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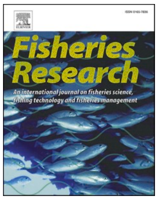

Let's measure it: An approach of high-resolution estimates of bottom fixed net fishing effort at national level

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ABSTRACT

Fisheries are one of the most important food sources for human consumption whilst being amongst the most impacting and extractive activities happening within the marine environment, which makes it imperative to properly manage this activity. To improve fisheries management, the precise quantification of fishing effort is of the outmost importance. Yet, present methods for effort estimation, especially at broad scales, are hampered by difficulties in data access and usually rely on coarse effort metrics or on costly data collection for quantifying fishing effort with higher resolution. In the present work, we propose an approach of high-resolution fishing effort estimates of net fishing, as length of nets operated by a given fleet, at the national level. It relies on sampling of effort, derived from classified and easy to access vessel tracking data – AIS, and fishery dependent data – logbook and landings data. The proposed methodology combines trip-based effort estimates, derived from AIS data, as a foundation to extrapolate the total fishing effort, through the number of fishing trips linked to official landings and logbook data. It is estimated that in the years from 2014 to 2020 an average of 180 200 km of static nets (gillnets and trammel nets), which corresponds to approximately 4.5 and 210 times the lengths of the equator and the Portuguese Atlantic coastline respectively, are used in Portuguese mainland waters each year, by a fleet of slightly more than 100 vessels. The presented methodology allows to quantify and study the variation of the nominal fishing effort, at country level, with a higher resolution than what is usually used and at very low cost. We argue that such methodologies need to be developed and explored in order to have better and more comprehensive estimates of fishing effort which will contribute and improve the sustainable management of fisheries and the marine environment.

1. Introduction

As the human population grows, so does the need for food production. Fisheries, as one of the most relevant sources of protein for human consumption, have been increasing since the 1970s (Anticamara et al., 2011). Besides its importance as a food source, it is also one of the most impactful and extractive activities happening in the marine realm (Pauly et al., 1998; Swartz et al., 2010), meaning that it needs to be properly managed in order to keep on contributing for human food security (Pauly et al., 2002).

One of the most relevant aspects for the sustainable management of fish stocks and the marine environment is to accurately know how much fishing pressure is being exerted, as it allows to understand the trends of catch rates and better estimate the impacts, such as bycatch and discards caused by a given fishery. This means that the precise estimate of the fishing effort is paramount to manage fisheries effectively and sustainably. Yet, for many countries and fisheries, data on fishing effort is still very unprecise and unreliable, making it imperative to improve the global fishing effort estimates, including at country level (Kieran, 2009; Anticamara et al., 2011).

Bottom contacting fishing gears are known to be the most impactful and most damaging forms of fishing (Glover and Smith, 2003; Hourigan, 2009). Bottom contacting nets such as gillnets and trammel nets are among the most commonly used fishing gear worldwide (Cashion et al., 2018) and are known for their impacts on the marine environment, such as ghost fishing (Erzini et al., 1997; Richardson et al., 2019) and habitat damage (Gonçalves et al., 2008; Dias et al., 2020). Therefore, the precise quantification of net fishing effort and the knowledge of its distribution

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is vital to improve ocean management and conservation. But, despite the improvements in mapping and quantifying of fishing effort, the quantification of the fishing effort at regional, national or even global level is still far from ideal (McCluskey and Lewison, 2008; Anticamara et al., 2011; Kroodsma et al., 2018; Leblond et al., 2019).

To study the fishing effort, different metrics and quantification approaches have been used throughout the years, such as the engine power (in kilowatts or horsepower) (Rijnsdorp et al., 2000; Eigaard et al., 2011), number of vessels (Rodríguez-Quiroz et al., 2010), size of vessels (Bordalo-Machado, 2006; Leitão et al., 2022), days at sea or fishing days (Rijnsdorp et al., 2006; Guiet et al., 2019) and the combination of these metrics (Joint Research Centre (European Commission) et al. 2022, 2023). These units of effort have been particularly useful when assessing the fishing effort at a broader scale, such as at national or regional level. Yet, broad units of effort may be problematic as they may lead to misleading conclusions. For example, it has been shown that catch per unit of effort (CPUE) can be a misleading index of abundance if inappropriate units of nominal effort are used (Gillis and Peterman, 1998), or that the spatial distribution of fishing effort based on fishing gear soak time do differ from effort distribution based on the time vessels spend at sea (Mendo et al., 2023).

To improve the estimates of effort resolution units and metrics, such as those based on the characteristics and dimensions of the fishing gears, like the total swept area for trawl fishing, the number of purse seine hauls, or the total number of hooks and length of nets used per unit of time and/or area, poses a big challenge. In many instances this precise quantification of effort is dependent on and only possible for very specific and usually costly fishery monitoring and sampling programs, such as those relying on onboard observers (Punt et al., 2000; Mandelman et al., 2008; Coelho et al., 2012). Such challenges make it unfeasible to estimate the fishing effort with the desired level of resolution, for all fisheries within wider areas or at a country level. There have been several studies though, that have estimated the fishing effort with higher resolution and with more precise metrics without being involved in large-scale fishery monitoring programs (Lauridsen et al., 2008; Akyol and Ceyhan, 2009; Gönener and Bilgin, 2009; Batista et al., 2015; Sara et al., 2017). But these studies focused on particular subjects, like bycatch (Gönener and Bilgin, 2009), or studied a subset of a fleet or addressed very narrow spatial areas, without the intention to estimate the total effort of an entire fleet or at a broad scale.

The introduction of vessel tracking devices has revolutionised fisheries research (Tetreault, 2005; Russo et al., 2018; Yang et al., 2019; Thoya et al., 2021). Thanks to data derived from Vessel Monitoring Systems (VMS), Automatic Identification Systems (AIS) and other GPS-based tracking devices, and especially when combined with fisheries dependent data, the study or fisheries productivity, the distribution of fished species, and the quantification and distribution of the fishing effort has seen tremendous developments (Russo et al., 2011, 2016, 2018; Jennings and Lee, 2012; Eigaard et al., 2016). Yet, in order to study an entire fleet's effort, either almost complete fleet coverage from vessel tracking data, or some other procedures that rely on a sample of the fishing fleet, is required (Russo et al., 2018).

As it is mandatory for all fishing vessels with Length Overall (LOA) above 12 m and it is continuously transmitting, VMS is the most comprehensive vessel tracking device that enables the study of the spatial and temporal effort attributes of an entire fleet (Russo et al., 2016, 2018). Yet, due to confidentiality regulations, access by researchers to this type of data is very difficult. Moreover, the transmission frequency is usually very low (1 – 2 h), which poses an additional challenge as some fisheries and fishing techniques such as small-scale fisheries and fisheries using passive gears require much higher data frequency, (Mendo et al., 2019; Sales Henriques et al., 2023).

AIS, on the other hand, has some relevant advantages compared to VMS data: it is of easy access and the data frequency is much higher (usually 1–5 min), which is ideal to study fisheries with short duration fishing operations (Mendo et al., 2019, 2023). Unfortunately, AIS systems also present some disadvantages that compromise the spatio-temporal coverage of the data. For example, for land-based AIS signals, if a vessel is too far away from a receiving antenna, the AIS transmission can be lost, the AIS signal is very dependent on weather conditions, and the AIS transponder can be manually switched off by the skipper (Russo et al., 2016; Emmens et al., 2021). These liabilities associated with AIS makes it difficult to have a comprehensive fleet coverage. In fact, the coverage of the fleets was usually low in many of the published works where AIS data was used to study fishing activities, either due to the poor fleet coverage by AIS or due to the high-quality data requirements used in the analysis (Natale et al., 2015; Russo et al., 2016; Sales Henriques et al., 2023).

In the work by Sales Henriques et al. (2023), the authors developed a methodology to classify vessel tracking data from passive fishing events from a polyvalent coastal fishing fleet operating bottom contacting nets and pots and traps. With the developed methodology, the authors were able to classify AIS data from 84 polyvalent coastal fishing vessels into the four common behaviours happening within a fishing trip: navigation; gear deployment; gear hauling and slow navigation (Fig. 1). This work allowed fishing effort of this fleet to be mapped and quantified as soak time, during the period from 2014 to 2020. But, due to the aforementioned disadvantages inherent to the AIS data and data quality requirements of the developed methodology, this work was only able to map and quantify a fraction of the total effort of this fishing fleet: 26.5 % of the fishing effort of 56 % of the polyvalent fishing vessels equipped with AIS (Sales Henriques et al., 2023).

In the present work, we develop and explore a new methodology to quantify the national fishing effort of static nets, as total length of nets, from a polyvalent coastal fishing fleet. To do so, we combine the sample of the fishing effort, obtained from the work by Sales Henriques et al. (2023) and fishery dependent data, as the foundation to extrapolate the total fishing effort of this fleet at a national level.

Given the global absence of complete fleet coverage with vessel tracking data (Paolo et al., 2024) to precisely estimate the total fishing effort with better resolution, it is vital to explore and develop methodologies to address this important knowledge gap. We hope that the proposed methodology represents a step forward and contributes to open up the discussion and incite others to develop and apply new methodologies to better estimate the fishing effort at a broader scale than what is currently done.

2. Methods

2.1. Rationale and required data

This approach relies on two different types of data: classified AIS data from polyvalent coastal fishing vessels and fishery dependent data: logbooks and/or daily landings/sales notes data, from here on referred to as landing data. The fishery dependent data was provided by the Directorate-General for the Natural Resources, Safety and Maritime Services (DGRM). The land-based AIS data was classified in the study by Sales Henriques et al. (2023). The AIS data classification procedure, which was able to map and quantify, as soak time, 26.5 % of the fishing effort of 56 % of the polyvalent fishing vessels equipped with AIS was able to identify more than 13200 fishing events using nets and pots and traps (Sales Henriques et al., 2023).

For each fishing event, which is composed of two tracks: 1 - gear deployment and 2 - hauling of the gear, we measure the length using tracking data from the deployment events. To measure the length of each fishing event, we summed the distances of consecutive AIS data points belonging to each deployment track from each fishing event.

2.2. Match of fishing effort with landings and logbook data

The next step was to cross the effort data (AIS data) with logbook and landing data. Given that the effort data, for each vessel was split into

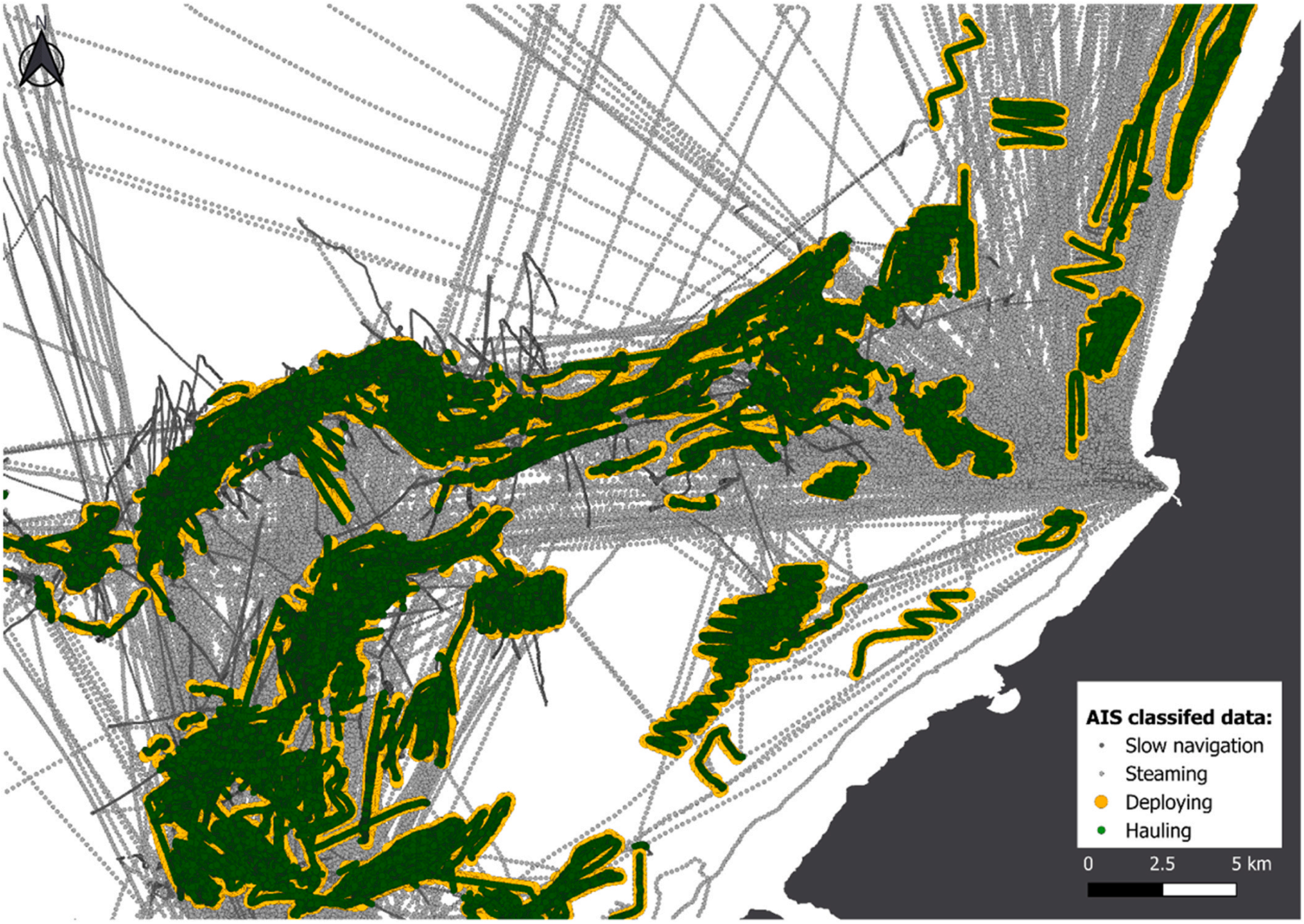


Fig. 1. Example of AIS data classified into the four most common behaviours within fishing trips using passive gears, under the approach developed by Sales Henriques et al. (2023). The classified AIS data was used as sample effort data to extrapolate the total fishing effort, in km of nets used, for vessels with LOA >14 m, operating within mainland Portuguese waters, during the period of 2014–2020.

isolated fishing trips based on the moment of departure (start of fishing trips) and arrival to port (end of fishing trips), we first identified the date and time each vessel arrived in port based on the last AIS datapoint of each trip. Then, for fishing trips with hauling events, we matched the fishing trips effort data with the information provided in landing and logbook data corresponding to that trip. The crossing of effort data (track data) with fishery dependent data (landings and logbook data) was based on vessel's ID and the date of arrival to port within track data and the field "landing date" within logbook and landing data. This procedure allowed us to get a data set where we have the information about the spatiotemporal attributes of the fishing operations, like date and time, location, duration (soak time) and length of the fishing event (s), and the respective information declared by fishers and recorded for landing events, such as the used fishing gear(s), the landing port and the respective yields, such as landed species and how much of each species was landed, in kg (Fig. 3).

2.3. Selection of trips that only used static nets, based on info from logbooks

Given that the current study aims to estimate the length of static nets used by the coastal fishing fleet, from the dataset resulting from crossing effort and fishery dependent data, we only selected the fishing trips that used static nets (gill nets and trammel nets) and no other gears. This procedure was done using the information within the logbook field "gear type", and only the landing trips that used these gears were kept.

2.4. Calculation of the average length of nets used per trip, by LOA class ($AvgNet_c$)

Because we are using a subset of the total fishing effort that we crossed with fishery dependent data, we needed to develop a methodology that allows to extrapolate the total fishing effort to a reasonable estimate of effort for the entire fishing fleet. Under our methodology, we assume that fishing vessels, on average, use the same length of nets within each fishing trip and that the total length of nets handled by trip is dependent on the size of the vessel. Under these assumptions, we calculated the average length of nets, from the AIS effort data, hauled in each trip and by vessel Length Overall (LOA) class. Therefore, the calculation of the average length of nets hauled in each trip, (from here on: AvgNet) was carried out for groups of vessels that were defined based on the vessel LOA.

According to the Portuguese legislation (Portuguese Ordinance No. 1102-H/2000), the length of nets allowed to be operated by vessel is dependent on the vessel size. Therefore, AvgNet was calculated for each LOA class as defined by the Portuguese legislation. The LOA classes that establish the maximum total length of nets allowed are: ≤ 9 m – VL0009; (9–12 m] – VL0912; (12–14 m] – VL1214; (14–16 m] – VL1416; (16–18 m] – VL1618; (18–20 m] – VL1820 and > 20 m – VL20+, where "(" means LOA sizes bigger than the stated LOA value and "]" includes the specified LOA value. Because we are dealing with coastal fishing vessels with AIS devices, the LOA classes that we considered were the ones that include vessels with LOA above 14 m. Despite AIS being mandatory only for vessel with LOA bigger than 15 m, there were 4 vessels with LOA between 14 m and 15 m within the classified AIS data. Therefore, to increase the number of vessels for the estimation of effort, we decided to include all vessels longer than 14 m (Table 1).

As the distribution of sampled values of km of nets used by trip (AvgNet) for each vessel LOA class did not follow any known distribution (Figure s1), we performed a nonparametric bootstrapping with replacement to the sampled data, with 10 000 resamples to obtain overall effort values with 95 % Confidence Intervals (CI). We then assessed the bias between the sampled AvgNet with the same effort unit derived from the bootstrap procedure and checked for significant differences through a t-test. If there was no difference between the sampled and bootstrap average effort values for each trip, we used the 95 % CI obtained from the sampling distribution of means from the bootstrapping (Table 1).

2.5. *Effort calculation: AvgNet x N fishing trips*

After obtaining values of AvgNet and respective upper and lower limits belonging to the 95 % CI used in each trip for the different LOA classes, we calculated the fishing effort for every polyvalent fishing vessel with LOA > 14 m, operating nets within Portuguese mainland waters from 2014 to 2020. Strictly speaking, the total net fishing effort of this fleet was calculated as the product of the number of landing events, as a proxy for fishing trips, and the AvgNet. More specifically, the effort (*f*) of vessel (v) during the month (m) for fishing trips ending in port (p) was calculated as the product of the number of fishing trips (Nt) per vessel (v) for month (m) landing in port (p) by the average km of nets used per trip (AvgNet) specific to the vessel's LOA class (c) as calculated from the AIS classified data:

$$f_{\mathrm{v,m,p}} = \mathrm{Nt}_{\mathrm{v,m,p}} \text{ x } \mathrm{AvgNet}_{\mathrm{c}} \tag{1}$$

As done for the vessels within the AIS classified dataset, from which we calculated the values of AvgNet before calculating the total effort of net fishing, we needed to select the fishing trips that used nets and no other gears. Since fishing vessels with LOA ≥ 12 m are required to use electronic logbooks (EU Control Regulation 1224/2009) and log which gears were used in their fishing trips, we selected only fishing trips/landing events that only operated static nets (trammel and gillnets) during the study period and then calculated the effort using Eq. 1 (Table 2).

The total fishing effort for landing events happened in port (p) during month (m) was calculated as follows:

$$f_{\mathrm{p,m}} = \sum_{v=1}^{V} f_{v,m,p} \tag{2}$$

where *V* is the total number of vessels.

2.6. *Effort validation*

As we used a subset of the total fishing effort to estimate the overall effort of a fleet, to validate the effort values from the AIS data calculation we adapted the model from the work of Russo et al. (2018) and assumed that landings (L), in kg, from a given vessel (v), during the month (m), landed in port (p) is given by:

$$\mathrm{L}_{\mathrm{v,m,p}} = f_{\mathrm{v,m,p}} \text{ x } \mathrm{LPUE}_{\mathrm{c,m,p}} \tag{3}$$

Where $\mathrm{LPUE}_{\mathrm{c,m,p}}$ is specific to the vessel's LOA class (c), landing in port (p), during month (m). In other words, the monthly landings of a given vessel in a given port during a given month is a result of the product of its effort and the average LPUE of its LOA class, landing in the same port during the same period (month).

To validate our approach, we used k-fold cross validation, with k = 25, where we split our data into 80 % as estimation data and 20 % validation data. Then, we calculated the $\mathrm{LPUE}_{\mathrm{c,m,p}}$ from the estimation dataset and for the validation dataset we calculated the predicted effort ($f'_{\mathrm{v,m,p}}$) through:

$$f'_{\mathrm{v,m,p}} = \frac{L_{v,m,p}}{LPUE_{c,m,p}} \tag{4}$$

Then, to assess the assumptions of effort derived from AIS data, we compared the estimated effort (*f*') with the calculated effort (*f*) and assessed the distribution of the residuals.

Table 2

Overall number of vessels and landing trips for the coastal polyvalent fishing fleet operating nets bottom nets during the period 2014–2020. The number of landing events were used as proxies for the number of fishing trips, under the assumption that each landing event corresponds to a fishing trip. The total effort of this fleet was calculated using the number of fishing trips (landing events) and the average km of nets used by each vessel LOA class.

LOA class	Number of vessels	Number of trips
VL1416	31	21 370
VL1618	37	30 643
VL1820	23	17 669
VL20+	15	9 891
TOTAL	106	79 573

3. Results

The crossing of the sample effort spatial data with landings and logbook data from fishing trips using nets, returned a dataset with 5478 fishing trips performed by 73 vessels. Fishing vessels can deploy and haul one or more sets of nets in one trip and in fact 8163 net fishing events were identified and measured within these fishing trips. Given that there was no significant difference ($p > 0.05$) between sampled average km of nets used per trip (AvgNet) and the same effort metric derived from the bootstrapping (Table 1), the sampled effort unit was used to calculate the overall fishing effort and the 95 % CIs were calculated from the bootstrap results. Table 1 provides a summary of the outputs of this initial procedure.

According to landings and logbook records, 106 vessels with LOA > 14 m, performed 79 573 fishing trips using bottom nets from 2014 to 2020. These trips ended in 15 different fishing ports along the Portuguese mainland coast, with the total number of trips corresponding to

Table 1

Summary of the calculation of the average length of hauled nets per trip, for the four LOA classes of vessels present in the AIS effort dataset, for which we were able to match trips with landing and logbook data. Due to the fact that the distributions of the length of nets used by trip did not follow any known distribution, bootstrapping procedure was performed with the purpose to: 1) assess if the sample mean would resemble the population mean derived from bootstrapping and 2) to calculate the 95 % Confidence Intervals (CI) of the length of nets being used per trip.

LOA class	Number of vessels	Number of trips	Average km of nets hauled/ trip (Sample data)	Average km of nets hauled/ trip (Bootstrap)	Bias Sample data VS Bootstrap	Standard Error (km) (Bootstrap)	95 % CI in km (Bootstrap)
VL1416	17	886	10.74	10.75	2.5	0.18	10.39 – 11.09
VL1618	31	2814	13.64	13.64	0.54	0.13	13.38 – 13.9
VL1820	22	1670	16.72	16.72	-0.12	0.21	16.31 – 17.13
VL20+	3	108	30.45	30.44	-11	1.73	27.06 – 33.86

the total effort of fishing vessels of the fleet operating bottom nets (Fig. 2 and Table 2).

The model presented in Eqs. (3) and (4) was developed for validation purposes and therefore it was tested as such. The performance of the presented methodology in predicting f' for the validation dataset showed to be good (Fig. 4A), meaning that the calculated values of average length of nets used by trip are reliable for extrapolating the total fishing effort for this fleet. It is note-worthy though, that despite the good overall prediction of f' ($R^2=0.9$) some variance is observed especially as the f increases. Nonetheless, as we see from the distribution of the residuals (Fig. 4B), it is clear that the mean value is equal to 0 and that the majority of the residual values are close to 0 and evenly distributed on both sides of the residual mean value.

Given the prediction and validation results described, the AIS calculated values of trip-based effort were used to estimate the fishing effort through the approach described in Eqs. (1) and (2).

We estimate that the total length of nets used during the study period was 1 261 497 km (95 % CI: 1 203 936–1 318 081 km), which corresponds to approximately 180 200 km of nets used per year along the Portuguese mainland coast. The effort intensity showed accentuated fluctuations along the study period without a conspicuous pattern. Yet, it seems that the effort was generally higher during most of the spring/summer months than the autumn/winter period (Fig. 5).

Not all vessel LOA classes contributed equally to the total fishing effort, and this contribution seems to be port-dependent and to remain relatively stable throughout the study period. For example, in the port of Aveiro, the vessel LOA class VL1618 had much higher values of effort when compared to the other LOA classes. On the other hand, the difference of effort between classes was not so distinct for the remaining ports where all the 4 LOA classes operated. It is also clear that the bigger vessels LOA class (VL20+) had a higher effort contribution in the neighbouring ports of Sesimbra and Sines. In the fishing ports from the south coast of Portugal, the effort contribution was predominantly from the two smaller LOA classes (Fig. 6).

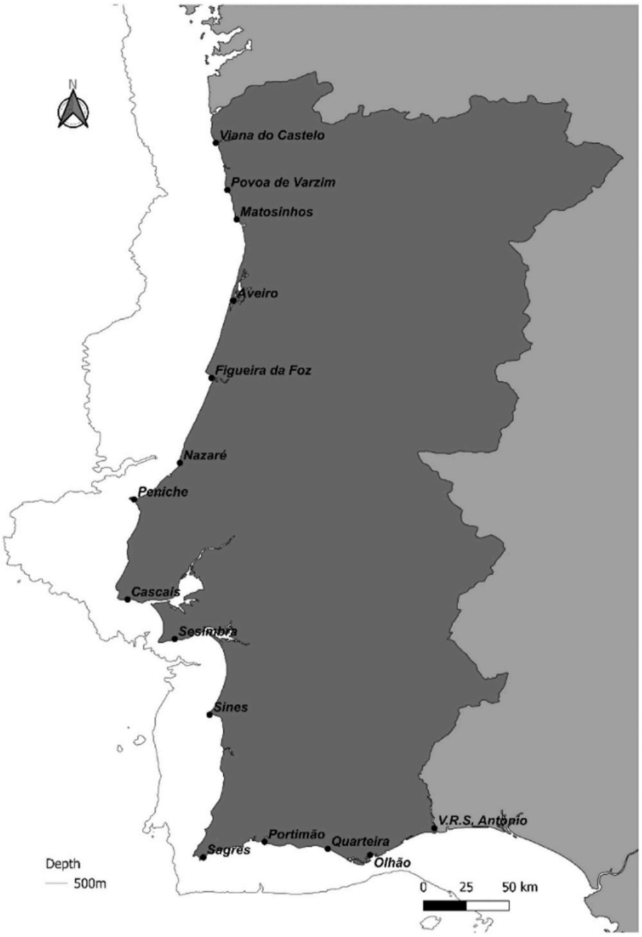


Fig. 2. Map of the Portuguese mainland, which represents the study region of the present work. The 15 landing ports present on the landings and logbook records are shown. The 500 m bathymetric line is displayed, as it represents a good proxy of the region where demersal net fishing occurs (Leitão et al. 2022; Sales Henriques et al. 2023).

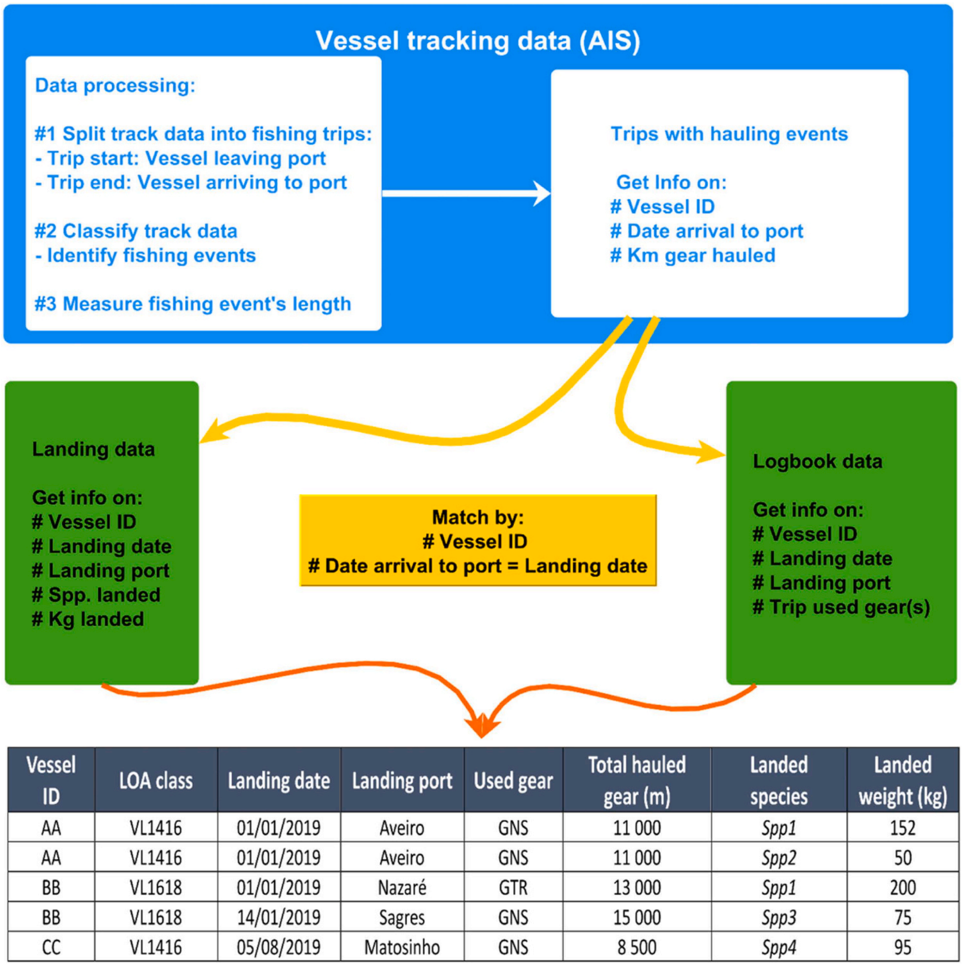
The distribution of net fishing effort remained constant throughout the study region during the studied period. The fishing port that showed highest levels of effort was Aveiro, followed by the port of Póvoa de Varzim and then by the port of Matosinhos. It is evident that the net fishing effort from this fleet segment occurs most predominantly in the upper central and northern region of Portugal, whist the effort in the southwest and south coast of Portugal is evidently lower (Fig. 7).

4. Discussion

Here we introduce an approach to calculate the nominal fishing effort at high resolution, i.e. length of nets used, at a national level. The approach relies on the combination of two data sources: 1 – a sample of high-resolution effort data derived from classified vessel tracking data, and 2 – fishery dependent data: logbook and landing data. This approach allowed to estimate the fishing effort of a fishing fleet operating static, bottom contacting nets, with a higher resolution than what is common for estimates of fishing effort at broader scales, in this case at national level.

Previous estimates of effort, especially at broader spatial scales, have mostly relied on coarser units of effort, such as the number of vessels, vessel sizes and lengths, engine power, number of fishing trips, fishing days and days at sea. Indeed, these effort metrics can be a good proxy of nominal effort in the absence of high-resolution effort data. The combination of some of these metrics has been acknowledged as an even better approach to improve fishing effort estimates (McCluskey and Lewison, 2008; Anticamara et al., 2011). For example, under the EU Data Collection Framework (DCF) the fishing effort for each type of gear, is reported at a resolution of engine power (kw) per day (kw*day), vessel size (Gt) per day (Gt*day) or by the number of active vessels (Joint Research Centre (European Commission) et al. 2022, 2023). Indeed, such metrics are, to some extent, good proxies for studying the fishing effort, but they do not necessarily reflect the actual nominal fishing effort for each vessel or each vessel LOA class. For example, and as shown in the present study, smaller vessels do indeed use shorter sets of nets per trips than bigger vessels, but the correlation between vessel LOA class and the length of nets used per trip is not linear. Moreover, using vessel LOA alone does not provide a good estimate of how many km of nets are used per trip. This means that without high resolution effort sampling methods, such as those relying on onboard observers or through the usage of high-resolution vessel tracking data, the average length of nets used by trip, for example, cannot be estimated.

When there is availability of vessel tracking data throughout a comprehensive portion of a fleet, the precise estimate of effort for a fleet segment at national or regional scale has been shown to be possible (Russo et al., 2019; Leitão et al., 2022). For example, Leitão et al. (2022) studied the spatial trend of LPUE from coastal polyvalent fishing vessels along the Portuguese mainland coast. Russo et al. (2019) was able to map and quantify the fishing effort of the Italian trawl fleet in the Mediterranean Sea. These broad and higher resolution effort assessments are only possible thanks to VMS data (Leitão et al., 2022), or with the combination of VMS and AIS data (Russo et al., 2019). Yet, VMS data is very hard to be accessed by researchers and its temporal resolution is not ideal for some types of fishing gears, such as passive gears (Mendo et al., 2019, 2023; Sales Henriques et al., 2023). Our approach addresses the lack of access to comprehensive sources of high-resolution effort data. It relies on a sample of effort derived from classified AIS data and



Vessel ID	LOA class	Landing date	Landing port	Used gear	Total hauled gear (m)	Landed species	Landed weight (kg)
AA	VL1416	01/01/2019	Aveiro	GNS	11 000	*Spp1*	152
AA	VL1416	01/01/2019	Aveiro	GNS	11 000	*Spp2*	50
BB	VL1618	01/01/2019	Nazaré	GTR	13 000	*Spp1*	200
BB	VL1618	14/01/2019	Sagres	GNS	15 000	*Spp3*	75
CC	VL1416	05/08/2019	Matosinho	GNS	8 500	*Spp4*	95

Fig. 3. Representation of the workflow to match the effort spatial data (AIS) with the fishery dependent data (Landing and Logbook data) and an example of the output. The process relies on the match through the ID of the vessel and the date of arrival to port (vessel tracking data) and the landing date (Landing and logbook data).

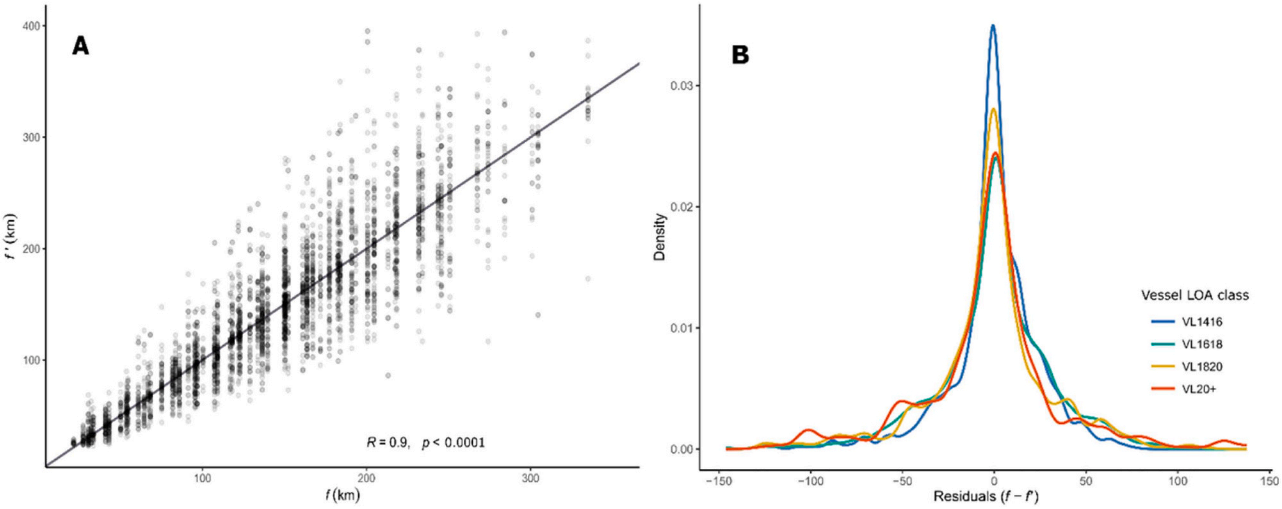


Fig. 4. A – Scatterplot representing the correlation between the calculated monthly effort as per the presented approach (*f*) and the estimated monthly effort (*f*') through the k-fold cross validation process. The Peason's correlation and corresponding *p*-value are shown. B – Distribution of the residuals between the calculated monthly effort (*f*) and the predicted monthly effort (*f*') for each LOA class. The highest density of the residuals is centred around 0 with an even distribution for both sides of the mean value (0).

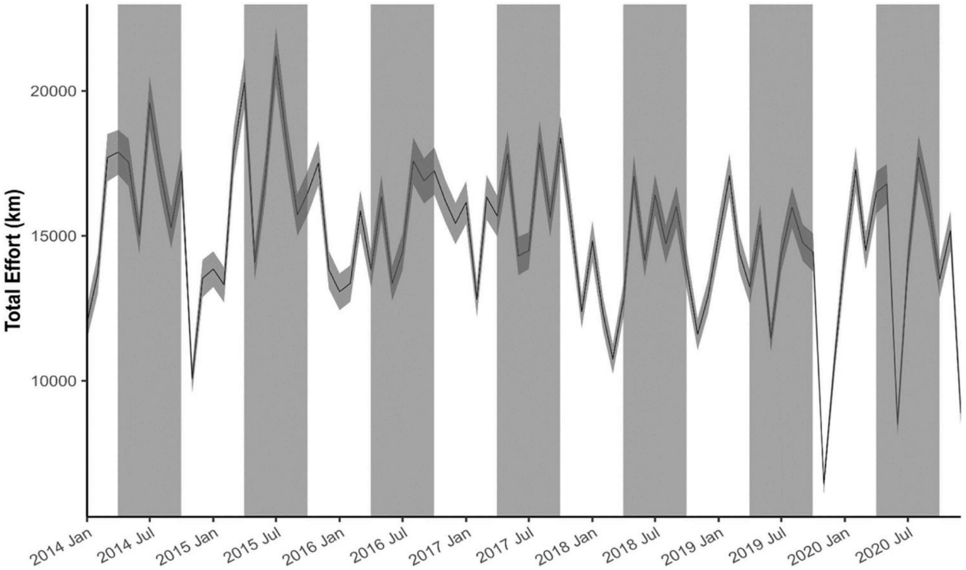


Fig. 5. Time series showing the evolution of the total monthly fishing effort from vessels with LOA > 14 m, as km of nets, along the Portuguese mainland waters. The shaded grey area along the black line represents the 95 % Confidence Interval and the vertical shaded bars represent the warmer months (April to September).

fishery dependent data to estimate the fishing effort for static nets at the national level, with a higher resolution than has been previously attempted.

The differences between the average effort values obtained directly from the effort sample AIS data and the bootstrapped values were very low, which not only gives us confidence in the AIS classification procedure and the way that we calculated the length of the fishing events, but also allowed us to provide a 95 % CI for the effort, when the original distribution of the AvgNet did not follow any known distribution. The resulting values of the AvgNet do follow the expected assumption that bigger vessels use longer nets. Yet, vessels from the LOA class VL20+ operated, on average, considerably longer sets of nets than the remaining LOA classes. The reason for this, has to do essentially with the fact that the trips from these vessels were longer than the remaining LOA classes. An assessment of the classified AIS data (data not shown) revealed that the trips of these vessels, on average, would last around 18 – 19 h, but could easily take 30 h. This period allows to operate longer sets of nets and even operate the same net twice within the same trip. For the remaining vessel LOA classes, trips lasted 9.5–14 h on average, which, associated with the smaller space on deck, does not allow setting and hauling of very long sets of nets. Yet, it is important to refer that even though we analysed 108 fishing trips from vessels from the LOA class VL20+, the AIS derived effort data is only from 3 vessels. This means that the effort values per trip need to be considered with caution, as the number of vessels is low and these 3 vessels could have a different behaviour than the remaining vessels from the same LOA class.

To verify if the effort values derived from the AIS data could be reasonable and therefore justify the landing values from this fleet, we followed the approach by Russo et al. (2018), adapted to our case study. Indeed, the predicted monthly effort (*f'*) and the calculated monthly effort (*f*) showed high correlation. It is noticeable nonetheless that as *f* increases the dispersion of *f'* increases as well. This is expected, as with the increase of effort, so does the differences of catches between vessels. These differences result from some vessels having considerably higher or lower monthly values of catches than the average catch of their LOA class, in port p, during month m. These catch differences may be due to many reasons, including the skills of some skippers compared to others which also translate in differences in catch consistency throughout the month, and also because bottom set nets include a variety of métiers, which is reflected in the catch landings species compositions and quantities (Szynaka et al., 2022). Also, abnormal high or low catches that can influence the overall monthly catch and how much of the catch is actually declared by the vessel can influence these results. Indeed, we did not expect to have small values of dispersion between *f* and *f'* as this is a very complex fishery with many variables that can influence its catches. Yet, from the distribution of the residual values (*f* - *f'*) it is clear that the majority of the values tend to be close to zero, which is also the mean value of the residuals.

The effort intensity along the study period seems to be higher during spring/summer months. This makes sense as this is the period when sea conditions are more favourable for fishing activities, especially in the central and northern coast of Portugal, and when the seafood consumption is generally higher. As expected, spatial distribution of fishing effort from this fleet is higher in the central and northern part of the country and our results corroborate those of Leitão et al. (2022). The fishing fleet in this region, because it is exposed to more adverse meteorological conditions with higher winds and swell heights, is composed of larger vessels. On the other hand, the southern region of Portugal is characterized by more favourable weather conditions and smaller fishing harbours, which makes this region predominantly characterized by small-scale fisheries, with fewer large coastal category fishing vessels. This is supported by our findings, as the two smaller vessel LOA classes operated mostly in the southern region of Portugal.

Another relevant finding of this study is that the spatial distribution of the effort remained stable throughout the study period, and the contribution of each LOA class for the total effort for each port also remained rather stable, supporting the idea of high port fidelity of these vessels.

To be able to extrapolate the overall fishing effort from a high-resolution sample of effort and fishery dependent data, we had to make some important assumptions. The first is that the vessel LOA dictates the length of nets used by trip. This is an obvious and widely used assumption, which is also supported by the results. The second assumption is that vessels, on average, operate the same net length in each trip. Indeed, on some occasions fishers may use more or less nets during a trip, but overall, fishers tend to have the same *modus operandi* within trips. Besides, given that nets operated by these vessels are many km in length, adding or removing one hauled net would greatly impact the time spent at sea. We also used the landing port as a proxy for the region where the vessel fished. Fishing trips within Portuguese mainland waters rarely last longer than a day, which means that fishers normally try to spend less time navigating than fishing and to do so, they need to

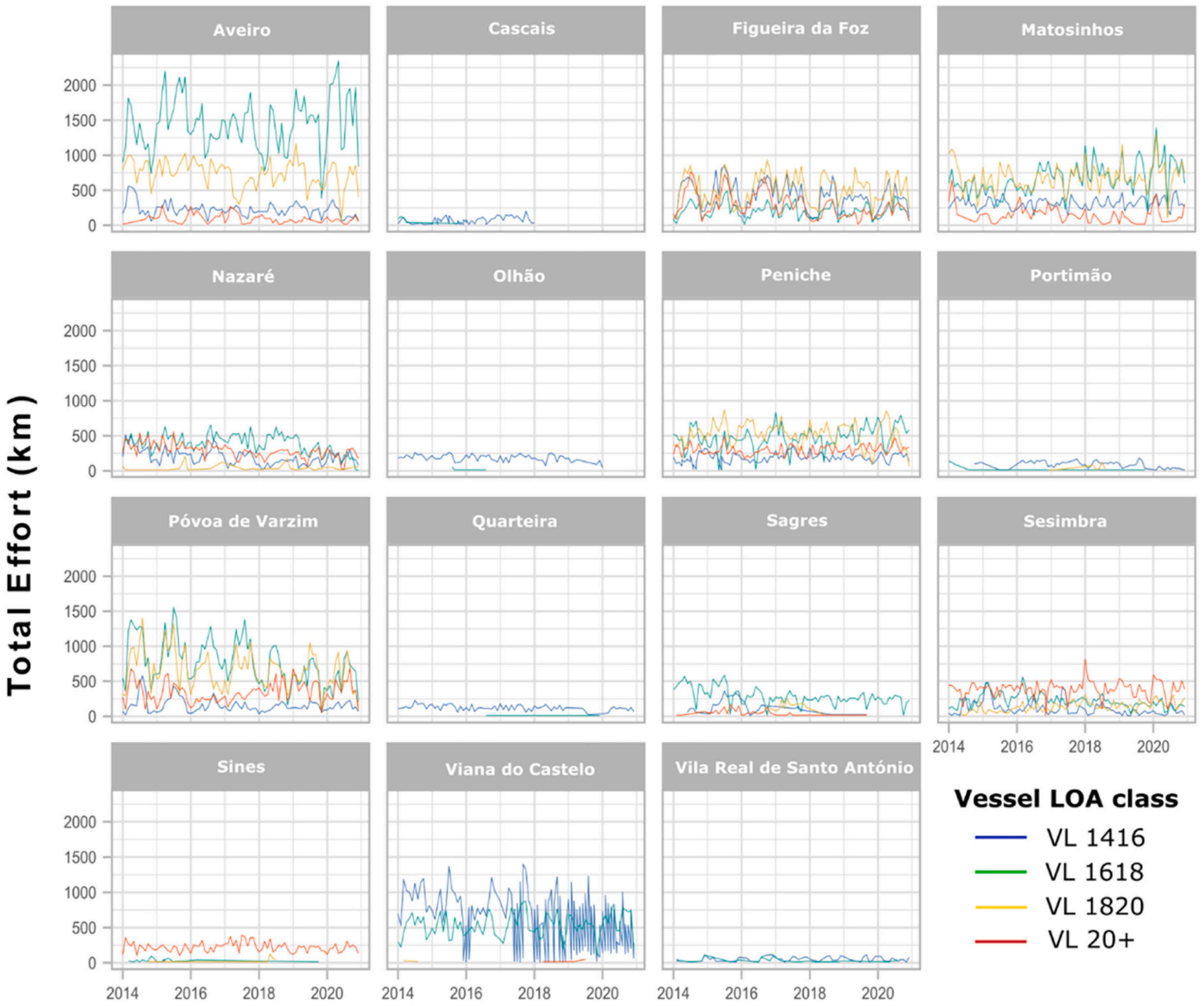


Fig. 6. Contribution of each vessel LOA class to the overall fishing effort allocated to each port and the total effort with the 95 % Confidence Interval. The amount of effort and the effort contribution from each LOA class varies distinctly among ports. Yet, it is observed that the proportion of effort contribution from each LOA class, within each port, remains relatively stable during the study period.

fish in the vicinity of the landing port.

Given that we are dealing with polyvalent fishing vessels, that can operate more than one type of gear, including within the same fishing trip, and because the algorithm developed by Sales Henriques et al. (2023) is not able to identify which gear was used on a given passive fishing event, we decided to not consider fishing trips where more than one type of fishing gear was used. Using multi-gear fishing trips to calculate the overall fishing effort would overestimate the fishing effort from net fishing by considering the effort of other gears. According to logbook data, of all fishing trips operating nets, only 87 % used this type of gear, whilst the majority of the remaining trips operated nets along with pots and traps. This is an important aspect to consider when interpreting the results presented in this paper, which means that the total net fishing effort might actually be underestimated.

There are also some relevant and practical parts of this approach that need to be discussed. The reason we used the gear deployment tracks instead of the hauling of the gear to measure the length of nets used on fishing events, i.e. the length of the fishing event, has to do with the fact that when a vessel deploys a fishing gear, it does it in a very consistent speed and direction, as fishers want the gear to be stretched. When the vessel is hauling the gear, the operation is carried out at a very slow speed and not necessarily in a very constant heading, as many unpredictable events can make the vessel change from the direction of the gear, such as gear fouling on hard bottom, entanglements or bad weather. To consider these changes of heading could overestimate the length of fishing events. Another aspect has to do with the calculation of the AvgNet: this calculation only considered hauled fishing events happening within the trip. This means that, for a given trip, deployed fishing events were not considered in the calculation of AvgNet, unless they were hauled in the same trip they were deployed. The reason for this is that by only considering hauled fishing events, we avoid overestimation of the effort from considering the length of the same fishing event twice, i.e., when it is deployed and when it is hauled. Moreover, hauling events are the most time-consuming parts of fishing trips operating nets, which is a relevant aspect when fishers have to decide how long the fishing trip will be. Also, given that crossing effort data with the landing data was carried based on the landing trips, the obvious procedure is to match the landed catch with the length of hauled nets

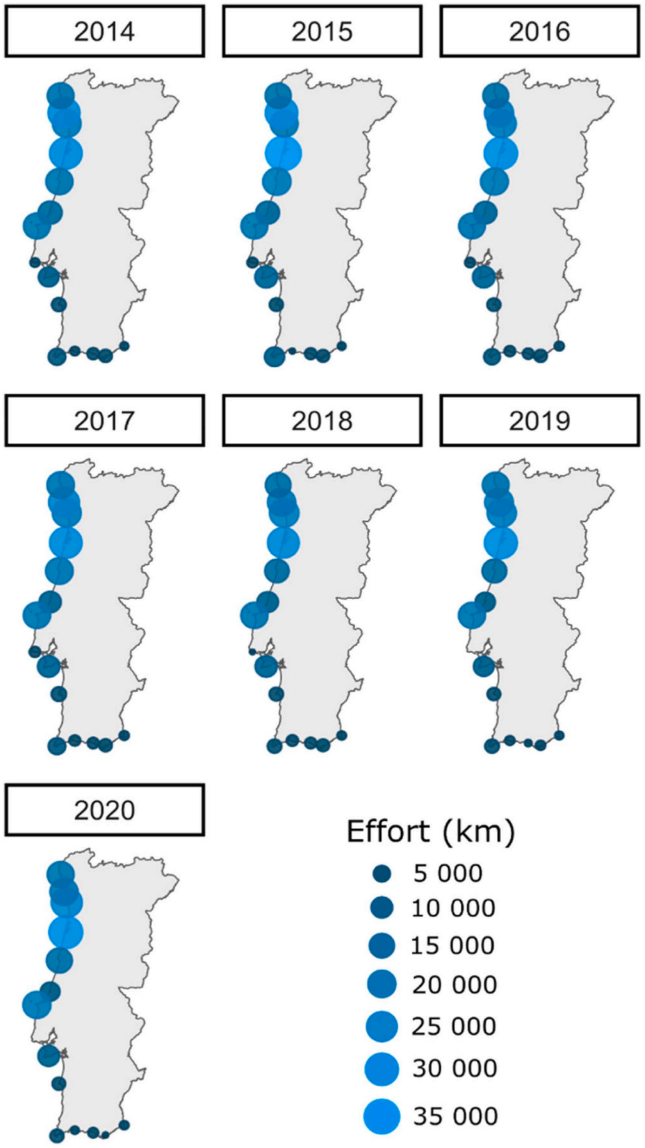


Fig. 7. Annual values of effort, in km of nets, calculated for the 15 landing ports, during the study period. Landing ports were assumed as a proxy for the region where fishing vessels operated before landing their catches since the majority of these vessels perform daily fishing trips, and when performing longer trips, landing events occur in the port nearest to the fishing ground.

responsible for that catch.

The assumption that fishing vessels from the same LOA class, on average, operate the same length of nets in each trip does not consider the entire complexity of the system responsible for the variance of the real length of nets used in each trip. Indeed, factors such as the skipper, configuration of the vessel, weather or target species, for example, can affect the length of nets operated in each trip. Yet, in order to extrapolate high resolution fishing effort for an entire fleet based on the number of fishing trips and a sample of AIS derived fishing effort, an average value of nets used each trip for each LOA class needs to be defined. To define an AvgNet for each vessel would only be possible with a complete fleet coverage of classified AIS or any other high resolution vessel tracking data.

Another relevant part of this approach is its dependency on the quality of the data used to calculate the fishing effort. AIS classified data proved to be a reliable source of trip-based effort. On the other hand, this data quality concern is particularly relevant for the fishery dependent data, i.e., logbooks and landing data. For example, if a vessel fails to catch anything during a trip or did not declare its catch, then that fishing trip, will not be in the quantification of effort. Another important concern of this approach has to do with the care with which fishers fill in the logbooks, especially when logging the gear(s) used. If a used gear is wrongly logged, then that trip might, or might not, be considered in the effort estimation. Nonetheless, the mandatory obligation for all vessels to log their logbooks and in the case for Portuguese fishing vessels, to declare their daily landings is a very important and useful circumstance for this approach. Indeed catch composition can assist in identifying which gears were used within a trip (Szynaka et al., 2021; Leitão and Campos, 2022), but in cases when more than one gear is used in the same fishing trips, this approach has proven less accurate.

Given that the current legislation does not require all fishing vessels to be equipped with high resolution and high frequency vessel tracking devices that cannot be switched off by skippers, to improve the resolution of fishing effort for passive fishing gears such as nets at a broad scale, approaches such as the one described in this paper need to be developed and applied. The true assessment of high resolution of fishing effort for all passive fishing gears will only be possible when high frequency vessel tracking devices are mandatory for all fishing vessels. Until then, methodologies such as the one presented in this study can fill an important knowledge gap on the quantification of nominal fishing effort of a very important and complex fishery, which will ultimately assist in improving ocean governance, fisheries management and conservation.

CRediT authorship contribution statement

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

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.

Data availability

The authors do not have permission to share data.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2024.107118.

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