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Beyond 'Trawler' in the Adriatic Sea: Reconstructing Eight Years of Fishing Pressure by Distinct Trawling Strategies

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Abstract

Trawling fisheries in the Adriatic Sea are among the most spatially intensive fishing activities in the Mediterranean, with significant implications for marine ecosystems and resource management. Understanding their spatiotemporal dynamics is essential for informing sustainable fisheries management and mitigating ecosystem impacts. We present an 8-year (2015–2022) high-resolution (0.01° × 0.01°) dataset of monthly trawling effort indicators reconstructed from Automatic Identification System (AIS) data across Geographical Sub-Areas (GSAs) 17 and 18. A key novelty of this dataset is the explicit classification of the three main trawling strategies – bottom, pelagic, and beam trawling. Reconstructed from 858 fishing vessels identified as performing trawling during the study period, the dataset includes detailed information on fishing hours, fishing days, vessel counts, gear type, and departure/destination GSAs, harmonised and disaggregated by country and trawling method. This harmonised and disaggregated dataset enables high-resolution assessment of fleet dynamics, fishing intensity, and spatial footprint. The novel reconstructed trawling-effort dataset is publicly available at: https://doi.org/10.17882/114473 and represents a valuable tool for researchers, fisheries managers, and policymakers. It directly supports Ecosystem-Based Fisheries Management (EBFM) and the revision of existing management plans in line with General Fisheries Commission for the Mediterranean (GFCM) recommendations.

1. Introduction

The future of our Oceans is increasingly shaped by growing competition for marine space, since economic activities as associated with the "blue economy", including offshore energy, aquaculture, shipping, and fishing, continue to expand and diversify. This evolving spatial configuration exerts interactive and cumulative pressure on marine ecosystems, demanding integrated management approaches capable of balancing development and conservation goals (Stelzenmüller et al., 2020). Ecosystem Based Management (EBM) offers an integrated approach for achieving such balance by reconciling the needs of ocean users with the conservation of the ecosystem in which humans are regarded as an integral part (Ansong et al., 2017; Foley et al., 2010; Kirkfeldt, 2019; Long et al., 2015). Effective implementation of EBM relies on high-quality, spatially explicit data describing both ecological components and human activities (Farella et al., 2021; Nygård et al., 2020; Pınarbaşı et al., 2017). Among the latter, information on the spatial distribution of fishing effort is particularly important because fishing represents one of the main pressures on marine ecosystems, affecting habitats, species, and ecological processes across multiple spatial scales (Jackson et al., 2001). Spatially explicit, gear-specific information is essential to assess cumulative and ecological impacts, identify vulnerable habitats and species, support marine spatial planning and conservation measures, and promote the sustainable use of marine resources in line with policy frameworks such as the Marine Strategy Framework Directive (MSFD) and Maritime Spatial Planning (MSP) (Coll et al., 2016; Farella et al., 2021; Halpern et al., 2008; Pennino et al., 2013).

Among fishing activities, trawling is one of the most destructive having a notorious amount of bycatch and untargeted catch (Cook, 2003; Lewison et al., 2004). Bottom trawling, in particular, physically disturbs marine ecosystems reducing benthic biomass and biodiversity (Buhl-Mortensen et al., 2016; Kaiser et al., 2006) while reducing the complexity of seabed habitats (Jennings et al., 2001; Pusceddu et al., 2014). Therefore, accurate information on the spatial and temporal patterns of trawling activity is crucial for assessing and mitigating its ecological impacts and for supporting ecosystem-based management of marine resources.

The spatiotemporal distribution of fishing activities has been one of the main existing knowledge gaps, which has progressively been addressed in recent decades thanks to the estimation of fishing activities from vessel-transmitted information (Kroodsma et al., 2018; Orofino et al., 2023; Souza et al., 2016). In 2004, the European Union introduced the use of Vessel Monitoring System (VMS, *Council Regulation 2371/2002*) for Monitoring, Control and Surveillance (MCS), and, since then, multiple studies regarding its use to estimate fishing effort have been published . Unfortunately, this system presents a significant gap as its access is limited to competent authorities and, therefore, its use for research scopes is not guaranteed. As an alternative, the easy-to-access Automatic Identification System (AIS, *Council Regulation 1224/2009* - originally born as an anti-collision device) can be used for the same purpose (Armelloni et al., 2021; Natale et al., 2015; Zhang et al., 2022), especially in wide areas such as the Mediterranean Sea (Ferrà et al., 2018; Vespe et al., 2016). Despite AIS being the only existing large-scale system supplying actively transmitted data (Ford et al., 2018), transmission records could get lost because of limited terrestrial receiver's range coverage (for radio systems), satellite communication hindrances, onboard technical issues, adverse meteorological conditions, or voluntary switch-offs of the device itself (Taconet et al., 2019; Yang et al., 2019).

Such issues may lead to incomplete transparency and underestimations of fishing intensity and spatial coverage (Coro et al., 2024; Ferrà et al., 2020; Tassetti et al., 2019). Furthermore, nowadays AIS is mandatory only for European fishing vessels ≥15 m in length, whereas VMS applies to European vessels ≥12 m, meaning that reliance on AIS alone may exclude non-EU countries and a significant segment of smaller vessels (Marsaglia et al., 2025; Council Regulation 1224/2009).

At the global level, Global Fishing Watch (GFW, http://globalfishingwatch.org), an international non-profit organisation that provided the first free, real-time public platform for monitoring global commercial fisheries, has advanced our understanding of fishing activity by satellite-based AIS (Kroodsma et al., 2018). Nevertheless, trawling strategies remain aggregated under a generic "Trawler" category, limiting the ability to distinguish their specific environmental pressures.

This limitation is particularly relevant for the Adriatic Sea since it is one of the most intensively trawled regions of the Mediterranean and hosting the highest regional annual swept-area ratio worldwide (Amoroso et al., 2018; Eigaard et al., 2017), where three trawling strategies coexist and exert varying pressures on marine ecosystems: bottom otter trawl (OTB), rapido trawl (a type of beam trawl, TBB) and pelagic trawl (including midwater pair trawl, midwater trawl, midwater otter trawl). These trawling strategies differ significantly in their target species, fishing practices, and environmental impacts (Table 1). Rapido trawlers, primarily targeting flatfish, have shown to severely affect the benthic environment by altering habitats and community structures (Depestele et al., 2016; Kaiser et al., 2002). In contrast, otter trawls, which primarily target demersal fish and shrimp, have a less severe impact, affecting only the surface layers of the seabed (de Groot, 1984; Polet and Depestele, 2010). Finally, the impact on benthic ecosystems of pelagic pair trawling is significantly lower as it is designed for catching small pelagic fish (Shannon et al., 2007), although bycatch of vulnerable species may still be relevant (Bonanomi et al., 2022).

Table 1. Summary table describing the main trawling strategies adopted in the Adriatic Sea and their main features. Species listed represent the most important components of the catch for each gear, selected based on average annual landings (tons) in GSA 17–18 (2015–2022), derived from the JRC fisheries dataset (European Commission, Joint Research Centre, 2026). Only the main species contributing to the majority of total landings are reported.

Trawling strategy	**Target species**	**Fishing method**	**Main environmental impacts**
Bottom otter trawl (**OTB**)	Demersal species (Top 5 – accounting for ~50 % of total landings): • European hake (*Merluccius merluccius*) • Red mullet (*Mullus barbatus*) • Mantis shrimp (*Squilla mantis*) • Deep-water rose shrimp (*Parapenaeus longirostris*) • Cuttlefish (*Sepia officinalis*)	A large net is dragged along the seabed. Otter boards (doors) use hydrodynamic force to keep the net mouth open horizontally.	High benthic disturbance; significant bycatch of juvenile fish and non-target species; "plowing" of the soft bottom sediment.

Pelagic trawl (**PTM**) - including midwater pair trawl, midwater trawl, midwater otter trawl	Pelagic species (Top 2 – accounting for ~90 % of total landings): • European sardines (*Sardina pilchardus*) • Anchovies (*Engraulis encrasicolus*)	The net is towed in the water column (midwater) without touching the bottom. Often performed by two vessels (Pair Trawling) to keep the net open.	Potential for high juvenile bycatch of target species; occasional accidental capture of sensitive species (marine mammals, seabirds, elasmobranchs, sea turtles).
Beam trawl (**TBB**) - mainly known as *rapido*	Benthic species (Top 5 – accounting for ~70 % of total landings) • Spine dye murex (*Bolinus Brandaris*) • Common sole (*Solea solea*) • Mantis shrimp (*Squilla mantis*) • Cuttlefish (*Sepia officinalis*) • Murex (*Murex spp.*)	The net mouth is held open by a rigid horizontal beam attached to heavy metal runners or "teeth" that dig into the sediment.	Severe physical damage to the seabed structure; high impact on infauna (creatures living inside the mud); high fuel consumption due to heavy gear drag.

Although Adriatic trawl fisheries have been extensively studied in terms of catch assemblages, fishery dynamics, and fishing footprint (Armelloni et al., 2021b; Bonanomi et al., 2018; Pulcinella et al., 2019; Russo et al., 2020), historical data detailing the distribution and patterns of specific trawling strategies remain scarce. Understanding and mapping these differentiated trawling typologies is therefore essential to inform sustainable fisheries management in the Adriatic Sea and support EBM.

To address this need, this data paper provides the first high-resolution, gear-specific dataset of trawling effort across the Adriatic Sea. The dataset spans 2015–2022, distinguishes between bottom, pelagic, and beam trawling, and covers Geographical Sub-Areas (GSAs) 17 and 18. Based on AIS data from 858 vessels, it includes monthly indicators of fishing hours, fishing days, vessel counts, gear type, and departure/destination GSAs at a 0.01° × 0.01° resolution. This resource aims to bridge the over mentioned knowledge gap, allowing a more precise assessment of the impacts associated with each trawling strategy. Such insights are essential for improving our understanding of their medium- to long-term effects on the ecosystem and for supporting decision-making that fosters more sustainable fisheries and resources management practices in the Adriatic Sea.

2. Data and Methods

The analysis was based on terrestrial (t-) AIS data purchased from a private provider (http://www.astrapaging.com/) and covering the adjacent FAO-GFCM Geographical Sub-Areas (GSAs) 17 and 18, which together constitute the most highly collaborative fisheries management zone in the Adriatic Sea and represents one of the most intensively exploited fishing grounds in the Mediterranean Sea . The dataset spans a period of 8 years (2015-2022) and includes approximately 20 million AIS records collected at a nominal 5-minute interval from 1,460 EU and non-EU fishing vessels.

The AIS dataset was first pre-processed to eliminate potentially erroneous pings, including duplicate points, positions located on land, and records with speeds exceeding 20 knots.

The cleaned dataset was then processed using the R4AIS workflow (Galdelli et al., 2021), a machine-learning framework developed using historical annotated data from the Adriatic Sea and subsequently refined in additional applications (Coro et al., 2022; Pulcinella et al., 2023). The workflow consisted of three main steps: (i) fishing trips identification, (ii) fishing gear assignment, and (iii) extraction of fishing tracks.

i) Fishing trips identification. Consecutive AIS records associated with each vessel/unique MMSI (Maritime Mobile Service Identity) were aggregated into individual trips, defined as the period between departure from and return to port. For each fishing trip, information on the departure and arrival harbour and corresponding GSA were retrieved.

ii) Fishing gear assignment. A cascade of classification algorithms was applied to search for speed and spatial clusters on singular fishing trips data. A *k-means* algorithm was iteratively used to vessel speed data using expert-defined centroids for each gear type, while a *dB scan* algorithm was applied to spatial positions (latitude-longitude). The proportions of AIS points belonging to the identified speed and spatial clusters were used to label each fishing trip as positive to one (or more) *candidate* fishing gear. A unique gear was then assigned on a monthly basis applying a Random Forest classifier (Liaw & Wiener, 2002) trained on a dataset manually validated by local experts. The features used to predict a *confirmed* monthly fishing gear were the proportion of the trips labelled as positive for each gear and the total number of the fishing trips in that month. The monthly gear-assignment procedure allowed vessels changing fishing strategy over time to be classified according to their dominant activity in each month. This improves the representation of seasonal gear use, although minor uncertainty may remain when vessels switch gear within the same month.

iii) Fishing tracks retrieval. Once a *confirmed* fishing gear was assigned, the corresponding *k-means* speed clusters were re-used to identify the actual fishing activity. For trawling gears, fishing tracks were reconstructed by connecting consecutive fishing points separated by less than 30 minutes, thereby avoiding false tracks between distinct fishing events.

Fishing effort was calculated for each fishing trip by allocating fishing hours to the grid cells intersected by the reconstructed fishing tracks. The final datasets were generated by aggregating fishing tracks associated with beam, pelagic and bottom otter trawlers onto a 0.01° (~1 km) spatial grid, and disaggregated by vessel flag country, the GSA where the fishing activity occurred, and the departure and arrival GSA of each trip. This approach enables the spatial distribution of fishing effort to be analysed while preserving information on the origin and operational range of fishing fleets. For each aggregation, fishing effort was expressed as fishing hours and fishing days, along with the number of vessels involved.

To support assessment of potential impacts on marine ecosystems, three fishing pressure indicators were calculated:

i) Extension (European Commission, 2008), indicator of the spatial extent of fishing activities. It was computed as the sum of grid cells with at least one fishing event divided by the total number of grid cells.

ii) Aggregation (European Commission, 2008), indicator of the extent to which fishing activity was spatially concentrated. It was computed as the sum of cells within which 90 % of the fishing activity was obtained, divided by the total number of grid cells.

iii) Trawling frequency (Amoroso et al., 2018), indicator of temporal intensity of fishing. It was computed as the average number of days between trawling events across the whole time series.

Considered together, these indicators, provide complementary insights on the spatial footprint and intensity of trawling, supporting EBM and regulatory assessment (e.g., MSFD, GFCM protocols). Fishing effort datasets are provided at monthly basis, capturing seasonal and interannual trends. In contrast, fishing pressure indicators were calculated for the entire study period, reflecting the cumulative spatial footprint and intensity of trawling across 2015–2022. The integration of these spatial and temporal dimensions allows for a robust analysis of fishing patterns, fleet dynamics, and potential ecological impact of trawling in the Adriatic Sea.
In particular, six .CSV files are provided (two for each trawling gear type), capturing monthly trawling activity, and derived fishing pressure indicators at 100th degree resolution.

Each .csv file follows a standardised structure to ensure consistency and ease of use:

- Variable names are reported in lowercase, with words separated by underscores (e.g., gsa_dep).
- In the fishing effort files, each row corresponds to a unique combination of gear type, grid cell, country, month, and GSA movement attributes (Table 2 and 3).
- In the fishing pressure indicator files, each row represents a unique combination of gear type, grid cell, and fishing pressure indicator values (Table 4 and 5).
- To reduce file size and improve data handling efficiency, grid cells with no recorded fishing activity were excluded from all datasets.

Table 2. Variables included in the fishing effort datasets

Variable name	Data type	Variable type and format	Description
gear	string	Categorical (XXX = 3-digit code)	Type of trawling gear used (OTB = bottom otter trawl, PTM = pelagic trawl, TBB = beam trawl).
lon	float	Continuous (decimal degrees)	Longitude (CRS = WGS84) of the 0.01° grid cell centroid where fishing occurred.
lat	float	Continuous (decimal degrees)	Latitude (CRS = WGS84) of the 0.01° grid cell centroid where fishing occurred.

country	string	Categorical	Flag of vessels (country name) reporting fishing activity in the given category (e.g., “Albania”).
month	integer	Categorical	Calendar month of observation (1-12).
year	integer	Categorical (XXXX = 3-digit code)	Year of observation.
gsa_fshg	string	Categorical (GSAXX = GSA + 2-digit code)	GSA where the fishing operation took place (e.g., “GSA17”).
gsa_dep	string	Categorical (GSAXX = GSA + 2-digit code)	GSA corresponding to the vessel's port of departure.
gsa_arvl	string	Categorical (GSAXX = GSA + 2-digit code)	GSA corresponding to the vessel's port of return.
fshg_hr	float	Continuous	Estimated total hours fished.
fshg_day	integer	Continuous	Estimated number of fishing days.
vessels	integer	Continuous	Number of unique vessels (count) reporting fishing activity in the grid cell for the specified variables.

Table 3. Example records from the fishing effort dataset, showing the structure and types of data captured.

gear	lon	lat	country	month	year	gsa_fshg	gsa_dep	gsa_arvl	fshg_hr	fshg_day	vessels
OTB	14.56	42.34	Italy	11	2019	GSA17	GSA17	GSA18	0.383	2	2
OTB	16.66	41.22	Albania	5	2022	GSA18	GSA18	GSA18	0.113	1	1
OTB	13.30	45.20	Croatia	10	2022	GSA17	GSA17	GSA17	1.510	5	4

Table 4. Variables included in the fishing pressure indicator datasets.

Variable name	Data Type	Variable type and format	Description
gear	string	Categorical (XXX = 3-digit code)	Type of trawling gear used (OTB = bottom otter trawl, PTM = pelagic trawl, TBB = beam trawl).
lon	float	Continuous (decimal degrees)	Longitude (CRS = WGS84) of the 0.01° grid cell centroid where fishing occurred.
lat	float	Continuous (decimal degrees)	Latitude (CRS = WGS84) of the 0.01° grid cell centroid where fishing occurred.
mean_freq	string	Categorical (frequency range)	Estimated trawling frequency, as average months between trawling events ("<3","3-6","6-12","12-24",">24").

extent	integer	Categorical	Extent of trawling activities (unique value, =1 if that gear is fishing in that cell).
aggreg	integer	Boolean (0/1)	Aggregation of the 90 % of trawling activities (1=yes; 0=no).

Table 5. Example records from the fishing pressure indicators dataset, showing the structure and types of data captured.

gear	lon	lat	mean_freq	extent	aggreg
OTB	12.25	44.68	3-6	1	0
OTB	12.35	44.69	<3	1	1
OTB	19.87	40.00	>24	1	0

3. Results

Using the R4AIS workflow, 858 vessels were identified as trawlers, accounting for nearly 59 % of the total fishing vessels included in the AIS dataset (Table 6). The number of active trawlers remained relatively stable throughout the 8-year period (2015-2022), ranging between 598 and 647 vessels annually. Overall, these vessels carried out 416,972 fishing trips, corresponding to approximately 6.53 million fishing hours. Mean fishing effort per trip also showed limited interannual variability, ranging from 14.57 to 16.67 fishing hours.

Table 6: Summary of the AIS validated effort dataset (GSAs 17-18, 2015–2022), resulting from the R4AIS workflow.

Year	Vessels	Trawling vessels	Fishing trips	Fishing hours	Fishing hours/fishing trip
2015	899	638	59,826	871,490.3	14.57
2016	991	644	63,168	932,005.9	14.75
2017	900	647	57,202	874,777.5	15.29
2018	866	611	46,754	779,429.8	16.67
2019	859	598	49,695	811,873.1	16.34
2020	874	601	47,716	771,018.0	16.16
2021	945	600	50,354	809,934.5	16.08
2022	984	609	42,257	678,616.7	16.06
Total	**1460**	**858**	**416,972**	**6,529,146**	**15.66**

3.1. Spatial and temporal distribution of trawling effort

A sensitivity analysis was performed to identify grid cells contributing negligibly to the total fishing activity. Following a conservative approach, a threshold of 0.33 hours per cell per year was applied, and cells below this threshold were excluded from subsequent analysis. This filtering led to a minimal reduction in total fishing effort, accounting for approximately 1 % for OTB and 2 % for PTM and TBB over the whole study period.

The analysis of the cumulative fishing effort revealed distinct spatial patterns across the three trawling strategies (Fig. 1). Beam trawling appeared predominantly concentrated in the northern Italian sector of the Adriatic Sea and in the nearshore areas along the central Italian coast, extending southward to the Gargano promontory. Pelagic trawling showed a broadly similar distribution, with a notable concentration in GSA 17, particularly in the north-central Adriatic.

OTB activity was more widely distributed throughout the entire Adriatic Sea, with higher fishing intensity observed along the western (Italian) coast than along the eastern (Balkan) side. However, substantial effort was also observed in areas dominated by non-Italian fleets, particularly in the Gulf of Trieste, the Croatian waters surrounding the Jabuka-Pomo pit, and the eastern part of the southern Adriatic pit.

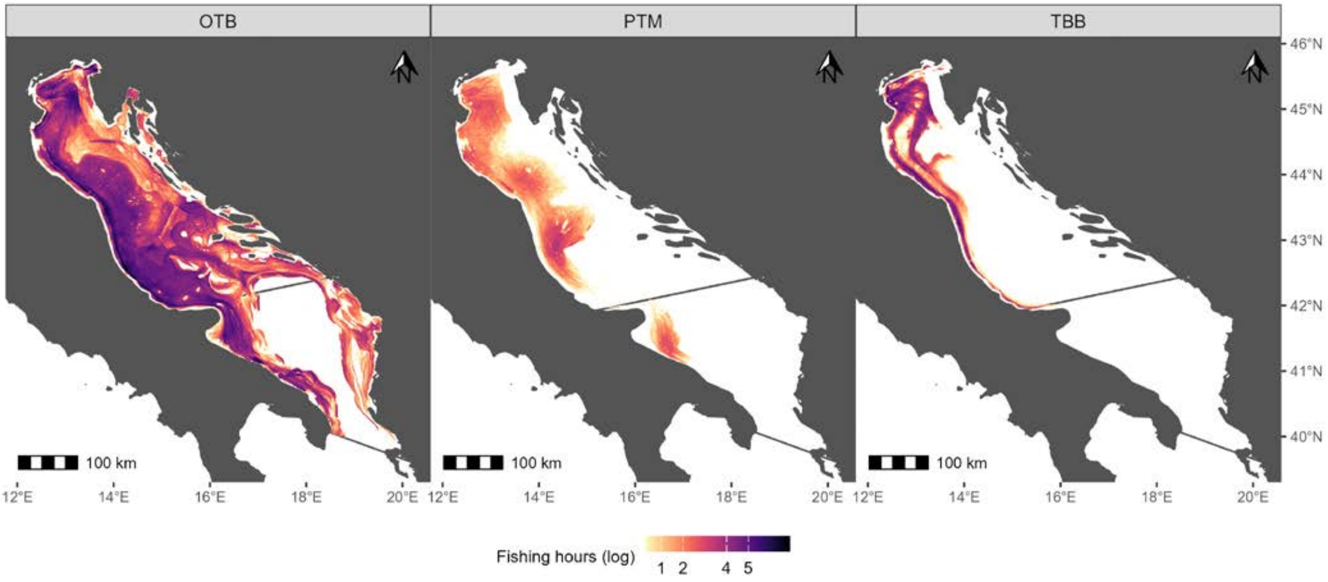

Figure 1: Cumulative fishing hours over the period 2015-2022, shown separately for bottom trawlers (OTB), pelagic trawlers (PTM), and beam trawlers (TBB). Fishing hours are in logarithmic scale to improve visualisation on a 0.01° grid.

The spatiotemporal analysis of annual fishing effort revealed relatively stable distribution patterns for TBB and PTM throughout the years (Fig. 2). In contrast, OTB exhibited significant temporal variations, particularly in the Jabuka-Pomo Pit. These changes coincided with the progressive implementation of management strategies and fishing bans over time, culminating in the establishment of the Fisheries Restricted Area (FRA) in 2017. The noticeable reduction in fishing effort following the FRA's implementation likely reflects the effectiveness of this management measure in reducing bottom trawling in sensitive areas.

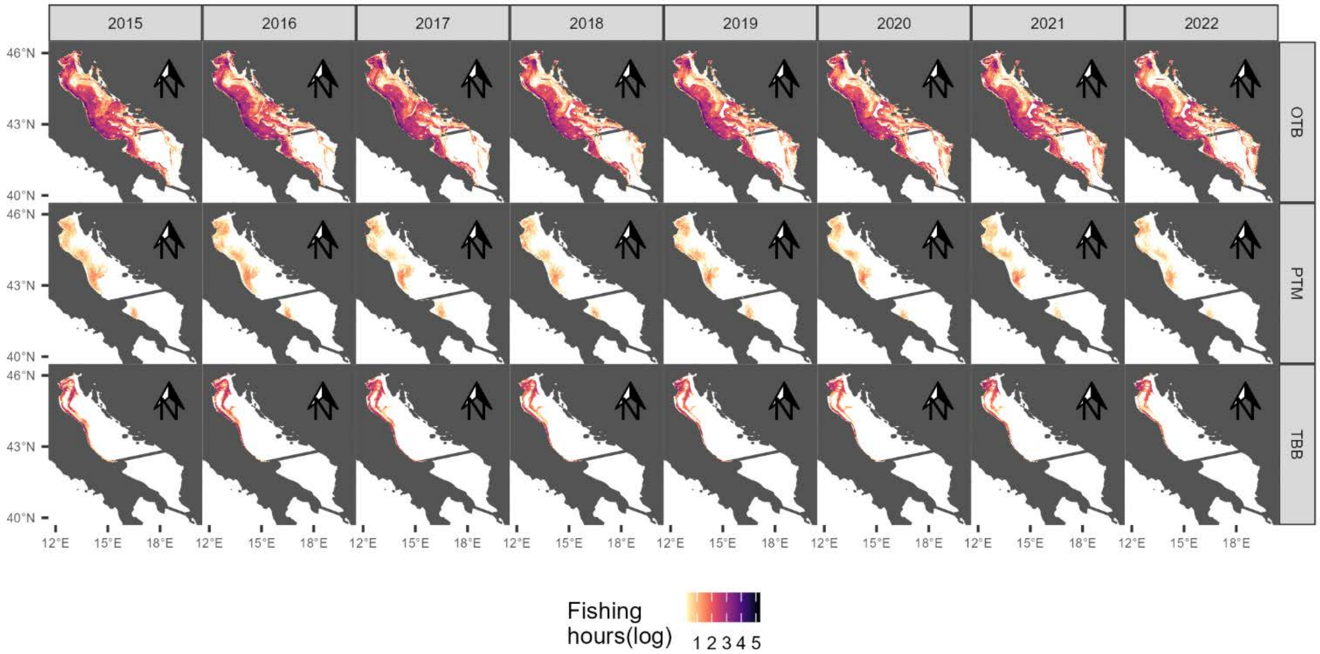

Figure 2: Annual fishing hours for the 3 trawling strategies that predominate in the Adriatic Sea. Fishing effort is reported in logarithmic scale to improve visualisation. Annual patterns were obtained aggregating monthly values at the resolution of 0.01°.

3.2. National and seasonal patterns of trawling effort

The time series analysis by trawl gear and vessel flag revealed that only OTB was conducted by vessels from multiple countries, whereas PTM and TBB were exclusively represented by Italian vessels (Fig.3).

Fishing effort associated with TBB and PTM was substantially lower than that of OTB and displayed a clear seasonal pattern. For both gears, fishing activity declined during summer months, particularly in July and August. TBB effort typically peaked in spring, exceeding 2,000 fishing hours in April and May, before declining sharply during mid-summer and gradually increasing again in autumn. A similar seasonal pattern was observed for PTM, although with lower overall fishing effort, characterised by higher activity during spring and fall and a noticeable drop during summer, likely reflecting seasonal closures.

Fishing hours deployed by OTB varied notably across Adriatic countries. Italian vessels consistently reported the highest fishing effort, with peaks in spring and early summer, reflecting both fleet intensity and seasonal cycles. A sharp decline occurred in early 2020 followed by a recovery in late 2020 and 2021, reflecting the disruption and subsequent resumption of fishing activities during the COVID-19 pandemic. Croatia maintained moderate levels of fishing hours, typically 7,000–9,000 hours per month during peak periods. Although affected by the 2020 disruption, activity showed a quicker recovery in 2021, surpassing 10,000 fishing hours in some months. Albanian vessels displayed a marked increase in fishing effort over time, from less than 200 fishing hours per month in 2015 to more than 2,900 hours by mid-2021, suggesting fleet expansion and improved reporting. Slovenia consistently reported the lowest effort, rarely exceeding 500 hours/month, while Montenegro, represented from 2018 onward, showed gradual increases in activity, peaking around 800–900 hours during summer 2019 before a pandemic-related decline and partial recovery.

Overall, the time series reflected clear seasonal effort peaks, the impact of COVID-19 in 2020 and heterogeneous recovery trends among national fleets, with Italy remaining dominant and Albania and Montenegro showing notable growth. The consistent summer reductions in effort, especially for Italy, suggest the influence of management regulations, target species availability, or operational limitations that affect the deployment of these more specialised gear types.

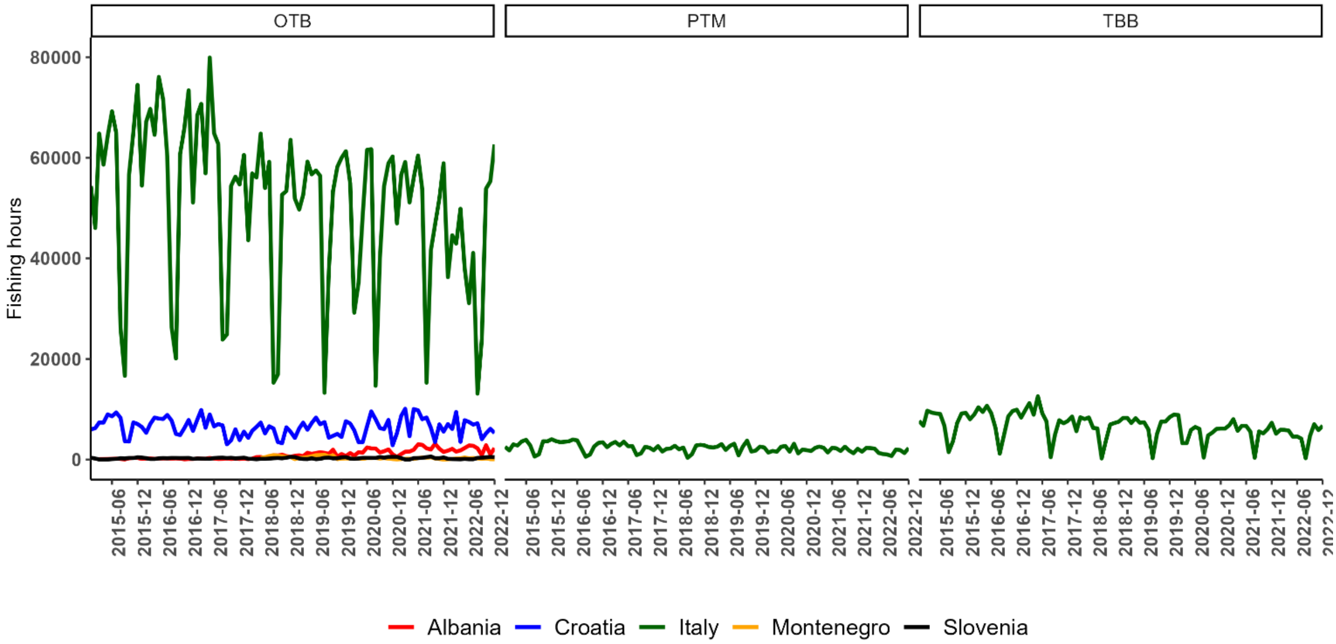

Figure 3: Summary of the monthly fishing hours deployed by trawl gear and country.

3.3. Fleet mobility

The analysis of the effort by fishing GSA and arrival GSA suggested that most of the activity performed in each Adriatic GSA was carried out by vessels returning, thus probably landing, to ports located in the same GSA (Fig. 4). However, a relatively amount of OTB fishing hours was deployed in the southern area of GSA 17 by vessels not arriving to GSA 17, most of them returning to GSA 18. While for PTM and TBB the amount of effort deployed by vessels not returning to the same GSA of fishing was lower, for TBB only few activities deployed in GSA 18 right in the boundary between both GSAs were recorded, and that effort was deployed by vessels returning to GSA 17.

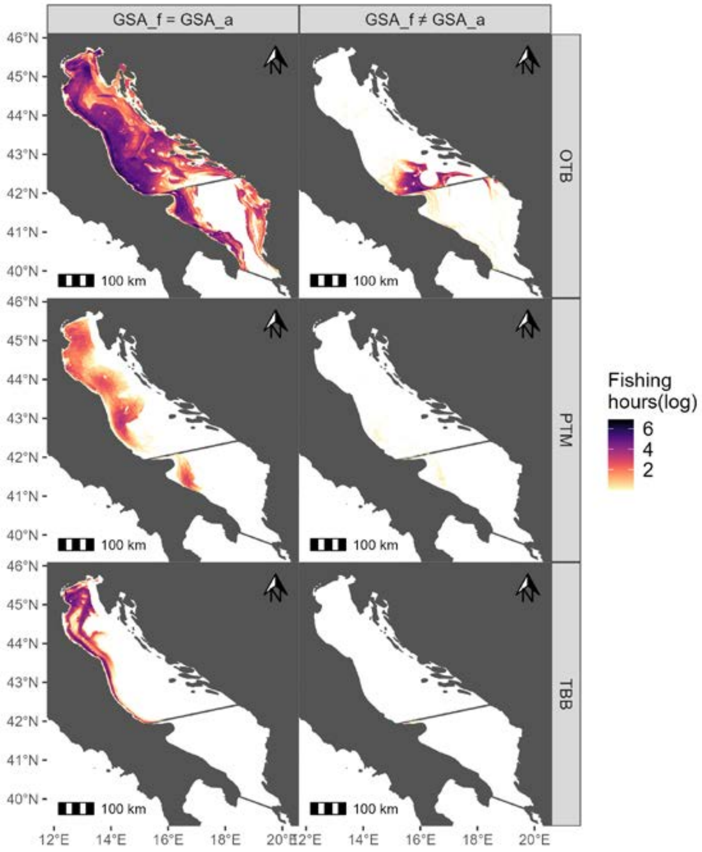

Figure 4: Cumulative fishing hours for the 3 trawling strategies, comparing fishing effort deployed by vessels that fished in a GSA and returned to a port in the same GSA (left panels; GSA_f = GSA_a) with effort deployed by vessels that fished in a GSA and arrived to a different GSA (right panels; GSA_f != GSA_a). GSA_f = GSA where fishing occurs, GSA_a= GSA where the vessel arrives.

3.4. Fishing pressure indicators

Fishing pressure indicators revealed the areas of the Adriatic Sea most heavily exploited by each trawling strategy. For TBB, approximately 86 % of the Adriatic Sea remained unexploited during the study period (Fig. 5). Fishing activity was primarily concentrated on the Italian side of the northern Adriatic, where fishing grounds were targeted at least once every less than 3 months or 3-6 months. Moving southward, fishing activity became increasingly confined to coastal and shallow-water areas. This pattern was further reflected by the aggregation indicator, which revealed that around 39 % of the exploited area accounted for 90 % of the total fishing activity (Fig. 6).

Similarly, PTM exhibited a high proportion of unexploited sea (~73 %), with fishing efforts also concentrated along the Italian coastline, but in deeper waters than those exploited by TBB (Fig. 5). In this case, approximately half of the exploited area was responsible for 90 % of the total fishing activity (Fig. 6).

OTB exhibited the broadest spatial footprint, with fishing activity spread across the entire Adriatic Sea (Fig. 5). The highest fishing frequencies were observed along the Italian coast, though recurrent fishing activity was also observed within the territorial waters of other countries, including the Croatian waters surrounding the Jabuka–Pomo Pit and the eastern portion of the southern Adriatic Pit. Unexploited areas associated with OTB gear type were mainly confined to the deepest southern pit. Additionally, the aggregation indicator showed that nearly 46 % of the exploited area accounted for 90 % of the total fishing activity, indicating a moderate concentration of effort despite the extensive spatial distribution of this gear type (Fig. 6).

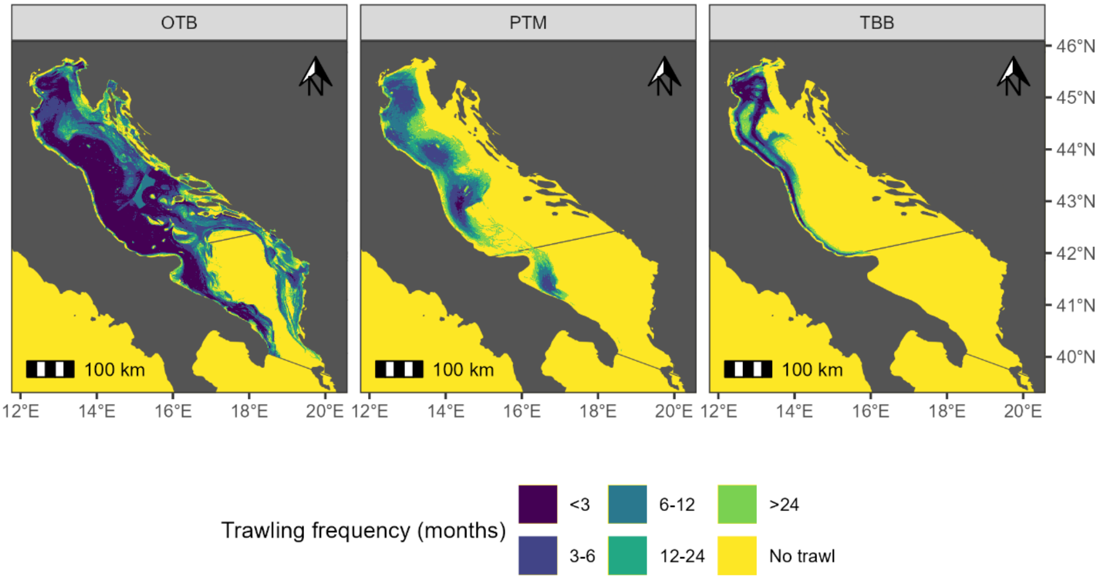

Figure 5: Spatial distribution of trawling frequency for the 3 trawling strategies during the study period.

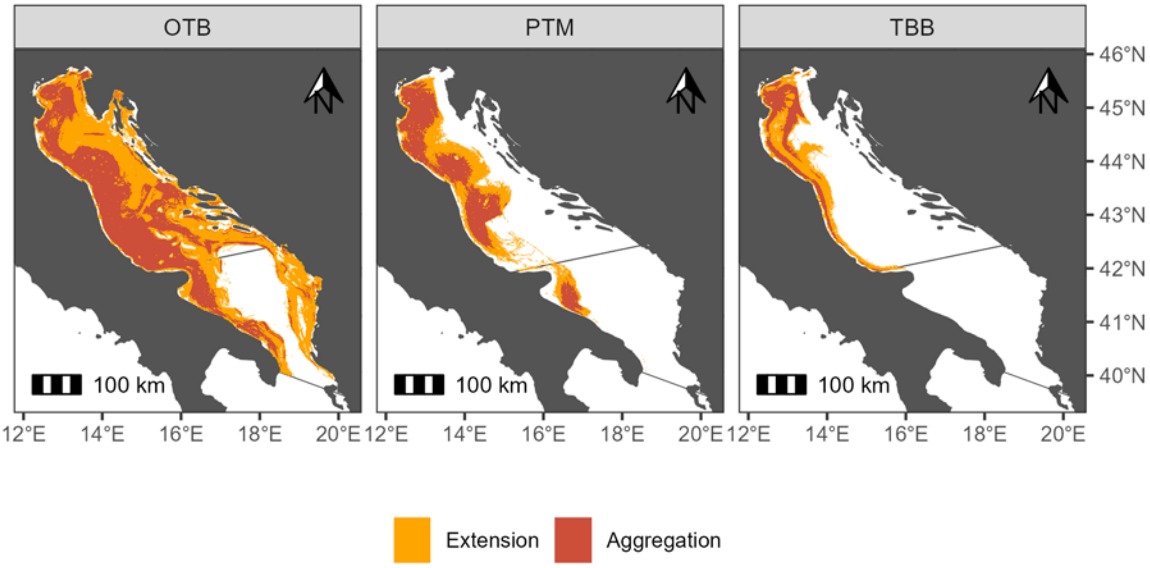

Figure 6: Spatial distribution of fishing pressure indicators of Extension (orange) and Aggregation (red) for the 3 trawling strategies during the study period.

4. Cross-validation

To assess the reliability and representativeness of the dataset, cross-validation procedures were conducted using two independent sources: the GFCM fleet register (https://www.fao.org/gfcm/data/fleet/register/en/) and the GFW data (https://globalfishingwatch.org/dataset-and-code-fishing-effort/). Together, these sources enabled the validation of both the fleet coverage and the spatial distribution of fishing effort, encompassing vessels from European Union and non-European Union countries.

GFW data are made available under the Creative Commons Attribution-Non-Commercial 4.0 (CC BY-NC 4.0) licence and were used exclusively for validation and benchmarking purposes.

4.1. Fleet Coverage

The completeness of the fleet represented in the dataset was assessed through cross-referencing with the GFCM Regional fleet register (GFCM-RFR, *Recommendation GFCM/33/2009/5*). This official register provides metadata on active fishing vessels operating in the Mediterranean, including vessel characteristics, gear type, and flag state. Fleet coverage was evaluated by comparing the number of vessels by fishing gear, distinguishing between vessels above and below 15 m in length overall (LOA).

Table 7 summarise the number of trawling vessels operating in the Adriatic Sea according to the GFCM-RFR (*Recommendation GFCM/33/2009/5*) reflecting the most recent information available at the time of analysis (July 2023 - October 2024).

Table 7. Number of vessels by fleet segment in the Adriatic Sea (GSAs 17-18), based on the GFCM-RFR. Trawl categories correspond to aggregated gear groups: PTM (Midwater pair trawls, Midwater trawls, and Single boat midwater otter trawls), TBB (beam trawl), OTB (Single boat bottom otter trawls and Twin bottom otter trawls). Vessels were further grouped into two LOA classes: ≤15m and >15m.

	Albania		Croatia		Italy		Montenegro		Slovenia		Total	
	≤15m	>15m	≤15m	>15m	≤15m	>15m	≤15m	>15m	≤15m	>15m	≤15m	>15m
Beam	0	0	0	0	10	57	0	0	0	0	10	57
Bottom	36	163	303	96	473	381	13	11	13	4	838	655
Pelagic	3	13	0	0	11	74	0	0	0	0	14	87
Total	36	179	303	96	494	512	13	11	13	4	862	799

The number of vessels obtained in our dataset for the most recent year available (2022; Table 8) appeared broadly aligned with what reported in the GFCM-FR (Table 7). For Italy, the number of vessels in our dataset was generally consistent with the GFCM-FR. In particular, the count of PTM matched exactly, suggesting good coverage for this fleet segment. Minor discrepancies were observed for TBB, and it is likely that a few vessels under 15 m are included due to having AIS transponders on board despite not being subject to mandatory AIS requirements.

In contrast, the OTB fleets of Albania, Croatia, and Montenegro appeared to be underrepresented in our dataset, particularly Albania. This result was expected, as AIS is not mandatory for Albanian fishing vessels. For Slovenia, however, the number of OTB vessels identified in our dataset exceeded the ones reported in the GFCM-FR, which may indicate differences in vessel classification, or potential overestimation in the vessel detection process.

Table 8. Number of vessels by trawl gear and country in 2022 estimated from the AIS data analysis.

	Albania	Croatia	Italy	Montenegro	Slovenia	Total
TBB			52			52
OTB	26	64	383	6	6	485
PTM			74			74

4.2. Effort Distribution

To validate both the temporal consistency of the fishing effort estimates and their spatial distribution, released trawling activities were aggregated across all trawling categories (pelagic, beam, and bottom trawls) and compared to apparent trawling

patterns accessed from the GFW platforms. The GFW dataset used for the comparison consisted of daily gridded apparent fishing effort data, expressed as fishing hours by flag state and gear type, at a spatial resolution of 0.01° (version 3.0, March 2025 release). Data were downloaded in May 2025 from the GFW Data Download Portal and subsequently filtered to retain only effort belonging to the trawling gear category. Following GFW guidance, these estimates represent apparent fishing activity inferred from AIS data and associated classification algorithms rather than direct observations of fishing operations.
At the grid cell level, the comparison of annual fishing effort showed a clear relationship between the two datasets across a wide range of values (Fig. 7). Following logarithmic transformation, most observations were distributed close to the line of perfect agreement, indicating a generally strong consistency between the two datasets. A high density of points was observed at low fishing effort values, reflecting the predominance of cells with limited fishing activity. Dispersion at low effort levels likely indicate the presence of small differences in detection and estimation, while larger discrepancies at higher values might suggest systematic differences in magnitude between the two approaches.

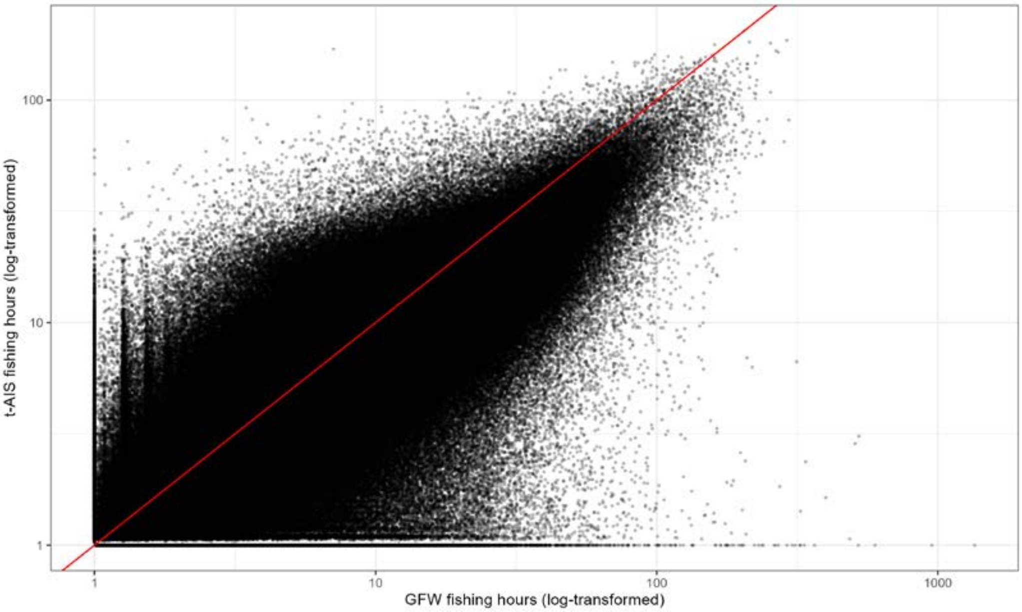

Figure 7. Scatterplot of annual trawling effort estimates from GFW and t-AIS at 0.01° resolution. Values are shown on a log scale (log10(x+1)). Red line represents the 1:1 relationship.

Absolute monthly values of trawling hours estimated in our dataset resulted generally lower than those reported by the GFW (Fig. 8), although both datasets exhibit highly similar seasonal patterns and interannual variability over the study period 2015-2022. A Pearson correlation test was applied to assess the linear relationship between the monthly fishing effort estimates derived from the two datasets. The test revealed a very strong positive and statistically significant correlation ($r = 0.927$, p-value < 2.2e-16), indicating high consistency between the two data sources and providing strong evidence that the observed association was not due to random variation. Furthermore, the 95 % confidence interval for the correlation coefficient, spanning 0.892 to 0.951, supported the robustness of this relationship. These findings suggest that the published dataset reliably reproduce the main temporal patterns of apparently fishing effort captured by the freely available and widely used GFW data. The consistency observed between the two independent datasets not only reinforces the credibility of the published data but also highlights its potential in fisheries monitoring, comparative research, and evidence-based policy making.

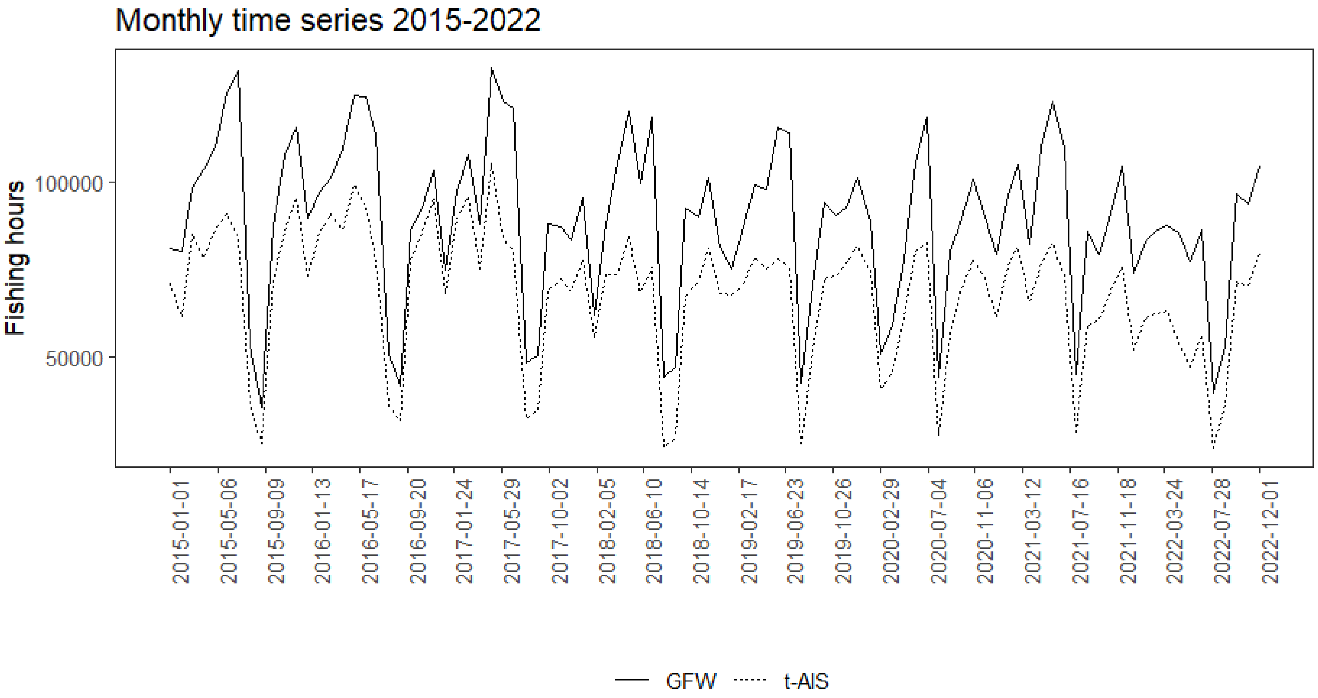

Figure 8. Monthly time series of fishing effort estimated in the presented dataset (dotted line) and GFW (solid line) data. Monthly values were obtained by summing the values of all 0.01° grid cells across all trawling categories (pelagic, beam, and bottom trawls). Fishing effort is expressed as total trawling hours per month.

Spatial discrepancies between datasets were evaluated by calculating the cell-level difference in annual estimated fishing effort (GFW minus t-AIS). This grid-cell level subtraction was performed at a spatial resolution of 0.1° to map areas of over- and under-estimation (Fig. 9). Aggregating the data at this scale minimises cell-level variability and positional uncertainty associated with different AIS-based detection approaches, allowing for a more robust comparison of large-scale spatial patterns between t-AIS and GFW datasets. The range of variation in fishing effort resulted higher in earlier years (2015–2019), with values approximately between −2000 and 2000 fishing hours per cell, while in later years (2020–2022) the range decreased, suggesting a progressive convergence between the two datasets.

Negative values (GFW < t-AIS), corresponding to higher fishing effort estimated in the t-AIS, showed a variable pattern in space and time. Between 2015-2017, two main clusters of negative values were observable in the northern Adriatic and in the central basin. From 2018 onwards, the extent of the northern cluster progressively decreased, while the central cluster started decreasing from 2019. These discrepancies are largely attributable to vessels identified as trawlers in the t-AIS dataset but not included in the corresponding GFW trawling category. To better understand the observed discrepancies, a subset of vessels operating within areas showing the largest differences between datasets was selected and manually inspected. Analysis of AIS-derived speed and heading profiles confirmed trawling behaviour, supporting the vessel classification adopted in the t-AIS dataset and suggesting that part of the observed disagreement may arise from differences in fleet classification. Vessel-specific examples are not presented to ensure compliance with data confidentiality requirements and to avoid disclosing potentially sensitive information derived from AIS records.

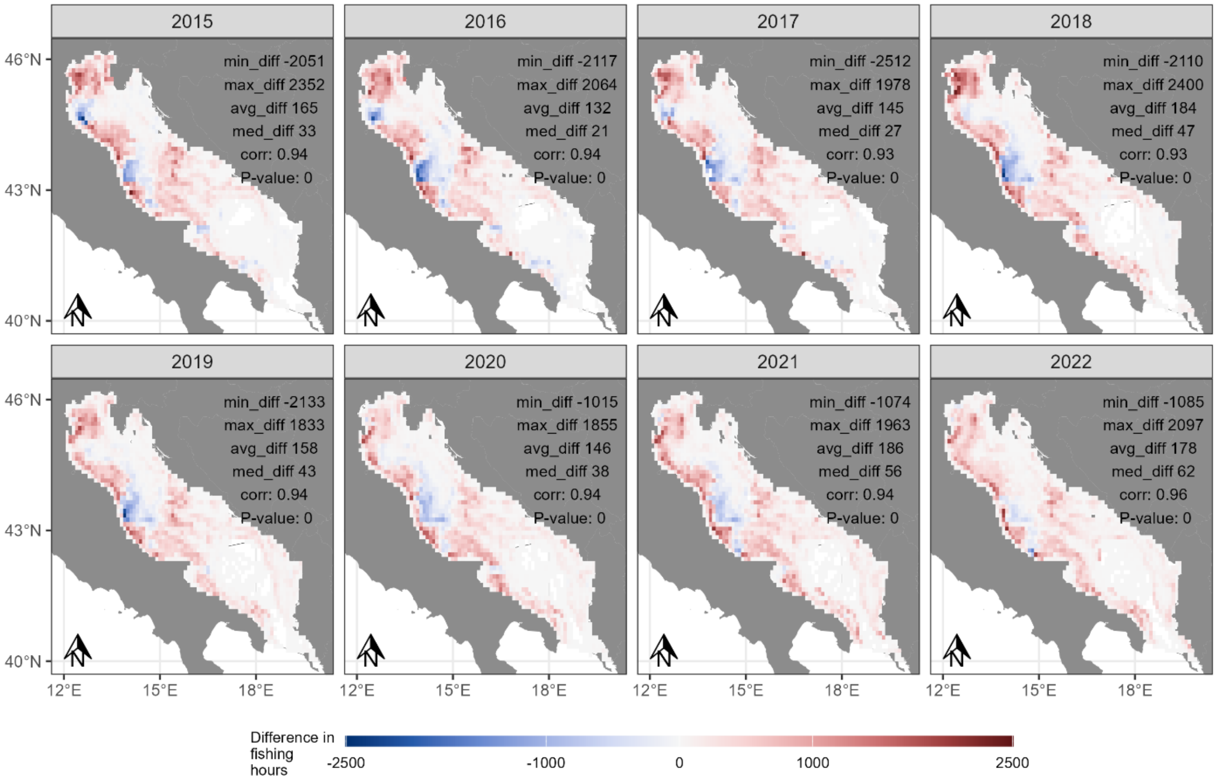

Figure 9. Difference in annual fishing effort estimated between the GFW and t-AIS dataset (GFW - t-AIS) aggregated at spatial resolution of 0.1°. To improve visualisation and reduce the influence of extreme outliers, the minimum and maximum cell values of each year was excluded.

This correspondence is further illustrated in Figure 10, which shows the aggregated fishing effort of vessels identified as trawlers in the t-AIS dataset but absent in the GFW trawling category. The resulting spatial distribution closely matches the areas characterised negative differences in Figure 9, particularly in the central Adriatic Sea. In contrast, the weaker signal observed in the northern Adriatic reflects the lower fishing effort associated with these vessels, resulting in a less pronounced spatial pattern.

Inspections of vessel classifications revealed that these vessels were generally assigned to alternative gear categories in the GFW dataset, mainly to the generic "fishing" category due to inconsistencies between registry-based and algorithm-based classifications. This explains the systematic underrepresentation of trawling effort in specific areas.

A further source of divergence between the datasets is the treatment of vessels exhibiting switch in fishing behaviour over time. The t-AIS dataset relies on a monthly classification of fishing activity, allowing vessels performing trawling only during specific periods are correctly included in the corresponding months, rather than being excluded entirely due to mixed or conflicting classifications. Conversely, vessels with mixed or variable fishing profiles may be assigned to broader or alternative categories in the GFW dataset, potentially reducing the amount of fishing effort represented within the trawling layer. This is particularly relevant for vessels alternating trawling with other fishing activities (e.g. longlining), which are retained in the t-AIS dataset but partially or entirely excluded from the GFW trawling layer.

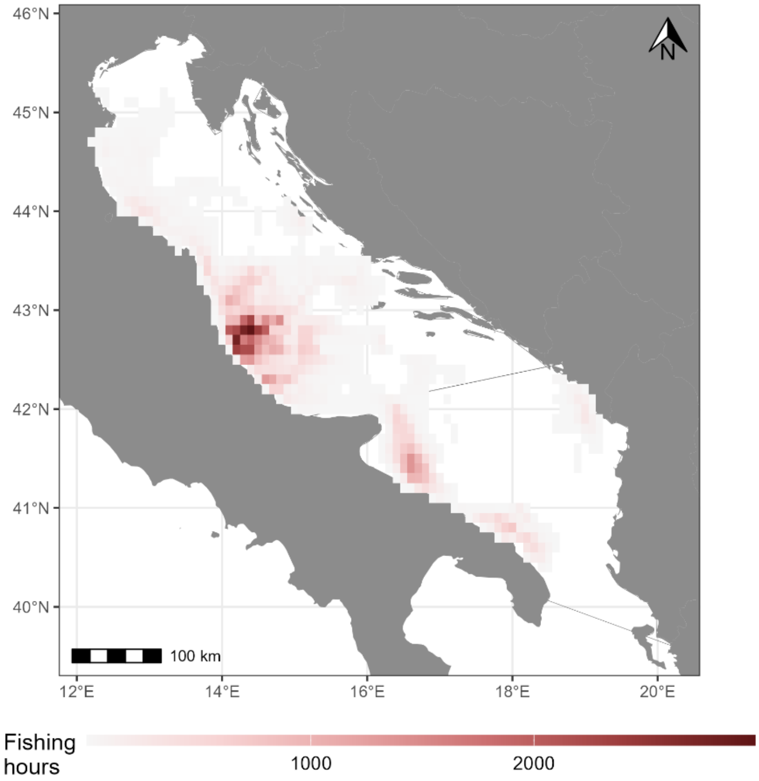

Figure 10. Spatial distribution of aggregated fishing effort (2015–2022) for vessels identified as trawlers in the t-AIS dataset but not included in the GFW trawling category.

Finally, spatial consistency of temporal trends was assessed by computing the Pearson correlation coefficient between annual fishing effort time series at the grid cell level (0.1° resolution) (Fig. 11). Correlation values were predominantly high across the study area, with most cells showing coherent temporal variability (strong positive values close to 1) between the two datasets at local scale. When restricting the analysis to statistically significant correlations ($p < 0.05$), the overall spatial pattern remained largely unchanged, further confirming the robustness of the observed agreement. Lower or negative correlation values were limited and spatially scattered and were mainly associated with areas of low fishing activity or local discrepancies in vessel detection.

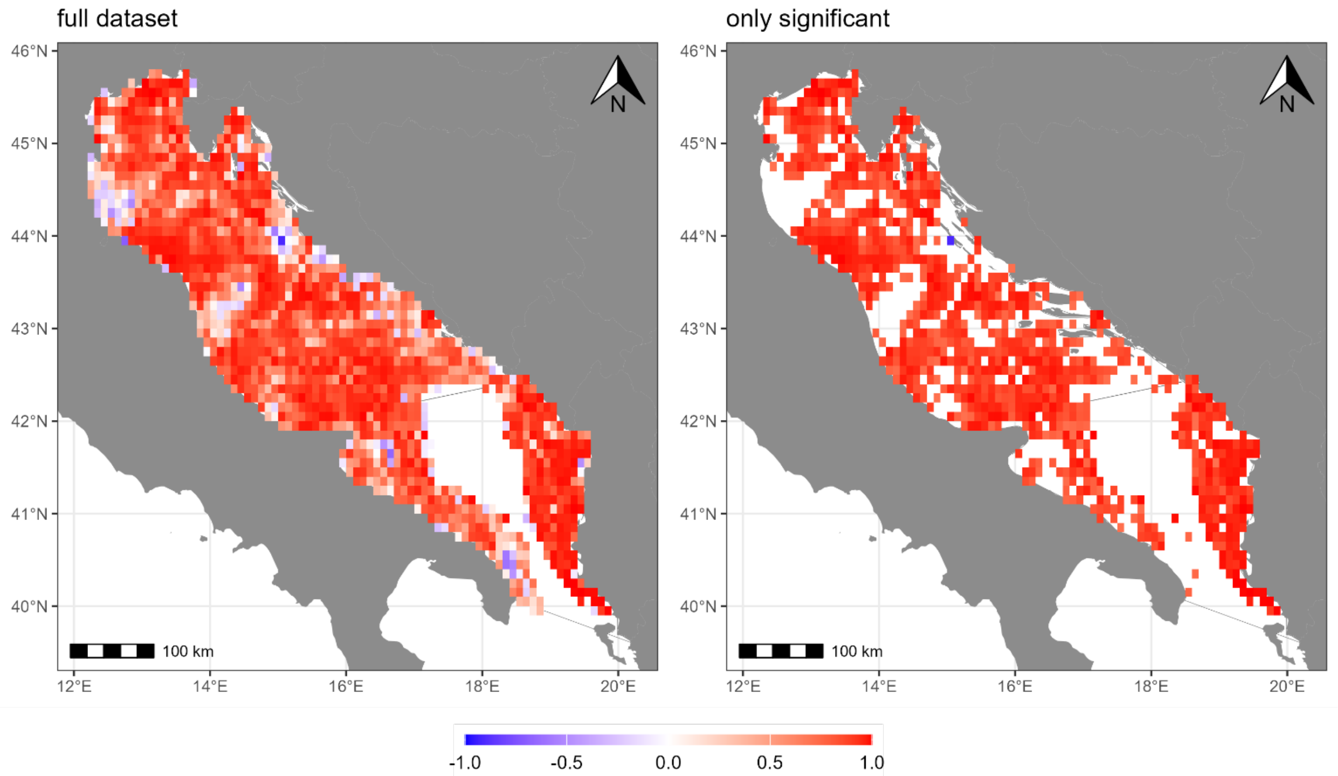

Figure 11. Spatial distribution of Pearson correlation coefficients between annual fishing effort time series derived from t-AIS and GFW datasets at 0.1° resolution (2015–2022). The left panel shows correlation values for all grid cells, while the right panel is restricted to statistically significant correlations ($p < 0.05$). High positive correlation values (in red) indicate strong agreement in temporal trends between the two datasets, while low or negative values (in blue) highlight localised discrepancies.

5. Discussion and Conclusions

The AIS-derived datasets released in this study provide a high-resolution reconstruction of OTB, TBB and PTM trawling effort and pressure indicators in the Adriatic Sea (GSAs 17 and 18), enabling detailed analyses of spatial and temporal patterns in fleets 'activity.

The key feature of this dataset lies in its ability to resolve fishing effort at both high spatial (0.01°) and temporal (monthly) resolution, while providing consistent coverage over an eight-year period and improved gear discrimination among OTB, TBB and PTM fisheries. This represents a significant advantage over existing large-scale/global fishing effort products, which often aggregate multiple trawling techniques into broader categories, thereby masking important differences in fishing practices and spatial distributions. Furthermore, the monthly classification approach improves the representation of fleet behaviour by capturing vessels that alternate between fishing strategies over time. In such cases, trawling activity is retained in the relevant months rather than being excluded due to mixed or conflicting gear classifications, resulting in a more complete and accurate representation of fishing effort.

The dataset supports a wide range of regional-scale scientific and management applications, and some examples are given in Table 9. Potential uses include studies of spatio-temporal dynamics, hotspot identification and spatial autocorrelation analyses, and the integration of fishing pressure into ecosystem and habitat models. From a management perspective, the dataset can inform maritime spatial planning, contribute to GFCM monitoring frameworks, and support MSFD Good Environmental Status assessments.

Table 9. Example of analytical uses and management/policy relevance of the released datasets.

Dataset	Where/when could it be used?	What could it be relevant for?
Fishing effort	• Spatio-temporal distribution of trawling effort • Monthly and interannual fleet trends • Effort linked to vessel mobility (via departure and arrival GSAs)	• Ecosystem model validation • GSA-level landing assignment as a proxy for operational area (implemented in Italian statistical records from 2020; STECF) • Maritime Spatial Planning conflict detection
Fishing pressure indicators	• Spatial footprint and intensity of trawling activities • Fishing pressure variation across areas and gear types	• MSFD Good Ecological Status assessments • GFCM monitoring protocols

Despite these strengths, several limitations should be considered when interpreting the dataset. First, AIS adoption is uneven across national fleets. Transmission rates and adoption vary considerably among Adriatic countries, leading to underrepresentation of fleets with lower AIS usage, particularly those from Albania and Montenegro, compared to better-monitored fleets such as Italy and Croatia.

Second, the classification of fishing activity is performed on a monthly basis. While this approach allows the detection of temporal variability in fishing strategies and ensures that vessels alternating between different gears are not excluded from the dataset, it may introduce minor uncertainties when gear switching occurs within a given month. In such cases, fishing effort may be slightly under- or overestimated for specific periods, although this effect is expected to be limited. Last, the dataset includes only vessels for which reliable AIS trajectories could be reconstructed and consistently classified. As a result, the total number of active vessels operating in the area may be higher than represented. This limitation is inherent to AIS, which lacks consistent coverage due to signal loss, limited receiver coverage or deliberate deactivation of transponders. Future improvements should therefore focus on addressing AIS data incompleteness (at least in regions affected by substantial AIS disruption or intentional shutdowns) by coupling for example the framework with trajectory imputation or deep learning-based interpolation (Galdelli et al., 2025) to reconstruct incomplete trajectories and enhance detection robustness.

Given these limitations, several recommendations can be made for data use. Comparisons of absolute fishing effort between countries should be interpreted with caution due to differences in AIS coverage, whereas the dataset is better suited for analysing temporal trends within fleets or gear types. Because AIS coverage and transmission obligations differ among Adriatic fleets, country-level comparisons of absolute fishing effort should be interpreted with caution. The dataset is therefore particularly suitable for analysing gear-specific spatial patterns, fleet mobility and temporal trends, rather than for directly comparing total fishing pressure among countries.

Fishing effort metrics should be interpreted as proxies of fishing pressure rather than direct measures of catch or ecological impact. For applications requiring ecological interpretation, integration with independent datasets (e.g., logbooks, stock assessments, or habitat sensitivity layers) is recommended.

Data access and availability

Reconstructed fishing pressure data is currently available for download through the SEANOE repository (Ferrà et al., 2026) and it is reachable at: https://doi.org/10.17882/114473. Data was released under Creative Commons Attribution license (CC-BY, 266 v. 4.0, https://creativecommons.org/licenses/by/4.0/deed.it). The expert-validated reference dataset used for Random Forest model training is not publicly available; it was created by authors and accessed by Global Fishing Watch by under a data-sharing agreement.

Code availability

The R code used to process AIS data was made available by Galdelli et al. (2021) at https://zenodo.org/records/4761890, while the scripts required to reproduce the plots reported in the present work are available within the data repository itself (https://doi.org/10.17882/114473, Ferrà et al., 2026).

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Author contribution

CF, ENA and ANT conceived the research idea. CF, ENA and ANT developed the methodology to reconstruct fishing effort and contributed to the collection and curation of data described in this paper. CF produced the results. CF wrote the original draft. ANT, ENA, GS and PL reviewed and edited the manuscript. ANT supervised the work and was responsible for its funding. All authors participated in the interpretation of results and gave final approval for publication.

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