Ocean and Coastal Management 269 (2025) 107789

Contents lists available at ScienceDirect

Ocean and Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman

Improving monitoring, control and surveillance efforts through vessel tracking and fishery dependent data

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ARTICLE INFO

Keywords:
Monitoring control and surveillance
Fisheries
Risk assessment
Unreported landing events
Vessel tracking and landings data

ABSTRACT

Fisheries are amongst the most extractive and damaging activities impacting the marine environment. To control and promote the sustainability of these activities, different laws and regulations were established. Yet, Illegal, Unregulated and Unreported (IUU) fishing activities are still present to these days and are one of the most threatening problems affecting marine life.

To improve the effectiveness of fishing control and surveillance efforts, risk assessment approaches have been proposed to detect risk units with higher probability of illegal actions, such as vessels, seasons or regions, to which control efforts should be given priority.

Vessel tracking and fishery dependent data have already proved their potential for gathering important information regarding different aspects of fishing activities, such as species distributions or the estimation of fishing effort. Yet, their usefulness for improving monitoring, control and surveillance efforts has not been fully exploited.

Here, we investigate how these two types of data can provide important intelligence, within a risk assessment approach, to identify risk units that have higher probability of failing with landing requirements and how such information can be used to improve fisheries' monitor, control and surveillance efforts.

Our approach is able to identify fishing vessels with higher tendency for not reporting their catches. We saw that a small fraction of fishing vessels are responsible for the majority of unreported landings and that unreported landing events tend to less frequent during the Summer. We also noticed that price variation of sold catches correlates with unreported landing events, which might indicate that it is one of the drivers affecting the seasonality of unreported landing events.

Such information is crucial when planning control and enforcement actions, which should focus on those with a higher tendency to act incompliantly and during the periods when this sort of behaviour is more frequent. By following this approach, such effort become more cost effective, which will strengthen the governance of the marine realm.

1. Introduction

The primary goal of fisheries regulations is to control fishing activities to make them as sustainable and less environmental damaging as possible. Yet, Illegal, Unreported, and Unregulated (IUU) fishing practices still persist to these days, are widespread, and are considered to be one of the most environmentally threatening activities occurring worldwide (Agnew et al., 2009; Pauly and Zeller, 2016).

It is commonly agreed that to progressively eradicate IUU fishing, strategic policy development and implementation of new approaches, with strong coordination across these levels and with different organizations and countries are needed (Gunningham and Sinclair, 1999; Auld et al., 2023). Under these premises, different treaties and regulations, such as the Agreement on Port State Measures (Hosch et al., 2019), and in the European Union (EU), Council Regulation (EC) No 1005/2008 have been adopted to prevent, deter, and eliminate IUU fishing (Temple et al., 2022). Furthermore, the EU established the European Fisheries Control Agency (EFCA) with the purpose of enhancing and coordinating Monitoring, Control and Surveillance (MCS) operations among EU member states (Home European Fisheries Control) in 2005.

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https://doi.org/10.1016/j.ocecoaman.2025.107789
Received 6 December 2024; Received in revised form 10 April 2025; Accepted 2 June 2025
Available online 10 June 2025

With the intention of collecting information about fishing activities and their respective catches, the European Common Fisheries Policy (CFP) mandates that fishing vessels' activity and the first sale of all catches to be recorded and reported (Reg (CE) 1224/2009). According to European Regulation (CE) Nº 1224/2009, the activity of some fishing vessels must be recorded by fishers on logbooks, and it is the responsibility of the Member States to ensure that the first sale and record of all catches is done at a fish auction or by registered buyers and organizations (Reg CE 1224/2009).

With regards to "unreported" within an IUU context, it refers to unrecorded fishing and fishing-related activities that have not been reported, or wrongly reported, to authorities. Unreported fishing is one of the most common practices of non-compliance (EFCA, 2022; Pauly and Zeller, 2015). For example, in 2022, 15 % of suspected infringements identified by EFCA were related to non-reporting or misreporting (EFCA, 2022), and it is estimated that one-fifth of global catches are not recorded and/or illegally caught (Pauly and Zeller, 2015; Long et al., 2020).

According to EFCA's 2022 annual report, 70.1 million Euros were spent in MCS efforts in 2022, which resulted in the identification of probable infringements in 8.6 % of the inspections performed. Indeed, the difficulty in identifying and detecting illegal practices is one of the major challenges when enforcing regulations (Agnew et al., 2009; Petrossian and Pezzella, 2018; Chuaysi and Kiattisin, 2020). That is why the understanding of the associated drivers, the quantification of the impacts and the identification of the many forms of IUU fishing activities is vital to deal with IUU fishing practices (Temple et al., 2022; Widjaja et al., 2023; Sumaila et al., 2020).

On broader scales, there have been several studies addressing the detection, estimation and quantification of IUU activities and their impacts (Agnew et al., 2009; Pauly and Zeller, 2015; Sumaila et al., 2006, 2020; Petrossian, 2015; Liddick, 2014). Yet, in order to improve fisheries management and enforce regulations through MCS efforts, the information on IUU should have higher spatial and temporal resolutions and be disaggregated by region, fleets, target species, or, ideally, by vessel (Temple et al., 2022; Macfadyen et al., 2016; Ford et al., 2018a).

Due to the high costs related with MCS practices and the difficulty in identifying illegal behaviours, which translates to the low effectiveness of MCS efforts (Da Rocha et al., 2012; Pramod et al., 2014; Doumbouya et al., 2017; Cochrane et al., 2020; Standal and Hersoug, 2023), it is agreed that the identification of units, or factors, with higher risk of being associated with IUU activities, such as seasons, gears and metier, fleets, vessels or targeted species, through risk assessments, is necessary to make MCS more cost-effective (Temple et al., 2022; Petrossian, 2015; MRAG, 2015). If risk assessments are made at vessel level for example, with the allocation of enforcement inspections directed to vessels that have been identified as probably non-compliant within a risk assessment framework, instead of simply allocating enforcement efforts randomly, MCS efforts could become more targeted and therefore more cost-effective (Temple et al., 2022; Ford et al., 2018a).

Vessel tracking data, such as VMS and AIS, have been advocated as an important source of information to improve fisheries management and transparency (Orofino et al., 2023; Dunn et al., 2018). Different studies showed and discussed the usefulness of such data in identifying probable IUU fishing activities, such as transhipment or fishing in conservation areas (Chuaysi and Kiattisin, 2020; Kumar et al., 2022; Iacarella et al., 2022), and identifying vessels with greater likelihood of non-compliant behaviours in order to make MCS efforts more effective (Orofino et al., 2023; Ford et al., 2018b).

Vessel tracking data, when combined with fisheries-dependent data, such as logbook data and landing/sales note data has also been acknowledged as a very useful source of information to improve fisheries management, such as to map fishing activities (Mendo et al., 2019; Tassetti et al., 2022), assess fishing impacts (Gerritsen et al., 2013), infer the distribution of captured species (Gerritsen and Lordan, 2011; Russo et al., 2018) or to improve estimates of fishing effort (Sales Henriques et al., 2024), for example. However, the combination of these two sources of data and its usefulness in identifying IUU fishing behaviours and making risk assessments to improve MCS efforts is yet to be explored.

In the current work, we exercise and explore how vessel tracking and official landing data can provide important information within an IUU risk assessment approach. We show how the proposed procedure can help identifying vessels that tend to fail to officially land their catches, and how the likelihood of this non-compliant behaviour changes seasonally. Then we hypothesize what might be some of the drivers promoting such behaviour, and we discuss how such information is relevant to plan and allocate MCS efforts in order to identify and consequently penalize non-compliant behaviours more effectively. More efficient MCS efforts will ultimately discourage illegal practices and improve the sustainable use of the marine resources and the marine environment.

2. Methods

2.1. Study region and fleet description

The present work focused its approach on the coastal polyvalent fishing fleet operating within mainland Portuguese waters. The size of these vessels ranges from 14m LOA (Length Overall) to 23m LOA, and they operate mostly static nets, trammel and gillnets, pots and traps, and longlines, although the latter has been less used than the other two types of gears (Leitão et al., 2025).

These vessels usually operate on a daily basis, which means that they perform daily fishing trips and it is very rare when they spend more than 24 h at sea. Their area of operation spans across the entire Portuguese coast, although their prevalence is higher in the central and norther region of Portugal and within the 500m bathymetric range (Fig. 1).

This fleet is highly diverse in terms of species it captures. Official landing data accounts for more than 350 species. However, the most landed species, in weight, are the common octopus (*Octopus vulgaris*), the hake (*Merluccius merluccius*), the pouting (*Trisopterus luscus*) and the monkfish (*Lophius* spp.).

2.2. Data description

This work combines sales notes/landing data (from here on end referred to as landing data) and vessel tracking data (AIS – Automatic Identification System) from the Portuguese polyvalent coastal fishing fleet operating within Portuguese mainland waters.

Daily landing data, from the period of 2014–2020, was provided by the Directorate-General for the Natural Resources, Safety and Maritime Services (DGRM) and it contained information about the vessel, the landing/sale date, landing port, landed species, their amount in kg and the value of the auctioned catch in Euros.

Under the approach developed by Sales Henriques et al. (2023), AIS data from coastal polyvalent fishing vessels operating nets and pots and traps, during the period of 2014–2020 was split into isolated fishing trips: a fishing trip started from the moment a vessel left port and ended when it returned to any given port. Then the AIS data was interpolated at regular timestamps of 1 min and classified into the four main behaviours a polyvalent fishing vessel performs during a fishing trip: navigation, gear deployment, slow navigation/drifting, and hauling of the gear. The aforementioned approach was able to identify and classify 13224 fishing trips from 84 coastal polyvalent fishing vessels during the 7-year period (Sales Henriques et al., 2023).

2.3. Assumptions and rational of the approach

According to EU regulation CE 1224/2009, Member States are responsible for ensuring that all fishing products are weighed and recorded and that the first sale and record of all landings is done at a fish

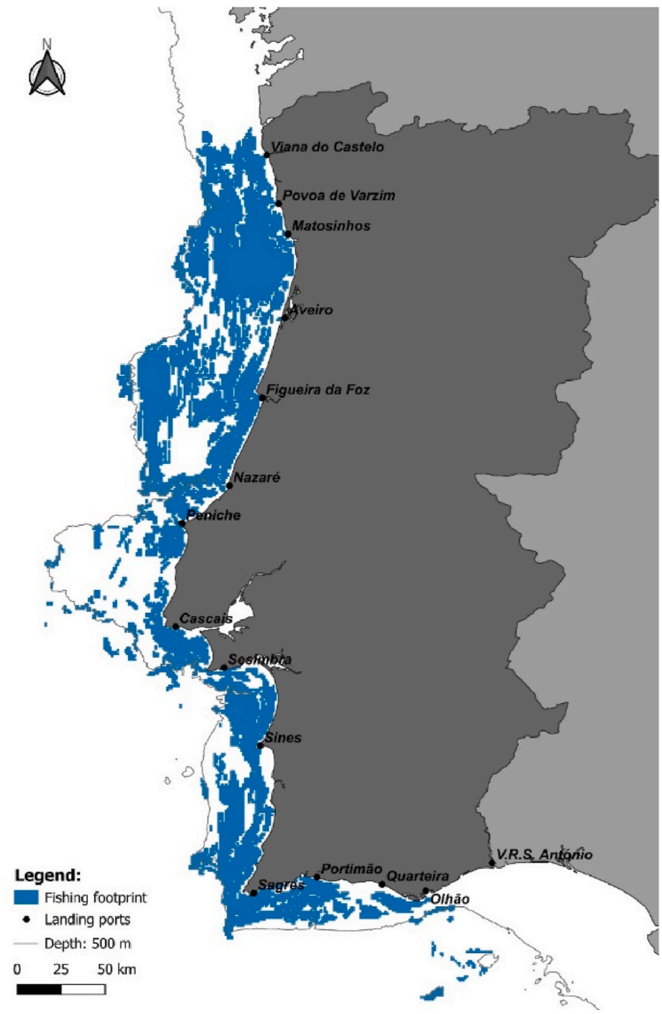

Fig. 1. Map of the study region, the landing ports and the fishing footprint of the analysed fleet. The footprint was mapped using the methodology developed by Sales Henriques et al. (2023).

auction or by registered buyers and organizations. Moreover, the Portuguese government decreed that landings and the first sales of all fishing products has to be carried out at DOCAPESCA by registered buyers (DL 81/2005), which is a State operated company responsible for the provision of services related to the first sale of seafood across the Portuguese mainland (http://www.docapesca.pt/).

Under the assumption that vessels follow the aforementioned regulations, we assume that for a given fishing trip in which fishing gears were hauled, the most likely scenario is that landing records for a given fishing trip, performed by that given vessel, should be present within the landing data recorded at DOCAPESCA.

2.4. Data fusion

The first step to combine the vessel tracking data with landing data was to select, within the classified AIS data, only the fishing trips where hauling of fishing gears occurred. This means that fishing trips without gear-hauling events were removed from the vessel tracking dataset, as these should not return any catch.

Due to the inherent problems of AIS data that affects the consistency of good quality data, such as poor data reception, the ability to turn OFF the AIS transponder by the skipper and the data quality and consistency requirements by the classification procedure (Sales Henriques et al., 2023; Emmens et al., 2021; Shepperson et al., 2018), the number of tracked and classified fishing trips varied greatly, ranging from 3 to 475 trips depending on the vessel. Therefore, to conduct an analysis where all fishing vessels had a representative number of fishing trips, we opted to proceed with the analysis only for vessels with more than 50 fishing trips within the classified AIS dataset.

The next step was to combine, for each vessel, the spatiotemporal information of fishing trips, i.e., the classified AIS data, with the respective landing data. This procedure was based on the date and time of arrival to port of each fishing trip, i.e. the end of each trip, within the AIS data (obtained from the last AIS datapoint of each trip) and the sale date stated on the landing dataset. Given that the present fleet does not freeze their catches, we assumed that the date of the catch sale to be the same as its landing date. However, due to the different schedules of the auctions in the different port facilities, it could happen that a vessel lands its catch later in the day, and because the next auction is in the following day, there would be a mismatch between trip data and landing data. Therefore, in order to avoid such situation, we only match track and landing data of fishing trips that arrived in port at least 1 h before the last auction happening within the same day as the date of port arrival. Given that different ports have different auction schedules, which can be consulted in http://www.docapesca.pt/, this data cleaning process was performed for each landing port.

2.5. Risk assessment at vessel level – unreported landing events

Under the reporting regulations described above, we assume that in a compliance scenario, for each fishing trip where gears were hauled, a record of the landing data should be present. Under this assumption we investigated, for each vessel, the number and percentage of fishing trips without records on landing data, from now on referred to as unreported landing events.

Given that combining vessel tracking data with official landing data allows to quantify the proportion of fishing trips without reported landing events, we decided to explore how such approach can be useful within a risk assessment approach. We aimed to identify the fishing vessels, i.e., the risk units, that are more likely to not follow with the aforementioned landing obligation. We follow the assumption that vessels with a higher percentage of unreported landing events are more likely to ignore such regulations (Vallejos B et al., 2023), which makes them preferential targets of MCS efforts.

Those “high-risk” vessels were identified based on a threshold that corresponds to the mean value of the percentage of unreported landing events from all analysed vessels. Which means that fishing vessels with higher percentage of unreported landing events than the mean value of the analysed fleet were identified as risk units, making them preferential targets for MCS efforts.

2.6. Seasonal variation of unreported landing events

To study the seasonal variation of unreported landing events, we used the combined vessel tracking with landing data, to calculate the total number of fishing trips captured with the AIS data and the proportion of those trips (percentage) without a corresponding landing event, in each month, by each vessel, during the period of 2014–2020. To study how the percentage of trips without landing events varies throughout the year, we fitted a Generalized Additive Model (GAM), with a Gaussian error distribution, to model the percentage of unreported landing events against the covariate month and considering the factor “vessel” as predicting variable with a random effect, when fitting the model to the data (Fig. 2).

The number of fishing trips recoded with the AIS in each of the 12 months for each vessel varied from 1 to 75 trips. Given that the aim was to model the variation of a proportion, this wide distribution of the number of fishing trips per month caused unwanted noise on the proportion values when there were few AIS-recorded fishing trips on a given month. Therefore, to provide a more robust analysis when modelling the variation of unreported landing events, we established a threshold of a

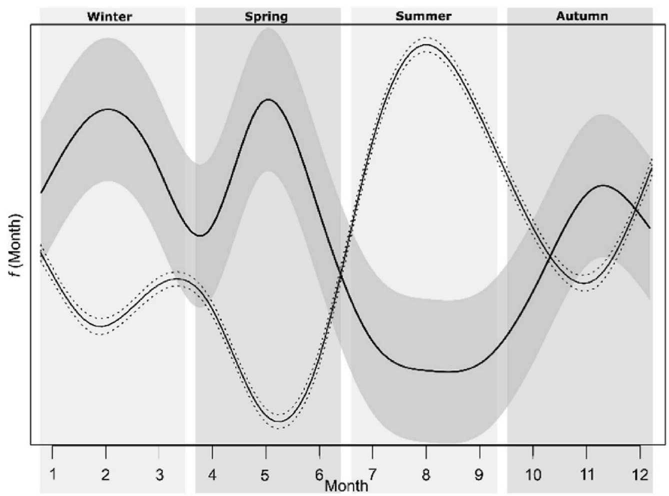

Fig. 2. Seasonal variation of the percentage of trips with unreported landing events (shaded CI) and the variation of the price per kg throughout the year (dashed CI lines). The four seasons are highlighted. The description of the models, with formulas, variables, R^2 and Deviance Explained can be found in Appendix section, Table A2. The plots and histograms from the resulting residuals can also be found in Appendix section Fig. A1 – Unreported landing events and Fig. A2 – Price of landed species.

minimum of fishing trips carried out by each vessel, for each of the 12 different months, during the period of 2014–2020.

This threshold was defined through an iterative approach of model selection, where the resulting Akaike Information Criterion (AIC) and Deviance Explained were monitored across increasing thresholds of minimum number of fishing trips used in the different GAMs. The minimum number of fishing trips was established when the rate of the model's AIC decreased or stopped to improve, and the rate of its Deviance Explained started to stabilize (Pedersen et al., 2019). Under this approach, a threshold of 19 fishing trips was defined as the minimum number of fishing trips carried out by each vessel, for each of the 12 different months, during 2014–2020. For a graphical representation of the iterative model selection process, check the Appendix section, Fig. A1. Moreover, the response variable (proportion of trips with unreported landing events) was transformed (arcsine square root) in order to comply with the GAM's assumptions (Zuur, 2012). The descriptors of the model, resulting adjusted R^2, Deviance Explained, "and the residual plots can be consulted on Appendix section Table A2 and Fig. A2, respectively.

To try to understand if the variation of the auctioned catch value could have an effect on the seasonal variation of the unreported landing events, we modelled the variable "price per kg" of all species landed by this fleet against the variable month. Again, we fitted a GAM and considered the factor "species" as predicting variable with a random effect when fitting the model to the data and transformed (square root) the dependent variable to comply with GAM's assumptions. The model description and its results can be found in the Appendix section (Table A2 and Fig. A3).

3. Results

3.1. Summary of the combined data

The classified AIS data returned 11847 fishing trips from 66 different polyvalent coastal fishing vessels, the number of fishing trips per vessel varied from 53 to 475 with a mean number of trips per vessel of 180 and a median of 142. Landings were reported for 84.1 % of these trips, i.e., landing records from the trips tracked with AIS were present within the landing dataset (Table 1). The remaining 15.9 % of tracked trips had no landing records, which is a value that falls close to the 15 % of infringements related to non-reporting or misreporting detected by EFCA in 2022 (EFCA, 2022).

Table 1
Summary table from the data used in the current work. Unreported landing events were identified when there was no landing record from fishing trips (recorded with AIS) that had gear-hauling events.

Data summary	
Number of trips with hauling events (classified AIS data)	11847
Number of vessels	66
Mean number of trips per vessel	180
Median number of trips per vessel	142
Number of trips with unreported landing events	1885
Total % of trips with unreported landing events	15.9

3.2. Risk assessment at vessel level – unreported landing events

On average, landings of 14 % of all fishing trips tracked with AIS data, from the 66 vessels, were not reported. This means that fishing vessels with more than 14 % of unreported landing events (23 out of 66 vessels) were identified as risk units. These vessels, which represent 1/3 of the analysed vessels, were responsible for nearly 85 % of unreported landing events identified in the present analysis.

It is also noteworthy that vessels showed a wide difference regarding the proportion of trips without landing records: some vessels did not miss any landing event in all their AIS recorded trips (0 % of unreported landing events), whereas some vessels did not land their catch more than 30 % of their AIS recorded trips. There was even one vessel that showed 61.4 % of unreported landing events (Tables 2 and 3).

3.3. Seasonal variation of unreported landing events

The percentage of fishing trips with unreported landing events throughout the year showed a non-linear behaviour (Fig. 2). The beginning of the year until mid-spring had the highest values in percentage of trips with unreported landing events, with a noticeable decrease during the Easter months of March and April. Then, after May, the percentage of unreported landing events decreased rapidly, reaching its lowest value in August. This means that there was an evident increase of reported landing events (in percentage) during the second half of Spring until August. From September to November, a steady increase of unreported landing events, is observed and in December, a slight drop in the percentage of unreported landing events is again observed.

The price per kg of auctioned catch showed a quite fluctuating behaviour throughout the year and contrary to the behaviour of unreported landing events (Fig. 2). It started the year with a decreasing tendency, until mid-Spring (May) when it reached its lowest value, except during the Easter months (March and April) when a slight increase of the price was observed. After that, it spiked until it reached its maximum during the Summer (August). From September until November the price decreased again and turned to increase in the last

Table 2
Summary table regarding the unreported landing events. The overall mean percentage of trips with unreported landing events was 14 % which was the threshold % value defined to classify fishing vessels as risk units. The number of vessels with more than 14 % of unreported landing events was 23 out of 66 and were responsible for nearly 85 % of the detected unreported landing events.

Summary of unreported landing events	
Mean % of unreported landing events	14.0
Median % of unreported landing events	7.0
Maximum % of unreported landing events (vessel level)	61.4
Minimum % of unreported landing events (vessel level)	0.0
Number of vessels with >14 % unreported landing events	23
Total % of unreported landing events from identified vessels	84.6

Table 3
Table with the first 20 vessels and the number of fishing trips recorded with AIS data. Fishing vessels with more than 14 % of unreported landing events are highlighted. The IDs of the vessels are anonymized due to confidentiality agreements. The complete table of all 66 vessels can be found in the Appendix section, Table A1.

Vessel ID	Number of trips - AIS	Number of trips without landing event record	% of trips without landing event record
ID-1	***475***	***137***	***28.8***
ID-2	***437***	***118***	***27***
ID-3	***433***	***142***	***32.8***
ID-4	***396***	***243***	***61.4***
ID-5	381	9	2.4
ID-6	***379***	***114***	***30.1***
ID-7	322	7	2.2
ID-8	286	11	3.8
ID-9	279	9	3.2
ID-10	275	9	3.3
ID-11	274	19	6.9
ID-12	***269***	***101***	***37.5***
ID-13	268	3	1.1
ID-14	***259***	***60***	***23.2***
ID-15	***257***	***81***	***31.5***
ID-16	256	12	4.7
ID-17	255	16	6.3
ID-18	253	5	2
ID-19	252	6	2.4
ID-20	***248***	***74***	***29.8***

month of the year (December).

4. Discussion

The wide variation in the percentages of unreported landing events amongst the different vessels seems to indicate that vessels behave very differently regarding their obligation of officially landing and selling their catch. This difference in behaviour, aligned with its seasonal variation, associated with the high costs and low effectiveness of MCS effort, corroborates with the statement that supports the need for improvement in MCS efforts which needs to be better allocated instead of being randomly deployed.

There have been other studies with the intent to acquire information that would translate into more cost-effective MCS efforts. Ford et al. (2018), for example, used AIS data to study loitering behaviours and rank vessels with higher probability of engaging in such behaviour. Iacarella et al. (2023) combined AIS data with aerial surveillance data to detect and estimate illegal fishing activities within conservation areas. Hosch et al. (2019) combines AIS data to infer vessel activity and their visit to major landing ports to make a risk assessment, at port level, to identify ports with higher risk of IUU-caught seafood passing through them.

Methodologies combining vessel tracking data with fishery dependent data to gather intelligence to improve MCS efforts are still very undeveloped. Moreover, the majority of IUU risk assessments have been done at wider resolutions, such as country, region or port level. Here, we discuss how these two types of data allow to make a risk assessment at a narrower resolution and identify vessels that could be more prone to fail with their landing obligations and when the probability of that happening is higher. Through the identification of such vessels and time periods, MCS effort can be better allocated by prioritizing the control and inspection to the identified vessels and seasons within the risk assessment.

We observed an evident discrepancy, at vessel level, on the proportion of trips without reported landing events, where one third of the analysed vessels (23 out of 66) were responsible for the majority (85 %) of the detected unreported landing events. Which means that identifying such vessels with higher probability of failing to follow a given regulation and prioritizing MCS effort towards them might be a good starting point to better allocate MCS efforts. This is particularly relevant within a risk assessment context, as those who have the tendency of not following a common regulation also tend to not follow other regulations that are transversal to all (Vallejos B et al., 2023).

In the present study, we defined a threshold to identify vessels as preferential targets for MCS efforts based on the average percentage of unreported landing events from the analysed fleet. This value was established merely as an example and can be tuned and adapted to management needs. Stakeholders, such as those responsible for controlling fishing activities, can define higher or lower thresholds based on different factors, such as the number of vessels they intend to inspect or the available budget allocated to MCS activities, for example.

It is important to stress that this approach does not aim, neither is able, to prove if a vessel is committing any illegality or if it is being fully compliant with regulations. Indeed, the absence of landing data after a fishing trip may not be related with incompliancy. For example, if a vessel, after a trip where gears were hauled, does not officially land any catch, there is always the possibility that the vessel neither captured nor kept any catch in that trip. Although possible, this is very unlikely, because these vessels haul more than 10 km of gears per trip (Sales Henriques et al., 2024), and they always capture more than one species with commercial value.

Another reason for the absence of landing record on the same day of a fishing trip could be related to the lower prices of some species during the period when they were fished: some species, like the *Octopus vulgaris*, can be frozen and sold afterwards without losing its market value. Which means that fishers may freeze their catch on land facilities and legally sell it when the demand and prices are higher for those species. Yet, given that we are dealing with a polyvalent fishing fleet that operate different gears, targeting and catching different species, the proportion of fishing trips capturing one single species is inexistent. So, in case when a given species would be stored/frozen to be sold when its price is higher, the remaining species that were caught on the same trip would still have to be officially landed when the vessel arrives to port.

Another incompliant behaviour that this approach is not able to detect, is when a vessel officially lands some, but not all, of their catch. This might be particularly relevant for high-value species, like lobsters (*Palinurus elephas*) for example. Which may be sold through other means than the official and legal one.

It is important to refer that given that we used AIS as vessel tracking data, which can be easily switched OFF by the skipper, if a fisher is aware of such an approach to identify unreported landing events, and in case the skipper does not intend to officially land his/her catch, he/she could make a fishing trip without AIS data being transmitted. This would result in the non-identification of the unreported landing event as the geospatial data from the fishing trip would not exist. Vessel tracking systems where the skipper is not able to switch OFF the track signal, such as VMS (Vessel Monitoring System) or other closed systems, would provide more robust results and indeed should be the preferential source of data used in risk assessments to plan MCS efforts.

Besides the identification of IUU risk units at vessel level, we also aimed to study how the seasons could affect and explain changes of unreported landing events. We saw that during the Summer, there is an evident reduction of the proportion of trips with unreported landing events. This result suggests that MCS effort would have a higher probability of detecting unreported landing events if deployed during Autumn, Winter and Spring's first half.

Given the seasonality of seafood consumption, which is higher during late Spring, Summer and festive seasons such as Easter and Christmas, which consequently increases the demand for these products (Love et al., 2023; Macdiarmid, 2014), the seasonal variation of unreported landing events is contrary to what the authors would initially expect. We would expect that the unreported landing events would increase during high-demand seasons, especially during late Spring and Summer, as, due to higher demand, and overall higher prices, it is easier to sell seafood products through other means than at auction, like directly to restaurants for example, which usually returns higher profits and allows fishers to avoid paying taxes. However, higher prices may also play an inverse role in this behaviour. The fact that the prices of seafood increase during Easter, Christmas and especially the Summer could play an important role on the reduced proportion of unreported landing events during these periods. Indeed, fishers may feel more compelled to land and sell their catch officially, since they will get higher profits than during the periods when the seafood prices are lower.

There is another important aspect within the Portuguese legislation that may have an important role in this result. According to the regulation nº 14 694/2003, which establishes the conditions for the annual renewal of vessel's fishing licences, a fishing vessel must prove that it maintains a regular activity throughout the year. To do so, vessels must have legally sold a minimum value that is equal to V, which is calculated as: $V = (T - 1) \times 12 \times NMW$; where T is minimum mandatory number of crewmembers onboard the vessel, and NMW is the National Minimum Wage of the current year. In other words, vessels must prove that they are able to pay the salary of its crew, as minimum wage, during the entire year.

Another very relevant aspect of this regulation, is that the period of fishing licencing renewal ends on the 31st of August of each year. Meaning that vessels must have officially sold at least a value that is equal to V by the end of August to be able to renew their licence. With that in mind, we hypothesize that another possible reasons that the proportion of reported landing events increase during Spring until the end of August has to do with the fact that fishers are officially selling more seafood products to reach the minimum selling value that will enable them to renew the vessel's fishing licences.

5. Conclusion

Combining vessel tracking data with fishery dependent data, such as landing data, has shown that it has the potential to unravel some of the human behaviours that are inherent to fishing activities, how fishers comply with regulations and how complex it is to monitor and control their behaviour. To be able to identify and to understand the drivers behind uncompliant behaviours and to know how they are performed across actors and seasons is vital to improve MCS efforts. We have seen that not all vessels behave the same way regarding the obligation of officially landing their catches and that the rate of unreported landing events varies considerably across the year. We also noticed that seafood price fluctuation and national regulations, with their requirements and timing may be important drivers behind unreported landing events. This type of information is vital to identify IUU risk units within a risk assessment and therefore to make MCS efforts more effective. Moreover, since past behaviours are a good predictor of present and future behaviours, especially when control and surveillance practices are ineffective (Vallejos B et al., 2023), this approach, which relies on past data, can still be used in a risk assessment to assist future MCS plans.

As we discussed, the use of AIS data in the presented approach might be a relevant aspect to consider when making such risk assessments. Indeed, the use of vessel tracking devices that cannot be switched OFF by the skipper, would be more appropriate. However, data such as VMS is confidential and very difficult to be accessed by researchers. Nonetheless, It is important to state that that the main scope of this work is to explore the usefulness of combining vessel tracking data with fishery dependent data in improving our knowledge on incompliant behaviours and to assist the improvement of the cost-effectiveness of MCS efforts.

Fishing activities are very complex, and the different drivers responsible for certain types of illegal behaviours do differ from fishery to fishery, species to species, and especially from country to country (Temple et al., 2022). This is why this sort of analysis are important so that we can better understand why and how illegal fishing practices are being carried out throughout the different fisheries around the world.

Another important conclusion that can be drawn from this study, yet slightly out of the main scope of this work, relates with the reliability of fishery dependent data when used to estimate fishing metrics, such as the fishing effort, for example (Ballesteros et al., 2024). Given that nearly 16 % of all fishing trips, (15.9 % of unreported landing events) would have not been detected through landing data, such estimates consequently may underestimate the real values. Moreover, this aspect may be even more relevant in studies at vessel level, given the evident discrepancy among the different vessels.

Increasing our knowledge on the complexity of IUU activities is the first step to improve the fight against them. By allocating MCS efforts to risk units with higher probability of committing IUU practices will increase the cost-effectiveness of MCS efforts in detecting and punishing illegal behaviours. This will then contribute to discourage such practices and ultimately, improve the governance and sustainability of fishing activities and the conservation of the marine environment (Cabral et al., 2018).

CRediT authorship contribution statement

Nuno Sales Henriques: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Tommaso Russo:** Writing – review & editing, Supervision. **Karim Erzini:** Writing – review & editing, Supervision, Funding acquisition. **Jorge M.S. Gonçalves:** Writing – review & editing, Supervision, Funding acquisition.

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.

Acknowledgement

The authors would like to thank our colleagues Luis Bentes, Pedro Monteiro and Frederico Oliveira, whose insights, ideas and discussion helped to improve this work. We are thankful to DGRM – Directorate-General for Natural Resources for providing the fishery-dependent data necessary to carry out this study. We would also like to thank the two anonymous reviewers and Peter Mous, how's comments and suggestions contributed for the improvement of this work. This work was funded in part by Portuguese national funds from FCT - Fundação para a Ciência e Tecnologia through projects UIDB/04326/2020, UIDP/04326/2020 and LA/P/0101/2020 to CCMAR; NSH was funded by the FCT PhD scholarship ID nr: 2020.05583.BD (https://doi.org/10.54499/2020.05583.BD).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2025.107789.

Data availability

The authors do not have permission to share data.

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