Interactions between wild fauna and farmed tuna in Maltese coastal waters

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Abstract

Atlantic bluefin tuna (*Thunnus thynnus*) ranching is a major aquaculture activity in Malta, yet interactions between tuna farms and wild fauna remain poorly documented. This study addresses this gap by identifying which wild fauna aggregate around farm sites, the drivers of these aggregations, and the resulting ecological and operational implications. Nineteen semi-structured interviews were conducted with tuna farm personnel and environmental monitors across four ranching sites, providing multi-year observations on species presence, behavior, and interaction patterns. In total, 41 wild fauna species and 143 observations were recorded. Aggregation was primarily driven by uneaten baitfish, habitat provisioning from cage structures, and proximity to migratory routes.

Findings indicate that tuna farms act as fish aggregating devices (FADs) that alter local trophic dynamics. Consumption of uneaten baitfish can reduce organic loading and improve the condition of aggregated fauna, offering localized ecological benefits. However, reliance on baitfish also perpetuates pressure on wild forage fish stocks, and predictable food subsidies may create ecological traps, behavioral dependency, and changes to natural movement patterns. This study provides the first baseline assessment of these interactions in Malta and highlights the need for long-term monitoring and adaptive management to balance aquaculture productivity with ecosystem sustainability.

Keywords: Atlantic bluefin tuna, aquaculture, fish aggregating devices, Malta, wild fauna interactions, marine protected areas

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Table of Contents

List of Figures

List of Tables

List of Abbreviations

ABT	Atlantic Bluefin Tuna
AF	Amateur Fishermen
AJDTL	AJD Tuna Ltd.
BMP	Best Management Practice
CBA	Capture-based Aquaculutre
CCA	Closed-cycle Aquaculture
DFA	Department of Fisheries and Aquaculture
ERA	Environment and Resources Authority
EU	European Union
FAO	Food and Agriculture Organization
FCR	Food Conversion Ratio
FFL	Fish and Fish Ltd.
HI	Hepatosomatic Index
ICCAT	International Conservation Convention for Atlantic Tuna
MBTFL	Mare Blue Tuna Farm Ltd.
MEPA	Malta Environmental Planning Authority
MFFL	Malta Fish Farming Ltd.

MML	Malta Maritime Ltd.
MPA	Marine Protected Area
MSc	Master of Science
NAS	North Aquaculture Site
SAC	Special Area of Conservation
SAZ	South uaculture Zone
SPA	Special Protection Areas

1 Introduction

1.1 Aquaculture

1.1.1 Global Aquaculture Development

Aquatic ecosystems have long been regarded for their attractiveness and, seemingly, endless supply of natural resources. Of them, marine and coastal areas have supported important ecosystems that have a crucial role as service provisioners and resilience enhancers, as well as supporting biodiversity corridors. Most notably, the essential provisioning services, such as the freshwater and food they provide, make them critical to conserve. However, as the human population and civilizations expanded, so has exploitation and consumptive demand of these resources.

Fishing and aquaculture practices date back to ancient times. Historical texts and depictions show the use of cultivated fishponds in ancient Egypt as early as 2500 BC, with later records from Mesopotamia, India, and the Roman Empire (Rogers, 2024). Over time, accumulation of experiential knowledge, paired with scientific and technological advancements, enabled the fishing industry to become increasingly exploitative to meet the rising demand.

By the 1970s and 1980s, evidence had mounted that overfishing was pushing wild fish stocks toward collapse. By the 1990s, most marine wild fisheries were either fully exploited or overexploited (FAO, 1995, 2022; Ottolenghi et al., 2004). Around this time, it became widely recognized that natural resources, while ample in their reserves, are not infinite and cannot withstand constant extraction, if future generations are to benefit from them.

This growing awareness led to global efforts in the mid- to late-20th century to protect natural marine resources and promote sustainability. Milestones in this effort include establishment of the League of Nations in 1920, and the United Nations in 1945, along with international agreements including the Rio Earth Summit and the Brundtland Report in 1987, all of which emphasized securing global peace, human well-being, and environmental stewardship (Yurtsever, 2019). These initiatives prompted a shift in global marine fisheries policy toward sustainability to ensure continued nutritional, economic, and social contribution (FAO, 1995, p. 6).

Resultingly, aquaculture emerged as a mechanism for improving global food security and reducing pressure on wild stocks (Guillen et al., 2024; Ottolenghi et al., 2004). International organizations – such as the Food and Agriculture Organization (FAO), and species-specific ones like the International Conservation Convention for Atlantic Tuna (ICCAT), were established to manage and promote sustainable fisheries and aquaculture. The FAO was established in 1945 as a specialized UN agency dedicated for international efforts against global hunger and to safeguard nutritional and agricultural resources (Phillips, 1981). In 1995, the FAO published the Code of Conduct for Responsible Fisheries, that was later accompanied (in 1997) with annotations, outlining best practices for aquaculture – such as feed management and site selection – as tools to enhance sustainability and food security (FAO, 1995). Similarly, ICCAT was established in 1966 to preserve tuna and tuna-like species in the Atlantic Ocean, in response to declining wild stocks and associated ecological, economic, and social risks (Collette & Nauen, 1983; Ottolenghi, 2008). As part of its remit, the ICCAT is responsible for setting total allowable catches (TACs) and farm capacity limits (in tons). Farm capacity is generally managed through biomass input (tons) limits and registered cages.

The FAO defines aquaculture as the "farming of aquatic organisms…/ [involving] some sort of intervention in the rearing process to enhance production, such as regular stocking, feeding, protection from predators, etc." (FAO, 1997, p. 6). A general consensus exists that, for an operation to qualify as aquaculture, it must involve intervention in an organism's life cycle and control of relevant environmental variables (FAO, 1997; Ottolenghi et al., 2004). However, consensus deviates on how aquaculture operations are categorized and referred to.

1.1.2 Aquaculture Operations: Closed-Cycle & Capture Based

Aquaculture can be broadly categorized into two practices: closed-cycle aquaculture (CCA) and capture-based aquaculture (CBA) (FAO, 1997). These categories are often defined in contrast to each other and referred to using different terms. CCA operations are often referred to as hatchery-based or full-cycle (Dempster et al., 2010; Liu & Sadovy de Mitcheson, 2008; Ottolenghi et al., 2004), while CBA is referred to as penning, caging, farming, or ranching (Mangion et al., 2014; Miyake et al., 2003; Ottolenghi et al., 2004; Stirling Aquaculture, 2012)). The ambiguity of terms has led to confusion in the literature, with overlapping definitions and emergence of 'semi-aquaculture' operations (Ottolenghi et al., 2004, p. 4). Ottolenghi et al. (2004) explain that CCA involves managing seed material throughout the organism's full life cycle.

Contrastingly, CBA operations source the "seed material - from early life stages to adults - from the wild, and its subsequent on-growing is made in captivity to marketable size using aquaculture techniques" (Ottolenghi et al., 2004, p. 4).

1.1.2.1 CBA Operations: ranching versus farming

CBA operations rely on capturing wild seed stock from one site and rearing the fish at another site. Within this model, two main practices exist: ranching (or fattening) and farming; these two are differentiated by the size and age of the seed, species, and duration of rearing (Ottolenghi et al., 2004).

Ranching operations use larger juvenile or sub-adult seed (generally under 30 kgs body mass) and rear them over shorter periods (2-7 months) to increase fat content and maximize market value (ICCAT, 2008). This is typically achieved by feeding high-fat diets and restricting swimming space to reduce muscle growth and increase fat accumulation. Some literature refer to fattening synonymously with ranching operations (Jelić Mrčelić et al., 2023; Mylonas et al., 2010). For the present study, and with particular relevance to ABT operations, ranching and farming are synonymous and assume the standards and goals set out by ICCAT for fattening operations.

On the other hand, farming operations involve the capture and rearing of juvenile seed (i.e., 8-30 kg total body mass) over longer periods (at least one year) to increase overall specimen biomass (ICCAT, 2008). Both practices utilize structured pens or cages to rear and grow the species, hence the operational nomenclature of penning and caging. However, they differ in the timing and scale of rearing.

1.1.3 CBA Operations in the Mediterranean

The top global producers of marine aquaculture: Egypt, France, Spain, Italy, Turkey, and Greece, are all Mediterranean countries (Barazi-Yeroulanos, 2010). This dominance results from proximity to key markets, stable sea conditions, and favorable physiochemical properties (Barazi-Yeroulanos, 2010; Tičina et al., 2020) for aquaculture. Both CCA and CBA operations take place in the Mediterranean, with the latter dominating the industry (Carvalho & Guillen, 2021).

CBA rose in popularity in the Mediterranean in the late 1990s, particularly with *Thunnus thynnus* (Atlantic Bluefin Tuna (ABT)) ranching in Spain, Croatia, Italy, and Malta (Guillen et al., 2024; Jelić Mrčelić et al., 2023; Mangion et al., 2014; Miyake et al., 2003; Mylonas et al., 2010). Modern CBA grew in popularity in response to the growing seafood demand, overfishing of wild stocks, and coastal nations' desire for economic diversification (FAO, 1997; Miyake et al., 2003; Ottolenghi et al., 2004; Rogers, 2024; Stirling Aquaculture, 2012).

The Mediterranean is positioned as a global leader in tuna ranching due to its critical location role in the European Union's (EU) ABT industry. EU produces over 80% of global ABT farming, both in weight and value, of which roughly 90% comes from the Mediterranean (Guillen et al., 2024). Moreover, ABT are highly active and migratory species – they have to keep swimming to breathe and travel distances of more than 6,000 miles – that spawn in two areas (Ottolenghi et al., 2004; Sean, 2019). The eastern stock spawns primarily in the Mediterranean Sea (May-July), while the western stock spawns in the Gulf of Mexico (Ottolenghi et al., 2004; Sean, 2019). However, recent research has identified additional spawning in the Slope Sea off the northeastern United States (Hernández et al., 2022; Richardson et al., 2016). Environmental habitat modeling suggests the Canary Islands may serve as a potential spawning area (Druon et al., 2016), though this remains unconfirmed by larval surveys. Substantial mixing occurs between the two stocks, particularly in feeding grounds, and is now explicitly incorporated into ICCAT management procedures (Fisheries, 2022; ICCAT, 2006). (ICCAT Rec. 22-09, 2022).

Globally, *T. thynnus* maintains a high commercial interest and value due to the influence of the Japanese sushi and sashimi market (Miyake et al., 2003; Ottolenghi, 2008). *T. thynnus* is particularly suited for CBA in regard to the commercial market, as the fattening enhances meat quality and taste, making it more desirable in markets such as seafood or sushi markers (Jelić Mrčelić et al., 2023). Guillen et al. (2024) found that more than 50% of ABT aquaculture is exported, with over 80% of these exports destined for Japan's sushi and sashimi market. The influence Japan maintains on the ABT market has created a feedback loop wherein ranching operations are most desirable as they produce the most profitable tuna (Guillen et al., 2024; Miyake et al., 2003). Malta accounts for about 42% of all EU ABT aquaculture production by weight and 44% by value as of 2021 (Guillen et al., 2024), and 57% as of 2023 (Eurostat, 2025). ABT ranching in Malta has taken off, emerging as a top producer over the years.

1.2 Aquaculture in Malta: Atlantic Bluefin Tuna (*Thunnus thynnus)* Ranching

1.2.1 Malta's Aquaculture Development & Regulatory History

Within the Mediterranean, Malta is well-positioned for ABT ranching due to its central location along the ABT migratory and spawning routes, and because of its deep, clear waters that provide optimal conditions for aquaculture (Miyake et al., 2003). Additionally, proximity to ABT's migratory route enables shorter transport times for captured ABT to the ranching sites, reducing stress on the fish, minimizing economic costs.

Aquaculture was first introduced to Malta in the mid to late 1980s, and took off on an industrial scale in the 1990s, specifically with seabass (*Dicentrarchus labrax*) and sea bream (*Sparus aurata*) farming, and later (in 1999) ABT (*T. thynnus*) ranching (FAO, 2025; Holmer et al., 2008; Stirling Aquaculture, 2012). Some of the major adverse environmental impacts of seabass and sea bream farming are: overlap of aquaculture sites and *Posidonia oceanica* beds (an endemic and highly important seagrass habitat found in the Mediterranean, including Malta's coastal waters); and pollution of commercial areas from fish farm effluent (Holmer et al., 2008; Ministry of Sustainable Development Environment and Climate Change, 2014). With the rise of aquaculture in Malta, the Malta Environmental Planning Authority (MEPA)[1] required all ABT ranching sites to be located at least 1 km from the shore and in suitable waters having strong currents, and distanced from important ecological benthic habitats such as seagrass meadows (FAO, 2025; Holmer et al., 2008; Mangion et al., 2014, 2017; Stirling Aquaculture, 2012).

In 2006, Malta's Fisheries Conservation and Control Division of the Ministry for Rural Affairs and the Environment (now the Department of Fisheries and Aquaculture (DFA)), which is responsible for aquaculture licensing and operational oversight, petitioned the MEPA to create a designated aquaculture zone to reduce operational impacts on the coast and adjacent waters (Holmer et al., 2008; Ministry of Sustainable Development Environment and Climate Change, 2014; Stirling Aquaculture, 2012). The plan was for this to span 9 km^2 and be located 6 km from the eastern coastline in waters that range 65-105 m in depth (Holmer et al., 2008; Stirling Aquaculture, 2012). MEPA approved the establishment of the South Aquaculture Zone (SAZ) based on

[1] Now Environmental Resources Authority (ERA)

environmental criteria including water depth, current patterns, and distance from sensitive benthic habitats. Later, a temporary North Aquaculture Site (NAS) was formed (Figure1).

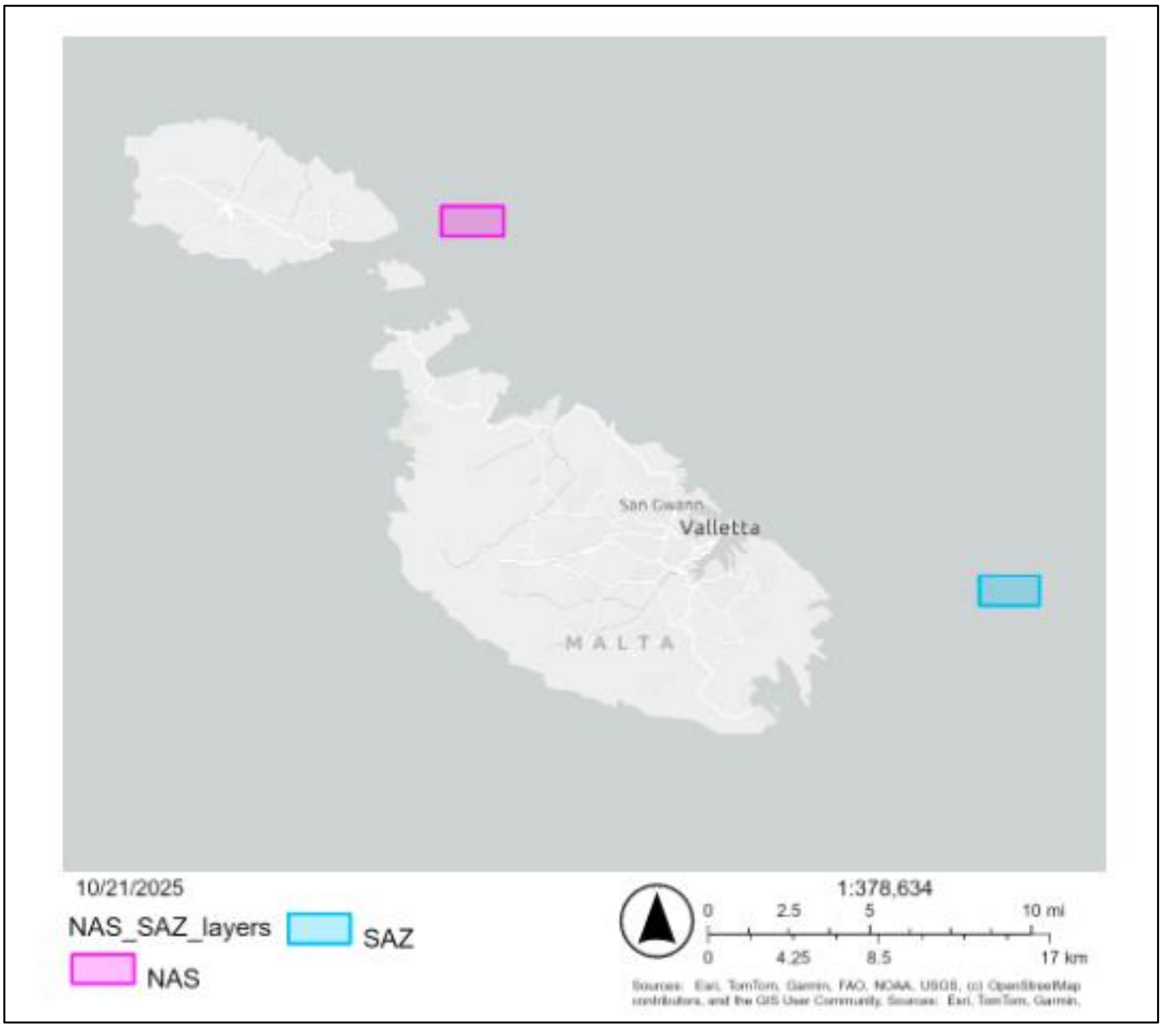

Figure 1 Location of Malta's North Aquaculture Site (NAS) with coordinates from the Department of Fisheries and Aquaculture (2024). Map created in ArcGIS using OpenStreetMap base layers.

In 2016, the MEPA was dissolved, and its environmental protection functions transferred to the newly established Environment and Resources Authority (ERA), which now oversees environmental monitoring and compliance for aquaculture operations, while the DFA continues to manage operational licensing and fisheries aspects (DFA, 2023; ERA, 2023). The ERA continues to enforce MEPA's 2006 framework with a five-area monitoring protocol covering benthic substrata, macrobenthic communities, water quality, and ecology (Holmer et al., 2008). Under ERA's guidelines, ABT farms are required to conduct regular environmental monitoring and submit reports documenting operational activities, stocking densities, feeding rates, mortality events, and any unusual environmental observations (Holmer et al., 2008). Additionally, the ERA, as Malta's designated Natura 2000 authority, oversees the integration of aquaculture operations with marine protected area management (ERA, 2023). This institutional structure creates a dual regulatory system, wherein the DFA manages fisheries and aquaculture operations while the ERA ensures environmental compliance and conservation objectives are met.

1.2.1 Malta’s Aquaculture Zones and MPAs

Malta has established an extensive Marine Protected Area (MPA) network through its commitment to the Natura 2000 framework. According to the ERA, Malta has dedicated 18 sites, over 4,138 km^2, to conserve important marine habitats and species. Special Areas of Conservation (SACs) and Special Protection Areas (SPAs) serve as Malta’s contribution to the European Natura 200 network (ERA, 2023). Figure 2 shows Malta’s SACs and SPAs, which cover about 35% of Fisheries Management Zone (which extends 25 nautical miles from Malta’s shores) (ERA, 2023). More specifically, the NAS is located within Malta’s SPA MT0000112 and SCA MT0000105, while the SAZ is located within SPA MT0000108 (Figure 3).

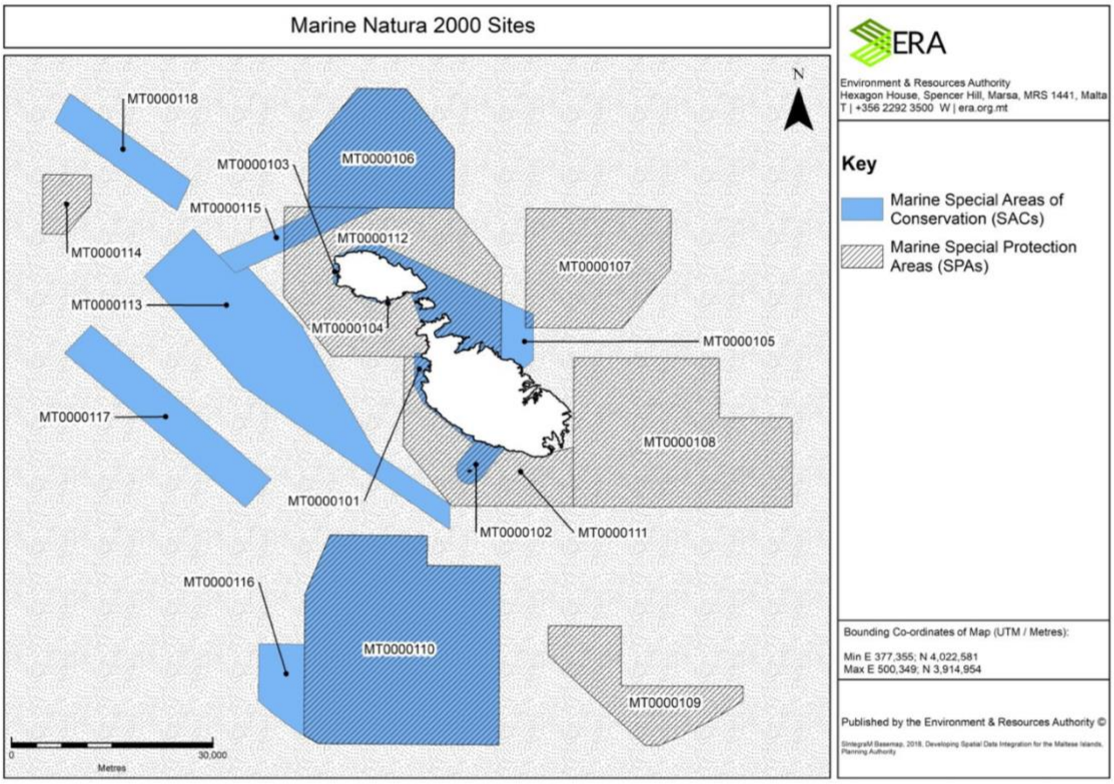

Figure 2 ***Marine Natura 2000 Sites*****. Photo source: Environment & Resources Authority (ERA), Malta.**

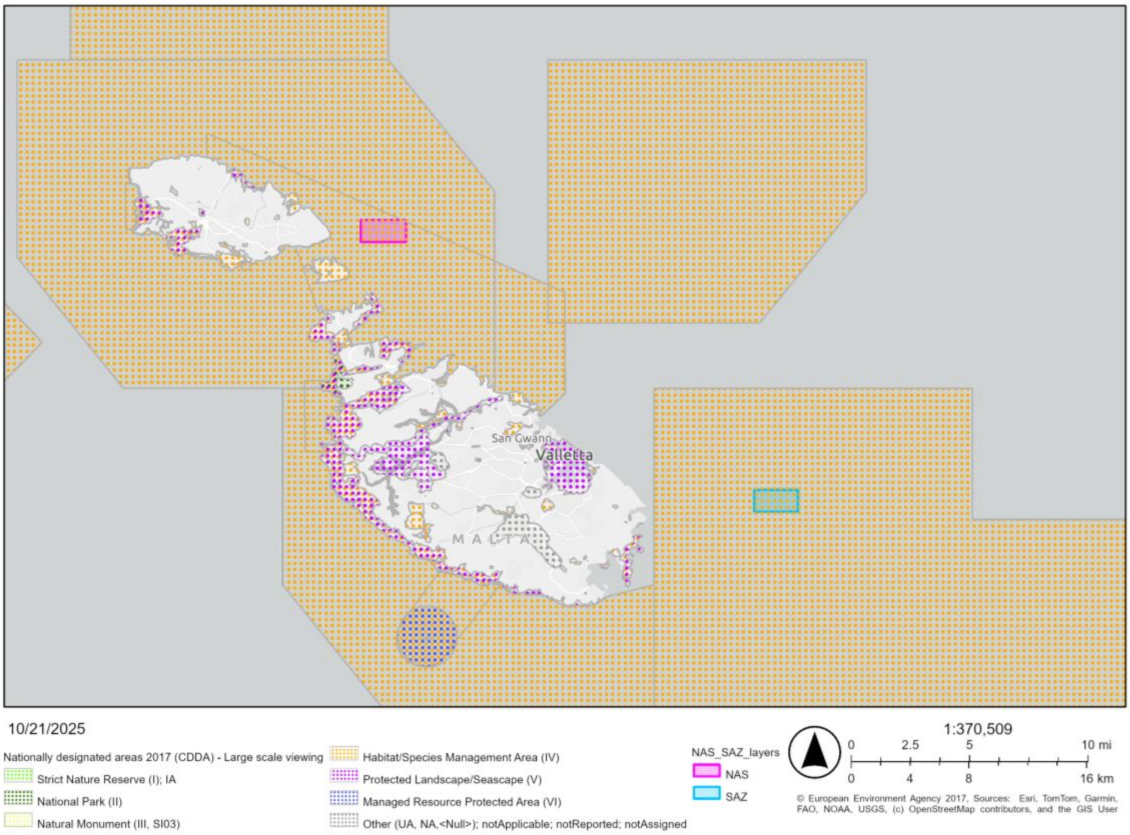

Figure 3 Overlap between Malta's Aquaculture Zones (NAS in pink and SAZ in blue) and Marine Protected Areas (dashed orange). Map created using data from the European Environment Agency (2023), CDDA Version 16 – Dynamic Web Map Service, ArcGIS REST Service, https://bio.discomap.eea.europa.eu/arcgis/rest/services/ProtectedSites/CDDAv16_Dyna_WM/MapServer**.**

Malta's Natura Sites were established with the goal of protecting coastal and offshore sites, and important marine habitats listed under the EU Habitats Directive (92/43/EEC), such as reefs and *P. oceanica* meadows, and to provide protection for seabirds under the Birds Directive (2009/147/EC) (ERA, 2023). The network protects both coastal and offshore sites, protecting important habitats such as *P. oceanica* meadows, reefs, sea caves, and open water areas that are important for marine megafauna (ERA, 2023).

1.2.2 Maltese ABT Ranching

Malta's aquaculture industry comprises both ABT ranching and closed-cycle farming of specific species like seabass and seabream (Holmer et al., 2008; Stirling Aquaculture, 2012). Two closed-cycle offshore farms – P2M and MFF Ltd. are registered with the local DFA (DFA, 2023). Conversely, six companies currently make up Malta's ABT ranching sector: AJD Tuna Ltd. (AJDTL), Malta Mariculture Ltd. (MML), Fish and Fish Ltd. (FFL), Mare Blu Tuna Farm Ltd. (MBTFL), Malta Fish Farming Ltd. (MFFL) and Ta' Mattew Fisheries Ltd. (DFA, 2023; Paolacci et al., 2024). Ta' Mattew Fisheries was not in operation in 2025 and was therefore not included in the present study. AJDTL & MML operate under joint ownership of Azzopardi Fisheries and are located adjacent to one another (Figure 4). They are considered as one farm in this study given that they operate in tandem, with shared resources, staff, and managers. AJDTL & MML are located within the NAS while FFL, MBTFL, and MFFL are sited within the SAZ. Cages belonging to AJDTL and MML are managed as one site (i.e., sharing resources and staff), whereas the three farms located within the SAZ are spaced over a considerably large area and operate independently (Figure 4 & 5).

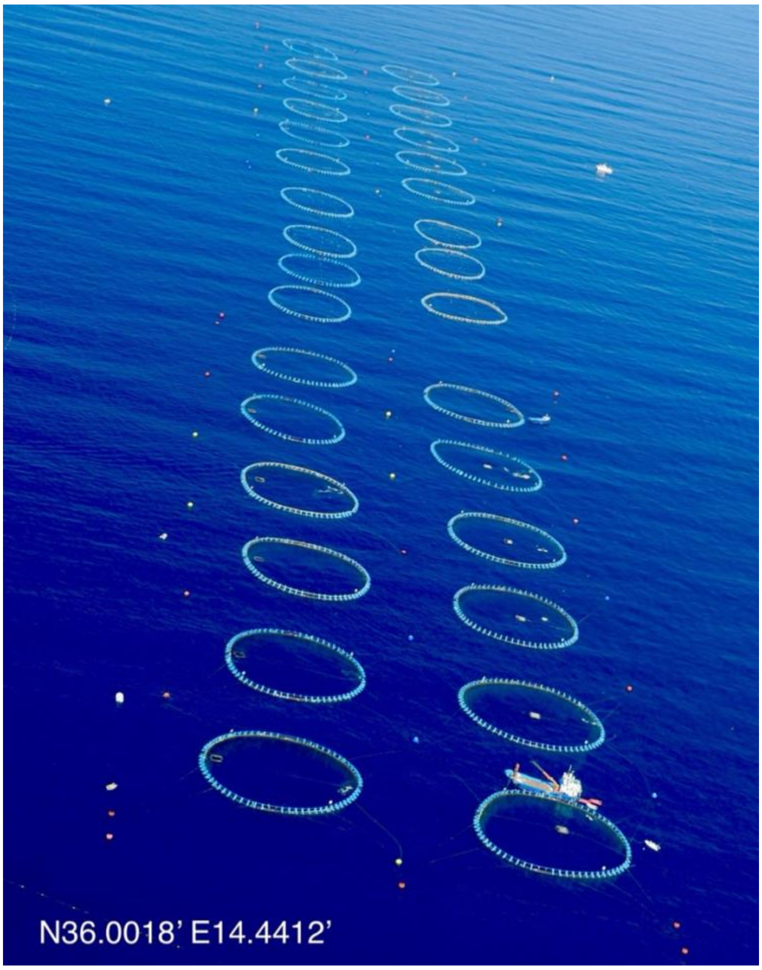

Figure 4 Aerial photo of ABT ranching pens operated by AJDT (left) and MML (right). Source: Airphoto Malta.

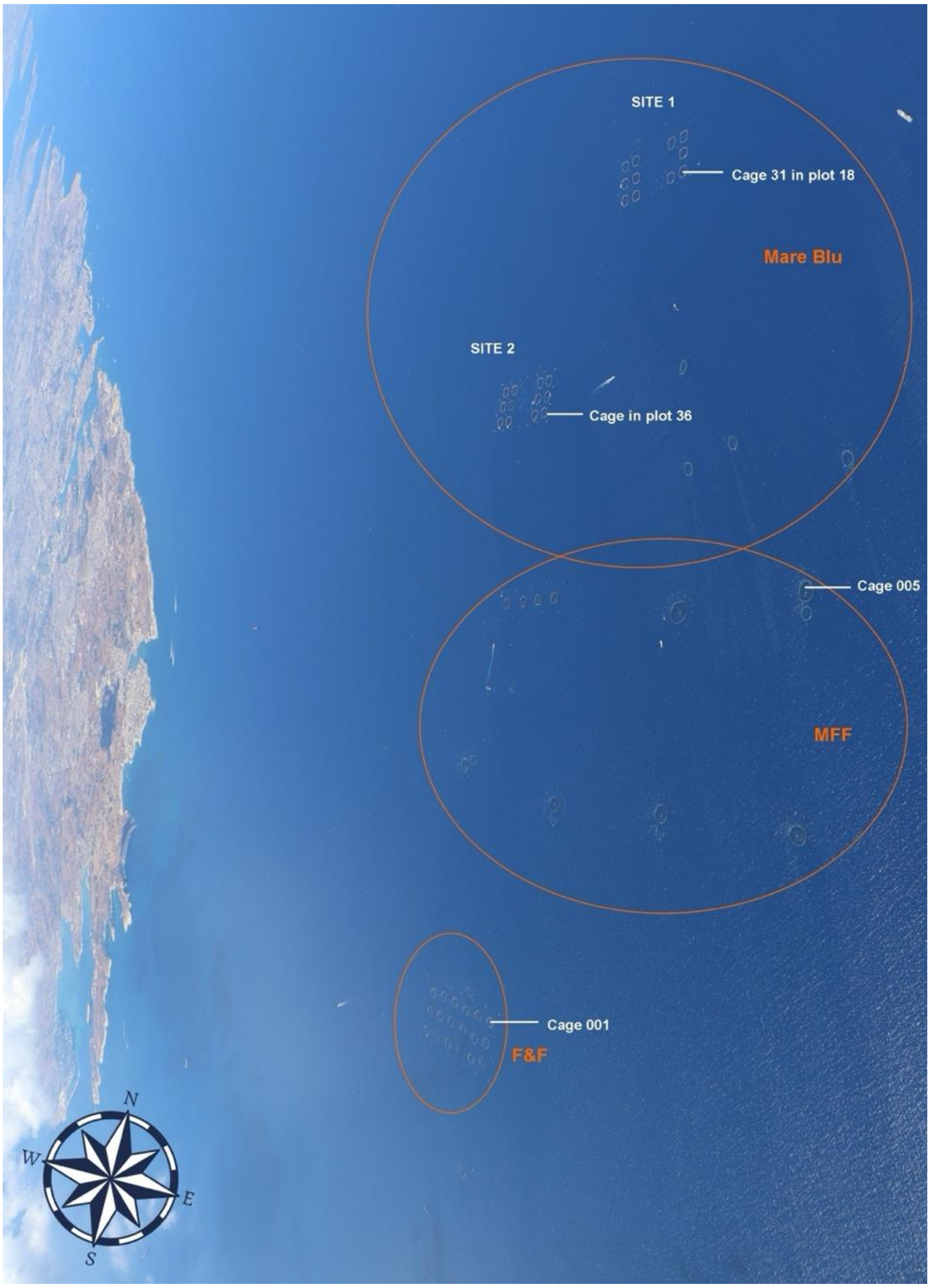

Figure 5 Aerial photo of ABT farms in the SAZ (MBTFL, MFFL, and FFL). Source: Airphoto Malta.

Maltese ABT ranches use pens that are about 50 m in diameter, with some farms employing an assortment of sizes (see Table 1). These pens (as shown in Figure 6) extend down around 25-35 m in the water column and are anchored to the seabed at various depths ranging from 50 m to 100 m (see Table 1). ICCAT determines the total farm capacity for ABT ranching operations in the Mediterranean. Maltese ABT farms operated at a maximum of 3,300 tons per farm in 2017 (Farrugia, 2018). As of March 2024, ICCAT reported farm capacity in tons, ranging from 2,200 – 4,200 tons (included in table 1) (ICCAT, 2024). Individual cage capacity is determined by the farm's total allowable capacity divided amongst the registered ABT pens in operation (ICCAT, 2024). Generally speaking, cage capacity is around 140 tons, but it can be more as farm capacity gets larger.

Figure 6 ABT cages at the AJDTL & MML site. Photo by Devin Seckar.

Local ABT farms generally use high-quality baitfish feed (mostly wild-caught mackerel or sardines, which are imported frozen) that is manually delivered by the staff after the feed has been thawed. The specific species used as baitfish is largely determined by availability, with one farm noting that one-year old herring was used (Tuna Ranching Manager, personal communication, July 25, 2025). Table 1 shows specific operational information for the ABT ranching companies that participated in this study.

Farm Name	Geographic Location	Number of cages	Cage size (diameter) (meters)	Cage Depth (meters)	Cage capacity (tons)	Total farm biomass (tons)	Farm distance from coast	Water depth at farm location (meters)
AJD Tuna Ltd. (AJDTL) & Malta Mariculture Ltd (MML)	NAS	24 total (12 for AJD and 12 for MML)	50	25	~ 140	2,500	~ 6 km	~ 50
Fish and Fish Ltd. (FFL)	SAZ	22	50	35	~ 140	3,000	~ 7-8 km	~ 60 - 90
Mar Blue Tuna Farm Ltd. (MBTFL)	SAZ	20 cages, with 19 in use and 1 reserved in case of emergency or damage.	50	30	~ 140	4,200	~ 6.4 km	~ 70 - 100
MFF Ltd. (MFFL)	SAZ	20	12 cages at 50 5 cages at 70 3 cages at 90	30	~ 140	4,000	~5 km	~ 65 - 80

Table 1 Maltese tuna ranch information. Operational details of the farms that participated in the study, including geographic location, number of cages, size of cages, cage capacity, total farm capacity, distance from shore, and water depth.

ABT ranching in Malta is seasonal; the activity is held between June and December of each year. **Adult wild ABT, typically having a body weight of around 100 kg, are captured by purse seiner boats in the southern Mediterranean Sea during their spawning migration in May and June (DFA, 2023; Stirling Aquaculture, 2012).** The ABT are transferred to tow cages and transported to the ranching sites, where they are fattened on a baitfish diet for about six months, or until their bodyweight increases by about 30% (DFA, 2023). Most of the Maltese ABT farms employ manual feeding in order to reduce uneaten baitfish accumulating on the seabed, to reduce economic loss and prevent ecological degradation, and hence comply with local regulations. Each farm has a mechanism that is controlled by the divers to shut off the ‘feeding cage’ at a certain point with the aim of customizing feed delivery to reduce waste. When the ABT arrive in Malta after transport, they are in a ‘feeding frenzy;’ hungry from the long distance travelled to the ranching site (Tuna Ranching Divers, personal communication, 2025). One farm noted they feed the newly settled ABT around 5-6% of their bodyweight in kg (generally about 200 tons per day) for the first two weeks, after which they reduce it to around 150 tons a day, to manage the frenzy and maintain good health (Tuna Ranching Divers, personal communication, 2025).

Generally, fattening is achieved by mid-late autumn, with some ranching operations extending into early winter to avoid market oversaturation (Mylonas et al., 2010). Ranching operations pause during the rest of the year, between January and May. During this fallow period, the marine ecosystem to allowed to recover from operational stressors (i.e., excess nutrients from uneaten baitfish and waste and physical disturbances, amongst others). The fallow period is particularly critical for maintaining ecosystem health.

1.3 Environmental impact

A review of capture-based ABT ranching (see the following sections) reveals impacts associated with operations that affect the marine environment in the vicinity. Most notable are the adverse effects of ranching, such as wild stock depletion, waste discharge and, and attraction of wild fauna to these sites.

1.3.1 Reliance on wild Stock

Capture-based ABT ranching relies on wild stock for both seed and feed, raising sustainability concerns. The reliance is problematic and antithetical to the driving force of aquaculture practices to reduce commercial pressure on wild fish stocks. After ABT aquaculture gained traction in the 1990s, concerns emerged regarding overexploitation. In 2009, *T. thynnus* was listed as Endangered (A2bd) on the IUCN Red List. In response, the ICCAT implemented a recovery plan and stricter allowable catch quotas. In 2021, ABT was reclassified as ‘Least Concern’ as a result of conservation efforts (Collette et al., 2023; IUCN Red List, n.d.). However, ranching operations relies on more than just ABT stocks; it also relies heavily on smaller trophic species used for feed. While there are benefits to using baitfish, which will be discussed in a later section (1.3.3 Aggregation of Wild Fauna), the driving concern regarding their use as feed is the reliance on wild stocks and the unsustainability of this practice.

Ottolenghi et al. (2004) and others emphasize that baitfish availability fluctuates with seasonal and stock dynamics, making it an unstable and unsustainable resource. It has been argued that the baitfish can even be used to promote food security in that they are appropriate for human consumption (Ottolenghi et al., 2004). Therefore, many criticize the ABT ranching industry for using baitfish and advocate the use of formulated feed (i.e., pellets) to achieve long-term sustainability (Guillen et al., 2024; Jelić Mrčelić et al., 2023). Guillen et al. (2024) examine this and highlight that other aquaculture sectors - such as seabass, seabream, and salmon culture - have transitioned to closed-cycle systems and more sustainable feed sources like pellets. Accordingly, they advocate for similar practices in ABT ranching. However, the main obstacle to adopting a closed-cycle system for ABT is the huge and yet unresolved difficulty to produce an artificial (non-fresh, i.e. baitfish) formulation that is accepted by the ABT. The dual reliance on wild stock for seed and feed must be considered when reviewing the environmental impact and ability for aquaculture to promote food security.

Formulated feed is more readily available for consumption by aggregated wild fauna, as shown at seabass and seabream farm sites (Mangion et al., 2014), as well as attracting a more diverse array of wild fauna (Bacher et al., 2012; Šegvić Bubić et al., 2011). In 2019, Skretting developed a pellet digestible by ABT that reduced the feed conversion ratio (FCR), improving efficiency (Acevedo et al., 2024; Skretting, 2019). In 2023, Skretting partnered with Next Tuna, a closed-cycle aquaculture company, to produce this feed (Buentello et al., 2022; Skretting, 2023). Case studies such as this indicate the potential for ABT ranching operations to transition to closed-cycle systems, and in so doing become more sustainable. However, ABT ranching operations have not yet successfully transitioned to pellet feed due to market and species preferences.

Historically, the consumers, and therefore the market, have preferred ABT grown on natural diets due to taste (Uchida et al., 2014). While consumer attitudes are evolving in favor of sustainable practices, wild-caught ABT is still preferred for the raw fish market (FAO, 2022; Guillen et al., 2024; Naylor et al., 2009). ABT also shows a taste preference for baitfish over pellets (Jelić Mrčelić et al., 2023; Mourente & Tocher, 2009). More specifically, wild-caught ABT, are seemingly uninterested in synthetic or pellet feed. One Maltese ABT farm manager noted that the efforts to transition wild-caught ABT to pellet feed is challenging as the species acts neophobic to this transition in adulthood, having grown in the wild on a wild and fresh diet (Tuna Ranching Manager, personal communication, July 25, 2025).

1.3.2 Uneaten Baitfish

T. thynnus are active, high energy, species requiring large quantities of feed. Their constant movement and relatively high body temperatures result in "only 5% of the total energy intake …/ used for growth" (Jelić Mrčelić et al., 2023, p. 8). This is why ranching operations emphasize two practices – penning/caging to reduce energy expenditure and maximizing feeding volume (fattening). Feeding the ABT high-quality baitfish while reducing their swimming area allows for prime market species conditions to be reached.

The intense feeding operations that are required have an impact on the surrounding marine environment. It has been well documented that overfeeding fish can result in the buildup of uneaten baitfish underneath the aquaculture cages (Guillen et al., 2024; Holmer et al., 2008; Vita & Marin, 2007). The uneaten baitfish used for farm feed floats down to the bottom underneath the cages. Ottolenghi et al. (2004) speculate that the daily feeding volume is generally 2–10 % of the total estimated species biomass. In Malta, at local ABT farm sites, this ranges from 800 to 3,000 tons of biomass (DFA, 2023), meaning that, in total, daily feeding at one site can reach up to 300 tons of baitfish. While this uneaten baitfish acts as the main factor for wild fauna attraction and aggregation, it also poses a risk to the environment. More specifically, too much of it can create conditions that change the assemblage or structure of the ecosystem's benthic and trophic systems (Agius et al., 2024b; Mangion et al., 2014; Tičina et al., 2020), as well as leading to deterioration of water quality, sometimes to the extreme that anoxic conditions of the seabed at low-energy sites can become a huge concern (Callier et al., 2018; Guillen et al., 2024; Russo, 2011).

Nutrient overload is widely cited as the primary environmental concern in ABT aquaculture (Callier et al., 2018; Guillen et al., 2024; Tičina et al., 2020). Uneaten baitfish and fish waste is inevitable. Organic loading resulting from excess feed and fish waste that increase sedimentation, and enhancing the presence of organic compounds (like nitrogen and phosphorous), eventually leading to increased microbial activity and, in extreme cases, hypoxic or anoxic conditions (Tičina et al., 2020). Maltese ABT farms are generally located at depths of between 50 m and 100 m, which helps mitigate adverse benthic impacts and protects sensitive species and habitats. In shallower areas, these effects are more pronounced.

Callier et al. (2018) report that such nutrient overload can "modify benthic conditions (i.e. infaunal communities, macro-epifaunal communities, sediment biogeochemistry)" (p. 931). The combination of excess feed alters environmental conditions such that only specialized opportunistic species are able to tolerate them, which may lead to reduced benthic macrofaunal diversity (Mangion et al., 2014). Moreover, the presence of excess feed attracts smaller trophic pelagic fish, thereby altering faunal assemblages in the vicinity of the cages (Callier et al., 2018). Thus, feeding must be carefully managed to balance productivity with ecological health.

1.3.3 Attraction and Aggregation of wild fauna

Studies have indicated that the offshore farm components deployed for CBA operations (i.e., aquaculture pens or cages in marine ecosystems) act as fish aggregation devices (FADs). Wild fauna are attracted to the area around and below the artificial structures, mostly as a result of uneaten baitfish that pass through the cage nets and which are a readily available source of food, and to habitat provision (Agius et al., 2024b, 2024a; Arechavala-Lopez et al., 2015; Callier et al., 2018; Dempster et al., 2002, 2006, 2010; FAO, 1997; Machias et al., 2005; Sanchez-Jerez et al., 2011; Stagličić et al., 2017). The floating structures offer shelter and supply abundant food by way of uneaten baitfish floating down for pelagic and demersal species, but may also attract wild ABT species (Arechavala-Lopez et al., 2015; Callier et al., 2018; Dempster et al., 2010; Sanchez-Jerez et al., 2011).

Research shows strong evidence that several wild fauna (including wild ABT species (Arechavala-Lopez et al., 2015), Bottlenose Dolphins (*Tursiops truncatus*) (Tičina et al., 2020), bottom-dwelling fish such as batoid species (Agius et al., 2024a), megabenthos (Agius et al., 2024b), sea birds (B. S. Cheng et al., 2016; C. Cheng et al., 2022), and marine mammals (Würsig & Gailey, 2002)) gather around FADs, resulting in a range of positive and negative effects with implications for both the wild fauna and the farm sites (Callier et al., 2018; Kemper & Gibbs, 2001; Würsig & Gailey, 2002).

Aquaculture sites offer structural complexity in the pelagic zone – a rare phenomenon in water exceeding a few meters. The equipment and physical structure of the cages (i.e., pens/cages, tanks ropes, netting, etc.) provide a surface area for other organisms to colonize. Often, primary producers (e.g., algae, bivalve molluscs) will attach and grow on the FADs (National Academies of Sciences, Engineering, and Medicine, 1988; Office of Protected Resources, 2017). Attraction of lower trophic species, whether biofouling communities or small pelagic fish that aggregate to feed on the former, creates a trophic web associated with the FAD.

The consistent food source and habitat provisioning for lower trophic species allows for larger macroinvertebrates (predators) to be attracted to the fish farm sites (FAO, 1997; Sanchez-Jerez et al., 2011; Stagličić et al., 2017). For example, primary producers, like algae or even small trophic species like *Spicara spp.,* aggregate for the uneaten baitfish. Therefore, larger carnivorous species are drawn to the abundant prey (Bonizzoni et al., 2014; Dempster et al., 2010; Sanchez-Jerez et al., 2011). While attraction and or aggregation boosts biodiversity, it also facilitates predator-prey relations and exposes the cultured species to vulnerabilities (such as disease, fishing-related mortality, etc.). Given the biodiversity-supporting role of these sites, placing aquaculture operations within Marine Protected Areas (MPAs) has been proposed to enhance ecological benefits and protect aggregated species (Dempster et al., 2002, 2006; Ottolenghi, 2008).

An important, and often overlooked, benefit of aggregation of wild fauna is the reduction of accumulated feed and farm waste on the seafloor. Particulate matter has been shown to decrease in the presence of wild fauna aggregation, with research confirming up to 25% removal of fish farm waste (Tičina et al., 2020, p. 4). Mangion et al. (2014) state that some 80% of particulate organic waste released from sea bass and sea bream farms in the Mediterranean is consumed by aggregated wild fauna before it settles on the seabed. Not only does this benefit the ecosystem in reducing adverse water quality, but it is also beneficial for the wild fauna. Wild fauna found aggregating around tuna farms have shown improved health conditions (i.e., “body condition,” liver condition, hepatosomatic index (HI)), which supports reproductive success and population growth (Bacher et al., 2012; Callier et al., 2018; Dempster et al., 2006; Stagličić et al., 2017, p. 90).

Dempster et al. (2006) present evidence that "coastal aquaculture and conservation can work together," demonstrating that under no-fishing conditions, fish farms can act as population sources for aggregated wild fish. Research shows that farm-associated fish exhibit enhanced fitness indicators (body condition, growth rates, spawning success) compared to non-associated species, suggesting that fish farm environments can support productive populations rather than serving as ecological traps (Bacher et al., 2012; Dempster et al., 2006; Stagličić et al., 2017).

However, Arechavala-Lopez et al. (2015) point out the danger of creating an ecological trap, wherein wild fauna become dependent on the attractive conditions (e.g., food and habitat provision) and hence become vulnerable to threats like harvesting by fishermen and disease. Moreover, some evidence suggests that FADs may alter the migration paths of some pelagic fauna, as is the case for wild ABT that aggregate in the Mediterranean as a result of such favorable conditions (Arechavala-Lopez et al., 2015; Bacher et al., 2012; Ballester-Moltó et al., 2015a; Russo, 2011).

Foundation research on the topic of wild fauna aggregation around ABT farm FADs has been conducted. Dempster et al. (2010), Sanchez-Jerez et al. (2011), and Arechavala-Lopes et al. (2015), provide key insights on the role of coastal and offshore fish farms acting as FADs. Together, these authors establish a range of observed interactions between ABT farms and local wild fauna in the Mediterranean at large. However, there is a lack of research on these interactions at ABT farming sites in Malta.

1.3.4 Interactions

An unavoidable outcome of wild fauna aggregation around ABT farms (and aquaculture sites at large) is increased interaction between wild species and the farm infrastructure. The most commonly cited interactions include feeding, predation, habitat use, physical entanglement, overlap with fisheries, and pathogen transfer. Understanding these processes is essential for anticipating and reducing the potential negative consequences of such interactions—for the wild fauna themselves (e.g., ecological traps and entanglement), for the farmed stock (e.g., stress, injury, pathogen transmission), and for the surrounding environment (e.g., trophic shifts and nutrient redistribution

Feeding on uneaten baitfish and waste feed is the most widespread and well-documented interaction between wild fauna and aquaculture sites (Dempster et al., 2002; Fernandez-Jover et al., 2011; Russo, 2011). This feeding behavior has dual effects. On one hand it benefits the ecosystem by reducing organic buildup and improving water quality, while also enhancing the condition of wild fish through access to high-quality feed (Fernandez-Jover et al., 2011; Mangion et al., 2014). On the other hand, the predictability of this resource can create ecological traps, as wild species become dependent on anthropogenic food inputs (Arechavala-Lopez et al., 2015; Callier et al., 2018; Fernandez-Jover et al., 2011; Russo, 2011). Reliance on farm-associated feeding opportunities can alter wild fauna behavior—modifying migration routes, habitat use, or even spawning site selection (Dempster et al., 2006; Fernandez-Jover et al., 2011). Russo

(2011) further noted that predator species such as amberjack (*Seriola dumerili*) and ABT (*T. thynnus*) expanded their hunting ranges up to 100 m around ABT cages, illustrating how the aggregative feeding dynamic reshapes local trophic interactions.

The formation of ecological traps is a particular concern for management. Continuous availability of feed and structural shelter may promote residency or behavioral dependency, while simultaneously exposing aggregated species to increased human pressures. In Malta, this risk is heightened because farm sites are situated adjacent to, or within, protected areas. Moreover, in Malta, there is a significant presence of amateur fishermen (AF), especially adjacent to the farm sites. Farm personnel noted that AF will linger as close to the farm borders as possible in the attempt to catch aggregated wild fauna (Figure 7) (Tuna Ranching Divers, personal communication, 2025; Tuna Ranching Manager, personal communication, 2025). Each farm has a buoy line that encircles their respective operations. Oftentimes, AF push these boundaries knowing that the sites act as FADs and therefore offer a rich fishing area.

Figure 7 Amateur fishermen along the border of MBTFL. Source: Mare Blu Tuna Farm (used with permission).

Another critical form of interaction is entanglement. As wild fauna are drawn to the cages for feeding or shelter, they may become caught in mooring lines, outer nets, or predator-exclusion meshes (Russo, 2011; FAO, 2009; Buscaino et al., 2010). Entanglement can lead to injuries or mortality of wild species (including turtles, dolphins, and rays) and often results in equipment damage that requires costly repair. Even after cage removal, abandoned net fragments can continue to trap marine fauna, functioning as 'ghost gear' (Russo, 2011).

Overall, these interactions illustrate that aggregation around ABT farms extends beyond simple attraction—it drives a web of ecological and operational consequences. Feeding and habitat provisioning can support nutrient recycling and biodiversity, yet they may also foster dependency, alter trophic pathways, and increase risks such as entanglement and ecological trapping. Although short-term studies have shown improved body condition and reproductive indices in farm-associated fish (Fernandez-Jover et al., 2011; Stagličić et al., 2017), the long-term fitness consequences—such as potential maladaptation or reduced competitive success—is not well understood. Continued research in Maltese ABT farms is needed to clarify the long-term ecological outcomes of these interactions and to inform mitigation strategies that balance production with conservation.

1.4 Objective of Study

This report aims to address existing knowledge gaps within Malta's ABT farming industry and provide valuable insights to help the ABT farm operators, environment and fisheries authorities, and other stakeholders; namely to better understand interactions of wild fauna with ABT farms, and implications thereof, thereby enabling better management in the ABT ranching sector.

2 Materials and Methods

This semi-qualitative study investigated the wild faunal species that are attracted to ABT farms in Malta, along with the types of interactions taking place, to better understand the impacts of ABT ranching on such fauna and hence contribute to better management of the potential impacts of fish farming on the environment. Interview questions were developed beforehand with the knowledge gained from a review of the literature and with the guidance of the project's main supervisor. The objective of the interviews was to gather first-hand information from ranching operators and staff, as well as stakeholders about any observed interactions with wild fauna, and on potential associated impacts. Participants for the study were primarily ABT farm divers, as they are the individuals in the water accumulating observations about wild fauna attracted to or aggregating around the farm sites. The method of data collection was guided by an in-person semi-structured interview, wherein the questions guided the conversation, allowing flexibility based on observations or expertise that encourage in-depth discussions.

Interviews were conducted from March to August in 2025 to gather first-hand observations of which wild fauna species were aggregating around farm sites and their behavior. Data collection occurred during the pre-season as well as into the beginning of the ranching season, which is usually from May to October. The main objective was to interview the divers of local ABT farms to record firsthand observations. In addition to this, two environmental monitors were interviewed, one representing marine ecology and the other ornithology. This study relied heavily on the willingness of the staff of the local ABT farms (Table 1) to participate and share knowledge.

Sample Site	**Interview Place**	**Recorded Responses**	**Interview Format**	***Notes***
AJDTL & MML	Office (after company meeting with environmental monitor (consultant))	3	Group*	*3 individuals, where one was translated for the another.
	Site visit to ABT farm in Malta	5	One-on-one	4 were on-site.
MFFL	Office (after company meeting with environmental monitor (consultant))	2	One-on-one	
FFL	Office	3	Group	
MBTFL	Office	4	One-on-one*	*3 individuals needed a translator (ABT ranch manager).
General Observations	Office	1	One-on-one	
	Zoom meeting	1	One-on-one	

Table 2 Breakdown of interviews conducted (n=19), including the number of responses for each farm, the place and format of the interviews, and any special notes.

Table 2 shows the details of the conducted interviews for this study. Interviews varied in place and format. The office visits with MBTFL and FFL were conducted at their respective locations in Malta, with MBTFL taking on two separate occasions. The group interviews, notwithstanding any need for a translator, occurred for the purposes of time efficiency for divers and their schedules as this was a volunteer effort. The group interviews were considered as individual responses, since the interview persons were all active and took turns answering the questions comprehensively. Overall, only four of the 19 responses were recorded in situ (i.e., at a ABT farm) due to unforeseen scheduling complications with the farms during peak season.

Responses were written down, and supplementary notes were taken to document contextual observations and non-verbal cues to enrich the data. The interview questions are included in Appendix A and are laid out in three segments. First, understanding site context, including water depth, geographic location of observations, type of feed use, and site capacity (see Table 1). Species-specific observations were collected during this segment. The second segment aimed to investigate the interactions taking place as a result of attraction to the ABT cages. The third and last segment focused on the impact of these interactions, trying to gauge whether there was ecological, industrial, or human vulnerability as a result.

The data is representative of cumulative observations from divers who have worked with the farm for several years, with their range of experience ranging some 7-24 years. So, the data represents observations over many years. Observations by the two environmental monitors were not site-specific, but rather 'general observations' of species recorded in association with ABT farms throughout Malta. Since their accumulation of general knowledge of interactions between ABT farms and wild fauna applies to all sites, it is used in the data analysis but omitted when assessing farm sites in comparison to one another, and the observations are referred to as 'general observations' in the data set.

Interviewees were asked for specific species observed aggregating near the farm sites. Responses varied in terms of species identification, ranging from some knowing Latin names to some describing the physical characteristics of the species. For those described and not known to be specific, collaboration with other interviewees and published literature on common fauna found in Maltese coastal water was used to determine specific species (e.g., mackerel and sardines).

The last phase of the project involved reviewing the questionnaire responses to identify connections between any reported interactions and their outcomes, thereby enhancing an understanding of the overall impacts. Species-specific data were summarized from the written responses and are presented in Table 3. The responses provided information on farm operations, feeding practices, and first-hand observations of wild fauna aggregation around ABT ranch cages at both the NAS and SAZ. Thematic analysis was used to identify trends within the responses that contextualized observed species and interactions.

3 Results

In total, 19 interviews were conducted from March to August in 2025, with personnel from three Maltese ABT ranching companies (including managers, site staff, and divers) as well as general environmental monitors (Table 2). Species-specific data from first-hand observations is presented first, followed by firsthand observations of interactions and behaviors of aggregated wild fauna.

3.1 Recorded Wild Fauna Species

Across all interviews, 41 species of wild fauna interacting with the ABT farms were recorded, with a total of 143 observations of individuals of wild faunal species documented. Table 3 displays the records of wild fauna species and the respective number of individuals for the given wild fauna species recorded, including common names, scientific name, and the respective ABT farm the observation came from.

Species (Latin name)	Species (common name)	AJDTL & MML	FFL	MBTFL	MFFL	General Observations	Total number of individuals
Octopus vulgaris	Octopus	1	0	0	0	0	1
Oegopsida spp.	Squid	1	0	0	0	0	1
Ophiocomina nigra	Black brittle star	1	0	0	0	0	1
Echinoidea spp.	Sea urchin	1	0	0	0	0	1
Prionace glauca	Blue shark	3	0	2	0	0	5
Isurus oxyrinchus	Mako shark (shortfin mako)	3	0	1	0	0	4
Aetomylaeus bovinus	Bull ray	1	0	0	1	1	3
Myliobatis aquila	Common eagle ray	0	0	0	0	1	1
Dasyatis pastinaca	Common stingray	0	0	0	1	1	2
Bathytoshia centroura	Roughtail stingray	0	0	0	0	1	1
Bathytoshia lata	Broad stingray	0	0	0	0	1	1
Batoidea spp.	Rays	7	3	2	1	0	13
Tetronarce nobiliana	Common (Atlantic) electric ray	1	0	0	0	0	1

Species (Latin name)	Species (common name)	AJDTL & MML	FFL	MBTFL	MFFL	General Observations	Total number of individuals
Torpedo marmorata	Marbled electric ray	0	0	0	0	1	1
Balistes capriscus	Grey triggerfish	1	3	0	1	0	5
Thunnus alalunga	Albacore tuna	0	0	0	0	1	1
Thunnus thynnus	Atlantic bluefin tuna	3	0	3	1	1	8
Euthynnus alletteratus	Little tunny	4	3	4	2	1	14
Katsuwonus pelamis	Skipjack tuna	1	0	0	0	0	1
Seriola dumerili	Greater Amberjack	1	3	0	1	0	5
Caranx crysos	Blue runner	1	0	0	0	0	1
Boops boops	Bogue	2	0	0	0	0	2
Zeus faber	John dory	1	0	0	0	0	1
Epinephelus marginatus	Groupers (Dusky grouper)	1	0	0	0	0	1
Gadus morhua	Salt fish (Atlantic Cod)	3	0	0	0	0	3
Sardinella aurita	Sardines (Round sardinella)	1	0	1	0	0	2
Trachurus trachurus	Atlantic horse mackerel	2	3	2	1	0	8
Trachurus mediterraneus	Saurel (Mediterranean horse mackerel)	0	0	3	0	0	3
Xiphias gladius	Swordfish	6	3	2	0	0	11
Spicara spp.	Low trophic fish	0	3	0	0	0	3
Caretta caretta	Loggerhead turtle	4	0	0	2	1	7
Larus michahellis	Yellow legged gulls	0	0	0	0	1	1
Larinae spp.	Seagulls	2	0	1	0	0	3
Various / Larinae spp.	Other gulls	0	0	0	0	1	1
Chlidonias niger	Black tern	1	0	0	0	1	2
Puffinus yelkouan	yelkouan (mediterranean) shearwaters	0	0	0	0	1	1
Calonectris diomedea	Scopoli's (cory's) shearwaters	0	0	0	0	1	1
Hydrobates pelagicus melitensis	Mediterranean storm petrel	1	0	1	0	1	3
Phalacrocorax carbo	Great cormorants	0	0	0	0	1	1
Morus bassanus	Northern gallant	0	0	0	0	1	1
Tursiops truncatus	Common bottlenose dolphin	8	3	3	2	1	17

Table 3 the number of recorded species from interviews (n = 143). Latin name and common name are followed by the number of observations from each farm site, as well as 'general observations.'

Figure 8 shows illustrates the respective number of individuals of wild fauna species recorded from the interviews. Overall, *T. truncatus* (Common Bottlenose Dolphin), *Euthynnus alletteratus* (Little Tunny), *Batoidaea spp.* (Rays), and *Xiphias gladius* (Swordfish) were among the most frequently-recorded wild fauna at the ABT farms. Interviewees also frequently mentioned observing shoals of smaller pelagic fish (e.g., Mackerel, Sardines, Bogue, etc.).

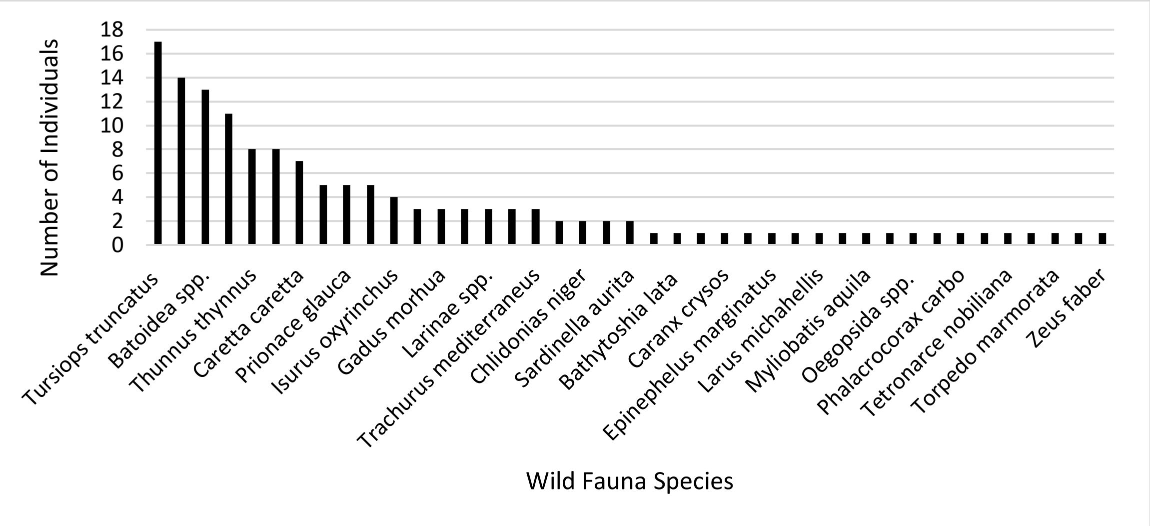

Figure 8 The number of individuals of wild fauna species recorded (n=143).

The environmental monitors recorded 19 wild fauna species that aggregated around the ABT farms. These observations were not specific in regard to the number of individuals of wild fauna species but rather show the known presence of a given species at the farm sites. The data represent qualitative non-site-specific trends.

The 19 wild fauna species recorded from the 'general observations' had some overlap with those identified by the divers (i.e., *T. thynnus, E. alletteratus, Carretta carretta, Aetomylaeus bovinus, and Chlidonias niger).* However, most of the species recorded were specific species (i.e., Yellow Legged Gulls, Scopoli's (Cory's) Shearwaters, Great Cormorants, Marbled Electric Ray, Common Sting Ray, Common Eagle Ray, and Albacore Tuna) that had not been observed by the divers, who rather cited more seabirds, rays, and tuna.

3.1.1 Taxonomy of Recorded Species

Overall, the recorded wild fauna species are from eight major taxonomic groups: Cephalododa*,* Ophiuroidea*,* Echinoidea, Chrondichthyes, Actinopterygii, Reptilia, Aves, and Mammalia. Table 5 shows how the taxonomic groups are represented in the data. Most of the records are for the Actinopterygii and Chrondichthyes. Actinopterygii and Chondrichthyes collectively account for well over 50% of the recorded species (in both data sets). Reptilia and Mammalia had multiple individual observations of one wild fauna species. Aves had various wild fauna species recorded, but most were identified from 'general observations' and there was a lack of quantifiable data. The rest of the taxonomic groups have relatively small counts, with Cephalopoda, Echinoidea, and Ophiuroidea collectively accounting for 3-10% of species. Figure 9 illustrates the data distribution across these eight groups.

Taxonomical Class	Number of Wild Faunal Species	Percentage	Number of Individual Observations of Wild Fauna	Percentage
Cephalopoda	2	4.88%	2	1.40%
Ophiuroidea	1	2.44%	1	0.70%
Echinoidea	1	2.44%	1	0.70%
Chondrichthyes	10	24.39%	32	22.38%
Actinopterygii	16	39.02%	69	48.25%
Reptilia	1	2.44%	7	4.90%
Aves	9	21.95%	14	9.79%
Mammalia	1	2.44%	17	11.89%
Total	41		143	

Table 4 Taxonomy of recorded wild fauna species and wild species individuals. Includes percentage of the data each taxonomic group represents.

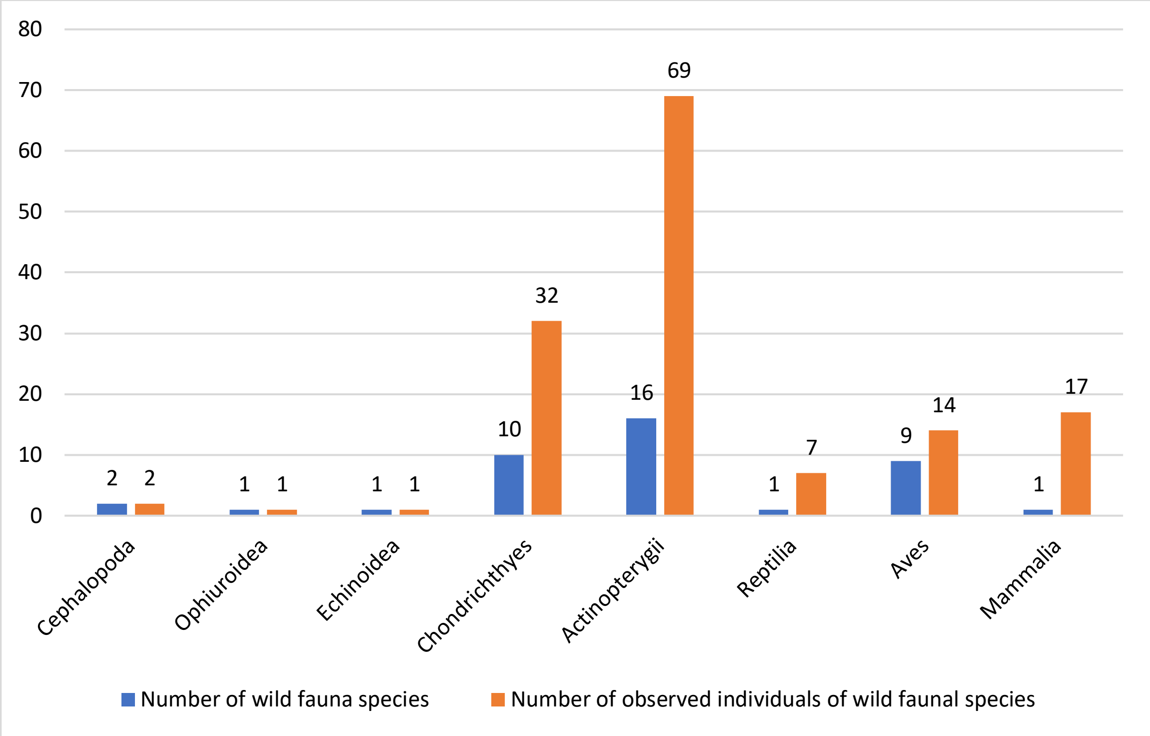

Figure 9 Taxonomic details for the recorded number of individuals (blue; n=143) and number of wild fauna species (orange; n=41).

Figure 10 displays the ten most observed wild fauna individuals along with their taxonomic group. Across the interviews, the most commonly reported individuals of wild fauna species were: *T. truncatus, E. alletteratus, Batoidea spp., X. gladius, T. thynnus, Trachurus trachurus, Caretta caretta, Balistes capriscus, Prionace glauca,* and *S. dumerili.* Most of these belong to Actinopterygii and Chondrichthyes, with Reptilia and Mammalia constituting the rest.

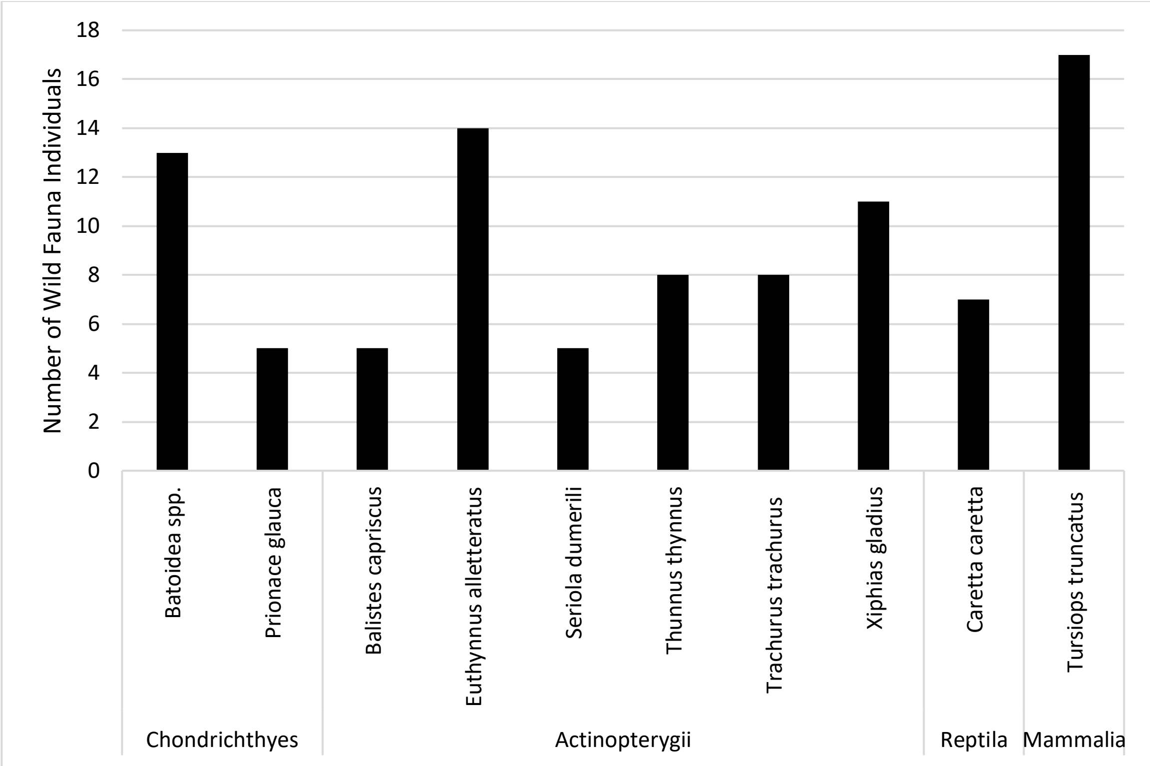

Figure 10 Top 10 wild fauna individuals recorded from interviews (n=143) and their taxonomic group.

3.1.2 Number of Observations of Wild Faunal Species (at Each Farm Site)

Of the 143 observations of individuals of wild fauna species documented, 124 were collected firsthand from farm staff (i.e., divers and personnel on site). Figure 11 shows the number of observations of wild fauna species reported from each farm site (AJDTL & MML, MBTFL, FFL, and MFFL) (n=124). AJDTL & MML had the highest number of observations at 62, followed by MBTFL with 25 observations, FFL with 24 observations, and MFFL with 13 observations.

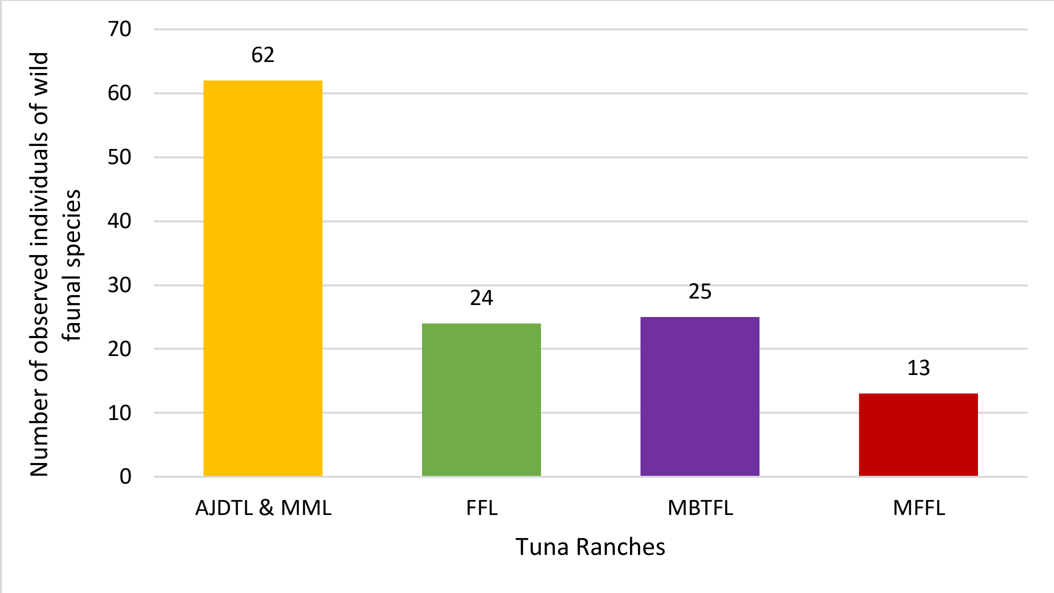

Figure 11 Recorded number of individuals of wild fauna at each farm site, (n=124).

3.1.3 Species of Wild Fauna Recorded (at Each Farm Site)

Across all interviews, 41 species of wild fauna interacting with the ABT farms were recorded. Of these, 28 were from divers (i.e., excluding the wild fauna recorded from 'general observations'). Figure 12 shows the number of wild fauna species reported by each farm. This graph shows how many of the 41 total wild fauna species were reported in associated with each farm site. AJDTL & MML had the largest number of observed wild fauna, followed by MBTFL reporting 12 species, MFFL reporting 10 species and FFL reporting 8 species.

'General observations' included records of 19 wild fauna species, which comprises 46% of the overall dataset. Of these wild faunal species, 13 were exclusively identified by 'general observations.' These 13 wild fauna species were batoid rays and seabirds.

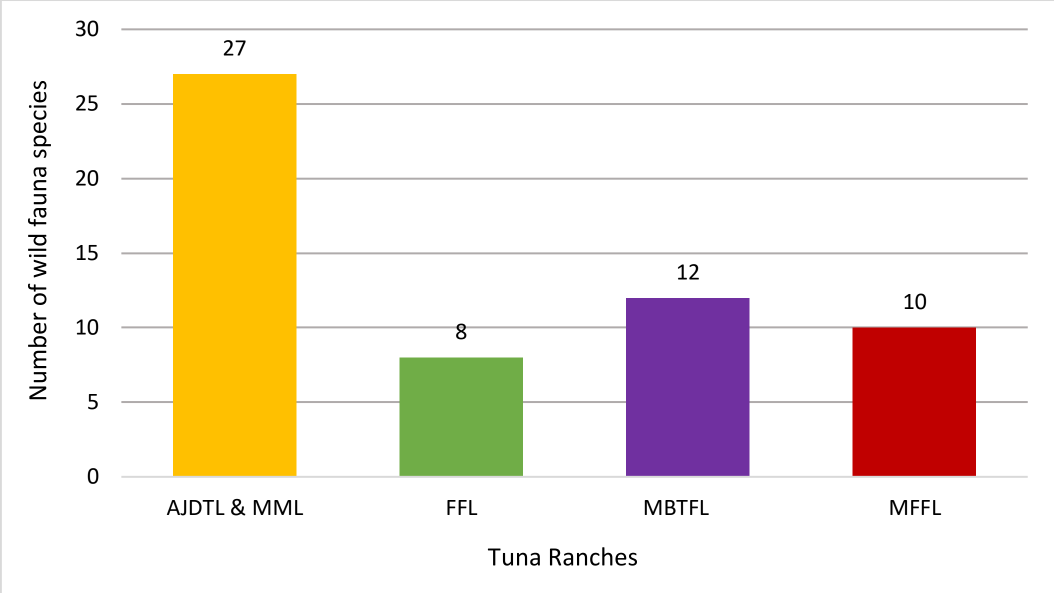

Figure 12 Recorded number of wild fauna species at each farm site, where the total number of species observed was 41.

3.1.4 Recorded Wild Fauna in the NAS and SAZ

The two farms, AJDTL & MML, located in Malta's NAS had higher recorded numbers of wild fauna species and individuals (Figure 13). However, in terms of the respective aquaculture site (NAS or SAZ), the distribution of such recorded observation counts and of number of species is even (Figure 14).

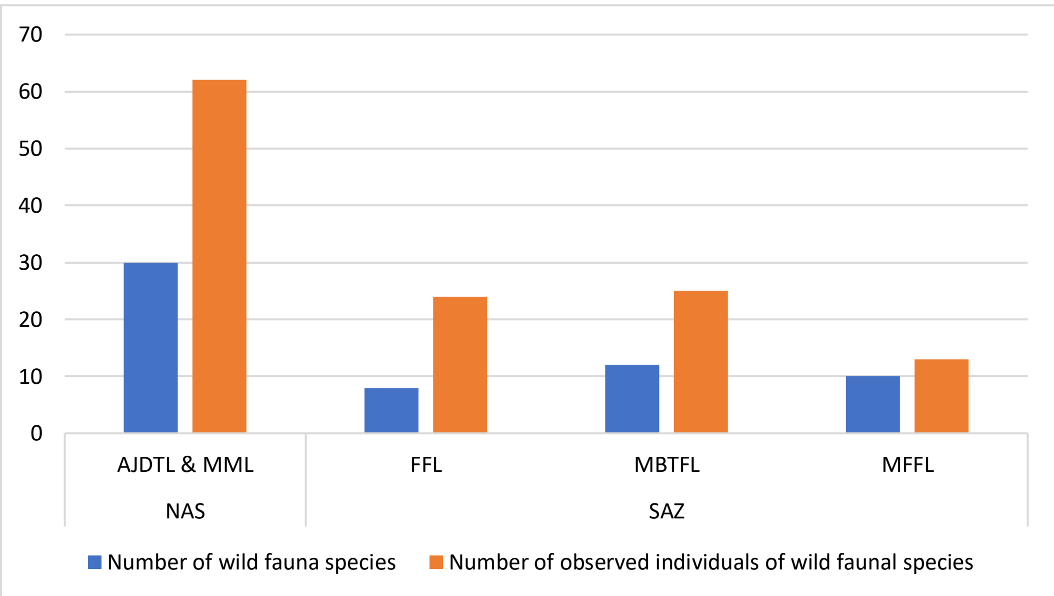

Figure 13 Recorded number of individuals (blue) and of wild fauna species (orange) from the four ABT farms in relation to the two offshore aquaculture sites where they are located.

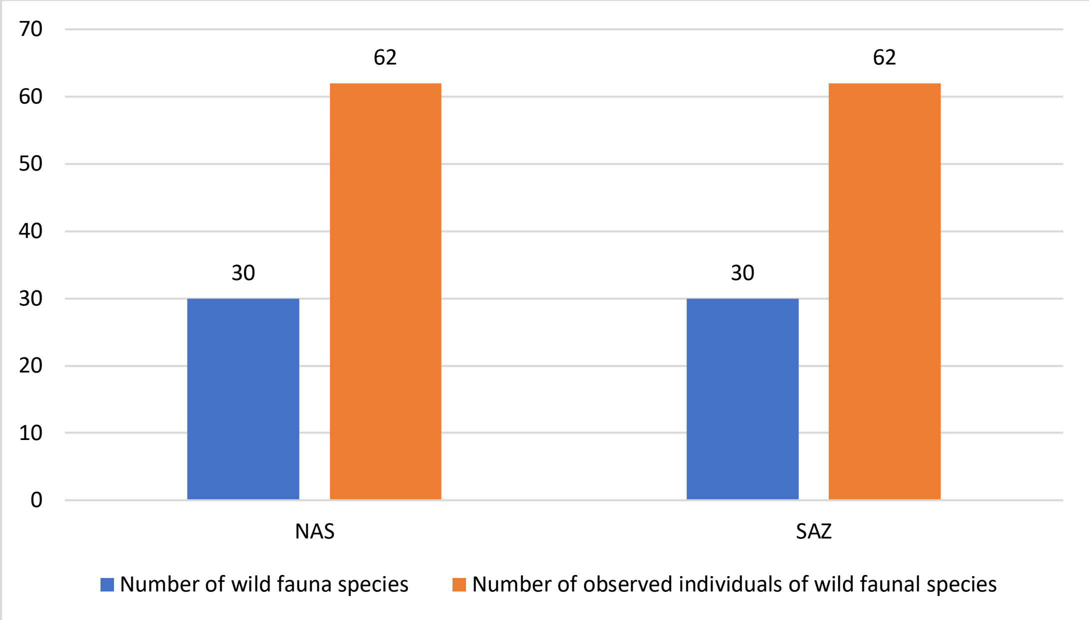

Figure 14 Recorded number of individuals (blue) and number of wild fauna species (orange) from the two offshore aquaculture sites.

3.2 Behaviour and Interactions of Wild Fauna

Interviews also provided firsthand observations of interactions and behaviors of aggregated wild fauna. Figure 15 shows the outcome from the thematic analysis of the interviews. Overall, the data showed trends in drivers of aggregation, like nearby migration route bringing certain wild fauna species closer to the farms or explicitly coming for feeding and / or habitat provisioning. Secondly, trends regarding interactions wild fauna species were having with the fish farms emerged, such as feeding or entanglement with farm equipment. Lastly, effects of observed aggregation also emerged, including damage to farm equipment of death of wild fauna. Within this last category, human presence was a substantial component. Many interviewees noted the presence of AF (all but two) near the ABT farms.

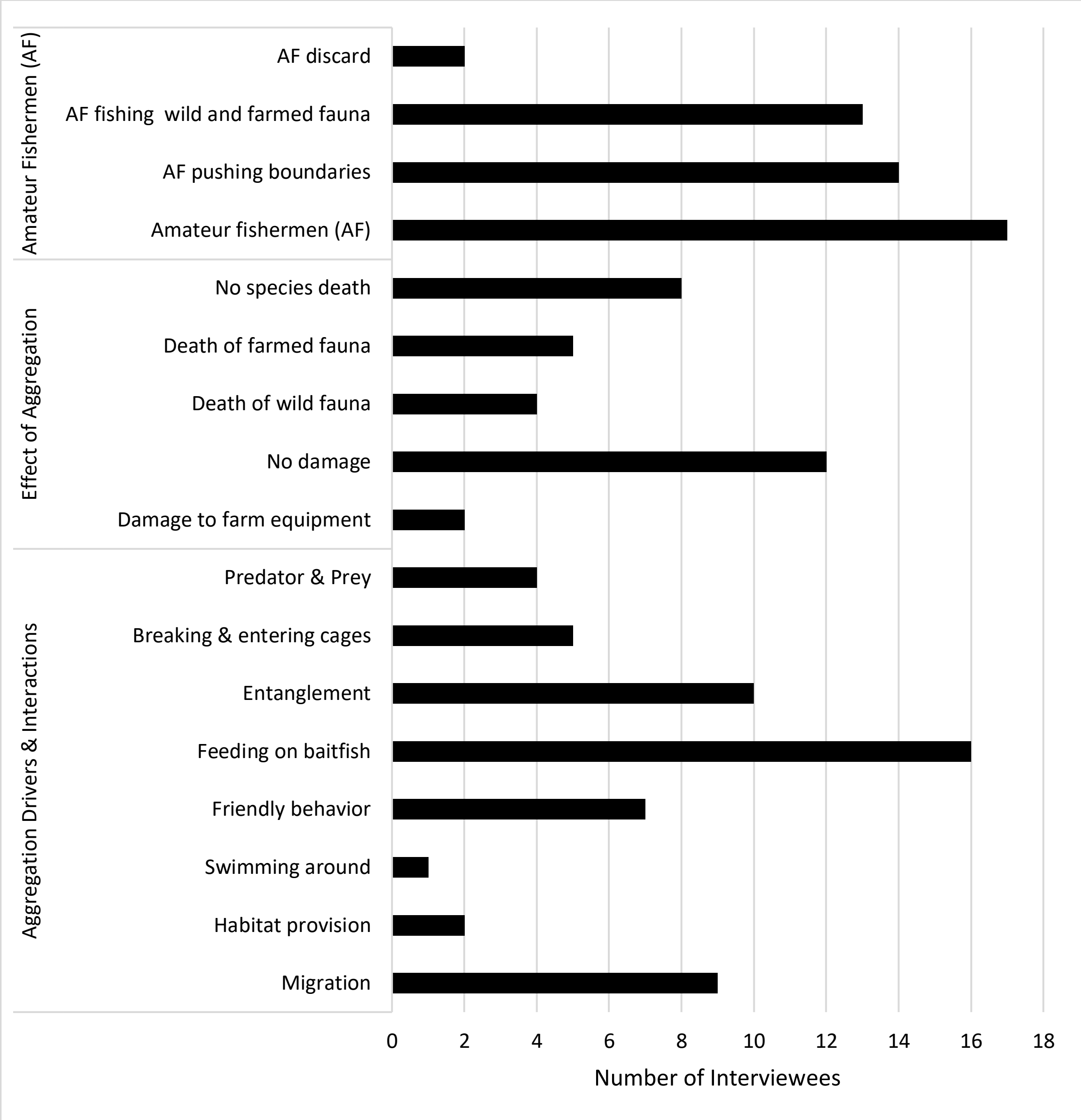

Figure 15 Observed behaviour and interactions of aggregated wild fauna at the ABT farms. Data shows the number of interviewees (n=19) that reported a thematic trend.

3.2.1 Drivers of Aggregation & Interactions

The majority of interviewees attributed aggregation behavior of wild fauna primarily to feeding opportunities. Other perceived reasons for aggregation were Malta's proximity to species migration routes (e.g., ABT and Bottlenose Dolphins), and habitat provisioning.

Of the 19 participants, 16 mentioned uneaten baitfish as a reason for aggregation, which was the top interaction observed. 84% of participants mentioned uneaten baitfish as a driver, noting that smaller pelagic fish aggregate around the cages for feeding. Moreover, 21% explicitly described a predator–prey driver, wherein larger species (e.g., *E. alletteratus*, *T. truncatus*) are attracted by the abundant smaller fish present in the vicinity of the cages. 11% observed wild fauna (*Boops boops* and *Spicara spp.*) feeding on algae growing on nets and farm structures (Tuna Ranching Divers, personal communication, 2025).

Additionally, social and behavioral factors of attraction / aggregation also emerged in the data. 47% of the participants mentioned migration routes influencing aggregated species. For example, *T. thynnus* and *T. truncatus* migration routes are located in Maltese coastal areas, so occurrence of these species' proximity is not unusual. Additionally, divers overall noted an increasing trend in the number of individuals of wild fauna species, but generally an established group of wild fauna species were known to aggregate. More specifically, many divers noted the continual presence of wild fauna species such as the little tunny, ABT, dolphins, bogue, and mackerel over the years but more individuals of these wild fauna species were seeming to be present.

The top interactions reported between wild fauna species and farm sites were: feeding on baitfish and net entanglement. 53% mentioned entanglement events. Interviewees noted that it is common for smaller pelagic fish to enter the pens, resulting in a feeding frenzy by the farmed (carnivorous) ABT. This is especially common after transport to farm sites in Malta (which can take weeks) when the farmed ABT are very hungry. Other trends in the observed interactions included social aggregation, wherein divers reported friendly interactions with wild fauna, specifically mentioning playful interactions with *T. truncatus*.

3.2.2 Impacts of Aggregation

10% of interviewees reported damage to nets or cages associated with net entanglement. Specifically, wild fauna species would attempt to swim into the cages, becoming entangled. Overall, there was little impact to farm operations resulting from entanglement and any damage incurred from entanglement was minor. Additionally, no breakouts of farmed ABT were recorded as a result of net damage. In total 47% of interviewees mentioned mortality events of either farmed ABT or wild fauna species. Interviewees often noted mortality resulted from entanglement or from wild fauna entering the pen and getting eaten.

A major impact of aggregation was the presence of AF. 89% of participants noted the presence of AF around the ABT farms. Moreover, 74% reported that farm boundaries were often encroached upon by AF, with 68% reporting AF fishing for farmed and wild fauna.

4 Discussion

Interview data confirms that Maltese ABT farms act as focal points for attracting wild fauna, serving both as feeding grounds and artificial habitats for a diverse assemblage of wild pelagic, demersal, and avian species that span multiple trophic levels. While the present findings align with existing Mediterranean literature on attraction / aggregation of wild fauna (Arechavala-Lopez et al., 2015; Mangion et al., 2014; Russo, 2011), they represent a first assessment of interactions between wild fauna (including fish fauna but not restricted to this group) and Maltese ABT farms. The gathered data, which spans a period of more than a decade, reveal that tuna farms modify local ecosystems through the creation of artificial trophic webs, which may contribute positively to biodiversity and ecological functioning if properly managed. However, multi-year studies are needed to understand patterns of wild fauna attraction / aggregation in the vicinity of local ABT farms, and the full impact of this over time, particularly as species may develop long-term dependency on such sites, raising concerns about them potentially acting as ecological traps.

4.1 Wild Fauna Species Aggregating Around Maltese ABT Farms

The wild faunal species recorded in this study align with previous Mediterranean studies identifying aquaculture sites as aggregation points for pelagic and demersal taxa (Arechavala-Lopez et al., 2015; Mangion et al., 2014; Russo, 2011). Across the data, the most commonly reported individuals of wild fauna species were: *T. truncatus, E. alletteratus, Batoidea spp., X. gladius, T. thynnus, T. trachurus, C. caretta, B. capriscus, P. glauca,* and *S. dumeril.* These species are generally Actinopterygii and Chondrichthyes, with only *C. carretta* (Reptilia*)* and *T. truncatus* (Mammalia) not being fish. Arechavala-Lopez et al. (2015) document similar aggregations of fish species from the Actinopterygii and Chondrichthyes in the vicinity of Mediterranean ABT cages, suggesting that Maltese ABT farms have similar attraction / aggregation trends.

Specifically, in 2011, a local study investigated pelagic wild fauna assemblages at Malta's ABT farms (Russo, 2011). Russo 2011 identified, through video analysis and scuba dives, wild fauna species aggregating at two farm sites, which were also a subject in the present study: AJDTL and FFL. Russo's (2011) study results identified 10 wild faunal species, six of which were also recorded in this study: *B. boops, T. mediterraneus, S. aurita, B. carolinensis, S. dumerili, E. alletteratus.* Three of these were amongst the most frequently observed wild fauna in the present study. Similarly, various studies on Mediterranean FADs found that Dolphins (*T. truncat*us) and Rays (*Batoidea spp.)* commonly aggregate in the vicinity of fish farms (Agius et al., 2024b, 2024b; Bonizzoni et al., 2014). Alignment of the data from this study with previous Mediterranean research affirms that Maltese ABT farms function as FADs and provides an understanding of which wild fauna species are attracted / aggregate in the vicinity of ABT farms.

C. carretta, T. truncatus, and *P. glauca* were not recorded in previous studies (Russo, 2011), suggesting that these species could be newly attracted to Maltese ABT farms. This may be a factor of persistent attractive mechanisms being extended to species whose presence near ABT farms has been recorded only recently and which may have nearby migration routes, as could be the case for these three species. Studies have been made that record aggregation of *T. truncatus* in the vicinity of fish farms in the Mediterranean, but no such studies have been carried out in Malta (Bonizzoni et al., 2014). Therefore, the present study contributes to the opportunity for longitudinal studies to better understand trends of attraction / aggregation of wild fauna to fish farms, in regard to the concerned species and individuals. Moreover, such assessment can be undertaken over the long term, i.e. over several years.

The present site-specific data indicate that each farm site had an aggregation of wild fauna species, but there was a difference in number of reports amongst different farm sites. Certain species, such as *E. alletteratus* and *T. truncatus*, were recorded by all interview groups (i.e., the ABT farms and 'general observations') while others, such as *T. thynnus*, *Batoidea spp.*, and *T. trachurus*, were observed by most (i.e., all but one group). All these species are also amongst the most frequently observed.

AJDTL & MML had higher values for both the recorded number of wild fauna individuals and of wild fauna species compared to the other farms. The difference is most likely due to data bias that resulted from interview sampling limitations (see section 4.5). Additionally, farm location and density may have contributed to higher data reports for the NAS farm sites compared to the SAZ ones. The cumulative effect of having two farms operating next to one another might create a larger aggregative footprint than the more dispersed farms at the SAZ. AJDTL and MML jointly operate 24 cages – only three more than the SAZ's 21-cage average. While this difference is not large, there may still be cumulative impacts resulting from such operational capacity. Ballester-Moltó et al. (2015) suggest that operational factors – including farm size, stocking density, and feeding intensity – influence wild fauna aggregation patterns. The combined effect of two co-located farms may create a more substantial FAD effect, attracting a wider array of species.

As previously mentioned, Actinopterygii and Chondrichthyes were the most predominant taxa in the present study, which is to be expected. These groups include highly mobile pelagic species that are drawn to aquaculture sites for opportunistic feeding and to exploit the structural complexity of the artificial cage habitat. On the other hand, the strong presence of Aves (22%) provides broader evidence that fish farms act as important foraging grounds. Studies on seabird behavior have shown that gulls, shearwaters, and cormorants frequently exploit aquaculture operations for feeding opportunities, responding to both the presence of farm-associated fish and organic waste (uneaten baitfish and fish waste) (Aguado-Giménez et al., 2016; Jaquemet et al., 2004). This pattern was reflected in the observed presence of *Hydrobates pelagicus melitensis* and *Puffinus yelkouan* in proximity to the farms, demonstrating adaptive behavior and opportunistic feeding strategies. Apart from these species, several of the interviewed divers observed the presence of gulls and other seabirds.

Overall, the 'general observations' affirm firsthand observations by the divers with regard to reporting species like *E. alletteratus*, *T. thynnus*, and *T. truncatus*. The 'general observations' data also provide species-specific information that may contextualize some of the divers' reports. For example, many divers noted the presence of Rays (*Batoidea spp.*) but were unsure of the species' identity. The experts who provided 'general observations' knew the species name (i.e., *Larus michahellis*, *Torpedo marmorata*, etc.) which the divers knew by common name or through description. Therefore, data from these 'general observations' support trends in wild faunal species aggregating in the vicinity of local ABT farms, and that these comprise a diverse assemblage of multiple taxa.

Understanding the specific aggregative effects of the various sites and their operations was not the objective of the present study but rather identifying the species that are generally involved in such interactions / aggregations. Future studies to determine differences in wild fauna aggregation amongst Maltese ABT farm sites would be helpful to monitor best management practices (BMPs) and their effect on wild fauna. Knowing specific data about the wild fauna at each of the farms would help craft BMPs that are adaptive to the species, thereby maximizing effectiveness. For example, understanding if the artificial trophic webs at each farm site are the same or if they have differences, being that some are in the North and some in the South, would aid in crafting effective monitoring and BMPs.

4.2 Behaviours and Interactions Recorded

Drivers of Aggregation

Interviews provided firsthand observations of aggregated wild fauna, revealing trends about perceived drivers of aggregation and of wild fauna interactions with the ABT farms. An overwhelming number of reports from interviewees attributed wild fauna aggregation to opportunistic feeding (both by way of uneaten baitfish and wild fauna predation on aggregated prey). These findings are supported by existing literature which indicate that uneaten baitfish is the largest attractive factor fish farms have as FADs (Fernandez-Jover et al., 2011; Russo, 2011; Sanchez-Jerez et al., 2011). A consequence of this is also attraction of higher trophic-level predators, since small pelagic fish (e.g., *Trachurus spp.*, *Sardinella* spp. *B. boops*) aggregate for feed and habitat provision, but their presence attracts large predators (e.g., *X. gladius*, *E. alletteratus*, and *T. truncatus*). This is consistent with previous findings that large mobile species aggregate near aquaculture sites due to prey aggregation and shelter provisioning effects (Bonizzoni et al., 2014; Dempster et al., 2010; Russo, 2011; Sanchez-Jerez et al., 2011). Russo (2011) observed predator-prey dynamics influencing aggregation in Malta, to the extent that large carnivorous demersal species, like *B. carolinensis* and *E. alletteratus*, were attracted. Consequently, an artificial trophic web is generated around a cage FAD. Many interviewees noted the presence of predator-prey dynamics resulting from attraction of wild fauna to the farm sites, corroborating that smaller species attracted to the feed become vulnerable to predation by larger predators, which recognize that abundant prey are present near the farm sites.

Dempster et al. (2009) documented that coastal farms attract "large and persistent aggregations of wild fish," hence constituting a significant ‘ecosystem effect.’ The present data reflect a diverse assemblage spanning multiple taxa, emphasizing the profound ecosystem effect FADs have. Attraction of higher trophic species plays a critical role in shaping food-web interactions around the farms, potentially influencing local trophic dynamics through top-down control. This artificial trophic web results in a high biodiversity at these sites. However, it also raises concerns for human–wildlife interactions, including potential competition with fisheries, and the possibility that fish farms may serve as ecological traps.

Lastly, mere swimming around fish farm sites by wild fauna was noted, which can be attributes to the proximity of the farm sites to key migratory routes, as is the case for species such as *T. thynnus* and *T. truncatus*. Many interviewees noted that migratory routes facilitated aggregation, as the species are already present close-by and need food or spawning grounds. These findings are supported by literature on Mediterranean fish farm aggregation trends. However, as studies point out, there is also the potential for FADs to shift migration routes to include the farm sites for, but not limited to, feeding opportunities. The altering of wild fauna behavior as a result of FADs has potential implications for the wild fauna species. Further studies regarding the long-term impact of the aggregated wild fauna's reliance on FADs and their opportunistic feeding, should be conducted to fully understand the impacts of the farm sites on the wild fauna.

Types of Interactions

Reported interactions included feeding on baitfish, species entanglement with farm equipment, and exposure to humans. Feeding on baitfish was the most observed interaction. As previously established, a major driver for attraction of wild fauna is for feeding opportunities, therefore, making it the most observed interaction. This was expected and followed on by asking about instances of entanglement, or in a broader sense – did the opportunistic feeding impact the farms. Some divers noted that the wild fauna species helped consume some of the uneaten baitfish, with others noted that entanglement was possible.

Reports of entanglement were generally attributed to a feeding frenzy, where the (carnivorous) farmed ABT are very hungry after transport or when a wild species enters the pens. Most of the divers reported that when the farmed ABT enter a frenzy, entanglement can occur, so BMPs are employed to control this (i.e., after transport, farmed ABT are fed extra to satiate them after the long journey and reduce or avoid entanglement events). Reports indicated death of farmed or wild fauna can occur as result of stress and / or bodily harm after entanglement. Therefore, divers do their best to reduce interactions through BMPs. Almost half of the participants noted that death of species, farmed or wild, was not common. This suggests that while entanglement is a highly reported interaction, it is not always followed by death of the organism. Similarly, interviewees noted that damage to farm equipment resulting from entanglement can happen, sometime small tears are created. However, no large species were reported to have broken into pens. Consequently, the impact of entanglement was reported to be a minor adverse impact.

An important, and often overlooked, interaction with wild fauna is human-related. Divers recounted that aggregated wild fauna were generally friendly, going as far as reporting playful interactions with *T. truncatus*. Although *P. glauca* was amongst the top reported wild fauna species, all divers noted feeling safe amongst the aggregated wild fauna. Conversely, many interviewees reported the occurrence of AF fishing for the aggregated wild fauna in the ABT pens themselves and around them (Tuna Ranching Divers, personal communication, 2025). All but two interviewees mentioned the presence of AF and their proclivity to encroach, sometimes even trespassing, the farm boundaries for fishing opportunities. Reports from ABT ranch staff and managers included instances of AF fishing within the farm boundaries. The fact that ABT farms attract wild fish is well known to the AF, hence their presence is inevitable. Farm site managers noted that, other than needing watchmen to monitor farm site borders, the AF have relatively minor impacts on operations; some AF leave behind discarded gear, but not a substantial amount. Despite this, farm staff and managers noted generally good relations with AF.

Much like the predator-prey dynamics, AF are attracted to farm sites and adjacent waters for the rich hunting grounds. The increase of human presence and boat traffic exposes the attracted / aggregated wild fauna to potential harm. While there were no reports of injury to wild fauna species from boat traffic, it remains a possibility, and as AF become more persistent, so too will the potential for harm.

The larger concern is that the ABT farms may become an ecological trap, luring wild fauna which will be at the risk of being harmed or harvested. It is crucial that regulation of AF and enforcement is consistent and comprehensive. While there are regulations in place to limit AF activity near aquaculture zones in Malta, these are not enforced thoroughly. This mostly results since it is hard to enforce boundaries by boat – the farms have watchmen, but they cannot physically stop the AF. It is important for the farms to report incidents to the appropriate authority, which they seem to do. Further research regarding AF and association of such activity with FADs in Malta will be useful. Understanding AF's point of view and motivation when it comes to things like site selection, perception of ABT farms, and their relationship with local authorities and the aquaculture industry at large, would help improve management and, potentially, stakeholder relations. Given the importance of both aquaculture and fishing in Malta, this would be a beneficial area for which to expand data collection.

The present findings provide insight into the variety of wild fauna that are known to aggregate around Maltese ABT farms. Additionally, the present results indicate interactions that have been observed. Overall, the results revealed generally minor impacts of wild fauna interactions with farm sites, with minimal damage to farm equipment and or death of organisms. Participants in the survey generally noted that with improved BMPs, interactions are easily managed, and divers are dedicated to monitoring the farmed ABT, and to observing interactions to gauge farm adaptive management.

4.3 Implications of the Aggregation and Interactions

The implications of Maltese ABT ranching sites as FADs include the potential for wild fauna species' alteration of migratory and foraging behaviour, the site becoming an ecological trap, the effects of consuming baitfish, and geographic location which may affect other marine organisms in nearby areas including MPAs.

As previously discussed, the potential for FADs to become behaviour modifiers and ecological traps is a big concern. Not only does the opportunistic feeding and habitat provisioning have the potential to shift wild fauna behavior, but it also exposes these species to concentrate in areas that overlap with human presence. Predation, whether it be from wild fauna species or human, is a considerable threat to aggregated or attracted wild fauna species. Russo (2011) found that predator species are known to extend hunting grounds up to 100 m around fish farms due to the aggregative effect of ABT cages and presence of abundant prey. Attraction / aggregation of wild fauna will lead to the exposure of the attracted wild fauna to threats associated with close proximity to humans, such as boat traffic related to farm operations, recreational vessels, and bats used by AF.

In Malta, fishing is prohibited within farm leasehold areas for both safety and biosecurity reasons, creating de facto no-take zones that extend throughout the water column (Sanchez-Jerez et al., 2011). Some 35% of Malta's current 25 nautical mile Fisheries Management Zone (FMZ) overlaps with marine protected areas. Increasing the presence of protected areas adjacent to or including aquaculture sites in MPAs but accompanied by bolstering enforcement, could be beneficial for local fish stocks and overall ecosystem health. Maltese ABT ranches are currently located within protected areas currently, so rigorous monitoring (that include longitudinal studies and consistent species identification) of attracted / wild fauna aggregations around ABT farms could bolster conservation.

An important factor is the attraction of protected or rare species to farm sites, as is the case for *T. truncatus*, *C. caretta*, and several elasmobranch species, some of which are not commonly found in Maltese waters. The ability for these sites to attract a diversity of species is indisputable. If the FAD's attractive influence continues to increase (as indicated over the years), which would necessitate detailed studies carried out over several years, then bolstering aquaculture sites with conservation goals and regulations could help wild fish stocks. By understanding more specific data trends, such actions would prepare the DFA, ERA, other government authorities and local ABT farms to better prepare for attraction / aggregation of wild species and ensure that these are protected, particularly during the peak farming seasons. This is especially important considering that the peak seasons are in summer when boat traffic, recreational activities, and tourism are at a peak. ABT farms and local environmental authorities need to proactively understand trends of attraction / aggregation of wild fauna so they may react appropriately with conservation management goals in mind. An important aspect of management actions is enhancing and standardizing data collection amongst stakeholders within the aquaculture industry to better understand attraction / aggregation and other species-specific activities.

Several studies have documented that farm-associated fish can exhibit enhanced fitness indicators compared to conspecifics in non-farm areas (Bacher et al., 2012; Dempster et al., 2006; Stagličić et al., 2017). If this pattern holds in Malta - a hypothesis requiring further investigation - then ABT farms could function as population sources, contributing enhanced abundance to broader regional populations. Moreover, the value of these sites will be enhanced by including them as protected areas to reduce vulnerabilities to wild fauna health and stocks.

The long-term impact of any enhanced state of wild fauna, such as body condition and spawning success, resulting from feeding on uneaten baitfish is unknown (Fernandez-Jover et al., 2011). While research has revealed beneficial effects from wild fauna consuming farm feed, longitudinal studies looking at how this impacts gonad health and overall breeding success and how aggregated wild fauna with conspecifics is lacking, particularly for Maltese ABT farms. Understanding what portion of uneaten baitfish, it being consumed by wild fauna would facilitate understanding of potential environmental impacts, as well as unhealthy or harmful biological effects for the attracted wild fauna.

In trying to understand potential adverse impacts, it is important to consider operational practices; namely, capture-based aquaculture's reliance on wild fish stocks for both seed and feed. The impacts of these two operational practices have underlying effects that can be substantial. At the beginning of operations, after transport once in Malta, the feed input is about 200 tons per farm per day; such high feeding satisfies the ABT which would be very hungry after transport from the site of capture to the farms. After about two weeks, the feed input is reduced to about 150 tons per day. This is maintained for about 3-5 months, depending on the time when the ABT are harvested. Overall, this means that a substantial amount of wild-caught baitfish is required as feed in the industry. Moreover, the ABT are wild-caught, so there is complete reliance on wild fish stocks to ensure sustainability of the industry. These two factors may result in profound ecosystem effects.

Additional research on the impacts of ABT ranching on wild fish stocks is important as this will provide foundational knowledge that can be used when discussing the possible environmental benefits of ABT ranching sites. Similarly, more research on a feed substitute would benefit the industry's sustainability; here it is noteworthy that the ABT ranching industry is mainly aimed not at reinforcing the food supply for humans but to provide culinary delicacies, such as sushi and sashimi. There is a certain cost for enjoying the luxury of a cuisine, which the environment should not have to pay for. So, transitioning away from reliance on wild-stocks for feed would dramatically reduce the industry's environmental impact. Understanding if there is an appropriate feed that the ABT would consume, and how this would affect the aggregated wild fauna species consuming uneaten feed, will help contribute to more sustainable and comprehensive management practices.

4.4 ABT Farms in Oligotrophic Waters

In Malta's oligotrophic waters, the biodiversity-enhancing contribution of aquaculture is particularly valuable. Baseline productivity is naturally lower in oligotrophic environments. Such environments are characterized by clear waters with limited phytoplankton production, and consequently limited higher-trophic-level productivity. Tičina et al. (2020) provide a review of "Marine Aquaculture Impacts on Marine Biota in Oligotrophic Environments of the Mediterranean Sea", they concluded that in such nutrient-poor systems, the controlled input of organic matter from aquaculture can enhance local productivity when balanced by wild fish consumption.

In this context, the organic matter released from aquaculture — both as uneaten baitfish and as fish waste — represents a nutrient subsidy to an otherwise nutrient-poor system. Tičina et al. (2020) explain that when organic input is efficiently consumed by aggregated wild fauna (as documented in this study and others), it can support enhanced local biodiversity without causing the negative impacts (e.g., eutrophication, anoxia) that may occur in more eutrophic systems or in systems where waste consumption is insufficient (Costa-Pierce & Bridger, 2002; Fernandez-Jover et al., 2011; Mangion et al., 2014). Machias et al. (2005) found strong attraction of wild pelagic fish communities near aquaculture sites in oligotrophic Mediterranean waters. These authors suggest that the trophic subsidies created by the farming activity can outweigh negative impacts when operations are properly sited and managed. The combination of structural complexity, food availability, and reduced fishing pressure, creates conditions for increased fish abundance, biomass, and fitness in attracted and aggregated wild fauna.

The degree to which ecosystem services provided by aquaculture operations contribute to a balanced and healthy ecosystem, are context-dependent, varying with the cultured species, production methods, environmental conditions, and management practices. In oligotrophic offshore environments, like the sea areas where Malta's aquaculture zones are located, properly managed operations could provide net positive ecosystem services, particularly when designed with conservation objectives in mind. For example, farm sites and their aggregative effect can boost biodiversity, and therefore productivity, in Malta’s coastal waters.

Managing the trophic subsidies (excess feed and fish waste) from aquaculture operations is critical to maintaining a proper ecosystem balance. Manually delivering feed and the efficiency with which aggregated wild fauna consume the uneaten baitfish and farm waste, are central. Excessive organic loading will overwhelm the ecosystem and cause degradation of benthic habitats, reduced oxygen levels, and shifts toward opportunistic species. Site features (i.e., deep waters, strong currents, and proactive monitoring), as outlined in the supporting literature, must be conducive to facilitating the management of inputs to account for fluctuations in feed consumption (FAO, 2025; Holmer et al., 2008).

The findings from this study, especially in conjunction with the previous study conducted by Russo (2011), position Malta as an example of well-managed ABT farms that have the potential to work in tandem with protected areas to benefit biodiversity and the ecosystem at large. Many participants noted improvements in feeding methods and development of BMPs in order to enhance sustainable operations within Malta's coastal waters (ERA regulations, protected area monitoring, etc.). Various participants mentioned the improvements that were implemented over the past 5-10 years; namely in adapting feeding rates to reduce waste and ecosystem degradation. In this regard, Malta's ABT ranching industry is efficient, utilizing manual feeding that adapts to fish hunger and biomass, and allows for benthic recovery during fallow periods.

4.5 Study Limitations

Several methodological considerations need to be acknowledged when interpreting the present results. Firstly, this study was conducted during the 2025 ranching season but represents data from cumulative years. There were scheduling conflicts and limitations, where some farms were more available than others, when collecting data that created uneven sampling across farm sites. Additionally, interviewees varied in their familiarity with exact species identifications and specific names, which may have created instances of misidentification. Observations collected from 'general observations' had a slightly different context compared to farm-collected data, which must be considered when reviewing all data to better understand the trends present.

An important factor is that this study collected data during one ranching season that represented the cumulative experience of interviewees. Because this study is semi-qualitative, an exact understanding of which wild faunal species aggregated (i.e., when, for how long, how many, in a group or alone, etc.) was not obtained. Rather, general information on attraction / aggregation of wild fauna was collected from individuals who observed this frequently. Accordingly, the trends that appear in this study offer a clear foundation of the predicted wild fauna species generally found to be attracted to ABT farms in Malta's coastal waters.

A large component of this study relied on the voluntary participation of Maltese ABT farms during the pre- and peak season. This invariably created challenges with availability for interviews and site visits. However, all ABT farms were extremely helpful and cooperative, but some were not as available as others. Challenges with successful holding of interviews limited this study. AJDTL & MML had at least twice as many interviews compared to the other farms. Conversely, MFFL provided significantly less interviews compared to the other farms. These differences resulted in uneven sampling across the farm sites. However, such limitation is common in aquaculture research when relying on operator observations (Ballester-Moltó et al., 2015b; Dempster et al., 2004).

Another limitation involved the process of species identification and language barriers. Interview participants varied in confidence and precision when identifying observed species. Some provided specific identifications (e.g., Bogue, Little Tunny, John Dory), while others offered more general descriptions (in one case the interviewee described the physical attributes of the Black brittle starfish that enabled recognition of this species). Moreover, language barriers necessitated translation during some interviews, which potentially may have led to species misidentification. Where ambiguity existed, conservative identification to genus or family level for species commonly found in Maltese coastal water was employed, thus prioritizing species accuracy over precision. This did create some discrepancies in the data presented, since responses varied widely, based on experience, and some may have been misidentified.

The 'general observations' from the two environmental monitors offered valuable complementary information on species not always conspicuous, or known, to ABT farm workers. One focused on marine ecology and the other on avifauna, enabled identifying species that some of the divers were only vaguely able to identify (i.e., as 'rays' and 'gulls,' rather than *Myliobatis aquila* or *Hydrobates pelagicus melitensis*, for example). These observations represent broader trends across multiple farms rather than site-specific data, while species abundances may have been underestimated as the researchers cited species presence without quantifying abundance (referred to general presence near

ABT farms). The two specialists confirmed ecosystem-wide patterns that are documented in the literature (Arechavala-Lopez et al., 2015; Sanchez-Jerez et al., 2011; Stagličić et al., 2017).

Despite these limitations, the present data provide valuable baseline information on wild fauna interactions with local ABT farms and support broader patterns documented in Mediterranean aquaculture research (Arechavala-Lopez et al., 2015; Stagličić et al., 2017; Tičina et al., 2020). Longitudinal studies, to understand data across different ABT ranching seasons, would offer more comprehensive data on the long-term effects of attracted and/or aggregated wild fauna, and of changes in the interactions.

5 Conclusions

This study addressed a knowledge gap regarding wild fauna interactions with Malta's ABT ranching operations, documenting 41 wild fauna species from 143 observations concerning observed attraction and / or aggregation of wild fauna during ranching seasons over the years. The results reaffirm that ABT farms in Malta function as fish aggregating devices (FADs), consistently attracting diverse wild assemblages—including pelagic fish, protected megafauna, and opportunistic predators. The most frequently reported interactions involved feeding on uneaten baitfish, entanglement with farm equipment, and non-aggressive behaviors such as playful swimming around cages. More than half of the participants reported only minor impacts (e.g., incidental damage or mortality), supporting the conclusion that well-managed ABT farms, such as those in Malta, can sustain aggregation without significant negative effects on the local environment.

In oligotrophic waters such as those surrounding Malta, these aggregations can generate localized ecological benefits: they introduce structural complexity into otherwise featureless pelagic zones, and wild fauna consumption of excess feed helps intercept organic material before it reaches the seafloor. Literature from similarly nutrient-poor systems supports this pattern, noting that when organic inputs are efficiently consumed, farms can enhance local productivity without triggering the eutrophic symptoms seen elsewhere. However, the presence of ecological benefits does not neutralize the risks. In fact, the same mechanisms that facilitate biodiversity enhancements—reliable food availability, structural refuge, and reduced fishing pressure within leaseholds—can simultaneously create conditions conducive to **ecological traps**.

Species that repeatedly aggregate at farm sites may experience an increased exposure to human pressures. Moreover, their behavior may be altered, such as inability to compete with wild conspecifics or disrupted migration patterns as result from predictable food opportunities. The widespread presence of AF around farm borders heightens this concern.

Critically, these site-level ecological dynamics exist within a larger contradiction: capture-based ABT ranching relies heavily on wild stocks to operate. The industry continues to depend on wild-caught juvenile ABT for seed and hundreds of tons of wild-caught baitfish per farm per day. This reliance undermines the core ethos of aquaculture as a mechanism for relieving pressure on wild fisheries. It also introduces an ethical dimension to evaluating cost versus benefits, given that the product being supplied—fattened ABT for the sushi and sashimi market—is a luxury commodity, not a food-security staple. When the ecological risks include altered behavior, potential ecological traps, and sustained pressure on baitfish stocks, it is necessary to critically consider whether these risks are justified in service of a high-end cuisine rather than broader societal nutritional needs.

At the same time, interview data indicate that improved feeding strategies, better waste management, and evolving BMPs have reduced some of the more immediate impacts on benthic communities and farm operations. There is clear potential for Malta to continue refining its operations, particularly given the country's governance structure, the overlap between aquaculture zones and protected areas, and the already strong coordination between regulatory agencies. Yet realizing this potential requires confronting the unresolved sustainability issues that remain central to the ranching model: dependency on wild seed, dependency on wild feed, and the lack of long-term ecological data on how repeated aggregation affects wild fauna health, reproduction, and fitness.

In moving forward, Malta is well positioned to play a leading role in shaping what a more sustainable future for bluefin ABT aquaculture could look like. Longitudinal monitoring, standardized species reporting, improved enforcement around aquaculture zones, and accelerated development of acceptable formulated feeds are all essential components. Ultimately, while ABT ranching in oligotrophic waters can generate localized ecological benefits under strong management, these benefits must be weighed against the system-wide impacts and ethical trade-offs of producing a luxury commodity through a method that remains fundamentally dependent on wild marine resources. The challenge—and opportunity—for Malta is to ensure that aquaculture contributes to ecological integrity rather than eroding it, especially in a context where the stakes for both wild fauna and marine ecosystems are increasingly high. Moreover, investigating a suitable alternative for feed would reduce the overall ecological impact the industry has.

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Appendix A

A.1 Interview Questions

A. Fish farm details

1. Operator's name:

2. Geographic location:
   i. Latitude

   ii. Longitude

3. First year of farm operation:

4. Period of year during which tuna are farmed

5. Size of farm [total stocking density]?

6. Size of tuna pens

7. Type(s) of feed used on farm?

8. Distance from the coast:

9. Water depth:

10. Sea currents:

11. General sea conditions:

12. Which wild fauna interact most with the tuna cages and what was the observed during the incidence/interaction?

Turtles	☐
Sharks	☐
Dolphins	☐
Other fish species (e.g. mackerel, batoids, swordfish, etc.)	☐

[For interviewer] Species name(s):

B. Interactions with Atlantic Bluefin Tuna (ABF):

1. During the operating time of the farm, have you seen wild individuals of this species aggregated around the cages? How many and which size/weight were they?

   a. If there was aggregation:

   - What was the particular period of the year of occurrence (season, at which time of the day or specific activity (e.g. feeding)?

   - Was there interaction of wild tuna with farmed species (e.g., breaking into cages, feeding of discarded feed, etc.)?

     - Did any of the wild tuna damage the tuna cage/net?

     - Was there death of the wild or farmed tuna? (e.g., from breaking into the cages, competition, etc.)

   - Did fishermen fish for the aggregated wild tuna?

     - What was the distance from farm?

     - What period of operation did this occur during (season, operational activity (e.g., feeding, etc.), etc.)?

2. Have you observed any feeding behavior of tuna at farms? Did they interact with scuba-diving workers?

3. Would you say the problem is major, minor or unimportant to the operation of your farm?

- Could you quantify the economic loss due to interactions (both direct and indirect) (e.g. loss of fishes, gear repair/replacements, reductions in growth of cultured fish, consequences of fishermen fishing for tuna in the vicinity of the farm etc.)?

4. Did any of the previous cited interactions occur from the first year of installation or has it become more frequent after several years?

   - Are the interactions reported to the authorities (e.g., Department of Fisheries and Aquaculture (DFA) Fisheries, Environment and Resources Authority (ERA), etc.)?

   - Does the farm keep a record of these interactions? Are there management practices in place to reduce the incidences and or effects?

Please provide any other comments you may have about the interaction between Atlantic Bluefin Tuna and fish farms: