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Conservation actions to reduce *Tursiops truncatus* depredation on static net small-scale fisheries in the Mediterranean Sea

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ADD – Acoustic Deterrent Devices

AIC – Akaike Information Criterion

CNR – Consiglio Nazionale delle Ricerche, or National Research Council of Italy

CPUE - Catch Per Unit Effort

dB - Decibel

DDD – Dolphin Deterrent Device

DiD01 – Dolphin interactive Dissuasor model 01

GLM – Generalized Linear Model

GPS – Global Positioning System

IUU Fishing – Illegal, Unreported, and Unregulated Fishing

kHz – kilohertz

ND – No GPS Data

NP – No Pinger

P – Pinger

ABSTRACT

Depredation by bottlenose dolphins (*Tursiops truncatus*) on static-net small-scale fisheries poses significant challenges for both marine conservation and the fishing community in the Mediterranean Sea. This study explores two conservation actions aimed at reducing dolphin depredation and promoting sustainable fisheries and dolphin populations. The aim of this study is to determine the effectiveness (1) of an acoustic deterrent device (ADD), pinger, in reducing depredation on trammel and gill nets and (2) of using a specific model of trap in place of traditional trammel nets as a mitigation tool. Acoustic and catch data were collected across two Sardinian sites to assess practical implementation and fishers' acceptance of these measures. For each fishing operation, catch data were collected and the catch per unit effort (CPUE) and species richness were obtained and analyzed. For the operations testing the effectiveness of pingers, Generalized Linear Models (GLMs) were used to analyze the data. It was determined that CPUE significantly decreased in the presence of dolphins, was higher on gillnets than trammel nets when dolphins were absent, and higher in nets with pingers versus nets without. Species richness significantly decreased as depth increased and in the presence of dolphins. For the operations testing the effectiveness of the traps versus trammel nets, CPUE was significantly higher in the traps, while species richness was significantly higher in trammel nets. While no single solution was proven to be universally effective, a combination of tailored approaches can potentially reduce depredation incidents. Our results underscore the need for an adaptive management framework that integrates scientific research, technological innovations, and socio-economic considerations to achieve long-term sustainability for both marine biodiversity and small-scale fisheries in the Mediterranean Sea. This study also highlights the importance of continuing to involve local fishing communities in the design and implementation of conservation strategies to enhance compliance and efficacy.

Key words: bottlenose dolphin, depredation, Mediterranean Sea, pinger, small-scale fishery

I. INTRODUCTION

The Mediterranean region is characterized by a rich diversity of marine life and a long-standing tradition of small-scale fishing, which is vital for the livelihoods of coastal communities. These fisheries are not just economic enterprises but also cultural heritage, with fishing techniques and knowledge being passed down through generations (De Juan et al., 2024). However, the interaction between marine megafauna and fisheries presents a complex challenge for both conservationists and fishers.

In the Mediterranean Sea, the common bottlenose dolphin (*Tursiops truncatus;* here after bottlenose dolphin) is a charismatic species whose conservation is of significant ecological and socio-economic importance. These dolphins are not only a major ecotourism attraction but also play a crucial role as top predators, helping to maintain marine ecosystem balance by regulating fish populations and fostering biodiversity (Wells et al., 2004; Mazzoldi et al., 2019). Their presence may indicate a healthy marine environment, which is essential for the overall health of oceanic ecosystems by maintaining higher biodiversity levels and diverse marine communities (Wells et al., 2004; Mazzoldi et al., 2019).

However, their depredation on static-net small-scale fisheries poses a serious problem. This depredation, characterized by dolphins taking entangled fish from nets and oftentimes, leaving holes in the nets or damaging them, leads to substantial economic losses for fishers, who rely on these catches for their livelihoods (Petetta at al., 2020). In some regions, depredation can result in damage to over 72% of fish catch, significantly impacting the income of small-scale fishers (Lauriano et al., 2009). Consequently, the sustainability of both dolphin populations and the fisheries they exploit is at risk (Revuelta at al., 2018).

Catch Per Unit Effort (CPUE) is a critical metric in fisheries science and management, used to quantify the efficiency and effectiveness of fishing efforts. It represents the amount of catch (fish or other marine organisms) obtained for a given amount of effort, which can be measured in various ways such as the number of hours fished, number of fishing trips, or the number of nets or hooks used. For this study, CPUE is defined as total biomass of fish divided by the length of the net (or the number of traps) standardized per 24 hours of soaking. By calculating CPUE, scientists and managers can assess the relative abundance of fish stocks, monitor changes in population sizes, and determine the sustainability of fishing practices. This metric is vital for making informed decisions about fishing quotas, limits, and conservation strategies to ensure the long-term health and viability of marine ecosystems and the communities that depend on them (Hoyle et al., 2024). For example, a high CPUE can indicate a productive fishery with abundant stocks, while a declining CPUE can signal overfishing or environmental changes impacting fish populations (Hoyle et al., 2024). Therefore, CPUE serves as an essential tool for understanding the impact of fishing operations.

The book "Training Manual on Fish Stock Assessment and Management" describes the estimation of length-weight relationships in fish and can be used alongside the data provided by FishBase, a comprehensive database that includes these relationships for numerous fish species to calculate individual fish biomass to be used when determining CPUE measurements (Sathianandan, 2015). FishBase utilizes the formula $W = aL^b$, which describes the non-linear relationship between a fish's length and weight, where W is weight, L is length, and a and b are species-specific parameters (FishBase, n.d.). This formula is based on the biological principle that fish growth in length and weight is influenced by environmental factors and physiological conditions. Typically, the exponent b is close to 3, reflecting isometric growth, meaning weight increases proportionally to the cube of length, though it varies among species and conditions. The “Training Manual on Fish Stock Assessment and Management” provides a detailed methodology for estimating these parameters using linear regression on logarithmically transformed data, facilitating accurate biomass estimations and condition assessments (Sathianandan, 2015). This rigorous approach ensures the reliability of FishBase data, supporting its role in global fishery assessments and management strategies (FishBase, n.d.; Sathianandan, 2015).

As top predators, bottlenose dolphins play a pivotal role in maintaining the health and balance of marine ecosystems by preying on a variety of fish and cephalopod species. This helps control population sizes, preventing any single species from dominating and causing ecological imbalances (Kiszka et al., 2022; Heithaus et al., 2008). A balanced ecosystem with healthy dolphin populations supports more robust fish stocks, as overgrazing by certain species is mitigated, leading to more sustainable fish populations available for fishers (Bearzi et al., 2009; Bearzi et al., 2002). Furthermore, dolphins' presence often indicates a robust marine environment, as they tend to thrive in healthy, productive ecosystems (Bearzi et al., 2009; Bearzi et al., 2002). Their role as apex predators helps maintain species composition and health of fish stocks that are commercially and locally valuable. Studies have shown that areas with healthy populations of top predators such as dolphins can sustain larger populations of prey species over a longer period of time, enhancing the potential for larger catch amounts (Worm et al., 2006). A balanced ecosystem supports the resilience of fish populations, allowing them to recover more effectively from fishing pressures and environmental changes. Consequently, the conservation of bottlenose dolphins is crucial not only for their survival but also for the sustainability and productivity of the marine ecosystems they inhabit, ultimately benefiting the fishing industry by maintaining a stable and abundant fish supply (Heithaus et al., 2008).

Depredation activities endanger dolphins by increasing their risk of injury or entanglement in fishing gear, which can lead to drowning or severe physical harm (Notarbartolo di Sciara et al., 2002). Entanglement incidents have been documented to cause significant injuries such as fin dislocations, lacerations, and even amputations, which can reduce the dolphins' ability to hunt and survive (Date, 2012). These interactions can also alter their natural foraging behaviors and diets, potentially impacting their health and fitness over the long term. Increased dependence on humans for food can also cause dolphins to lose their wariness around fishing boats, leading to more frequent and potentially dangerous interactions with humans. These interactions can result in dolphins becoming more aggressive or more likely to approach boats and fishing gear, increasing the risk of injury for both dolphins and fishers (Foroughirad and Mann, 2013; Díaz López, 2019).

The first documented reports of dolphin depredation in the Mediterranean emerged around the 1500s when the first decree was established declaring the worry about dolphin interactions with fisheries near France, though it is likely that such interactions have occurred for much longer given the Mediterranean’s extensive history of fishing. Initial accounts primarily described damage to fishing gear and loss of catch, with fishers observing dolphins removing fish directly from their nets (Notarbartolo di Sciara, 2002). These early reports highlighted the economic impact on small-scale fisheries, noting significant reductions in fish landings and increased operational costs due to damaged gear. Researchers began to systematically study these interactions in the late 20th century, identifying specific patterns and factors contributing to depredation incidents (Wells et al., 2004). This growing body of evidence underscored the need for targeted conservation strategies to mitigate adverse effects on both dolphins and fisheries, laying the groundwork for understanding the complex dynamics between dolphins and fishers, and prompting further investigations into potential solutions such as acoustic deterrents and gear modifications.

Static-net fisheries, including gillnets and trammel nets, are widely used due to their efficiency and low cost. However, these nets are highly susceptible to dolphin depredation, which has been increasingly reported over the past few decades. The Mediterranean's high density of both human and dolphin populations in this semi-enclosed sea leads to frequent interactions, exacerbating the issue (Gonzalvo et al. 2015; Wells et al., 2004).

Dolphin depredation on static net fisheries can arise from several interrelated causes. Dolphins may be attracted to these nets because they trap fish, providing a concentrated and convenient food source (Bearzi et al., 2009). In areas where natural prey is scarce or where there is intense competition with other predators, dolphins might increasingly rely on these artificial feeding opportunities (DeMaster et al., 2001). Additionally, nets that are improperly managed or left unattended can become more accessible to dolphins, leading to increased interactions (Li Veli et al., 2023). Some dolphin species exhibit learned behaviors where individuals or groups become adept at accessing and exploiting the nets, perpetuating the issue within populations (Brakes and Dall, 2016). Environmental factors such as changes in fish populations or habitat degradation may also drive dolphins to exploit these fisheries more frequently (Bearzi et al., 2010; Notarbartolo di Sciara et al., 2002).

Overfishing, especially, can significantly exacerbate bottlenose dolphin depredation on static net fisheries. As natural fish stocks are depleted, dolphins may increasingly turn to artificial feeding sources such as static-net fisheries to meet their dietary needs (DeMaster et al., 2001). Additionally, the disruption of marine ecosystems caused by overfishing can alter dolphin foraging behavior and habitat use, making them more reliant on fisheries bycatch as a supplementary food source (Bearzi et al., 2010; Notarbartolo di Sciara et al., 2002). Furthermore, the decreased abundance and diversity of prey species can force dolphins to become more opportunistic and persistent in their interactions with static nets, increasing the frequency of depredation events (Chávez-Martínez et al., 2022). This dependency highlights the need for integrated fisheries management and conservation strategies.

Bottlenose dolphins in the Mediterranean typically prey on a variety of fish and cephalopod species. They prefer demersal and pelagic fish such as mullet (Mugilidae), seabass (*Dicentrarchus labrax*), and various species of cephalopods, including squid and cuttlefish (Blanco et al., 2001). These species are also highly valued by local fishers, leading to direct competition between dolphins and fishers. The economic impact on fishers is substantial, as high-value fish, such as sea bass and mullet, command significant prices in local markets, contributing to the fishers' livelihood and regional economy (Tixier et al., 2021).

In Sardinia, Italy, small-scale fishers target a range of commercially important species using static nets including the European hake (*Merluccius merluccius*), red mullet (*Mullus barbatus*), and gilthead seabream (*Sparus aurata*), which are crucial to the local economy (Tixier et al., 2021).

Previous studies have documented the extent and impact of depredation, yet effective mitigation or prevention measures remain elusive (Lucas and Berggren, 2023; Tixier et al., 2021). Strategies such as acoustic deterrent devices (ADDs), gear modifications, and temporal and spatial management, have been tested with varying degrees of success. ADDs, like the pingers that were used in this study, have shown some promise in reducing depredation incidents by emitting sounds that deter dolphins from approaching fishing nets (Waples et al., 2013). Pingers have been effective in some fisheries, increasing fish catch biomass by up to 28% as in the study done by Buscaino et al. (2009), but their effectiveness can vary depending on dolphin behavior and environmental conditions. Gear modifications, such as using more robust materials, altering the design of nets, or using alternative gear, have also been explored (Hamilton and Baker, 2019). Despite these efforts, the complexity of dolphin behavior and the diverse socio-economic contexts of Mediterranean fisheries necessitate a multi-faceted approach to develop sustainable solutions.

The impact of dolphin depredation on small-scale fisheries affects not just the economy but also ecological balance and community livelihoods. The decline in fish stocks due to depredation, coupled with damaged fishing gear, increases operational costs and reduces income for these fishing communities. Moreover, the reduction in fish catch due to dolphin interactions can affect the market availability of certain fish species, and therefore impact consumer prices and supply chains (Li Veli et al., 2023). The loss of fish catch can lead to increased pressure on already vulnerable fish populations, exacerbating overfishing issues and threatening marine biodiversity (Pauly et al., 2002).

Behavioral responses of bottlenose dolphins to fishing activities are complex and can vary significantly based on environmental conditions and prey availability (La Manna et al., 2023). Thus, the need for localized and context-specific strategies to mitigate dolphin-fishery interactions is pivotal. For instance, in the waters around Sardinia, dolphins' depredation patterns can be influenced by seasonal changes and fishing practices, suggesting that adaptive management approaches that account for these variables could enhance mitigation efforts (La Manna et al., 2022). Further, fishers' attitudes towards dolphins and their willingness to adopt mitigation measures are crucial for the success of conservation strategies (La Manna et al., 2023). In fact, fishers who are directly engaged in the design and testing of new techniques are more likely to adopt and effectively use these measures (La Manna et al., 2023). This participatory approach not only enhances the practicality of mitigation strategies but also fosters a sense of ownership and responsibility among fishers, which is critical for the long-term success of conservation efforts.

Due to the large economic losses incurred by fishers due to depredation, effective mitigation measures could significantly improve the economic stability of fishing communities, reducing conflicts between fishers and conservationists, and contributing to the overall sustainability of marine resources. (La Manna et al., 2024)

La Manna's research aligns with broader findings on the issue. For instance, Gnone et al. (2011) have demonstrated that habitat preferences and distribution patterns of bottlenose dolphins in the Mediterranean are strongly influenced by the availability of prey and human activities, further complicating the management of fisheries. Additionally, Gnone et al. (2011) emphasize the importance of long-term monitoring and research to understand the population dynamics of dolphins and their interactions with fisheries, advocating for sustained efforts to develop and implement effective mitigation strategies.

In addressing these challenges, other researchers have also explored innovative solutions. For example, there have been some studies that have investigated the use of deterrent devices and alternative fishing gears, finding that such approaches can reduce depredation but require ongoing adaptation and monitoring to remain effective (Lucas and Berggren, 2023; Tixier et al., 2021). It is a necessity of ecosystem-based management practices that consider the cumulative impacts of human activities on marine ecosystems, including fisheries and dolphin populations (Kenny et al., 2018).

Organizations such as the CNR (Consiglio Nazionale delle Ricerche, or National Research Council of Italy) and the LifeDelfi project are at the forefront of initiatives aimed at mitigating the conflict between bottlenose dolphins and small-scale fisheries in the Mediterranean Sea. One significant strategy they are promoting is the seasonal replacement of traditional trammel and gill nets with more dolphin-friendly fishing gear, such as traps. The CNR conducts extensive research on dolphin behavior, fishery dynamics, and the effectiveness of alternative fishing gear (Consiglio Nazionale delle Ricerche, n.d.). Their scientific studies provide critical data that emphasize the development of innovative solutions to reduce dolphin depredation. They collaborate with engineers and marine biologists to design and test new types of fishing gear that minimize interactions with dolphins. This includes the creation of traps that are less likely to attract dolphins compared to traditional nets. The CNR oversees the implementation of pilot projects where new gear is tested in real fishing environments. They monitor these trials to assess the performance and impact of the gear on both fish catches and dolphin behavior. On top of implementation, the CNR also conducts workshops and training sessions for fishers, educating them on the benefits of using alternative gear and how to operate it effectively.

LifeDelfi is a European Union-funded project focused on the conservation of dolphins and other marine life. It works to promote sustainable fishing practices that protect marine biodiversity. LifeDelfi engages with local fishing communities to raise awareness about the impact of dolphin depredation and the importance of adopting dolphin-friendly fishing methods. They foster collaboration between fishers and conservationists. LifeDelfi provides financial and logistical support for the deployment of alternative fishing gear. This includes grants for purchasing traps and other necessary equipment. LifeDelfi works with policymakers to create supportive regulations and incentives for fishers who adopt sustainable practices. They advocate for policies that balance the needs of marine conservation with the economic interests of fishing communities. The replacement of traditional nets with traps is timed seasonally to coincide with periods when dolphin depredation is most prevalent. This reduces the likelihood of dolphins associating fishing activities with easy prey. Traps are selected and designed to target the same species as traditional nets but with reduced bycatch and less attractiveness to dolphins. Both the CNR and LifeDelfi Project are involved in the rollout and continuous evaluation of this strategy. They collect data on fish catch rates, economic impacts, and changes in dolphin behavior to refine the approach. CNR, their partners and projects such as LifeDelfi are making significant strides in promoting the use of alternative fishing gear that reduces dolphin depredation, thereby supporting both marine conservation and the sustainability of small-scale fisheries in the Mediterranean. Their collaborative efforts illustrate the importance of integrating scientific research, technological innovation, community involvement, and policy support to address complex environmental challenges. (Consiglio Nazionale delle Ricerche, n.d.; LifeDelfi, n.d.).

This study aims to evaluate two conservation actions (ADDs and alternative fishing gear) to mitigate or prevent bottlenose dolphin depredation on static net small-scale fisheries in the Mediterranean Sea, based on data collected from projects that are supported by the CNR and by the LifeDelfi project, supported by the European Union. By reviewing current mitigation techniques and their effectiveness, conducting field experiments, and engaging with local fishing communities, we seek to provide a comprehensive strategy that balances ecological conservation with the economic needs of fishers. This research underscores the importance of adaptive management frameworks that incorporate scientific research, technological advancements, and stakeholder collaboration to address this complex issue. The involvement of local fishing communities in designing and implementing conservation strategies is crucial for enhancing compliance and efficacy (Gilman et al., 2022).

This research hopes to foster a harmonious coexistence between dolphins and fishers, ensuring the long-term viability of both marine ecosystems and human communities in the Mediterranean region. This approach will help to maintain the delicate balance needed to protect marine biodiversity while supporting the cultural and economic fabric of Mediterranean coastal societies.

II. METHODOLOGY

Two main conservation actions were taken with the aim to reduce or eliminate the risk of bottlenose dolphin depredation: 1) attaching a pinger to two types of nets (gill nets and trammel nets); and 2) replacing trammel nets with a trap (trapula pot) designed to eliminate bottlenose dolphin bycatch and convince fishers to adopt different gear to eliminate depredation consequences. The data was gathered from coastal areas along the Sardinian coastline. This area is characterized by diverse marine habitats and a variety of fishing activities. The target species, the bottlenose dolphin, is commonly found in these areas, often interacting with local fisheries. The fishing operation locations comparing nets with pingers to nets without pingers are depicted in Figure 1, across two main sites on the Sardinian coastline. 69 operations had pingers attached to the nets and 69 did not as a control.

Figure 1 – (A) The locations of all fishing operations part of the first conservation action across two sites along the Sardinian coast. 'P' denotes fishing operations with a pinger attached to the net, while 'NP' denotes fishing operations without a pinger attached to the net. (B) Map of Sardinia with the location of the Gulf of Asinara to be used as a reference for the location of the operations on a larger scale.

The GPS coordinates for the pinger/no pinger fishing operations are listed in Table 1. Operation 3NP is not depicted as there was no GPS data ("ND") collected during that fishing operation. An operation without a pinger was compared to an operation with a pinger attached to the net that had similar parameters (location, soak time, depth, and gear type) and the same date of placement.

GPS Coordinates for Fishing Operations Comparing the Effectiveness of Pingers					
Fishing Operation	**Latitude**	**Longitude**	**Fishing Operation**	**Latitude**	**Longitude**
1P	40.937600	8.785000	1NP	40.950250	8.801058
2P	40.930150	8.780210	2NP	40.941883	8.816367
3P	40.936950	8.766017	3NP	ND	ND
4P	40.894217	8.568183	4NP	40.898550	8.552333
5P	40.878450	8.613900	5NP	40.887200	8.631583
6P	40.957650	8.816400	6NP	40.944100	8.808217
7P	40.938483	8.797933	7NP	40.932900	8.796117
8P	40.886033	8.631333	8NP	40.886033	8.631333
9P	40.893683	8.599167	9NP	40.887250	8.606967
10P	40.940767	8.806300	10NP	40.935517	8.801717
11P	40.925250	8.777133	11NP	40.920200	8.759500
12P	40.890017	8.638117	12NP	40.892350	8.623367
13P	40.900250	8.609306	13NP	40.894194	8.601683
14P	40.953133	8.820150	14NP	40.961633	8.826667
15P	40.966100	8.826817	15NP	40.976433	8.825750
16P	40.890217	8.633933	16NP	40.879850	8.623183
17P	40.881367	8.609300	17NP	40.896783	8.606950
18P	40.908683	8.680483	18NP	40.902900	8.666433
19P	40.902900	8.657550	19NP	40.902167	8.643717
20P	40.886567	8.622600	20NP	40.896283	8.637283
21P	40.901817	8.648833	21NP	40.906333	8.667267
22P	40.878283	8.621333	22NP	40.890133	8.634017
23P	40.865200	8.607500	23NP	40.901133	8.601217
24P	40.902717	8.650350	24NP	40.910383	8.650733
25P	40.914483	8.665950	25NP	40.916333	8.688033
26P	40.908667	8.575100	26NP	40.897500	8.584500
27P	40.882167	8.620500	27NP	40.888167	8.629083
28P	40.903117	8.628250	28NP	40.907633	8.646167
29P	40.911867	8.659700	29NP	40.915650	8.682167
30P	40.891083	8.619800	30NP	40.884950	8.619800
31P	40.899667	8.650333	31NP	40.889167	8.563850
32P	40.899550	8.637867	32NP	40.899550	8.637867
33P	40.913083	8.676950	33NP	40.919567	8.689033
34P	40.898750	8.584533	34NP	40.913083	8.676950
35P	40.869917	8.609017	35NP	40.883700	8.609217
36P	40.896250	8.649150	36NP	40.899817	8.530633
37P	40.906350	8.673267	37NP	40.912917	8.685083
38P	40.899017	8.582617	38NP	40.892467	8.575567
39P	40.887750	8.616133	39NP	40.888450	8.639500
40P	40.956167	8.824233	40NP	40.949167	8.816367
41P	40.933550	8.788400	41NP	40.939800	8.804833
42P	40.912500	8.563800	42NP	40.904783	8.575183
43P	40.885367	8.617317	43NP	40.885283	8.623167
44P	40.926600	8.763183	44NP	40.929650	8.775767
45P	40.938033	8.795633	45NP	40.954067	8.816617
46P	40.894033	8.607433	46NP	40.902833	8.607250
47P	40.897100	8.647433	47NP	40.899950	8.645350
48P	40.936133	8.786283	48NP	40.946067	8.813633
49P	40.946067	8.813633	49NP	40.957467	8.825517
50P	40.928067	8.785150	50NP	40.937017	8.799417
51P	40.945517	8.805233	51NP	40.950017	8.815400
52P	40.903067	8.607500	52NP	40.905550	8.620700
53P	40.901867	8.643333	53NP	40.899000	8.632117
54P	40.963617	8.809417	54NP	40.951233	8.805367
55P	40.941633	8.803267	55NP	40.933133	8.792333
56P	40.904167	8.646533	56NP	40.911150	8.642917
57P	40.916300	8.601083	57NP	40.913800	8.587883
58P	40.922533	8.764950	58NP	40.924917	8.782467
59P	40.931467	8.795250	59NP	40.944800	8.808767
60P	40.914889	8.601819	60NP	40.907283	8.621567
61P	40.893833	8.642133	61NP	40.904167	8.652900
62P	40.930000	8.749717	62NP	40.925817	8.760683
63P	40.928983	8.773683	63NP	40.932717	8.795317
64P	40.907800	8.609133	64NP	40.913333	8.620367
65P	40.893633	8.641167	65NP	40.906500	8.648167
66P	40.898183	8.644983	66NP	40.904783	8.653833
67P	40.906133	8.664583	67NP	40.906133	8.664583
68P	40.952000	8.817950	68NP	40.944800	8.808767
69P	40.932717	8.795317	69NP	40.929967	8.769200

Table 1 - The GPS coordinates for the fishing operations comparing nets with pingers to nets without pingers.

The fishing operation locations comparing catch data from trammel nets to the trapula pots are depicted in Figure 2. The GPS coordinates for the trammel net/trap operations are listed in Table 2. Control fishing operations using traditional trammel nets were compared to fishing operations using the trapula pots conducted in similar locations and timeframes.

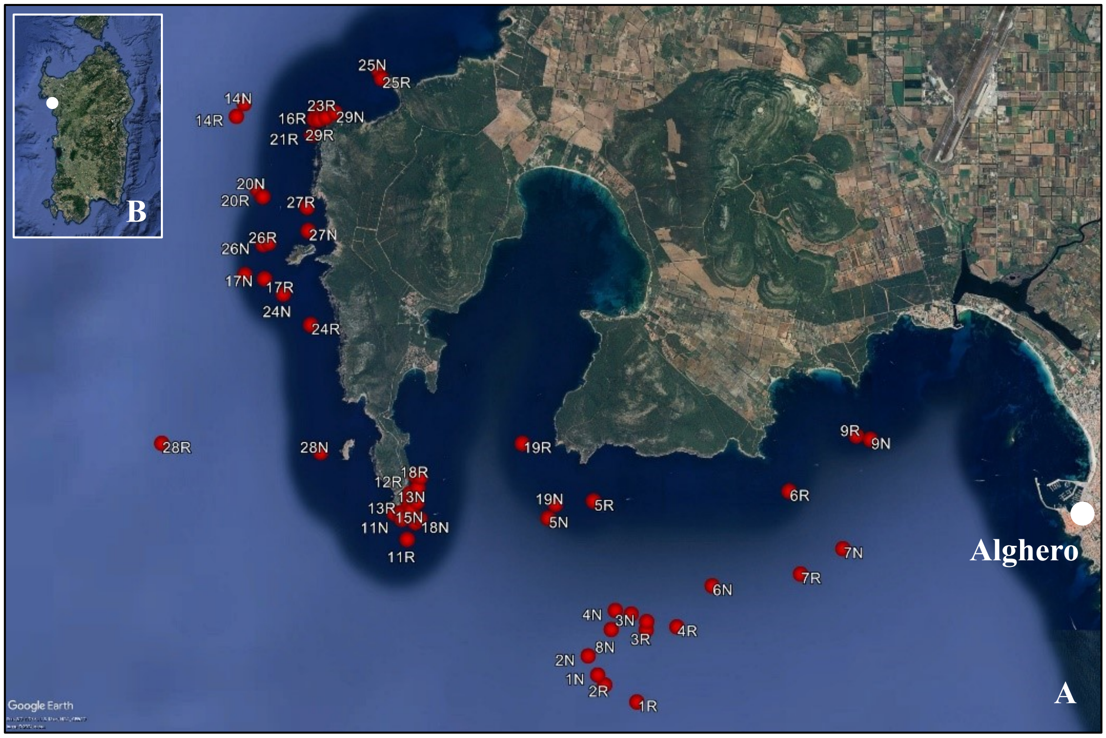


Figure 2 – (A) The locations of all fishing operations part of the second conservation action used to compare traditional trammel nets to the substitute trapula pot. ‘R’ denotes fishing operations using the traditional trammel nets, while ‘N’ denotes fishing operations using the substitute trapula pot. (B) Map of Sardinia to be used as a reference for the location of the operations on a larger scale.

GPS Coordinates for Fishing Operations Comparing Traditional Trammel Nets to the Small Trapula Pot

Fishing Operation	Latitude	Longitude	Fishing Operation	Latitude	Longitude
1R	40.527950	8.216467	1N	40.532517	8.207733
2R	40.530830	8.209306	2N	40.535746	8.205601
3R	40.541550	8.218667	3N	40.542833	8.215200
4R	40.540660	8.225403	4N	40.543429	8.211666
5R	40.561950	8.206800	5N	40.559050	8.196667
6R	40.563612	8.250464	6N	40.547613	8.233274
7R	40.549600	8.253000	7N	40.553883	8.262450
8R	40.540133	8.218550	8N	40.540217	8.210750
9R	40.572998	8.265461	9N	40.572377	8.268607
10R	40.559752	8.163550	10N	40.560428	8.166002
11R	40.555450	8.165183	11N	40.558850	8.164000
12R	40.566272	8.167003	12N	40.563186	8.165735
13R	40.561437	8.165559	13N	40.561763	8.167447
14R	40.627020	8.126950	14N	40.629170	8.128680
15R	40.564150	8.167548	15N	40.558314	8.167003
16R	40.627350	8.145500	16N	40.628000	8.144880
17R	40.599517	8.133283	17N	40.600200	8.128900
18R	40.565982	8.168119	18N	40.558925	8.168033
19R	40.571697	8.190905	19N	40.561417	8.198309
20R	40.613430	8.132850	20N	40.614730	8.131580
21R	40.623880	8.143770	21N	40.626550	8.144380
22R	40.559965	8.163758	22N	40.559902	8.162238
23R	40.628020	8.147370	23N	40.626470	8.145320
24R	40.591749	8.143632	24N	40.596962	8.137451
25R	40.633450	8.159400	25N	40.634870	8.158720
26R	40.605630	8.134250	26N	40.605330	8.132950
27R	40.611647	8.142783	27N	40.607664	8.143051
28R	40.571660	8.110367	28N	40.570168	8.145861
29R	40.626850	8.146930	29N	40.627630	8.149050

Table 2 - The GPS coordinates for the fishing operations comparing traditional trammel nets to the trapula pots.

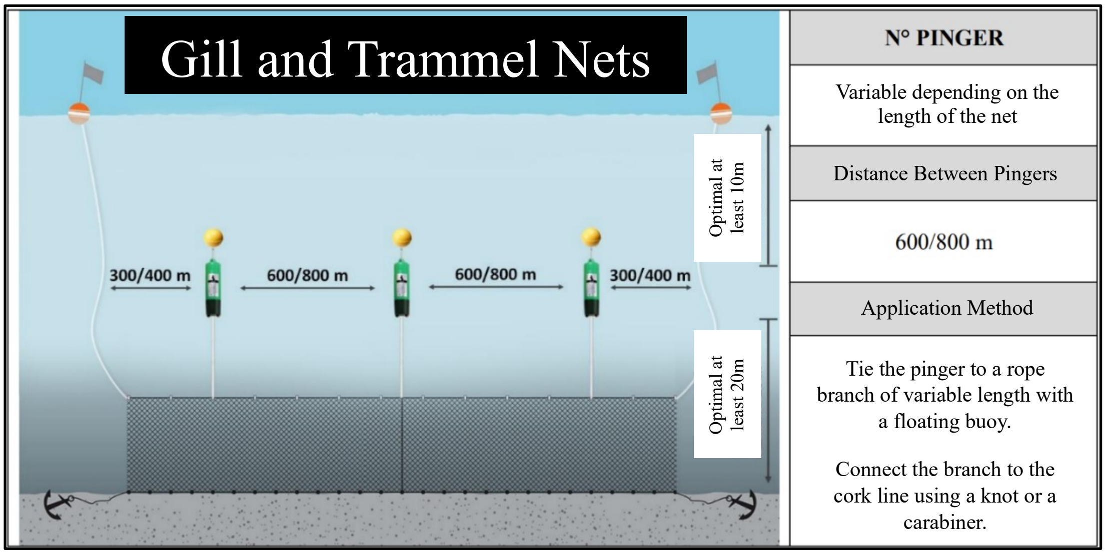
All fishing operations were conducted by fishers who sell their catch in the markets. No fishing operations were for purely experimental purposes.

Conservation Action 1: Acoustic Deterrent Device

The pingers used in this study were the Dolphin interactive Dissuasor model 01 (DiD01) which is a version of the Dolphin Dissuasive Device (DDD) as displayed in Figure 3. The DiD01 is designed to be in stand-by mode until marine mammals are detected within range of the pinger using their echolocation clicks. Once marine mammals are detected, the DiD01 begins to produce ultrasound emissions. DiD01 reacts to the acoustic signals from marine mammals and interferes with them to create an obstacle in the detection of their prey. Being in stand-by mode, and only emitting signals when marine mammals are detected, increases the battery life of the pinger, reduces acoustic pollution in comparison to other pingers that run continuously, and reduces the likeliness of habituation by marine mammals. The DiD01 emits acoustic signals at frequencies between 5 and 500 kHz. This model of pinger emits sounds at random intervals with an emission power of 165dB. This model of DDD was chosen based on this characteristic of emitting frequencies at random intervals to prevent habituation of the dolphins (STM Industrial Electronics, n.d.)

Figure 3 - The Green Line of Dolphin Deterrent Devices. Model DiD01.

Pingers were attached to nets using knots directly on the line or with carabiners. Each net type had pingers positioned at strategic points to maximize acoustic coverage. Figure 4 depicts the design and setup of the pinger attachment to gill and trammel nets. For nets shorter than 600 meters, one pinger was attached in the center of the net.



N° PINGER
Variable depending on the length of the net
Distance Between Pingers
600/800 m
Application Method
Tie the pinger to a rope branch of variable length with a floating buoy. Connect the branch to the cork line using a knot or a carabiner.

Figure 4 - The setup of the pinger(s) on gill and trammel nets.

A total of 138 fishing operations were conducted comparing nets with pingers (69 operations) to nets without pingers (69 operations).

The control and experimental version of each fishing operation was conducted in similar locations at similar times to keep other variables such as location and time as consistent as possible without interfering with each other.

Conservation Action 2: Replacing Trammel Nets with Traps

Trammel nets were tested with an experimental trap (trapula pot) designed to eliminate bottlenose dolphin bycatch and depredation. The trammel nets had lengths between 350 and 550 meters and were made of nylon.

The trapula pots were designed to allow fish entry while preventing dolphin bycatch. They measured 40 centimeter height x 100 centimeter width and were constructed from a metal frame with nylon line. The mesh was diamond shaped. Figure 5 depicts the design of the trapula pot. It was designed to be both effective in catching fish, having three chambers (displayed on the left of Figure 5), and preventing dolphin depredation while also being space efficient on fishing vessels, with the ability to flatten during storage (displayed in the right side of Figure 5) (Petetta et al., 2020).

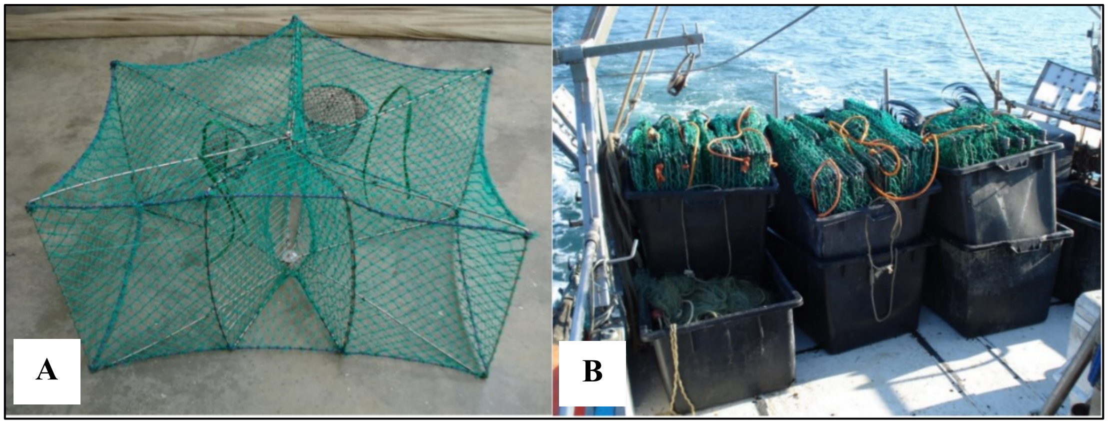


Figure 5 – (A) The trapula pot, used in the project, expanded. (B) The trapula pot folded.

A total of 58 fishing operations were conducted comparing the trammel nets (29 operations) to the trapula pots (29 operations). The process involved training fishers on the use of the new trapula pot and standardizing their deployment to match the conditions of trammel net operations. The effectiveness of the trapula pots was evaluated by comparing the CPUE and species richness to those obtained by traditional trammel nets.

The control and experimental version of each fishing operation was conducted in similar locations at similar times to keep other variables such as location and time as consistent as possible while still avoiding interference with each other.

Data Collection

The locations of all fishing operations were recorded using GPS devices to ensure precise spatial data. During fishing operations comparing nets with and without pingers, the presence of dolphins was noted by the fishers. After each fishing operation, catch data was collected by taking pictures of the fish laid out near a ruler (Figure 6); their lengths to be measured later using ImageJ software to obtain CPUE measurements. The biomass of each fish was obtained using the length of each fish measured in ImageJ and a formula developed for each species from parameters listed in FishBase, the global species database of fish species.

Figure 6 - Some of the landings of one of the fishing operations laid out next to a ruler to be measured using ImageJ.

Differences between Control and Experimental Operations

There were some differences between compared operations, but otherwise were kept as similar as possible.

1. **Date** – The date was kept the same for all pairs of operations (nets with and without pinger, trammel nets and trapula pots) being compared to ensure consistency between operations based on variables such as weather conditions and time of season.
2. **Soak Time -** There were slight differences in soak time due to the preferences of the fishers or ease of placing and removing the fishing gear based on location, time of day, and sea conditions for the operations comparing the effectiveness of using a pinger. For the operations comparing the trapula pot to trammel nets, differences in soak time were standardized using the CPUE formula.
3. **Net Length** – The net length varied in some instances but for most compared operations, the length was kept the same.
4. **Gear Type -** There was only one instance in which two compared operations used different net types during the pinger/no pinger operations (gillnet used in the pinger operation and trammel net used in the no pinger operation).

5. **Latitude and Longitude -** There were differences between the latitude and longitude of the pairs of operations (nets with and without pinger, trammel nets and trapula pots) being compared, but this was due to preventing as much interference as possible between operations so that other variables such as time of day could be kept consistent (GPS coordinates seen in Tables 1 and 2).
6. **Depth of Fishing Site** – Since the effect of depth on species richness was being tested, there were, at times, large differences in depth of fishing site between sites that were not being compared, for example, sites with no pingers attached to them. The depths between compared fishing sites, for example, 1P and 1NP, were kept the same or very close for the majority. However, there were compared sites that had differences greater than one meter due to the preferences of fishers and the difficulty of setting nets and traps of compared operations at the same depth but far enough away from other nets and traps so that they do not interfere with each other.

Data Analysis

Conservation Action 1: Acoustic Deterrent Device

The 69 fishing operations without pingers were compared to the 69 operations with pingers. Generalized Linear Models (GLM) were used to check for significant differences between CPUE and species richness.

Conservation Action 2: Replacing Trammel Nets with Traps

The 29 trammel net operations were compared to the 29 operations using the new trapula pots. Two-sample t-tests assuming equal variances were used to determine significant differences in CPUE and species richness between the trammel nets and trapula pots.

III. RESULTS

Conservation Action 1: Acoustic Deterrent Device

CPUE

CPUE had a significant correlation with the presence of dolphins (Figure 7), type of net (Figure 8), and presence of pingers (Figure 9). The GLM results are displayed below in Table 3. The p-values for gear type, dolphin presence, and pinger presence were significant, having a value less than 0.05. The intercept p-value was extremely low, indicating that even without any predictors, the baseline level of CPUE is statistically significant. Depth was not significant in terms of CPUE (Table 3).

The dispersion parameter for the Gamma distribution, which affects the distribution's shape, was estimated, with a value of 0.4484302 indicating a good fit.

The distribution of residuals was close to zero, with values ranging from -1.834 to 1.9459. These values suggest that the model has a good fit.

The null deviance was 88.366 on 137 degrees of freedom when no predictors are used. The residual deviance was 57.578 on 133 degrees of freedom, which is a considerable reduction from the null deviance, indicating a good model fit.

The Akaike Information Criterion (AIC) had a low value of 1400.1, indicating a better model in terms of predictive accuracy.

The model converged after 7 Fisher scoring iterations, which is typical and suggests that the model fitting process was stable.

The use of the Gamma family with an inverse link function was effective in modeling the relationship between the predictors and CPUE.

	Estimate	Standard Error	t-value	Pr(>|t|)
Intercept	1.4820E-02	3.5060E-03	4.2260	**4.3900E-05**
Gear (Trammel)	7.6770E-03	2.1880E-03	3.5090	**6.1400E-04**
Dolphins (Yes)	4.8000E-03	2.2630E-03	2.1210	**3.5758E-02**
Depth	-1.6190E-03	8.2480E-05	–1.9620	5.1795E-02
Pinger (Yes)	-3.3110E-03	1.4230E-03	-2.3270	**2.1472E-02**

Table 3 – GLM results for CPUE. Significant p-values are shown in bold.

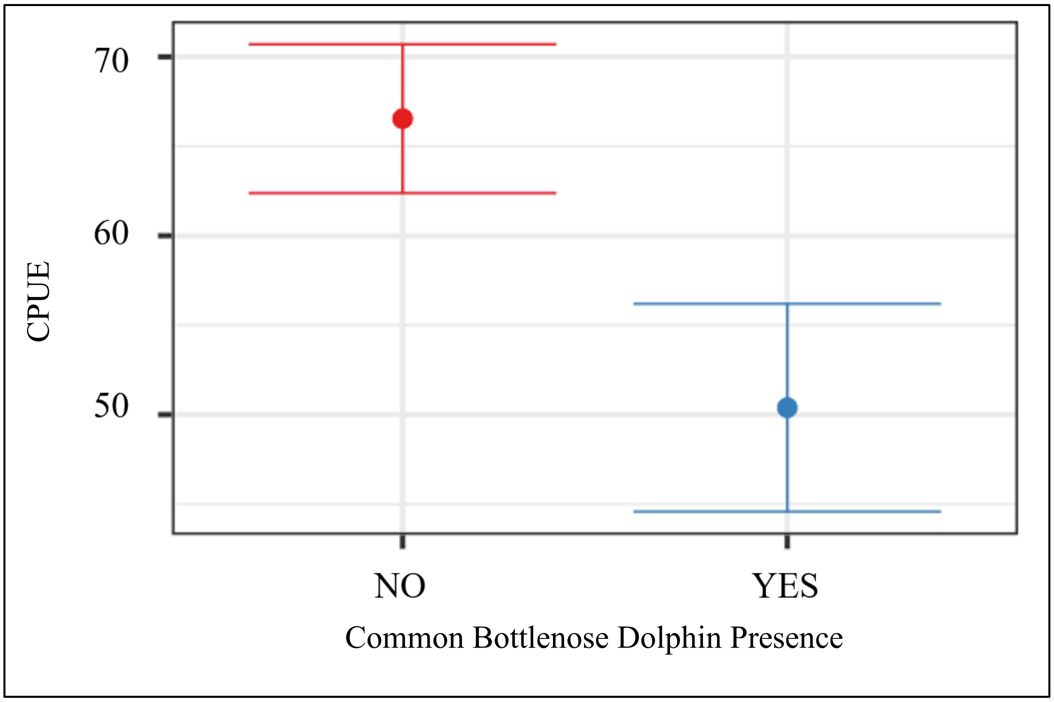


Figure 7 - CPUE in relation to dolphin presence.

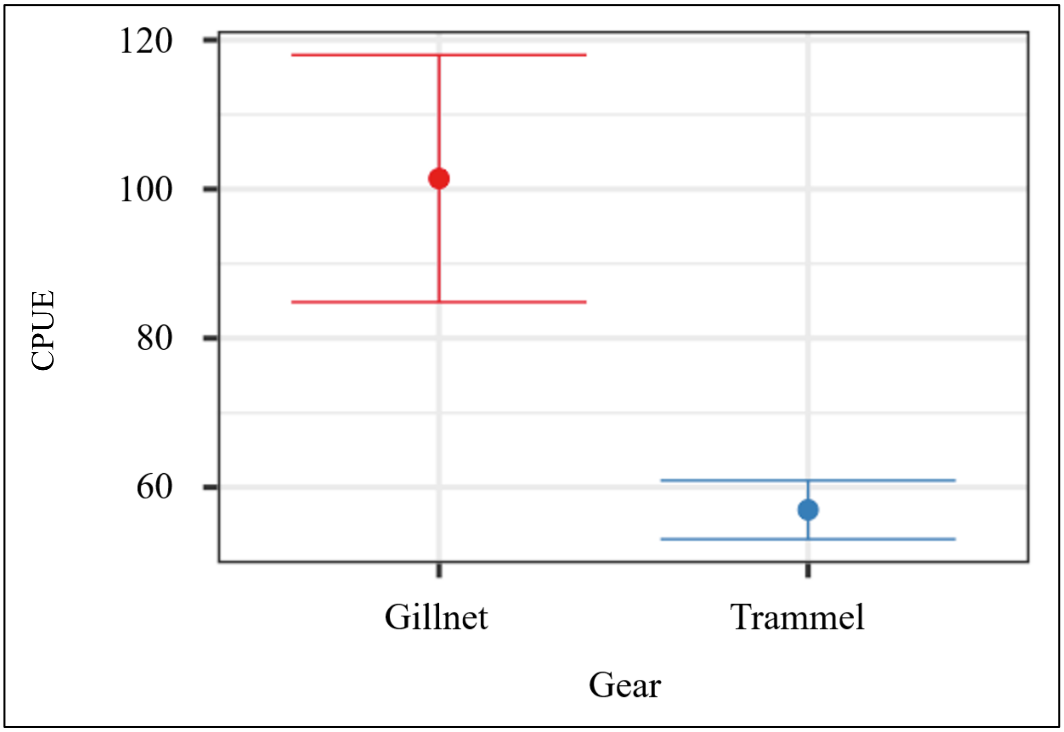


Figure 8 - CPUE in relation to net type. CPUE was higher for gillnets than trammel nets when dolphins were not present.

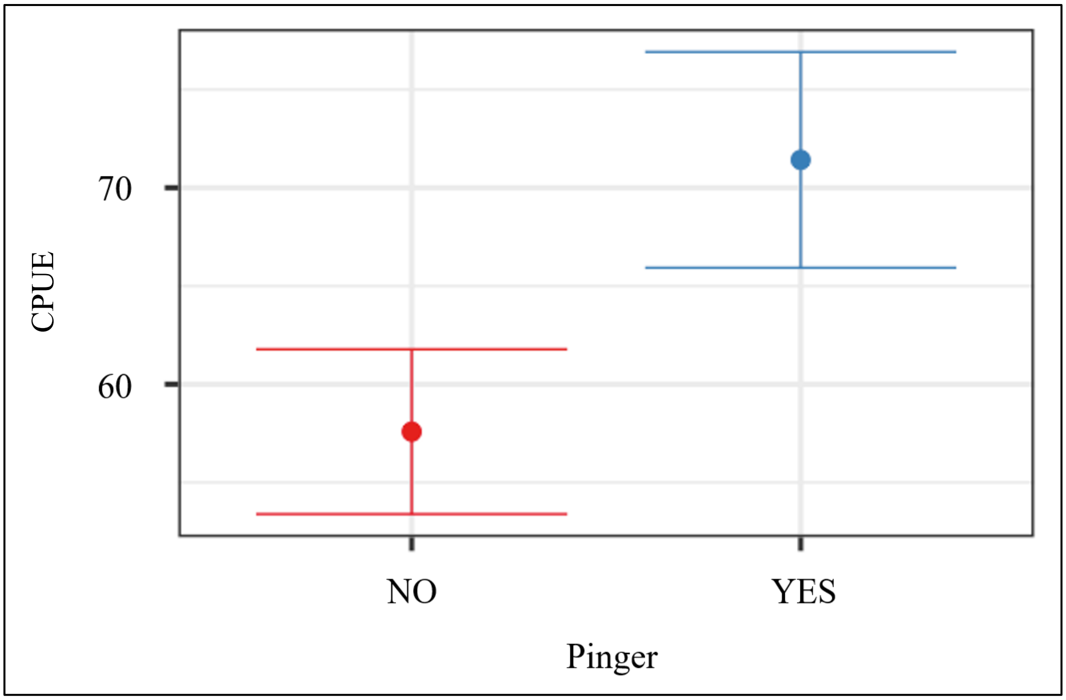


Figure 9 - CPUE in relation to presence of pinger.

Species Richness

Species richness had a significant correlation with the presence of dolphins (Figure 10) and depth (Figure 11). The GLM results are displayed below in Table 4. The p-values for dolphin presence and depth were significant, having values lower than 0.05. The intercept p-value was extremely low, indicating that the baseline level of species richness is statistically significant without any predictors. Pinger presence and gear type were not significant in terms of species richness.

The dispersion parameter for the Poisson distribution, assumed to be 1, aligns with the Poisson distribution's characteristic of equal mean and variance.

The distribution of residuals ranged from -2.29024 to 2.66254, with most residuals being close to zero, indicating that the model fits the data well.

The null deviance was 126.569 on 137 degrees of freedom when no predictors are used in the model. The residual deviance was 93.809 on 133 degrees of freedom. The reduction in deviance from the null model suggests that the model captured some of the variability in species richness.

The Akaike Information Criterion (AIC) had a low value of 612.42, indicating a better model in terms of predictive accuracy.

The Poisson regression model effectively predicted the relationship between predictors and species richness given the low AIC value, residual deviance, and convergence after only four Fisher scoring iterations, which is typical, suggesting that the model fit the data well.

	Estimate	Standard Error	z-value	Pr(>|z|)
Intercept	2.0170	1.7645e-01	1.1431e+01	**<2e-16**
Gear (Trammel)	1.4838e-01	1.1183e-01	1.3270	1.8455e-01
Dolphins (Yes)	-3.3043e-01	1.1697e-01	-2.8250	**4.7300e-03**
Depth	-8.8450e-03	4.3100e-03	-2.0520	**4.0130e-02**
Pinger (Yes)	1.9911e-02	6.6831e-02	2.9800e-01	7.6576e-01

Table 4 – GLM results for species richness. Significant p-values are shown in bold.

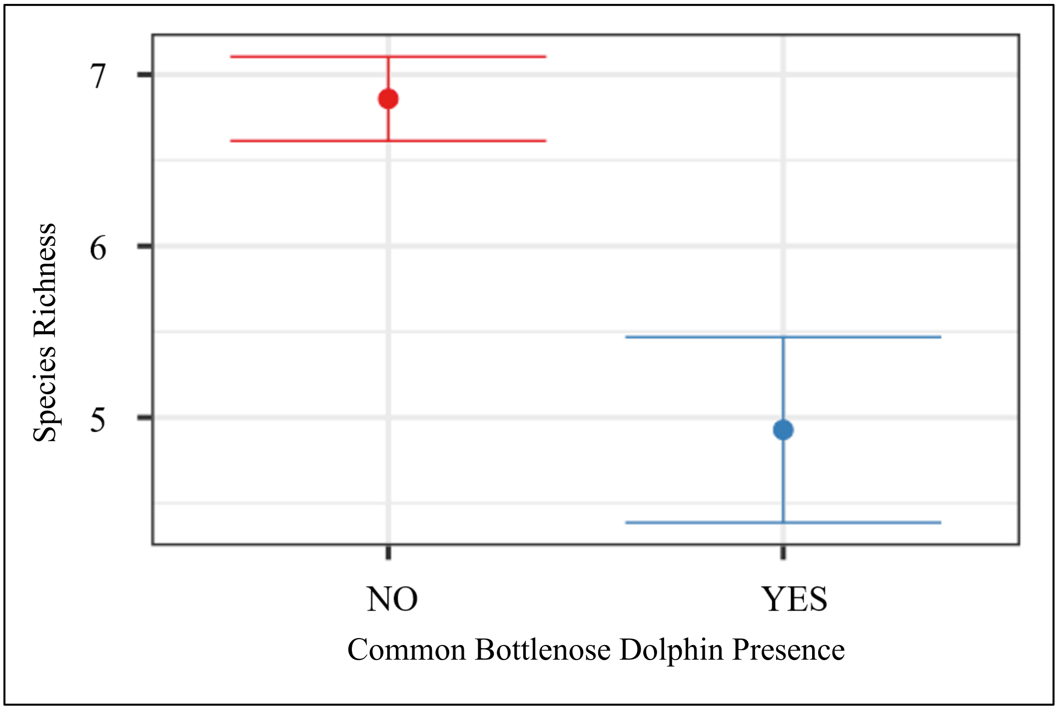


Figure 10 - Species richness in relation to dolphin presence.

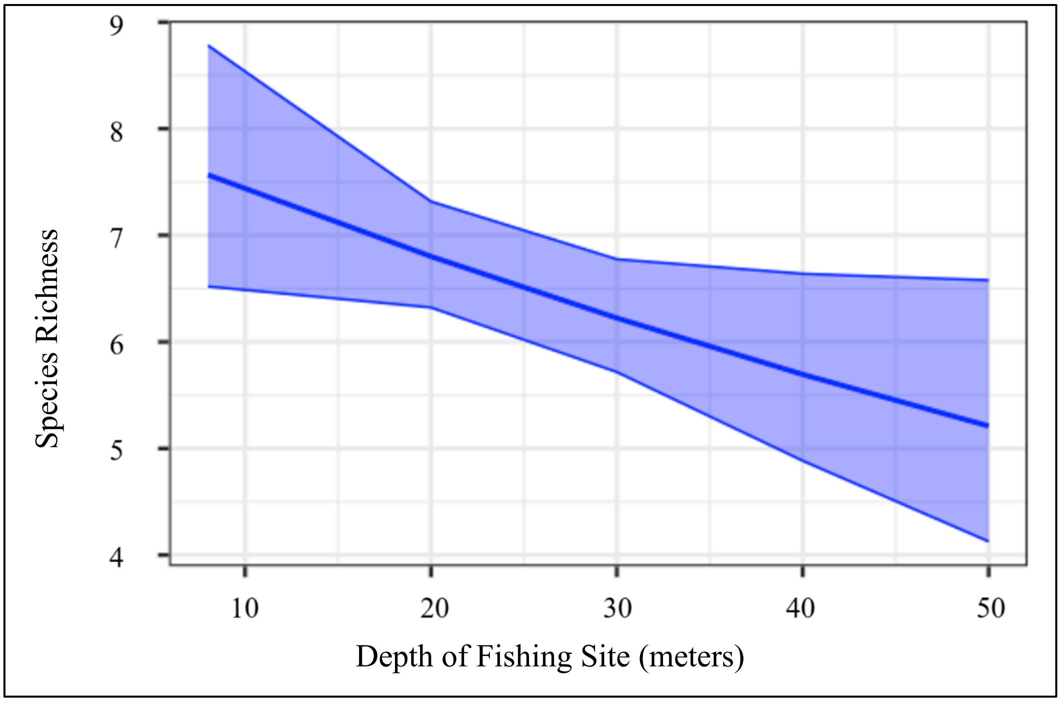


Figure 11 - Species richness in relation to depth of fishing site. The shaded area around the blue line represents the confidence interval, indicating the range within which the true value of species richness is likely to fall with a 95% confidence level.

Conservation Action 2: Replacing Trammel Nets with Traps

CPUE was significantly higher for the trapula pots than trammel nets. The t-test results show a statistically significant difference in CPUE between the trapula pots and trammel nets, with the trapula pots resulting in a significantly higher CPUE. (Table 5). The average CPUE using the trapula pots is 42.90 kg with a standard deviation of 26.07 kg. The average CPUE using the trammel nets is 12.43 kg with a standard deviation of 8.36 kg.

	Trap	*Trammel Net*
Mean	42.8979	12.4261
Variance	704.1812	72.3918
Observations	29	29
Pooled Variance	388.2865	
Hypothesized Mean Difference	0	
df	56	
t Stat	5.8885	
P(T<=t) one-tail	1.15E-07	
t Critical one-tail	1.6725	
P(T<=t) two-tail	2.31E-07	
t Critical two-tail	2.0032	

Table 5 - The results of the t-test assuming equal variances for a significant difference in CPUE when replacing traditional trammel nets with the trapula pots.

Species richness was significantly higher in trammel nets than in the trapula pots. The t-test results show a statistically significant difference in species richness between the trapula pots and trammel nets, with the trammel nets resulting in a significantly higher species richness (Table 6).

The average species richness using the trapula pots is 3.86 with a standard deviation of 1.55 kg. The average species richness using the trammel nets is 9.93 with a standard deviation of 4.34 kg. The sample variance in species richness for the trapula pots is about 2.48 and 19.50 for the trammel nets.

	Trap	*Trammel Net*
Mean	3.8621	9.9310
Variance	2.4803	19.4951
Observations	29	29
Pooled Variance	10.9877	
Hypothesized Mean Difference	0	
df	56	
t Stat	-6.9718	
P(T<=t) one-tail	1.93E-09	
t Critical one-tail	1.6725	
P(T<=t) two-tail	3.85E-09	
t Critical two-tail	2.0032	

Table 6 - The results of the t-test assuming equal variances for a significant difference in species richness when replacing traditional trammel nets with the trapula pots.

IV. DISCUSSION

This study aimed to evaluate the effectiveness of pingers and the trapula pots as mitigation tools to reduce bottlenose dolphin depredation on static net small-scale fisheries in the Mediterranean Sea. The statistical approach used in this study provides strong evidence supporting the effectiveness of traps in mitigating common bottlenose dolphin depredation and highlights the nuanced effects of different fishing gear on marine biodiversity. The findings underscore the importance of employing rigorous statistical methods to evaluate the impact of conservation tools, ensuring that management decisions are based on solid empirical evidence. The use of generalized linear models could further account for variability and improve the strength of the analysis (Zuur et al., 2010). The results offer valuable insights into the impacts of these conservation measures on CPUE and species richness, highlighting the complex dynamics between marine megafauna and fisheries. It is important to recognize that the data contributing to this research is still ongoing and statistical analysis was conducted on the data currently collected at the time of writing.

Key Findings

1. Conservation Action 1: CPUE and species richness in relation to dolphin presence

Our study found that the presence of dolphins significantly decreased both the CPUE and species richness across different fishing operations for conservation action 1. This substantial reduction highlights the considerable impact of dolphin depredation on local fisheries and represents a significant economic loss for fishers. The economic challenges posed by dolphin depredation are multi-faceted. Firstly, fishers may face increased operational costs. To compensate for lost catch, fishers might extend their fishing trips, use more gear, or fish in less familiar areas, all of which can increase fuel and labor costs. Additionally, damaged fishing gear due to dolphin interactions requires repairs or replacements, further escalating costs. To mitigate these economic losses, government intervention might be necessary. Subsidies or compensation programs could help sustain the livelihoods of affected fishing communities. Such interventions have been suggested in previous research and are critical for maintaining the economic viability of fisheries in regions with high dolphin activity (Bearzi et al., 2011). Without these subsidies or compensation programs, fishing communities might struggle to remain economically viable, leading to increased unemployment. Our findings align with previous research documenting similar reductions in CPUE in regions affected by dolphin depredation. For instance, studies by Lucas and Berggren (2023) and Tixier et al. (2021) have reported substantial decreases in fish catch due to dolphin interactions. These studies emphasize the widespread nature of the problem, and the consistent challenges faced by fisheries worldwide.

2. **Conservation Action 1: Relationship between CPUE and gear type**

   CPUE was significantly higher when using gillnets compared to trammel nets in the absence of pingers and dolphins. This difference suggests that gillnets may be more efficient or effective in capturing the target species under the given conditions.

   The higher CPUE observed with gillnets could be attributed to various factors such as the design and functionality of the gear, which might allow for more efficient entanglement, and therefore, capture of fish. In contrast, the lower CPUE with trammel nets could suggest they are less effective under the same conditions, possibly due to differences in mesh size, construction, or behavior of the target species in response to these nets.

   Furthermore, the confidence intervals represented in Figure 8 show a wider range for gillnets, indicating some variability in CPUE, while the narrower range for trammel nets suggests more consistent but lower performance. The findings imply that in scenarios where dolphins are not present, gillnets might be the preferred choice for maximizing catch efficiency, but the variability also suggests a need for further investigation into the factors influencing this efficiency.

3. **Conservation Action 1: Relationship between CPUE and species richness to pinger presence**

   Nets equipped with pingers showed a slightly higher CPUE compared to those without pingers, suggesting that pingers may deter dolphins to a certain extent. However, the presence of pingers did not significantly affect species richness, indicating that while they might be effective in reducing dolphin interference with nets, they do not substantially alter the composition of the catch. This finding is crucial as it highlights the need for pingers that not only reduce depredation but also maintain or enhance biodiversity. The limited impact on species richness also suggests that pingers, as currently designed, might not address the broader ecological impacts of fishing activities. This is consistent with studies such as Goetz et al. (2014), which reported results that showed evidence of negative impacts of pingers on fish, inducing stress.

   However, it is crucial to consider the role of dolphins in this context. Dolphins typically exhibit selective feeding behaviors, preferring certain species of fish over others. This predatory preference can lead to changes in the local abundance and distribution of fish species, which may confound the effects of pingers on species richness. For example, if dolphins preferentially consume certain fish species, these species might be underrepresented in areas with high dolphin activity, irrespective of the presence of pingers. Conversely, fish species that are less preferred by dolphins might appear more abundant in such areas.

Therefore, while our study shows that pingers do not directly relate with changes in species richness, the presence of dolphins and their specific preferences of certain fish species should be considered as a potential variable influencing the observed patterns in fish populations during the pinger/no pinger operations (Blanco et al., 2001). Further studies could benefit from detailed observations of dolphin activity and diet composition to better understand the complex interactions between predator presence, prey availability, and the effects of pingers on marine ecosystems. Studies done to understand how pingers impact species richness without the presence of dolphins, would also be beneficial to increasing understanding on how both dolphins and pingers combined have an impact on species richness and which variable plays a larger role and under which circumstances.

The effectiveness of pingers in deterring marine mammals, including dolphins, can vary significantly based on the frequency and sound pattern emitted by the devices. The frequency refers to the pitch of the sound, measured in hertz, while the sound pattern includes the timing, duration, and modulation of the sound pulses. Research has shown that dolphins, along with other marine animals, can habituate to consistent noise signals over time (Houser et al., 2013).

Habituation is a behavioral adaptation where an animal's response to a stimulus decreases after repeated exposure. For example, if pingers consistently emit the same sound at a fixed frequency and regular interval, dolphins might initially avoid the area due to the unfamiliar or startling noise. However, as they repeatedly encounter this predictable sound without experiencing any real threat, they may become accustomed to it and no longer react by avoiding the area. This process can undermine the long-term effectiveness of pingers in deterring dolphins (Gönener and Özsandıkçı, 2017).

To prevent habituation, it is recommended to use pingers with variable frequencies and irregular sound patterns similar to the model used in this study. Variable frequency pingers emit sounds at different pitches within a certain range, making it harder for dolphins to predict and become accustomed to the noise. Irregular sound patterns involve varying the timing, duration, and modulation of the sound pulses, adding another layer of unpredictability. These variations are more likely to maintain the pingers' effectiveness over time by continuously presenting a novel and potentially disturbing stimulus to the dolphins. Additionally, incorporating periods of silence or changing the amplitude (loudness) of the sound can further enhance the deterrent effect (Gönener and Özsandıkçı, 2017).

It is important to note that water and weather conditions were not recorded during this study which could have impacted the function of the pingers. The distance that the sound from a pinger travels can vary based on several factors aside from the type of pinger, its frequency, and power output. The environmental conditions in the water, such as temperature and salinity can also impact the function. Generally, pingers are designed to be heard by marine mammals within a specific range to deter them from approaching fishing gear. It is difficult to know for sure that there was no interference between nets with pingers and nets without pingers.

Nets equipped with pingers could potentially interfere with other fishing operations if different fishers set their nets too close to each other without realizing it as possible to be seen by some of the GPS coordinates in Tables 1 and 2. If multiple nets are deployed in close proximity, the overlapping signals could create confusion, either repelling the target species or causing the dolphins to avoid a broader area than intended. This unintended effect could reduce the effectiveness of the pingers, leading to diminished catches for all fishers involved. Additionally, the dense concentration of acoustic signals might cause disorientation in marine mammals, affecting their natural behaviors and potentially leading them to avoid critical feeding or migration areas. The lack of coordination and communication between fishers setting nets in the same vicinity could exacerbate these issues, highlighting the need for careful spatial planning and collaboration when using pingers to ensure that their benefits are maximized without unintended negative impacts on other fishing operations and marine life (Dawson et al., 2013).

4. Conservation Action 1: Species richness in relation to depth

Figure 11 shows a downward trend in species richness as the depth increases. Depth of the fishing site is defined as the depth the nets were set at which is also usually the total depth since the nets are typically set on the seafloor. This means that species richness tends to decrease as the depth of the fishing site increases. The width of the shaded area (confidence interval) increases with depth, suggesting greater variability or uncertainty in species richness estimates at greater depths. There is a clear negative relationship between depth and species richness: as the depth increases from 0 to 50 units, species richness decreases. This negative relationship indicates that shallower fishing sites tend to have higher species richness compared to deeper sites.

The increasing width of the confidence interval with depth suggests that there is more uncertainty or variability in species richness at deeper sites.

Since species richness was adversely affected by the presence of common bottlenose dolphins and decreased with increasing depth of fishing sites, these findings could suggest that common bottlenose dolphins may preferentially target deeper fishing areas, and/or that the areas shallower than 50 meters naturally support a higher diversity of species due to other factors such as the presence of the seagrass beds. Fishers tended to prefer to operate in shallower waters (less than 50 meters), which they said was a response to common bottlenose dolphin behavior favoring hunting at depths greater than 50 meters which could be due to the presence of seagrass beds, specifically *Posidonia oceanica*, which typically end around this depth at 40 to 45 meters (Telesca et al., 2015). These seagrass beds provide a rich habitat for a variety of marine life, including fish and invertebrates that common bottlenose dolphins prey upon (Lattanzi et al., 2024). Beyond the seagrass beds, the open water offers a different array of prey species that are more abundant and accessible without the dense underwater vegetation. The transition zone at the edge of the seagrass beds creates a diverse and dynamic environment where common bottlenose dolphins can exploit both the resources of the seagrass habitat and the deeper, open waters (Notarbartolo di Sciara, 2002).

The relationship between depth and species richness highlights the importance of understanding spatial dynamics in fisheries management and the need to consider habitat characteristics when implementing conservation measures as well as considering the observations of the fishers. Furthermore, the spatial distribution of fish species in relation to depth can be influenced by many other environmental variables such as temperature, salinity, and habitat structure (Farré et al., 2016).

5. Conservation Action 2: CPUE comparison between nets and traps

Our study revealed that the CPUE was significantly higher in trapula pots compared to trammel nets, suggesting that the trapula pots might be a more efficient method of fishing, particularly in the context of dolphin depredation. This increased efficiency can be attributed to the design characteristics of traps that potentially reduce the likelihood of dolphin interactions.

Traps are generally designed to capture fish by using a combination of entry funnels and restrictive pathways that lead fish into a confined area. This design not only makes it more challenging for dolphins to access the trapped fish but also minimizes the opportunities for depredation. Dolphins may find it difficult to reach the fish due to the physical barriers and narrow openings, which can help protect the catch from being consumed or damaged by dolphins. As a result, traps can achieve higher CPUE.

Conversely, our findings indicated that species richness was higher in trammel nets than in the trapula pots. Trammel nets, which are composed of multiple layers of mesh, tend to catch a wider variety of species due to their broader, more flexible netting structure. This setup allows trammel nets to capture a more diverse array of fish sizes and species, including those that might not fit through the openings of a trap. The higher species richness in trammel nets suggests that while traps may excel in catching larger quantities of specific target species, trammel nets are better suited for capturing diverse marine species.

The trade-off between catch efficiency and species diversity is a crucial consideration for fisheries management. Traps, while more effective in increasing CPUE, may lead to a more selective catch that prioritizes certain species over others. This could result in a loss of biodiversity if the traps preferentially capture specific species while allowing others to escape. On the other hand, trammel nets, with their broader mesh design, support the capture of a diverse range of species, which is important for maintaining the ecological balance of marine environments.

This trade-off highlights the need for fisheries management strategies that balance the goals of maximizing catch efficiency with the preservation of species diversity. Strategies that prioritize only CPUE might lead to overfishing of target species and disruption of the marine ecosystem, potentially harming the sustainability of fish populations and other marine organisms (Hoyle et al., 2024).

The observations of this study are consistent with previous studies that have documented similar trade-offs in other fisheries. For example, research by Bearzi et al. (2011) has highlighted how different fishing gear can impact both the efficiency of catch, and the diversity of species captured. These studies underscore the importance of considering both economic and ecological factors when evaluating fishing methods.

To address these challenges, future research should focus on the design and implementation of more selective fishing gear that balances the goals of maximizing CPUE with maintaining species diversity. Innovations in trap design, such as adjustable mesh sizes or exclusion devices that allow non-target species to escape, could help achieve this balance. Research by Gilman et al. (2022) emphasizes the need for developing such selective fishing gear to enhance both catch efficiency and ecological sustainability.

6. **Conservation Action 2: Species richness in nets versus traps**

   The comparison of species richness between nets and traps resulted in insights into the ecological impacts of each fishing method. While traditional trammel nets captured a higher diversity of species, the use of the trapula pots demonstrated a significant advantage in terms of reducing bycatch and depredation, and therefore minimizing unintended ecological consequences. This result aligns with the conservation goal of promoting sustainable fishing practices that do not compromise marine biodiversity. The higher species richness observed in nets may be attributed to their broader capture range, but this comes at the cost of higher bycatch, which can negatively affect non-target species populations. On the other hand, traps, with their more selective design, provided a viable alternative by targeting specific species, thus supporting the dual objectives of maintaining fishers' livelihoods and protecting marine ecosystems. These findings underscore the importance of integrating species richness considerations into the evaluation of alternative fishing gear to balance economic and conservation goals effectively.

Errors and Limitations

Despite the comprehensive approach taken in this study, several limitations and potential sources of error should be acknowledged, which may influence the interpretation of the results.

1. **Variability in Dolphin Behavior:** Bottlenose dolphins are known for their complex and adaptive behaviors, which can vary significantly across different populations and environments. The dolphins' responses to ADDs and traps used in this study may not be indicative of behaviors in other areas or under different environmental conditions, potentially limiting the broader applicability of the results.

2. **Continued Data Collection:** The data collection period is still ongoing, and although already extensive, the results may be different after continued observation and data collection.

3. **Technological and Operational Challenges:** The use of ADDs and modified traps presented operational challenges that could influence the outcomes. For instance, variations in the deployment and maintenance of these devices, as well as potential malfunctions, could have affected their effectiveness, introducing a source of bias in the results.

4. **Fishers' Compliance and Reporting Accuracy:** The effectiveness of conservation measures heavily relies on the compliance and accurate reporting

by the fishers involved. Any inconsistencies or inaccuracies in data reported by the fishers, whether intentional or unintentional, could lead to skewed results. Furthermore, the willingness of fishers to participate may have influenced the sample's representativeness.

5. **Environmental and External Factors:** External factors such as weather conditions, oceanographic variables, and other anthropogenic activities (e.g., tourism, commercial fishing) were not fully controlled or accounted for in this study. These factors could have influenced both dolphin behavior and fish availability, potentially confounding the results.
6. **Potential Observer Bias:** Although measures were taken to standardize observations, the potential for observer bias exists, especially in qualitative assessments of dolphin interactions and fishers' responses. Human error in data recording and interpretation could introduce inaccuracies, particularly in behavioral observations.

By recognizing these limitations, future research can address these gaps, contributing to a more nuanced understanding of the complex interactions between marine predators, fisheries, and conservation strategies.

Implications for Conservation, Fisheries Management, and Future Research

This study underscores the importance of adaptive management frameworks that integrate scientific research, technological innovations, and socio-economic considerations. Future research should address several key areas to enhance the sustainability and effectiveness of conservation actions. Specifically, the following points are crucial for future conservation and research efforts:

1. **Long-term Monitoring and Adaptation**

   Continued monitoring of dolphin behavior and depredation patterns over the long term is essential to understand the adaptive responses of dolphins to mitigation measures and to refine these strategies accordingly. Long-term data collection can reveal trends and shifts in dolphin behavior, as well as in fish populations, that might not be apparent in short-term studies, providing a more comprehensive understanding of the effectiveness and potential unintended consequences of mitigation tools. This approach also helps to create a management system more likely to succeed in the dynamic marine environment (Lewison et al., 2004). Long-term research is also crucial for identifying and protecting critical habitats and migration routes essential for dolphin conservation (Langhammer et al., 2024). Furthermore, long-term studies can track changes in the economic viability of fisheries as they adapt to new conservation measures, offering insights into the persistence of depredation behaviors and the durability of implemented solutions as well as to gain a more in depth understanding of the combined impacts of different conservation measures. Such studies inform adaptive management strategies by providing data on the effectiveness of different mitigation measures over time (Cury et al., 2005).

2. **Behavioral Ecology Studies**

   Detailed research into the behavioral ecology of bottlenose dolphins, including their prey preferences and social learning mechanisms, can provide deeper insights into the factors driving depredation. Understanding the social structure and learning behavior of dolphins can help in designing more effective deterrent strategies that target the specific cues dolphins use to locate and depredate fishing gear. Behavioral studies can also identify critical habitats and foraging areas that might need additional protection to reduce conflict between dolphins and fisheries (Rendell and Whitehead, 2001). Additionally, studying the interactions between dolphins and other predators can provide insights into their ecological role and the broader impacts of their foraging strategies (Heithaus et al., 2008).

3. **Technological Innovations**

   Advancements in acoustic deterrent devices and other bycatch reduction technologies should continue to be explored, with a focus on minimizing acoustic habituation and maximizing deterrent effectiveness without harming marine life. Innovations such as variable-frequency pingers or devices that emit signals mimicking natural predator sounds could enhance effectiveness and reduce the likelihood of dolphins becoming accustomed to a single type of stimulus (Bruno et al., 2021). Additionally, the development of environmentally friendly materials for fishing gear that reduce the ecological footprint of fishing activities should be prioritized (Hoang et al., 2023).

   Further advancements in the field can be achieved through the development and testing of new technological solutions, including AI and machine learning applications to predict and prevent depredation events. These technologies could analyze patterns in dolphin behavior and fishing activities, providing real-time alerts or recommendations for minimizing depredation risks. Non-invasive tracking devices on dolphins, along with advances in telemetry and remote sensing technologies, have the potential to transform conservation strategies (Kleivane et al., 2022). Integrating these technologies into a comprehensive monitoring system would enhance the ability to detect and respond to depredation events in real-time (Lennox et al., 2017).

4. **Socio-economic Impact Assessment**

   Understanding the economic and social impacts of depredation and mitigation measures on fishing communities is crucial. Strategies that are economically viable, are culturally appropriate, have buy-in from fishers, and are ecologically sound are more likely to gain acceptance and be successfully implemented. Engaging with local fishers, being one of the main stakeholders, and involving them in the management process to understand their needs, concerns, and suggestions can lead to the development of more practical and accepted mitigation measures (Pomeroy and Berkes, 1997). Socio-economic assessments can also identify potential economic incentives or compensation schemes that might support fishers in adopting new technologies or practices. Additionally, education and awareness programs could help in building local capacity for sustainable fishing practices and conservation efforts. It is crucial that fishers understand that maintaining dolphin populations since they are top predators will also help maintain species richness and will keep their income consistent in the long term, even if they are content with their catch presently.

   Community-based monitoring programs can empower local stakeholders to take an active role in managing marine resources and contribute valuable local knowledge to scientific studies which is one of the keys to the success of conservation initiatives (Pretty, 2003). Furthermore, building trust and collaboration between scientists, managers, and fishers can lead to more effective and sustainable solutions (Gutiérrez et al., 2011).

5. **Policy Integration**

   Integrating the findings from this research into broader fisheries management and conservation policies can help create a cohesive strategy that addresses both ecological and socio-economic goals. Policymakers should consider the diverse impacts of dolphin depredation and mitigation measures on different stakeholders, ensuring that regulations support sustainable fishing practices while protecting marine biodiversity. Cross-sector collaboration between government agencies, research institutions, and non-governmental organizations can facilitate the development and implementation of comprehensive management plans and more effective integration of current policies (Food and Agriculture Organization, n.d.). Additionally, international cooperation is essential for addressing transboundary conservation challenges and ensuring the protection of species like dolphins (De Santo, 2013).

Conclusions

By focusing on these aspects of future research, we can develop more robust conservation measures that promote the coexistence of dolphins and fisheries, ensuring the long-term viability of both marine ecosystems and human communities in the Mediterranean region. Addressing the multifaceted challenges of dolphin depredation mitigation requires a holistic approach that combines scientific research, technological innovation, and community engagement. Through sustained efforts and adaptive management, it is possible to mitigate the negative impacts of depredation while supporting the sustainability and resilience of small-scale fisheries. It is crucial that we balance the health of the environment with the well-being of small-scale fisheries (Pauly and Zeller, 2016).

This research highlights the significant impact of dolphin depredation on small-scale fisheries and underscores the need for effective mitigation strategies. However, the research presented is just one piece of the puzzle in understanding the broader challenges faced by marine ecosystems. Even if depredation mitigation measures are successful, overfishing and pollution remain fundamental issues that detrimentally impact marine ecosystems and dolphin food sources. Overfishing has led to significant declines in fish populations, altering marine food web structures and causing trophic cascades that diminish biodiversity (Lewison et al., 2004; Pauly et al., 1998; Jackson et al., 2001). Pollution exacerbates this issue, with chemical contaminants and plastics leading to bioaccumulation and biomagnification in dolphins, while nutrient runoff causes eutrophication and hypoxic zones (Rios et al., 2007; Ross, 2000; Diaz & Rosenberg, 2008). Additionally, noise pollution from shipping, industrial activities, and military exercises disrupts the acoustic environment of marine mammals, impairing their ability to communicate, navigate, and locate prey effectively (Weilgart, 2007). Chronic exposure to elevated noise levels can lead to stress, displacement, and reduced foraging efficiency in dolphins (Arcangeli, 2022). Addressing these root causes requires comprehensive and integrated management strategies, including sustainable fishing practices, pollution reduction, and international cooperation to combat illegal, unreported, and unregulated (IUU) fishing (Derraik, 2002; Carpenter et al., 1998; Agnew et al., 2009). Implementing ecosystem-based management approaches that consider the cumulative impacts of human activities can provide a holistic framework for achieving sustainable fisheries and biodiversity conservation, ensuring the long-term health and sustainability of both marine ecosystems and human communities (Pauly et al., 2002; Kenny et al., 2018).

It is exciting to note that data collection is still ongoing, and as more data becomes available in the future, it will provide an even larger sample size that could further refine and enhance the results presented in this thesis.

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