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Original research article

Fishing effort and enforcement in the Azores Marine Protected Areas: How prevalent is illegal fishing?

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ABSTRACT

Fishing is a significant global food source, providing protein for millions of people. The Food and Agriculture Organization (FAO) is committed to ensuring access to high-quality food, reducing hunger, and promoting sustainable fisheries to address global population growth and hunger. However, illegal, unreported, and unregulated fishing poses a significant challenge, threatening marine biodiversity and food security. Portugal has the 10th largest Exclusive Economic Zone (EEZ), with waters around mainland Portugal, the Azores, and Madeira. This research focuses on the Azores region, known for its traditional multispecific fishery around the island slopes and seamounts. The region's fisheries face data scarcity issues and complicating effective management. By combining Vessel Monitoring System (VMS) records from 2016 to 2022 and Portuguese Navy (PoN) Fiscalization Reports (FISCREP) from 2015 to 2022, it was possible to use appropriate metrics to characterize the fishing effort and analyze the effectiveness of the inspections conducted in the Azores EEZ. The Total *Boat-Meter* (TBM) metric combines the number and length of boats to quantify the fishing effort better. The analysis shows that the fishing effort in the protected areas is very high, highlighting the pressure on the protected ecosystems. The findings aim to assist regulatory institutions and researchers in assessing fishing pressure and promoting sustainable fisheries management in the Azores to preserve marine ecosystems.

1. Introduction

Over generations, a global effort has been made to ensure worldwide access to balanced, high-quality food and reduce hunger (Swaminathan, 2016). The Food and Agriculture Organization (FAO), a specialized United Nations (UN) agency established in 1945, leads international efforts to achieve food security (FAO, 2024). The FAO aims to make fisheries more sustainable and productive while ensuring fishing practices contribute to food security and the well-being of fishing-dependent communities. These efforts are crucial in the face of global population growth to address and ideally eliminate worldwide hunger (Dodson et al, 2020; Gerlach, 2024).

As a worldwide food source, fishing plays a significant role as a source of protein for the livelihoods of millions worldwide. It is one of the major food production industries that relies on the natural cycles of a highly diverse group of wild populations (FAO, 2022), but this comes with a cost. Illegal (Agnew et al., 2009) or excessive exploitation (Willis et al., 2023) could directly endanger marine life and the quality of product distribution. Since it is uncontrolled, it decreases global food security and increases the probability of health issues for the worldwide population. To guarantee sustainable fisheries management, marine biodiversity conservation, balancing stakeholder interests, combating illegal fishing, and promoting scientific research, the FAO began creating fishing areas in the 1960s (FAO, 2024), as illustrated in Fig. 1. FAO fishing areas are regions of the world's oceans designated for managing and regulating fisheries, providing a framework for data collection, reporting, management, and conservation efforts aligning with strategic objectives to protect ocean resources for future generations. Regarding the Azores, some studies have indicated that the actual fishery catch was 17 % higher than the official figures (Pham et al.,

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2013) and that approximately 40 % of limpet harvesting took place in restricted zones (Diogo et al., 2016), clearly highlighting the issues surrounding Illegal, Unreported, and Unregulated Fishing (IUUF) and its threat to biodiversity and hindrance to ecosystem conservation.

The international community has long been concerned about Illegal, Unreported, and Unregulated Fishing (IUUF), which leads to the loss of social and economic opportunities and negatively impacts food security and environmental stability (Agnew et al., 2009). In 1995, the FAO code of conduct included a plan of action with strategic objectives to prevent, detect, and eliminate IUUF (Food and agriculture organization, 2001; Kao, 2015). Just like in other fields, it is essential to combat and avoid actions that could endanger one of the most critical worldwide protein sources (Gomna & Rana, 2007; Herpandi et al., 2011).

In the 1970s, member states adopted Exclusive Economic Zones (EEZs) (Juda, 1991; Pohl, 2019), which brought attention to the need to address various fishing-related issues such as access to shared resources, conservation, fleet management, and international fishing relations (Nemeth et al., 2014). This led to developing policies like the EU's Common Fisheries Policy (CFP), which oversees sustainable fishing practices, market regulations, and international agreements to ensure responsible management and conservation of marine resources (Casey et al., 2016; European Union, 2013). In the EU's CFP context, Portugal's national fishery authority, the Directorate-General for Natural Resources, Safety and Maritime Services (DGRM), oversees inspection activities and fishery data collection. It also ensures proper data sharing between member states and third parties as needed.

Portugal has the 10th largest EEZ in the world, including the waters around mainland Portugal, the Azores, and Madeira, which makes it challenging to control with limited resources (Rahman, 2019). The Azores region is characterized by traditional multispecific fishery, exploiting marine resources around the islands slopes and seamounts (Torres et al., 2022). The area has an economically and culturally crucial coastal subsistence fishery, but it remains understudied, poorly regulated, and lacks independent monitoring (Torres et al., 2022). Due to the collapse of limpet fisheries in the 1980s, Limpet Protected Zones (LPZs) were implemented, and seasonal fishing closures were introduced in the Azores region (Diogo et al., 2016). The establishment of Marine Protected Areas (MPAs) has also increased fish abundance and alleviate the impacts of fishing on existing marine ecosystems (Keppeler et al., 2017). The most relevant MPAs in the Azores region are *Condor*, *Princess Alice*, and *Dom João de Castro* (Governo Regional dos Açores, 2023a,b,c), since they are vital for ecological conservation, sustainable fisheries management, and supporting scientific research. In 2008, the *Condor* MPA was designated as a protected scientific observatory, given its importance for deep-sea species and human impact studies. It is also a habitat for coral gardens and commercially valuable demersal fish. The *Princess Alice* MPA is an oceanic plateau crucial for pelagic species and supports migratory species like sharks and tuna. In contrast, the *Dom João de Castro* MPA is a volcanic seamount with unique hydrothermal vents and coral gardens, serving as a marine reserve.

These MPAs were selected because *Condor* has historically been heavily fished, with enforcement largely depending on voluntary compliance due to logistical challenges (Morato et al., 2010). Likewise, *Princess Alice* remains a significant fishing ground, attracting considerable effort despite its MPA designation (Afonso et al., 2020), while *Dom João de Castro* has faced limited enforcement, making it vulnerable to illegal fishing (Abecasis et al., 2015). Furthermore, historical fisheries catch reconstructions indicate that unreported fishing activities have resulted in significant underestimations of fishing pressure in the Azores, highlighting the need for improved monitoring and protection in these MPAs (Pham et al., 2013).

Understanding and managing fisheries' impact on the Azores marine ecosystem requires a comprehensive approach to quantifying fishing efforts and their effects. Much of the focus has been on quantifying fishery catches as a measure of fishing intensity in a given area (Halpern et al., 2008; Chuenpagdee et al., 2006). This process involves systematically collecting and analyzing data on the number and size of fish caught over specific periods. This information allows regulatory institutions and researchers to evaluate the impact of fishing on local fish populations and the overall health of the marine ecosystem. One of the main challenges in understanding the impact of fisheries on marine ecosystems is the lack of data, such as the number of boats, the amount of gear used, and the frequency of fishing activity. Mapping the fishing effort offers a way to quantify the relative intensity of fishing pressure over large areas. However, challenges in quantifying and documenting this fishing activity have impeded efforts to describe and map coastal fisheries, especially for small-scale or artisanal fleets (Moore et al., 2010). These challenges must be overcome because illegal fishing is a reality that must be combated and, if possible, eliminated.

The number and type of species caught can present a helpful metric. However, it does not directly address one of the critical issues of fisheries sustainability, namely fishing gear's direct and collateral impacts on habitats and their species (Chuenpagdee et al., 2003; Lewison et al., 2004). The boat's length, the number of boats, and other characteristics of fisheries are key variables that describe the fishing effort and can serve as complementary metrics (Le Pape & Vigneau, 2001).

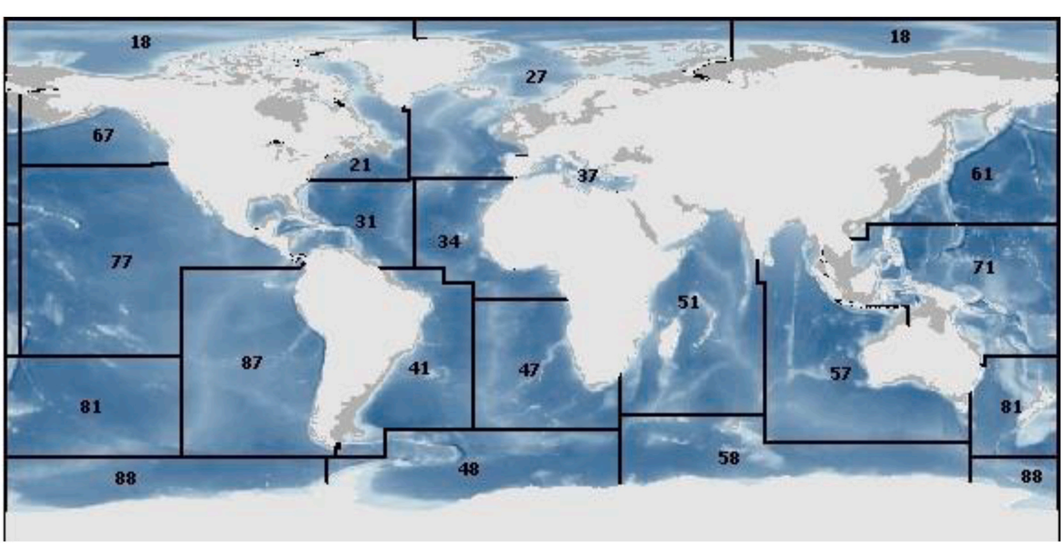

Fig. 1. Representation of FAO Fishing Areas, numbered to indicate specific marine regions worldwide, facilitating the management, monitoring, and sustainable use of global fishery resources. Adapted from FAO (2024).

Furthermore, understanding these impacts requires comprehensive data collection beyond catch numbers, incorporating information on the types of gear used and the frequency and distribution of fishing activities. Our metrics should accurately represent what we want to analyze and quantify. It is essential to derive valuable knowledge from these metrics. We are not seeking complexity but information that can be translated into meaningful knowledge. The more significant this knowledge is for our daily lives, the more valuable it becomes.

To study the impact of fisheries in the Azores region, we will present an overview of the fishing inspection areas and frequency, alongside a comparison of maps utilizing commonly used reference metrics and a metric named Total *Boat-Meter* (TBM). The study developed by Dunn et al. (2010) introduced the TBM metric to quantify fishing effort more effectively. This metric combines the number of boats and their respective lengths, offering a more comprehensive measure of fishing capacity and effort. The metric is particularly beneficial in areas dominated by artisanal fisheries, where commonly used metrics may not fully capture the extent of fishing activities. This analysis will combine Vessel Monitoring System (VMS) records from 2016 to 2022 and Portuguese Navy (PoN) Fiscalization Reports (FISCREP) from 2015 to 2022 from the Azores region. Using the most recent data available will enhance the relevance of the conclusions drawn from the analysis.

Despite establishing MPAs in the Azores region, many studies highlight ongoing non-compliance problems stemming from weak enforcement. Abecasis et al. (2015) cautioned that MPAs in the Azores risk becoming paper parks without sufficient surveillance and regulatory measures. Similarly, Martins et al. (2011) found that illegal harvesting within no-take zones has undermined conservation efforts, as limpets have struggled to recover due to widespread non-compliance. Pham et al. (2013) demonstrated that official fisheries statistics significantly underestimate total catches in the Azores EEZ, with IUUF representing a substantial portion of unreported removals. Furthermore, Diogo et al. (2016) discovered that a high percentage of observed fishing activities occurred in restricted areas, highlighting the ineffectiveness of seasonal bans and area-based protections without active enforcement. This study builds on prior research by introducing the TBM metric to quantify fishing effort more accurately, addressing the limitations of traditional metrics that often overlook the full scope of artisanal fisheries in the Azores. Furthermore, it includes the latest enforcement and monitoring data to provide a revised assessment of inspection effectiveness and regulatory enforcement in MPAs. Utilizing the most current data available improves the relevance of the conclusions derived from the analysis.

The article is structured as follows: After introducing the problem and describing the contributions and objectives in this section, Section 2 explores the procedures and preprocessing performed for data collection. Section 3 de-fines the problem and the adopted analysis methodologies. Section 4 presents and initially analyzes the obtained results. Section 5 provides a more indepth analysis of the existing fishing effort, concluding the potential endangerment of ecosystems and marine life in the Azores region. Finally, in Section 6, conclusions are provided, and further research work and development topics are suggested.

2. Data collection & preprocessing

To retrieve knowledge, it is essential to have representative and reliable data for analysis. Data preprocessing is another crucial step that is essential to the success of the analysis, involving data merging and filtering to guarantee a high-quality and reliable dataset. Section 2.1 will describe the internal data collection that represents data collected by Portugal. Section 2.2 will define the external data collection from the European Union (EU). Finally, Section 2.3 will explain the preprocessing performed to merge and filter all this data, creating a valid and highly reliable dataset.

2.1. Internal data collection

The PoN data comes from two distinct sources: (i) the Portuguese Naval Command (PoNC), particularly the Maritime Surveillance Operations Section, and (ii) the Directorate of Analysis and Information Management (DAIM). The PoNC manages naval operations, trains military personnel, and develops strategies and technologies. It also oversees maritime defense and security, including the Maritime Zone Commands, Marine Corps Command, Lisbon Naval Base, and operational forces. Within the PoNC, the Division of Operations includes a Maritime Surveillance Operations Section, ensuring compliance with maritime legislation and promoting navigation safety and environmental protection. The DAIM is a subdivision of the Superintendence of Information Technologies (SIT) and is responsible for exercising technical authority in various data management and analysis domains. Its duties include data administration, establishing and maintaining a reference architecture for information systems, conducting statistical analyses, and applying operational research methodologies.

The data provided by PoNC contains FISCREP from January 1, 2015, to December 31, 2022. FISCREP is a report conducted by the PoN each time an inspection takes place aboard a commercial, recreational, or leisure fishing vessel, whether national or foreign, operating in national waters. This report is sent to the relevant authorities and contains all requested information gathered during the inspection. It is especially important if an infraction is detected, where an Infraction Code (IC) is attributed. The report is sent to the operational control entity, the local maritime department, and the port captaincy. The report is registered if the vessel is national and suspected of infractions. In Moura et al. (2023), it is possible to access a synthetic version of this dataset, which is confidentially protected for public release, allowing a comprehensive study of its content (Moura et al., 2024).

The data provided by DAIM consists of VMS data from the Maritime Operational Navigation and Information CAPabilities (MONICAP) system (Afonso-Dias et al, 2004; de Deus et al, 2012) from January 1, 2016, to December 31, 2022. MONICAP is a satellite-based VMS that, at regular intervals, provides data to the fisheries authorities concerning the location, course, and speed of the vessels. The data used includes vessel identification code, date, time, latitude and longitude, course, and speed, which are essential for tracking and monitoring vessel activity.

Although the periods for the FISCREP and MONICAP datasets do not entirely overlap, each can be utilized independently to provide valuable insights for different time frames, illustrating the current state of affairs in fisheries management.

2.2. External data collection

The Community Fleet Register (CFR) number for each vessel will be used to access the European Union Fleet Register (EU-FR) (European Union, 2024) to gather the necessary vessel details for the study. The EU-FR is a publicly available dataset established in 1989, containing information about all EU-flagged fishing vessels authorized for fishing and required to be registered. This register helps identify vessels, monitor fishing capacity, and provide statistical data. It includes administrative details such as the vessel's name, port, International Maritime Organization (IMO) number, technical characteristics like length, tonnage, fishing gear, and historical events such as fleet entries or exits. The CFR number, unique to each vessel, allows for cross-referencing between MONICAP and FISCREP data. We have gathered data on active vessels until April 15, 2024, focusing on the variables outlined in Table 1.

2.3. Data preprocessing

After obtaining the necessary data from internal and external sources, as previously mentioned, it is crucial to preprocess the data to ensure the reliability of the dataset. The initial step involves defining the

Table 1
Description of the selected variables collected from the EU-FR dataset.

Name	Description
Country of Registration	Country where the vessel is registered
CFR	Community Fleet Register
Registration Number	Unique registration number assigned to the vessel
Event Start Date	Start date of the license validity
Event End Date	End date of the license validity
Main Fishing Gear	Main fishing gear registered for the vessel
Year of Construction	Year the vessel was constructed
LOA	Length Overall of the vessel (meters)
Country of Import/Export	Country of import or export

geographical scope of the study, as it is critical to grasp the geographic boundaries of the Azores EEZ segment. Using the Portuguese Hydrographic Institute (PoHI) digital platform named *Hidrográfico* + (Instituto Hidrográfico, 2024), the geographical limits of the Azores EEZ were obtained. This information was then complemented by creating *shapefiles* for each of the considered MPAs (Tempera et al., 2013; Governo Regional dos Açores, 2023a,b,c).

After defining the study's geographic area and the specific MPAs of interest, we conducted several preprocessing tasks to align the dataset with the study parameters. Initially, the internal data (Section 2.1) was filtered to match the study period and merged with the external data (Section 2.2) to include vessel information. MONICAP signal records were filtered to cover only the defined Azores area for regional relevance. Finally, we considered only records of fishing vessels with speeds below 5 knots, as higher speeds were classified as *in transit* according to speed thresholds from prior studies (Breen et al., 2014; Shepperson et al., 2017), including those in the Azores region (Campos et al., 2023). Moreover, vessel speed serves as a well-established proxy for fishing behavior, and employing speed thresholds to differentiate fishing activity from transit has been validated as an effective and reliable method in earlier research (Breen et al., 2014; Campos et al., 2023; Shepperson et al., 2017).

3. Problem formulation & methodologies

The study area is described by the obtained geographic areas of the Azores EEZ and its relevant MPAs, as illustrated in Fig. 2. As described before, the number and type of species caught can present a helpful metric. Still, it is essential to be able to characterize the direct and collateral impacts of the fishing gear used on habitats and their species.

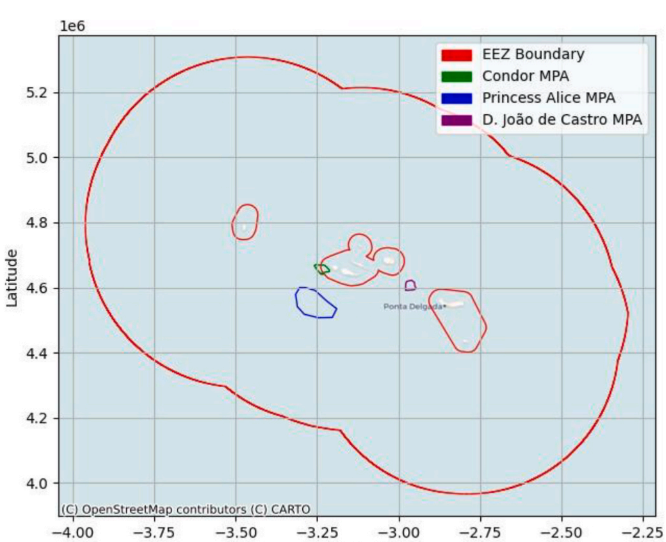

Fig. 2. Representation of the EEZ of the Azores and the MPAs within it.

To analyze the fishing activity, we have created grids for each area using polygons of different sizes: (i) 20 × 20 km to mark the Azores EEZ, (ii) 10 × 10 km to enclose the surrounding area of the three MPAs, and (iii) 3 × 3 km for the three studied MPAs. For each area, metrics will characterize the fishing effort and determine if illegal fishing occurs. We will use the following relevant metrics to retrieve knowledge from the data and evaluate the existence of illegal fishing. The fishing effort will be characterized using the following metrics:

- Record Count (RC) - Number of records in each grid cell, as described in Section 3.1;
- Average Length Overall (ALOA) - This metric provides a view of the size of the vessels operating within each grid cell, as described in Section 3.2;
- Boat Count (BC) - Number of unique vessels operating in each grid cell, as described in Section 3.3;
- Gear Diversity (GD) - Number of distinct registered fishing gears used in each grid cell, as described in Section 3.4;
- Total *Boat-Meter* (TBM) - Measurement of the intensity of activity in each grid cell as a proportion of the total vessel length, as described in Section 3.5;
- Intensity per Square Kilometer (ISK) - Obtained by normalizing the TBM metric by the grid cell area, as described in Section 3.6.

For the inspection effort, we will use the following metric:

- Infraction Rate (IR) - Ratio between the existing Presumable Infractions (PI) and the total number of inspections conducted in each grid cell, as described in Section 3.7.

3.1. Record Count (RC)

This simple metric only represents the number of records whose locations fell inside a specific grid cell. A different number of records, denoted by m_l, will be considered for each grid cell for $l = 1, \ldots, K$.

3.2. Average Length Overall (ALOA)

All the records whose locations fell inside each grid cell within the study area were selected. Let us denote these records indexed by i, ranging from 1 to m_l. The ALOA for all the records in a specific grid cell l can be obtained as follows:

$$ALOA_l = \frac{1}{m_l} \sum_{i=1}^{m_l} LOA_{l,i} \tag{1}$$

where $LOA_{l,i}$ is the LOA of the vessel in record i in grid cell l. This metric provides information about the vessel sizes within each grid cell. A higher value indicates the presence of larger vessels, while a lower value suggests that smaller vessels are more common in that area.

3.3. Boat Count (BC)

The BC metric denotes the number of unique vessels operating in each grid cell. It is obtained by counting the unique CFR codes, represented by $j = 1, \ldots, p_l$, in each grid cell record. This metric indicates the number of distinct vessels operating in the area, and its value is denoted by p_l.

3.4. Gear Diversity (GD)

This metric represents the number of registered fishing gears used within each grid cell. Every boat has registered a main fishing gear, providing information about the various fishing methods employed in each grid cell. The GD value will be denoted by g_l.

3.5. Total Boat-Meter (TBM)

The TBM metric is obtained by combining the ALOA with the RC in each grid cell l, according to:

$$TBM_l = ALOA_l \times m_l \tag{2}$$

which sums up to the total of all $LOA_{l,i}$. Unlike the *standard* ALOA, this metric measures the intensity of fishing activity as a proportion of the total vessel length, indicating the overall fishing effort in terms of vessel size, irrespective of the individual vessel sizes. A higher TBM suggests more significant fishing activity, as it combines both the number of vessels and their respective sizes.

3.6. Intensity per square kilometer (ISK)

The ISK metric is obtained by normalizing the TBM by the area of the considered grid cell l, indicating the fishing intensity per unit area, denoted by A. For example, in a grid cell of 3 × 3 km, the area is 9 square kilometers. The ISK metric is obtained as follows:

$$ISK_l = \frac{TBM_l}{A_l} \tag{3}$$

The ISK metric considers the area of each grid cell, allowing for a more accurate comparison of fishing activity across regions of different sizes.

3.7. Infraction Rate (IR)

The IR metric is calculated by taking the ratio of existing PI to the total number of inspections T_l conducted within each grid cell l. This metric is defined as follows:

$$IR_l = \frac{\sum_{i=1}^{M_l} PI_{l,i}}{M_l} \tag{4}$$

where M_l represents the number of inspections conducted in cell l, $PI_{l,i}$ is a variable that can take the values 1 or 0, with 1 indicating an inspection considered as PI and 0 representing an inspection considered as non-PI.

4. Fishing effort: analysis & evaluation

The dataset from FISCREP comprises 10,446 ship inspection actions between 2015 and 2022, as illustrated in Fig. 3, with the number of inspections decreasing in recent years. Out of the inspections conducted, 8822 were found to be legal, demonstrating full compliance with all regulations. Conversely, 1624 inspection actions, representing approximately 15.6%, were classified as PI. This classification indicates that some irregularities related to safety or fishing were identified during the inspections. A PI suggests potential noncompliance with maritime safety and the sustainable, legal fishing practices mandated by current legislation.

Fig. 4 illustrates a choropleth map that illustrates the IR using a 20 × 20 km grid cell in the Azores region. The map overlays the georeferenced inspection locations and differentiates between PI and non-PI inspections. A zoomed-in view provides more detailed insights into the area surrounding the MPAs.

The map indicates that regions with more inspections tend to have elevated IRs, particularly within the MPAs and along the potential routes leading to these protected zones. This pattern suggests a concentration of PI inspections inside and around the MPAs.

Another essential factor is to analyze the evolution of the number of inspections performed on the mainland, Azores, Madeira, in the Azores area exterior to the chosen MPAs and inside the Azores MPAs. From Fig. 5, it is observed that the Mainland consistently had the highest number of inspections until 2019, reaching a peak of 104 inspections in 2017. However, there was a significant decline in inspections from 2018 onwards, with the lowest number recorded in 2021 at 15 inspections, followed by a slight increase to 26 inspections in 2022. Considering the vast amount of existing fishery activities across the Portuguese EEZ (Cardoso et al., 2019; Gaspar et al., 2022), the number of inspections performed is insufficient.

When analyzing in more detail the Azores region, as described in Fig. 5, a relatively stable number of inspections was performed from 2015 to 2019, with annual inspections ranging from 32 to 43. Notably, in 2020, the number of inspections in the Azores was 34, slightly surpassing those in the Mainland, which had 32. Despite this brief increase, the Azores experienced a sharp decline in inspections in the following years, with only eight inspections in 2021 and 5 in 2022. However, it should be noted that inspections within the MPAs have experienced a decline since 2017. This trend culminated in only one inspection in these areas in 2022.

Fig. 6 illustrates the evolution of the IR across the same regions detailed in Fig. 5 from the period of 2015–2022. When analyzing the gathered data and focusing on fishing-related infractions, the Azores have the highest percentage of fishing-related infractions among the total declared PIs, with 58.8% of their infractions related to fishing activities. The Mainland follows with 48.3%, and Madeira has the lowest percentage at 40.0%.

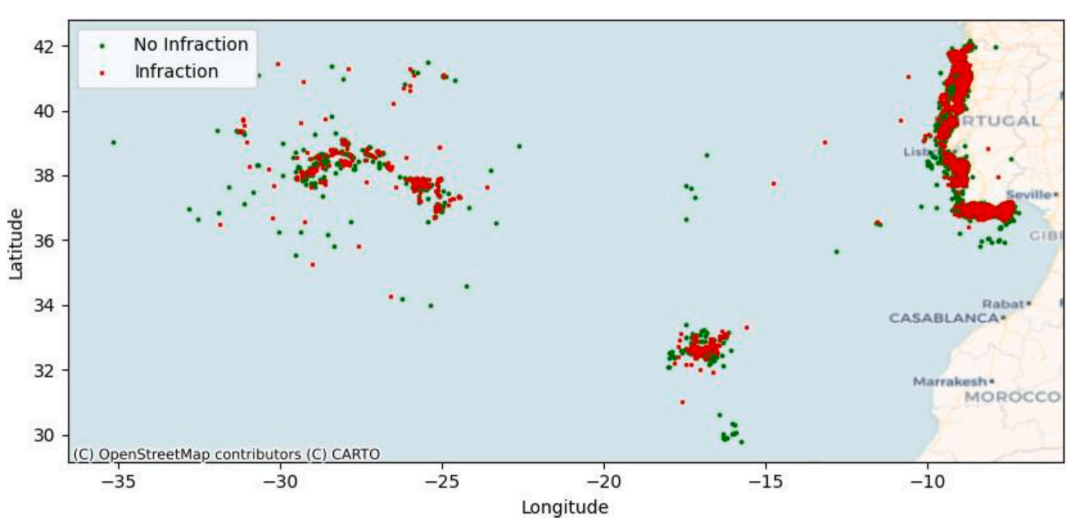

Fig. 3. Performed ship inspections between 2015 and 2022, indicating PI (*red*) or compliance - no infraction (*blue*) based on geographic location.

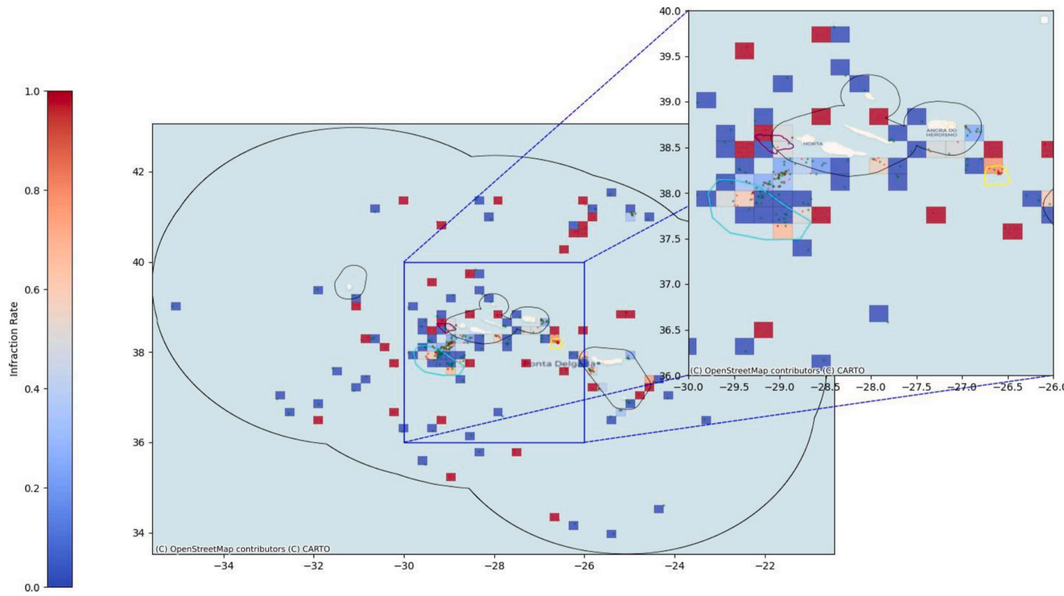

Fig. 4. IR in the Azores EEZ from 2015 to 2022 using a 20 × 20 km grid, with detailed zoom for the area near the analyzed MPAs.

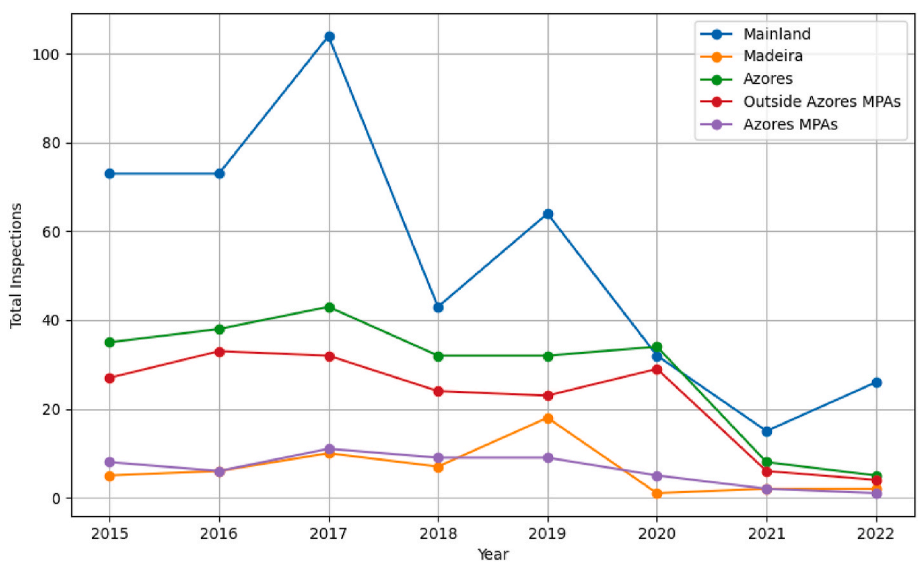

Fig. 5. Conducted inspections in the Mainland, Madeira, Azores, outside the MPAs, and within the Azores MPAs from 2015 to 2022.

Although it might initially seem that the IR has been decreasing within the MPA zones, with a sharp increase only observed in 2022, it is important to note that the number of inspections in these areas during the last two years was almost negligible. When the number of inspections was higher, from 2015 to 2020, the highest IRs were predominantly recorded within the selected MPAs.

By starting the analysis of the regions of interest using the metrics described in Section 3 applied to the VMS data, it is possible to create choropleth maps. Fig. 7 represents the choropleth map for the RC metric in the Azores EEZ in 2022 using a 20 × 20 km grid. We applied a threshold to improve visualization to ensure that high maximum values do not overshadow intermediate values. Expressly, the color scale was limited to a range between zero and the average value plus three times its standard deviation. This process will be repeated for other visualizations when the variable's maximum is too high, which would otherwise overshadow the other obtained values.

By analyzing Fig. 7, it is also possible to state that there was a higher RC near the Territorial Sea (TS) compared to the edge of the Azores EEZ. Over the years, a higher RC was observed in the central group of islands in 2016, 2017, 2019, and 2020. In 2018, 2021, and 2022, higher transmission counts were recorded in the Azores archipelago's central and eastern groups. Additionally, the cells within the area of the selected MPAs exhibit very high counts, particularly *Princess Alice*, not only in 2022 but also in all other years.

Fig. 8 illustrates the choropleth map for the BC metric in the Azores EEZ in 2022 using a 20 × 20 km grid. This map reveals a higher concentration of vessels in the Central and Eastern Groups and at some edges of the Azores EEZ, similar to what is observed in the maps from 2017 to 2021, as illustrated in Appendix A.

Also, in Appendix A, we present the distribution of BC values across MPAs and non-MPAs and also a comparison of BC distributions across the *Condor*, *Dom João de Castro*, and *Princess Alice* MPAs, from 2016 to 2022. To manage the spread of the data and remove outliers, we applied the Interquartile Range (IQR) method. In this approach, we calculate the first quartile (Q1) and the third quartile (Q3), with the IQR defined as $IQR = Q3 - Q1$. Outliers are then identified by determining the

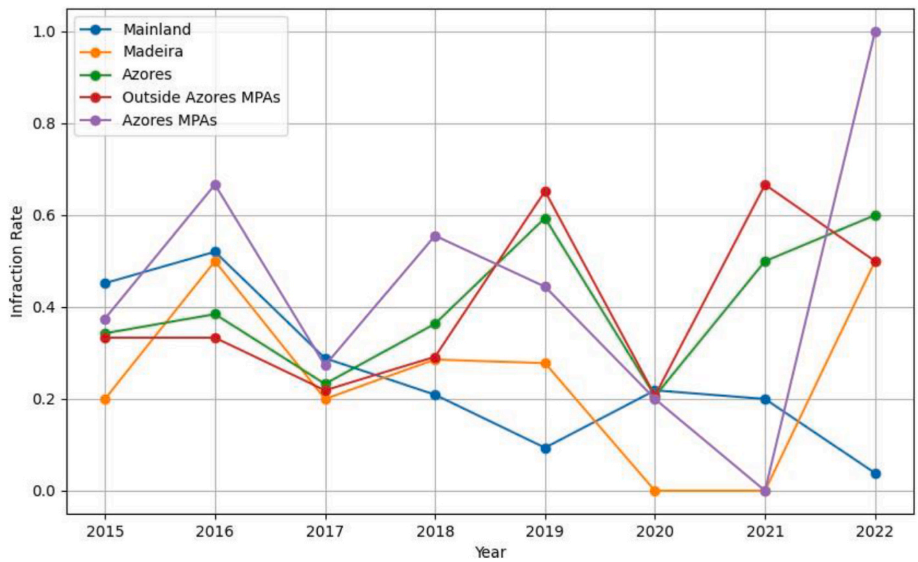

Fig. 6. IRs in the mainland, Madeira, Azores, outside the MPAs, and the Azores MPAs from 2015 to 2022.

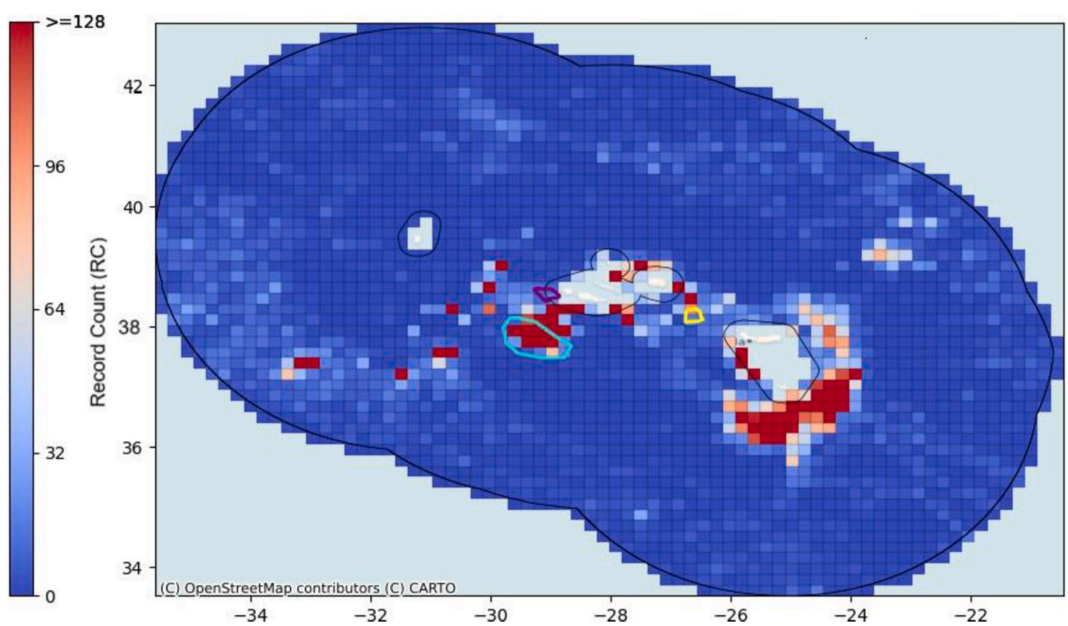

Fig. 7. RC in the Azores EEZ in 2022 using a 20 × 20 km grid.

acceptable range $R = [Q1 - 1.5 \times \text{IQR}, Q3 + 1.5 \times \text{IQR}]$, which filters values falling outside this interval. Additionally, we truncated the violin plot so as not to extend beyond the range of the data and to provide a more accurate visual representation. This approach gives a clearer depiction of the data, reducing the impact of outliers and making the central trends more apparent for better analysis.

The analysis of the results shows that the chosen study MPAs have many vessels operating at low speeds. The significant presence of these vessels at low speeds suggests that they are engaged in fishing activities rather than merely transiting through the area. In the Azores, the number of vessels operating at low speeds has ranged between 218 recorded in 2019 and 326 recorded in 2018, with 230 vessels recorded in the most recent year. Among these vessels, a significant number operated at low speeds in the specific MPAs: at least seven vessels in *Condor*, 17 in *Princess Alice*, and 13 in *Dom João de Castro*.

Upon closer observation of the MPAs, as illustrated in Appendix A, the BC remains very high for all the analyzed years in the *Princess Alice* MPA, followed by the *Dom João de Castro* MPA. Conversely, the BC is relatively low only in the *Condor* MPA, particularly from 2018 to 2022. These numbers are high for such relatively small regions, possibly indicating a concentrated fishing effort that could substantially impact the local marine environment and biodiversity.

Fig. 9 describes the choropleth map for the ALOA metric in 2022. From 2016 to 2022, we observed that the length of the boats had become longer and that records of bigger vessels were being detected closer to the TS and the MPA areas.

Upon analyzing the previously illustrated choropleth maps, it is evident that the number of recorded vessels is high in the three MPAs selected for this study, and the average vessel size raises questions about the existence of a potential impact. While the vessels in the protected areas are not the largest, their average size is relatively high, indicating significant fishing activity in these regions. The substantial presence of sizable vessels suggests that these protected areas are under considerable pressure, which could significantly impact the marine environment.

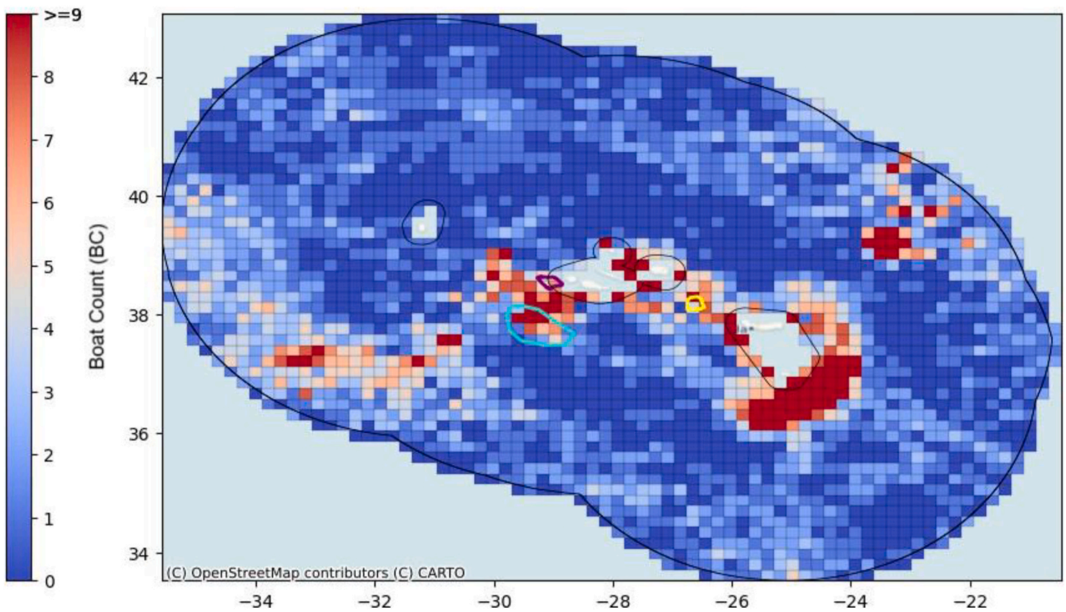

Fig. 8. BC in the Azores EEZ in 2022 using a 20 × 20 km grid.

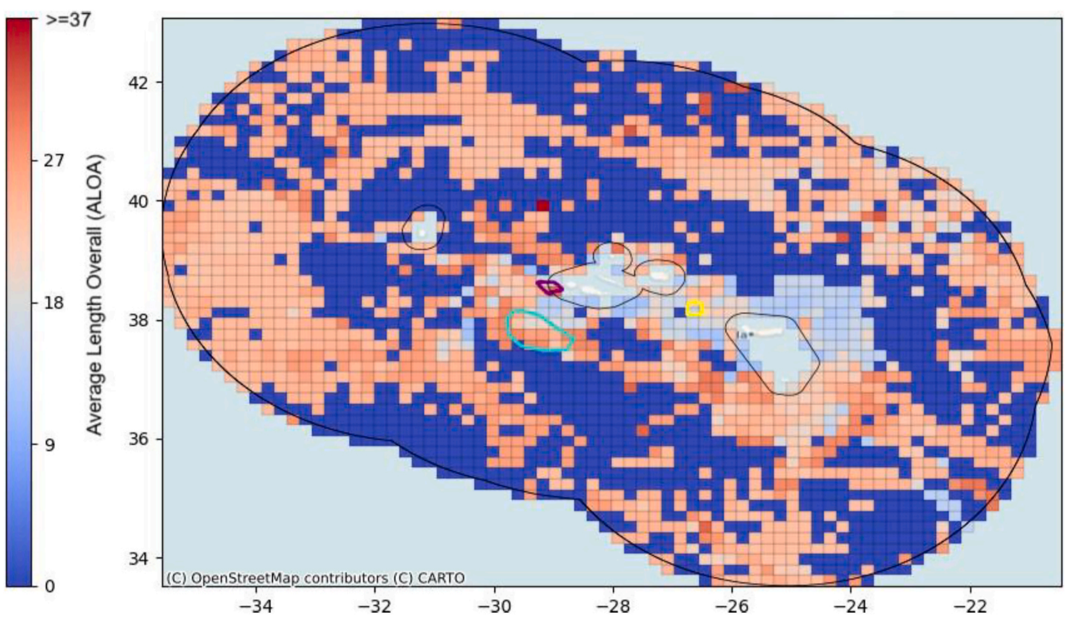

Fig. 9. ALOA in the Azores EEZ in 2022 using a 20 × 20 km grid.

We can determine the range of values in these locations by analyzing the grid cells defined for the chosen MPAs in more detail. Regarding the obtained ALOA metric values, as illustrated in Fig. 9, the *Condor* MPA presents a value range between 6.7 and 31.6, the *Princess Alice* MPA a value range between 0.0 and 29.9, and the *Dom João de Castro* MPA has a value range between 15.5 and 22.5. These values are generally relatively high and are comparable to those in regular fishing areas that are not designated as protected, indicating a potential threat to these sensitive regions.

In addition to simply analyzing the range of the ALOA values across MPAs, we conducted a detailed analysis using violin plots, as shown in Figs. 10 and 11. Using the same approach applied to BC and ISK, we also employed the IQR method for outlier removal in the case of ALOA. Additionally, we truncated the visualization of the plots to ensure that the values do not extend beyond the observed range of ALOA in each area. These plots allow us to visualize the distribution better considering the 10 × 10 km grid cells surrounding the MPAs, as shown in Fig. 4. This comparison reveals the differences in the distribution inside and outside the MPAs, making it possible to highlight the contrasts across the three individual MPAs.

The analysis of Figs. 10 and 11 reveals a notable concentration of higher ALOA values within the MPAs, particularly in *Princess Alice*, which generally exhibits slightly higher values compared to the other MPAs. However, in 2022, this difference is more pronounced due to an increase relative to 2021. We observed a significant rise in larger ALOA values in this region, indicating that larger vessels operate more frequently in this protected area. The rising ALOA values raise concerns about their impact on ecosystem conservation, underscoring the importance of this study and the need for measures to monitor and prevent illegal fishing activities within the MPAs.

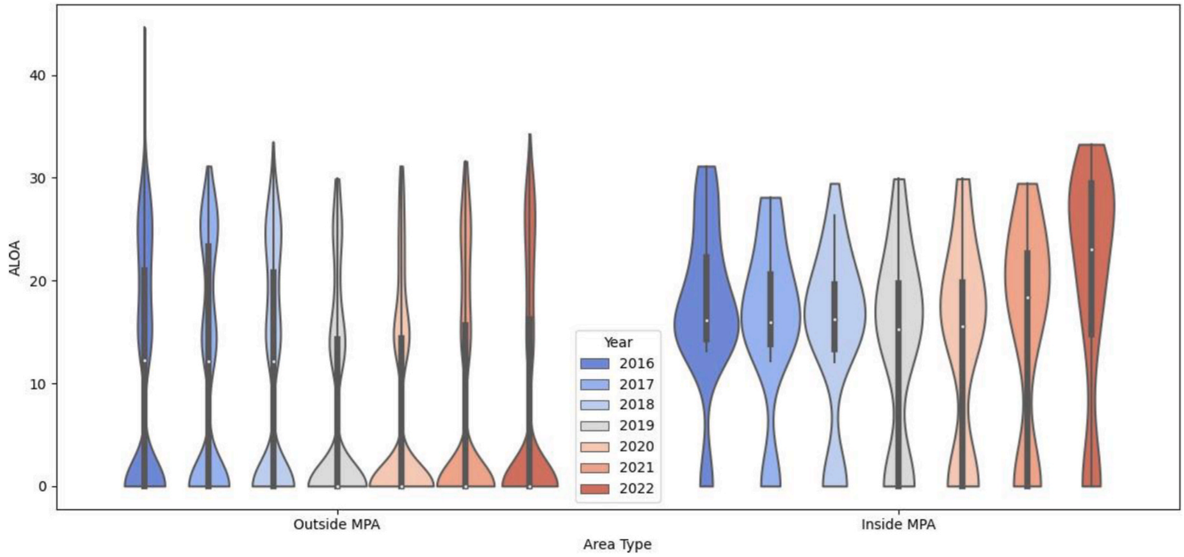

Fig. 10. ALOA violin plot outside and inside the MPAs between 2016 and 2022 using a 10 × 10 km grid.

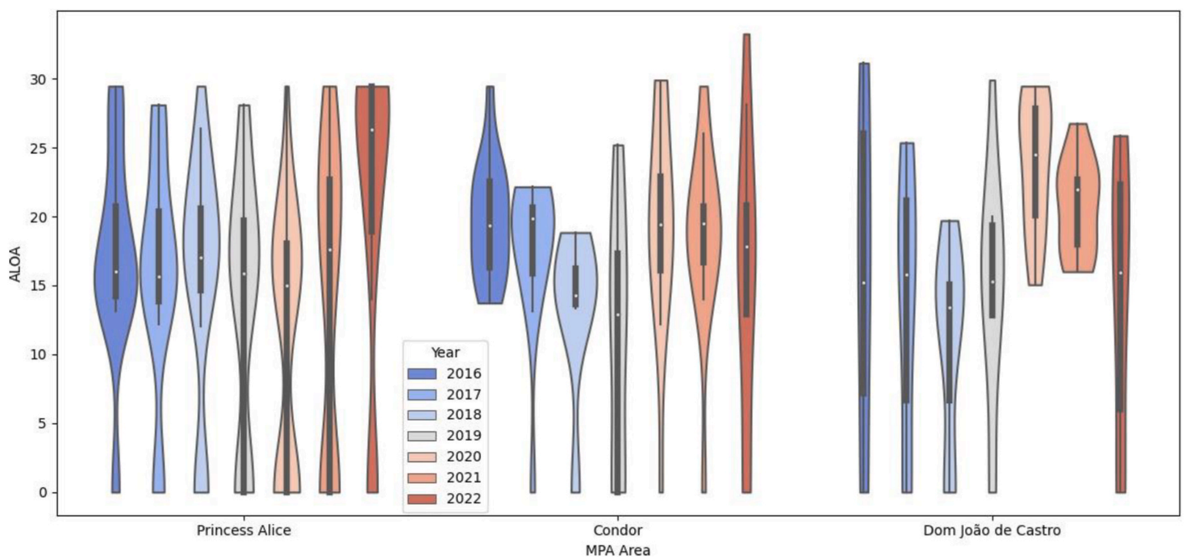

Fig. 11. ALOA violin plot across the 3 MPAs between 2016 and 2022 using a 10 × 10 km grid.

5. Is illegal fishing occurring in the Marine Protected Areas (MPAs) of the Azores?

Apart from using the relevant metrics and partially drawing some conclusions, it is essential to characterize the fishing effort and determine if illegal fishing occurs. Taking into account the previously described data and now using a metric more focused on the fishing effort, the ISK, as illustrated in Fig. 12, it is observed that there is a high effort near the coast, particularly in the south, and significantly higher in the central block of the archipelago and southeast of the eastern block. These high values are especially pronounced in the *Princess Alice* MPA.

In addition to simply analyzing the range of ISK values across MPAs, we conducted one more time a detailed analysis using violin plots, considering the 10 × 10 km grid cells surrounding the MPAs, which may be seen in Appendix A. We also employed the IQR method for outlier removal using the same approach applied to BC and ALOA. We truncated the visualization of the plots to ensure that the values do not extend beyond the observed range of ISK in each area.

In this detailed study, we observe a pattern similar to the BC distribution, with very high ISK values across all MPA areas, without a clear distinction between the three MPAs. These values indicate that, over the years, fishing effort have been significantly higher in these protected areas, not showing an increase or a decrease over time. This contradicts the true purpose of MPAs, which is to prevent any activity. This finding raises concerns that these areas may not be as well-protected as intended.

Considering the presence of more extreme BC and ISK values in Princess Alice, in Fig. 13, we present the average BC and ISK evolution in the three MPAs from 2016 to 2022, using a 10 × 10 km grid. Additionally, we show the proportion of grid cells with values exceeding or matching the defined threshold for each metric, obtaining 9 for BC and 6 for ISK, which we may call extreme values for the variables. It is important to note that BC's threshold was initially defined using a 20 × 20 km grid. Although the threshold for ISK was also determined using the 20 × 20 km grid, this does not affect the analysis since ISK is normalized, allowing for direct comparison between grids of different sizes.

By observing the graphs in Fig. 13, we notice only a slight decline in

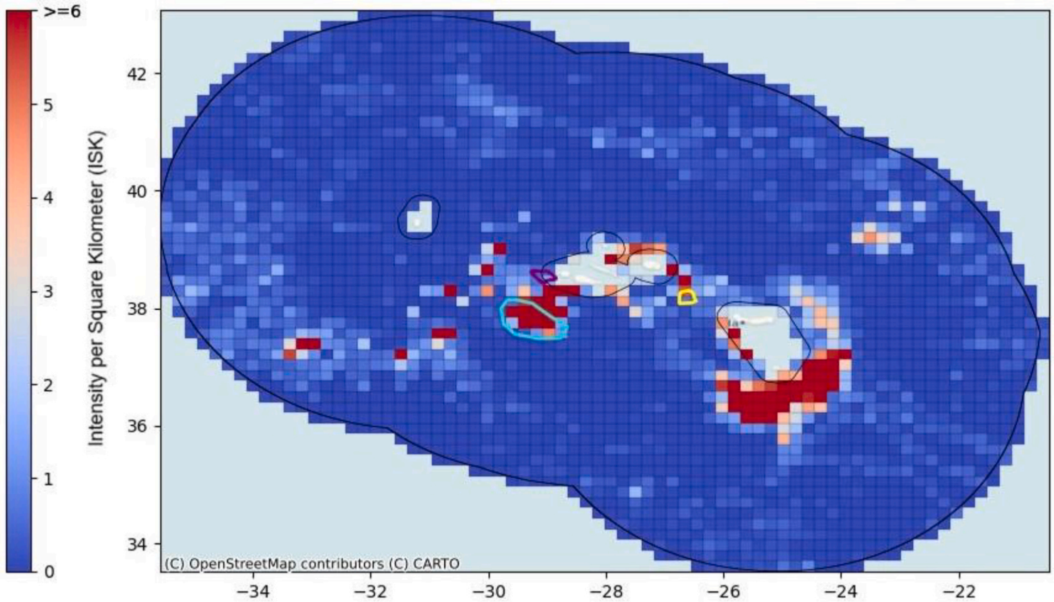

Fig. 12. ISK in the Azores EEZ in 2022 using a 20 × 20 km grid.

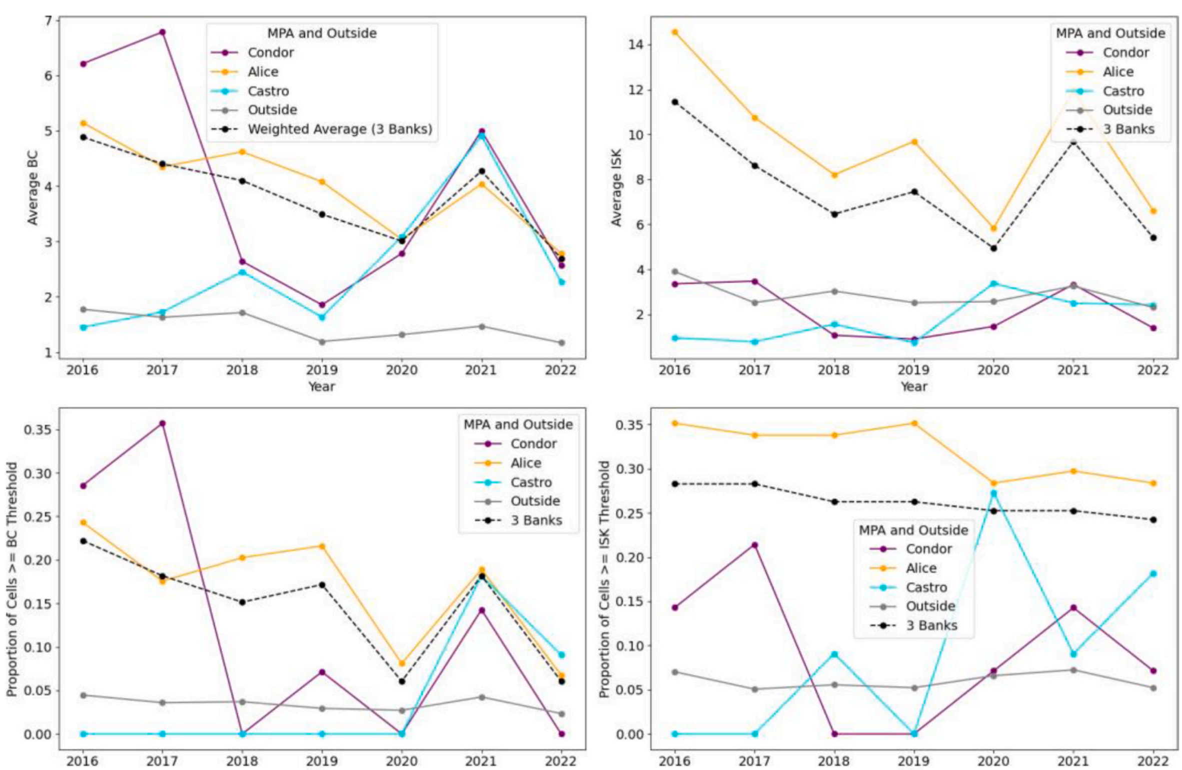

Fig. 13. Average values of BC and ISK and proportion of cells (10 × 10 km grid) whose values are over the corresponding thresholds in the 3 MPAs and outside of the MPAs from 2016 to 2022.

the average number of vessels per 100 square kilometers. However, the values remain alarmingly high. When examining the proportion of extreme values, it is evident that only the *Dom João de Castro* MPA recorded zero extreme values until the pandemic year. Since then, it has registered extreme values.

The ISK analysis reveals that the *Princess Alice* MPA consistently exhibits the highest average intensity each year, with the percentage of extreme values ranging from 30% to 35%. This is exceptionally high for an MPA where fishing is prohibited (Governo Regional dos Açores, 2023c). Additionally, we observe an increasing trend in the average ISK for the *Dom João de Castro* MPA, along with a rise in locations with extreme ISK values. This raises significant concerns about illegal fishing in this area.

To simplify the study, we will focus on the two vessels that frequented the area most often, which we will refer to as $vessel_1$ and $vessel_2$. The first vessel, $vessel_1$, has 373 records within the *Princess Alice* MPA out of 1612 records in all EEZ, representing approximately 23.14% of its presumably fishing activity. In Fig. 14, we can see a visualization of its

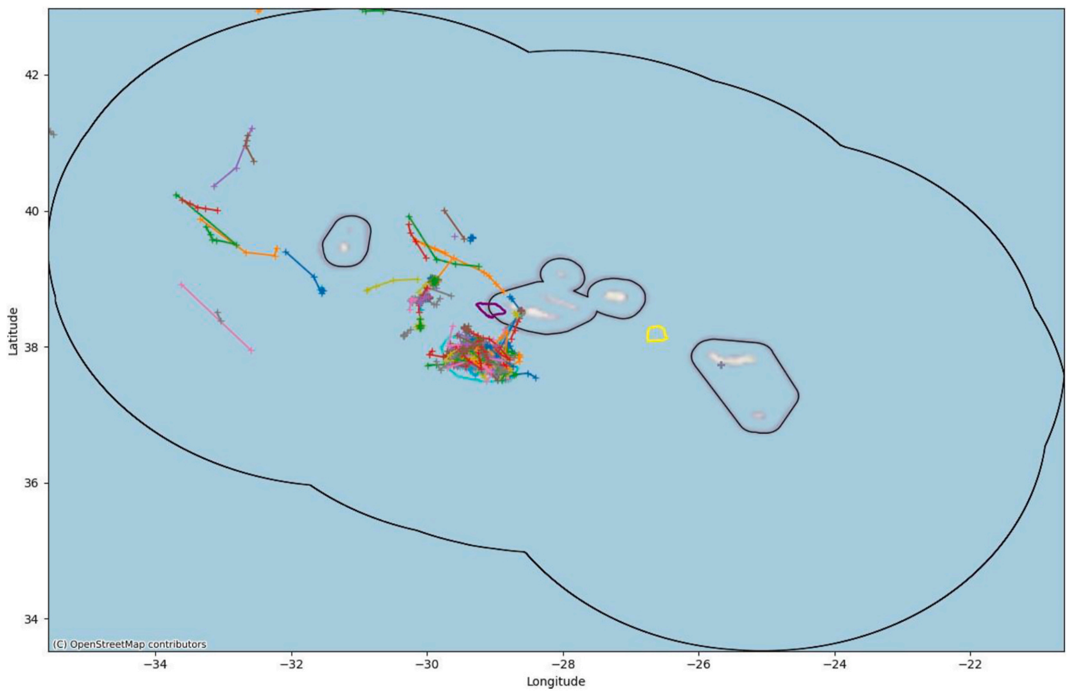

Fig. 14. Daily activity of $vessel_1$ at speeds less than 5 knots, with each color representing a different day.

lowspeed activity.

Knowing that some of these records are associated with vessel maintenance activities, we removed all records with zero speed. Considering the remaining records, this vessel was active for 203 days, and of these, 62 days were spent in the *Princess Alice* MPA, representing 30.54% of the total presumable fishing activity.

Fig. 15 shows a sample of 10 days of the referred activity in the mentioned MPA. The activity corresponds with the fishing operations of a Longliner (LL), the type of vessel that $vessel_1$ is registered as. Besides the average speed of this vessel during these 10 days, which was 3.18 knots, there are also frequent course changes, which are common in this type of fishing.

Analyzing the activity of $vessel_2$, also registered as a LL, Figs. 16 and 17 show its activity in 2022 and over ten days within the Princess Alice MPA, respectively. Again, the conclusions are not significantly different. For $vessel_2$, out of 2024 records at low speeds, 716 were recorded at the *Princess Alice* MPA, accounting for 35%. However, if we look only at the records where the speed is nonzero, this reflects 45.96% (478 out of 1040). These records were made during 78 days of activity within the *Princess Alice* MPA out of 192 days, meaning 40.63% of its low-speed

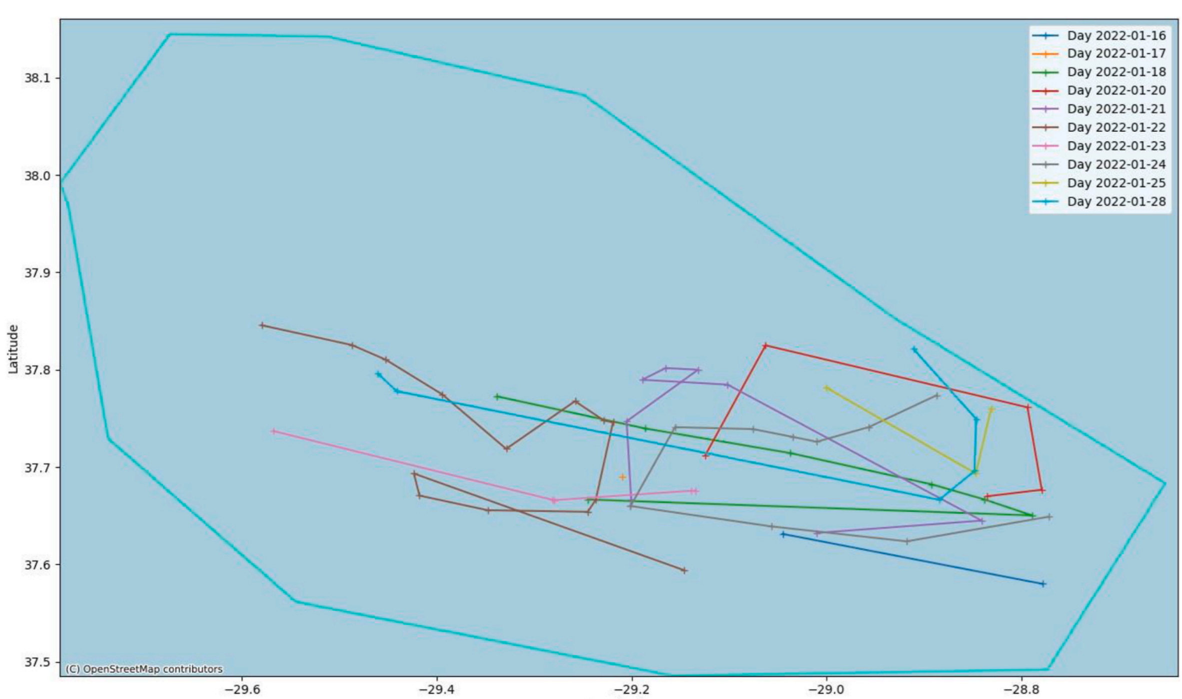

Fig. 15. Low-speed activity (<5 knots) of $vessel_1$ during the first 10 days in the Princess Alice MPA, with each color representing a different day.

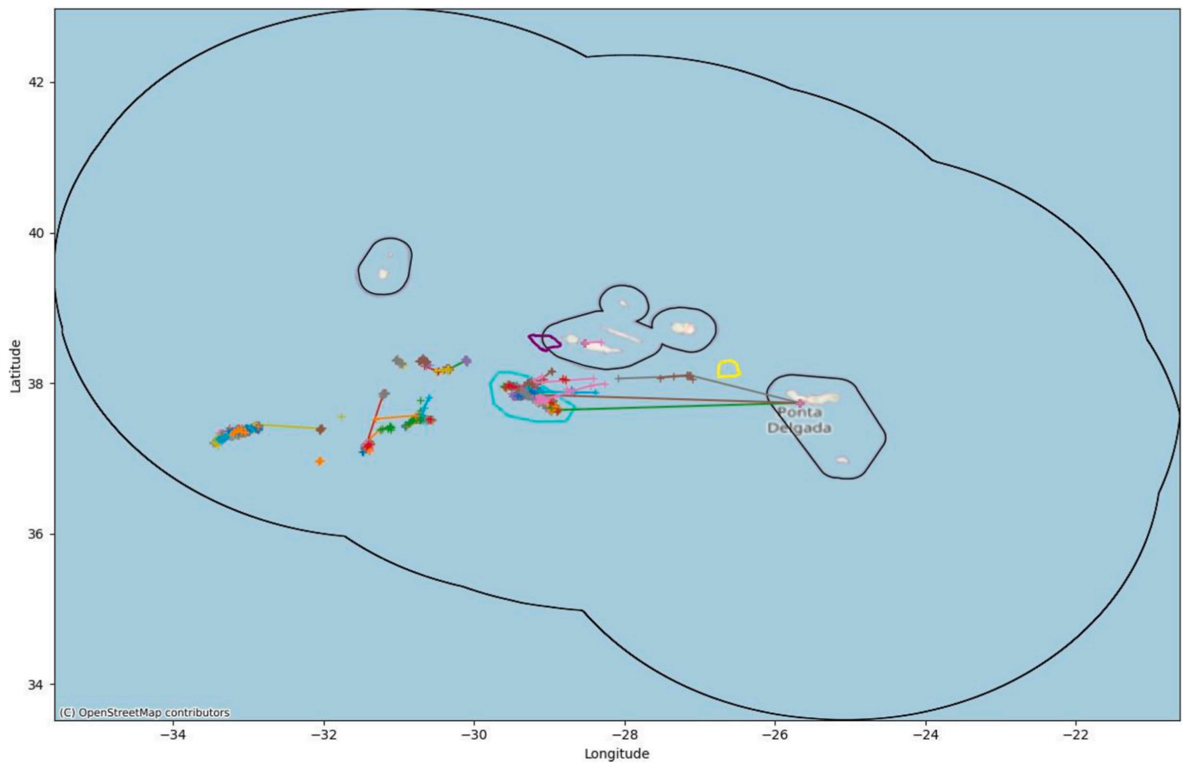

Fig. 16. Daily activity of $vessel_2$ at speeds less than 5 knots, with each color representing a different day.

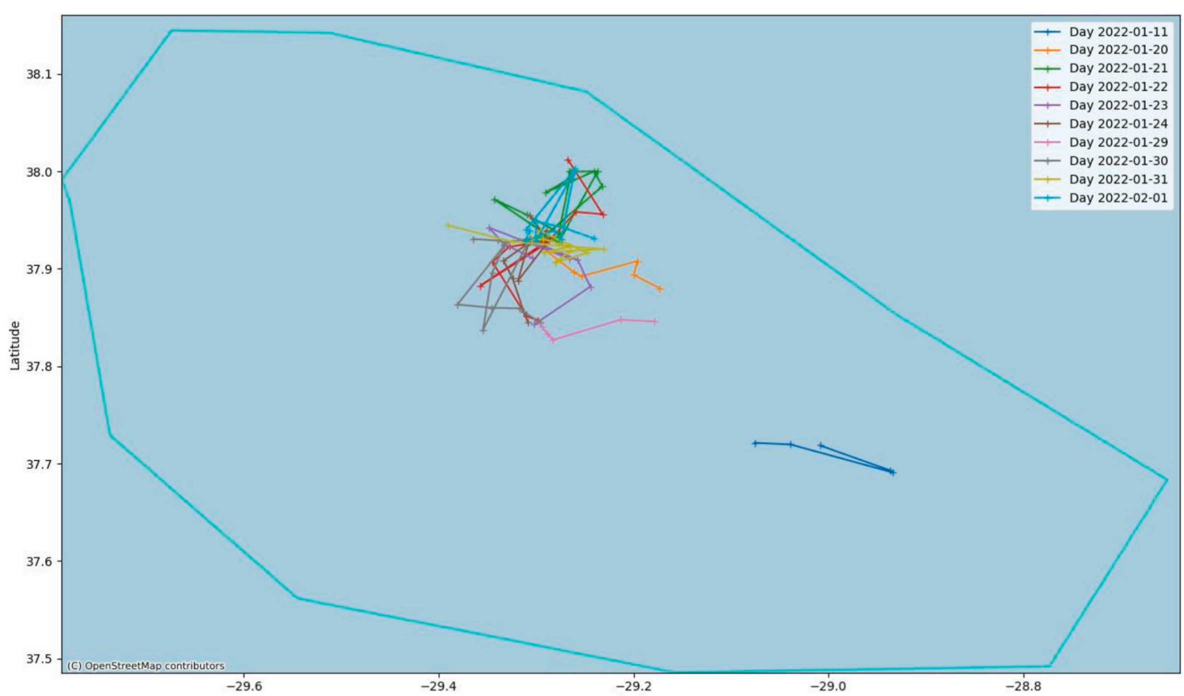

Fig. 17. Low-speed activity (< 5 knots) of $vessel_2$ during the first 10 days in the *Princess Alice* MPA, with each color representing a different day.

activity took place within the MPA. Once more, observing just ten days of activity at the *Princess Alice* MPA, it is evident that this aligns with the typical fishing activity of $vessel_2$, which is also a *Longliner*.

The observed activity of these two vessels is concerning, prompting an investigation into whether they have been inspected during the period of our records. Crossreferencing the CFR codes of these vessels with the FISCREP records, we found that $vessel_1$ was inspected only once in 2018, with no infractions identified. On the other hand, $vessel_2$ was inspected eight times, of which only three resulted in presumed infractions. However, these infractions were limited to types X, XIII, and XIV, defined as follows: *Improper marking or identification of fishing gear, Miscellaneous: Non-existent/invalid maritime registration,* and *Miscellaneous: E.g., lack of onboard documents, lack of pyrotechnics, expired life-saving equipment, expired fire extinguishers, among others.*

To determine if the fishing activity in the MPAs is derived from various types of fishing gear, we will analyze the GD metric and identify which activities were most frequent in these MPAs in 2022. Some fishing gears are more detrimental than others, making this analysis crucial for understanding the impact on these protected areas. The GD clearly describes the variety of fishing gears used in the study area, as shown in Fig. 18. Vessels operating at low speeds typically have one of the following registered five main fishing gears (FAO, 2021; Moura et al., 2024): (i) LHP, which designates *handlines and handoperated pole and lines*, (ii) LLS, which designates *set longlines*, (iii) LLD, which designates *Drifting longlines*, (iv) FPO, which designates *pots*, and (v) GNS, which designates *Set gillnets* (anchored).

Among the five main fishing gears used in the MPAs, vessels predominantly use LHP and LLS, the most common in the Azores. LHP, or *handlines*, may be used with or without a pole or rod. For fishing in deep waters, the lines are usually operated using reels. LLS, or *set longlines*, consist of a mainline and snoods with baited or occasionally unbaited hooks at regular intervals, generally placed on or near the bottom (FAO, 2024). This observation aligns with the fact that the two studied vessels are of the type LL, whose main fishing gears are recorded to be mainly LLS, LHD, and LHP.

Fig. 19 displays the most frequently used main fishing gears in 2022, illustrated by a 20 × 20 km grid. It shows that the most commonly used main fishing gear in the MPAs are LLS, LLD, and LHP. To provide an overview of the most frequent fishing gears, in Appendix A, we may observe the most frequent fishing gears in the area closest to the MPAs from 2016 to 2021. Overall, there has been minimal variability in the most frequent fishing gears during this period, indicating stable patterns of fishing activity in these regions. Even if LHP and LLS have less physical impact on the marine habitat than trawling, the repeated use of these methods can still disturb the local environment and susceptible habitats like the referred MPAs. According to (FAO, 2024), this type of gear may lead to the incidental catch of turtles, certain species of sharks, other endangered species, and even seabirds. The use of LHP and LLS in MPAs can be sustainable if adequately managed and regulated. However, without appropriate oversight, these methods can still contribute to illegal fishing and bycatch, undermining the conservation goals of MPAs.

The indepth analysis raised several concerns about the high fishing pressure on the MPAs. Not only are many vessels significantly present, but they also frequently visit these areas, seemingly without fear of enforcement.

6. Conclusions & future work

The issue of illegal fishing is a pressing concern for marine ecosystems worldwide. In the Azores region, the analysis of fishing efforts within MPAs such as *Condor*, *Princess Alice*, and *Dom João de Castro* reveals significant insights into the intensity and distribution of fishing activities. By leveraging the ISK metric, we can quantify and understand the fishing effort in these regions.

Our study focused on vessels operating at low speeds ($<$ 5 knots), indicative of fishing activities rather than transit. The findings demonstrate a substantial presence of fishing vessels within the Azores EEZ, with the number of vessels ranging from 218 in 2019 to 326 in 2018 and 230 vessels recorded in the most recent year. Notably, many of these vessels operated within the specific MPAs: (i) at least 7 in *Condor*, (ii) 17 in *Princess Alice*, and (iii) 13 in *Dom João de Castro*. This high vessel concentration in relatively small areas suggests an intense fishing effort that could impact the local marine environment and biodiversity.

A detailed study on vessel activities revealed that some vessels operating within the MPAs may spend up to 40% of their overall activity in these areas, indicating frequent presence and potential high impact on these sensitive regions. These findings indicate that the fishing activities in the Azores MPAs, particularly in the *Princess Alice* MPA, are substantial and comparable to regular fishing areas not designated as protected. The *Dom João de Castro* MPA also shows concerning trends of increasing fishing efforts. The large number of vessels and the high fishing records suggest significant fishing pressure that could threaten the marine ecosystems within these protected areas. This pattern observed in 2022 is consistent with previous years, reinforcing the concern of potential illegal fishing in the Azores' MPAs.

The analysis using the ISK metric and detailed vessel activity records demonstrates that illegal fishing is a tangible concern in the Azores MPAs. The high fishing intensity and the decrease in fishing inspections performed in the Azores EEZ and in these sensitive regions highlight the need for enhanced regulatory measures and sustainable fishing practices to protect marine bio-diversity and ensure the long term health of these vital ecosystems. Other machine learning approaches could enhance this study by leveraging temporal information and pattern analysis to extract

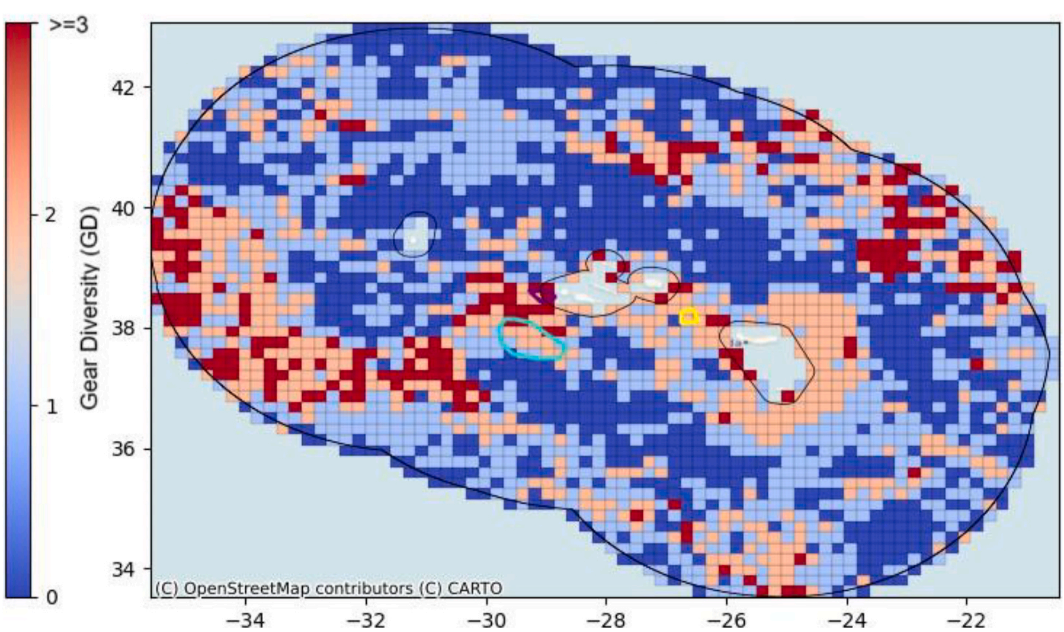

Fig. 18. GD in the Azores EEZ in 2022 using a 20 × 20 km grid.

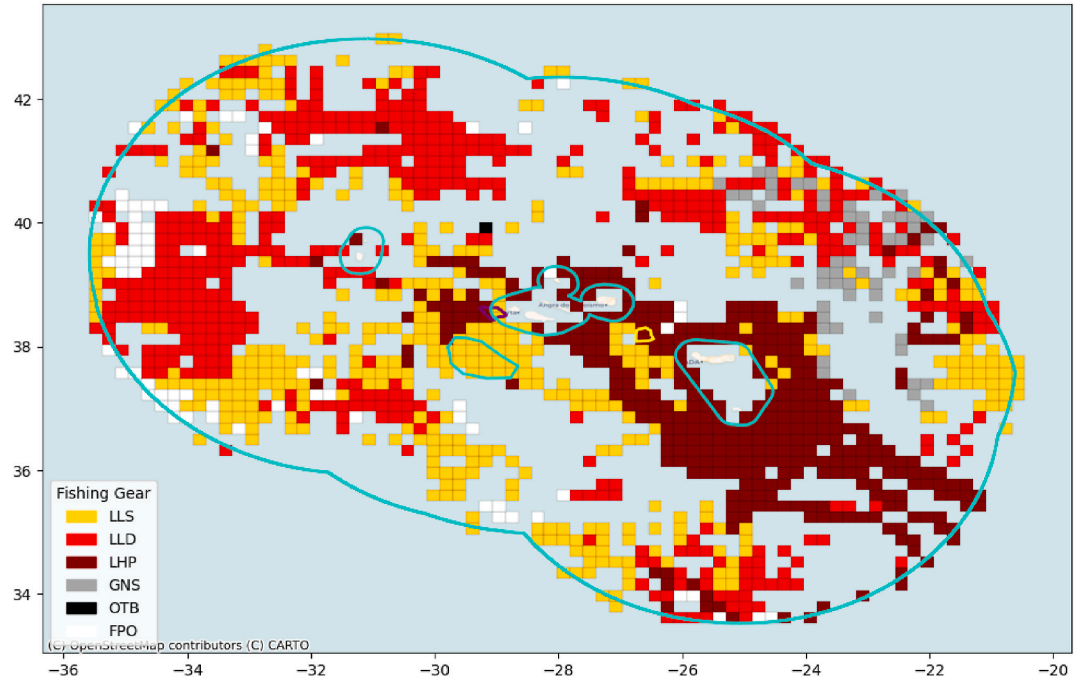

Fig. 19. Most frequent main fishing gear in 2022 using a 20 × 20 km grid.

additional insights from the data. Gaining more knowledge from data is always a key goal in data science, and if we can achieve this using different methods on the same dataset, we can improve the efficiency of our analysis. The analysis quantifies fishing effort and enforcement in MPAs but does not measure ecological harm. It highlights risks of high fishing pressure in protected areas that could cause long-term ecological issues if unaddressed. Using a below 5-knot speed threshold, supported by past studies, also introduces uncertainty due to varying fishing behaviors among fleets and gear types.

To address the pressing issue of illegal fishing in the Azores, especially within the MPAs such as *Condor*, *Princess Alice*, and *Dom João de Castro*, a multifaceted approach is essential. This approach should encompass regulatory frameworks and practical actions involving stakeholders, including local communities, fishers, regulatory authorities, and researchers.

Increasing the frequency and scope of inspections is critical to ensuring compliance with fishing regulations. This includes both at-sea and port inspections. Expanding VMS to track fishing vessel activities in real-time or near real-time is highly recommended. Ensuring all fishing vessels, including small-scale and artisanal boats, are equipped with VMS will enhance monitoring capabilities. Real-time or near real-time supervision by the competent authorities can be implemented in two ways. Firstly, preventive actions can be taken to deter potential violations by identifying the vessels and convincing them not to repeat the registered actions. Secondly, a punitive approach with stringent penalties for repeated offenders for illegal, unreported, and unregulated fishing activities will help deter non-compliance. Another possible approach is to use Unmanned Vehicles (UVs) for improved area patrolling and to gather evidence, such as images of fishing vessels engaged in illegal activities within MPAs. In addition to these tasks, UVs can conduct search and rescue operations, provide immediate assistance on the scene, and collect important information to aid in Command and Control (C2) tasks. Furthermore, exploring emerging technologies like satellite imagery and acoustic sensors could also enhance remote MPAs surveillance.

Future research could integrate VMS data with ecological surveys to evaluate the impact of fishing on fish populations in MPAs, utilize machine learning models for vessel tracking data to improve fishing behavior classification, and include additional behavioral indicators or complementary data sources to enhance effort estimation. This research should also investigate socioeconomic factors affecting compliance to strengthen enforcement strategies for more effective MPA management.

The findings underscore an urgent need for stronger enforcement mechanisms and real-time monitoring strategies. Implementing these measures could reduce the impact of illegal fishing in the Azores' protected areas and ensure the long-term sustainability of marine resources. A coordinated effort among all stakeholders is necessary to balance the fishing industry's needs with conserving marine ecosystems for future generations.

CRediT authorship contribution statement

Ricardo Moura: Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Nuno Pessanha Santos:** Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis. **Maria Eduarda Catarino:** Writing – review & editing, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization.

Ethics statement

This study was conducted in accordance with the ethical guidelines and standards for research involving aquatic organisms and fisheries science. All experimental procedures complied with institutional, national, and international regulations governing aquaculture and fisheries research.

Where applicable, ethical approval was obtained from the relevant institutional ethics committee. The study ensured the humane treatment of aquatic animals, adhering to the principles of the **3Rs (Replacement, Reduction, and Refinement)** to minimize potential harm.

No human subjects were involved in this research. If applicable, informed consent was obtained from all stakeholders or participants involved in fisheries-related surveys or interviews.

The authors declare that there are no conflicts of interest related to ethical concerns in this study.

Declaration of Generative AI in Scientific Writing

The authors acknowledge the use of generative artificial intelligence (AI) tools in the preparation of this manuscript. Specifically, ChatGPT was employed for language editing, grammar refinement or formatting assistance.The conceptualization, scientific content, data analysis, and interpretation remain entirely the responsibility of the authors, and all findings have been critically reviewed and validated by the research team. No AI-generated text, figures, or tables were included without thorough verification and modification by the authors.The authors confirm compliance with the ethical guidelines of *Aquaculture and Fisheries* regarding the responsible use of AI in scientific writing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aaf.2025.05.002.

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