Movement ecology of the longnose emperor (*Lethrinus olivaceus*) in Rangiroa Atoll

Insights from acoustic telemetry and local ecological knowledge

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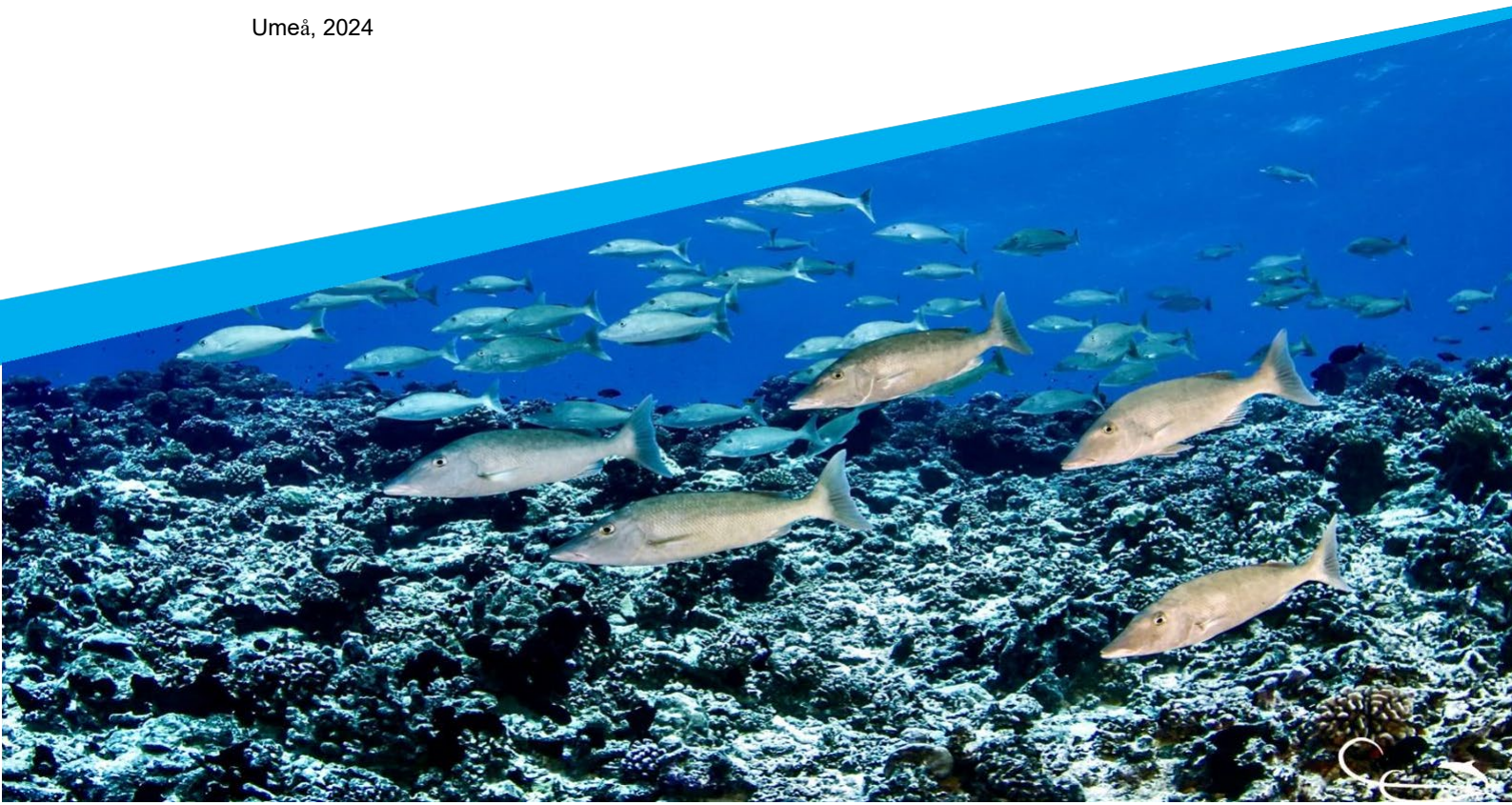

Movement ecology of the longnose emperor (*Lethrinus olivaceus*) in Rangiroa Atoll. Insights from acoustic telemetry and local ecological knowledge

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Abstract

Understanding the movement and migratory patterns of reef fish is essential for effective fisheries management, particularly in regions intrinsically reliant on marine resources, such as Rangiroa Atoll in French Polynesia. The longnose emperor (*Lethrinus olivaceus*) is a keystone species in the local fishery, yet its spatial ecology and the influence of environmental factors, such as the lunar cycle, remain underexplored. This study aimed to address these knowledge gaps by investigating the migration patterns, spatial utilization and ecological behaviours of longnose emperors within the Rangiroa lagoon, while also integrating local ecological knowledge to support future sustainable resource management efforts. To this aim, acoustic telemetry was employed to track the movements of 75 individuals across a network of 80 receivers deployed throughout the Rangiroa lagoon and its two major passes (i.e. Tiputa pass and Avatoru pass), from September 2023 to May 2024. Complementary interviews with local fishers provided a holistic understanding of the species' behaviour. The results revealed that longnose emperors undertook distinct movement patterns, with longnose emperors exhibiting site fidelity to specific areas, such as the lagoon sides of Avatoru and Tiputa passes, and in the regulated fishing zone (ZPR). Movements were markedly influenced by lunar cycles, with fish aggregating near the passes during new moon phases, highlighting a predictable pattern that increases their vulnerability to fishing. Additionally, local ecological knowledge aligned with our findings, fishers reported similar spatiotemporal patterns, observing longnose emperors migrating and aggregating near passes and shorelines during darker lunar phases. The study underscores the need for adaptive management strategies that consider these distinct, lunar-driven movements of Rangiroa's longnose emperor, and integrate both scientific data and local knowledge to ensure the sustainability of this important fishery resource.

Keywords: Lethrinus olivaceus, acoustic telemetry, lunar cycle, local ecological knowledge, movement ecology, fishery management.

Table of contents

List of figures

Abbreviations

DRM	Direction des Ressources Marine
LEK	Local Ecological Knowledge
SPR	Spawning Potential Ratio
TNC	The Nature Conservancy
UD	Utilisation Distribution
ZPR	Zone de Pêche Règlementée (Regulated fishing zone)

1. Introduction

The movement and migration patterns of tropical reef fish are fundamental aspects of their ecology, directly influencing population dynamics, species interactions, and the structure of marine ecosystems (Green *et al.*, 2015). However, these central patterns are often complex and challenging to document (Cooke *et al*., 2022). Many tropical reef fish species exhibit behaviours such as site fidelity, home range variability, and seasonal or spawning migrations (Adams *et al*., 2019). Understanding these movement behaviours may prove to be crucial in the effective management and conservation of fish populations, as they are often tightly linked to key ecological processes such as predation, foraging, and reproduction (Hixon, 2015). Moreover, fish movements can also increase their vulnerability to fishing pressure, as species that displace through migration corridors or aggregate at predictable times and locations can be more easily targeted by fishers (Taylor *et al*., 2017). With the rising pressure on marine ecosystems from overfishing, habitat destruction, and climate change, understanding these spatiotemporal movements has become increasingly important. This is especially true for small-scale fisheries and major fishery resources on which communities are exclusively dependent. The communities and the fish species could respectively undergo irreversible changes in their livelihood or their dynamic due to the increasing need for fish resources and the rising fishing pressure (Sadovy de Mitcheson and Erisman, 2012; Filous *et al*., 2019).

The lunar cycle is another important factor that plays a significant role in the behaviour and ecology of many reef fish species, influencing patterns of movement, spawning, and feeding (Domeier and Colin, 1997). Lunar phases are known to synchronize spawning activities in a wide range of reef fish, with many species timing their reproductive events to coincide with specific lunar phases (Robertson *et al.*, 1990). For instance, the gravitational pull of the moon affects tidal cycles, which in turn influence water currents, temperature, and salinity — all of which can trigger specific behaviour (Naylor, 2001). These tidal changes often provide beneficial conditions for eggs and larvae dispersal, enhancing the potential species dispersal and recruitment (Johannes, 1978). Thus, species such as the longnose emperor (*Lethrinus olivaceus*) and the bonefish (*Albula glossodonta*) are thought to engage in lunar synchronization as an adaptive strategy to optimize reproductive success (Sadovy de Mitcheson and Colin, 2012; Filous *et al.,* 2020). Spawning during specific lunar phases, particularly around the new and full moons, often

results in large spawning aggregations. These aggregations increase the likelihood of successful fertilization due to the greater concentration of reproductors in the area, which results in a higher concentration of gametes in the water column (Molloy *et al*., 2011). Moreover, these different lunar phases also correspond with variations of nocturnal illumination, which can influence detectability during spawning events. For example, spawning during darker lunar phases (e.g. new moon) may reduce predation risk due to a decreased ability of predators to locate the spawning fish or their eggs (Takemura *et al*., 2004). Fishers frequently exploit these predictable lunar cycles to maximize their catches, targeting species that are aggregating and therefore more vulnerable during these periods (Johannes *et al.*, 2000). Documenting these interactions between lunar phases and fish movements is crucial for the development of fisheries management strategies. Knowing where and when fish are most vulnerable could guide management efforts based on these spatiotemporal cues, helping to reconcile resource conservation with the needs of local communities.

Lethrinid species, such as the longnose emperor, are among the most exploited fish in the Pacific (Currey *et al*., 2013). This species is a prominent reef fish in the tropical and sub-tropical regions and is commonly found throughout French Polynesia. The longnose emperor, locally known as *'O'eo*, is a keystone fishery resource for Rangiroa's community, and its traditional fishery has harvested this species during their known aggregation periods for more than 5 decades for subsistence and commercial ends (Morize, 1985; Chauvet and Galzin, 1996; Lagouy, 2012). Rangiroa's longnose emperor fishery was characterized as one of the largest domestic fisheries for coral reef species in French Polynesia (DRM, 2019). Therefore, this species is of particular interest due to its historical importance in Rangiroa's fishery and supports an important economic part of local livelihood (Filous *et al*., 2021a). The longnose emperor is known to exhibit complex movement patterns, including seasonal migrations associated with spawning and site fidelity (Currey *et al*., 2009; Machaieie and Silva, 2020). Spawning aggregations are a critical aspect of its life history, as these events concentrate individuals in predictable locations, making them particularly vulnerable to overfishing and, in the process, affecting the species' recruitment success (Russel, 2001; Claydon, 2004; Sadovy de Mitcheson *et al*., 2008; Sadovy de Mitcheson and Erisman, 2012). Despite its importance, there remain significant gaps in the understanding of the movement ecology and the spawning behaviour of the species, particularly in the context of exploitation in local fisheries.

Therefore, one key area to study this species is the Rangiroa atoll, in the Tuamotu archipelago. This atoll historically and today still remains a major source of lagoon fish, especially longnose emperor, for Tahiti (i.e. the population centre), and other more populated islands in French Polynesia (Caillart and Morize, 1990; Chauvet and Galzin, 1996, Filous *et al*., 2021a). In 2015, recognizing the critical importance of the lagoon fishery, the community of Rangiroa acknowledged the need to

implement marine resource management measures. Together with the Marine Resources Department ("Direction des Ressources Marines" [DRM]) they established a "Zone de Pêche Règlementée" (ZPR), a regulated fishing area where fishing is prohibited in most of the zone, in order to protect critical habitats and support the sustainability of fish stocks. However, no studies have yet assessed the impacts of this management measure. Furthermore, a recent study from Filous *et al.* (2021a) highlighted the need for targeted conservation efforts for Rangiroa's longnose emperor*,* motivated by the low spawning potential ratio (SPR) stemming from the extensive fishing effort during its spawning aggregation. The index indicated a fully exploited fish stock, prompting the implementation of a community-based management strategy to establish a commercial size limit.

Acoustic telemetry has emerged as a powerful and ubiquitous tool for studying the movement ecology of marine species but also as an important source of information for marine resources management and conservation, as it can provide detailed data on residency, home range, and migratory behaviour (Hussey *et al*., 2015; Crossin *et al*., 2017). By implanting acoustic transmitters into fish and tracking their movements with networks of acoustic receivers (i.e. hydrophones), deployed in the surrounding environment, researchers can gain detailed insights into how species use space and how their movements are influenced by biotic and abiotic factors, such as the lunar cycle (Mourier *et al*., 2019; Filous *et al*., 2020). This method has been particularly effective in identifying home ranges, migratory corridors, and spawning sites for various fish species (Taylor *et al.*, 2017).

In addition, local ecological knowledge (LEK) has been proven to be particularly valuable in studying fish behaviour, identifying aggregation sites and providing information on fish stocks (Robinson *et al*., 2004; Martins *et al*., 2018; Adams *et al*., 2019). Traditional knowledge about the timing, and locations of fish aggregations influenced by environmental factors, and how these have changed over time, provides a more holistic understanding of species ecology and thereby aids in the design of more effective management strategies (Hamilton *et al*., 2012; Crossin *et al*., 2017). LEK has been particularly valuable in providing preliminary insights into fish migration timing, spawning timing and location, and habitat use, which can help define hypotheses about spawning behaviour and guide the placement of acoustic receivers in telemetry studies (Baird and Flaherty, 2005; Machaieie and Silva, 2020).

The longnose emperor fishery in Rangiroa shows important catches around the passes and during the new moon periods, suggesting recurrent migrations to these areas synchronized with the darker lunar phases. This also suggests that the local community already understands how these fish move around the lagoon in order to maximize their fishing success. The primary aim of this study was to investigate and document migration patterns and space use of a cornerstone fishery resource of Rangiroa atoll, the longnose emperor. To achieve this, passive acoustic telemetry and local ecological knowledge (LEK) were utilized to address critical questions,

including whether longnose emperors exhibit distinct migratory and site fidelity behaviours within the specific areas of Rangiroa's lagoon (e.g. in the ZPR, the lagoon side of the passes, the passes), and if so, how these movements change with the lunar phases. Finally, the study sought to provide valuable insights into the species' ecology, thereby complementing the ecological knowledge of the local community and informing the development of appropriately adapted marine resource management strategies.

2. Material and methods

2.1 Study area

Rangiroa is the second largest open atoll in the world (~1,700 km^2) and is located in the Tuamotu archipelago, in French Polynesia (Figure 1), about 355 km northeast of Tahiti. The interior lagoon is 1574.5 km^2 and stretches almost 80 km long with an average depth of 20 m (Lagouy, 2012). In 2022, its total population was estimated to be more than 3900 residents of which a rough estimate of 20% seem to actively participate in the longnose emperor fishery (TNTV, 2022; INSEE, 2023). The atoll is defined by two main large passes located on the north coast: *Hiria* (550 m wide) at Tiputa commune, commonly named Tiputa pass and *Hutuaara* (450 m wide) at the commune of Avatoru, commonly named Avatoru pass. These waterways are important for atoll ecosystems and significantly contribute to lagoon species' richness and dynamics (Mellin *et al*., 2006; Planes *et al*., 2012). A wide variety of fish species move through these two passes and use them for different purposes, such as migration for reproduction or lagoon colonization (Dufour, 1994; Fisher *et al*., 2018). The interior lagoon is a biologically rich environment and is composed of a multitude of pinnacle reefs (Planes *et al*., 2012).

Rangiroa's lagoon is characterized as one of the most productive among the Tuamotu islands and longnose emperors are commonly found throughout the lagoon as well as on the external reef slopes. Rangiroa is also a significant reef fisheries centre and one of the principal suppliers of reef fish in French Polynesia, particularly to the major population centres of Papeete and Moorea (Dufour, 1994). The lagoon fishery is structured into three main categories: use of fish traps, handline, and spearfishing. Fish traps are recognized locally to yield larger catches, particularly of longnose emperors (Filous *et al.*, 2021a). As observed in other tropical atolls worldwide, the majority of the fishing efforts are concentrated in areas known for higher fish abundance, such as passes, lagoon pinnacles, and shore reefs (Sattar *et al*., 2012). These areas are likely where fishers observe and harvest longnose emperors, a crucial activity given the significance of small-scale commercial fishing to the atoll's economy. The longnose emperor fishery remains vital, as it is a key economic resource for the local population (Filous *et al*., 2021a).

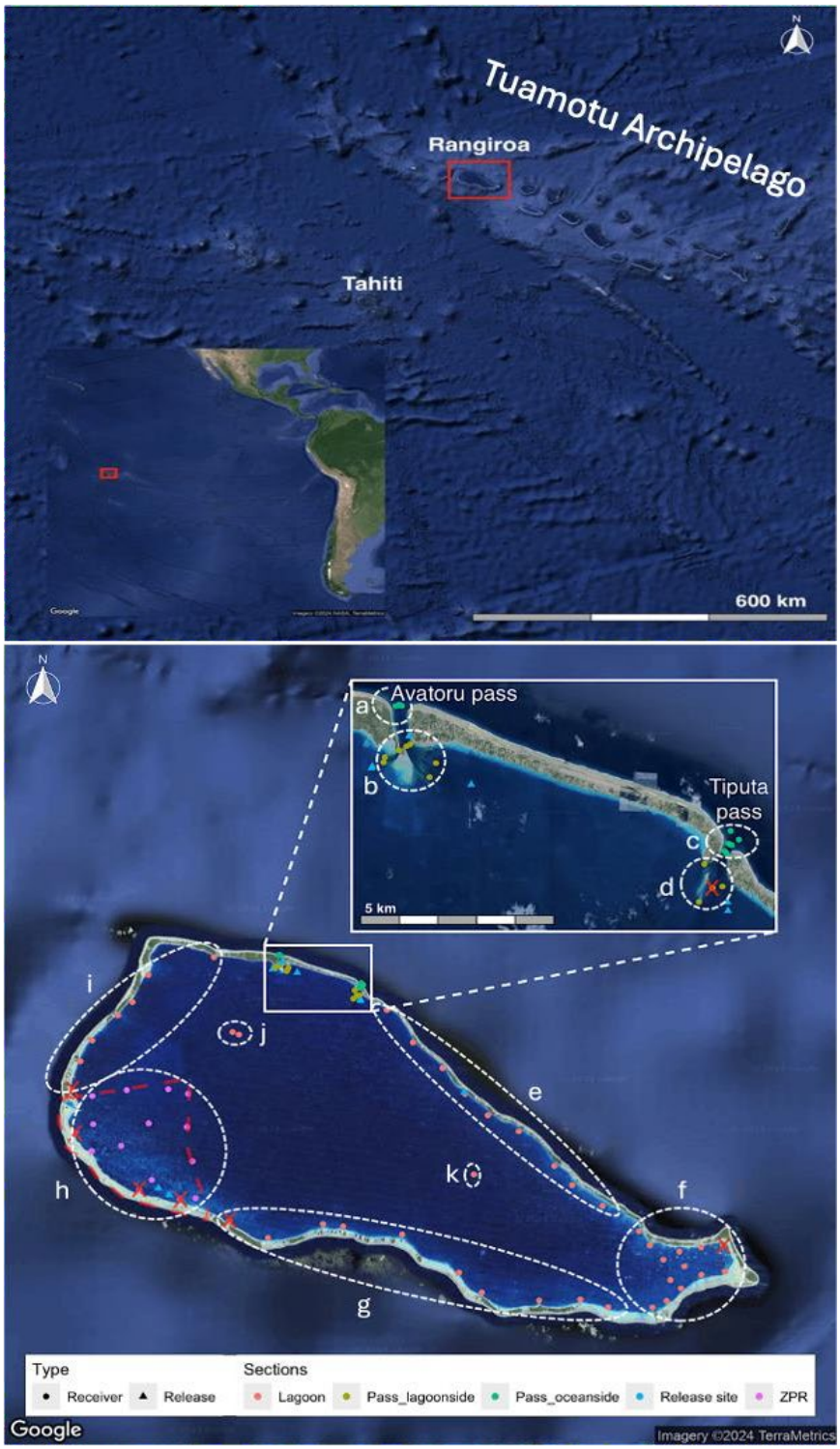

Figure 1. The location of Rangiroa Atoll in the Pacific Ocean, as part of the Tuamotu archipelago in French Polynesia (top) and the deployed network of acoustic telemetry receivers (below). The ZPR is represented by the red dashed line and the dots represent the locations of VR2W acoustic receivers, whereas the triangles represent the capture/release sites. The colour of the dots represents the grouping sections of receivers, as indicated by the legend and the letters represent the different subsections for the analysis (a: oceanside_avatoru; b: lagoonside_avatoru; c: oceanside_tiputa; d: lagoonside_tiputa; e: north_east; f: east; g: south; h: ZPR1; i: west; j: center_west; k: center_east). Lost receivers are marked with a red cross.

In 2015, a regulated fishing area, known as the "Zone de Pêche Règlementée" (ZPR), was established in the southwestern part of the lagoon, named *Te Roto Uri Fa'ahotu* (Figure 1). This area, covering 160 $km^2$and representing about 10% of the lagoon, is well-known to fishers, for its significance as a productive fishing ground The ZPR was established in response to community concerns about declining marine resources, with the local population, led by the mayor, spearheading its creation, while the *Direction des Ressources Marines* (DRM) assisted in formalizing its legal implementation. Fishing is prohibited in the ZPR except for subsistence fishing from the islets located within its boundaries (DRM, 2023).

2.2 Passive tracking using acoustic telemetry

By equipping individual fish with acoustic transmitters (tags), passive acoustic telemetry allows documentation of essential information (e.g. residency, space use, and migratory corridors). These tags send out coded ultrasonic signals that are detected, decoded and stored when in the proximity of specific hydrophones (receivers) moored within the waterbody. Each tag transmits a tag-specific ID and other sensors also provide bio-logging data, such as current, depth and activity, if a specific fish is equipped with such a sensor. As a result, the tagged individuals can be tracked within a network of receivers (Hellström *et al.,* 2022; Nemeth. R.S. *et al.,* 2023).

2.2.1 Receivers' deployment and offload

To examine fish space use and movement patterns, potential migratory pathways were verified with the deployment of VR2W-69 kHz omnidirectional acoustic receivers (Innovasea, Bedford, NS, Canada) in the entire lagoon of Rangiroa with a focus on the ZPR area, the lagoon shorelines and the two major passes. The collaboration with the DRM and the Tamataroa 2023 research project (Blancpain Ocean Commitment, 2023), enabled the deployment of an extensive array in Rangiroa's lagoon, resulting in a total of 80 receivers. As presented in Figure 1, the distribution of the receivers was grouped into 4 different sections, illustrating different geographical areas of Rangiroa: *ZPR*, *Lagoon, Pass_lagoonside and Pass_oceanside*. The final completed coverage consisted of 42 receivers along the interior coastlines and the interior lagoon, 23 receivers for the passes and 15 receivers in the ZPR. Receivers were installed along the shorelines of the atoll in order to capture migration patterns and space preferences with potential pre-aggregation areas or other migration routes. Receivers located in and around the two main passes, Hiria (Tiputa pass) and Hutuaara (Avatoru pass), were to capture the periodicity and frequency of potential pre-aggregation and migration behaviour. Given the diminished receiver detection range as tested by the Tamataroa research

team, likely attributed to the strong currents, the noise, and water turbidity, the design of the receiver array around these channels was informed by the pass morphology, current patterns, and from fishers' knowledge about fish pathways and bottom structure. Consequently, to enhance the likelihood of detecting tagged fish from both the left and right sides of these passages, 8 receivers were strategically positioned at the lagoon openings. Additionally, 12 receivers from one of the other research projects were deployed within the passes to effectively cover their interiors. Then, in order to record space utilization within the regulated area (ZPR), the 15 receivers were homogeneously distributed to cover as much surface as possible and to optimize detection probability considering the complex bottom structure due to the presence of multiple pinnacles (Figure 1).

All receivers were deployed by the end of August 2023, at depths ranging from 5.1 m to 22.9 m with hydrophone pointing upwards. The receivers' network was designed to capture medium-distance (< 300 m) fish movements from each receiver and general fish movements between the lagoon and the passes. In the lagoon area, receivers were attached to mooring stations composed of a 50 kg cemented concrete block and a vertical line tightened with a submerged 24 cm diameter hard plastic buoy (Figure 2A). As recommended by the manufacturer, the receivers were moored at about mid-depth for the shallower stations (from 2 to 9 m) and at about 4 m above the concrete blocks for the deeper stations (> 10 m). In contrast, receivers around the passes were mounted differently using the same anchors as the Tamataroa project since these areas were more dynamic due to the current in the passes (Figure 2C). They consisted of 16 mm stainless-steel rebars reinforced with 20 mm galvanized tubes fixed with epoxy resin in the hard bottom pavement or reef. The rebars were installed on dead portions of the reef to minimize damage to corals. Receivers were secured with a stainless-steel cable crimped to fixed metal rings.

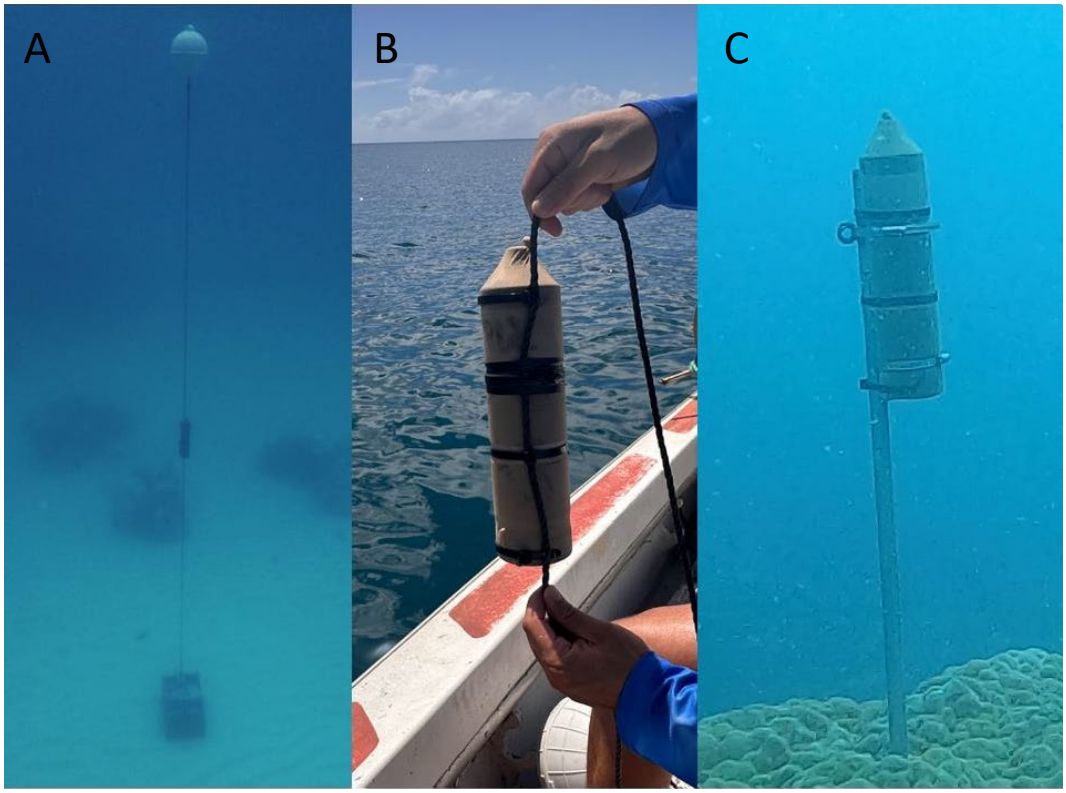

Figure 2. Deployment systems used to install the acoustic receivers in the Rangiroa lagoon. A: Mooring station to deploy receivers on sandy areas. B: Attachment of a prepared receiver on a mooring line. C: A receiver deployed on a hard bottom structure and in a dynamic area (i.e. passes).

To maintain optimal listening performance, the receivers were initially coated with Vaseline® (petroleum jelly) and encased in nylon stocking fabric to mitigate biofouling — a technique based on prior field experience (Figure 2B). Additionally, the receivers' condition was periodically verified and cleaned when necessary, to ensure functionality throughout the study period (Heupel *et al*., 2006). Data stored on receivers were downloaded in March and May 2024 using VUE software and Innovasea's Fathom Mobile application (Innovasea, Bedford, NS, Canada).

The deployment of acoustic receivers (permit ARRETE n° 9469 VP) was made possible through collaboration with the Rangiroa community (Rairoa magazine, 2023). Community meetings at Tiputa and Avatoru city halls facilitated discussions with local leaders and lagoon users (e.g. fishermen, divers, tourist operators), ensuring community involvement and consent for resource use (Filous *et al*., 2020).

2.2.2 Fish tagging

A total of 75 longnose emperors (n females = 25, n males = 20, n undetermined = 30) were captured and tagged. As in Adams *et al*. (2019), the involvement of and collaboration with local fishers proved to be essential in the capture success. With their assistance, four primary locations were selected for fish capture during the new moon period in September 2023. Three of these sites were traditional fishing

grounds: Avatoru Pass (n = 23), Tiputa Pass (n = 10), and a private fish trap (n = 26), while the fourth was within the ZPR (n = 16, Table 1). The capture and tagging of longnose emperors in the ZPR were conducted under permit ARRETE n° 8416 ZPR/DRM issued by DRM.

Table 1. Longnose emperor tagged in Rangiroa lagoon in September 2023 with length, sample size and the closest receiver array.

Site	Array	N individuals	Mean FL (cm)	Min/Max FL (cm)
Avatoru pass	Lagoonside_avatoru	23	44.8	34.5 / 55.5
Tiputa pass	Lagoonside_tiputa	10	46.3	41 / 54.4
Fish trap	North_east	26	49.5	45.5 / 56.5
ZPR	ZPR1	16	55.1	49 / 60

At the trap, fish were randomly sampled with a dip net to address animal welfare concerns, while in all other capture locations, fish were caught using traditional local hook-and-line methods. Before tagging, each fish was assessed for health; those with normal buoyancy, no injuries, and strong vigour proceeded, while fish showing signs of barotrauma, angling effects or injury were released. At all tagging sites, fish were handled individually to limit any induced stress.

Tagging procedures followed Murchie *et al.*, 2012. Fish were placed in a padded cradle on a covered boat, with continuous gill irrigation provided by a 12DCV bilge pump (SEAFLO® 01 Series 350GPH) to ensure proper ventilation during measurements and transmitter implantation. A wet microfiber cloth covered the fish's eyes to reduce stress, and an assistant secured the fish on the operating cradle. No anaesthetics were used to minimize predation risk, as sharks were frequently present during tagging events. A total of 75 V-13 69 kHz coded transmitters were deployed: 55 V13-1x-BLU-1 (transmission rate 80–160 s, battery life of 1460 days), 20 V13-AP-1x-BLU-1 (transmission rate 40–80 s, battery life of 476 days) and 20 V13-TP-1x-BLU-1-204 m (transmission rate 40–80 s, battery life of 567 days) (Innovasea, Bedford, NS, Canada). The V13-AP transmitters included acceleration and pressure (depth) sensors, while the V13-TP transmitters were equipped with temperature and pressure sensors. However, the sensors' data were not analysed in the current study.

Transmitters were surgically implanted intracoelomically into each fish via a 2 cm incision in the abdominal wall and closed with an interrupted nylon suture (PDS 3/0, FS-1 reverse cutting needle, Ethicon, New Brunswick, NJ). Surgical equipment and transmitters were disinfected in a 5% povidone-iodine solution (Betadine) prior to the surgery to reduce infection risk. When possible, the sex of the tagged individual was determined during surgery by examining the presence of gonads in the abdominal cavity. The release date, fork length (FL) to the nearest cm, transmitter ID, fish ID and tagging location were recorded. Additionally, each fish

received a unique external dart (spaghetti) tag (10 cm PDL, Hallprint, Australia) for identification in the event of recapture in local fisheries.
After surgery, fish were held at the side of the boat and released once they demonstrated normal swimming behaviour and buoyancy, and the release site presented no sign of immediate predation (e.g. reef sharks, barracudas). In contrast, at the fish trap, fish were placed in a floating mesh pen at low density (< 8 fish) for approximately 30 min to recover, then slowly towed away from the fish trap complex to reduce the risk of predation or recapture before release into the lagoon. The handling procedure duration, from the capture to the release, was minimized to limit induced stress on the fish.

2.3 Quantitative data processing and analysis

2.3.1 Data filtering

Preliminary visualization of fish detection and movements was performed using Fathom Central software (Innovasea, Bedford, NS, Canada). To minimize false detections, single detections in the receiver network were excluded using the *actel* package in R (Version 4.4.1), with the *residency()* function's *min.total.detections* argument set to 2. Data were then plotted for each individual to assess for presumed mortality. Fish showing abnormal detection patterns, such as disappearance shortly after release or prolonged presence at a single receiver, were considered dead and excluded from the dataset (Klinard and Matley, 2020).

2.3.2 Movement patterns and space use

Movement pattern analyses of the longnose emperor were conducted in R using the Actel and RSP packages (Flávio and Baktoft, 2021). For these analyses, receivers were grouped into four sections (Figure 1): *ZPR* for the receivers deployed in the ZPR, *Lagoon* for the receivers distributed throughout the lagoon, *Pass_lagoonside* for the receivers deployed on the lagoon side of the passes and *Pass_oceanside* for the receivers installed on the oceanic side of the passes.

To focus on the movements between different parts of the lagoon and the passes, specific receiver arrays were defined for each geographic area. In the *Pass_oceanside* section, two arrays were designated: Tiputa pass (*oceanside_tiputa*: 8 receivers), and Avatoru pass (*oceanside_avatoru*: 4 receivers). In the *Pass_lagoonside* section, the arrays included the lagoonside of Tiputa pass (*lagoonside_tiputa*: 4 receivers) and Avatoru pass (*lagoonside_avatoru*: 7 receivers). In the *Lagoon* section, six arrays were distributed along the coastlines and inner islets: *south* (10 receivers), *east* (13 receivers), *north_east* (9 receivers), *center_east* (1 receiver), *center_west* (2 receivers) and *west* (6 receivers). The *ZPR* section consisted of a single array (*ZPR1*: 17 receivers).

As reported by Filous *et al.* (2021), the lagoon sides of the passes are assumed to be pre-spawning sites, while the oceanic sides are hypothesized to be spawning locations for the species. To analyse group movement to these areas, space use, migration patterns and site fidelity were assessed using the *residency() and plotDetections()* functions. The *global.ratios* output from the residency analysis was used to visualize migration behaviour, identifying fish presence over time at the presumed pre-spawning (*Pass_lagoonside*) and spawning (*Pass_oceanside*) sites. Valid movements and detections were plotted using the *ggplot2* package to visualize the movement of each tagged fish from the release date to the last detection. A movement was considered valid when a fish entered and exited a section or array, confirmed by at least one detection at entry and one at exit. This data was used to map movements through the sections and arrays throughout the study period.

To analyse spatial use and assess differences in space utilization among tagged fish from the four release sites, telemetry data were processed using the Refined Shortest Path (*RSP*) package. The *runRSP()* function (Niella *et al*., 2020) estimated realistic in-water shortest displacement between detection pairs, allowing for a more accurate depiction of fish movement. A least-cost path analysis was then performed to calculate the utilisation distribution (UD), representing the distribution probability of a fish being found at a given point (Van Winkle, 1975). This analysis was conducted using dynamic Brownian Bridge Movement Models (dBBMM) with the *dynBBM()* and *getAreas()* functions in the RSP package. A 25% and 50% UD represent core use areas, where fish spend most of their time, with the 25% UD being the most concentrated usage area. The 95% UD indicates the total space used (i.e. extended range) (Horne *et al*., 2007).

2.3.3 Lunar cycle and spatiotemporal distribution

To assess the spatiotemporal distribution of Longnose emperor movements across lunar cycles, a network analysis following the methodology of Jacoby and Freeman (2016) was performed in R. Fish detections were first categorized by the eight lunar phases—new, waxing crescent, first quarter, waxing gibbous, full, waning gibbous, last quarter and waning crescent—corresponding to the detection times at a specific receiver. The lunar phase at each detection was determined using the *lunar.phase()* function from the *lunar* package. After classification, data were filtered by lunar phases, and fish movements were incorporated into network analyses for each phase. Receiver locations were represented as nodes, with their size proportional to detection frequency. Fish movements, or node connectivity, were shown as lines between these nodes, with edge density representing this connectivity in the analysis.

Network models were constructed using the *graph_from_data_frame()* function in the *igraph* package. For each lunar phase, the networks were summarized by

calculating the number of nodes, the mean distance between nodes (i.e. average movement length in kilometres), the edge density index (i.e. number of possible connections present in the network), and the mean and standard deviation of node betweenness centrality (i.e. the importance of a receiver based on how often it acts as a bridge along the shortest path between two others) (Csardi, 2015; Jacoby and Freeman, 2016).

2.4 Local ecological knowledge assessment

> "Few people would claim to know as much about how to catch fish as a good full-time fisherman. When it comes to understanding fish behavior and the many environmental factors that help determine and predict it, marine biologists must often take a back seat."
>
> — (Johannes, 1981)

A key component of the study was integrating local ecological knowledge (LEK) into the interpretation of acoustic telemetry results. Movements and presence of the species are well known locally with approximately 20% of the Rangiroa community involved in its exploitation (e.g. fishers, fishmongers and restaurants) (TNTV, 2022).

To gather information on LEK, a list of potential participants (n = 48) was initially established with people known from prior professional relationships, some were listed with the help of the local mayor and his deputies, and others were met around popular fishing places (e.g. docks and marinas). Each person was contacted by phone or directly met to organize a time for an interview. Then, informal in-person interviews, following Adams *et al*. (2019), were conducted between the 18th of January and the 11th of February 2024 with 25 individuals engaged in the longnose emperor fishery. These participants, either fishers or fishmongers, had years of experience and in-depth knowledge of the Rangiroa lagoon and the surrounding islets.

The informal, open-format interviews were designed to build and maintain trust with the participants, allowing the collection of valuable information about their fishing grounds and their general observations (Adams *et al*., 2019). Each interview lasted between 40 minutes and 1.5 hours and was conducted in relaxed familiar environments, such as on the lagoon shore or at the interviewees' homes. Discussions centred on topics including spatiotemporal fishing patterns, the periodicity and locations of longnose emperor aggregations, movement patterns, and perceptions of spawning behaviour in relation to the lunar phases, with observations from Filous *et al*. (2021a) used to guide the conversation. All participants were asked the same core questions in a non-structured format:

- When do you usually go fishing?
- When you target longnose emperor (*'O'eo*), which lunar phase is it?

- Could you tell me where you fish for *'O'eo*?
- Have you ever observed schools or aggregations of *'O'eo*? If yes, can you tell me where?
- When you observed *'O'eo* aggregations, how and where did they appear to move?
- In your opinion, why do they aggregate in these locations?
- Where do you think they spawn?

All interviews were recorded with the interviewees' consent, to ensure accurate data collection and comprehensive analysis. The recordings were subsequently transcribed for further analysis. When discussing specific locations, participatory maps of Rangiroa were used, allowing interviewees to mark areas of interest (Machaieie and Silva, 2020). For consistency, local place names and lunar phases were transposed into the nomenclature used in the acoustic telemetry data analysis. Information considered highly relevant was emphasized when multiple participants provided similar responses. If any details were unclear to the interviewees, questions were clarified using local terminology.

For data analysis, validation, and interpretation, criteria from Machaieie and Silva (2020) were applied: (1) species knowledge shared by more than one participant; (2) knowledge of migration and aggregation sites confirmed by more than one participant; (3) verification of positive responses regarding the species, its fishery, and movement patterns. Key characteristics of the answers were categorized and grouped to highlight major observations. Building trust and securing community involvement were essential for this process. Participating in community activities and showing interest in their relationship with natural resources were fundamental to fostering engagement and collecting valuable data.

3. Results

3.1 Migration patterns and space use

Fish movements were recorded over 254 days, from the first detection on 2023-09-11 to the last on 2024-05-22, yielding 67,106 valid detections from 66 individuals. Of the tagged fish, 21% used both Avatoru and Tiputa passes, while 5% were recaptured and retained by fishermen in October 2023, November 2023, and January 2024. A majority of the tagged fish (64%) were still detected four months after tagging, suggesting optimal release conditions post-tagging. Among the receivers, 14% registered no detections, and 9% were lost. Of the non-detecting receivers, 5 were from the *east* array, 2 from the "south" array, 2 from the ZPR, 1 from the *west* array, and 1 temporarily deployed in Tiputa pass (ocean side) during a receiver offload (red crosses in Figure 1).

The movement patterns and residency of individual fish were tracked and analysed over time, as illustrated in Figure 3. Approximately 71% of the tracked fish displayed distinct migratory behaviour between different sections, which were categorized into three main movement types (Figure 3A, B, and D). The remaining 29% of tracked fish stayed within a specific area and did not show migration to other sections (Figure 3C).

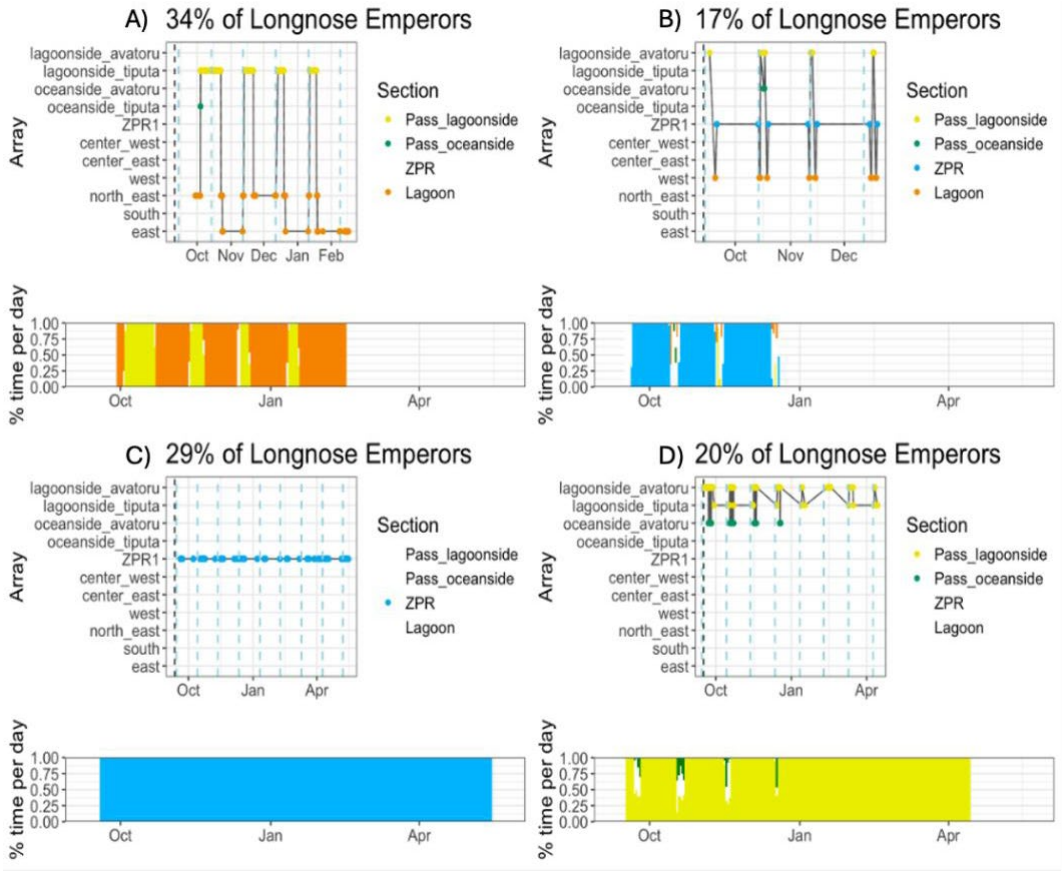

Figure 3. Plotted detections recorded by the receivers (top) and the residency (percentage of time spent per day in section) (below) of the four main movement patterns exemplified by four of the tagged longnose emperors from their first to last detection period. The black vertical dashed line represents the release date, and the blue dashed lines are the monthly new moon dates. The dots represent the detections on a corresponding receiver station, and the solid line represents valid movement events. A) Example of an eastern migration pattern, between the passes and the arrays "east"/"north_east", exhibited by 34% of the studied fish and represented by the movements and residency of tag A69-1604-25551. B) Example of a western migration pattern, between the passes and the arrays "ZPR1"/"west", exhibited by 17% of the studied fish and represented by the movements and residency of tag A69-1604-25578. C) Example of a restricted movement pattern in one section exhibited by 29% of the studied fish and represented by the movements and residency of tag A69-1604-25571. D) Example of localized movements between the lagoon side and the ocean side of the passes exhibited by 20% of the studied fish and exemplified with the movements and the residency of tag A69-1604-25581.

Residency analysis revealed that 34% of the analysed fish consistently moved between the eastern lagoon areas, specifically the *east* and *north_east*, and the pass areas (both lagoon and ocean sides). This eastern coastal migration pattern is exemplified by the fish shown in Figure 3A. These fish predominantly resided in the *Lagoon* section, demonstrating strong site fidelity, but exhibited regular monthly migrations to the pass areas.

In contrast, 17% of the fish exhibited concentrated movements in the western portion of the lagoon, specifically between the ZPR, the *west* array, and the passes (Figure 3B). This behaviour suggests a western coastal migration route, with the

residency analysis indicating strong site fidelity to the ZPR, demonstrated by the extended time spent in this area. These fish also made regular monthly movements to the passes, although they spent less time there compared to the ZPR.

However, some fish (29%) exhibited more restricted movement patterns, remaining primarily within one or two sections (Figure 3C). Of these, 63% were predominantly detected in the ZPR, 16% in the *north_east* array of the lagoon section, and 21% within the lagoon side of Tiputa pass. This strong presence in specific areas, with minimal movement into other sections, reflects strong site fidelity and suggests these locations function as core habitats.

Finally, 20% of the fish predominantly moved between the lagoon and ocean sides of the passes (Figure 3D), with few excursions to other sections. Similar to the fish depicted in Figures 3A and 3B, these individuals displayed monthly movements between the sections. Residency analysis revealed that they spent the majority of their time in the *Pass_lagoonside* section, with a significant percentage of their overall time allocated to this area.

The fish exhibited frequent transitions between sections and arrays, indicating broad use of the atoll lagoon with periodic movements towards critical areas, such as the lagoon and ocean sides of the passes (Figures 3A and 3B). Residency analysis revealed that these visits were brief, averaging 5 days between these areas of the passes and occurred monthly. The fish showed fidelity to specific areas, particularly the *Pass_lagoonside* of the Avatoru and Tiputa passes, suggesting possible social behaviours, before visiting the ocean side of the passes. While some individuals exhibited complex movement patterns, transitioning across multiple sections and arrays, others remained confined to one or two areas throughout the study.

The space use analysis revealed that fish also showed varying movement patterns depending on their release location (Figure 4). Fish tagged at Avatoru and the fish trap exhibited the broadest spatial use across the atoll, while those from Tiputa showed slightly less extensive movements. Fish from the ZPR exhibited more localized movement patterns. Although these distinctions were not abrupt, they were evident, with overlap across the study sections. Fish tagged at Avatoru pass extensively used of the western side of the atoll, particularly between the ZPR, west coast, and passes. Fish tagged at Tiputa pass primarily utilized the lagoon near the Avatoru and Tiputa passes. Fish tagged in the ZPR remained concentrated within the boundaries of the ZPR, suggesting it as a core habitat. Finally, fish from the fish trap demonstrated broader movement, with transitions across the east, northern and southern coasts, the ZPR, and passes.

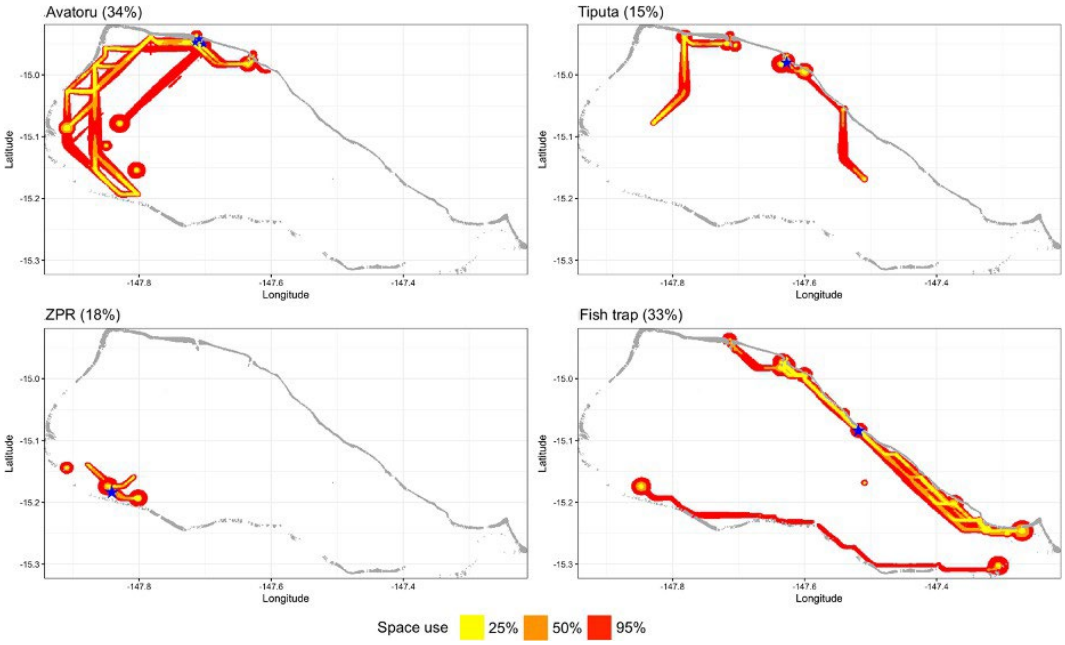

Figure 4. Spatial use of the tagged longnose emperors depending on their release location, with the four release sites marked by a blue star. Of the tagged fish, 34% were released from Avatoru, 15% from Tiputa, 18% from the ZPR, and 33% from the fish trap. The 25% (yellow) and 50% (orange) utilisation distribution (UD) represents the core areas used by the fish, while the 95% (red) UD represents the extended range of the fish.

3.2 Influence of the lunar cycle on fish movement

The movement plots in Figure 3 demonstrated synchronized fish movements toward the pass areas (both lagoon and ocean sides) during new moon periods, as marked by the blue dashed lines. The observed pattern was present in 51% of individuals, with fish moving between the lagoon or ZPR sections and the pass areas, as well as between the lagoon and ocean sides of the passes (20%). However, individual variation was noted: some fish exhibited high activity during the new moon, while others remained more stationary. For instance, the fish represented by Figure 3C (n= 24) tended to remain within a single section, such as the ZPR.

Network analysis of longnose emperor movements revealed distinct patterns across the eight lunar phases. Presumed spawning migrations appeared to align with the waning crescent, new moon, and waxing crescent phases. During these periods, fish activity increased, with more detections near the passes and greater connectivity, as indicated by larger node sizes (representing detection frequency) and denser edge networks (lines connecting receivers) (Figure 5). In contrast, during the full moon and waning gibbous phases, movements were more localized, with the shortest mean distances of all the phases (i.e. average of < 3 km travelled). Low edge density and minimal betweenness suggest a more clustered network centred around areas, like the ZPR or lagoon edges (Table 2). Following the waning

gibbous, network complexity and lagoon-wide movements increased significantly. Between the waning crescent, new moon, and waxing crescent phases, node counts peaked and edge densities expanded across the lagoon (Table 2). The larger node size around the passes indicates higher fish concentration and activity during these lunar phases (Figure 5).

Table 2. Summary of network characteristics across the eight lunar phases. The node count represents the number of receivers that detected fish activity. The mean distance indicates the average distance (in kilometres) travelled by fish between nodes. Edge density reflects the ratio of connections between nodes, while betweenness represents the number of movements through a receiver situated along the shortest path between others in the network.

Moon phase	Node count	Mean distance (km)	Edge density	Mean (sd) betweenness
Full	22	1.85	0.07	0.86 (1.73)
Waning gibbous	21	2.88	0.08	2.48 (4.60)
Last quarter	38	7.97	0.07	69.47 (86.83)
Waning crescent	49	7.58	0.07	99.69 (132.87)
New	50	5.86	0.09	107.25 (163.17)
Waxing crescent	43	7.50	0.11	119.24 (164.47)
First quarter	43	10.52	0.08	42.41 (66.96)
Waxing gibbous	33	15.19	0.09	11.83 (15.56)

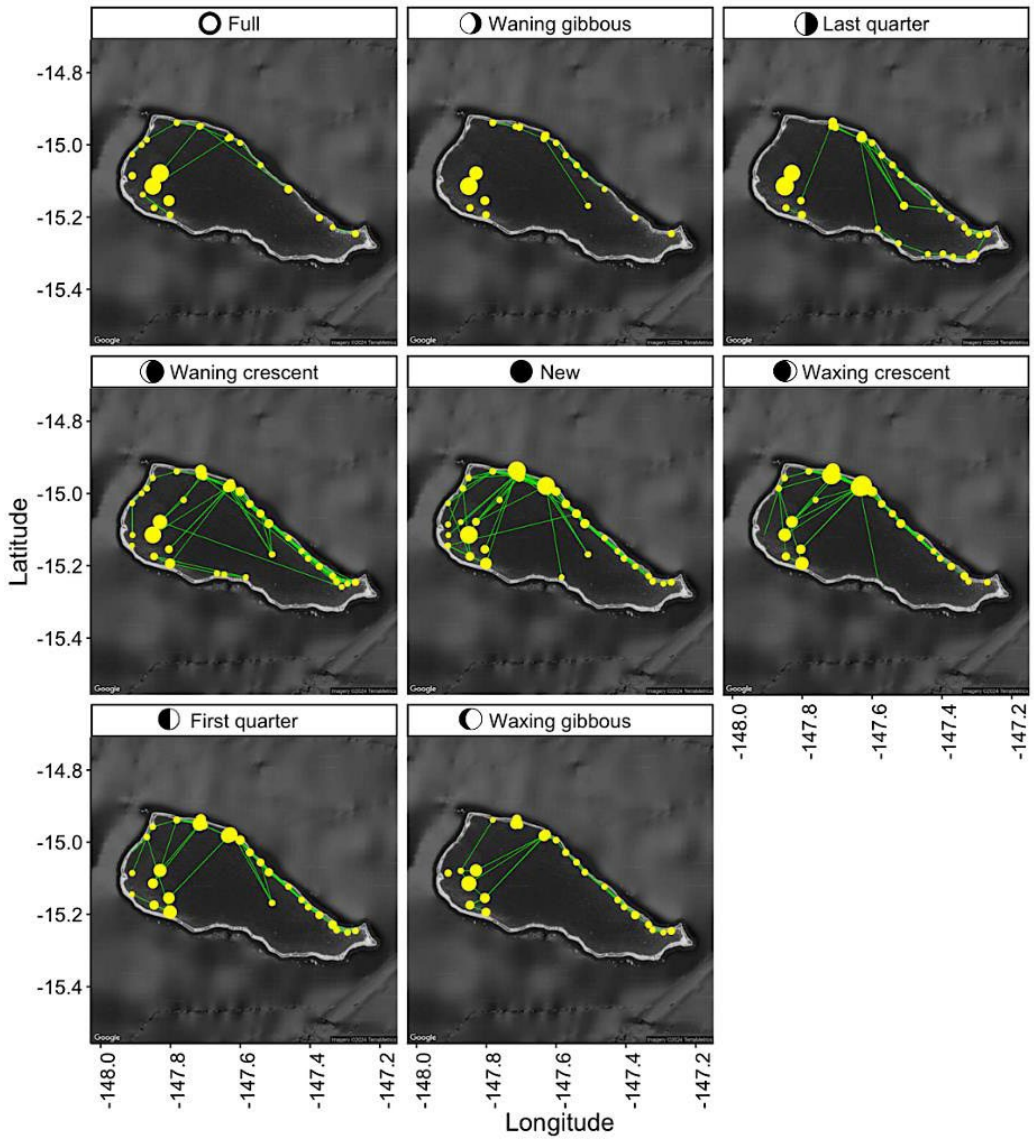

Figure 5. A unipartite plot illustrating longnose emperor detections within the acoustic network across the eight lunar phases, from September 2023 to May 2024, overlaid on georeferenced satellite imagery of the Rangiroa Atoll. Yellow circles represent receivers (nodes), with their size scaled to node weights (i.e. the number of detections). Green lines indicate edges, representing fish movements between nodes.

3.3 Local ecological knowledge of longnose emperor movements

A total of 25 fishers and fishmongers from Rangiroa were interviewed about their knowledge of longnose emperors and their movements. Most participants (60%) were full-time fishers who fished weekly, year-round. Part-time fishers (32%) targeted specific periods, with 40% fishing only between Austral spring and fall

and 20% only during the new moon. The remaining 8% were fishmongers who purchased and sold fish from these events.

All interviewees targeted longnose emperors during the new moon to waxing crescent. Most (84%) also started fishing from the waning crescent, and one participant mentioned fishing could continue until the last quarter of the lunar cycle. While 16% reported fishing during the full moon, this occurred in different locations than during the new moon, particularly on the inshore pinnacles of the lagoon's southern side.

Most interviewees indicated fishing on presumed pre-spawning aggregation sites (red triangles in Figure 6), mainly at the lagoon side of Tiputa pass (76%), especially in front of the Tiputa village, with 60% also fishing near Avatoru pass. Fewer fished at presumed spawning sites on the ocean side of the passes — 32% targeted the outside of Avatoru, and 20% the outside of Tiputa, citing strong currents and predators (e.g. reef sharks) as challenges. Other key locations included inshore pinnacles (24%), the southern coast near the ZPR (12%), and the northeast coastline (16%), where fish traps were installed due to fish migration along the shore.

Regarding ecological observations, all respondents noted longnose emperor aggregations, primarily around the passes — 84% at Avatoru and 76% at Tiputa - and along the northeast (28%) and eastern (44%) lagoon sections. Aggregations were also reported around ZPR reef pinnacles (28%), in shallow channels (*hoa*) in the eastern lagoon (12%), and on the outer reef slope near the ZPR (8%). (Figure 6). Most respondents (84%) believed these aggregations were for spawning, while others suggested feeding (20%) or as a collective predator avoidance strategy (8%). Notably, 76% believed spawning occurred on the ocean side of the passes, based on the presence of gravid females, while 12% believed spawning occurred inside the lagoon, away from the passes.

Regarding movement patterns, 52% of the respondents described typical paths, generally following the lagoon's coastline (Figure 6). Some (12%) described circular movements from the south to the passes and back through the west and ZPR (red track, Figure 6), while 20% mentioned eastward loops from the passes, through the lagoon's centre, along the southern coast, and back via the northern coast (blue track, Figure 6). Others (8%) reported linear movements from the southern lagoon, through the centre to the passes (yellow track, Figure 6). Additionally, 12% described group movements along the northern coast between the east and the passes (green track, Figure. 6).

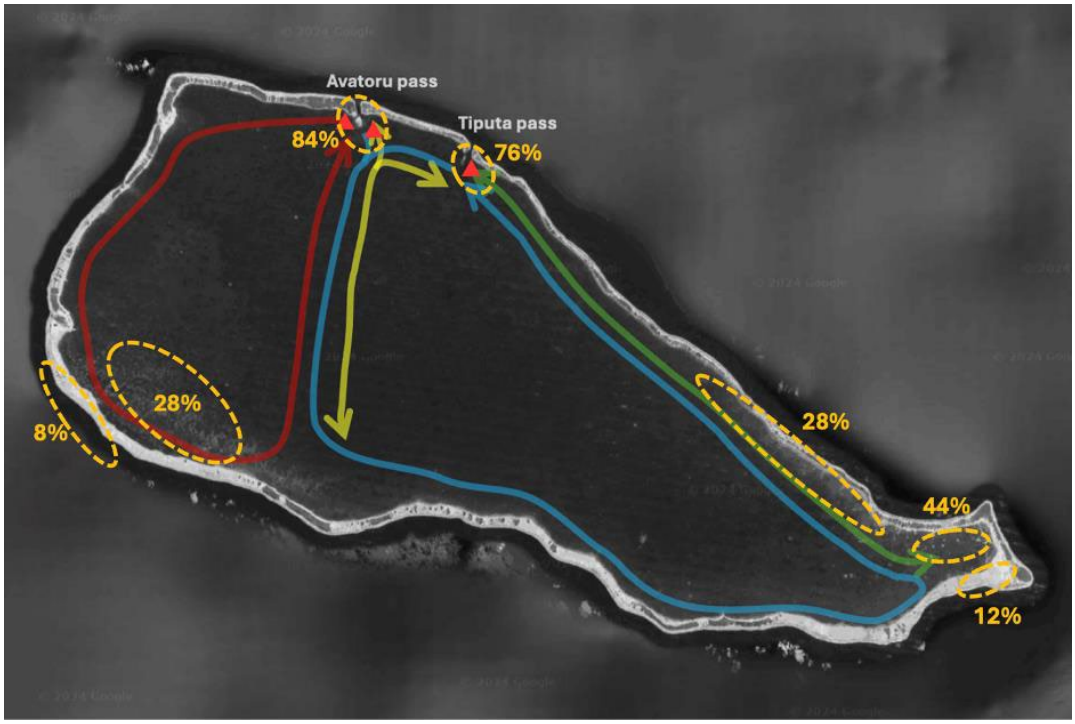

Figure 6. A map of the Rangiroa Atoll summarizing key observations on longnose emperor movements based on participant interviews. Red triangles indicate the most frequented fishing grounds, and presumed pre-spawning aggregation sites, with 76% of participants fishing at Tiputa's lagoon side and 60% at Avatoru's lagoon side. Dashed circles represent the percentage of participants who observed fish aggregations in this area. The lines depict the main migration pathways described by at least two participants: red (12%), blue (20%), yellow (8%) and green (12%).

4. Discussion

This study advances our understanding of the migratory patterns, space use, and ecology of longnose emperors within the Rangiroa lagoon, a vital reef fishery resource in French Polynesia. It provides key insights into their ecological behaviour, particularly in relation to lunar cycles and site fidelity. The findings reveal a complex interplay between movement behaviours and abiotic factors, with distinct patterns emerging in response to lunar phases and the spatial characteristics of the atoll. Consistent with Filous *et al*. (2021a), longnose emperors were concentrated around the lagoon sides of both passes during darker lunar phases. The tagged fish exhibited a monthly cyclicality in and around the passes which exposes them to recurrent fishing mortality.

Migrations, aggregations, and space use of longnose emperors inside the Rangiroa lagoon

The movement patterns observed in this study reveal distinct migratory behaviour of longnose emperors within the Rangiroa lagoon, particularly between the northern and western coasts and the two major passes. Telemetry data showed varied space use, with both broad and localized movements. Notably, longnose emperors displayed fidelity to key habitats, including the ZPR and the Avatoru and Tiputa passes, returning to these areas monthly, particularly during specific lunar phases, suggesting their critical role in the species' life cycle. These findings align with previous studies that documented similar migratory behaviours in lethrinid species, where movements to specific locations coincide with spawning periods (Taylor and Mills, 2013; Babcock *et al*., 2017).

The observed aggregation patterns around the passes, particularly around the new moon, corroborate the findings of Filous *et al*. (2021a). While spawning was not directly observed, the presence of gravid females found around Avatoru and Tiputa passes during these periods, suggests a likely association with key life history events, such as spawning. This behaviour has also been documented in other emperor species, such as spangled emperor (*Lethrinus nebulosus*) and other coral reef fish, such as camouflage grouper (*Epinephelus polyphekadion*) and bonefish (*Albula glossodonta*) (Robinson *et al*., 2004; Sadovy, 2007; Mourrier *et al*., 2019; Filous *et al*., 2020).

The aggregation behaviour of longnose emperors observed in Rangiroa aligns with similar patterns documented across the Indo-Pacific. Reef fish, including emperors, typically aggregate at strategic sites for reproduction and feeding (Fisher *et al.,* 2018). In Rangiroa, the species' migrations to the passes from September to May suggest a prolonged reproductive period, consistent with Sadovy (2007), who reported that longnose emperors undertake monthly spawning migrations for up to six consecutive months. Johannes (1981) similarly found emperors to aggregate and spawn year-round, particularly during the new moon phase (up to five days after the new moon), at specific sites such as the ocean side of reefs or channels. Local knowledge from Rangiroa corroborates these findings, noting targeted fishing activities around the passes until the waxing crescent moon phase. Additionally, Currey *et al*. (2013) observed seasonal displacement patterns in emperor species from the Great Barrier Reef, with peak reproductive activity during the Austral Spring (September - October).

A key finding is the clear relationship between longnose emperor movements and lunar cycles, with synchronized movements towards the passes during new moon periods. This behaviour is well-documented in other reef fish species, where lunar cues trigger spawning migrations (Sadovy de Mitcheson and Colin, 2012; Chakraborty, 2018). The reduced illumination levels and specific tidal conditions associated with the new moon likely create favourable conditions for spawning by reducing predation risk and enhancing fertilization success (Takemura *et al*., 2004; Molloy *et al*., 2011). Similarly, Taylor and Mills (2013) demonstrated that the thumbprint emperor (*Lethrinus harak*) undertakes nightly spawning migrations between specific lunar phases which coincide with a strong ebbing tide. The network analysis highlights the structured and predictable movement patterns, with increased connectivity and activity around the passes during the waning crescent, new moon, and waxing crescent further supporting the hypothesis that these areas may serve as key habitats for temporary pre-spawning aggregations and spawning sites (Mourier *et al*., 2019). However, individual variations in movement patterns were observed, with some fish displaying broad movements and others remaining within specific sections of the lagoon. This may reflect different reproductive strategies or spawning locations, emphasizing the potential ecological importance of certain areas, such as the ZPR, for particular groups. Similar intra-specific variability in migratory behaviour has been noted in other lethrinids, such as redthroat emperors, where some individuals restrict their movements while others travel greater distances (Currey *et al*., 2014).

Another possible explanation for these differences is fisheries-induced behavioural shifts, where fish avoid areas with high fishing pressure (Guerra *et al*., 2020). Fisheries-driven changes in fish behaviour have been shown to induce effects beyond their survival and permanently affect population dynamics (Diaz Pauli and Sih, 2017). That said, although this study did not analyse the direct effects of fishing pressure, the longnose emperor in Rangiroa has been subjected to

intensive fishing pressure for more than five decades (Lagouy, 2012), potentially leading to adaptive behaviours to sustain reproductive success while avoiding heavily fished routes. This is similar to patterns observed in thumbprint emperors in Vanuatu, where fish restricted their movements to unfished areas (Léopold *et al*., 2017). Such behaviour aligns with the concept of protected areas functioning as refuges that offer essential resources like food, shelter, and breeding grounds, thereby contributing to the sustainability of reef fish populations (Roberts *et al*., 2002; Halpern and Warner, 2003).

Insights from incorporating local ecological knowledge (LEK) for effective management

The longnose emperor's predictable migrations, occurring monthly around the new moon, increase its vulnerability to targeted fishing during critical reproductive periods. This pattern, observed in Rangiroa and other locations such as the Seychelles (Robinson *et al.,* 2004), suggests that unsustainable fishing may occur when spawning aggregations are targeted. To address this, integrating temporal dynamics into management strategies, like seasonal closures during key lunar phases, could reduce fishing pressure and promote reproductive success, thereby enhancing long-term sustainability (Russ, 2002; Sale *et al*., 2005; Cinner *et al*., 2012).

However, managing spawning migration fisheries presents several challenges, as highlighted by Crossin *et al*. (2017). One significant challenge is the dynamic nature of fish movements and the inherent variability in individual behaviour, which complicates the design and enforcement of management measures. As shown in the study, longnose emperor exhibits varying degrees of site fidelity, with some individuals remaining within specific areas like the ZPR, while others migrate to the pass areas, increasing their vulnerability to fishing (Afonso *et al*., 2009). Acoustic telemetry provides critical insights into these challenges by offering detailed data on fish movements, habitat use, and the extent of site fidelity. This technology also reveals some limitations of static management measures, such as fixed protected areas, in addressing the dynamic nature of fish behaviour.

The telemetry data revealed that fish frequently move from the protected area to the passes multiple times throughout the year, exposing them to the risk of fishing. Crossin *et al*. (2017) emphasize that the success of fisheries management depends not only on understanding where and when fish aggregate but also on how their movements may change in response to external pressures, including fishing. This underscores the importance of integrating telemetry data into a broader, more flexible management framework that can accommodate the variability of fish movements. Another challenge would be the implications of such management measures to the local community which depends almost exclusively on lagoon resources. Therefore, a livelihood-sustainable approach, before implementing any

management strategy, would allow more flexibility and guidance toward a more comprehensive framework that is compatible with resource conservation, culture and socio-economic needs of the community (Allison and Ellis, 2001; Ferrol-Schulte *et al*., 2013). One benefit of this approach is that it encourages more active and meaningful participation in management decisions by individuals who directly depend on the resource. For example, the livelihood approach challenges traditional fisheries management by highlighting that increasing fishers' living conditions is not simply about improving fishing efficiency. It recognizes that fishers often engage in fishing opportunistically. Like longnose emperors' fishers who go fishing when this fish is aggregating and therefore, are not solely dependent on fishing for survival. This flexible engagement suggests that orthodox fisheries management may be unadapted. Instead, diversified livelihoods and mobility among sectors should be supported, as these can benefit resource conservation and lead to more sustainable management practices (Allison and Ellis, 2001).

The observed site fidelity of longnose emperors to areas like the ZPR and the passes underscores the importance of these habitats, suggesting that managing these key areas, especially during periods of high aggregation, is crucial. One strategy for the conservation of tropical reef fishes exhibiting high mobility and spatial regrouping is the implementation of adapted temporary fishing closures in these key areas during periods of aggregation (Rhodes and Warren-Rhodes, 2005). Afonso *et al*. (2009) argued that adopting such conservation strategies during the increased periods of mobility, such as the new moon periods for the longnose emperors, would participate in the protection of key ecological times, such as the spawning periods, and would still enable the fishing benefits outside of these temporal closures. In the case of the longnose emperor in Rangiroa, a potential strategy could be to limit or close fishing in the passes during the darker periods of the lunar cycle, with the aim of allowing the species to reach its presumed spawning grounds and reproduce. This approach has previously been employed in the management of the bonefish in Anaa atoll. Engaged in a community-based management framework, it aimed to increase the reproductive success of this important fishery species and ensure the sustainability of its fishery (Filous *et al*., 2021b).

Furthermore, it is possible to implement spatial and temporal closures independently, but they can also be employed in conjunction with other management strategies, such as the designation of conventional protected areas, like the ZPR. This approach would offer dual effects: on the one hand, it prevents fishing in the designated area, and on the other, it establishes a mechanism to prohibit the catching or possessing of fish during critical periods in locations of particular importance to the species in question (Rhodes and Warren-Rhodes, 2005). As a regulated area, the ZPR contributes to the species' conservation. However, this study did not account for the direct effects of this regulated area on the emperors' population, but the interviews revealed that regulations are not

consistently adhered to due to the current lack of enforcement, with fishers frequently observed fishing within the ZPR area. As reported by Campbell *et al*. (2012), despite regulations being "on the books", the ecological success of any protected area depends on complex socioeconomic dynamics and compliance with actual fishery regulations is not systematic, especially when regulated areas are widely dispersed, thus likely with no enforcement.

In addition to scientific data, integrating local knowledge into fisheries management is crucial for developing effective and culturally appropriate conservation strategies. Hamilton *et al*. (2012) highlighted the valuable role that local ecological knowledge plays in understanding the behaviour and ecology of reef fish species, including their spawning aggregations. This valuable source of information, which encompasses the traditional knowledge and observations of local communities, can provide insights into historical patterns of fish movements, the locations of spawning sites, the timing of reproductive events and potential stock status indicators marked by changes in the landings (Sadovy de Mitcheson and Colin, 2012). Interviews with Rangiroa residents revealed that fishing for longnose emperors is closely tied to the lunar cycle, with most fishers targeting the species from the waning crescent to the waxing crescent, aligning with the periods of increased fish activity detected in this study. Moreover, the interviews highlighted key fishing locations, such as the lagoon sides of Avatoru and Tiputa passes, which were also identified as critical areas in the telemetry study. These aggregation sites, the pass areas, and the migration paths discussed by the interviewed participants revealed and complemented the telemetry findings and can help to highlight these areas of concern for future management. The involvement of local communities in the decision-making process would ensure that management strategies are not only ecologically effective but also socially sustainable, especially from a perspective of future community-based resource management (SPC, 2024).

Finally, the variability in fish movements suggests that management strategies must be adaptative and responsive to changing conditions of species displacement. By aligning management strategies with natural cycles and understanding individual variability in behaviour, fisheries management can achieve a balance between resource conservation and sustainable use (Babcock *et al*., 2017; McClanahan *et al*., 2008; Govan, 2009). Knowledge of fish spawning aggregations, their locations, and timing is fundamental for effective population management, whether through the creation of protected areas or other non-permanent fishing management measures such as temporal closures (Samoilys and Church, 2004; Samoilys *et al.*, 2006). The integration of LEK and acoustic telemetry data into fisheries management frameworks thus plays an important role in improving conservation outcomes and ensuring the sustainability of major fishery resources like the longnose emperor.

Study limitations and future improvements

This study offers critical insights into the spatial ecology, movement patterns, and space use of longnose emperors in Rangiroa Atoll but several limitations warrant consideration. Firstly, the spatial coverage of the acoustic receivers' network, while extensive, may not have been sufficient to capture all movements of the tagged individuals, particularly in areas beyond receiver range, such as the lagoon's centre, the exterior of the atoll, or other plausible passageways found between the islets. The receivers concentrated along the shore, with limited deployment in open lagoon areas and the outer reef, leading to a higher tracking resolution near the inner shore. As noted in Lees *et al*. (2021), large areas present challenges for acoustic telemetry design. This limitation could result in an underestimation of the full extent of the species' migratory behaviour, particularly in relation to movements undertaken inside the large Rangiroa lagoon. Expanding receiver coverage in future studies would allow for a more comprehensive understanding of the species' full migratory range.

Moreover, detection variability inherent to acoustic telemetry networks, influenced by environmental factors like noise, water currents, turbidity, and complex seabed structures, may have impacted the detectability of the tagged individuals, leading to potential detection (Reubens *et al*., 2019, Huveneers *et al*., 2016). For instance, low detection rates on some receivers located in more complex areas, like the eastern side of the lagoon and the ZPR, likely resulted from intricate seabed features such as pinnacle reefs and shallow sand beds (Currey *et al*., 2014). This detection variability may result in an underestimation of the actual fish movement ranges or could obscure the detection of certain behaviours, particularly in areas where habitat types differ. Cagua *et al*. (2013) determined that topography, but also environmental noises held the greatest influence on detection distance compared with other environmental factors (e.g. wind, thermocline and depth). Similarly, Payne *et al*. (2010) showed an increased environmental noise can significantly affect the detection frequency of the deployed transmitters and provide contradictory results in animal movement patterns interpretation. A better understanding of environmental influences on detection could refine future analyses.

The study duration, limited to part of the year (9 months), may not fully capture the seasonal and inter-annual variability of longnose emperor movements, with peaks during specific periods like austral spring (Currey *et al*. 2013). A full-year study would help document similar patterns in Rangiroa, particularly during the presumed low-activity periods of the species. Additionally, inter-annual monitoring could assess the impact of environmental variability and climate change, as climatic events like El Niño/La Niña can significantly affect fish recruitment and fishery success (Aburto-Oropeza et al., 2010).

Incorporating sensor data from transmitters, in addition to monitoring fish activity, could offer valuable insights into key ecological events, such as spawning. This approach would enable detailed tracking of vertical movements and depth utilization, providing a more nuanced understanding of habitat use, as demonstrated by Currey *et al.* (2014). By analysing this sensor data, it would be possible to compare differences between males and females, as well as assess how these behaviours are influenced by environmental factors like temperature fluctuations during critical reproductive and migratory events. This would greatly enhance our understanding of the species' life cycle and inform more targeted conservation strategies.

Conclusion

This study aimed to contribute to the broader understanding of the migratory behaviour, space use, and ecology of the longnose emperor (*Lethrinus olivaceus*) within the Rangiroa lagoon, a key reef fishery resource in French Polynesia. By integrating local ecological knowledge, the research also sought to empower/provide the Rangiroa community with valuable insights to support future resource management efforts.

The findings underscore the intricate interrelationship between the species' behavioural patterns and abiotic factors, particularly lunar cycles, which significantly influence their spatial movements and site fidelity. The observed monthly cyclicality in movement, particularly around the lagoon sides of Tiputa and Avatoru passes during darker lunar phases, highlights the vulnerability of the species to recurrent fishing pressures. Furthermore, the species' tendency to remain in specific locations —such as the lagoon sides of the passes, the northern shore, and the ZPR—emphasizes the ecological importance of these areas, consistent with similar studies on lethrinid species, indicating that these locations are of critical importance for the species' life cycle.

The integration of local ecological knowledge with acoustic telemetry data provided valuable insights into the species' behaviour, reinforcing the need for management strategies that are both ecologically effective and socio-economically viable. The predictable nature of longnose emperor aggregations, driven by lunar cycles, presents a challenge for management but also an opportunity for adaptive strategies. Consequently, management and conservation strategies, such as temporal (e.g. the darker lunar phases) and spatial closures of key areas for the longnose emperor (i.e. the lagoon sides of the passes and along the migration pathways like the northern coast), could be applicable in a context of a community-based fishery management framework. This would safeguard the species' reproductive success while allowing the Rangiroa community to manage and sustain their fishery.

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Popular science summary

In the tropical waters of the Rangiroa Atoll, an island in French Polynesia, a unique fish named the longnose emperor plays a vital role in the local community's life and culture. For decades it has been a key food source for the islanders and a significant part of their livelihood. However, with growing fishing pressures and little knowledge about this species, concerns are rising about its future.

To get a better understanding of these fish, we tracked 75 longnose emperors using small transmitters, allowing us to follow their movements via hydrophones in the lagoon. We discovered that they often return to the same spots, such as the areas near the two major passes, and a regulated zone known as the ZPR. These findings suggest that these locations are critical for the fish's life cycle, especially during their reproduction periods.

We also found that these fish are highly influenced by the moon. They tend to gather in specific areas of the lagoon during darker moon phases, particularly around new moons. These groups make them an easy target for fishers, which could lead to overfishing if not managed carefully.

In addition, we included the knowledge of local fishers, who have long observed the behaviour of these fish. By combining this traditional knowledge with modern technology, we've gained a clearer picture of how to protect the longnose emperor.

This research highlights the need for careful management of fishing activities in Rangiroa, especially during the new moon periods. By understanding when and where these fish gather, we can create strategies that allow the community to continue fishing while ensuring that this fish remains abundant for future generations.

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