

Uncertainty in AIS/VMS-based Classification of Fishing Activity: Behavioural and Bathymetric Constraints in Demersal Trawl Fisheries

Erik Font Fabra^{1,*}, Agustí Martín Mallofré², Jorge Moncunill Marimon³, Xavier Martínez de Óses⁴, Ana Pacheco Jiménez⁵, Gabriel Pintos Amengual⁶, Ernesto Madariaga Domínguez⁷

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ABSTRACT

Accurate interpretation of fishing activity from vessel tracking systems remains a key challenge in spatially regulated fisheries. Although Automatic Identification System (AIS) and Vessel Monitoring System (VMS) data provide detailed information on vessel movement, fishing activity must be inferred from indirect behavioural proxies, introducing uncertainty, particularly at fine spatial scales.

This study analyses the demersal trawl fleet operating from the port of Llançà (Gulf of Lion, GSA-07, northwestern Mediterranean) to evaluate how fishing activity is characterised in relation to depth-based regulatory frameworks. Using high-resolution AIS data, vessel trajectories are reconstructed and classified through movement-based indicators, primarily vessel speed. Spatial analysis is conducted by combining vessel positions with multiple bathymetric datasets, including hydrographic chart data and digital bathymetric models.

The results show that a substantial proportion of low-speed vessel activity cannot be unambiguously classified as fishing, reflecting overlap between operational states. In parallel, spatial classification of vessel activity relative to depth-based regulatory limits varies depending on the bathymetric dataset used, leading to inconsistent interpretations near regulatory boundaries. These effects are particularly pronounced in areas where fishing activity is concentrated close to depth limits.

Overall, the findings demonstrate that the interpretation of fishing activity in spatially regulated fisheries is strongly influenced by the combined effect of behavioural and spatial uncertainty. This highlights the need for uncertainty-aware monitoring approaches to improve the consistency and robustness of activity classification in regulatory and scientific contexts.

These findings demonstrate that fishing activity classification in spatially regulated fisheries cannot be treated as deterministic and must explicitly account for both behavioural and spatial uncertainty.

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¹Doctorando & Capt. - ORCID: [0009-0004-0688-0800] - Department of Nautical Science and Engineering, Barcelona School of Nautical Studies (FNB), Universitat Politècnica de Catalunya – BarcelonaTech - erik.font@upc.edu

²Dr. Capt. - Department of Nautical Science and Engineering, Barcelona School of Nautical Studies (FNB), Universitat Politècnica de Catalunya – BarcelonaTech - agustimartinmallofre@gmail.com

³Dr. Capt - ORCID: [0000-0002-0773-6710] - Department of Nautical Science and Engineering, Barcelona School of Nautical Studies (FNB), Universitat Politècnica de Catalunya – BarcelonaTech - jordi.moncunill@upc.edu

⁴Dr. - Department of Nautical Science and Engineering, Barcelona School of Nautical Studies (FNB), Universitat Politècnica de Catalunya – BarcelonaTech - francesc.xavier.martinez@upc.edu

⁵Doctorando. - ORCID: [0009-0007-5881-5367] - Universidad de

1. Introduction.

Demersal trawl fisheries in the Mediterranean Sea operate under strong spatial constraints, where fishing activity is closely

Cantabria. School of Maritime Engineering. Gamazo, 1. 39004. Santander, Spain. ana.pacheco@alumnos.unican.es

⁶Investigador independiente. ORCID: [0000-0001-9262-9786] - gabrielpintosomegal@gmail.com

⁷Dr. - ORCID: [0000-0002-0847-1152] - Universidad de Cantabria. School of Maritime Engineering. Gamazo, 1. 39004. Santander, Spain. madariaga@unican.es

*Corresponding author: Erik Font Fabra. E-Mail: erik.font@upc.edu.

linked to seabed characteristics, depth ranges and habitat distribution (Colloca et al., 2013; Maynou, 2014). In the north-western Mediterranean, the Gulf of Lion (GSA-07) constitutes a key fishing area, combining high productivity with complex bathymetry and a dense framework of spatial management measures.

Fisheries monitoring has been substantially enhanced using satellite-based vessel tracking systems. Within the European Union, the Vessel Monitoring System (VMS), implemented under Council Regulation (EC) No 1224/2009 and detailed by Commission Implementing Regulation (EU) No 404/2011, provides periodic positional data used for both control and scientific purposes. These data have been widely applied to reconstruct spatial fishing effort and activity patterns (Mills et al., 2007; Bastardie et al., 2010; Hintzen et al., 2012).

The increasing availability of Automatic Identification System (AIS) data has further improved the temporal resolution of vessel tracking, enabling fine-scale analyses of fishing behaviour (Natale et al., 2015; Kroodsma et al., 2018). However, both AIS and VMS provide indirect observations of fishing activity. As gear deployment and fishing operations are not directly recorded, activity must be inferred from behavioural proxies, typically vessel speed, introducing classification uncertainty (Hintzen et al., 2012).

At the same time, Mediterranean fisheries management relies heavily on spatial regulations, including closures and depth-based restrictions defined through isobaths (European Union, 2006; European Union, 2019). These spatial restrictions are further reinforced by national regulations establishing depth-based closures and management zones in the Gulf of Lion (España, 2012; 2018; 2020; 2022).

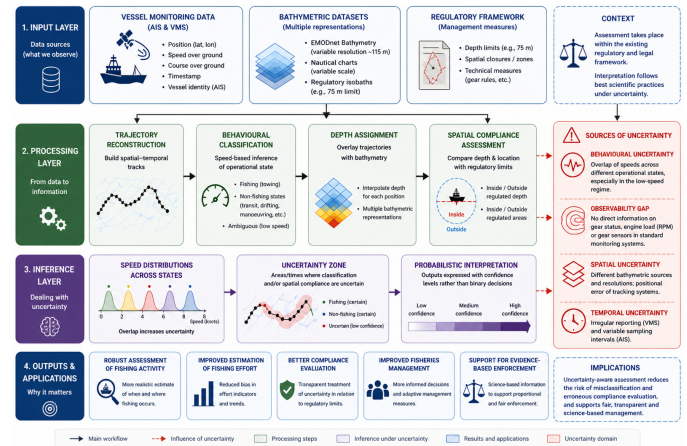
Bathymetric information is derived from heterogeneous sources, such as hydrographic charts and digital bathymetric models, which differ in resolution, purpose and update frequency (EMODnet Bathymetry Consortium, 2020). These differences may result in spatial discrepancies in isobath positioning, particularly in areas with complex seabed morphology, leading to alternative interpretations of the same vessel position relative to regulatory boundaries.

Taken together, these aspects introduce two interacting sources of uncertainty: (i) behavioural uncertainty associated with movement-based classification of fishing activity, and (ii) spatial uncertainty related to bathymetric representation of regulatory limits. While both sources have been addressed separately in previous studies, their combined effect remains insufficiently explored.

This study addresses this gap through the analysis of the demersal trawl fleet operating from the port of Llança (GSA-07). Using high-resolution AIS data and multiple bathymetric datasets, the study evaluates how fishing activity is characterised under spatially regulated conditions and examines the interaction between behavioural inference and spatial representation.

The overall structure of the analytical framework adopted in this study is summarised in Figure 1.

Figure 1: Conceptual framework for uncertainty-aware assessment of fishing activity in demersal trawl fisheries using AIS/VMS data, multi-source bathymetry, and regulatory constraints.



Source: Authors.

2. Literature review.

The use of vessel tracking data to characterise fishing activity has been widely developed over the past two decades. Early studies based on Vessel Monitoring System (VMS) data demonstrated the potential to reconstruct spatial patterns of fishing effort using positional information combined with behavioural assumptions (Mills et al., 2007; Bastardie et al., 2010). These approaches were later refined with statistical and rule-based methods to infer fishing activity, typically relying on vessel speed as a proxy for gear deployment (Hintzen et al., 2012).

The increasing availability of Automatic Identification System (AIS) data has significantly improved the temporal resolution of vessel tracking, enabling more detailed analyses of fishing behaviour and spatial dynamics (Natale et al., 2015; Kroodsma et al., 2018). AIS data have been extensively used to map fishing effort at global and regional scales, as well as to investigate fishing patterns in relation to environmental and regulatory factors. However, as with VMS, AIS-based analyses rely on indirect inference, as fishing activity is not directly observed.

A central limitation of movement-based approaches lies in the overlap between operational states. Similar vessel speeds may correspond to different activities, including active fishing, gear handling, drifting or transit at low speed. This behavioural ambiguity has been recognised as a key source of uncertainty in the classification of fishing activity (Hintzen et al., 2012), particularly in demersal trawl fisheries, where speed ranges may not be clearly separable.

In parallel, spatial analyses of fishing activity are strongly influenced by the quality and resolution of bathymetric data. Bathymetry plays a critical role in demersal fisheries, where fishing grounds are closely associated with depth ranges and seabed characteristics (Colloca et al., 2013). However, bathymetric information is derived from heterogeneous sources, including hydrographic surveys and digital bathymetric models,

which may differ in spatial resolution and accuracy (EMODnet Bathymetry Consortium, 2020). These differences can result in discrepancies in the positioning of isobaths, particularly in areas with complex seabed morphology.

Despite the extensive use of vessel tracking data and bathymetric information in fisheries research, behavioural and spatial uncertainties have generally been addressed separately. Studies focusing on activity classification have emphasised movement-based inference, while spatial analyses have largely assumed a fixed representation of the seabed. The combined effect of these uncertainties on the interpretation of fishing activity, particularly in relation to depth-based regulatory limits, remains insufficiently explored.

This study builds on existing approaches by explicitly integrating behavioural inference from AIS data with multi - source bathymetric validation, addressing the interaction between movement - based classification and spatial representation within an uncertainty-aware analytical framework.

3. Methodology.

3.1. Study area and fleet characteristics.

The study focuses on the demersal trawl fleet operating from the port of Llançà, located in the Gulf of Lion (GSA-07, north-western Mediterranean). This area is characterised by a relatively narrow continental shelf and a marked bathymetric gradient, where fishing activity is concentrated within specific depth ranges associated with target species.

The analysed dataset corresponds to a subset of vessels representative of the local fleet, with continuous operational activity during the study period. Three representative vessels were selected for detailed analysis; while the analysis is case-specific, the methodological framework is transferable to similar demersal trawl fleets.

3.2. Data sources.

The analysis is based on the integration of vessel tracking data and bathymetric information from multiple sources.

- **AIS data** were used to reconstruct vessel trajectories at high temporal resolution, including position, speed over ground and course.
- **VMS data** were used as a source for fishing/vessel monitoring, providing positional information at lower temporal resolution compared to AIS. Under the European Union regulatory framework, VMS reporting intervals typically range from 1 to 2 hours, depending on vessel characteristics and control requirements (European Commission, 2009). This lower frequency limits the ability to capture fine-scale vessel behaviour, particularly in comparison with AIS data, which can provide position updates at intervals of seconds to minutes.
- **Bathymetric data** were obtained from:
 - hydrographic chart references (IHM)

- digital bathymetric models (EMODnet Bathymetry Consortium, 2020)

These datasets differ in resolution and purpose, providing the basis for evaluating spatial uncertainty.

Table 1: Data sources used in the analysis.

Data type	Source	Variables	Purpose
AIS	Vessel tracking system	Position, speed, course, date and time	Trajectory reconstruction
VMS	Vessel tracking system for fishing purposes	Position, date and time	Trajectory reconstruction
Bathymetry A	Hydrographic charts (IHM)	Depth	Regulatory reference
Bathymetry B	EMODnet (2020)	Depth grid	Spatial comparison

Source: Authors.

3.3. Trajectory reconstruction.

AIS and VMS data were processed to reconstruct vessel trajectories through sequential positioning records. Data cleaning procedures included the removal of incomplete or inconsistent records and the segmentation of trajectories into continuous operational tracks.

The resulting trajectories provide a high-resolution representation of vessel movement, forming the basis for behavioural inference.

3.4. Behavioural inference.

Fishing activity was inferred using vessel speed as the primary proxy. Speed thresholds were used to distinguish between different operational states, following established approaches in the literature (Hintzen et al., 2012).

However, particular attention was given to low-speed segments, where different operational states may overlap. These include active fishing, gear handling, drifting and low-speed transit.

Table 2: Conceptual classification of vessel activity based on speed.

Speed range	Likely activity	Uncertainty level
High speed	Transit	Low
Medium speed	Manoeuvring	Moderate
Low speed	Fishing / non-fishing	High

Source: Authors.

3.5. Spatial validation and bathymetric comparison.

Vessel positions were spatially analysed in relation to bathymetric information derived from multiple datasets. Depth values associated with vessel positions were obtained using both hydrographic chart references and digital bathymetric models.

Differences between datasets were evaluated qualitatively in terms of:

- depth values at specific positions
- spatial displacement of isobaths

- implications for classification relative to regulatory limits

Table 3: Comparison of bathymetric data sources.

Parameter	Hydrographic charts (IHM)	EMODnet model
Data type	Survey-based	Gridded model
Resolution	Variable	Regular grid
Purpose	Navigation	Scientific
Uncertainty source	Generalisation	Interpolation

Source: Authors.

3.6. Uncertainty framework.

The analysis integrates two sources of uncertainty:

- **Behavioural uncertainty**, associated with the inference of fishing activity from movement-based indicators
- **Spatial uncertainty**, associated with differences in bathymetric representation

These uncertainties are particularly relevant in areas close to depth-based regulatory limits, where small variations in speed interpretation or bathymetric data may lead to different classification outcomes.

The methodological framework integrating these components is illustrated before in Figure 1.

4. Results.

4.1. Vessel trajectory patterns.

The reconstructed AIS/VMS trajectories show a consistent spatial concentration of vessel activity within the continental shelf area of the Gulf of Lion. Vessel movements are characterised by repeated track patterns, with relatively stable directions and limited spatial dispersion, consistent with demersal trawl operations.

Fishing activity appears to be concentrated within specific depth ranges, with trajectories frequently aligned along bathymetric contours. This spatial behaviour reflects the dependency of demersal trawl fisheries on seabed characteristics and depth-related distribution of target species.

These spatial patterns are illustrated in Figure 2, where vessel positions and trajectories are represented in relation to bathymetric information.

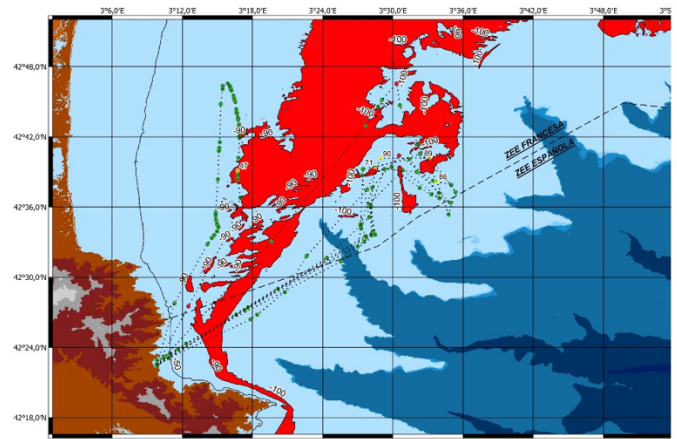
4.2. Behavioural patterns and speed distribution.

The analysis of vessel speed along reconstructed trajectories shows distinct operational regimes. High-speed segments are clearly associated with transit, while intermediate speeds correspond to manoeuvring or changes in course.

However, low-speed segments represent a substantial proportion of the observed activity and cannot be unambiguously classified. Within this range, vessel movement patterns are consistent with multiple operational states, including active fishing, gear handling and non-fishing activities.

This overlap confirms the presence of behavioural ambiguity in speed-based classification, particularly in demersal trawl fisheries where operational speeds are relatively narrow.

Figure 2: Spatial distribution of vessel trajectories in the Gulf of Lion (GSA-07) over bathymetric data, showing the concentration of demersal trawl activity near depth-based regulatory boundaries.



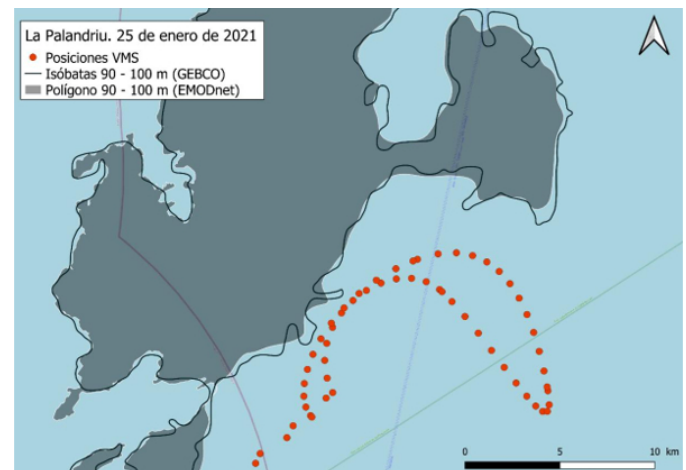
Source: Authors.

4.3. Spatial classification relative to bathymetry.

The spatial analysis of vessel positions relative to bathymetric data reveals differences depending on the dataset used. When vessel positions are evaluated against hydrographic chart references and digital bathymetric models, discrepancies arise in the classification of activity relative to depth-based limits.

These differences are particularly evident in areas close to regulatory isobaths, where small variations in depth values or isobath positioning may lead to alternative interpretations of the same vessel position.

Figure 3: Vessel positions in relation to alternative bathymetric datasets (EMODnet and GEBCO) illustrating spatial discrepancies in depth-based classification.



Source: Authors.

The effect of these differences is conceptually illustrated in Figure 3, showing how spatial classification may vary depending on bathymetric representation.

4.4. Combined behavioural and spatial uncertainty.

The combined analysis of vessel speed and bathymetric position highlights the interaction between behavioural and spatial uncertainty. In areas where vessel activity is concentrated near regulatory depth limits, low-speed segments coincide with zones where bathymetric discrepancies are most relevant.

As a result, the classification of fishing activity in these areas becomes particularly sensitive to both the interpretation of movement patterns and the choice of bathymetric dataset.

This combined effect introduces variability in classification outcomes, even when based on the same underlying vessel trajectory data.

5. Discussion.

The results highlight two interrelated sources of uncertainty in the interpretation of fishing activity derived from vessel tracking systems: behavioural uncertainty associated with movement-based classification, and spatial uncertainty related to bathymetric representation of regulatory limits.

Behavioural classification based on vessel speed has been widely adopted in fisheries research as a proxy for fishing activity (Mills et al., 2007; Bastardie et al., 2010; Hintzen et al., 2012). However, the findings of this study confirm that such approaches are inherently limited in demersal trawl fisheries, where operational speeds may overlap across different activity states. In particular, low-speed segments cannot be unequivocally associated with active fishing, as they may also correspond to gear handling, drifting or manoeuvring. This ambiguity has been previously identified (Hintzen et al., 2012) and is further supported here by the observed trajectory patterns.

In parallel, the spatial component of fishing activity classification is strongly dependent on the bathymetric dataset used. As shown in the results, different bathymetric sources (e.g. E-MODnet and GEBCO) may lead to variations in isobath positioning, particularly in areas of complex seabed morphology. Similar limitations have been reported in gridded bathymetric models, where interpolation and resolution constraints introduce spatial uncertainty (EMODnet Bathymetry Consortium, 2020).

A key contribution of this study lies in the explicit consideration of the isobath used for regulatory purposes. Unlike global or model-derived bathymetric datasets, hydrographic chart isobaths (IHM) are often constructed through interpolation and generalisation processes, rather than representing direct measurements at a consistent resolution. As a result, the regulatory boundary itself may not correspond to a uniquely defined physical feature, introducing an additional layer of uncertainty that has received limited attention in previous studies.

The interaction between behavioural and spatial uncertainty is particularly relevant in areas where fishing activity is concentrated near depth-based regulatory limits. In such cases, small variations in vessel speed interpretation or isobath positioning may lead to different classification outcomes for the same trajectory. This combined effect is illustrated in Figures 2 and 3, where both vessel distribution and bathymetric variability contribute to classification ambiguity.

These findings have important implications for fisheries management and compliance assessment. Current monitoring frameworks often rely on deterministic interpretations of vessel activity based on positional data, implicitly assuming that both behavioural indicators and spatial references are sufficiently accurate. However, the results suggest that such assumptions may not hold in practice, particularly in demersal trawl fisheries operating near regulatory thresholds.

Recent studies using AIS data at global scale (Kroodtsma et al., 2018) have demonstrated the potential of high-resolution tracking for fisheries monitoring, while also highlighting the need for cautious interpretation of inferred activity. In line with these findings, the present study supports the development of uncertainty-aware approaches that explicitly account for both behavioural and spatial variability.

The findings further suggest that current monitoring and compliance frameworks may assume a level of spatial and behavioural precision not fully supported by the underlying data. In particular, reliance on fixed bathymetric thresholds combined with inferred behavioural indicators may lead to deterministic interpretations that do not adequately reflect inherent uncertainty. This highlights the need for more cautious and uncertainty-aware approaches in both scientific and regulatory applications.

Additional data sources, such as engine parameters (e.g. RPM), could improve the discrimination of vessel operational states by providing direct indicators of propulsion and gear deployment. However, such data are not currently integrated into standard monitoring frameworks, representing a relevant avenue for future research.

These findings are consistent with practical cases where the interpretation of vessel activity based on positional data has been challenged, highlighting the relevance of uncertainty in both scientific and regulatory contexts (Juzgado Central de lo Contencioso-Administrativo nº 12, 2025).

6. Conclusions.

This study has examined the interpretation of fishing activity in demersal trawl fisheries using vessel tracking data in a spatially regulated context. The results demonstrate that both behavioural inference from AIS/VMS data and spatial classification based on bathymetry are subject to significant uncertainty.

From a behavioural perspective, the use of vessel speed as a proxy for fishing activity remains limited by the overlap between operational states, particularly at low speeds. This confirms that movement-based classification alone does not provide an unambiguous representation of fishing activity in demersal trawl fisheries.

From a spatial perspective, the analysis shows that different bathymetric datasets (e.g. GEBCO and EMODnet) lead to variations in isobath positioning, which in turn affect the classification of vessel activity relative to depth-based regulatory limits. Importantly, the isobath used for regulatory purposes (IHM) is not always directly observed but may be derived through inter-

polation, introducing an additional and often overlooked source of uncertainty.

The combined effect of behavioural and spatial uncertainty is particularly relevant in areas where fishing activity is concentrated near regulatory boundaries. In such contexts, small variations in data interpretation may lead to different classification outcomes for the same vessel trajectory.

Overall, the findings highlight the need for uncertainty-aware approaches in the monitoring and assessment of fishing activity. Incorporating both behavioural and spatial variability into analytical frameworks can improve the robustness of fisheries monitoring systems and support more consistent interpretation in both scientific and regulatory contexts.

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