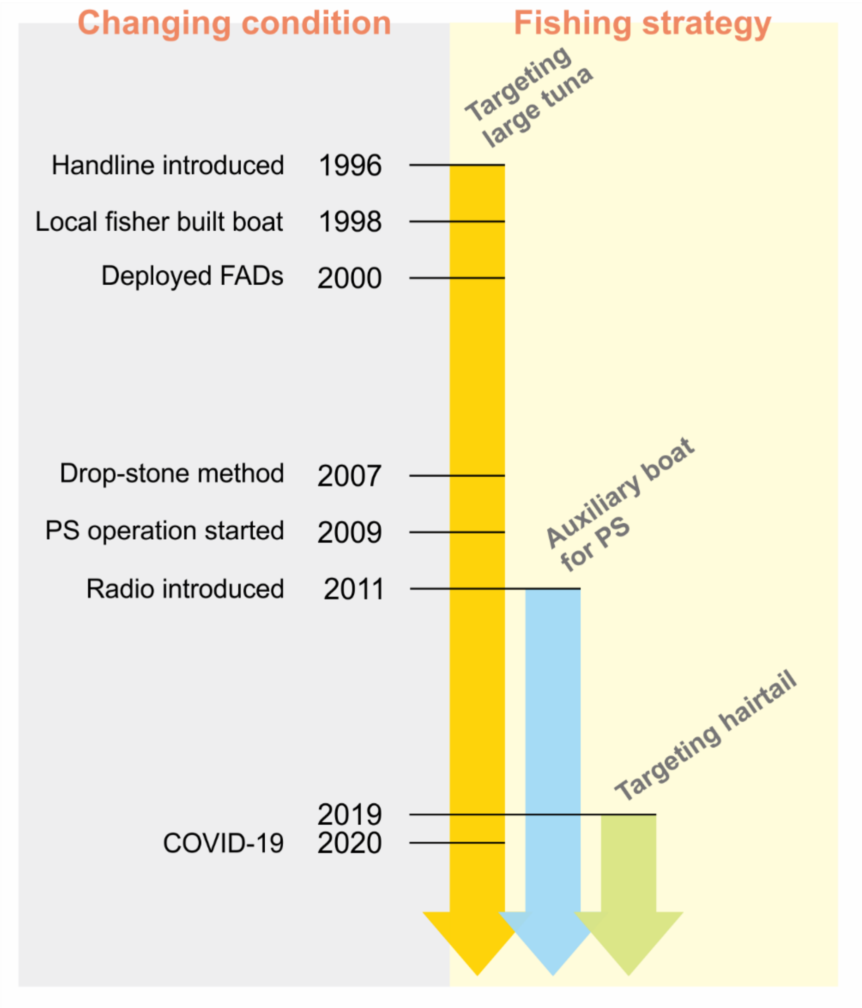


Figure 22. The changing conditions and development of the handline fishery over time (left – grey area) that influence diverse fishing strategies (different coloured arrows) of the handline fishery in Pondok Dadap.

3.4.3 Fishing Tactic

The fishing tactic of fishers in terms of selecting fishing locations varied according to the types of fishing strategies and were influenced by three variables: FAD ownership, technology used, fishing group and fishing experience (Table 9). These variables are interrelated and involved in the captains' decision-making processes. Respondents who owned and used private FADs would follow a straightforward pattern, prioritizing visits to their own FADs first rather than traveling to purse seine FADs. Purse seine FADs can be an alternative option when their private FADs were unproductive.

Radio telecommunication allowed captains to gather diverse potential productive FADs locations provided by different information-sharing networks. Captains with radio had accesses to the handline community radio, exclusive radio group, and purse seine radio. In contrast, captains without radios had limited sources for acquiring information about when and where to fish.

"*We visited the fishing port, asking friends and our private FAD group who had arrived from the sea about the potential location of productive FADs before our fishing trip".* Respondent 2 and 9

The community radio primarily monitors locations and facilitates emergency assistance for its members. When members encounter issues with their vessels, the radio community operator arranges for towing and the delivery of spare parts by another member. The designated responsible member must adjust their travel route according to the instructions of the radio community group. Experienced fishers (with over 10 years as captains) use this public community radio to gather more information.

"*Naive captains often share information about their fishing success and locations on the community radio channel. If we shared that kind of information on this public channel, the next day there would be hundreds of vessels approaching. We prefer to remain silent and listen for information from other captains".* Respondent 8 and 20

Moreover, most captains are more likely to report sharing information with an exclusive radio group of a small number of members. This exclusive group commonly emerges from trustworthy interpersonal exchanges of information embedded in kinship and friendship. A captain usually begins working as a fishing crew member and, over the years, becomes a captain or owns his vessel. The captain tends to recruit family members as fishing crew on his vessel, and previous fellow crew members become his fishing group. This applies to both the FAD group and the exclusive radio group. Some fishers targeting large tuna keep manage good relationship with purse seine captains because they need information about unharvested FADs from them. Despite the differences in target species between purse seine and handline fishing, harvested FADs by purse seiners affect the availability of large tuna.

"*We have access to contact purse seine captains even though we do not have collaboration with them, which is important for gaining information about their unharvested FADs because large tuna cannot be found around harvested FADs*". Respondents 1

Table 9. Information flow and fishing tactic of handline vessels in terms of selecting fishing locations.

Fishing strategy associated with FAD	Have FADs?	Technology	Source of information	Movement pattern
Targeting large tuna	Yes	GPS	FAD group	- Captains gather information about productive FAD locations. - Directly head to and visit private FADs. - Visit PS FADs nearby when private FADs unproductive.
		- Radio - GPS	- FAD group - close radio group - community radio - PS radio	- Real-time productive FAD locations were gathered from information sources. - Captains visit handline or PS vessels that need logistic or spare part supplies, as informed by community radio group. - Captains directly visit private FADs or visit PS FADs when private FADs were unproductive. - Captains request PS to encircle private FADs and share the catches with PS and the FAD group before the end of the season. - Help PS operation as the last option to cover the travel costs, particularly during the bad season for large tuna.
	No	GPS	Fishing port/ friends	- Captains gather information about productive FAD locations in the fishing port. - Visit potential PS FADs locations
		- Radio - GPS	- FAD group - close radio group - community radio - PS radio	- Real-time productive FAD locations were gathered from information sources. - Captain visit handline or PS vessels that need logistic or spare part supplies, as informed by community radio group. - Visit potential PS FADs locations. - Help PS operation as the last option to cover the travel costs, particularly during the bad season for large tuna.
Collaborate with PS as auxiliary boat	No	- Radio - GPS	- Close/ hunting group - community radio - PS radio	- Captains directly visit collaborator PS FADs. - Captains visit handline or PS vessels that need logistic or spare part supplies, as informed by community radio group. - Travel around to find harvestable FADs in inform PS. - Help PS operation. - Maintain PS FADs.

Traditional captains targeting large tuna mentioned that the residence time at FADs as dependent on the catch rates. They spent more time at productive FADs and vice versa.

"*We would stay at a FAD if we gained good catching rates*". Respondent 1-30

In contrast, 'hunter' captains tended to have shorter residence times compared to traditional captains targeting large tuna because they travel around, visiting and monitoring their collaborative purse seine FADs.

"I visited approximately more than 20 FADs in 12-day last trip". Respondent 12

3.4.4 Fishers' Ecological Knowledge (FEK) of Fish Behaviour

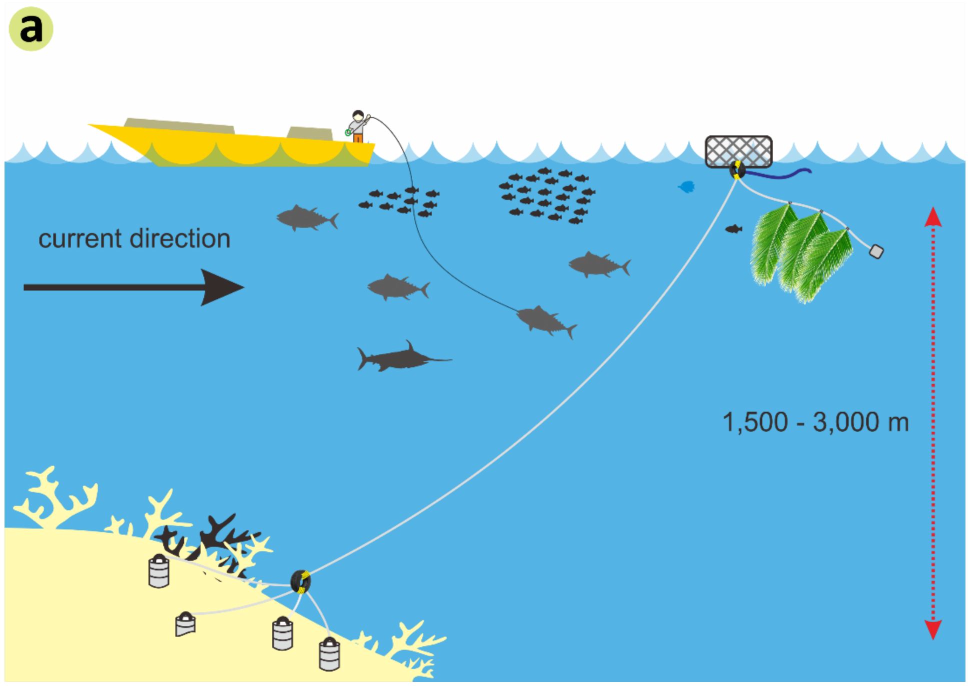
Current and Fish Distribution Around FADs

All the respondents believed that current was the most important variable driving tuna aggregation and creating an ideal condition for fishing operations. They distinguished three different current conditions: dead/weak, moderate, and strong currents. Moderate currents led to small pelagic fish and tuna aggregating in the up-current area of the FAD structure, making this area approximately 20-300 m from the buoy the most effective fishing spot (Figure 23). Strong currents were associated with no fish around the FAD (non-productive FADs), as tuna depart from the FAD during strong currents. Uncertain fish distribution around the FAD occurred in dead current conditions.

"*Fish were randomly distributed and difficult to locate. Even though there was a high abundance of tuna around a FAD, they usually had less feeding motivation and were unresponsive to the baits when the current was dead.*" Respondent 2 and 26

Respondents also believed that tuna perform vertical migration, swimming shallower an hour after sunrise and in the afternoon to forage for preys, while swimming deeper during the day due to warmer water temperatures on the surface. Attractants were another important factor for tuna aggregation. Respondents maintained the FAD by replacing the attractants (coconut leaves) every 2-3 months. A well-maintained FAD effectively attracts tuna and increase their residency times.

"*The availability of small pelagic fish sheltered around coconut leaves attracts large tuna and cause them to remain at the FAD".* Respondent 11



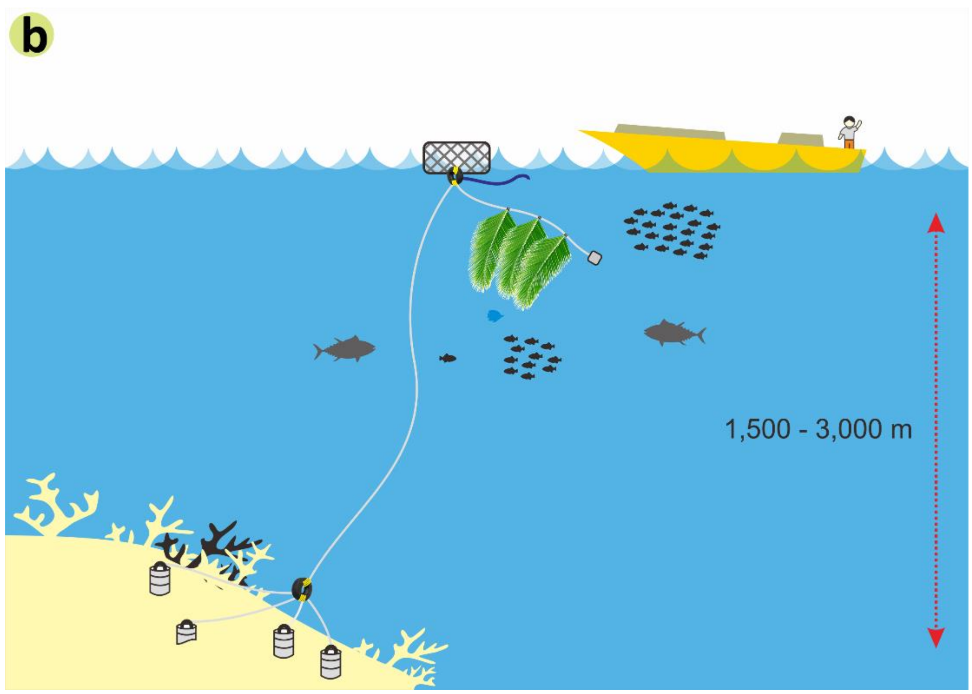


Figure 23. Moderate current is indicated by a tensed slack rope with fish distributed in up-current area (a) and dead current conditions result in fish being randomly distributed around the FAD (b).

3.4.5 Impact of COVID-19

Most of the respondents mentioned the COVID-19 pandemic had a significant impact on the fishery. The price of large tuna plummeted to around £2.5 per kilogram (kg) 50% lower than normal price before COVID-19 pandemic, while the price of small pelagic fish, skipjack, and juvenile tuna remained relatively stable. This led captains to switch target species and adjust their fishing strategies as large tuna became an unfavourable target.

According to the Pondok Dadap Monitoring and Statistic Report 2022, a lower number of handline fishing trips were observed during the pandemic as most of the migrant fishers stopped their operation. Partial lockdown regulations in numerous districts in Indonesia restricted the activity of their residents and suspended the licenses of migrant fishers. The data also showed that the CPUE of handline vessels increased during the pandemic in 2020 and 2021 (Table 10).

Table 10. CPUE of four tuna species landed by handline vessels.

Year	Trip	CPUE
2017	3012	1468.25
2018	3008	1557.17
2019	2848	1457.39
2020	1973	1954.12
2021	2791	1892.72

3.5 Discussion

3.5.1 Fishing Behaviour and Decision-making Processes Behind Them

The handline fishery demonstrates an opportunistic fishing practice, combining seven types of fishing gears and techniques in a single trip adapting to spatial and temporal availability of multiple target species associated with FADs. Despite using similar types of fishing gear, fishers exhibit a combination of three distinct long-term strategies: targeting large tuna, serving as auxiliary vessel for Jakarta purse seiners and targeting hairtail fish. Diverse fishing strategies options are influenced by changing conditions and development in the fishery (Salas et al., 2007). Christensen and Raakjær (2006) divided changing conditions into controllable variable, over which the fishers have influence and uncontrollable variable, which are beyond their control. According to this definition, we identified the operation of Jakarta purse seine fleets and the increased demand for hairtail fish (*Trichiurus spp*) as uncontrollable variable and the introduction radio telecommunication controllable variable. Dynamic response to changing conditions and uncertainties in the fishery triggered diversification fishing strategy as resilience strategy (Himes-Cornell and Hoelting, 2015).

Cooperative mechanisms were performed by handline fishers to address the competitive situation and resource fluctuations caused by the operation of Jakarta purse seine fleets overlapping with their fishing area. As described by Salas et al. (2007) these cooperative mechanisms were developed as strategies to deal with catch variability and minimize conflict during fishing operations. Two commons cooperative actions between fishers were information exchange and catch sharing. Furthermore, adoption of radio technology in the fishery promoted information-sharing networks between handline and purse seine captains. The combination of both cooperative mechanisms and technology advancements drives strategy diversification in the handline fishery (Torres-Irineo et al., 2014, Salas et al., 2007, Cooke et al., 2021).

The interannual variability of catches and price influences the strategy choices of fishers (Kasperski and Holland, 2013). The majority of fishers continue to target large tuna as their main strategy because the high value of large tuna makes the cost of searching effort negligible compared to even a single successful encounter with schools of large tuna. Their main strategy targeting large tuna was desired in order to maximize profit. However, during the off-season for large tuna or periods of resource scarcity, fishers lower their desire from profit maximization to merely obtaining enough revenue to cover travel costs particularly the last days of fishing trip (Salas et al., 2004). They switch strategy to cooperative modes by approaching purse seiners and expecting catch sharing. Fishers also divert their fishing efforts to target small pelagic, skipjack and juvenile tuna remain associated with FADs, as well as hairtail fish in different regions un-associated with FADs. This diversification was particularly evident during COVID-19 pandemic when the price of large tuna plummeted 50% lower than normal price.

The tactical decisions of handline fishers regarding the allocation of fishing effort between FADs vary according to their strategy (Little et al., 2004). FAD ownership, information-sharing networks, and fishing experience are three factors that influence tactical decision-making and diverse movement patterns between FADs. FAD ownership determines the priority of heading to either handline private FADs or purse seine FADs. In this study, Information-sharing networks are related to the technology used. Radio telecommunication allowed fishers access real-time information through various information-sharing network: handline community radio, exclusive radio groups, and purse seine radio. A higher proportion of captains installed radios and engaged in these networks, enriching their knowledge about potential productive FAD locations that underpins their tactical decisions about where to go in real time (Calderwood et al., 2023). In contrast, minority fishers without radio had limited sources of information and knowledge. Turner et al. (2014) found in their study in the Northumberland lobster fishery that information sharing networks are essential and likely contribute to fishing success especially fishers with greater access to information and reciprocated ties. Positive productivity is also linked to well-connected information-sharing networks (Barnes et al., 2017).

In handline fishery, experienced fishers typically gather extensive information from Information-sharing networks to augment their knowledge about productive FAD locations. They filter this information based on trustworthiness and success rate of their sources. However, they are secretive about their successful fishing locations, sharing this information only with an exclusive group. In contrast, less experienced fishers often actively share their catch and location successes through public community radio. This may explain how less successful fishers with less experience contribute to the knowledge base of successful fishers, as found by Turner et al. (2014). The tactics of less experienced and experienced also differ regarding productive FADs and vessel crowding. Experienced fishers tend to avoid crowded productive FADs and instead seek out the next FADs nearby. In contrast, less experienced fishers are more likely to stay at the crowded productive FADs. As mentioned by Valle-Pereira et al. (2022), individual fishing experience and skill influence the fishing tactics and chance of success.

3.5.2 Fish Behaviour

Moderate current conditions were the most favourable for fishing operations as reported by the respondents, as large tuna tend to distribute on the up-current side of the FADs. This makes it easier for fishers to locate the tuna and achieve a high catch rate while setting their fishing gears effectively. Fishers believe that surface school of small pelagic fish, skipjack and juvenile tuna forage fouling organisms surrounding FAD ropes in the up-current area during moderate current conditions. This attracts large tuna and creates a feeding frenzy. Chapman (2000) supported this observation, describing the up-current side of FADs as the main feeding zone for large tuna in her study in Pacific Island. Additionally, cannibalism has been observed on skipjack, yellowfin and bigeye tuna (Essington et al., 2009, Silva et al., 2022). In the Lesser Antilles, handline fishing associated with FADs also involves setting the gear up-current to drift past the FAD, with most of the fish caught in this area (Beverly, 2003, Wecafc, 2002).

3.5.3 COVID-19 Impact to Fishery

The closure of local and regional tuna markets during partial lockdowns lowered the demand for large tuna, causing the price of the commodity to plummet (Roziqin et al., 2021, Ferrer et al., 2021). On the other hand, partial lockdown regulations restricted migrant fishers from traveling to Pondok Dadap fishing port. This reduction in competition benefited local handliners, as evidenced by higher catch per unit effort during the pandemic in 2020-2021 (Anonymous, 2022). Local fishers also diverted their fishing strategy, targeting different species in other regions un-associated with FADs and targeting small pelagic fish, skipjack and juvenile tuna that remain associated with FADs, which proved to be more profitable due to their relatively stable prices compared to large tuna.

3.5.4 Shifting Strategy

Jakarta industrial purse seine fleets are based in Nizam Zachman Oceanic Fishing Port (OFP) in Jakarta, approximately 500 miles the fishing grounds, with fishing trips lasting about six months. Unlike tuna purse seine fishing operations in several countries, the Indonesian tuna purse seine fishery on the South Coast of Java has no auxiliary vessels to support their operation. In contrast, Japanese, Spanish, and Philippine purse seine fleets are commonly supported by various of auxiliary vessels: search boats, carrier boats, light boats, supply boats, and ranger boats to enhance operations and reduce cost.

Search boats play an important role in expanding the searching range of catcher vessels, detecting fish aggregation, and providing light during fishing operation (Itano et al., 2007). Carrier boats transport catches from the catcher vessel to the fishing port. Supply boats visit FADs to estimate the size of tuna aggregations, inform the catcher vessel about harvestable FADs, and guard FADs from competitors (Moreno et al., 2007a). Interestingly, all these auxiliary vessels' roles are performed by handliners in the Indonesian fishery. Most fishers believe that since the operation of Jakarta purse seine fleets, their catch rates decreased, and their fishing grounds have become farther away. They argue that mutual collaboration with Jakarta purse seine is the best adaptation strategy. This trend has become favourable as more captains switch strategies to become ‘hunters’ for purse seiners and vessel owners build larger vessels with bigger storage capacities to tranship fish from Jakarta purse seine fleets to Pondok Dadap fishing port.

3.6 Conclusion

The results of this study indicate that qualitative methods help to further investigate and understand quantitative data. Variability in fishing tactics and strategies among handline fishers, including the decision-making processes and motivations behind them, can be identified. In this study, fish behaviour was obtained through Fisher Ecological Knowledge (FEK) to support scientific fish observation around FADs. Mixed-methods approaches are applicable for complex fisheries systems, allowing us to answer a broader range of research questions and strengthen the resulting evidence through the corroboration and integration of findings.

Chapter 4: Fish Distribution, Behaviour, and Abundance Estimate Around Anchored Fish Aggregating Devices (FADs): Integrating Acoustic and Stereo-cameras for FADs Observation

4.1 Abstract

Deep-water anchored Fish Aggregating Devices (FADs) attract various species of fish in pelagic ecosystems. The aggregation of different fish species in large numbers and at various developmental stages is a common and natural behaviour in the world's tropical and subtropical oceans. However, collecting in-situ scientific data on fish aggregation in pelagic ecosystems is challenging due to the nature of FAD locations, which are distributed far from coastlines and over broad offshore areas. Here, we demonstrate that implementing a novel technique combining non-destructive underwater acoustics with stereo-cameras can effectively monitor fish aggregation around FADs. We found that fish tend to aggregate in the up-current area of FAD structures, with a decline in density as depth increases and a concentration in water layers approximately 50 m and 150 m deep. High-density schools of small fish were observed in shallower waters, while deeper waters were characterized by single or small groups of larger fish. A total of 11 fish species from 7 families were identified during stereo-camera sampling, and the estimated number of fish around FADs corresponded to densities of 4037 fish nmi^{-1} within the area of FAD 1 and 1805 fish nmi^{-1} within the area of FAD 2, with both surveys being dominated by Rainbow Runner (*Elagatis bipinnulata*). Our results show that fish biodiversity and abundance can be effectively assessed using a combination of acoustics and stereo-cameras, despite limitations such as the acoustic blind zone and camera depth issues. We anticipate that this technique can be further developed and complemented with other tools, such as side-scan sonar and fishing experiments, to eliminate uncertainties. Reliable sampling methods for FAD observation are crucial as baseline data for FAD management.

4.2 Introduction

Various demersal/reef and pelagic fish species at different developmental stages naturally aggregate or associate around floating objects (Dempster and Taquet, 2004, Gooding and Magnuson, 1967, Orue et al., 2019). A total of 333 species belonging to 96 families at different developmental stages in tropical and subtropical oceans have been recorded as being attracted to floating objects, including commercially valuable species (Capello et al., 2012, Castro et al., 2002, Orue et al., 2019, Baidai et al., 2020). Several theories have been advanced to explain this aggregative and associative behaviour, including predator avoidance, social interactions, and feeding motivations, but for most species, this behaviour remains poorly understood (Filmalter, 2015, Capello et al., 2022). Knowledge of the behaviour and reaction of fish to floating objects has been used by fishers to attract and concentrate fish by building and deploying floating structures called fish aggregating devices (FADs) to increase the efficiency of fishing gear and improve their catches (Dempster and Taquet, 2004, Dagorn et al., 2013).

FAD fishing negatively impacts tuna, non-target species, and their habitats (Capello et al., 2023). Increased FAD effort results in a higher catch of juvenile tuna and non-target bycatch species such as sharks, rays, and billfishes (Griffiths et al., 2019). Griffiths et al. (2019) predicted a 43% decline in these vulnerable, long-lived bycatch species over the next 20 years with simulated FAD effort at 100%. Sharks and other vulnerable species are likely to become entangled in the submerged materials of FADs, such as attractants (Mandelman et al., 2022). Fish discard is also associated with FADs, as found by Chan et al. (2014) who estimated that 0.4-8% of tuna and non-tuna species are discarded in global tuna purse seine fisheries. Massive FAD deployments lead to changes in pelagic habitat modification and contribute to marine debris (Dupaix et al., 2021, Imzilen et al., 2021).

Understanding fish behaviour around FADs is essential to mitigate undesirable consequences and the ecologically negative impact (Forget et al., 2015, Mandelman et al., 2022). Capello et al. (2023) suggested a science-based framework for the effective management of FADs that incorporates fish behaviour studies to support management decisions. Various approaches to studying fish behaviour around FADs have been conducted globally, including the use of active acoustic methods (Doray et al., 2006, Josse et al., 2000, Moreno et al., 2007c, Brehmer et al., 2006), electronic tagging (Holland and Brill, 1990, Véras et al., 2020, Pérez et al., 2022, Dagorn et al., 2000, Matsumoto et al., 2014, Tolotti et al., 2020), visual surveys (Taquet et al., 2007, Gaertner et al., 2008) and fishing experiments. Collecting in-situ scientific data on fish aggregation in the pelagic ecosystem is challenging due to difficulties in accessing their natural environment, particularly in locations where FADs are usually distributed far from coastlines and over broad offshore areas.

Integrating underwater acoustics with stereo-cameras offers advantages to observing fish behaviour, species richness and abundance around FADs (Landero-Figueroa et al., 2016). Both are non-destructive methods and complement each other. Acoustic sampling allows the distribution and abundance of many pelagic marine fauna to be assessed over a large area in a relatively short period. However, it has limited ability to identify the sources of backscatter and must rely on ground-truth information to provide the size and species composition of the targets. Traditionally, ground-truth information is obtained through net sampling (Underwood et al., 2020). However, in environments where net sampling is difficult or inappropriate, optical sampling using video or camera may be a better approach (Koslow, 2009, Landero-Figueroa et al., 2016, Mann et al., 2008). The output of stereo-camera sampling is expected to complement the limitations of acoustic sampling by allowing identification to the species level and providing length frequency distributions.

Acoustic sampling techniques and their associated post-processing systems have become a critical tool for fisheries-independent research in both marine and freshwater environments (Simmonds and Maclennan, 2008, Kubečka et al., 2009, Taquet et al., 2007). Numerous research organizations have adopted acoustic methods to estimate fish populations (Misund, 1997, Rivoirard et al., 2008), study behaviour (Freeman et al., 2004), and map species distribution (Mackinson et al., 1999, Maravelias, 2001, Massé et al., 1996, Swartzman et al., 1992) across diverse aquatic ecosystems (Appenzeller and Leggett, 1992, Simmonds and Maclennan, 2006).

Two basic measurement methods in acoustic sampling are echo counting and echo integration. Echo counting can be used to derive an abundance estimate of individual targets (individual echoes) when organisms are dispersed by simply counting individual fish and estimating the size structure of fish sampled from target strength distributions. Echo integration, on the other hand, can be used to derive the abundance of aggregated targets, which would be impossible to derive using echo counting, by summing the echoes within a sampling volume when fish are aggregated (Mann et al., 2008).

Brehmer et al. (2019) combined Underwater Visual Census (UVC) and single video camera recordings with acoustic methods for FAD observation to identify fish species, distribution, and abundance. UVC has limitations in depth and duration and is subject to numerous biases, such as intra-observer errors in estimating fish numbers and lengths, as well as fish avoidance behaviour (Edgar et al., 2004, Grane-Feliu et al., 2019, Hellmrich et al., 2023). Additionally, both UVC and single video camera recordings are unable to provide size distributions of fish observed around FADs, which are necessary to complement acoustic abundance estimates (Brehmer et al., 2019). Calibrated multicamera systems that apply the optical triangulation principle known as videogrammetry can provide a high degree of measurement accuracy and precision, surpassing direct visual estimation even by skilled observers (Harvey et al., 2001, Gruen, 1997, Fedorov et al., 2018). This method can reliably derive spatial data (length, area, and volume) as well as spatiotemporal measurements such as rates, velocity, and acceleration (Neuswanger et al., 2016). Compared to other measurement techniques, videogrammetry offers many advantages: non-contact and non-destructive measurement, the ability to sample a large number of targets and moving objects, good temporal resolution, precise and reliable results, and fast recording and processing (Cappo et al., 2003, Gruen, 1997, Smith et al., 2011).

The aim of this chapter was to develop a scientific research and monitoring method for FADs using a novel technique that combined acoustics with an ROV stereo-camera system. The study had three key objectives: (i) to test the hypothesis that fish assemblage abundance was distributed on the up-current side of the FADs according to FEK of fish behaviour, (ii) to assess fish biodiversity, and (iii) to estimate the relative abundance of fish around FADs.

4.3 Materials and Methods

4.3.1 Sampling Sites

The study area is located off the south coast of Java, in the Eastern Indian Ocean (FAO area 57). Six acoustic surveys were conducted around six different anchored FADs in three regions along the south coast of Java: Palabuhanratu - West Java (PL1 and PL2), Sadeng - Yogyakarta (SD1 and SD2), and Pondok Dadap - East Java (SDB1 and SDB2) between November 2016 and August 2021. The FADs, owned by local fishers, were situated 60 to 200 miles from the coastline and moored in waters 1,500 to 4000 meters deep (Figure 24). Additionally, underwater video surveys using a stereo-camera system were conducted simultaneously during the SDB1 and SDB2 acoustic surveys. Prior to these surveys, trials of the video system were performed on an offshore tuna net cage at the Research Institute for Mariculture Gondol in Bali, Indonesia, to determine the optimal deployment method, test performance, and observe potential fish avoidance behaviour.

Acoustic surveys require species composition and size information from additional survey elements to convert acoustic data into estimates of fish numbers. Without this information, area backscatter values from acoustic surveys only indicate the presence of fish and their spatial distribution. The area backscatter values collected from PLBR1, PLBR2, SD1, SD2, SDB1, and

SDB2 were independently used to identify the spatial distribution of fish around FADs. Acoustic data from SDB1 and SDB2 were then separately analyzed to convert area backscatter values into density estimates, using species composition and size proportions obtained from simultaneous complementary stereo-camera sampling.

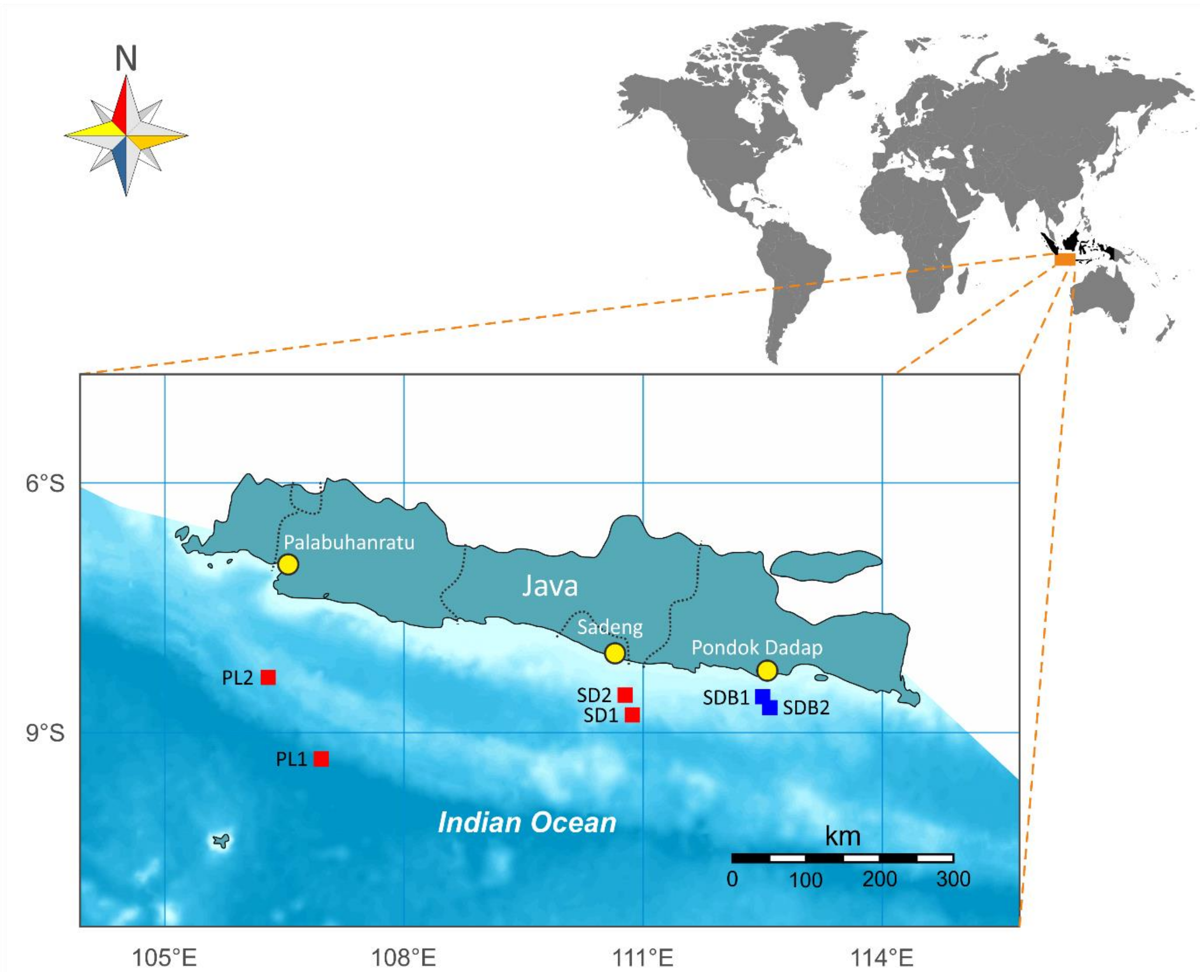


Figure 24. Acoustic surveys (red boxes) and integrated acoustic with stereo-cameras surveys (blue boxes).

The dates of each survey, trip length, and the abbreviated names used in this paper are provided in Table 11.

Table 11. Detail information about all surveys in this study.

Survey and area	Data sampling	Date	FAD coordinates
PLBR1 – Palabuhanratu	Acoustic	2 November 2016 NW monsoon	9.3990º S, 106.9567º E
PLBR2 – Palabuhanratu	Acoustic	3 November 2016 NW monsoon	8.3556º S, 110.2728º E
SD1 – Sadeng	Acoustic	8 December 2017 NW monsoon	8.8390 º S, 110.9462º E
SD2 – Sadeng	Acoustic	8 December 2017 NW monsoon	8.5874 º S, 110.8635º E
SDB1 – Sendangbiru	Acoustic, stereo-cameras	23 August 2021 SW monsoon	8.6117 º S, 112.6324 º E
SDB2 – Sendangbiru	Acoustic, stereo-cameras	26 August 2021 SW monsoon	8.6971 º S, 112.6790 º E

In addition, temperature data were collected during PLBR1, PLBR2, SD1, and SD2. However, during SDB1 and SDB2, Conductivity Temperature Depth (CTD) data were lacking. The seasonal pattern of the study site is driven by the northwest monsoon from November to March and the southeast monsoon from June to August, with inter-monsoonal period I in April-May and period II in September-October.

4.3.2 Data Collection

Acoustic Data

Acoustic-trawl surveys are widely used around the world to estimate fish density, biomass, and distribution. Although these surveys rely on trawling for the identification and classification of acoustic backscatter, they are often referred to as ‘acoustic surveys’ because trawling, as an integral component, provides species identification and length frequency distributions (Simmonds et al., 2009, Lawson and Rose, 1999, Doray and Boyra, 2021b, Zwolinski et al., 2009). In this study, trawling was replaced by a stereo-camera system, which converts acoustic backscatter into density estimates using the proportion of fish species and size. A similar approach was employed by Scoulding et al. (2023), who integrated an acoustic-optical survey method for estimating the abundance of fish in reef habitats north of Bernier Island, Shark Bay, Australia.

Acoustic surveys were carried out onboard ~15 m commercial fishing vessels equipped with SIMRAD scientific echosounder EY60. All of the surveys utilized side-mounted transducers operating at 38 kHz frequencies, connected to a General Purpose Transceiver (GPT) onboard the vessel. The side-mounted echosounder was the most suitable deployment option for these small fishing vessels. Echosounders were frequently calibrated using the standard sphere technique following Simmonds and Maclennan (2008) at Sadeng fishing port jetty (5-7 m), Yogyakarta. The operational standard settings of the echosounders are shown in Table 12. The raw acoustic data were automatically recorded on hard disk using ER60 software in digital files (.raw, .bot, .idx).

Table 12. Standard echosounder setting used for all surveys

Parameter	Value
Frequency	38 kHz
Transducer	Split beam
Pulse duration	1.024 ms^{-2}
Power transmits	1500 watt
Sound speed	1547 ms^{-2}
Absorption coefficient	5.72 $dBkm^{-2}$
S_V threshold	-70 dB
TS threshold	-60 dB

Acoustic data were collected along a systematic “star survey” pattern with eight branches (each 1.2 nmi long) according to Josse et al. (1999) at a maximum vessel speed of ~5 knots during daytime. Based on the size distribution and a target strength-length relationship model, the densities of fish can be obtained (Simmonds and Maclennan, 2008). Knowledge of the composition and acoustic properties of the FADs' fish community is crucial for accurate density estimates. Since marine organisms responsible for the echo returns cannot be imaged directly, species composition and length-frequency information are needed to aid the interpretation of acoustic data and to infer the taxa and size of targets (Mcclatchie et al., 2000). Moreover, the numerical abundance proportion of all species that produce backscatters can be estimated.

Stereo-video Cameras Video Recording

The underwater stereo-video camera system consisted of two GoPro (model 7 Silver) video cameras mounted horizontally 24 cm apart on an aluminium base bar, with the cameras inwardly converged at a 5-degree angle to optimize the field of view and maximize visibility. Additional original GoPro waterproof housings were used to increase the cameras' depth rating from 10 m to 60 m, according to the information in the housing product specifications. Three-dimensional measurements using the two calibrated GoPro cameras (Figure 25) enabled us to measure the dimensions and positions of objects based on the triangulation of their different positions in images taken from two distinct angles.

The stereo-video camera system was mounted on a small Remotely Operated Vehicle (ROV) Chasing Gladius Mini using a GoPro quick-release surfboard adhesive mount. The quick-release buckle clips were laminated with waterproof marine epoxy glue to maintain the fixed positions of the right and left cameras. The ROV has five thrusters and can move at speeds of up to 4 knots to a depth of 50 m, with ±45° adjustable tilt-lock mode in all directions, thus providing stability, the ability to manoeuvre quickly, and ease in reaching areas where fish assemblages were detected by acoustics.

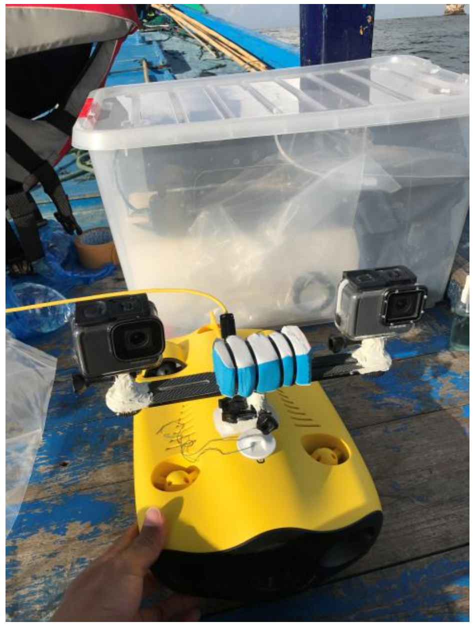


Figure 25. Stereo-cameras system mounted on small ROV.

The side-by-side stereo-camera system was corrected and calibrated prior to sampling using a distortion correction checkerboard and a calibration frame (Figure 26) (Neuswanger, 2014). Calibration is required to define the 3-D coordinate system. The calibration frame, consisting of known points called nodes arranged in grids on two parallel planes, was filmed. The 3-D coordinate system was defined by providing the positions of all nodes on all planes of the physical frame and was used throughout the video (Neuswanger, 2014). The recording workflow involved two steps: first, a synchronization event was captured using a side-by-side stereo-camera setup, followed by the recording of footage of fish around FADs.

(a) (b)

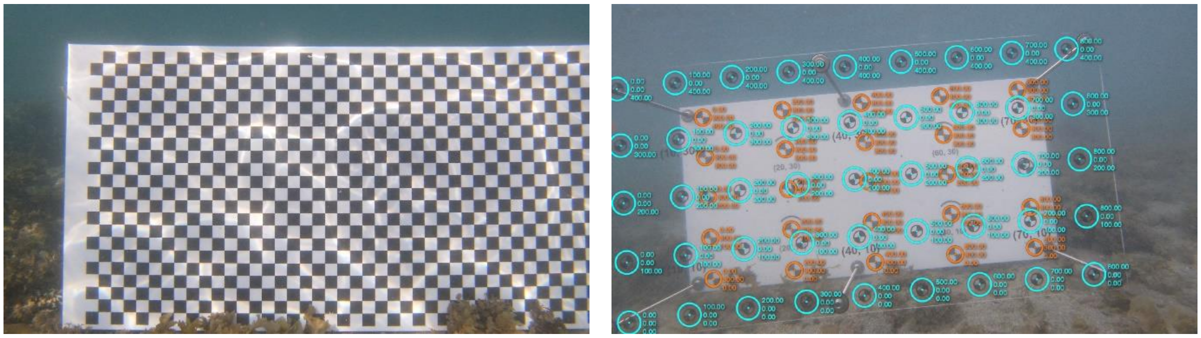


Figure 26. Distortion correction and calibration of stereo-cameras system using chessboard (a) and calibration frame (b).

There are two circumstances that form the basis for performing video sampling for acoustic identification: the observation of numerous echotraces or very dense echotraces, and changes in echotrace characteristics indicated by morphology, density, or position in the water column (Doray et al., 2010). Simmonds et al. (1991) suggested that the proportion of effort allocated between ground-truthing, and acoustic sampling should consider the distribution pattern of the fish within the survey area. Greater priority should be given to ground-truthing when the target is evenly dispersed but exhibits high variability in species composition and size distribution.

When fish schools were acoustically detected in the echogram, acoustic sampling continued with the boat moving at a slower speed, while simultaneously deploying the ROV with the stereo-camera system, which was returned to the fish schools' location (Figure 27). Stereo-camera sampling, serving as ground truth, was conditioned on the positions and paired of particular acoustic images considered representative of the echotrace community (Petitgas et al., 2003, Campanella and Taylor, 2016). The battery life of the ROV and GoPro cameras is less than two hours; thus, video sampling was limited to a maximum of two samples per FAD, with 45 minutes per sample. Watson (2006) suggested that at least 36 minutes of filming time is required to obtain measurements of the majority of fish species, and 60 minutes is advisable to obtain measurements of numerous targeted fish species.

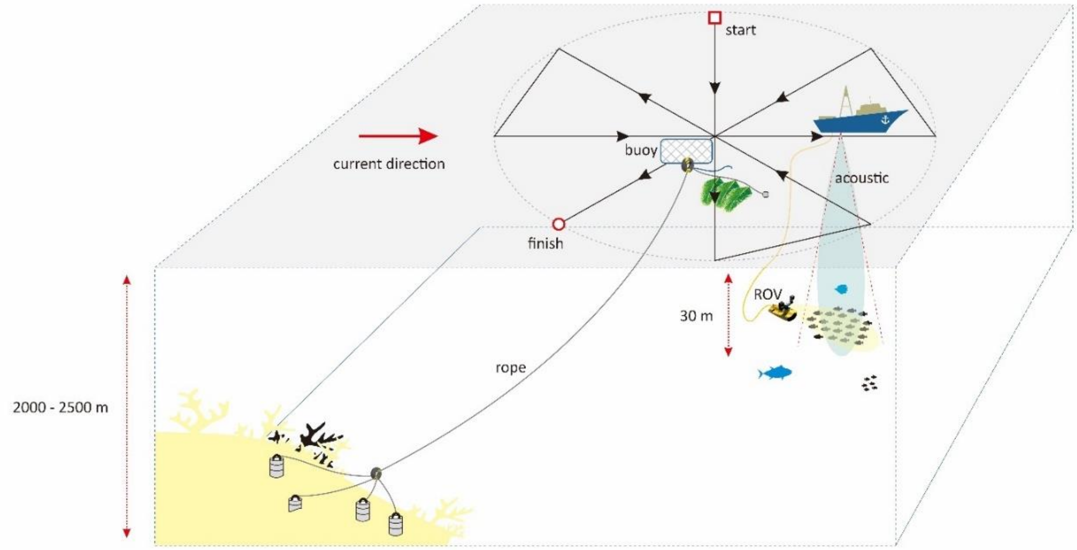


Figure 27. Survey patterns used during acoustic surveys around FADs integrated with stereo-cameras attached on ROV

Accuracy Evaluation of Stereo-cameras

Simple simulations were performed to investigate calibration and measurement accuracy of the stereo-camera system developed for FAD observations (Figure 28). This was achieved by estimating the precise lengths of objects with known lengths. Two different sizes of metal jigs (8 cm and 17 cm) were placed 1 m and 2 m in front of the stereo-camera system as simulation objects, respectively.

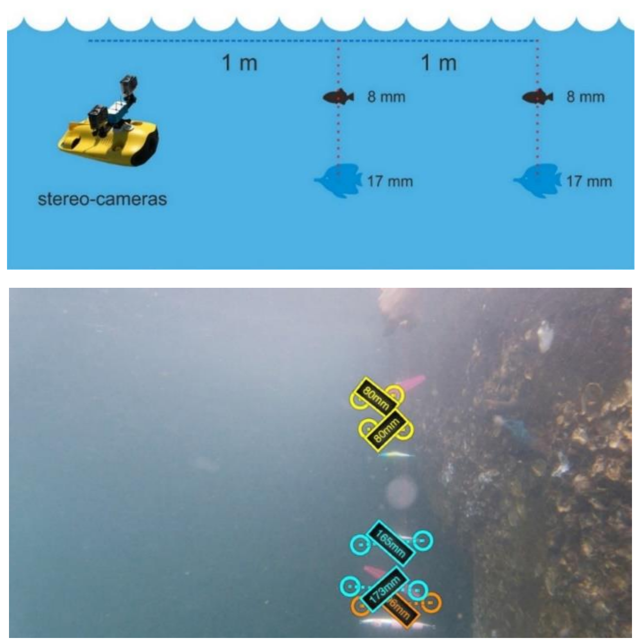


Figure 28. A simulation test using stereo-camera deployments was conducted, where two different sizes of metal jigs were placed at two different distances in front of the camera system (top). The mean relative error of measurement was then calculated based on the distance and size of the objects (bottom).

4.3.3 Data Analysis

Echogram Processing and Echo Abundance Estimation

Raw acoustic backscatter data were post-processed using Echoview software version 4 (Figure 29). The operational frequency was set at 200 kHz, with a maximum depth of up to 300 m due to the restricted depth range of acoustic energy. Two classification approaches were employed to characterize the acoustic backscatter: manual classification based on visual scrutinization of the echogram, and apportionment based on information from stereo-camera surveys, where species proportions were directly assigned to neighbouring echo traces (Ices, 2015). Numerical species proportions derived from stereo-camera sampling were then allocated to all echo traces within the survey echogram (Lekanda et al., 2024).

The classification of acoustic targets to the fish species level was performed based on knowledge of fish behaviour, characteristics of school formations, density, and the vertical position of backscatters. Post-processing thresholds were also applied to eliminate backscatter attributed to non-fish species. A high threshold was used to reduce noise and exclude echo energy from non-biological targets, while a low threshold was set to detect low densities of targets, although this increased noise levels (Watkins and Brierley, 1996).

The S_A values of echo integration were observed at 0.1 nmi intervals. Backscattered acoustic energy was converted to fish density using the target strength (TS) - fish length function (Maclennan and Simmonds, 2013):

$$TS = 10.\log\left(\frac{\sigma}{4\pi}\right) = 20\log L - b\ (dB) \tag{6}$$

where:
b = constant parameter of TS,
σ = backscattering cross section
L = fish length (cm).

where b = 42 is a constant parameter of TS for non-tuna species around FADs according to Lopez et al. (2016), due to the absence of tuna in the stereo-camera recordings during the study. Acoustic target strength is a key element required in acoustic surveys to convert echo intensity into estimates of fish density. It is a function of fish body density and length, representing the capability of fish body mass to reflect sound energy (Bertrand and Josse, 2000, Johannesson, 1983). A fish with a large swimbladder will have a higher acoustic reflection than a fish with a smaller or no swimbladder (Foote, 1980). Adequate knowledge of the TS characteristics of target species is important to improve accuracy of acoustic abundance estimates (Horne, 2003, Traynor, 1996).

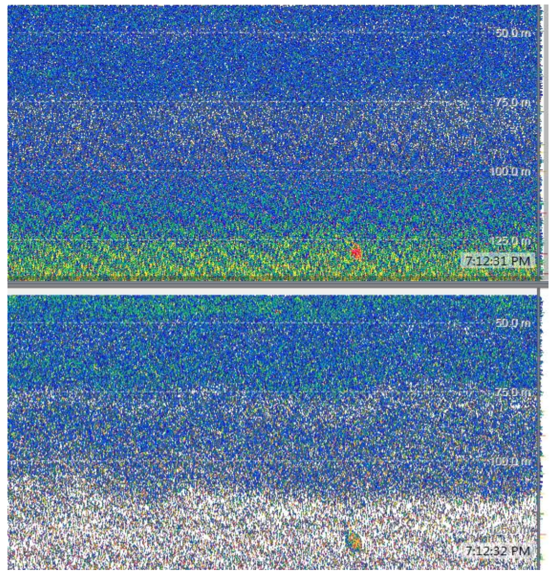


Figure 29. Echoview echogram showing fish backscatter (red).

The area density of scatterers in length group *i* was calculated as follows (MacLennan and Simmonds, 2013):

$$\rho_{Ai} = \left(\frac{\bar{S}_A}{\sigma_{Ai}}\right) \quad (7)$$

Where σ_{Ai} is the backscattering cross-section of length group *i* in the survey area. Echo Density (N) is then converted into fish density per length group by:

$$N_i = \rho_{Ai} \,.\, C_i \quad (8)$$

where C_i denotes proportion of length group *i,* calculated as:

$$C_i = \frac{p_{i\,.\,i^2}}{\sum_{i=1}^{n} p_i} \quad (9)$$

Where p_i is the length frequency of length group *i*, which in this study was 1 cm length groups. The total numbers of fish can be obtained directly by summing the numbers of fish in all length groups.

Species Identification and Size Distribution

Direct capture techniques, such as trawling, purse seining, and other fishing gear, are commonly used to characterize acoustic echo traces to specific species and obtain body length information (Doray et al., 2006, Koslow et al., 1997). However, these methods are typically constrained by their destructive nature, high costs, and the requirement for reliable vessels to conduct sampling. UVC and single video camera recordings offer non-destructive and cost-effective alternatives, but they cannot provide accurate size distributions of oceanic fish observed around FADs. Additionally, UVC is subject to intra-observer errors in estimating fish numbers, fish avoidance behaviour, and limitations related to the depth and duration of observations (Taquet et al., 2007). The affordability of stereo-camera systems allows for the measurement of body length, providing data on species diversity, abundance, and size structure, which facilitates the parameterization of acoustic target strength to estimate biomass with high temporal and spatial resolution (Letessier et al., 2017, Scoulding et al., 2023).

Neuswanger (2014) developed an open-source Mac application called VidSync to analyse synchronized videos (stereo-video), which is available for download from the official website (www.vidsync.org). We used VidSync version 1.72 on MacOS 12 and M1 processors for the manual digitation of all underwater video recordings around FADs. A total of four videos were recorded during the SDB1 and SDB2 surveys (two 45-minute videos per survey). For each video selected for analysis, a starting time was chosen following the last visible disturbance associated with camera deployment. The two videos from the side-by-side cameras (left and right) were synchronized based on a synchronization event, such as a lighter flick or finger snap. The workflow for video processing was as follows:

1. Detect plumblines and calculate distortion parameters to correct the lens distortion (Figure 26a).
2. Digitize the calibration frame nodes and calculate the calibration to establish the perspective of each camera (Figure 26b).
3. Define types of objects (species observed) and events (length measurement).
4. Click on the study subject in both cameras to input screen coordinates.
5. Export the measurement results.

The orientation, origin and scaling of the 3-D coordinates adopt a parallel front and back frame in the x-z plane, with bottom left of front frame grid is the origin (0, 0, 0). The faces of the front and back calibration frames are at y = 0 and y = d, respectively, where d is the separation between frames, which 30 cm in this study. Undistorted screen coordinates in pixels are $(u_{u,}\ v_u)$ after performing nonlinear distortion correction. Those coordinates represent the real-world $(x_{,}\ z)$ coordinates, established by manually inputting the coordinates of the dots on each face of the calibration frame. Based on correspondences between $(x_{,}\ z)$ and $(u_{u,}\ v_u)$ coordinates of each node on one planar face of the calibration frame, VidSync estimates the projection transformation matrix H ($H_{3\times 3}$ of rank 3) and converts the $(u_{u,}\ v_u)$ coordinates into $(x_{,}\ z)$ coordinates. The screen coordinates are represented as $(u_{u,}\ v_u, 1)$. Calibration frame plane coordinates $(x_{,}\ z)$ are recovered from $H\ .\ (u_{u,}\ v_u, 1)$ by factoring out *a* scalar w such that the third element equals 1 (Neuswanger, 2014, Neuswanger et al., 2016):

$$w\begin{pmatrix} x \\ z \\ 1 \end{pmatrix} = \mathrm{H}\begin{pmatrix} u_u \\ v_u \\ 1 \end{pmatrix} \quad (10)$$

The Direct Linear Transformation (DLT) method was used to determine homography (H). The accuracy of the homography transformation improved with at least four points correspondences to define an overdetermined linear system. The two homographies on the front (H_f) and back (H_b) convert each point in screen coordinates $(u_{u,}\ v_u)$ into two 3-D points: $(x_f\ , 0, z_f)$ and $(x_b\ , d, z_b)$ representing each face of the frame, and can define a line of sight from the camera through the measured object (Neuswanger, 2014, Neuswanger et al., 2016, Neuswanger et al., 2014).

Measurements of body length (FL) were only conducted when video images exposed the entire horizontal profile of the fish, allowing measurement by clicking on the fish's head and tail (Figure 30). The clicks are expressed in (x, z) coordinates in the planes of the front and back faces of the calibration frame according to the homography transformation. Furthermore, the known *y* coordinates of the front and back frame faces were used to convert the head and tail 2-D points into two 3-D points, enabling us to define the line of sight from the camera through the fish's head and tail.

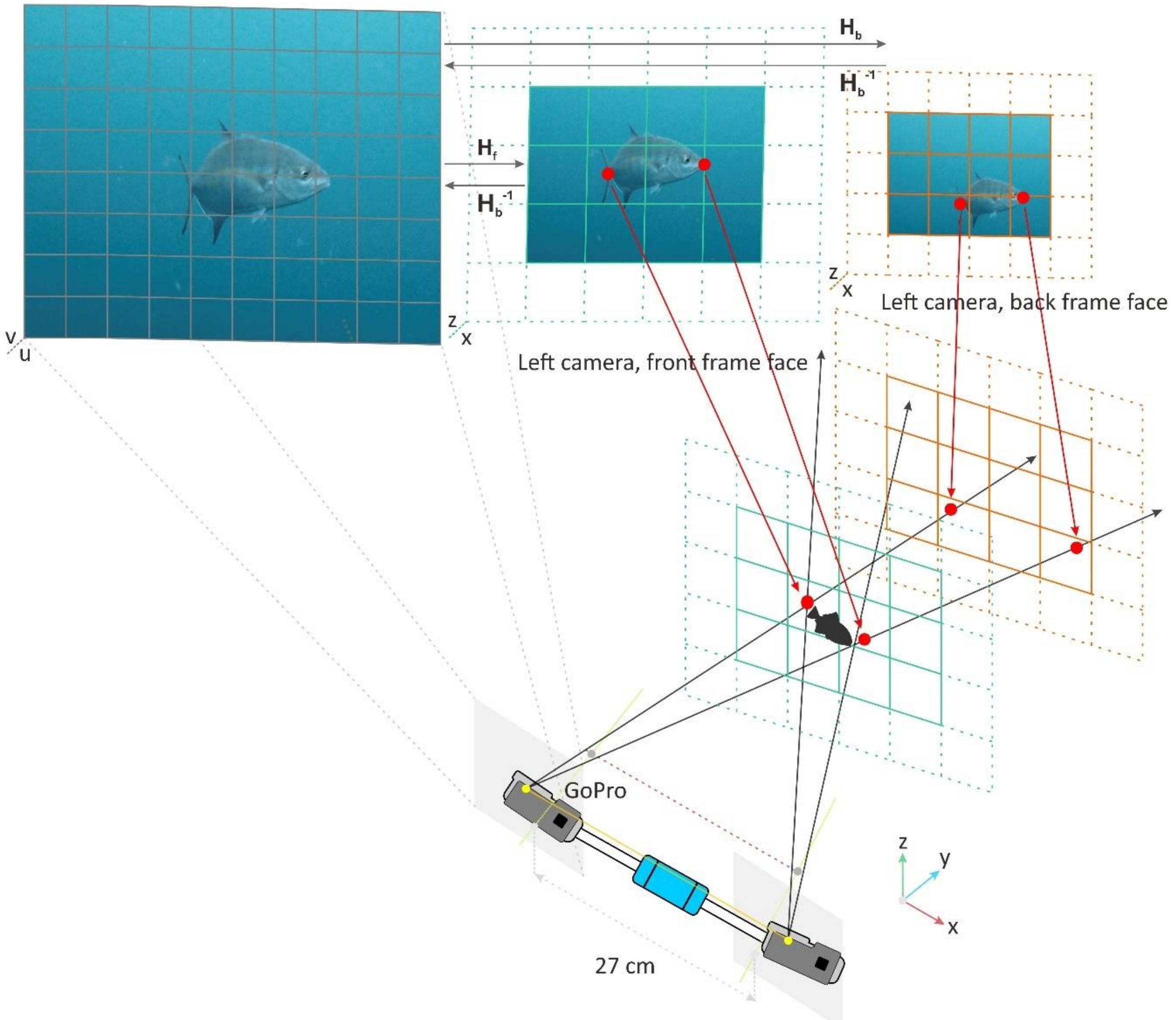


Figure 30. Screen and calibration frame perspective of the 3-D coordinate systems for measuring fish length (modified from Neuswanger et al., 2016).

3-D positions were calculated by estimating the intersections of lines of sight (Figure 30) from two cameras after defining the measured points by clicking the screen. VidSync uses Closest Points of Approach (CPA) method, which defines the midpoint of the shortest possible line segment that connects the two lines from the two cameras (Neuswanger et al., 2016, Neuswanger et al., 2014).

Video images were reviewed, and the relative fish abundance was estimated as the maximum number of each species of fish present in the camera's field of view at one time (MaxN) (Priede et al., 1994, Watson, 2006, Watson et al., 2010). The first step in performing measurements was to define the fish species observed in the video images as object categories. The number of objects represented the number of species observed, and the index number was automatically updated. Fish belonging to each species category were counted when the majority of individuals of that species were observed in a single frame. These counts were then associated with a length measurement event for size estimation. VidSync includes built-in examples of event types (e.g., salmonid foraging) to assist in the process.

Stereo-camera Trial

The stereo-video camera system used during the trial enabled highly accurate and precise videogrammetry measurements (Table 13). The mean trial measurement (20 measurements) of the 8 cm metal jig was 8.06 cm (SD = 0.20) and 8.10 cm (SD = 0.23) when observed from 1 m and 2 m from the stereo cameras, respectively. For the 17 cm metal jig, the mean measurements were 16.75 cm (SD = 0.53), 16.88 cm (SD = 0.44), and 17.24 cm (SD = 0.55) when observed from 1 m, 2 m, and 3 m from the stereo cameras, respectively. The mean relative error of the trial measurements is shown below. The 8 cm metal jig was poorly visible from 3 m away from the camera system.

The results indicate that the camera system is well corrected and calibrated in terms of both the non-linear distortion and the 3-D line of sight from the camera to the object being measured. Unsurprisingly, two factors were identified as sources of uncertainty: the distance of the object from the camera system and the length of the object. For all target lengths, the accuracy and precision of measurements decreased as the distance from the cameras increased. Furthermore, at all distances, measurements of shorter objects were more accurate and precise in absolute length units.

Table 13. The mean relative error of measurement varied with the distance and size of the object

Distance (m)	Size of object (cm)	
	8	17
1 m	0.18%	0.26%
2 m	0.23%	0.23%
3 m	-	0.29%

The relative error in the length estimate of all measurements is less than 1%. VidSync provides high precision and accuracy in videogrammetry measurements comparable to other commercial videogrammetry software such as the SeaGIS suite. Both VidSync and SeaGIS are accurate to approximately 1% of the true length of the measured object. López-Macías et al. (2023) found SeaGIS measurements to be more accurate than VidSync, with 0.22% and 0.63% error, respectively.

The VidSync videogrammetry system is more cost-effective, being significantly cheaper than the commercial software, which costs approximately US$6351. VidSync is freely available and operates on a Mac computer, with the only additional cost being less than US$300 to print a calibration frame on acrylic or polycarbonate material.

Environmental Analysis

A generalized additive model (GAM) was used (mgcv library and R version 4.1.1 http:// https://cran.r-project.org) to predict and understand the factors influencing the geographical distribution of area backscatter values S_A (also known as NASC, m^2 nmi^{-2}) from six acoustic surveys, which are proportional to fish densities (Larsen, 2015). For the analysis, five predictor variables were included in the model: coordinates (longitude and latitude), position of the S_A relative to the FAD's buoy (categorical; up-current or down-current), the distance from the FAD's buoy in nautical miles, the depth of S_A observed in meters, and the temperature (°C).

The term te(Longitude, Latitude), representing a tensor product smooth was fitted over a two-dimensional spatial surface, while other smoothing functions were applied using spline-based smooths as thin-plate regression. The Restricted Maximum Likelihood (REML) method was chosen for the estimation of the variance parameters, and the best-fitting distribution was selected from among the Poisson, Tweedie, binomial, and negative binomial distributions based on the fit to the full model. Moreover, the best-performing model was identified by multi-model inference according to the lowest Akaike's Information Criterion (AIC). The model equation is thus defined as:

$$tw(SA) = te(Longitude, Latitude) + Position + s(depth, by = Position) + s(temperature) \quad (11)$$

4.4 Result

4.4.1 Spatial Distribution of Area Backscatter Values

S_A values indicate signal scattering incidences indicating aggregation of fish. There were in total 136 area backscatter S_A observations, ranging between 0.1 to 2980.6 (m^2/nmi^2) (mean ± SD = 228.6 ± 396.8 m^2/nmi^2), proportional to fish abundance recorded for all surveys (Rueda-Roa et al., 2017). The highest mean S_A value was observed in SDB1 (446.9 ± 700.3 m^2/nmi^2) with 22 area backscatter observations, followed by PLBR2 (341.9 ± 356.3 m^2/nmi^2) with 43 area backscatter observations, PLBR1 (268.3 ± 313.1 m^2/nmi^2) with 19 area backscatter observations, SDB2 (84.3 ± 68.6 m^2/nmi^2) with 10 area backscatter observations, SD1 (45.4 ± 62.9 m^2/nmi^2) with 11 area backscatter observations, and SD2 (3.7 ± 3.9 m^2/nmi^2) with 31 area backscatter observations, respectively. Fish assemblages around FADs tended to occupy the horizontal range from 0.02 to 1.25 nmi (0.24 ± 0.31 nmi) from the FADs' buoy locations and were vertically distributed from 9.46 to 245.48 m (71.29 ± 46.16 m) (Figure 31).

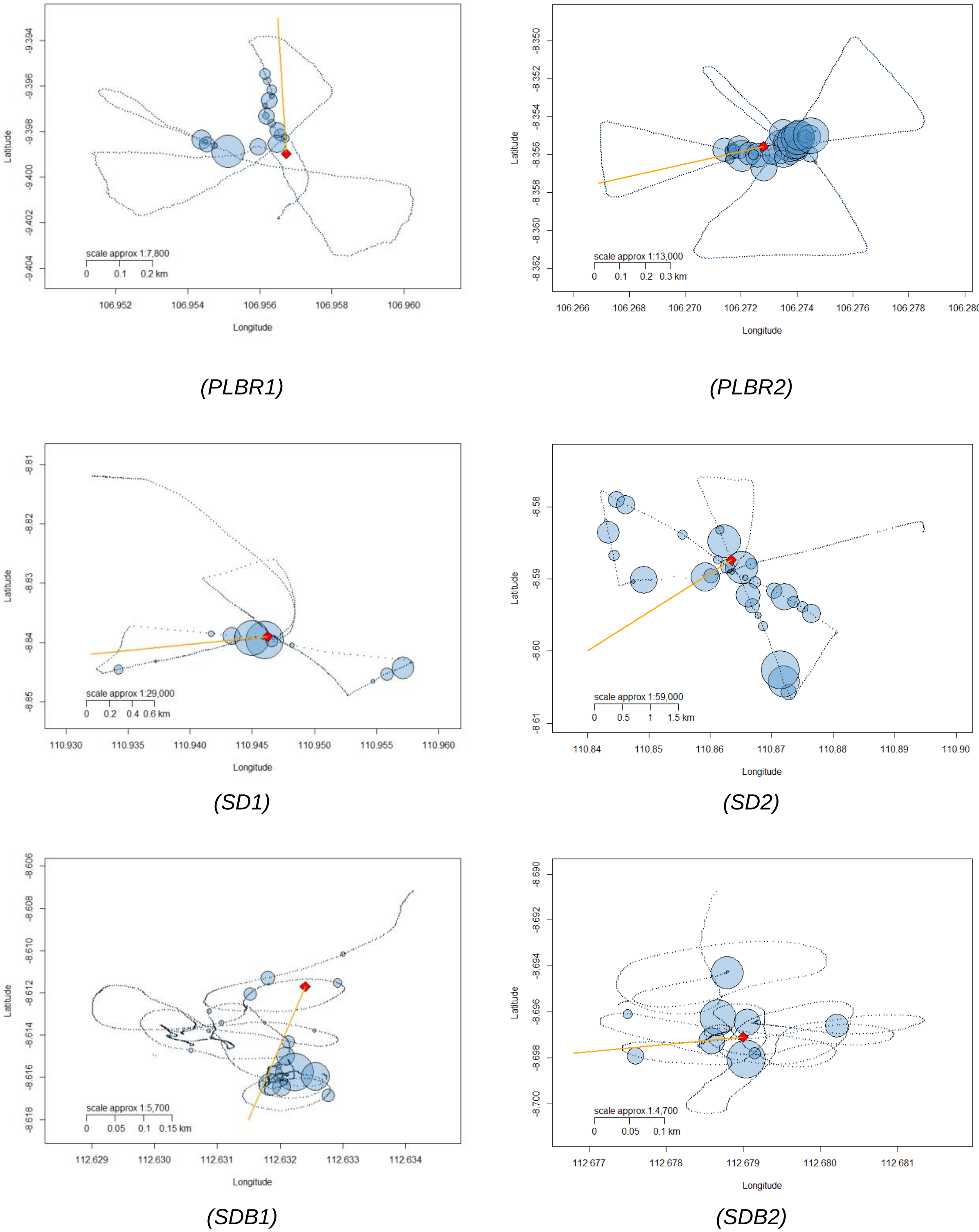


Figure 31. Horizontal distribution of S_A for all surveys. The FAD's buoy (red square) and the anchor line position indicates the up-current area (orange line).

Most of the fish assemblages were observed staying in the up-current area of the FAD or around the anchor line held against the current (Figure 32). A total of 89 backscatter S_A observations were found up-current, with values ranging from 0.1 to 2980.6 m^2/nmi^2 (225.7 ± 419.1 m^2/nmi^2), while 33 backscatter S_A observations were found down-current, with values ranging between 0.7 to 1271.5 m^2/nmi^2 (316.8 ± 390.3 m^2/nmi^2).

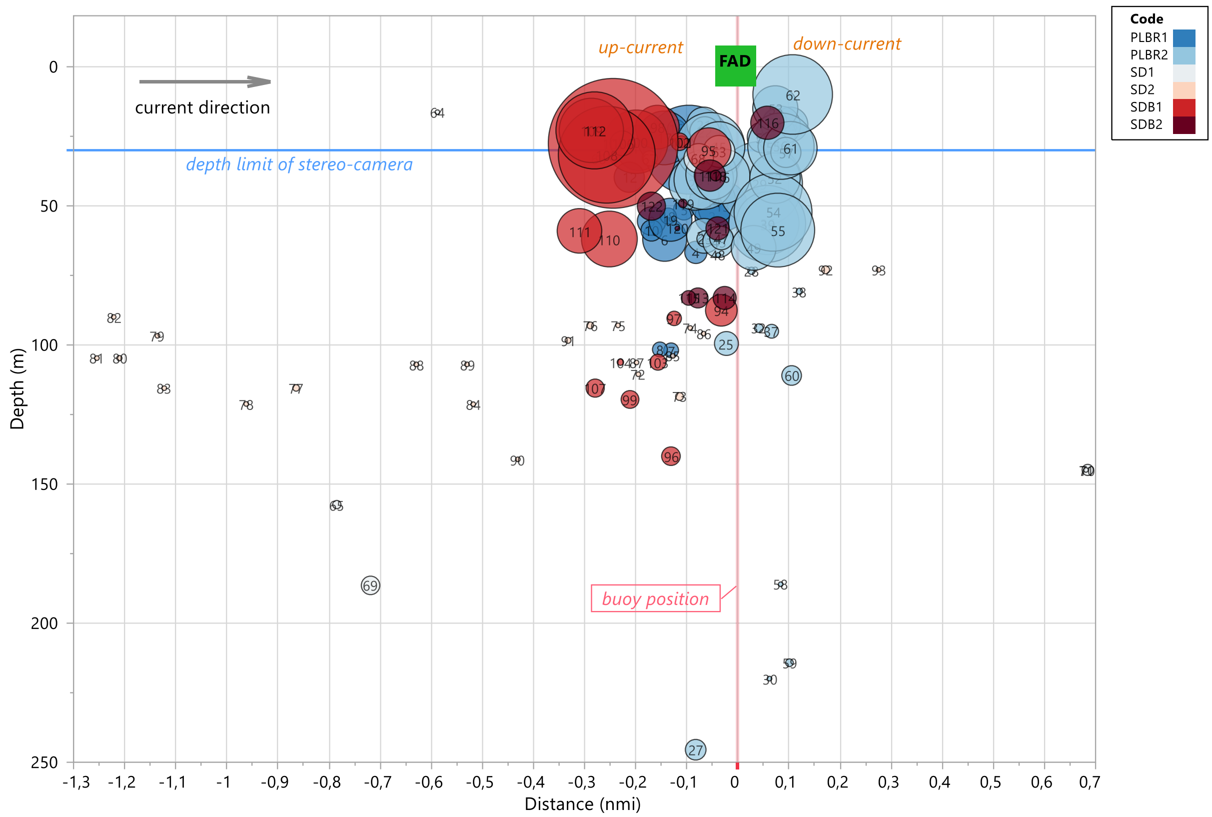


Figure 32. Vertical distribution of fish relative to FAD position and current direction.

The average temperature during PLBR1, PLBR2, SD1, and SD2 were 26.03 ± 5.41 °C ranged from 12.19 to 30.1 °C, 22.28 ± 7.69 °C, from 10.76 to 32.58 °C, 27.53 ± 3.59 °C, from 15.15 to 28.92 °C, 28 ± 2.27 °C, and from 19.75 to 29.33 °C, respectively. Overall, mean temperature shows relatively small variation with depth for all locations. The thermocline layer during the SD1 survey was shallower, starting at around 75 m (27 °C), while the thermocline layers for other surveys were deeper than 90 m (°C). The distribution of S_A values was apparently correlated with depth, higher number of fish assemblages were distributed above the thermocline layer with S_A ranging from 0.4 to 2980.6 (m^2/nmi^2) (Figure 33). While individual species were observed within and below the thermocline indicated by low S_A ranging from 0.1 to 75.35 (m^2/nmi^2).

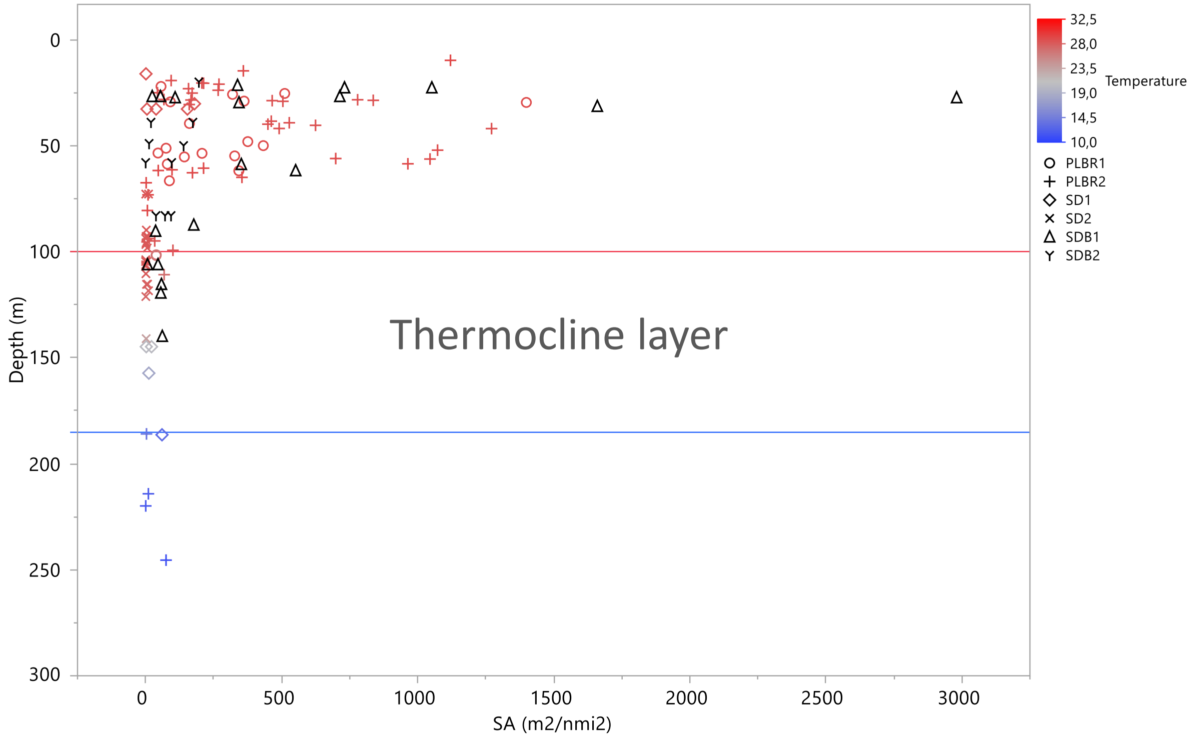


Figure 33. S_A values distribution in depth and temperature. Survey in black color represents no available of temperature data.

The horizontal and vertical distribution of S_A during SDB1 and SDB2 acoustic surveys that simultaneously were accompanied by underwater video surveys shown in Table 14.

Table 14. Mean S_A values per depth and distance from buoy SDB1 and SDB2

Depth (m)	Distance (nmi)			
	0.0 – 0.1	0.1 – 0.2	0.2 – 0.3	0.3 – 0.4
10 – 30	539.4	1131.4	4872.60	
30 – 50	666.1	152.8	1660.2	
50 – 70	96	0.4	551.6	351.9
70 – 90	380.9			
90 – 110		82.6	7.2	
110 – 130			57.3	
130 – 150		6.5		

No significant collinearity was found among variables included in the GAM model to predict and understand the factors influencing the geographical distribution of area backscatter values S_A across six acoustic surveys. Including the interaction effect between the Depth smooth and Position as a factor variable resulted in the lowest AIC and improved the fit of the model. and improved the model's fit. This improvement was also demonstrated by comparing the models using deviance. Patterns in SA density around FADs in the Southern Java are best explained by spatial coordinates (Longitude, Latitude), Position (up-current, down-current), interaction between Depth and Position, and Temperature (Table 15). The GAM analysis, using a Tweedie family distribution, returned a power parameter of 1.99 and explained 74% of the deviance.

Table 15. Parameter estimates of GAM

Parameter	Coefficient	SE	t-value	Df	p-value
Parametric terms					
Intercept	2.680	0.262	10.248	1	< 0.001
PositionUpcurrent	1.491	0.296	5.051	1	< 0.001
Smoothing terms					
Longitude, latitude				6	< 0.001
Depth:PositionDowncurrent				1	< 0.01
Depth:PositionUpcurrent				6	< 0.001
Temp				1	< 0.05

There was no statistically significant relationship between density of SA and distance from buoy ($p_{dist} = 0.9$). The relationship between explanatory variable and the response variable is linear when df is close to 1 and non-linear when the df is > 1. The relationship between SA density and spatial coordinates (smoothed Longitude Latitude interaction) was non-linear indicated by df = 6. The SA density was increased with increasing latitude and decreasing longitude with bimodal and monotonically relationships, respectively (Figure 34a). However, high uncertainty of that spatial differences of SA density might be raised due to no available information about the activity associated with those FADs. The FADs can be newly harvested or have not harvested for certain time during the studies that highly affect the fish assemblages.

The interaction effect of the depth as smoothed variable and the position as linear variable with two factors: up-current and down-current to SA density also showed bimodal and linear relationships, respectively. The SA density was highly depth driven with declines in SA values at increased of depth in both different areas. However, two peaks of SA density were found in water layer ~ 50 m and ~ 150 m in up-current area and did not occur in down-current area (Figure 34c). Furthermore, temperature only had a slight negative effect on the SA density with linear relationship (Figure 34d).

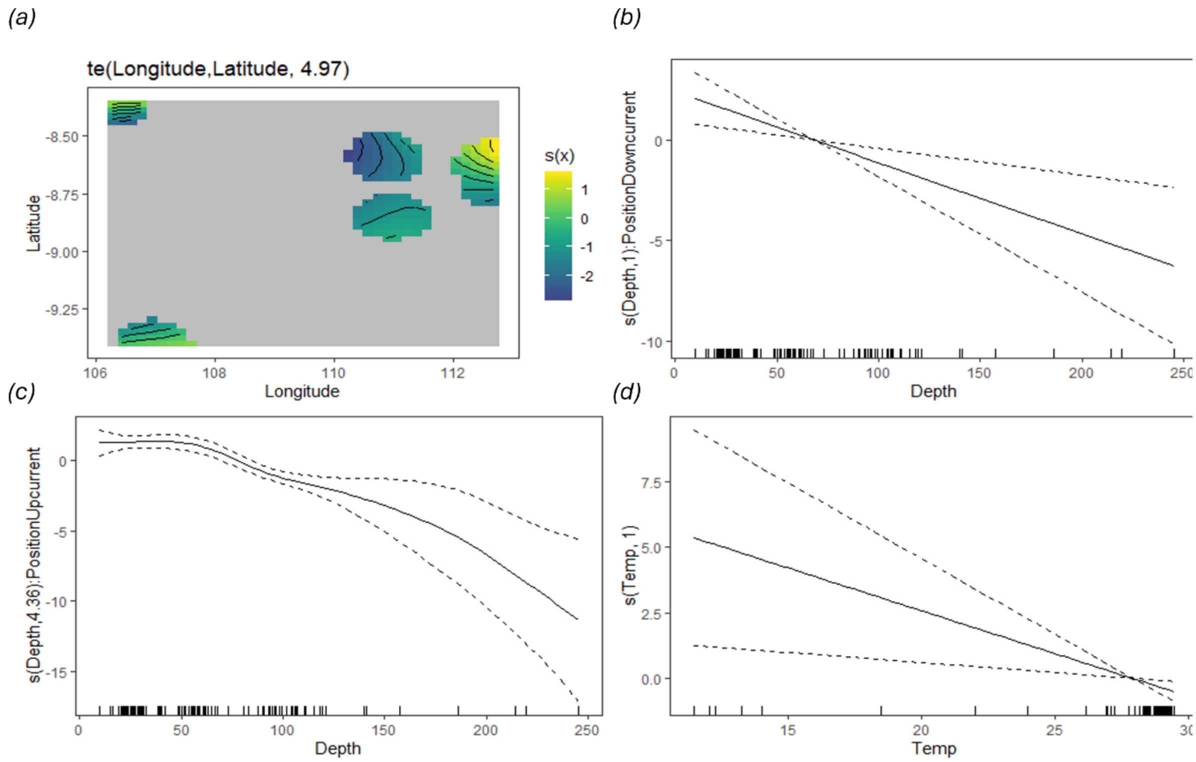


Figure 34. Term plots for each of the predictor variables retained in the best-fitting GAM for SA density response variable. Coordinates (a), Depth:PositionDowncurrent (b), Depth:PositionUpcurrent (c), and Temperature (d)

4.4.2 Species Identification and Size Distribution

A total of 11 fish species from 7 families were recorded during stereo-cameras video sampling, with FAD 1 (SDB1 survey) recording 8 species and FAD 2 (SDB2 survey) 8 species (Table 16). Rainbow runner (*Elagatis bipinnulata)* was the most dominant species and easily identified observed in both surveys SDB1 (91.7%) and SDB2 (69.4%), respectively. The other seven species sampled in SDB1 survey were only made up less than 10%, while in SDB2, cottonmouth jack *Uraspis secunda* was ranked the second most dominant species contributing 19.8% and the other six species only made up 11.1%. In contrast, skipjack tuna (*Katsuwonus pelamis)*, dolphinfish (*Coryphaena hippurus)* and whale shark (*Rhincodon typus*) were observed in SDB1 survey but were not observed in SDB2 survey. Furthermore, three species were observed during SDB2 but were not observed during SDB1 are cottonmouth jack (*Uraspis secunda)*, largescale triggerfish (*Canthidermis macrolepis)*, and wahoo (*Acanthocybium solandri)*. The taxonomy tree of all species observed during SDB1 and SDB2 stereo-cameras video sampling shown in Figure 35.

Table 16. Number of fish species and % of occurrence.

Family Species	Common name	FAD 1 (SDB1) n	FAD 1 (SDB1) %	FAD 2 (SDB2) n	FAD 2 (SDB2) %
Teleost fish					
Carangidae					
Elagatis bipinnulata	Rainbow runner	453	91.7	231	69.4
Seriola rivoliana	Longfin yellowtail	21	4.3	12	3.6
Carangoides orthogrammus	Island trevally	6	1.2	18	5.4
Uraspis secunda	Cottonmouth jack			66	19.8
Balistidae					
Canthidermis macrolepis	Largescale triggerfish			2	0.6
Kyphosidae					
Kyphosus vaigiensis	Brassy chub	7	1.4	1	0.3
Scombridae					
Acanthocybium solandri	Wahoo			2	0.6
Katsuwonus pelamis	Skipjack tuna	2	0.4		
Coryphaenidae					
Coryphaena hippurus	Dolphinfish	3	0.6		
Cartilaginous fish					
Carcharhinidae					
Carcharhinus falciformis	Silky shark	1	0.2	2	0.6
Rhincodontidae					
Rhincodon typus	Whale shark	1	0.2		

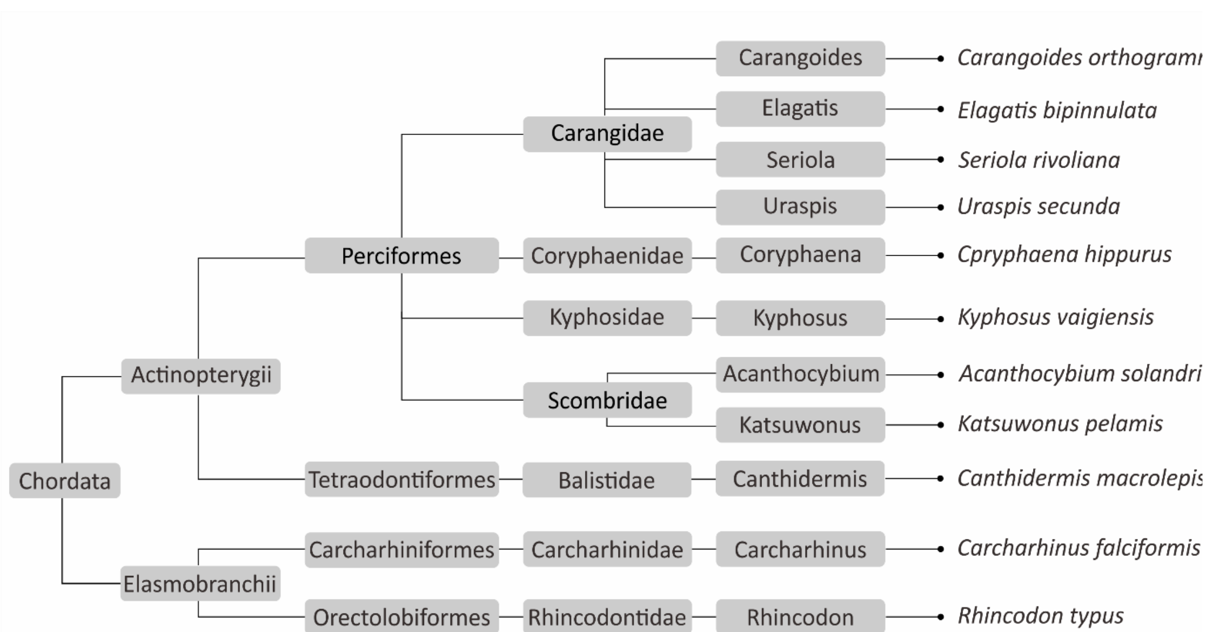


Figure 35. Taxonomic tree of observed pelagic fish from SDB1 and SDB2.

Length estimates were generated by videogrammetry FL measurement for 143 fish in SDB1 and 56 fish in SDB2, respectively. Fish varied in length from *Kyphosus vaigiensis* of 13.8 cm to *Rhincodon typus* of 630.2 cm for SDB1 and from *Elagatis bipinnulata* of 13.4 cm to *Carcharhinus falciformis* of 122 cm for SDB2 (Figure 36). The size distribution of the most numerous species *Elagatis bipinnulata* of both SDB1 and SDB2 surveys show that schools were composed mainly of immature fish 23.7 – 39.9 cm (32.2 ± 3.6 cm) dominated by two groups of modal peak 33-34 cm and 13.4 – 38.2 cm (16.8 ± 6 cm) dominated by a group of modal peak 14 cm.

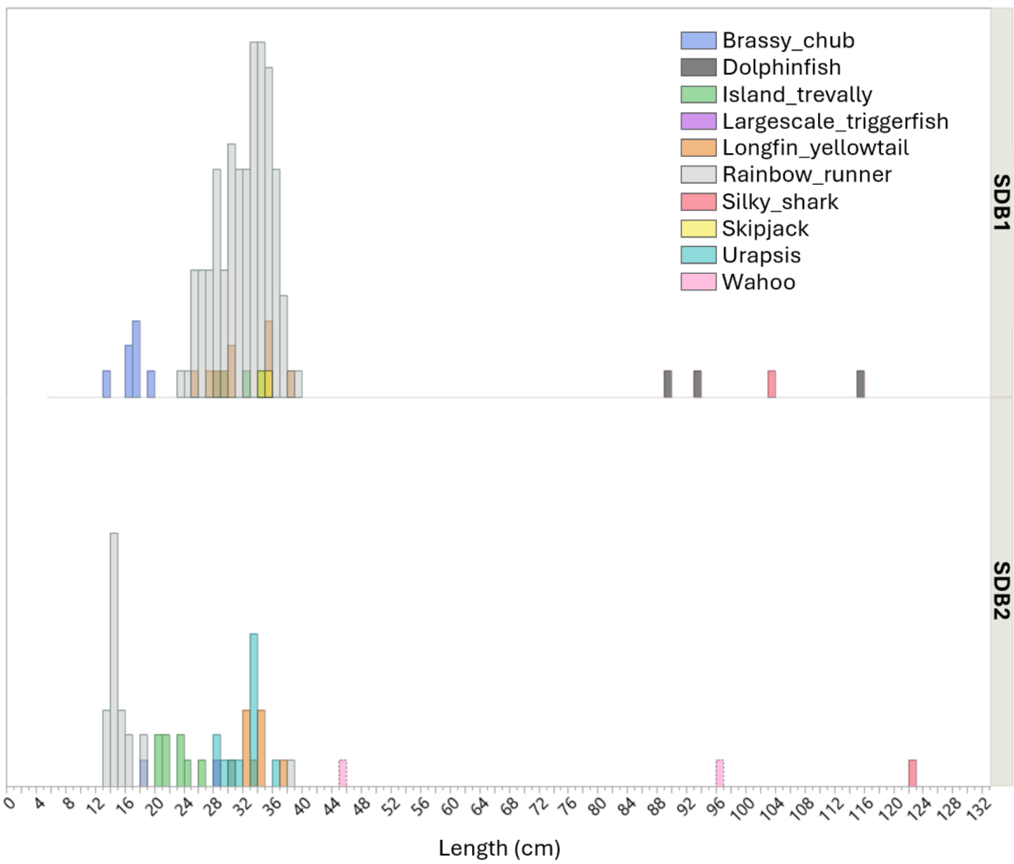


Figure 36. Length distribution of recorded fish by stereo-cameras

4.4.3 Observed Behaviour

Fish were likely showing positive and neutral behaviour in response to the presence of the cameras system. Positive reactive behaviour was exhibited by longfin yellowtail, rainbow runner and island trevally with several instances approaching the camera system (Figure 37). A similar finding was reported by Doray et al. (2006) , where rainbow runners were attracted to the camera during FAD observations using a drifted underwater camera system. However, neutral behaviour was the most common reaction for majority of fish species observed and no avoidance behaviour exhibited by any fish species. Lorance and Trenkel (2006) also observed undisturbed behaviour in most fish observed in the mid-slope of the Bay of Biscay using ROV video records.

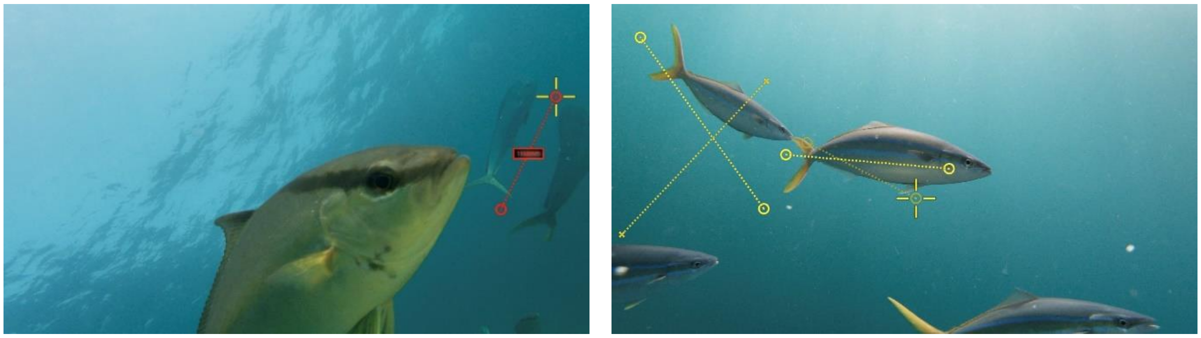


Figure 37. Longfin yellowtail (left) and rainbow runner (right) were observed approaching the camera system.

Behaviour interactions of single and mixed species groups of fish associated with FADs were observed. Rainbow runner often switched their single species aggregations from shoaling to schooling mode. The shoaling behaviour was observed when the group swam relatively close to the attractants and rope of the FADs (Pitcher, 1998). While schooling behaviour were performed by the group when relatively farther from the attractants and rope of the FADs (Miller and Gerlai, 2012, Misund, 1991). Other fish of the Carangidae family: cottonmouth jack, island trevally and longfin yellowtail were observed shoaling in a group with relatively small number of individuals. Six cottonmouth jack and an island trevally were shoaling together, circling the FAD's attractant with six longfin yellowtails were close to them. In another observation, two longfin yellowtails and four island trevallies were shoaling close to the cameras-system. Two silky sharks were observed swimming followed by numbers of rainbow runner (Figure 38). The first shark was followed by two rainbow runners, and a second shark accompanied by sixty-two rainbow runners. Moreover, varied fish species from a different family were also aggregating in a looser group consisting of two and seven individuals: dolphinfish, wahoo, and brassy chub. While whale shark, largescale triggerfish and skipjack tuna were observed as solitary individuals only.

Figure 38. Silky shark followed by rainbow runner (up-left), shoaling of multi species of carangidae fish family (up-right), dispersed aggregations of fish close to the attractant (down-left), and solitary whale shark (down-right).

4.4.4 Fish Abundance

Table 17 shows abundance estimates for the acoustic surveys SDB1 and SDB2. The number of fish detected corresponded to densities of 4037 fish nmi^{-1} within area of FAD 1 (SDB1) and 1805 fish nmi^{-1} within area of FAD 2 (SDB1). *E. bipinnulata* was the most abundant fish observed in both surveys SDB1 and SDB2 corresponding to densities 3601 fish nmi^{-1} (89.2%) and 1558 fish nmi^{-1} (86.3%). In contrast, other species only contributed less than 10% of the total densities in both FADs.

Table 17. Estimates of fish abundance around two FADs: SDB1 and SDB2.

Species	Abundance (fish number)	
	SDB1	SDB2
Elagatis bipinnulata	540	234
Seriola rivoliana	26	3
Carangoides orthogrammus	8	11
Uraspis secunda	0	20
Canthidermis macrolepis	0	1
Kyphosus vaigiensis	30	1
Acanthocybium solandri	0	0
Katsuwonus pelamis	2	0
Coryphaena hippurus	0	0
Carcharhinus falciformis	0	0
Rhincodon typus	0	0

4.5 Discussion

4.5.1 Spatial Distribution

Acoustic sampling experiments confirmed that fish distributions beneath anchored FADs were predominantly concentrated in the up-current area of the FAD structure, with aggregations acoustically categorized into schooling and scattered fish. Dense fish schools were significantly influenced by depth, with the highest fish density observed in shallow waters between depths of 9.8 to 75 m (peaking around 50 m) above the thermocline, with no significant variation in horizontal distribution within a range of 0.02 to 1.25 nautical miles from the buoy. In contrast, numerous scattered fish, corresponding to single individuals or small groups, were found at all depths from 15 to 250 m (peaking around 150 m) from the buoy, compared to dense schools. Similar results were reported by Doray et al. (2006) in their acoustic characterization of pelagic fish aggregations around anchored FADs in Martinique (Lesser Antilles), where pelagic fish aggregations were primarily observed in the up-current direction within a radius of 400 m from the anchored FAD and were characterized by dense fish schools in the sub-surface layer between 20 and 100 m. Lopez et al. (2016) , in their study of fish species associated with FADs using an echosounder buoy in the Indian Ocean, also found high densities of non-tuna species in the surface layer below 25 m, while the dominant unstructured aggregations of fish were distributed deeper than 80 m. Another study in the Western Indian Ocean off the Seychelles Islands by Moreno et al. (2007c) observed loose and medium fish aggregations between 0 and 40 m and shoals of individuals between 0 and 250 m.

Size-dependent vertical stratification of pelagic fish aggregation was observed characterized by smaller fish forming schools in shallower waters and large fish scattered in deep water (Doray et al., 2006, Josse et al., 2000). Similarly, in this study, we found acoustically dense fish schools present in shallow waters above the thermocline, as confirmed by stereo-camera sampling, which was dominated by small-sized *E. bipinnulata*. However, due to the depth limitation of stereo-camera sampling, we were unable to identify and measure the scattered fish in deeper waters. Various pelagic fish species exhibit temperature preferences that influence their vertical movement and distribution (Magnuson et al., 1979, Neill, 1979). The temperature differences within the thermocline may act as a barrier to fish movement (Ross, 2000).

Using electronic tagging techniques, Marsac and Cayré (1998) and Holland and Brill (1990) reported the up-current orientation of fish around anchored FADs off La Reunion island and Hawaii. Pelagic predators such as yellowfin tuna, big eye tuna, and dolphinfish were tracked and caught predominantly in the area upstream of the anchored FAD. Moreover, Kojima (1960) combining trolling and diving techniques to study behaviour of fish gathering around bamboo rafts “tsukegi” at Hamada Sea, Japan, described that fish attracted to bamboo rafts aggregated up-current of the raft and tended to stay parallel to it or gathering around the anchor line while swimming against the current. The motive of up-current orientation displayed by pelagic predators may be associated with intercepting incoming prey more efficiently before the prey can use the FAD structure for shelter (Holland and Brill, 1990, Marsac and Cayré, 1998). This supposition is supported by Klima and Wickham (1971) that the observed distribution of baitfish groups maintained an up-current position relative to the FAD. Small pelagic fish may be encouraged to the region similar reason, to intercept phytoplankton and zooplankton efficiently or attracted by fouling organisms that utilize the anchor line as habitat for colonization. Ropes that are used to anchor the FADs to the sea bottom provide settlement media for algae, small crustaceans, and barnacles as food sources for many organisms that aggregate and associate with FADs (Blasi et al., 2016). Many small fish (demersal/reef or pelagic), juvenile fish and pelagic predators prey on those rafting flora and fauna which can be found growing on anchor ropes (Ida, 1967, Safran and Omori, 1990, Shaffer et al., 1995, Manooch Iii and Hogarth, 1983). Nelson (2003) found that fish are five times more numerous on average at FADs with the presence of rafting organism compared to FADs where these organisms were absent.

Fishers exploit the behaviour of large tuna, which tend to aggregate on the up-current side of FADs, attracted by the presence of small pelagic fish, skipjack, and juvenile tuna, creating a feeding frenzy. This behaviour facilitates the efficient location of tuna and enhances catch rates when fishing gear is strategically deployed. Numerous studies have identified the up-current side of FADs as the primary feeding zone for large tuna, where cannibalism on skipjack, yellowfin, and bigeye tuna has been documented (Chapman, 2000, Essington et al., 2009, Silva et al., 2022). Handline fishers employ various handlining and trolling techniques, easily switching between them in a single trip. They set their gear up-current of the FADs to drift past the devices, where the majority of fish are captured (Beverly, 2003, Wecafc, 2002). In this area, artificial lures are used to catch juvenile yellowfin tuna, juvenile bigeye tuna, skipjack, and small pelagic fish. These freshly caught small pelagic fish and juvenile tuna are then rigged on larger hooks as live bait to catch larger tuna over 20 kg (Chapter 3).

Juvenile yellowfin and bigeye tuna are commonly caught as bycatch in purse seine fisheries associated with FADs, which primarily target skipjack, contributing to the decline of both tuna stocks (Bailey and Sumaila, 2010). In more selective fisheries, such as handlining, catch-and-release practices can serve as a voluntary conservation strategy, allowing fishers to release juvenile yellowfin and bigeye tuna used as live bait during fishing operations in the up-current area (Brownscombe et al., 2017).

According to the Fisher Ecological Knowledge (FEK) described in Chapter 3, handline fishers on the South Coast of Java believed that currents were the most important variable driving tuna aggregation and creating an ideal condition for fishing operations. Moderate currents led to the aggregation of small pelagic fish and large tuna in the up-current area of the FAD structure. Fish behaviour is strongly influenced by currents, which affect temperature and food availability in the sea (Moberg et al., 2011, Pankhurst and Munday, 2011, Preston et al., 1987, Volkoff and Rønnestad, 2020). Similarly, studies by Jauharee et al. (2021) and Macusi et al. (2017) on tuna behaviour at FADs, using Local Ecological Knowledge (LEK) in the Maldives and Southern Philippines highlighted that the vast majority of fishers, drawing on their extensive practical experience, agreed that currents have the greatest impact on fish aggregations at FADs.

Anchored FAD structures may act as wake-forming obstacles and create hydrodynamic microhabitats that are attractive to fish. Steady sea current flow past the structure that consists of a massive thick anchor line laying down up to 4000 m and sub-surface attractors can create velocity gradients which form vortices (Vogel, 2020, Zdravkovich, 1997, Liao, 2007). Furthermore, a sequence of vortices that is shed from the sides of the structure will generate a turbulent wake downstream known as Karman Vortex Street fluid phenomenon (Tapia and Chellali, 2010). This turbulent flow condition provides an energy-rich environment that fish can take benefit from to enhance swimming performance and reduce their locomotory cost (Breder, 1965). Fish interact with unsteady flow regimes by choosing the optimal location for station holding and alter their swimming mode: swimming in the bow wake in front of (up-current) the FAD structure, slaloming between vortices to utilize the unsteady Karman street in the downstream of the FAD structure and simply regular swimming outside the wake in the uniform flow field in the downstream of the FAD (Beal et al., 2006, Liao, 2007, Liao et al., 2003, Breder, 1965, Ježov, 2013, Harvey et al., 2022). On controlled laboratory studies to determine the most energetically favourable region for fish to hold station among those three locations, Liao et al. (2003) and Taguchi and Liao (2011) found that fish are swimming in the bow wake using the least amount of energy and oxygen compared to swimming in the Karman street and free stream swimming. This may explain why fish are aggregating in an up-current area of the anchored FAD structure, combining an energy-optimizing strategy and maximizing net energy gain by intercepting incoming prey more efficiently in the region. Unlike anchored FADs, drifting FADs float freely on the ocean surface driven by the current. In contrast, Filmalter (2015) and Schaefer and Fuller (2005) observed the opposite behaviour pattern showed by tagged silky shark, yellowfin tuna, bigeye tuna and skipjack tuna around drifting FAD and drifting vessels. Fish were consistently located down current of those drifting objects could be due more efficient way to determine location of the objects.

4.5.2 Fish Behaviour

Using a small ROV to conduct camera video surveys around FADs was advantageous to cover a wider area, provided better stability and allowed quick manoeuvre to reach the area where a fish assemblage had been detected by the acoustic system. However, there is bias associated with this method when positive reactive behaviour occurred and could result in over-estimates. Most of the fish that observed around FADs did not react and showed neutral behaviour in response to the camera system presence. Although, some species exhibited positive reactive behaviour. Avoidance or attraction reaction of fish to the ROV are likely to be species specific and influenced by a variety of sound produced by the ROV (Laidig et al., 2013, Stoner et al., 2008).

We observed behavioural interactions of single and mixed species groups of fish that associated with FADs. Silky sharks displayed a circular movement in an anticlockwise direction followed by rainbow runners. Numerous studies have observed associated behaviour between rainbow runner with sharks. Potthoff (1969) observed whitetip sharks *(Carcharhinus longimanus)* were occasionally accompanied by rainbow runners in the mid-tropical Atlantic. Rainbow runners have also been recorded associated with silvertip shark *(Carcharhinus platyrhynchus),* Glapagos shark *(Carcharhinus galapagensis)*, and grey reef shark *(Carcharhinus amblyrhynchos)* (Limbaugh, 1963, Papastamatiou et al., 2007). This interaction behaviour between rainbow runners with a wide variety of sharks might serve similar purposes for searching and hunting (foraging) or scraping (Auster et al., 2016, Thompson and Meeuwig, 2022). Circling behaviours similar to silky shark were also observed across various marine megafauna in relation to foraging (Narazaki et al., 2021). The shark's skin covered with abrasive placoid scales being used as favourite scraping surface (parasite cleaners) by small reef and large pelagic fish (Papastamatiou et al., 2007, Thompson and Meeuwig, 2022).

Switch mode of single species aggregation of rainbow runner from shoaling to schooling when relatively farther from the attractants and rope of the FADs may linked to higher probability of surviving predators as also observed by Misund (1991), schooling fish pack more closely in responding to vessel sound. Moreover, De Kerckhove and Shuter (2022) observed on his study that predator consumption rates decline as prey density increases. A possible decrease of fearfulness when close to the attractant have caused them to spend more time shoaling than schooling (Miller and Gerlai, 2012). Anti-behaviour pattern was also observed for fish that live in the seafloor habitat. Laidig et al. (2013) observed that fish demonstrated normal swimming patterns when close to the seafloor, the fearfulness is increased as fish distance above the seafloor increased, and fish exhibited anti-predator reactions.

4.5.3 Abundance Estimates and Size Structure

Integrating acoustic data with stereo-camera video surveys proved to be an effective method for estimating the abundance of fish aggregated beneath FADs. Stereo-camera video sampling was successfully conducted to provide species identification and determine size distributions, enabling the conversion of acoustic backscatter data into fish density estimates. Scoulding et al. (2023) employed similar approaches, combining acoustics and optics to estimate fish density in complex reef habitats where direct capture sampling for acoustic ground truth was not feasible.

We estimated in total 606 and 270 fish corresponding to densities 4037 fish nmi^{-1} within the area of FAD 1 (SDB1) and 1805 fish nmi^{-1} within the area of FAD 2 (SDB1), respectively. Rainbow runner was the most dominant species observed in both surveys and represented 89.2% and 86.3% of all species. However, we identified limitations of the combined acoustic and stereo-camera system. During the SDB1 we observed schools of bait fish at close proximity to surface jumping out of the water while the whale shark attempted to chase them. Nevertheless, we were not able to detect these bait fish schools in the acoustic data. In certain circumstances small pelagic fish were observed close to the surface, likely positioned within the blind zone area of an echosounder. The potential for missing fish species within the blind zone is relatively high, considering that the schools of certain small pelagic species can occur as close as ~ < 1 m from the surface (Doray and Boyra, 2021a). It is also obvious the effect of avoidance reactions will also be high when high densities of fish are found in the shallower water (Vabø et al., 2002). Vessel radiated noise will be distorting the natural distribution estimates as fish swim out either horizontally or vertically out of the path of the vessel.

Similarly, the schools of the bait fish were also absent during stereo-video camera sampling. The small size of bait fish in combination with their discrete coloration ranging from dark grey to silver have function to mirror spatially homogeneous backgrounds. Their highly reflective flanks and dark dorsal surface reflects light in such a way that it matches the background light against which the fish is viewed (Brady et al., 2015, Fréon et al., 2005). In addition, small pelagic fish are also able to swim fast supported by a streamlined body shape and forked caudal fin. These factors may explain why they were not detected by cameras. An additional limitation of the stereo-camera system was the maximum depth of observation of ~ 30 m. In contrast, dense fish schools were acoustically observed between the depths of 9.8 – 75 m while individually scattered fish can be found as deep as 250 m. Therefore, there is a high potential of missing observations of individuals and schools out of range of the stereo-camera system and thus may result in biased assessment of both species composition and length allocated to convert acoustic backscattering data into fish densities.

Side scan sonar can be a complement acoustic and stereo-camera system sampling in order to solve the proximity of schools to the surface issue and thus eliminate a degree of error. Sonar enables the detection of fish schools in shallow water and obtains a larger sampling volume compared to conventional echo sounder surveys. Vartdal (2012) observed that in a survey of shallow water (40-60 m), potential increases of biomass detected by sonar was 66.5% compared to the conventional echo sounder estimate. Moreover, consumer-grade camera like GoPro underwater action cameras may offer cost-effective and robust video observation for monitoring aquatic environments. However, more advanced camera systems with better housing and lights are required to address depth and resolution issues of consumer-grade cameras for anchored FADs observation. Another option is the application of additional complementary tools that are capable of distinguishing the major species groups throughout the water column that had been located acoustically. Angling can be an alternative ground truth tool for identifying size classes of fish. Fernandes et al. (2016) found in their study that angling provided the same length information as the trawls, was much more efficient in term of time sampling (less time) and provided an adequate sample 100% of the time.

Two factors were identified as sources of uncertainty in the stereo-camera measurements: distance of the object from the camera system and length of the object. Precision and accuracy were improved as distance from the cameras decreased and as the length of the target decreased. In addition, visually ambiguous of target can be the major driving factor of random sampling error resulted from unreliable defining the two-point events (one for head, one for tail) during measurement process. The accuracy evaluation test also demonstrated that the ability to define the two-point events of the target was affected by the colour of the target.. Neuswanger (2014) described that the difficulties in distinguishing unclear two-point events can arise due to motion blur, camouflage, a high-contrast background, turbidity, poor lighting, image noise, poor image resolution, video interlacing, and occlusion by closer objects.

4.6 Conclusion

The results of this study indicate that acoustic sampling experiments confirmed the hypothesis that dense fish schools were significantly influenced by depth, with fish tending to aggregate in the up-current area of FAD structures. High-density schools of small fish were observed in shallower waters, while deeper waters were characterized by single or small groups of larger fish. On the other hand, implementing a scientific research and monitoring method for FADs using a novel technique that combines acoustics and an ROV stereo-camera system effectively assesses fish biodiversity and estimates the relative abundance of fish around FADs. However, uncertainties arise due to the acoustic blind zone and camera depth limitations. These issues can be mitigated by complementing these methods with other tools like side-scan sonar and fishing experiments.

Chapter 5: General Discussion and Recommendations

There is a notable scarcity of detailed scientific literature on small and medium-scale tuna fisheries, particularly regarding the behaviour and spatiotemporal distribution of their efforts. In developing countries like Indonesia, weak management systems, budget constraints, and limited human resources often restrict efforts to monitor fisher behaviour. Obtaining reliable information on fisher behaviour is increasingly challenging due to the diversity of fishing techniques and the highly varied catch composition. Conversely, numerous studies have examined the behaviour of fish around Fish Aggregating Devices (FADs) worldwide, but most of these studies have employed a single scientific method, such as electronic tagging, visual surveys, or fishing experiments alone. Fisher Ecological Knowledge (FEK) has untapped potential when combined with scientific knowledge to understand fish behaviour around FADs. This thesis bridges this gap by integrating a diverse range of knowledge sources, incorporating both quantitative and qualitative research, to investigate fishers' and fish behaviour around FADs.

The results of Chapter 2 demonstrated that satellite-based GPS trackers have potential use in medium-scale handline fisheries operating in offshore waters, which are not covered by conventional trackers relying on cellular networks. These trackers effectively identify the movements and activities of handline fishing fleets along the south coast of Java. The distribution of FADs can be estimated by differentiating between intensive and extensive search patterns of fishers within the tracking data, using the Area-Restricted Search (ARS) optimality model as the theoretical basis. According to Mendo et al. (2019), the recent development of low-cost tracking systems facilitates the collection of data from small and medium-scale fishing vessels. This data can be analyzed to reveal movement patterns, such as speed and turning angle, to efficiently generate information on variations in fishing behavior and the spatial distribution of fishing effort (Mendo et al., 2019, Mills et al., 2007).

In this study, limitations arise from the low-resolution tracking interval set on the trackers. Observer data confirmed that intensive searches can last less than five minutes when encountering a low-productive FAD. This may lead to a certain number of FADs being undetected and potentially underestimating their number, as the satellite tracking device record positional data at 1-hour intervals. We suggest increasing the recording interval of trackers to 2.5 minutes to cover the entire event and activities during handline fishing operations. However, a higher resolution for accurately capturing vessel movements implies a trade-off with shorter battery life. The use of external battery packs and solar power for the SPOT trackers could mitigate this issue (Frawley et al., 2021).

In Chapter 3, interviews with fishers revealed that they perform short intensive searches when encountering low-productive FADs. They can visually assess the area around the FAD and determine the absence of large tuna in less than five minutes, then decide to depart to another FAD based on their instincts and past foraging experiences. Fishers believe that sea current conditions and the absence of tuna prey around FADs are the main indicators of the abundance of large tuna (Jauharee et al., 2021, Marshall et al., 2013). This suggests that tactical decision-making regarding optimal patch-departure time is influenced by the accumulated skills of fishers (Little et al., 2004, Valle-Pereira et al., 2022).

The Marginal Value Theorem (MVT) model was tested, assuming that fishers need to balance the benefits of remaining at the current FAD against the prospect of performing an inter-FAD search to identify a higher catch rate if they leave (Busch and Olofsson 2012). Fishers are likely to stay longer at productive FADs where the catch rate remains high and move more quickly from low-productive FADs where the catch rate drops rapidly. Generalized Additive Model (GAM) analysis was used to define multiple variables influencing fishers' residence time, including coordinates (productive area effect), day of the year (seasonality effect), distance of FADs from the fishing port (distance of FADs effect), series of fishing days (day of trip effect), and fishing port region (fishing base effect).

All variables significantly impacted fishers' residence time, except for the fishing port region (fishing base effect) variable between Palabuhanratu and Yogyakarta. Despite differences in fishing ports, fishers based in both Palabuhanratu and Yogyakarta exhibited similar residence times. In contrast, fishers based in the Pondok Dadap fishing port showed a lower mean residence time compared to other regions. Fishers are likely to spend more time at FADs located in the northeastern area, specifically between 12° to 8.5° S and 106° to 114° E. This area may represent a migration route for tuna, which migrate northwest during the east monsoon season to the second transitional season (Semedi et al., 2023). Residence time increased with greater distances from the fishing port, as more distant fishing grounds can offer greater fish yields and higher economic rents due to reduced fishing pressure and more abundant target species (Frawley et al., 2021, Cabrera and Defeo, 2001). Greater distance from the fishing port does not necessarily imply a southern direction but can also refer to the northeastern area close to the land, as indicated by the coordinates variable (productive area effect).

In temporal terms, the monthly trends of fishers' residence time showed a unimodal peak in August and were lowest in April. These findings are consistent with the seasonality of tuna on the South Coast of Java, which occurs during the southeast monsoon between June and October (Hargiyatno et al., 2021). CPUE and interview data also confirmed a similar seasonal pattern of the tuna season, approximately from May to September (Anonymous, 2022). The tuna season increases the productivity of FADs, thereby increasing the residence time of fishers. The duration of fishing trips had a positive effect on residence times, peaking at about six days, but showed a negative relationship beyond six days. According to the interviews (Chapter 3), fishers have FAD locations on their GPS, which are used as reference points. During the first several days, they head south to the furthest FAD, visiting many FADs along the way, and then turn back, heading north. Fishers tend to find productive FADs around the midpoint of the fishing operation duration.

Heterogeneity in fishing behaviour among handline fishers was observed (chapter 2). This variation includes differences in the duration of fishing trips, inter-FAD distances, distances of FADs from the fishing port, traveling time between FADs, and residence times at FADs. However, it is difficult to understand fisher motivations or underlying decision-making processes from movement data alone (Foley and Timonen, 2015, Rapp, 2007). To complement this limitation, qualitative methods were used. These methods help to identify and interpret heterogeneity in fishing behaviour, identify the variability of fishing tactics and strategies, and explore the decision-making processes and motivations behind them (Chapter 3) (Tenny, Brannan, and Brannan, 2017). This mixed-methods approach provides new insights and understanding that are unattainable with only one method. It allows for answering a broader range of research questions and strengthens the resulting evidence through the corroboration and integration of findings (Dencer-Brown et al., 2022).

The qualitative study revealed that, despite using similar types of fishing gear, the handline fishery exhibits a complex combination of three distinct long-term strategies: targeting large tuna, serving as auxiliary vessels for Jakarta purse seiners, and targeting hairtail fish. According to Salas et al. (2007), diverse fishing strategies are influenced by changing conditions and developments in the fishery. Dynamic responses to these changing conditions and uncertainties have triggered the diversification of fishing strategies as a resilience strategy (Himes-Cornell and Hoelting, 2015).

Traditionally, handline fishers targeted large tuna as their main strategy. The operation of Jakarta purse seine fleets on the south coast of Java, overlapping with handline fishing grounds, triggered conflicts between the two fisheries. The introduction of radio telecommunication facilitated communication between handline and purse seine captains, leading to fishing collaboration. The relationship occurred on different levels of collaboration, from simply helping to fulfil the logistics needs of purse seiners, maintaining their FADs, and assisting in fishing operations to sharing the cost of FAD deployment and building handline boats together. In return, they gained catches shared by purse seiners, typically small pelagic fish, skipjack, and juvenile tuna. According to Salas et al. (2007), these cooperative mechanisms were developed as strategies to deal with catch variability and minimize conflict during fishing operations. Two common cooperative actions between fishers were information exchange and catch sharing. The combination of both cooperative mechanisms and technology advancements drives strategy diversification in the handline fishery (Torres-Irineo et al., 2014, Salas et al., 2007, Cooke et al., 2021)

The tactical decisions of handline fishers regarding the allocation of fishing effort between Fish Aggregating Devices (FADs) were derived from their strategy and influenced by multiple variables: FAD ownership, information-sharing networks, and fishing experience (Little et al., 2004). For traditional fishers targeting large tuna, FAD ownership determined whether they prioritized heading to private handline FADs or purse seine FADs. Fishers typically followed a straightforward pattern, prioritizing visits to their own FADs before traveling to purse seine FADs. On the other hand, radio telecommunication provided fishers with real-time information through various information-sharing networks. A higher proportion of captains preferred installed radios and engaged in these networks, enriching their knowledge about potentially productive FAD locations. This information underpinned their tactical decisions about where to go in real-time and decreased uncertainty in finding better-quality FADs (Calderwood et al., 2023). Fishers employing a 'hunter' strategy used radios to communicate with purse seiners. These 'hunter' fishers travelled frequently, visiting and monitoring their collaborative purse seine FADs. Serving as auxiliary vessels for Jakarta purse seiners, they tended to have shorter residence times compared to traditional fishers targeting large tuna. In contrast, a minority of fishers without radios had limited sources for acquiring information about when and where to fish. These fishers tended to perform less complicated inter-FAD movement patterns. The tactics of less experienced and experienced fishers also differed regarding information sharing and movement patterns. Experienced fishers typically gathered extensive information from public information-sharing networks to augment their knowledge about productive FAD locations. However, they were secretive about their successful fishing locations, sharing this information only with an exclusive group. They also avoided crowded, productive FADs, instead seeking out nearby arrays of FADs. One fishing area of the Jakarta purse seine fishery comprised a cluster of FADs to minimize fuel costs (Libre et al., 2015). This tactic accommodates tuna movement behaviour, in areas with high density of FADs, the connectivity between FADs increased. At this area tuna tend to visit more FADs and increases their stay time (Pérez et al., 2020)

In contrast, less experienced fishers often actively shared their catch and location successes through public community radio. They were more likely to stay at the crowded productive FADs. Individual fishing experience and skill influence the fishing tactics and chance of success (Valle-Pereira et al., 2022).

COVID-19 pandemic had a significant impact on the fishery. The closure of local and regional tuna markets during partial lockdowns lowered the demand for large tuna, causing the price of the commodity to plummet (Roziqin et al., 2021, Ferrer et al., 2021). On the other hand, partial lockdown regulations restricted migrant fishers from traveling to Pondok Dadap fishing port. This reduction in competition benefited local handliners, as evidenced by higher catch per unit effort during the pandemic in 2020-2021 (Anonymous, 2022). Local fishers also diverted their fishing strategy, targeting different species in other regions un-associated with FADs and targeting small pelagic fish, skipjack and juvenile tuna that remain associated with FADs, which proved to be more profitable due to their relatively stable prices compared to large tuna.

Two illegal fishing practices were identified within the handline fishery. Satellite tracking data analysis revealed that 47.95% of the total estimated number of FADs violated the spacing requirement regulated by the Ministry Decree No. PER.18/MEN/2021 regarding fishing gear and auxiliary gear deployment in Indonesian territory. According to this decree, FADs must be deployed at a minimum distance of 10 nautical miles apart. When the distances between FADs decrease, tuna tend to visit more FADs, resulting in higher connectivity. Consequently, they spend less time traveling and more time staying around FADs (Pérez et al., 2020).

Another illegal practice revealed during interview data collection. Mutual collaborative between handline and Jakarta purse seine became common practice contributed lack transparency of reporting catches sharing. Despite being caught by Jakarta purse seiners, the transhipped fish are reported as handline catches at the landing port (Obaidullah, 2023). Misreporting result in inaccurate data, which hinders our ability to assess population status and manage fisheries sustainably (Rudd and Branch, 2017)

Fishers' knowledge about tuna behaviour around FADs, derived from their extensive practical experience, also provided valuable information to complement scientific observations of FADs. Fishers believed that sea current was the most important variable driving tuna aggregation and creating an ideal condition for fishing operations. Moderate currents led to small pelagic fish and tuna aggregating in the up-current area of the FAD structure, making this area the most effective fishing spot. Surface school of small pelagic fish, skipjack and juvenile tuna forage fouling organisms surrounding FAD ropes in the up-current area during moderate current conditions attracts large tuna and creates a feeding frenzy. Similar fishing practices are also performed by handline fisheries in the Lesser Antilles, with most of the fish caught in the up-current area (Beverly, 2003, Wecafc, 2002).

Interestingly, acoustic sampling experiments confirmed that distributions of fish beneath anchored FADs were mostly concentrated in the up-current area of the FAD structure (chapter 4). According to acoustic data and GAM analysis, distribution of fish distinct into two areas: shallow water, typically characterized by high-density schools of small fish, and deeper water, characterized by single or small groups of large fish. Unfortunately, the speed and direction of sea current unable to measured due to equipment limitation during the surveys.

The up-current orientation displayed by large pelagic fish may be associated with intercepting incoming prey more efficiently before the prey can use the FAD structure for shelter (Holland and Brill, 1990, Marsac and Cayré, 1998). This hypothesis is supported by Klima and Wickham (1971), who observed that baitfish groups maintained an up-current position relative to the FAD. Similarly, small pelagic fish may be drawn to these regions to efficiently intercept phytoplankton and zooplankton, or they may be attracted by fouling organisms that utilize the anchor line as a habitat for colonization. The ropes used to anchor FADs to the sea bottom provide a settlement medium for algae, small crustaceans, and barnacles, which serve as food sources for many organisms that aggregate and associate with FADs (Blasi et al., 2016). Chapman (2000) identified the up-current side of FADs as the main feeding zone for large tuna in her study in the Pacific Islands, noting that cannibalism has been observed among skipjack, yellowfin, and bigeye tuna (Essington et al., 2009, Silva et al., 2022)

Combining acoustic and stereo-camera video surveys has proven effective in assessing fish biodiversity and estimating the relative abundance of fish around FADs. In this study, a total of 11 fish species from 7 families were identified using stereo-camera video sampling. This data was then used to characterize the acoustic backscatter through an echo-integrating process. The fish abundance corresponded to densities of 4037 fish nmi^{-1} and 1805 fish nmi^{-1} within the areas of two sampling sites, respectively.

However, limitations of the combined acoustic and stereo-camera system were identified. There is a relatively high potential for missing fish species within the blind zone near the surface. For stereo-camera systems, sources of uncertainty include the inability to detect small fish with discrete coloration and the maximum depth limitations of the cameras. Dense fish schools were acoustically observed at depths ranging from 9.8 to 75 meters, while individually scattered fish were detected at depths of up to 250 meters. In contrast, the stereo-camera system has a maximum observation depth of approximately 30 meters. Consequently, there is a significant potential for missing observations of both individual fish and schools that are beyond the range of the stereo-camera system. This limitation could result in a biased assessment of species composition and length, which are essential for converting acoustic backscattering data into accurate fish density estimates. Additional tools can be used to complement these limitations and eliminate uncertainties. Side-scan sonar enables the detection of fish schools in shallow water and obtains a larger sampling volume compared to conventional echo sounder surveys (Vartdal, 2012). Fishing experiments, such as angling, can serve as an alternative ground-truthing tool for obtaining the identifications and sizes of fish at greater depths (Fernandes et al., 2016).

5.1 Policy Recommendations

Monitoring and enforcement of offshore fisheries are challenging, time-consuming, and costly (Bailey et al., 2012). Implementing a low-cost tracking system with a high resolution of recording intervals in the handline fishery can effectively provide behavioural information about when and where fishers are traveling. It offers insights into fishing grounds, fishing activities, and the distribution of FADs.

Surveillance and statistics officers have limited capability to distinguish whether catches are caught by purse seine or handline during port inspections. Collecting Fishers' Ecological Knowledge (FEK) would help generate indicators to distinguish catches associated with handline or purse seine methods. Experienced fishers possess valuable knowledge about fish and fisheries, and they can provide crucial information regarding these issues (Turner et al., 2014). In addition, handline tracking information can be combined with vessel monitoring systems (VMS) tracking data from purse seine as alternative option to identify transhipment activities between them. Using vessels position data, Park and Stamato (2020) developed a framework for generating and visualizing a global network of transshipment using social network analysis to identify illegal transhipment. Seto et al. (2022) combined vessel position data verified by observer encounters to identify potential illegal transhipments in the Western and Central Pacific Ocean.

Rapid development of nanosatellite in low earth orbit enabling practical and affordable in vessel tracking, detection and identification using various sensors (Pekkanen et al., 2022, Qi et al., 2022). In July 2024, the Ministry of Marine Affairs and Fisheries of the Republic of Indonesia, in partnership with GOMspace Denmark, launched a constellation of 20 nanosatellites equipped with optical imaging and high-frequency detection capabilities (Gomspace, 2024). This initiative provides an opportunity to apply advanced technology to monitor small and medium-scale fishery particularly for offshore illegal activities (Lin et al., 2022).

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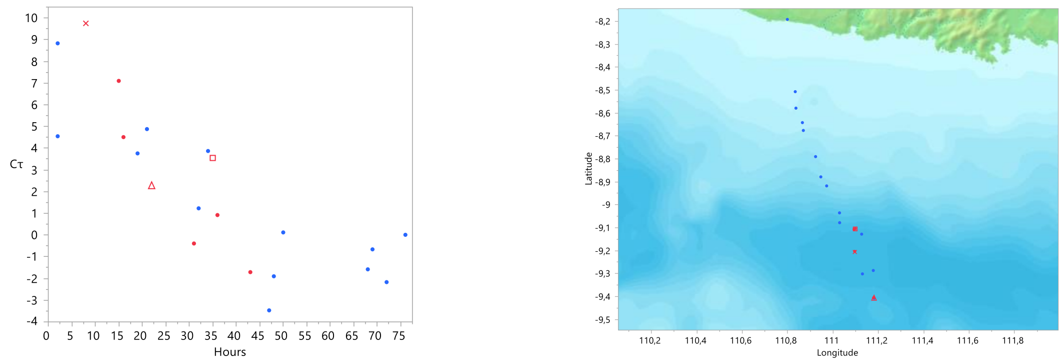
Appendix A: Area Restricted Search (ARS)



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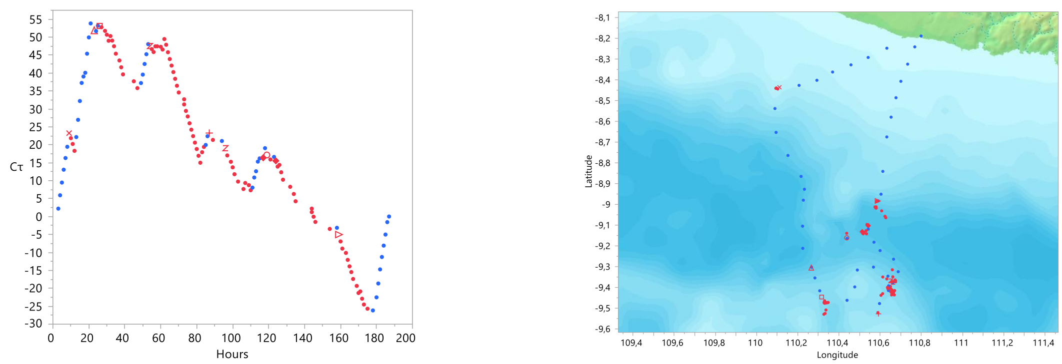

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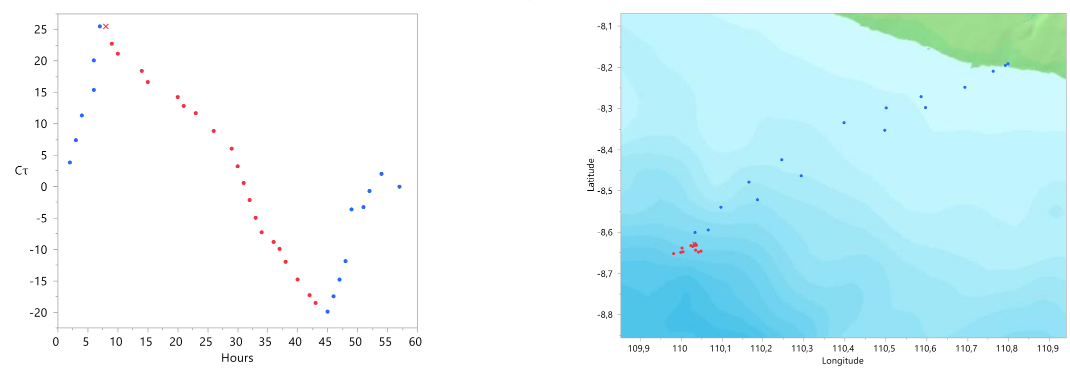

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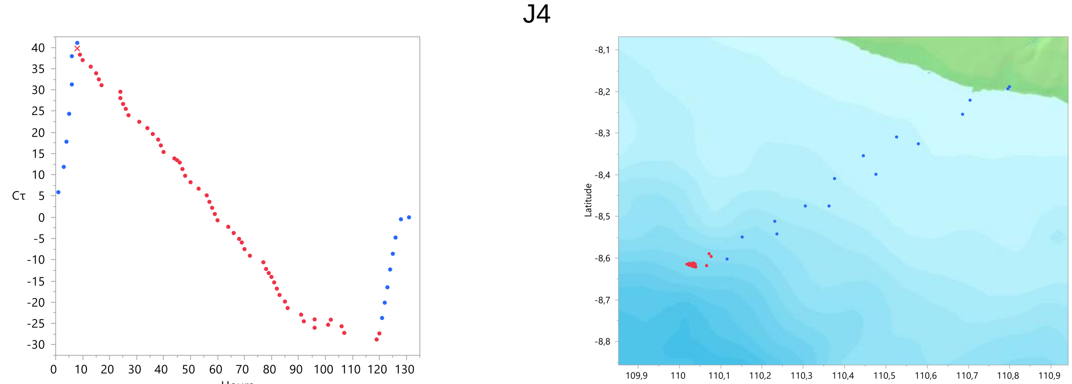

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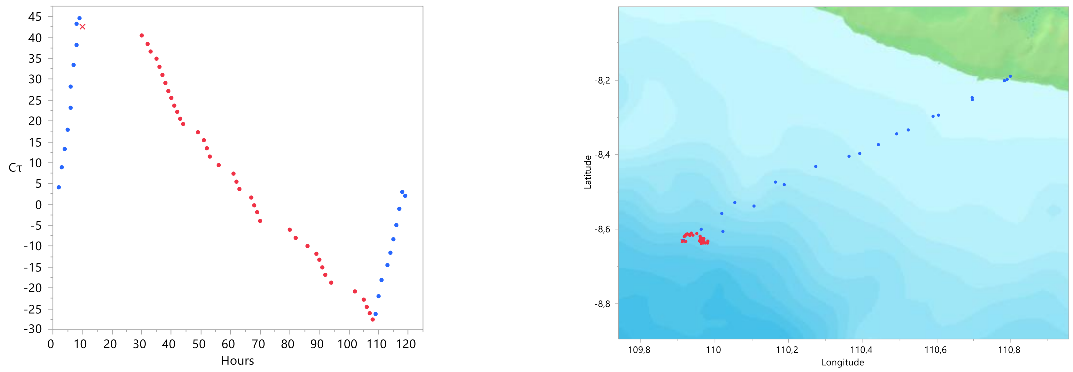

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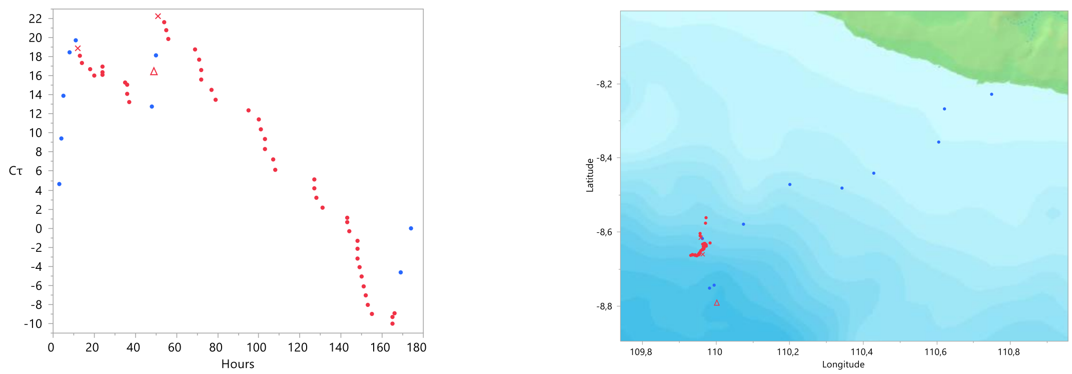

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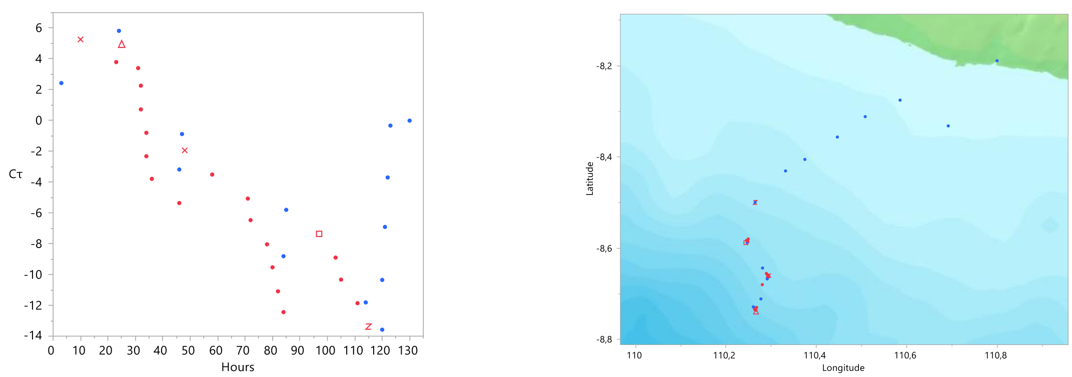

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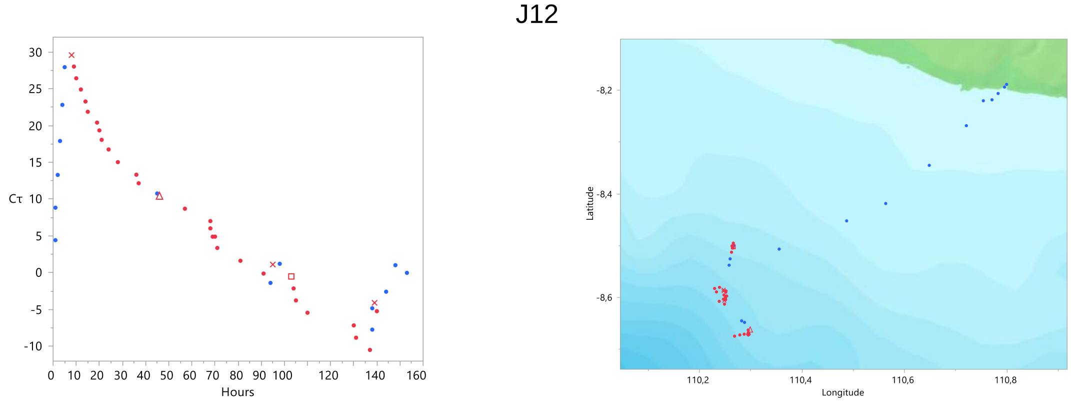

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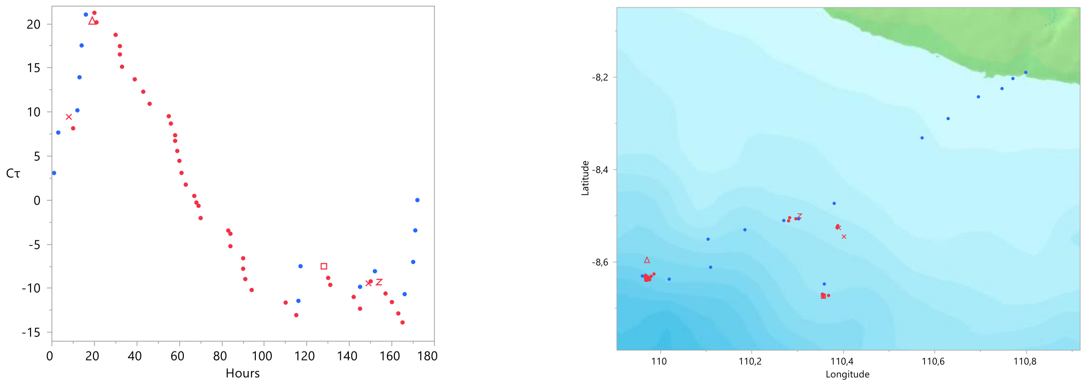

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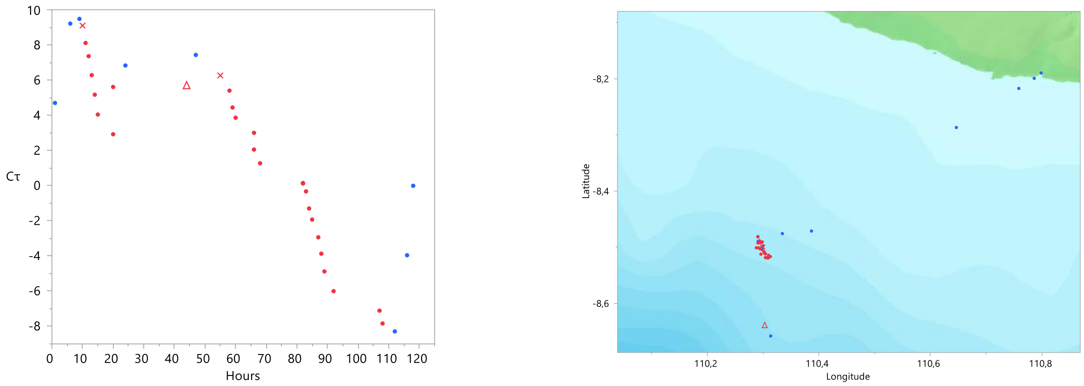

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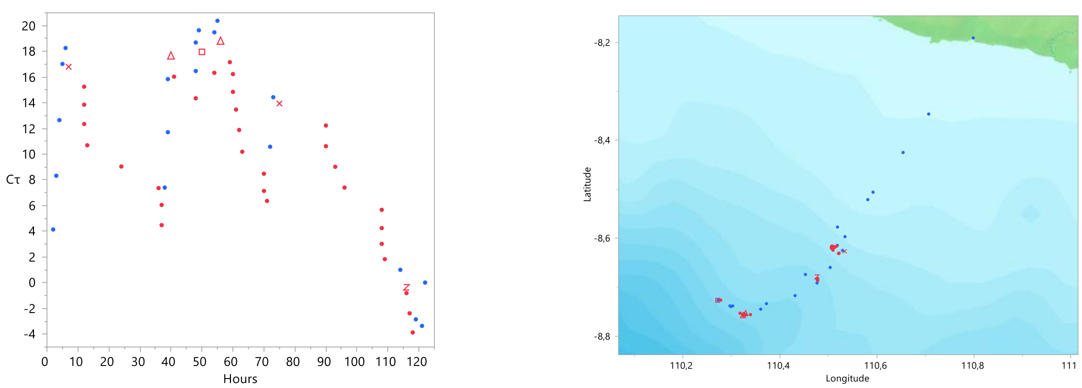

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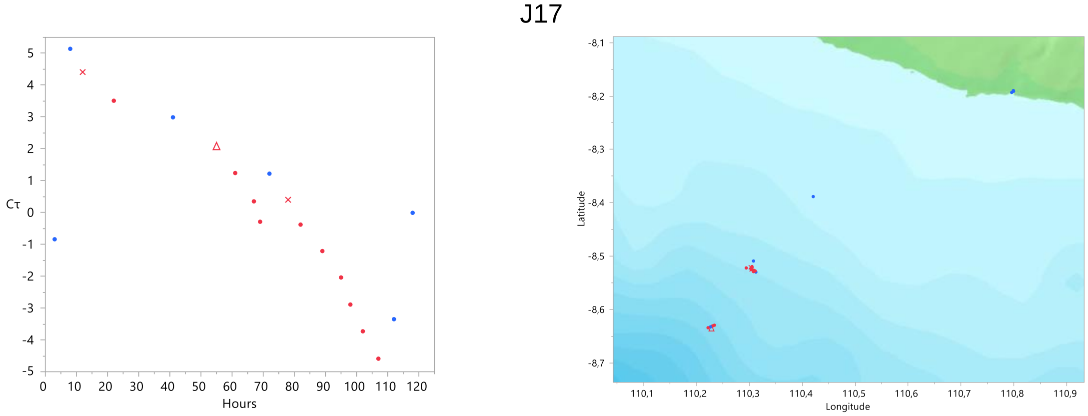

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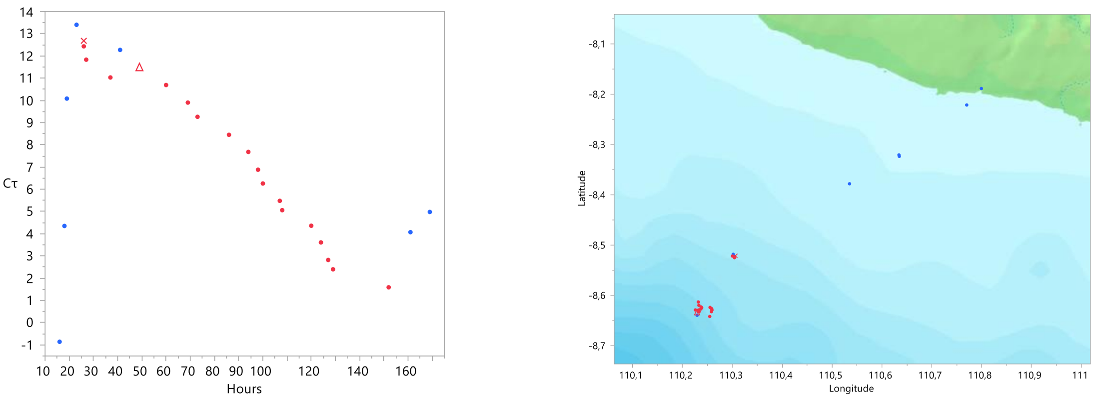
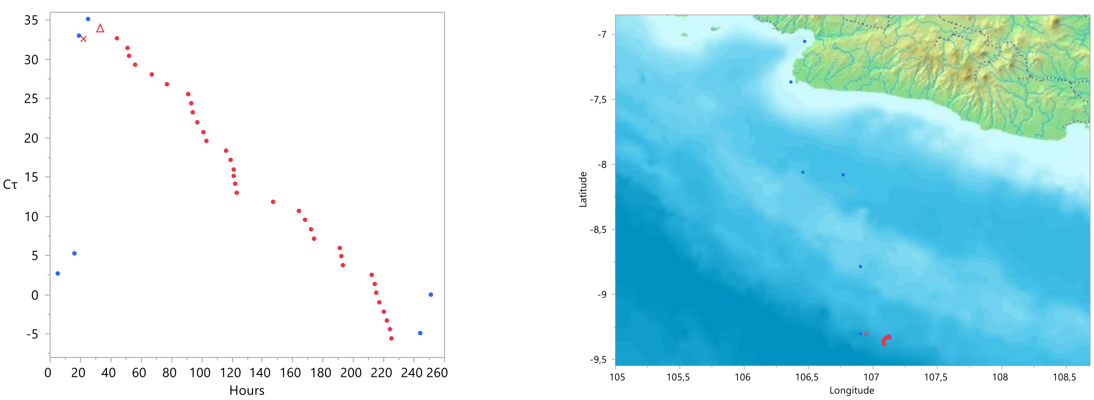

Cτ
Hours
Latitude
Longitude

J21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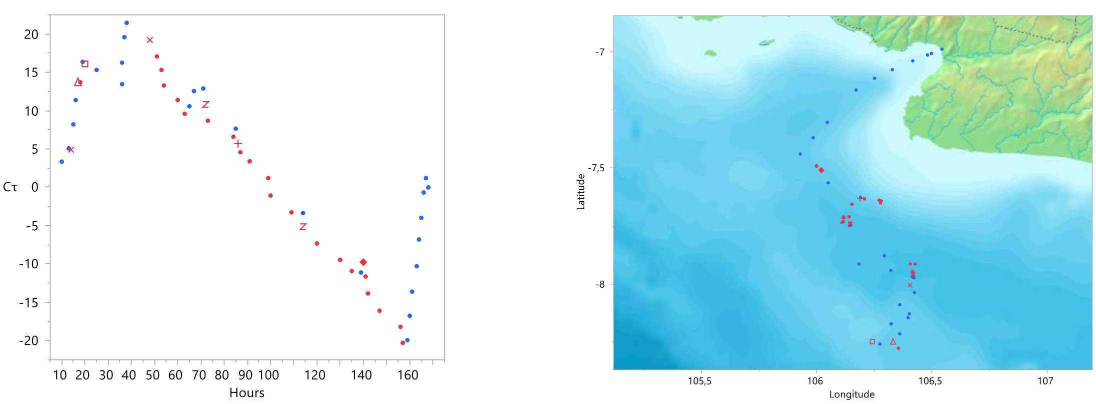
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Hours
Latitude
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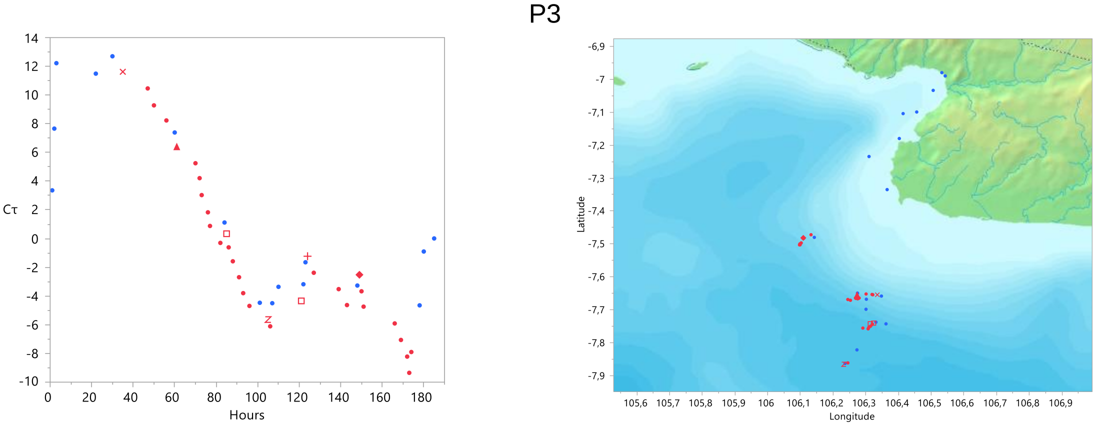
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Hours
Latitude
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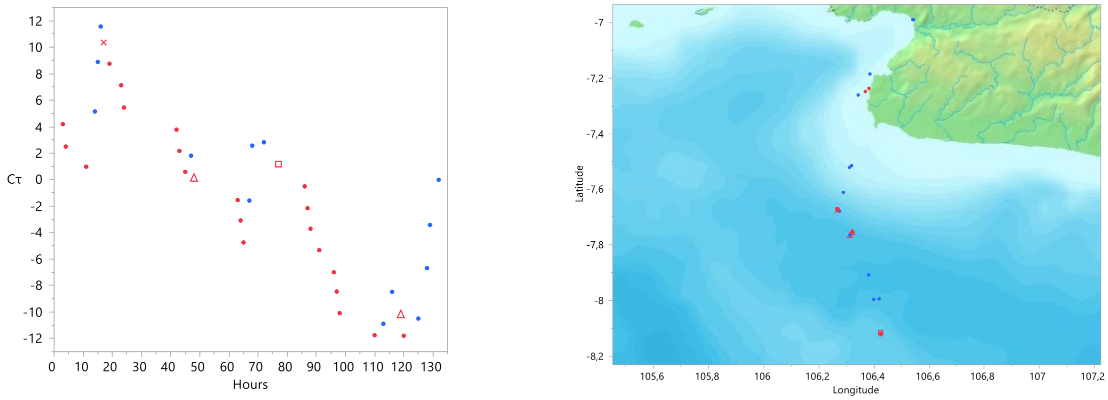
Cτ
Hours
Latitude
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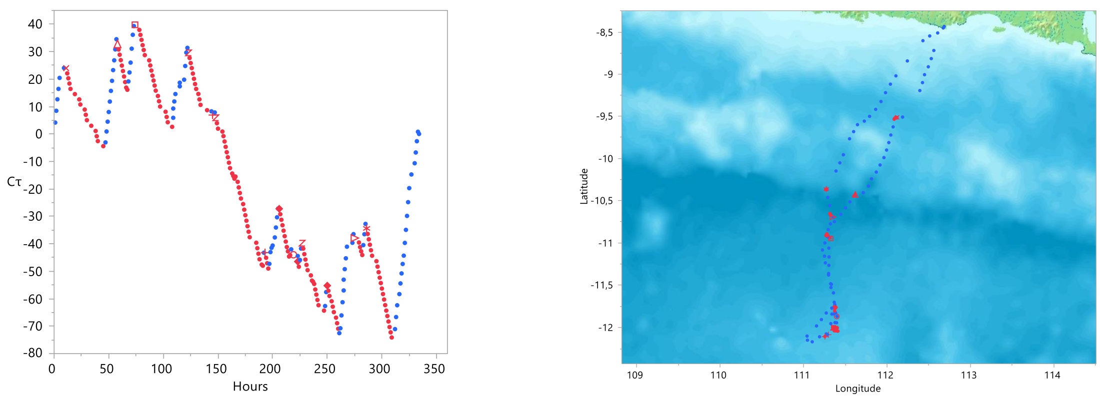
P5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Hours
Latitude
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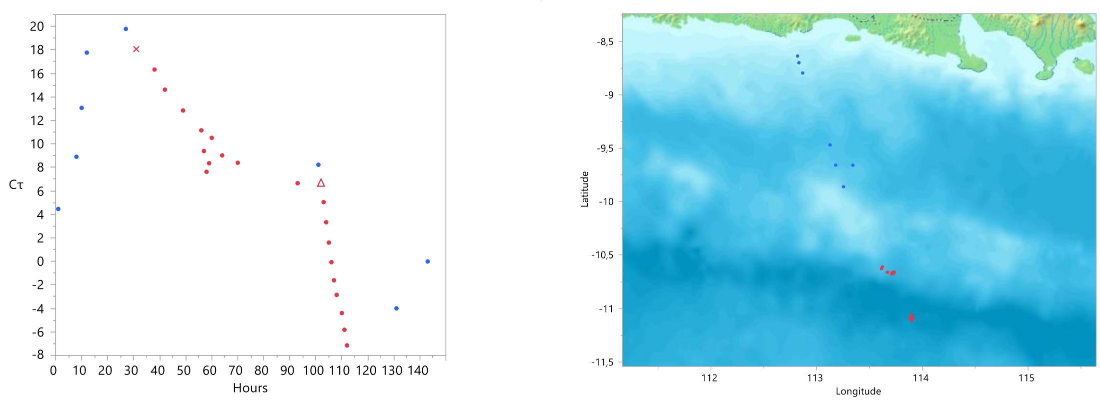
S1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Hours
Latitude
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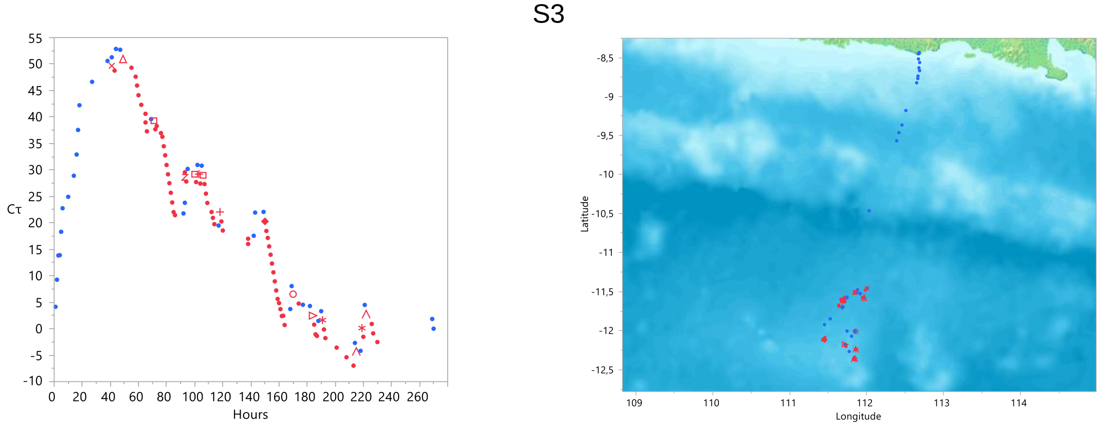
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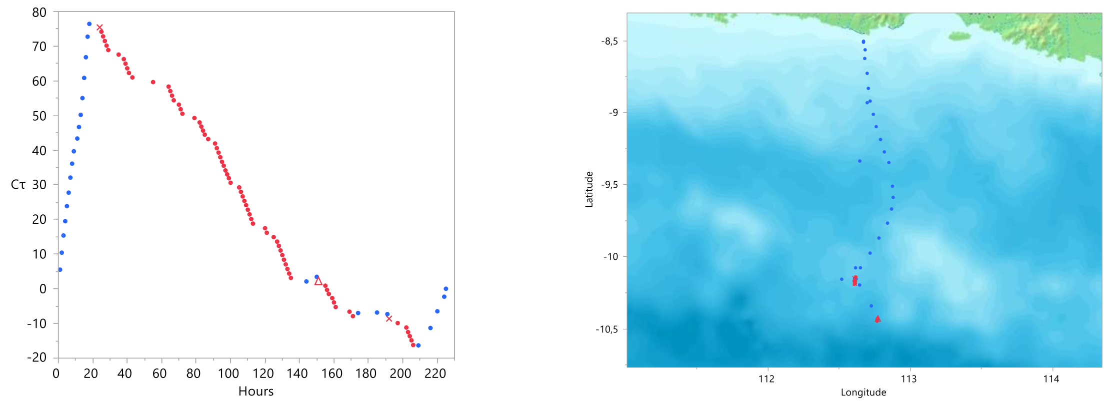

Cτ
Hours
Latitude
Longitude

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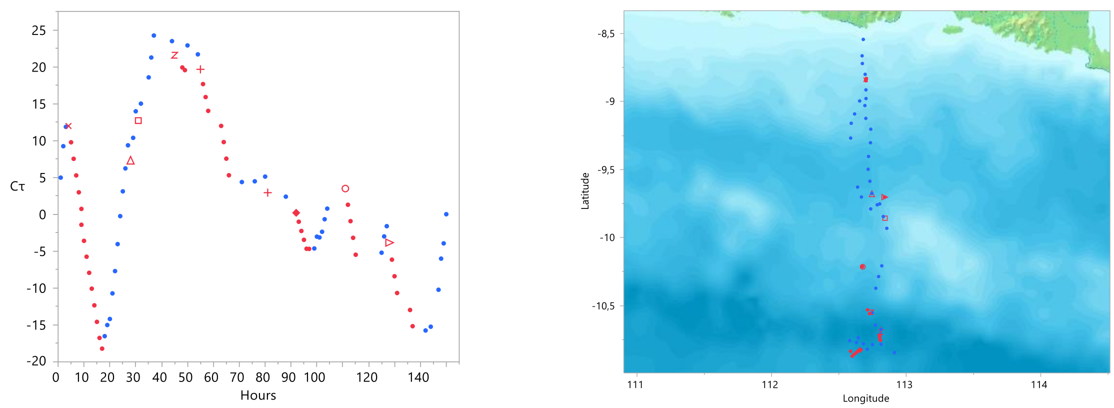

Cτ
Hours
Latitude
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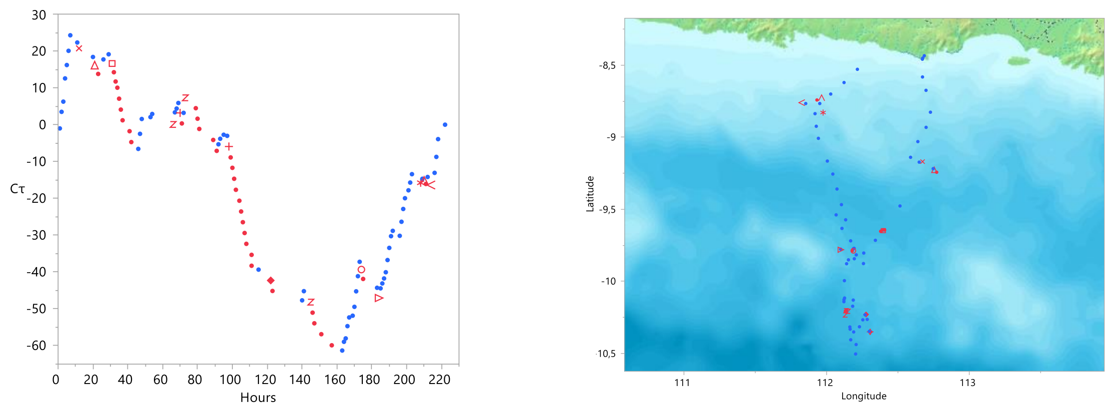
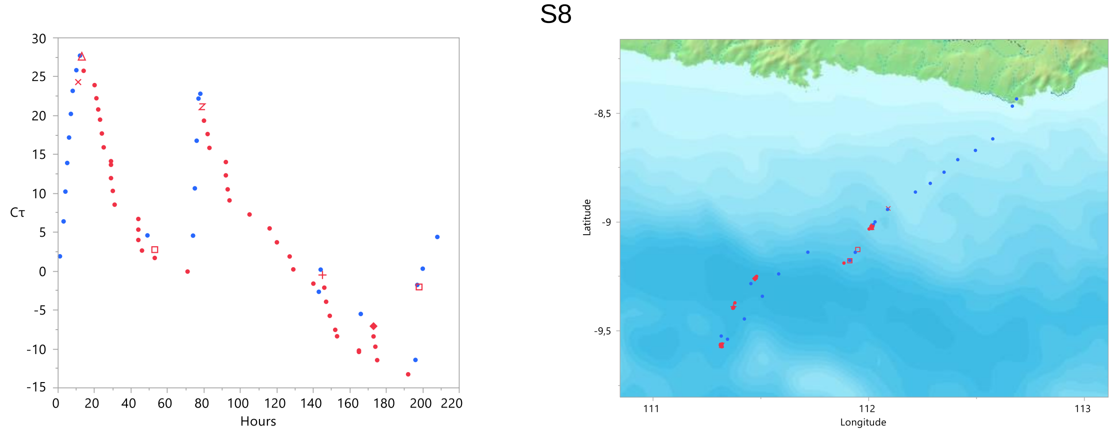


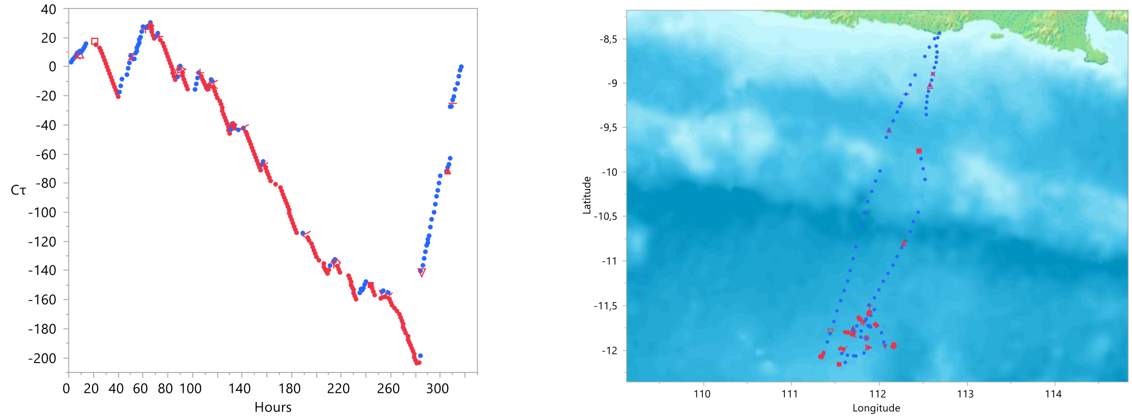
Cτ
Hours
Latitude
Longitude

S8



Cτ
Hours
Latitude
Longitude

S9



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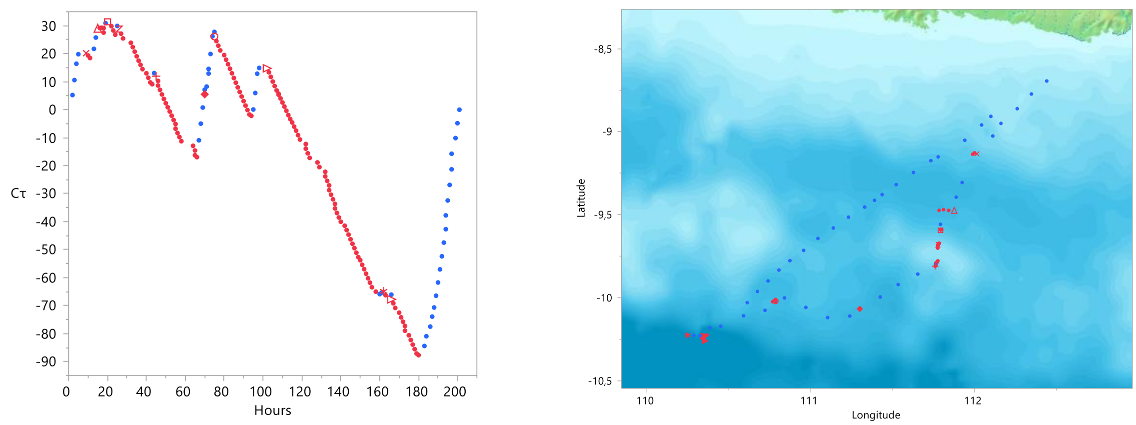

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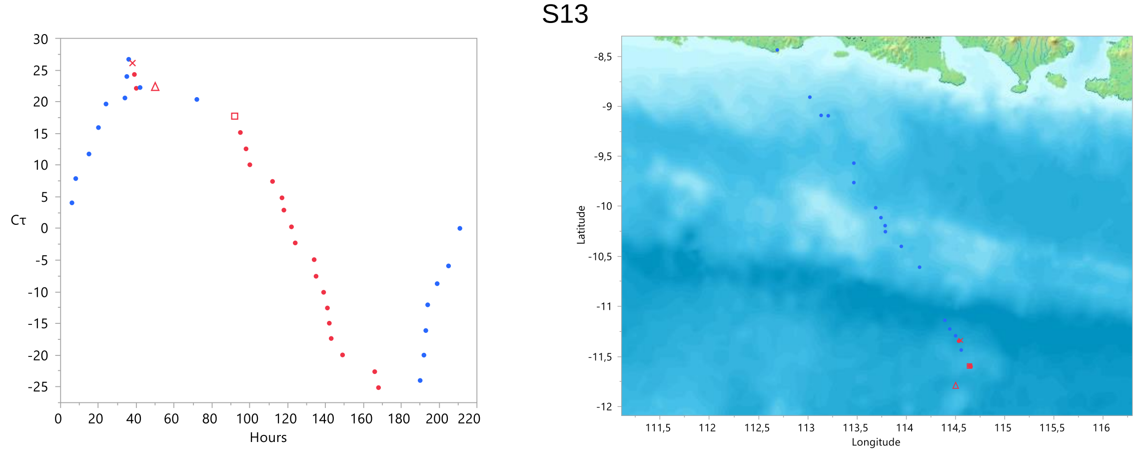
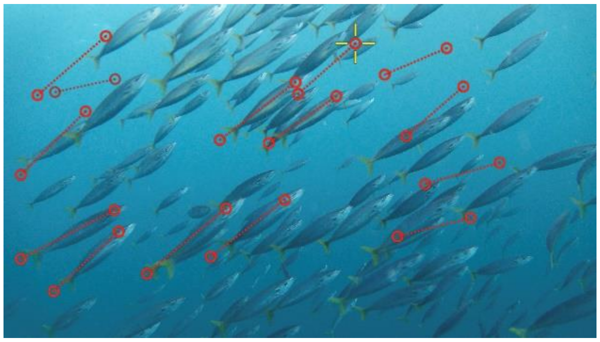


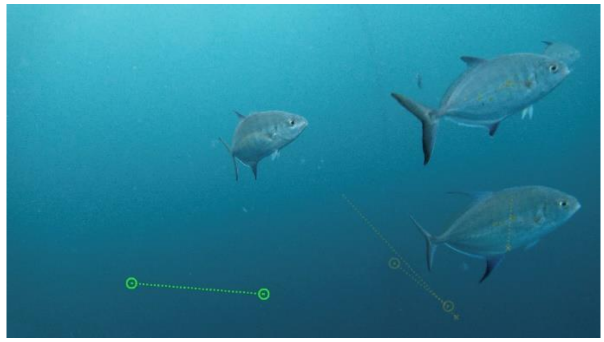
S15

Figure 39. Track segmentation all sampling areas (J = Yogyakarta, P = Palabuhanratu, and S = Sendangbiru). Red tracks indicating intrapatch search/ intensive search/ ARS and blue tracks indicating interpatch search/ extensive search or turn back to fishing port. Different marker types represent different FADs visited.

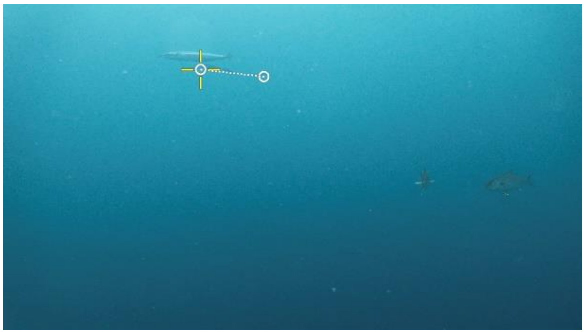
Appendix B: Stereo-cameras Observation



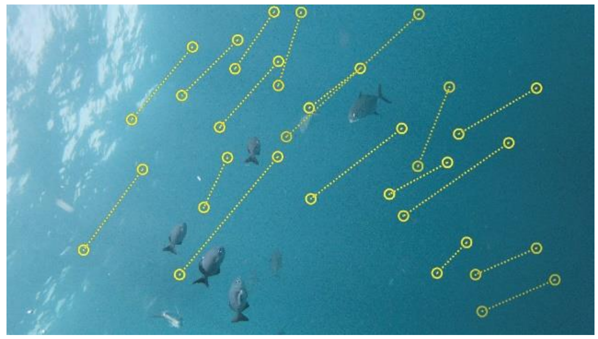
Rainbow runner



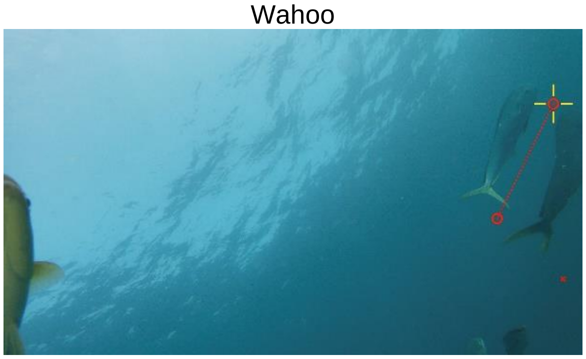
Island trevallies



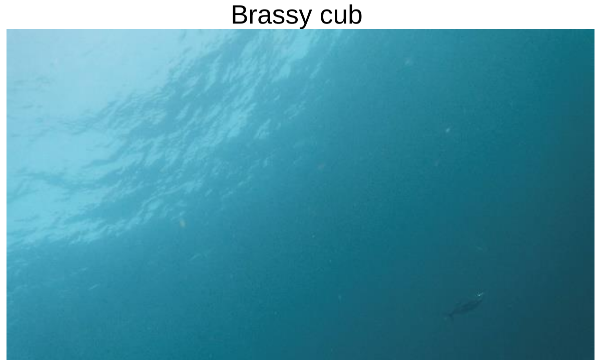
Wahoo



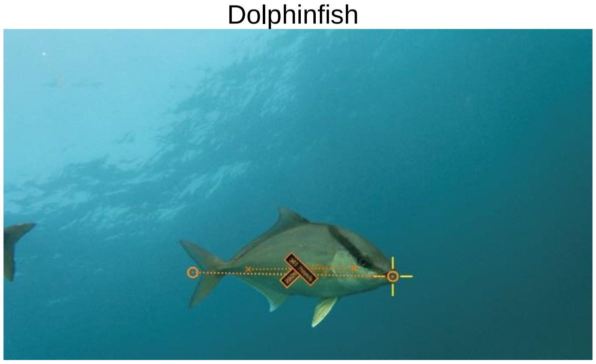
Brassy cub



Dolphinfish



Skipjack



Longfin yellowtail

Pondok Dadap – Fishing Port

Appendix C: Interview Sheet

Participant Interview Number:
Years Fishing Experience:

<u>Fishing FADs</u>
Can you tell me about fishing using FADs?
<u>Probes</u>
How many vessels can be fishing a FAD at the same time?
Do you avoid FADs with many vessels?
Do you avoid FADs that someone else has just fished?

<u>Tracking Questions – using individual tracking data</u>

- **How do you decide which FAD to go to first?**
- **How long did you stay there? Why?**
- **What did you catch and how much?**
- **Which gear did you use?**
- **How did you decide to move on?**

Repeat for each FAD

- **How long was your fishing trip?**
- **How much did your fishing trip cost?**
- **How much did you spend on fuel? Food? Other costs?**
- **Did the price of fuel affect your trip? E.g. when you moved FADs, how far you travelled?**
- **How far did you travel?**
- **What technology did you use on your trip? E.g. GPS, fish finder, radio**

<u>Changes in catch</u>
Can you tell me about any changes in your catch since you started fishing?
<u>Probes</u>

- Has the time you spend fishing changed over this time?

<u>Ownership</u>
Can you tell me about ownership of the vessel, fishing gear and FADs?
<u>Probes</u>
Who owns the vessel or fishing gear?
Do you own any FADs?
Do you own FADs alone or with other owners? How many FADs do you own/part own?
How are the FADs shared between different vessels?
How are the FADs maintained?
How do you share profits between different vessels or FAD owners?

Appendix D: Statistical Output

GAM Chapter 2

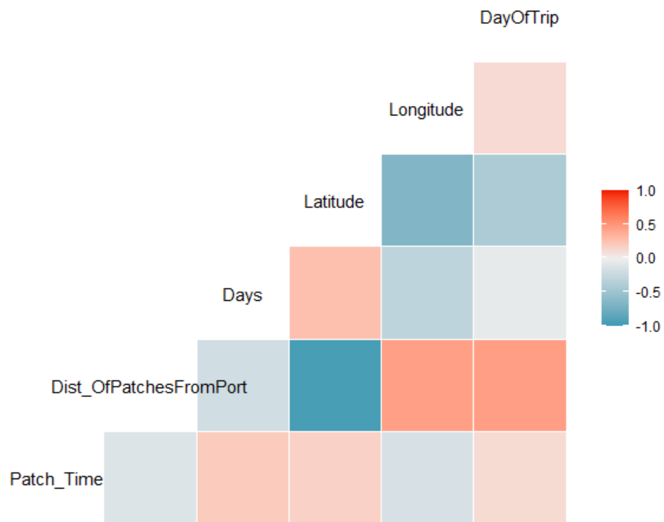
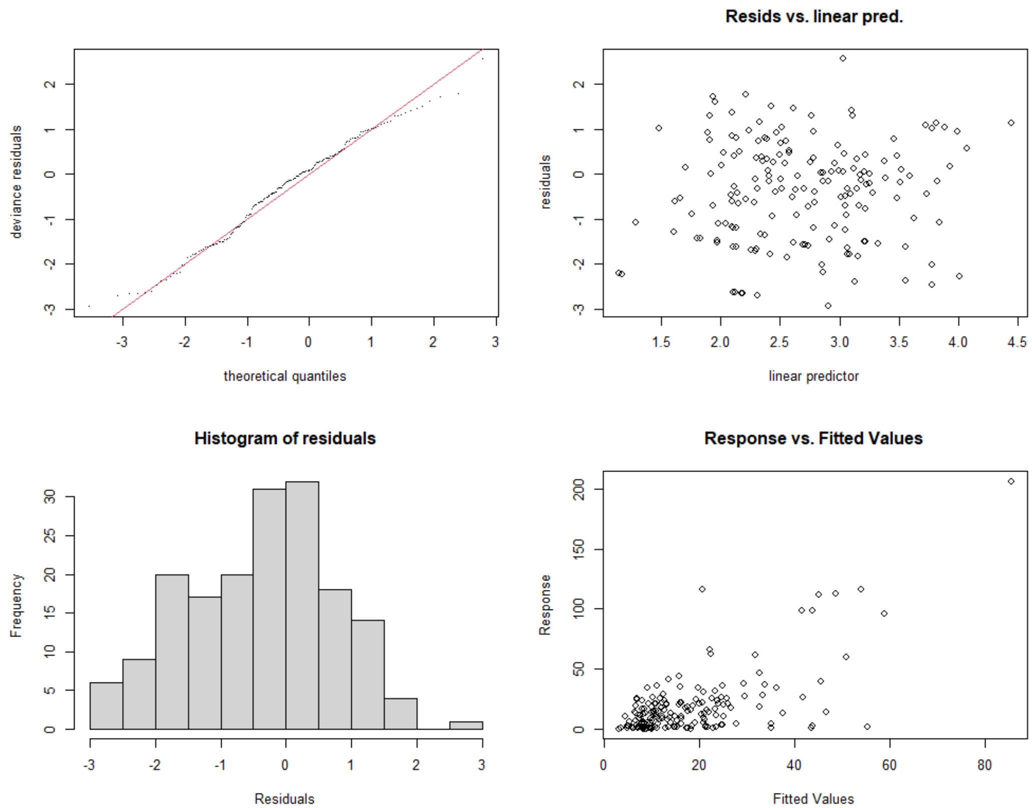
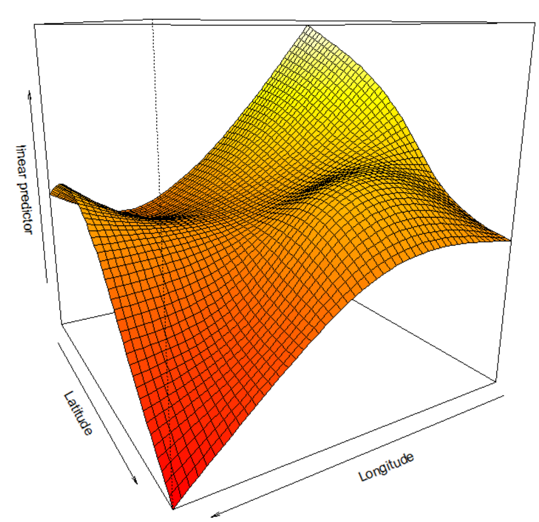


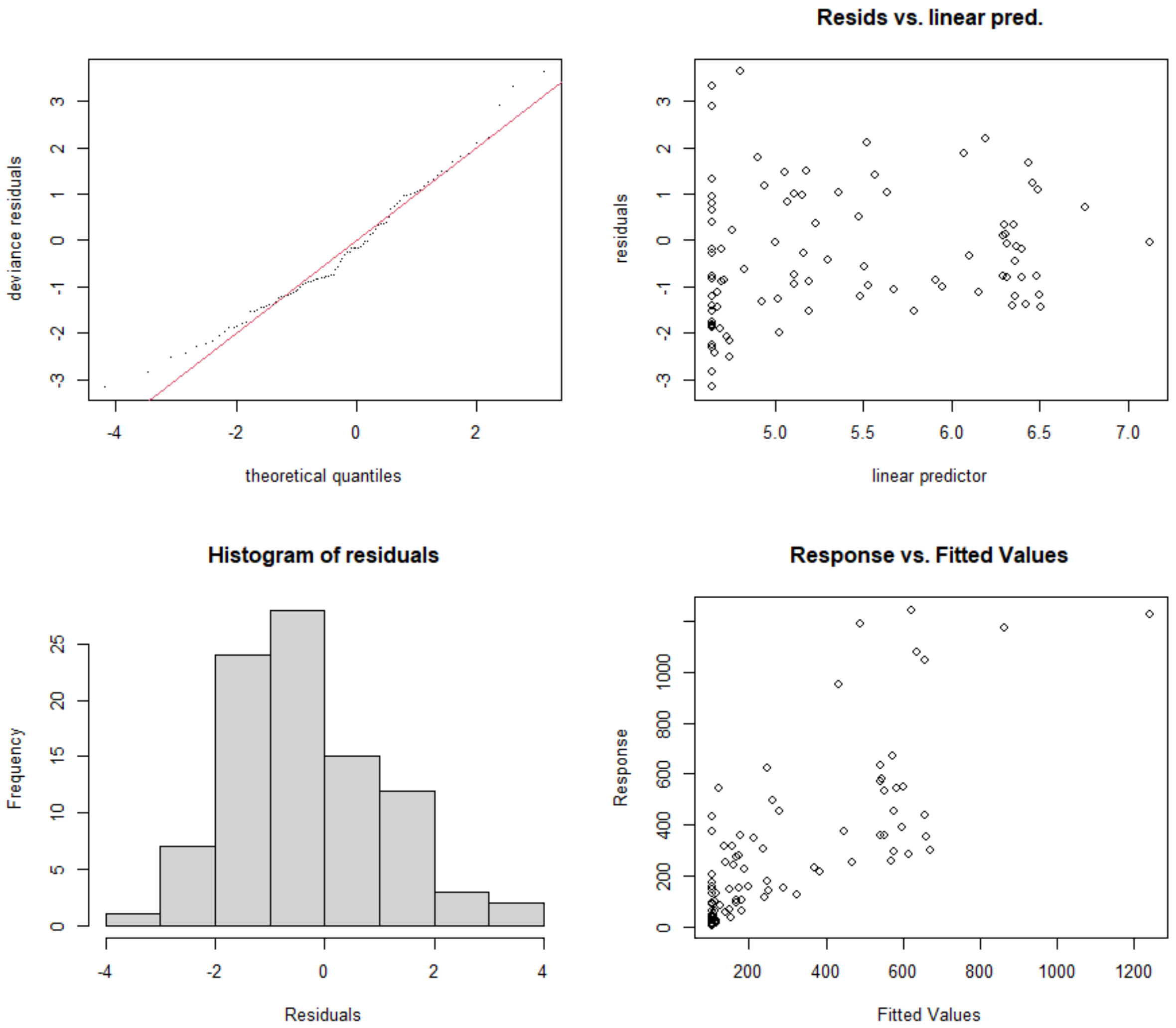
Figure 40. Pearson correlation matrix showing the relationship between explanatory variables. Strong positive correlation indicated by +1, while strong negative correlation indicated by -1. Correlation vaues ranged -1 t0 +1 with 0 indicates no correlation.

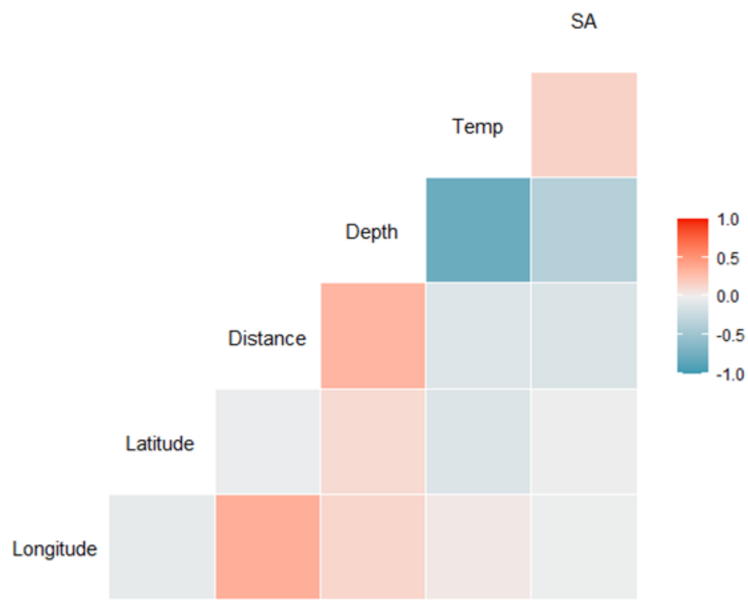
```
Family: Tweedie(p=1.962)
Link function: log

Formula:
Patch_Time ~ te(Longitude, Latitude) + s(Days, bs = "cc") +
    s(Dist_OfPatchesFromPort) + s(DayOfTrip) + Region

Parametric coefficients:
                  Estimate Std. Error t value Pr(>|t|)
(Intercept)         3.1531     0.2249  14.017   <2e-16 ***
RegionPelRatu       0.7031     1.1590   0.607   0.5450
RegionSendangbiru  -0.9284     0.4374  -2.123   0.0353 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
                            edf Ref.df     F  p-value
te(Longitude,Latitude)    3.178  3.343 3.014 0.024463 *
s(Days)                   1.543  8.000 0.691 0.020331 *
s(Dist_OfPatchesFromPort) 1.000  1.000 7.807 0.005831 **
s(DayOfTrip)              3.196  3.982 6.188 0.000127 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.356   Deviance explained = 28.6%
-REML = 638.82  Scale est. = 1.2304    n = 172
```


Resids vs. linear pred.
Histogram of residuals
Response vs. Fitted Values
deviance residuals
theoretical quantiles
residuals
linear predictor
Frequency
Residuals
Response
Fitted Values

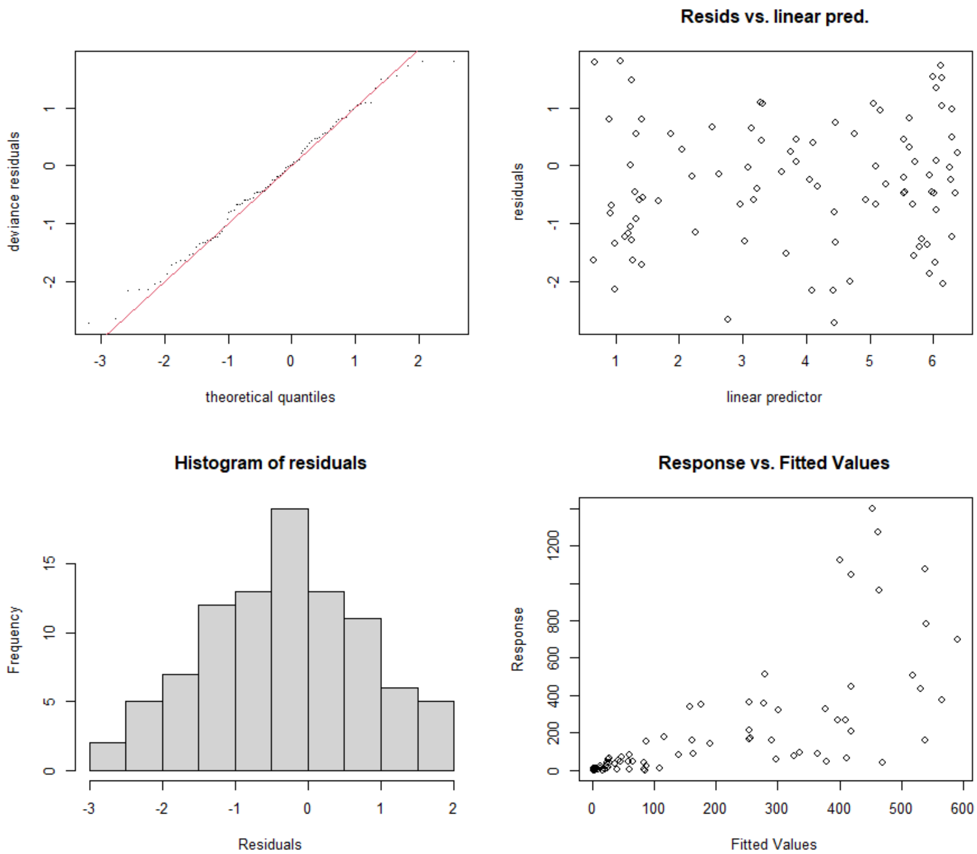

linear predictor
Latitude
Longitude

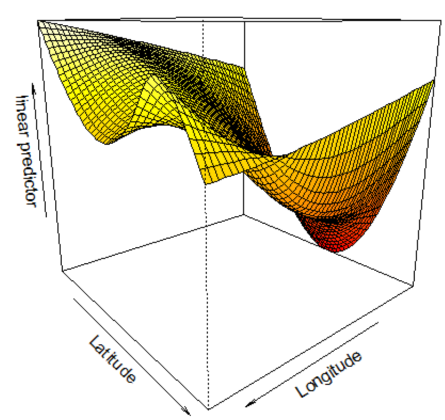
```
Family: Tweedie(p=1.771)
Link function: log

Formula:
PatchMinutes ~ s(GainMoney)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  5.36066    0.07778   68.92   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
               edf Ref.df     F p-value
s(GainMoney) 4.487  5.312 18.69  <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =   0.56   Deviance explained = 51.3%
-REML = 587.13  Scale est. = 1.8781    n = 92
```

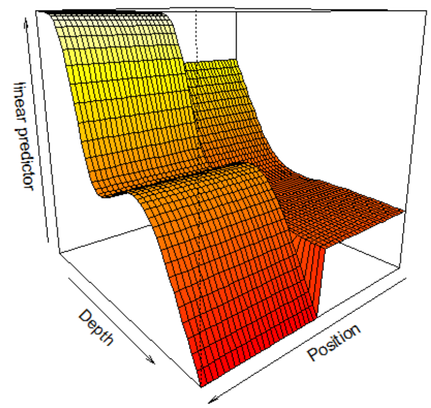


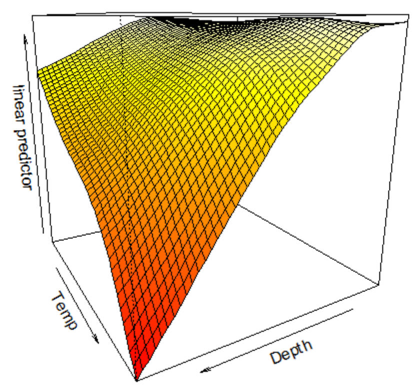



```
Formula:
SA ~ te(Longitude, Latitude) + Position + s(Depth, by = Position) +
    s(Temp)

Parametric coefficients:
                Estimate Std. Error t value Pr(>|t|)
(Intercept)       2.6809     0.2616  10.248  4.0e-16 ***
PositionUpcurrent   1.4917     0.2954   5.051  2.8e-06 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
                              edf Ref.df     F  p-value
te(Longitude,Latitude)       5.416  6.213 6.523 1.01e-05 ***
s(Depth):PositionDowncurrent 1.000  1.000 8.227   0.0053 **
s(Depth):PositionUpcurrent   5.187  6.292 7.021 4.23e-06 ***
s(Temp)                      1.000  1.000 5.110   0.0266 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.416   Deviance explained =   74%
-REML = 463.87  Scale est. = 1.2118    n = 93
```


Resids vs. linear pred.
Histogram of residuals
Response vs. Fitted Values
deviance residuals
theoretical quantiles
residuals
linear predictor
Frequency
Residuals
Response
Fitted Values


linear predictor
Latitude
Longitude


linear predictor
Depth
Position


linear predictor
Temp
Depth

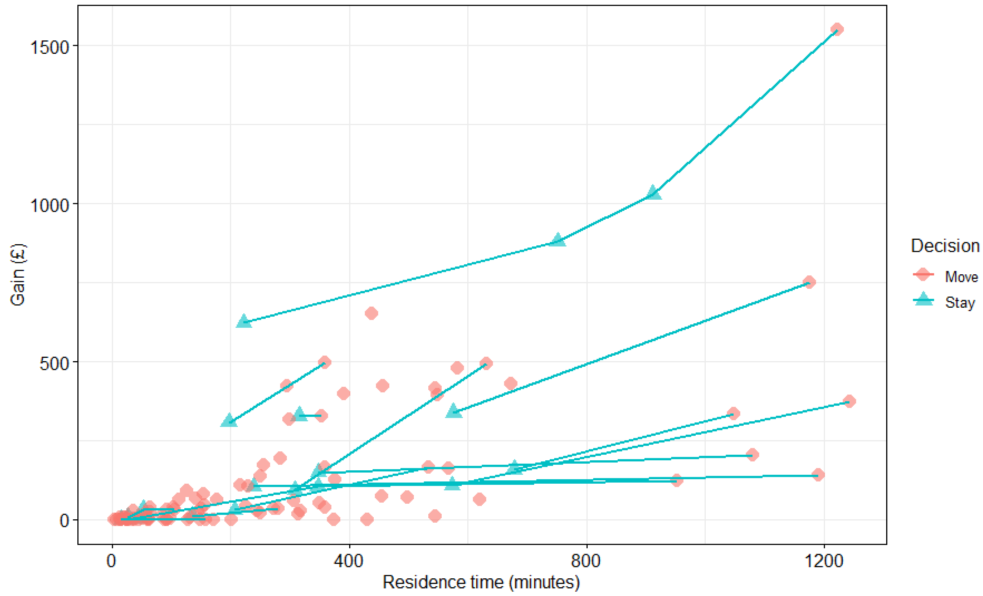


Figure 41. FADs visited with single (single red circle) and multiple (blue triangle to red circle) setting-hauling operation during observer samplings.