OCS Study
BOEM 2024-060

Can observations of fishing vessels from wildlife surveys be used to improve estimates of fishing activity from AIS and VMS?

US Department of the Interior
Bureau of Ocean Energy Management
Office of Renewable Energy Programs
Sterling, VA

Can observations of fishing vessels from wildlife surveys be used to improve estimates of fishing activity from AIS and VMS?

September 2024

Authors:

Klaus B. Huebert[1]
Matthew S. Kendall[2]
Ayman Mabrouk[1]
Daniel S. Dorfman[1]
Christopher F.G. Jeffrey[1]
John D. Christensen[2]
Arliss J. Winship[1]

[1] CSS, Inc., under contract to NOAA, National Ocean Service, National Centers for Coastal Ocean Science

[2] NOAA, National Ocean Service, National Centers for Coastal Ocean Science

Prepared under Interagency Agreement Number M21PG00009
by
National Oceanic and Atmospheric Administration
National Ocean Service
National Centers for Coastal Ocean Science
Marine Spatial Ecology Division
1305 East-West Hwy, SSMC-4, N/SCI-1
Silver Spring, MD 20910

US Department of the Interior
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DISCLAIMER

This study was funded, in part, by the U.S. Department of the Interior, Bureau of Ocean Energy Management (BOEM), Environmental Studies Program, Washington, DC, through Interagency Agreement Number M21PG00009 with the U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), National Ocean Service (NOS), National Centers for Coastal Ocean Science (NCCOS). This report has been technically reviewed by BOEM, and it has been approved for publication. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of BOEM or NOAA, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

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CITATION

Huebert KB, Kendall MS, Mabrouk A, Dorfman DS, Jeffrey CFG, Christensen JD, Winship AJ (National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD). 2024. Can observations of fishing vessels from wildlife surveys be used to improve estimates of fishing activity from AIS and VMS? Sterling (VA): U.S. Department of the Interior, Bureau of Ocean Energy Management. 56 p. OCS Study BOEM 2024-060.

ABOUT THE COVER

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ACKNOWLEDGMENTS

Dozens of organizations and countless individuals have contributed to the data compilations used here. Many individuals provided access to essential databases on vessel tracking and observations, recommended ancillary information, offered insight into the methods used to collect data, and discussed ways to improve aspects of the analysis. In particular, we thank Robert Kenney (NARWC); Kelly Spalding-Behner, Lynnphuong Nahn, and Jimmy Zhu (NMFS/OLE); Rex Roebeck (USCG); Tim Cole, Angela Silva, and Doug Christel (NEFSC); Tim White (BOEM); Julia Willmott (Normandeau Associates Inc.); Nils Bolgen (MassCEC); and Orla O'Brien (NEA). Bryan Costa and Charles Menza provided internal review of the draft report. Kelly Spalding-Behner, Tim Cole, Doug Christel, and Robert Kenney reviewed portions of the draft report. NCCOS is funded by BOEM to manage and maintain the NWASC 2020–2024. Contract work for NCCOS was completed by Consolidated Safety Services, Inc.

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List of Abbreviations and Acronyms

Short form	Long form
AIS	automatic identification system
BOEM	Bureau of Ocean Energy Management
CCS	Provincetown Center for Coastal Studies
CI	confidence interval
EcoMon	NOAA Northeast Fisheries Science Center Ecological Monitoring Program
EWS-North	Early Warning System, Sea to Shore Alliance/Clearwater Marine Aquarium Research Institute
EWS-South	Early Warning System, Florida state agencies
FV-C	NARWC code for lobster/crab vessels
FV-H	NARWC code for party (“head”) boats
FV-S	NARWC code for shrimpers
FV-T	NARWC code for trawlers/draggers
FV-U	NARWC code for unspecified fishing vessels
Herring	NOAA Northeast Fisheries Science Center Atlantic Herring Acoustic Survey
NARWC	North Atlantic Right Whale Consortium
NEA	New England Aquarium/Massachusetts Clean Energy Center/Northeast Large Pelagics Survey Consortium
NNE	NOAA Northeast Fisheries Science Center Large Pelagic Survey
NWASC	Northwest Atlantic Seabird Catalog
NYSERDA	New York State Energy Research and Development Authority
Stellwagen	Stellwagen Bank National Marine Sanctuary Seabird Survey
VMS	vessel monitoring system

Summary

Describing fishing activity is an important component of assessing the economic impact of offshore energy development on commercial fisheries. The objective of this study was to explore a way to improve estimates of fishing activity off the US Atlantic coast by linking two independent types of data: 1) fishing vessel locations from vessel-mounted GPS tracking systems (i.e., automatic identification system [AIS], and vessel monitoring system [VMS]) and 2) fishing vessel locations observed as ancillary data during wildlife surveys (e.g., North Atlantic Right Whale Consortium, Northwest Atlantic Seabird Catalog). The analysis was designed to estimate the proportion of vessel sightings in wildlife surveys that was spatially consistent with synchronous vessel positions interpolated from GPS tracking system data. Such a proportion could then potentially be applied as a correction factor to GPS tracking data to estimate the number of vessels not being tracked and thereby estimate total fishing activity. Each sighting from the wildlife surveys was classified as either a potential match or non-match with the nearest estimated synchronous position of tracked vessels. Potential matches were defined as sightings close enough (i.e., <5 km) to tracked vessels that they could have been the same boat. Non-matches were defined as sightings with no tracked vessels nearby. The analysis was restricted to fishing vessels in parts of the Atlantic continental shelf with sufficient data and was conducted for different data subsets including individual wildlife survey datasets, fishing vessel type, year, season, and geographic area. There were 4,574 fishing vessel sightings from wildlife surveys in years that could be compared with the available AIS data (2019–2021), and 18,400 that could be compared with the available VMS data (2011–2020). The criteria used to evaluate the suitability of a potential correction factor were a high proportion of matches, low uncertainty in the proportion of matches, and low spatiotemporal variability in the proportion of matches. Overall, only 9% of sightings had potential matches in the AIS data. Similarly, only 13% of sightings had potential matches in the VMS data. After accounting for expected false matches using a hypothetical control dataset, the percentage of sightings with matches in the AIS and VMS data decreased to 5% and 8%, respectively. Unfortunately, no subsets of survey data were identified where all 3 evaluation criteria justified the use of the matched proportion as a correction factor for either AIS- or VMS-based estimates of fishing activity. Few datasets had the majority of vessel sightings matched to AIS or VMS tracks; the ones that did had a highly uncertain estimated proportion; and there were large inconsistencies in the estimated proportions among years, seasons, and subregions of the analysis. Consequently, use of the proportion of vessel sightings from wildlife surveys matched to GPS vessel tracking data as a correction factor for fishing activity is not recommended for any of the survey datasets or subsets examined here. Larger sample sizes, consistent identification of fishing vessel types, and more precise vessel location estimates would improve the ability to estimate AIS/VMS coverage from wildlife survey data.

1.0 Introduction

The Bureau of Ocean Energy Management (BOEM) is responsible for approving construction and operations plans for wind-energy facilities on the US continental shelf. Describing fishing activity is an important component of economic impact assessments of offshore energy development on commercial fisheries. The objective of this study was to explore a way to improve estimates of fishing activity by linking two independent types of data: 1) fishing vessel locations from vessel-mounted GPS tracking systems and 2) observed locations of fishing vessels recorded as ancillary data during wildlife surveys.

Assessments of fishing activity regularly use automatic identification system (AIS) and vessel monitoring system (VMS) data (Natale et al. 2015, Shepperson et al. 2018, Vince et al., 2021). In both systems, GPS transceivers are installed on fishing vessels, which broadcast vessel identification, position, and time/date. However, not all commercial fisheries require VMS monitoring (NOAA 2022, 50 C.F.R. § 648.10). Only vessels ≥65 ft (approximately 20 m) long in commercial service within 12 nautical miles from shore (approximately 22 km, US territorial seas) are required to use AIS equipment (80 Fed. Reg. 5282 [March 2, 2015]). Additionally, some vessel operators turn off or disable their transceivers (e.g., to hide their position or while operating outside 12 nautical miles from shore), and in other situations, the location data fail to be archived. As a result, estimates of fishing activity obtained from these data sources alone are underestimated by an unknown amount. Linking information from an independent source of boat sighting data may yield a more complete understanding.

Wildlife surveys for evaluating offshore distributions of seabirds, marine mammals, and other organisms often record ancillary data about sightings of fishing vessels. These ship-based and aerial surveys sometimes also record the date, time, location, and type of fishing vessels observed. Theoretically, if the vessel locations and times recorded by wildlife surveys and vessel tracking systems are sufficiently resolved and compatible, the two sets of data can be compared to determine if the boats sighted on wildlife surveys are transmitting their positions and if they are being properly archived. Through this comparison, it may be possible to correct for underestimates of vessel activity derived from GPS tracking data alone and thereby improve the accuracy of estimates of fishing activity and better inform economic impact assessments. Since ancillary vessel observations from wildlife surveys have never been used in this way, it is unknown if their consistency, positional accuracy, and temporal resolution are sufficient to enable reliable comparison with the vessel tracking data.

The goal of this study was to determine if fishing vessel tracking data could be linked to existing sighting records of vessels from concurrent wildlife surveys. The primary metric of interest was the proportion of boats sighted in the wildlife surveys that matched vessels tracked by AIS/VMS. For example, if 80% of the sighted fishing vessels could be matched with archived GPS vessel tracks, then the remaining 20% of vessel activity would be missing from estimates based solely on vessel tracking data. Equally important was whether the matched proportion would have sufficient precision to be used as a potential correction factor (e.g., GPS estimate / proportion matched = corrected GPS estimate). This analysis was conducted for fishing vessels across various subsets of data, including individual wildlife survey datasets, fishing vessel type, year, season, and geographic areas, focusing on parts of the Atlantic continental shelf with adequate data coverage.

2.0 Methods

The project study area encompassed the Atlantic continental shelf from Maine to Florida (Figure 1) due to the growing plans to lease and develop offshore wind energy in some areas (Figure 2). The inshore boundary of the study was the shoreline, and the offshore boundary was constrained by the extent of the vessel sightings from the wildlife surveys, which were entirely on the continental shelf or shelf edge (Figure 1). The time frame for the analysis was constrained by the available vessel observation and tracking data, which spanned from January 2011 through December 2021.

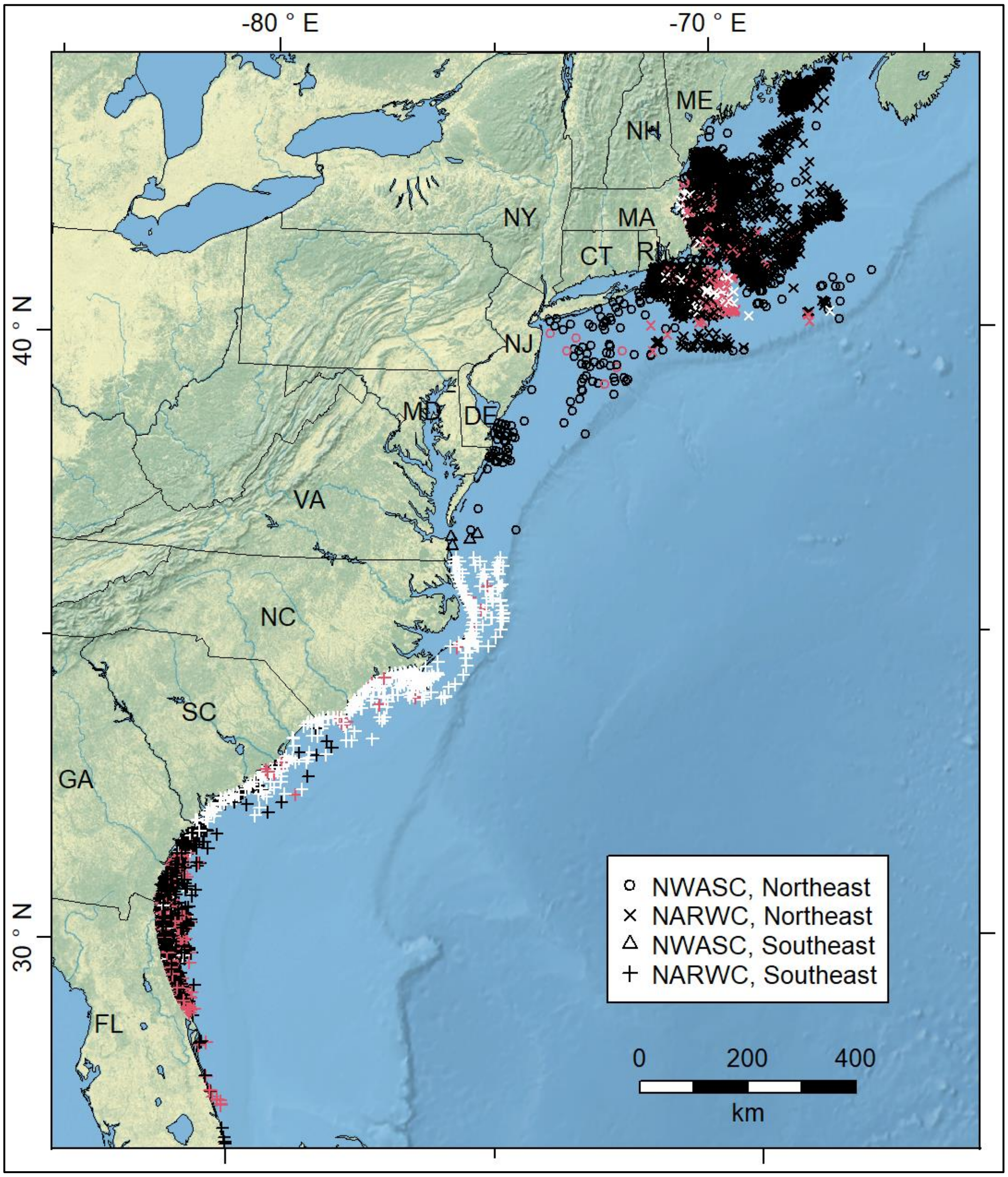

Figure 1. Atlantic shelf study area, with fishing vessels observed in wildlife surveys.

Surveys were from North Atlantic Right Whale Consortium (NARWC) and Northwest Atlantic Seabird Catalog (NWASC) databases divided into Northeast (Maine to Eastern Shore of Virginia) and Southeast (southern Virginia to Florida) regions.

Sightings in 2011–2018 (black) overlapped in years with available vessel monitoring system (VMS) data only, sightings in 2019–2020 (red) overlapped with both VMS and automatic identification system (AIS) data, and 2021 sightings (white) overlapped with available AIS data only.

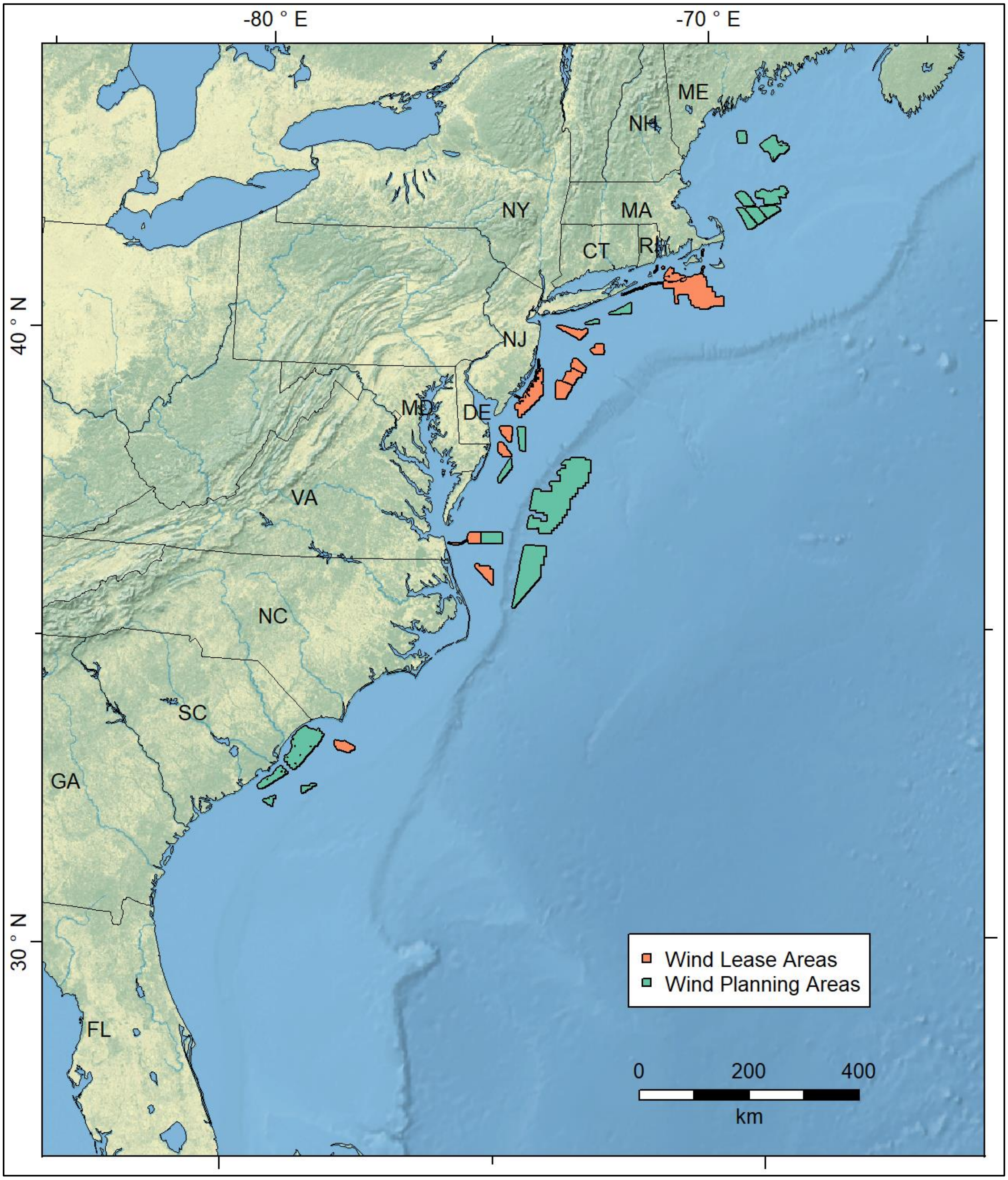

Figure 2. Offshore wind lease and planning areas in the study area.

Outlines show lease areas as of July 2024 and planning areas as of April 2024 (BOEM 2024)

2.1 Description of the Data

2.1.1 Vessel Tracking Systems

Although they are independent systems that were created for different purposes, both AIS and VMS tracking data have been used for understanding the distribution of fishing vessel activities (Natale et al. 2015, Shepperson et al. 2018). The maritime AIS is primarily a collision-avoidance system by which vessels continuously broadcast their identity and position to others by radio signals. Since 2016, AIS devices have been required onboard all commercial vessels 65 ft or longer in the US territorial sea (within 12 nautical miles from shore) including fishing vessels (80 Fed. Reg. 5282 [January 30, 2015]). For example, in the Northeast region, approximately 15% of vessels with commercial fishing permits for 2019–2021 were ≥65 ft in length (NOAA Greater Atlantic Regional Fisheries Office 2024) and thus equipped with AIS transceivers. For some fishing gear types, this percentage may be larger. For example, as of 2004, roughly one-third of bottom trawl and two-thirds of mid-water trawl fishery vessels in the Northeast were ≥65 ft in length (Orphanides and Magnusson 2007). The transmission range of AIS data is estimated to be 13–74 km between vessels or from vessel to terrestrial base station, depending on transmitter and receiver characteristics, weather, and other factors (IMO 2015, Last et al. 2015, Robards et al. 2016). Due to this short range, reception and archiving of AIS messages at base stations often depends on a chain of vessel-to-vessel transmissions and can result in large temporal gaps in coverage (Natale et al. 2015, Shepperson et al. 2018). AIS messages are also received and archived using a network of satellites; however, those too are often incomplete due to gaps in satellite coverage, insufficient signal power, and interference of messages from vessels broadcasting at the same time (Natale et al. 2015, Robards et al. 2016, Shepperson et al. 2018). Collectively, these issues result in frequent gaps in AIS locations, especially beyond 100 km from shore. Additionally, power can be turned down or off on AIS equipment, such that fishing vessels intentionally leave no AIS records (Vince et al 2021, Shepperson et al. 2018, Robards et al. 2016).

The AIS data for this project were obtained from the US Coast Guard and were available from both terrestrial and satellite AIS receivers for the study area from January 1, 2019 to December 31, 2021. Data consisted of average positions at intervals of 5 minutes, which provided sufficient resolution for comparison with the wildlife survey observations. Terrestrial and satellite data were combined to create AIS tracks. Positional accuracy was not factored into the analysis, because GPS errors are generally assumed to be <10 m. Although several other parameters are recorded, only vessel type (i.e., AIS vessel code 30 for fishing vessels), identification, date, time, and location were utilized in this analysis.

The other vessel tracking system dataset used in this study was the VMS, which is primarily used to monitor compliance of commercial fishing vessels in US waters (NOAA 2022). The system uses satellite-based communications from onboard transceiver units, which vessels in certain fisheries are required to carry. Since VMS was specifically designed for transmission via satellites, archived records of VMS positions were assumed to have been complete, except for intentionally or unintentionally malfunctioning VMS transceivers. Compared to AIS, VMS data and equipment are sometimes viewed as reliable and tamper-proof (Vince et al. 2021), although other sources assume some tampering even with VMS (King et al. 2009). Vessels statutorily required to use VMS off the Atlantic coast include a wide spectrum of, but not all, commercial fishing fleets (NOAA 2022). Notably, most commercial shrimp, crab, and lobster fishing activity in this region does not involve VMS monitoring requirements. Changes in VMS coverage during the period of interest include added VMS requirements for fishing mackerel in 2014, longfin squid/butterfish in 2016, and *Illex* squid in 2017[1]. Vessel position is reported once hourly for most vessels and every 30 minutes for permits in the scallop fishery. VMS data were obtained from NOAA's National

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[1] D. Christel, personal communication, April 5, 2024.

Marine Fisheries Service, Office of Law Enforcement. Data including fishing vessel type, anonymized identification, date, time, and location were requested for the period from January 2011 through December 2021. Similar to AIS, positional accuracy of the coordinates is assumed to be <10 m and was not considered in the analysis. A nondisclosure agreement and acceptable use form was completed to comply with statutory protections under the Magnuson–Stevens Fisheries Conservation and Management Act. It is also important to note that, for both the VMS and AIS datasets, the objective of the analysis was not to identify individual vessels, report violations, or detect noncompliance. Individual vessel identifiers were anonymized and used only to determine which consecutive track points came from the same vessel in order to interpolate positions during the analysis.

Vessel tracking data for this analysis extended from 23.733° to 45.024° North latitude and −65.700° to −83.023° East longitude. For both AIS and VMS data, duplicate records with the same combination of vessel identification, location, and timestamp were removed. In cases where the same vessel had multiple positions at the same timestamp, a mean location was calculated.

2.1.2 Wildlife Survey Datasets

Two large databases for wildlife surveys compiled from 2011 to 2021 were used as sources of fishing vessel observations. These databases were the Northwest Atlantic Seabird Catalog (NWASC) (O’Connell et al. 2011, Coleman et al. 2016, Winship et al. 2023) and the North Atlantic Right Whale Consortium sightings database (NARWC) (Kenney 2015, 2021). A total of 20,103 fishing vessel sightings were included in the final analysis from both datasets (Table 1).

The NWASC is a database for marine bird observations that seeks to inform coastal and offshore planning activities (O’Connell et al. 2011, Coleman et al. 2016, Winship et al. 2023). The NWASC database includes contributions from many entities including government agencies, nongovernmental organizations, industry, and academics. It provides standardized information on the data provider, date, time, location of the observation platform or sighting, type of platform (e.g., aerial, shipboard), and type of fishing vessel observed. Nearly 80% of the fishing vessel sightings in the time period of interest were from shipboard surveys; however, since 2016, fishing vessel observations were exclusively from aerial surveys. Fishing vessel observations from the NWASC represented less than 2% of all vessel sightings used in the analysis (Figure 3).

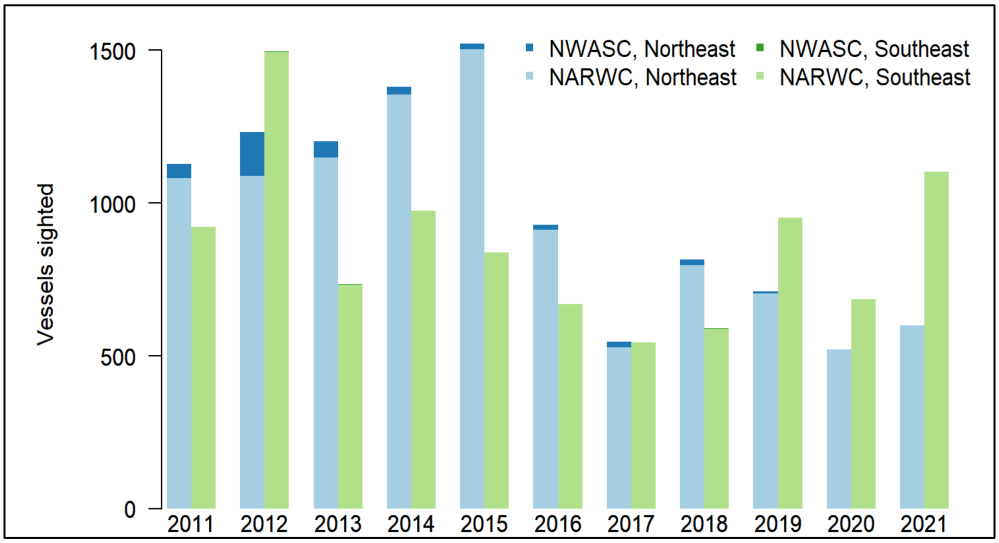

Figure 3. Annual number of fishing vessels sighted in NARWC and NWASC.

NWASC = Northwest Atlantic Seabird Catalog, NARWC = North Atlantic Right Whale Consortium

The other large database used in this analysis was the NARWC sightings database. NARWC is a collaborative data-sharing group of individuals working on research and conservation of North Atlantic right whales. It comprises over 600 data providers from many organizations including academic and industry groups, US and Canadian government agencies, and state and provincial authorities. Aerial observations of fishing vessels from NARWC represented the vast majority (98%) of all vessel sightings used in the analysis (Figure 3). Contributors to the NARWC database report standardized variables for fishing vessel observations including the data provider, date, time, location of the observation platform, type of platform (e.g., aerial, shipboard), and type of fishing vessel (Table 1). Missing data fields for some datasets were filled in by contacting data providers (e.g., declination angles for vessel sightings from the NOAA Northeast Fisheries Science Center Large Pelagics Survey).

Table 1. Categories of commercial fishing vessels sighted in wildlife surveys (2011–2021), with NWASC sightings adapted to NARWC types (Kenney 2021)

Type	NARWC Description	N
FV-C	Lobster/crab/other pot/trap fishery	4,511
FV-H	Party (“head”) boat	369
FV-S	Shrimper	8,400
FV-T	Trawler/dragger	5,029
FV-U	Unspecified type	1,709
Other	Other	85
Total	--	20,103

NWASC = Northwest Atlantic Seabird Catalog, NARWC = North Atlantic Right Whale Consortium.

It is important to note that both databases are composed of many separate survey programs conducted by multiple organizations using broadly similar (e.g., aerial or shipboard visual transects) but not identical methods. The details of the methods and protocols for counting fishing vessels vary among the data contributors and even within a particular survey program because the protocols may change over time. Degree of emphasis on reporting vessels during wildlife surveys also varied. As a result, only a generalized description of survey protocols and data derived from aerial and shipboard platforms is provided here. Also provided is summary information on relevant spatial (i.e., methods for estimating boat position) and temporal (i.e., years, quarters) aspects of the vessel observation data that constrained the analytical approach and scope of the results. For both databases, all observations of recreational/sport fishing vessels were excluded because they were not expected to have AIS and/or VMS equipment. Observations with timestamps between 22:00 and 05:00 Eastern time (i.e., likely a time-recording error given these were daytime visual surveys) and observations outside US waters (i.e., across the US–Canadian border) were excluded. Groups of fishing vessels of the same type that were close to each other and were sighted at the same time were recorded as a single observation, so tight groups of vessels had the same statistical weight as sightings of individual vessels.

Only nine wildlife surveys, five from NARWC and four from NWASC, had sufficiently large numbers of sightings (≥50) to enable robust evaluation. In this report, they were abbreviated as NNE (NOAA Northeast Fisheries Science Center Large Pelagic Survey), NEA (New England Aquarium/Massachusetts Clean Energy Center/Northeast Large Pelagics Survey Consortium), NYSERDA (New York State Energy Research and Development Authority), CCS (Provincetown Center for Coastal Studies), EcoMon (NOAA Northeast Fisheries Science Center Ecological Monitoring Program), Stellwagen (Stellwagen Bank

National Marine Sanctuary Seabird Survey), Herring (NOAA Northeast Fisheries Science Center Atlantic Herring Acoustic Survey), EWS-North (Sea to Shore Alliance/Clearwater Marine Aquarium Research Institute/Early Warning System), and EWS-South (Florida state agencies/Early Warning System).

General Description of Aerial and Shipboard Surveys

Aerial surveys accounted for more than 98% of the recorded vessel observations. These surveys were typically flown at altitudes of 200–350 m and speeds of about 190 km/h along predetermined transects sampling an area of interest. Two observers, one on each side of the aircraft, searched visually from below the aircraft upward toward the horizon. When a target animal or object such as a fishing vessel was seen, observers waited until it was perpendicular to the aircraft and then noted the aircraft coordinates. Vessel distance from the aircraft coordinates was then recorded either in the form of right-angle distance intervals (e.g., 1.8–3.7 km or 3.7–7.4 km) or using declination angles from directly below the aircraft (0°) to the vessel (e.g., angles were visually estimated using markings on the aircraft window or wing struts). Distance was used in combination with aircraft altitude, heading, and aircraft side to calculate an estimated location for each fishing vessel sighting. Some aerial surveys used georeferenced digital images instead of human observers (n=74 sightings), resulting in fishing vessel sightings with especially accurate locations (approximately 10-m positional uncertainty[2]).

Shipboard surveys accounted for less than 2% of the fishing vessel observations and came almost exclusively from the NWASC. As with the aerial surveys, ships typically followed predetermined survey lines arranged in parallel or sawtooth patterns to cover survey areas. Protocols commonly called for ships to travel at a constant speed and for observers to count all seabirds in a 300-m wide strip extending from one or both sides of the ship (e.g., Tasker et al. 1984, NEFSC 2020, BOEM 2020). Fishing vessel sightings were not necessarily limited to the surveyed strip, however, and may have extended to the horizon for some surveys.

It is important to note that information about sightability of vessels, or the number of fishing vessels that may be missed in wildlife surveys, was neither available nor required for this analysis. Only the time and location of sighted fishing vessels were needed. Any vessels missed due to sightability (e.g., fog), simply not recorded for some reason (e.g., observer fatigue or task priority), or even double counted (e.g., on edges of adjacent survey lines) during wildlife surveys, did not affect the analysis as long as there was no systematic bias in the boats that were unreported or double counted. The analysis was robust to potential sightability issues, because it focused on the proportion of boats seen in the wildlife surveys that was matched to archived AIS/VMS records.

General Patterns and Limitations of the Wildlife Survey Data

All surveys in both datasets occurred only during daylight hours. Therefore, nighttime locations and activities of fishing vessels, essentially during half of the study period, are beyond the scope of this analysis. There were marked differences among fishing vessel sightings in the Northeast (Maine to Eastern Shore of Virginia) and Southeast (southern Virginia to Florida) regions in terms of the most common vessel types, typical distances from shore, and seasonal distributions by quarter. In the Northeast, the most commonly sighted fishing vessel type was trawlers/draggers (NARWC code FV-T; Table 1), followed by lobster/crab vessels (FV-C), and unspecified fishing vessels (FV-U). Of the specified types, FV-T and FV-C made up 55% and 44%, respectively. While some FV-T and FV-C sightings ranged from <100 m to >215 km from shore, 95% of FV-T sightings occurred 1.0–127.0 km from shore (median: 8.1 km), and 95% of FV-C sightings occurred 1.0–74.1 km from shore (median: 9.3 km). Substantial proportions of sightings (27% of FV-T and 19% of FV-C) were located outside the US

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[2] Willmott, J personal communication, February 23, 2023.

territorial sea (i.e., >12 nautical miles from shore). For all vessel types pooled in the Northeast, the percentage of sightings by quarter of the year (Q1–Q4) was 26% in Q1, 45% in Q2, 9% in Q3, and 20% in Q4. Both FV-T and FV-C were most commonly sighted in Q2 and least commonly sighted in Q3. In the Southeast in contrast, 88% of sightings were classified as shrimpers (FV-S), 5% as FV-C, 4% as head boats (FV-H), and 3% as unspecified. Sightings of shrimping vessels were concentrated relatively close to shore, with 95% of vessels sighted at 0.5–10.9 km from land (minimum: 1 m, median: 4.1 km, maximum: 81.5 km). The percentage of sightings outside the US territorial sea was much larger for FV-H (51%) than for FV-S (1%) and FV-C (1%). For all vessel types pooled in the Southeast, the abundance of fishing vessel sightings was much higher in Q1 (61%) and Q4 (38%) than in Q2 (<1%) and Q3 (<0.1% with no FV-S observations).

It is important to note that temporal and spatial patterns in the obtained data reflected a combination of not only true differences in fishing vessel abundance but also stark differences in survey effort and reporting protocols among wildlife surveys. For example, there was a large decline in the annual number of vessels observed in the Northeast around 2016 (Figure 3). This corresponds to the year when the NNE survey, an important contributor of vessel sighting data, stopped recording vessels[3], not an actual decline in the number of fishing vessels. As a result, only 30% of the observations from the Northeast region took place after 2016, and any changes in fishing activity (e.g., spatial distribution, use of AIS/VMS) since that year are relatively underrepresented. As an example of spatial biases and limitations associated with wildlife survey data, the continental shelf off Virginia, Maryland, Delaware, New Jersey, and New York had lower numbers of vessel sightings compared to areas farther north and south. This was primarily due to lower levels of wildlife survey effort, since none of the five largest wildlife survey datasets included this area due to their focus on high-use habitats of North Atlantic right whales. Analyses for these and other underrepresented subsets of the data (year, season, area, vessel type) may have been subject to higher levels of bias and less-robust results.

2.2 Analysis Framework

The analysis was designed to estimate the proportion of vessel sightings in wildlife surveys that was spatially consistent with synchronous vessel positions interpolated from AIS and VMS tracking system data (Figure 4). For both tracking systems, the estimated synchronous position of the tracked vessel nearest to each sighting from the wildlife surveys was classified as either a potential match or non-match. Potential matches were defined as sightings close enough to tracked vessels that they could have been the same boat. Non-matches were defined as sightings with no tracked vessels nearby. The potential match vs. non-match distance threshold was set to 5 km as described in subsequent sections and was based on the estimated precisions of the sighting and tracking data and the need to minimize the potential for false matches (i.e., sighting and tracking positions too far apart to be the same boat). Importantly, even though this threshold was set to minimize the potential for false matches, it was still possible that a vessel tracked within 5 km of a sighting was not the same vessel seen. For example, a small commercial fishing vessel (e.g., a shrimper) without AIS equipment could have been sighted in a wildlife survey and appear to be a potential match with a larger vessel (e.g., a trawler) tracked by AIS. The probability of false matches was expected to be higher in times and areas of high fishing activity. Hence, at this stage of the analysis, matches are only referred to as "potential matches." To control for false matches and estimate the proportion of sightings with true matches (identical vessels), a control dataset with hypothetical sightings was also created.

The analysis involved seven steps (Figure 4). Steps 1–4 link vessel sightings and tracking data in terms of potential matches compared to non-matches. Steps 5 and 6 estimate the proportions of matched sightings

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[3] Cole, TVN personal communication, January 31, 2023.

and their uncertainties, and step 7 evaluates the use of these estimates for the premise of the study: as correction factors for fishing activity estimates purely from AIS/VMS data. All data were projected into UTM zone 18 for spatial analyses, and all calculations were conducted using custom scripts in R version 4.3.0 (R Core Team 2023).

1. Process the vessel sighting data

- Estimate vessel locations
- Extract sighting data/times for subsequent steps

⇩

2. Create a control dataset

- Use same vessel coordinates calculated in step 1
- Offset the date/time by 7 days
- Use as a control dataset (hypothetical vessels) to compare with tracking data

⇩

3. Process the AIS/VMS tracking data

- Extract all vessel tracks near sighting and control points in space and time
- Interpolate vessel positions between AIS/VMS points to exact sighting and control times

⇩

4. Classify sightings/tracks as potential matches or non-matches

- Potential match defined as a vessel sighting within 5 km of an AIS/VMS track
- Non-match defined as no AIS/VMS tracks within 5 km of a vessel sighting

⇩

5. Estimate true proportion of matched sightings

- Account for false matches
- Subset the results by year, season, location, and vessel type

⇩

6. Simulate sampling error

- Bootstrapping of matches and non-matches
- Bootstrapping of control matches and non-matches

⇩

7. Evaluate suitability of correction factor

- For AIS/VMS fishing activity estimates
- By year, season, location, and vessel type

Figure 4. Processing steps in the analysis framework

Note: AIS = automatic identification system, VMS = vessel monitoring system.

2.2.1 Processing the Vessel Sighting Data

The first step in linking sightings and tracking data was to quantify the uncertainty of sighting positions from wildlife surveys. The precision of estimated locations varied greatly by dataset. Few fishing vessel positions were measured with good precision (e.g., 0.4% of sightings using georeferenced aerial images), some were estimated with moderate precision (e.g., 22.9% using distances and angles relative to survey aircraft positions), and the majority were estimated with low or unknown precision (e.g., using the position of the observer as opposed to the vessel). A combination of published survey methods, surveyor interviews, expert opinions, survey data, and geometric calculations were used to quantify the uncertainty in sighting positions.

Sightings derived from georeferenced digital aerial photographs (e.g., collected by NYSERDA), were expected to be most precise (approximately 10-m uncertainty[4]). Those required no calculations or further processing to refine their positions.

Datasets with distance bins or declination measurements from observer aircraft to sightings were expected to be of moderate precision. The two large datasets in this category were from the Northeast Fisheries Science Center (NNE) (16.5% of total sightings) and the New England Aquarium (NEA) (6.4% of total sightings). For the NNE dataset, aircraft heading and declination angle to vessels were recorded in whole degrees, and aircraft altitude was almost always recorded as the nominal value of 229 m. Given a 229-m altitude and 87° declination angle to a fishing vessel, for example, sighting coordinates would be located approximately 4.4 km from that side of the aircraft. Declination was the greatest source of error and uncertainty in this dataset with higher angles toward the horizon, resulting in greater uncertainty. In the previous example, the estimated location for an 88° declination is approximately 2.3 km farther away. To avoid this potential source of error at observation angles approaching the horizon, sightings beyond 87° were excluded from analysis. Three other sources of measurement error had much smaller effects on sighting positions. These were errors in recording heading or not accounting for crabbing of the aircraft, discrepancy in actual altitude, and errors in recording the exact time of a sighting. For each 1° error in heading, which was approximated using GPS “course made good” output[5], the estimated vessel location would be displaced by approximately 1.7% of the right-angle distance from aircraft to vessel (e.g., 77 m at 229-m altitude and 87° declination). In extreme cases, the crabbing angle may have been as high as 20°[6]. Every 10 m of discrepancy from the nominal altitude would introduce a location error of approximately 190 m. Given an airspeed of approximately 50 m/s, every 1 s of error in the sighting timestamp would result in an error of approximately 50 m. While it was not possible to determine exact values, the combination of these sources of error was estimated to result in sighting coordinates <2.5 km from true vessel positions in most cases in the NNE dataset. In some rare cases, sighting coordinates may have been >2.5 km from true vessel positions (for example, when declination angles >88° were recorded

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[4] Willmott, J personal communication, February 23, 2023.
[5] Kenny, RD personal communication, March 25, 2024.
[6] Cole, TVN personal communication, April 10, 2024.

as ≤87°, or when errors in declination, altitude, and sighting time randomly happened to be aligned in the same direction).

For the NEA dataset, aircraft altitude and heading were recorded in whole meters and degrees, respectively, and relative vessel position was described by declination angles or distance intervals. Distance interval size was often a large source of uncertainty, with n=245 vessels reported in the 1.8–3.7 km interval, and n=154 vessels in the 3.7–7.4 km interval. The midpoint of distance intervals was assumed for estimating vessel coordinates. In contrast, declination angle and altitude were smaller problems, with hypothetical errors of ±1° declination resulting in location errors of <20 m in 94% of cases (<250-m maximum error) and hypothetical errors of ±10 m in altitude resulting in location errors of <20 m in 96% of cases (<65-m maximum error). For each 1° error in heading, the estimated vessel location would be displaced by approximately 1.7% (e.g., 97 m for the midpoint of the 1.8–3.7 km interval). Similar to the NNE dataset, combined error in positions was estimated to be <2.5 km in most cases for the NEA dataset.

Sightings that used coordinates of the survey aircraft or ship as estimates for fishing vessel positions were expected to be the least precise. Suspected error increased with the distance at which sightings were reported. Since fishing vessels were only of secondary interest to most of these surveys, the typical distance at which sightings were reported may have varied unpredictably among observers (e.g., below the aircraft or even >20 km toward the horizon). Therefore, not even a general estimate of error in sighting positions could be determined as was done for NYSERDA, NNE, and NEA. Rather than excluding the sightings that used aircraft or boat position from the analysis, they were evaluated in the same way as other datasets (i.e., using a threshold of 5 km for establishing matches vs. non-matches), as described below in step 4 of the analysis process (Figure 4 and Section 2.2.4).

2.2.2 Creating a Control Dataset

In step 2, each vessel sighting was used to create a paired “control” sighting exactly ±7 days from the actual sighting time at the exact same location (+7 days for Q1 and Q2 and −7 days for Q3 and Q4, to ensure AIS/VMS data were available at the beginning and end of their respective time periods). Control sightings were not actual vessel sightings but rather hypothetical sightings that were used to estimate the probability that a different tracked vessel could have occurred near an actual sighting by coincidence. In other words, control sightings served as a control for false matches, such as a sighted small commercial vessel without AIS (non-match) being mistaken for a large vessel with AIS (potential match) at approximately the same time and place. The seven-day interval was chosen as a control, because similar general fishing activities (i.e., high- and low-traffic areas) might be expected based on the same time of the day, day of the week, and seasonal patterns, but it was unlikely that tracked vessels would be in exactly the same locations one week apart.

2.2.3 Processing the AIS/VMS Tracking Data

In step three, AIS and VMS data were used to approximate the synchronous positions of all tracked vessels in the general vicinity of sightings from wildlife surveys and the corresponding control sightings. For each sighting, a list of VMS and AIS vessels with tracks within 50 km and within 3 hours before and after the actual sighting was compiled. This was done to reduce the number of distance calculations needed to identify potential matches to a reasonable number of vessels. For each such vessel, the location at the exact sighting time was estimated. Then, only the synchronous AIS and VMS locations closest to each sighting were saved and used in later steps of the analysis

Although the available coordinates of AIS and VMS tracks had the precision of GPS (<10 m in most cases), vessel positions were only available at specific intervals of 30 or 60 minutes for VMS and 5 minutes (with some longer gaps) for AIS. For example, most VMS messages were transmitted on the hour at 60-minute intervals (e.g., 09:00, 10:00, and so on). Vessels sighted at any time off the transmitted times were estimated to be at a location between the downloaded coordinates, using linear interpolation of consecutive AIS and VMS track points immediately before and after the sighting. For example, if a sighting occurred at 09:15, the vessel positions were estimated to be 25% of the way between their tracking coordinates at 09:00 and 10:00.

In contrast to VMS, the AIS dataset was closer to ideal for this analysis. Due to the high (5-minute) temporal resolution and high (GPS) spatial accuracy, interpolation errors of synchronous AIS positions >1 km could arise only due to extreme deviations from typical vessel speeds or gaps in AIS coverage.

Due to the detailed temporal and spatial resolution of AIS data, they were also used to estimate the influence of interpolating VMS vessel positions on our matching process. For this analysis, a simulation experiment was conducted, in which the 5-minute resolution AIS positions were compared to a reduced AIS dataset with positions only every 60 minutes, which mimicked the temporal resolution of the VMS data. This approach assumed that the speeds and turns of vessels monitored by AIS and VMS were similar. For the simulation, it was assumed that vessel sightings nearest to the 5-minute resolution AIS data were the correct vessels and their positions were the actual vessel positions. Next, vessel positions from the 60-minute resolution AIS data at the time of the sightings were interpolated as described above for the VMS data. This interpolated position was then compared to vessel positions from the 5-minute resolution AIS. The interpolated position resulted in the correct vessel (i.e., the same vessel as in the 5-minute resolution AIS data) appearing nearest to sightings in 87% of cases, some other vessel appearing nearest in 13% of cases, and no nearby vessels in <1% of cases. In terms of the distance from sighting positions to the nearest approximated AIS positions, the error due to interpolation was ≤2.3 km in 90% of cases. This distance (i.e., 2.3 km), coupled with the potential error in estimating positions from the wildlife survey data (i.e., approximately 2.5 km for the NNE and NEA), informed the next step of the analysis framework to determine which boat sightings potentially matched tracked vessels.

2.2.4 Classify Sightings and/or Tracks as Potential Matches or Non-Matches

Step 4 was to classify the AIS and VMS positions nearest to each sighting as either potential matches or non-matches, based on the estimates of positional uncertainty in AIS/VMS (i.e., 2.3 km) and wildlife surveys with good-to-moderate precision (i.e., approximately 2.5 km). A conservative threshold of 5 km was selected, meaning that only pairs of tracking and sighting coordinates within 5 km of each other were considered potentially the same vessel. For wildlife surveys with moderate or better precision, most combinations of positional errors of sightings and interpolation errors of tracked vessel positions were expected to be below this distance, since 5 km was sufficiently far to accommodate even some rare cases with errors beyond the 90th percentile in one or both datasets. Using a shorter distance threshold would miss actual matches given positional uncertainty, whereas a larger distance would result in an overly large number of false matches.

Individual sightings were not scrutinized beyond this classification, and all further analysis was based on distributions of potential match vs. non-match classifications. Potential matches and non-matches were calculated in exactly the same way for control and actual sightings.

2.2.5 Estimate Proportion of True Matched Sightings

In step 5, the proportion of vessels in the sighting data that had true matches in the AIS and VMS tracking data was estimated. Step 4 provided the number of sighted vessels with potential matches, but those included both true matches and false matches (i.e., other tracked vessels that happened to be nearby). The control sightings generated in step 2 were used to estimate the number of false matches that should be subtracted from the potential matches. The following example illustrates these calculations. Consider a scenario where 40 of 100 vessel sightings in the data had potential matches in the AIS and VMS tracking data and the other 60 sightings were non-matches. If 20 of the 100 corresponding control sightings were also classified as potential matches, then all 20 must have been coincidental false matches, due to the fact that control sightings were hypothetical (with no possible true matches). Therefore, the ratio of false matches to non-matches in the control sightings was 20 / 80 = 0.25. Since the control sightings were very similar to the sighting data (same locations, same time of day, same day of the week, ±1 week), it was assumed that this ratio also applied to the sighting data, in which case the expected number of false matches in the sighting data would be 0.25 * 60 = 15. The expected number of true matches would then be 40 − 15 = 25. Therefore, the estimated proportion of vessels in the sighting data that had true matches in the tracking data would be 25 / 100 = 0.25.

2.2.6 Simulate Sampling Error

One of the main sources of uncertainty in the proportion of true matches from step 5 was sampling error. When the sample size was small, the observed proportion of true matches could have differed substantially from the true proportion simply by chance. In step 6, the uncertainty in the estimated proportion of true matches arising from sampling error was estimated with bootstrapping. Bootstrapping assumed that the observed sightings were representative of their respective wildlife survey programs. Thus, additional samples that might have occurred were simulated by resampling the observed data. The observed matches and non-matches were randomly sampled with replacement to generate 1,000,000 new samples, each of the same original size. For example, consider the scenario above where there were 100 vessel sightings, 40 of which were matches and 60 of which were non-matches. In each iteration of the bootstrapping procedure, those 40 matches and 60 non-matches were randomly sampled with replacement to create a new set of 100 sightings. Due to random chance, the number of matches and non-matches in the new sample would not necessarily be 40 and 60, respectively. For example, they might be 38 and 62, or 45 and 55, etc. The control dataset was similarly resampled to generate 1,000,000 new control samples. The proportion of true matches was then calculated for each of the 1,000,000 paired observed and control samples as described for step 5, resulting in a distribution of proportions of true matches. The 95% confidence interval (CI) of the mean was used to characterize uncertainty in the proportion of true matches, i.e., the proportion of sightings consistent with synchronous vessel locations from tracking systems after accounting for false matches.

2.2.7 Evaluate Suitability of Correction Factor

The main intent of the study was to determine whether matched wildlife survey sightings could be used to correct for fishing vessel activity that was missed by AIS/VMS records for various reasons. Note that the application of correction factors would simply involve dividing VMS/AIS fishing activity estimates by the corresponding proportion of true matches with wildlife survey sightings. For example, if VMS-based estimates were consistently missing 25% of fishing activity, then the proportion of true matches should be 75%, and applying a correction factor of 75% (raw estimate / 0.75 = corrected estimate) would successfully correct for this problem. To evaluate if the proportion of true matches (step 5) and its uncertainty (step 6) would make for a useful correction factor, results were determined separately for each wildlife survey dataset and vessel tracking system.

Results were first separated into the two main regions, the Northeast and Southeast, since these involved different types of fisheries (i.e., predominantly shrimpers in the Southeast, but trawler/draggers and lobster/crab vessels in the Northeast) (Figure 1). Results were also compared separately for AIS and VMS tracklines. Then, for each dataset with a sufficient number of sightings (i.e., >50), estimates were made for subsets of data partitioned in several ways to understand different sources of variability. Temporally, each dataset was partitioned into subsets by year and by quarter, in order to examine the degree of interannual or seasonal variation. Spatially, each dataset was partitioned into three clusters using K-means clustering. This created three subsets of data representing areas with roughly similar sizes and numbers of sightings in most cases and was used to demonstrate spatial variability within a dataset. Results for specific fishing vessel types were analyzed for FV-T and FV-C in the Northeast, and for FV-S, FV-C, and FV-H in the Southeast. Region-wide sample sizes for other vessel types were all <50.

Three factors were used to evaluate whether the matched proportion metric was suitable as a correction factor for AIS- or VMS-based fishing activity estimates. The first was simply the value of this metric. It was considered favorable when the proportion was >0.5, which would mean that more than a simple majority (>50%) of tracked vessels would be used to correct for a minority of vessels missing from tracking system records. A lower proportion would mean that over half of the corrected number of boats would be coming from the process described here (i.e., a majority of the vessels would be merely inferred rather than actually observed). The second factor was the size of the 95% CI of the mean proportions. A CI range of <25% (e.g., a mean value estimated in the range from >40% to <65% matched) was considered favorable. Larger values would represent quite a lot of uncertainty in an attempt to correct or improve an estimate of boat activity. Proportions close to 0% or close to 100% were expected to have the smallest CI ranges. In the former case, a low matched proportion would indicate against applying a correction factor, irrespective of a narrow CI. In the latter case, factors 1 and 2 would be in agreement. The third factor was the presence of large and unpredictable spatiotemporal variability across surveys or subsets of data. Large variability was identified by non-overlapping 95% CIs among years, seasons, or spatial clusters. Non-overlapping CIs among years, for example, suggest that the correction factor would not be consistent enough to apply over time.

3.0 Results

3.1 Linked Wildlife Survey and Tracking Data

3.1.1 Nearest Tracked Vessels

Of the 20,103 fishing vessel sightings from wildlife surveys included in the analysis, 4,574 and 18,400 were from years that could be compared with available AIS (2019–2021) and VMS (2011–2020) data, respectively. Overall, only 9% of sightings had potential matches in the AIS data, i.e., were within 5 km of any vessels tracked by AIS (left of the threshold in Figure 5A). Similarly, only 13% of sightings had potential matches in the VMS data (left of the threshold in Figure 5C). All of the other fishing vessel sighting locations in wildlife surveys (87%–91%) were farther than 5 km away from the nearest vessel tracked by either AIS or VMS. After accounting for expected false matches (Figure 5B and 5D; see Section 2.2.5), the percentage of sightings with matches in the AIS and VMS data decreased to 5% and 8%, respectively.

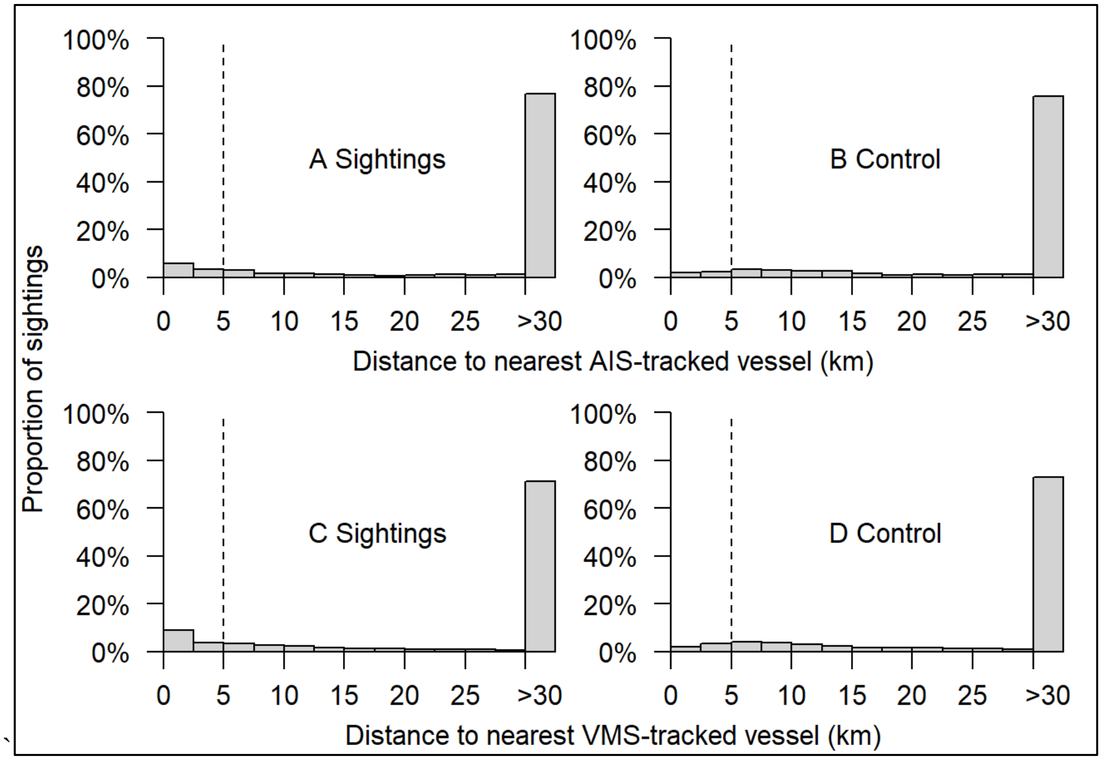

Figure 5. Estimated distances from fishing vessel sighting (A, C) and control (B, D) data to nearest fishing vessels tracked by AIS (A, B) and VMS (C, D)

Dashed vertical line represents the 5-km threshold for potential matches compared with non-matches. AIS = automatic identification system, VMS = vessel monitoring system.

Surveys with higher proportions of potential matches tended to also have higher proportions of false matches (Tables 2 and 3). Among wildlife survey datasets with moderate sample size (n>50), none had potential matches with AIS for over 15% of sightings (Table 2), whereas four out of nine had potential matches with VMS for over 25% (maximum 63%) of sightings (Table 3; Figures 6 and 7). For both AIS and VMS, distributions of distances from sightings to nearest synchronous tracked vessels were heavily skewed toward longer distances, with a majority of nearest distances >30 km (e.g., Figures 6 and 7 for VMS). Pairs of sighting and tracking locations that were so far apart were unlikely to be the same boat and extremely unlikely for datasets with moderate or better precision. Four datasets had pronounced peaks in sightings at <2.5 km from VMS tracks (Figures 6 and 7), including both datasets of known moderate precision, NYSERDA (highest precision, highest peak), and the shipboard survey Stellwagen. This shorter distance from VMS tracks is consistent with higher precision in these survey datasets. The EcoMon dataset was the only one with a peak at 2.5–5 km, suggesting that this shipboard survey had the next-highest precision. Control datasets did not show pronounced peaks in distance from VMS tracks at <5 km for any of the surveys. No datasets showed more than slight peaks in sightings at <5 km from AIS tracks.

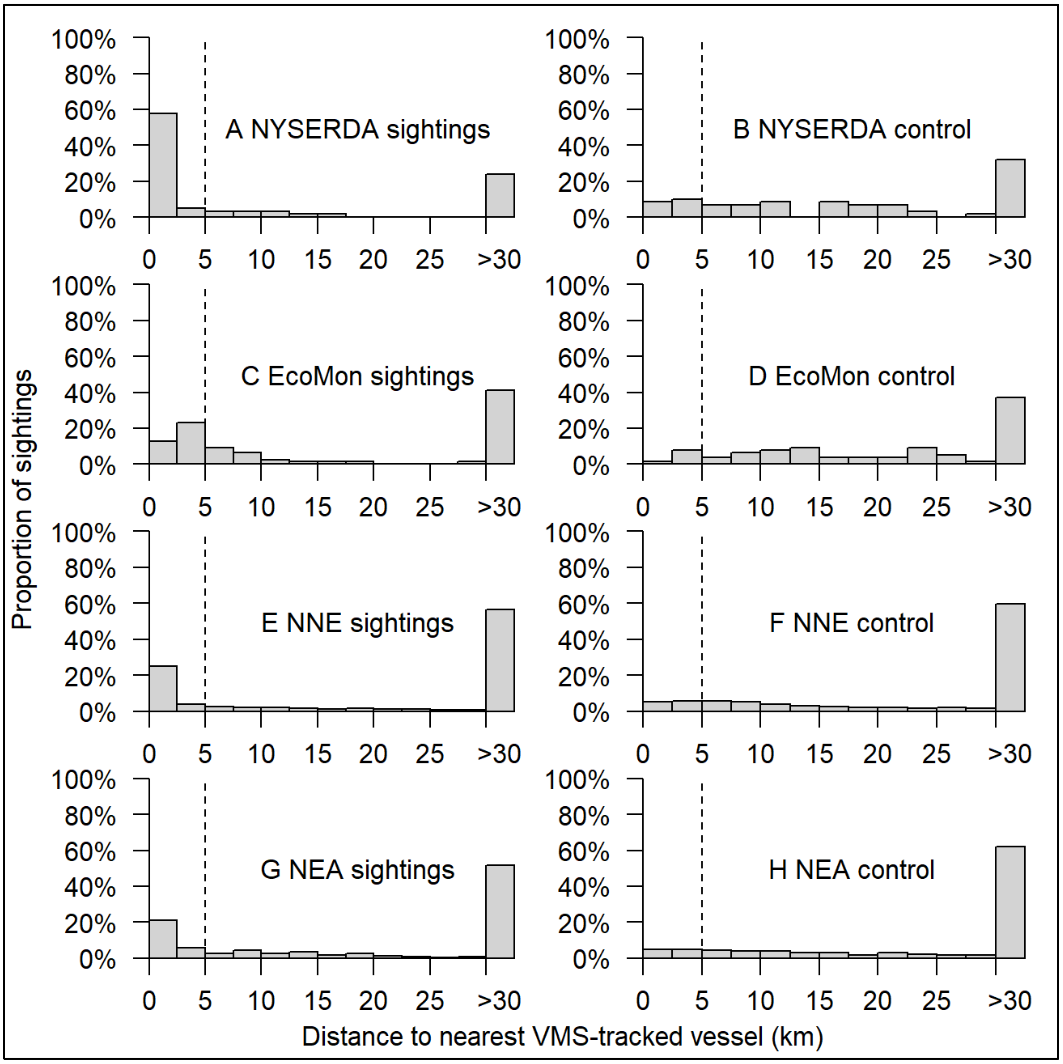

Figure 6. Estimated distances from fishing vessel sighting and control data to nearest VMS-tracked fishing vessels for wildlife surveys with >25% potential matches with VMS.

Dashed vertical line represents the 5-km threshold for potential matches compared with non-matches.

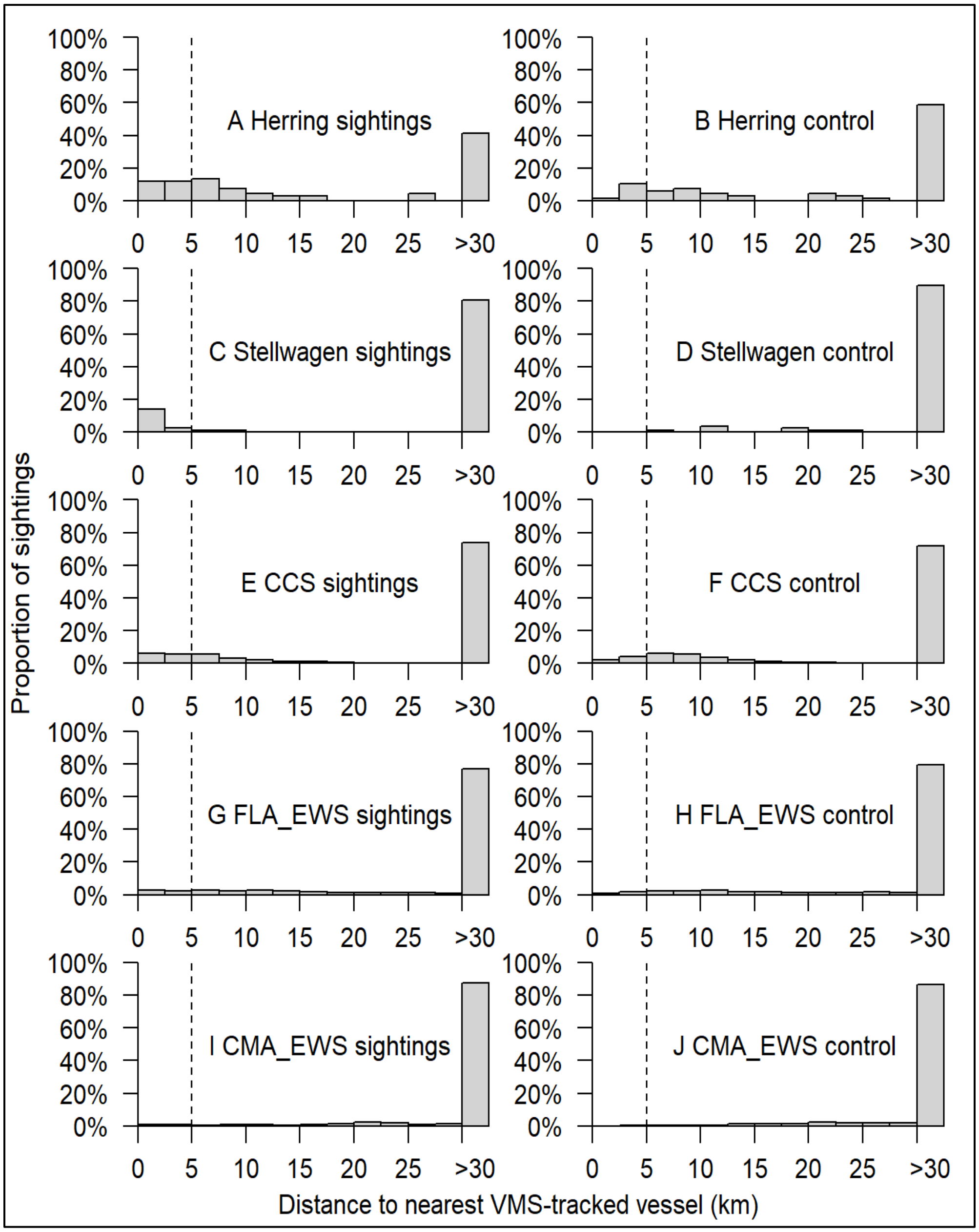

Figure 7. Estimated distances from fishing vessel sighting and control data to nearest VMS-tracked fishing vessels for wildlife surveys with <25% potential matches with VMS.

Dashed vertical line represents the threshold for potential matches compared with non-matches.

Table 2: Estimated proportions of potential and true matches of fishing vessels recorded in wildlife surveys to 2019–2021 AIS tracking data

Region	Survey	Method	Years	N	Potential Matches	Control	True Matches
--	--	--	--	--	Mean (95% CI)	Mean (95% CI)	Mean (95% CI)
NE	NEA[1]	B	2019–2021	532	0.02 (0.01–0.04)	0.01 (0.00–0.01)	0.02 (0.01–0.03)
NE	CCS[1]	C	2019–2021	1,264	0.01 (0.01–0.02)	0.01 (0.00–0.01)	0.01 (0.00–0.01)
SE	EWS-North[1]	C	2019–2021	1,116	0.14 (0.12–0.16)	0.04 (0.03–0.06)	0.10 (0.08–0.13)
SE	EWS-South[1]	C	2019–2021	1,625	0.15 (0.13–0.17)	0.09 (0.08–0.11)	0.07 (0.04–0.09)
NE	Other[1,2]	A–E	2019–2021	37	0.00 (0.00–0.00)	0.00 (0.00–0.00)	0.00 (0.00–0.00)

[1] North Atlantic Right Whale Consortium sighting database, [2] Northwest Atlantic Seabird Catalog, A: georeferenced digital aerial photos (high precision), B: aircraft position plus relative vessel location (moderate precision), C: aircraft position (low precision), D: vertical aerial photos (moderate precision), E: opportunistic sightings (unknown precision). AIS = automatic identification system, N = number, CI = confidence interval.

Table 3: Estimated proportions of potential and true matches of fishing vessels recorded in wildlife surveys to 2011–2020 VMS tracking data

Region	Survey	Method	Years	N	Potential Matches	Control	True Matches
--	--	--	--	--	Mean (95% CI)	Mean (95% CI)	Mean (95% CI)
NE	NNE[1,2]	B	2011–2016	3,315	0.29 (0.27–0.30)	0.11 (0.10–0.12)	0.20 (0.18–0.22)
NE	NEA[1]	B	2011–2020[4]	1,093	0.27 (0.24–0.30)	0.10 (0.08–0.12)	0.19 (0.16–0.22)
NE	NYSERDA[3]	A	2016–2019	59	0.63 (0.51–0.75)	0.19 (0.09–0.29)	0.54 (0.37–0.69)
NE	CCS[1]	C	2011–2020	5,172	0.12 (0.11–0.13)	0.06 (0.06–0.07)	0.06 (0.05–0.07)
NE	EcoMon[3]	F	2011–2013	78	0.36 (0.26–0.46)	0.09 (0.04–0.15)	0.30 (0.17–0.42)
NE	Stellwagen[3]	F	2012–2015	78	0.17 (0.09–0.26)	0.00 (0.00–0.00)	0.17 (0.09–0.26)
NE	Herring[3]	F	2011–2012	68	0.24 (0.13–0.34)	0.12 (0.04–0.21)	0.13 (0.00–0.27)
SE	EWS-North[1]	C	2011–2020	1,641	0.02 (0.01–0.02)	0.00 (0.00–0.01)	0.01 (0.01–0.02)
SE	EWS-South[1]	C	2011–2020	6,761	0.05 (0.05–0.06)	0.03 (0.02–0.03)	0.03 (0.02–0.04)
NE, SE	Other[1,3]	A–F	2011–2020[4]	135	0.26 (0.19–0.33)	0.14 (0.08–0.20)	0.14 (0.03–0.24)

[1] North Atlantic Right Whale Consortium sighting database, [2] NOAA Northeast Fisheries Science Center, [3] Northwest Atlantic Seabird Catalog, [4] No data in some years, A: georeferenced digital aerial photos (high precision), B: aircraft position plus relative vessel location (moderate precision), C: aircraft position (low precision), D: vertical aerial photos (moderate precision), E: opportunistic sightings (unknown precision), F: shipboard (unknown precision). VMS = vessel monitoring system, N = number, CI = confidence interval.

3.1.2 Proportion of Vessels Matched by Dataset in the Northeast Region

Of the nine surveys with >50 fishing vessel sightings, seven took place in the Northeast region (Tables 2 and 3; Figure 8). There was substantial spatial overlap among these surveys. For example, all sightings in the NEA survey were also located inside the spatial extent of the NNE survey.

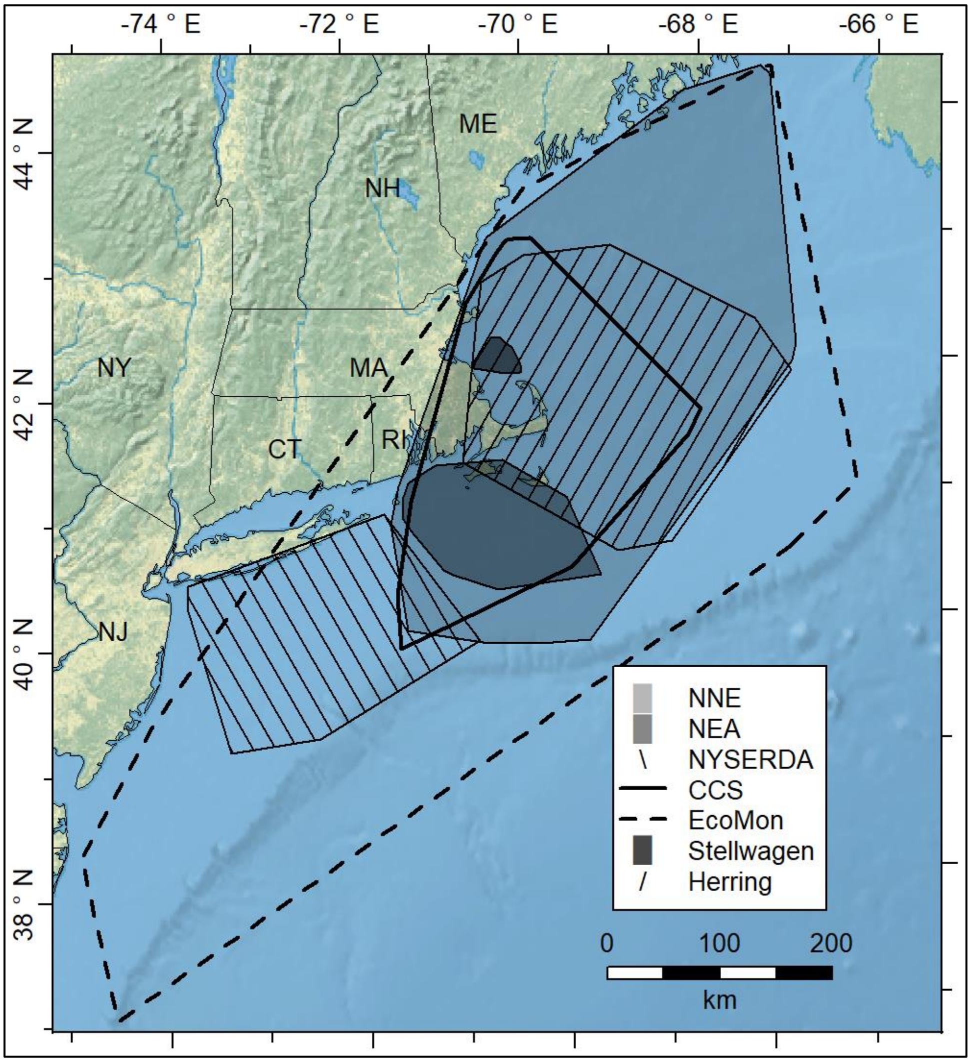

Figure 8. Spatial extent and overlap of wildlife survey data in the Northeast region.

In the Northeast region, approximately 55% of sightings with known vessel types were trawlers/draggers (FV-T), and approximately 45% were lobster/crab/pot/trap vessels (FV-C). All Northeast surveys and survey data subsets (year, quarter, vessel type, or spatial cluster) had low proportions of estimated true matches with AIS. The highest estimated mean for any subset was 4%. Consequently, further details on spatiotemporal patterns with AIS are only summarized in abbreviated form in Appendix A. Comparisons with VMS are broken out below into results for each of the seven datasets with sufficient sample size.

NNE Fishing Vessel Sightings Matched to VMS

Overall, only 20% of the NNE vessel sightings were considered true matches with VMS tracks after accounting for the expected number of false matches (Figures 9 and 10). The 95% CI for this estimate was 18%–22%. None of the analyzed subsets of NNE data had a favorable value of >50% matched. The CI sizes for all subsets were favorable (<25%).

There was an unfavorably large amount of interannual (14%–29%), seasonal (12%–26%), vessel type (6%–40%), and spatial (11%–29%) variation among subsets. This resulted in distinct (non-overlapping) CIs for 2015 and 2014/2016, Q1/Q2 and Q3/Q4, FV-T and FV-C, and cluster 3 compared with other clusters.

The subset with the maximum proportion of matched sightings was FV-T at only 40%.

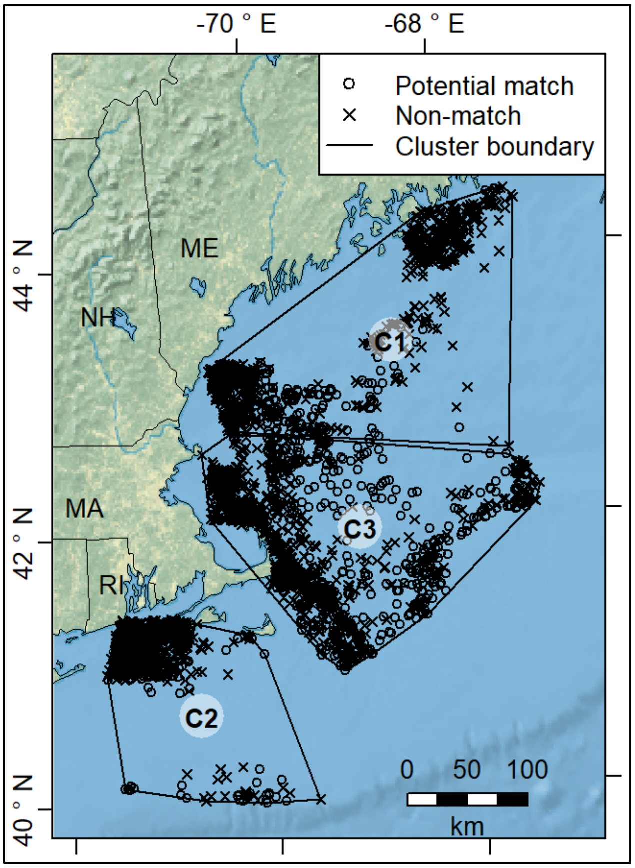

Figure 9. Potential matches of NNE sightings and VMS tracks.

C1–C3 = clusters

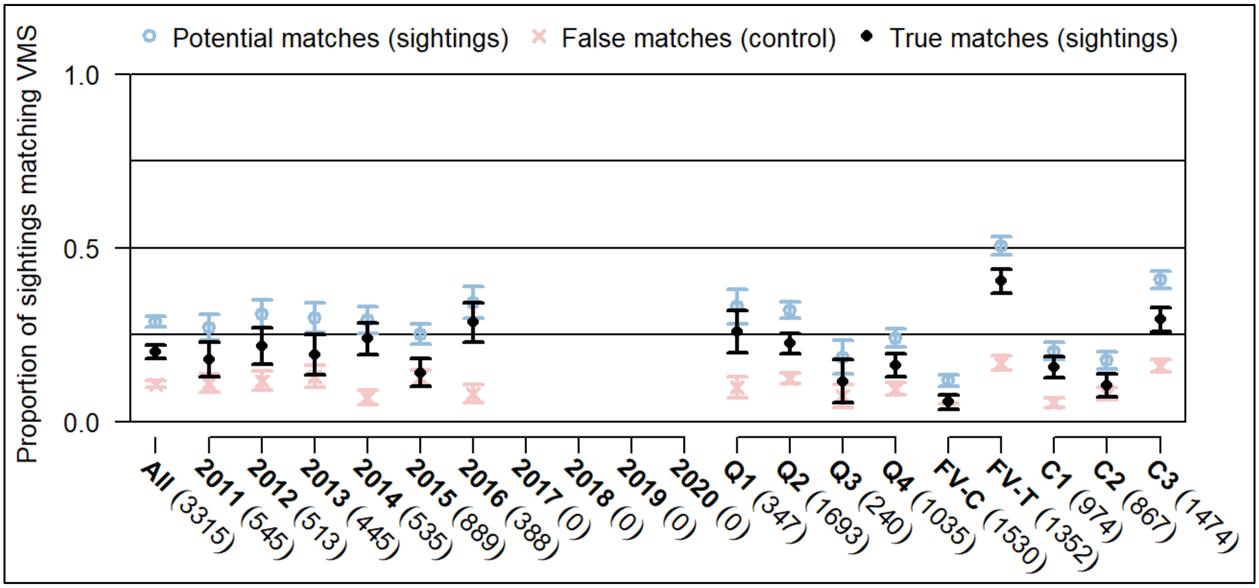

Figure 10. Proportion of sightings matching VMS (mean and 95% CI) for NNE data pooled by year, quarter, vessel type, and spatial cluster (with sample sizes).

NEA Fishing Vessel Sightings Matched to VMS

Overall, only 19% (CI: ±3%) of the NEA vessel sightings were considered true matches with VMS tracks after accounting for the expected number of false matches (Figures 11 and 12). Only the 2015 analysis subset had a favorable value of >50% matched. The CI sizes for all subsets were favorable (<25%), although the CI value of zero for 2011 was an artifact of 0% matched sightings (n=1).

Among the remaining analysis subsets, there was an unfavorably large amount of interannual (7%–51%), seasonal (15%–32%), vessel type (15%–34%), and spatial (11%–34%) variation. This resulted in distinct (non-overlapping) CIs for 2015 and other years, Q1 and Q3, FV-T and FV-C, and cluster 2 compared to other clusters.

The subset with the maximum proportion of matched sightings was 2015 at 51%.

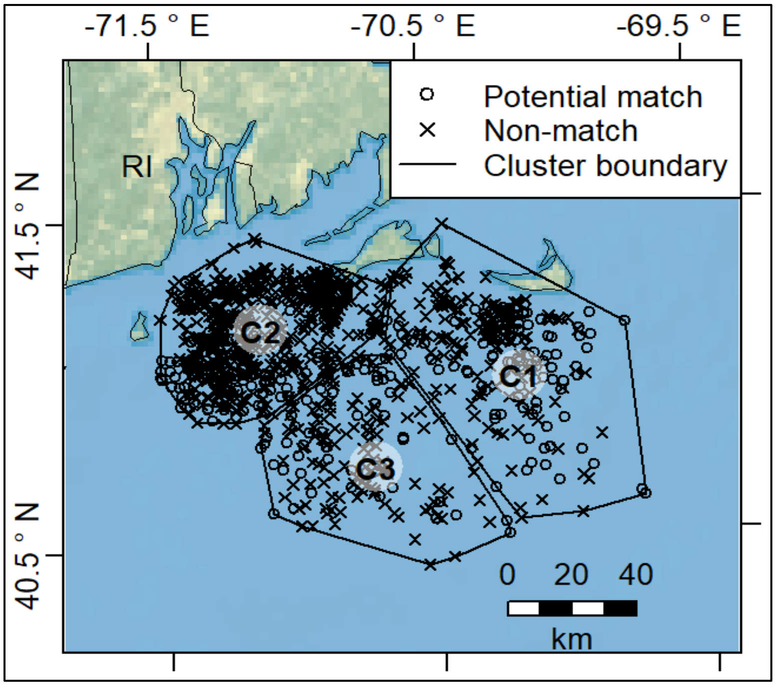

Figure 11. Potential matches of NEA sightings and VMS tracks.

C1–C3 = clusters

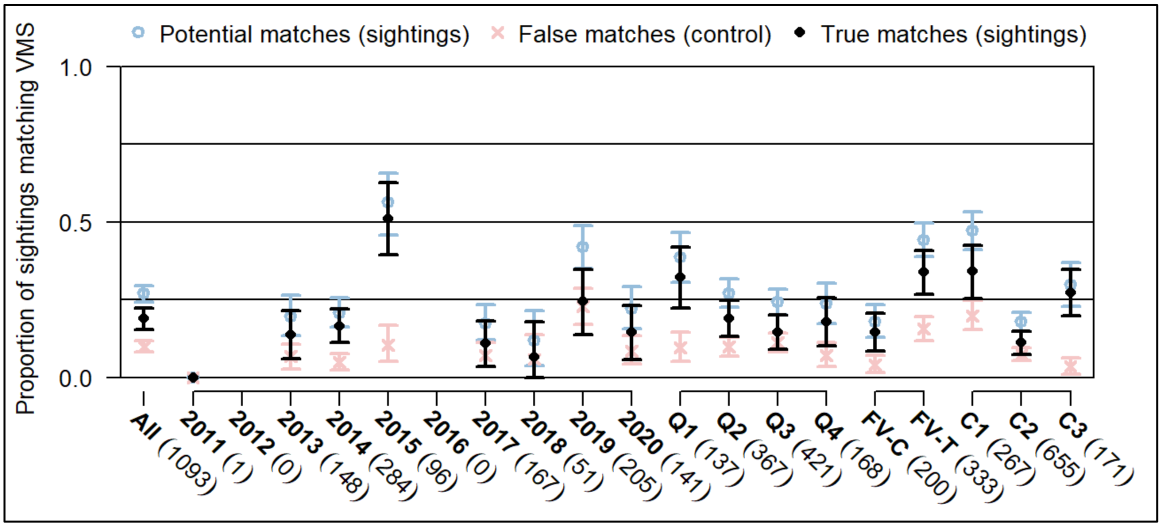

Figure 12. Proportion of sightings matching VMS (mean and 95% CI) for NEA data pooled by year, quarter, vessel type, and spatial cluster (with sample sizes).

NYSERDA Fishing Vessel Sightings Matched to VMS

Overall, only 54% of the NYSERDA vessel sightings were considered true matches with VMS tracks after accounting for the expected number of false matches (Figures 13 and 14). The CI for this estimate was 37%–69%. In contrast to the NNE and NEA datasets, the majority of analyzed NYSERDA data subsets had a favorable value of >50% matched. However, the CI sizes for all subsets except 2019 were unfavorable (>25%) due to small sample sizes, and the CI value of zero for 2019 was an artifact of 100% matched sightings (n=5).

There was an unfavorably large amount of vessel type (29%–87%) and spatial (11%–84%) variation among subsets, resulting in distinct (non-overlapping) CIs for FV-T and FV-C, and cluster 1 and cluster 3. Interannual (33%–100%) and seasonal (20%–69%) variation was substantial, but did not result in distinct CIs (excluding 2019).

The subset with the maximum proportion of matched sightings was FV-T at 87%.

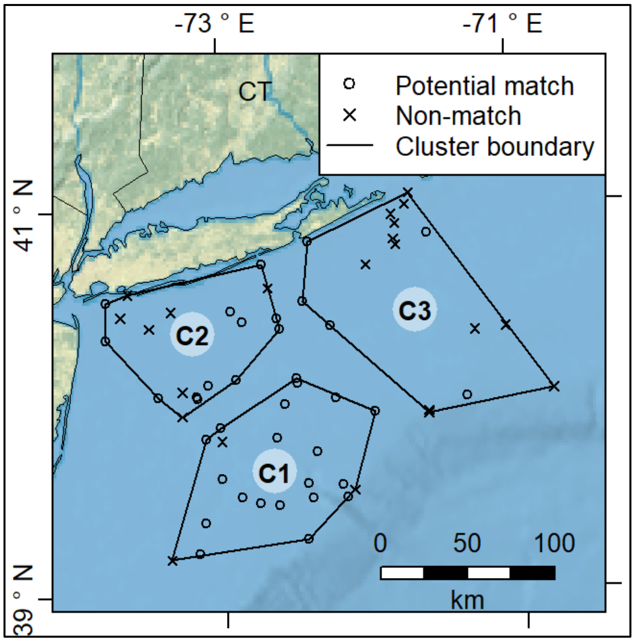

Figure 13. Potential matches of NYSERDA sightings and VMS tracks.

C1–C3 = clusters

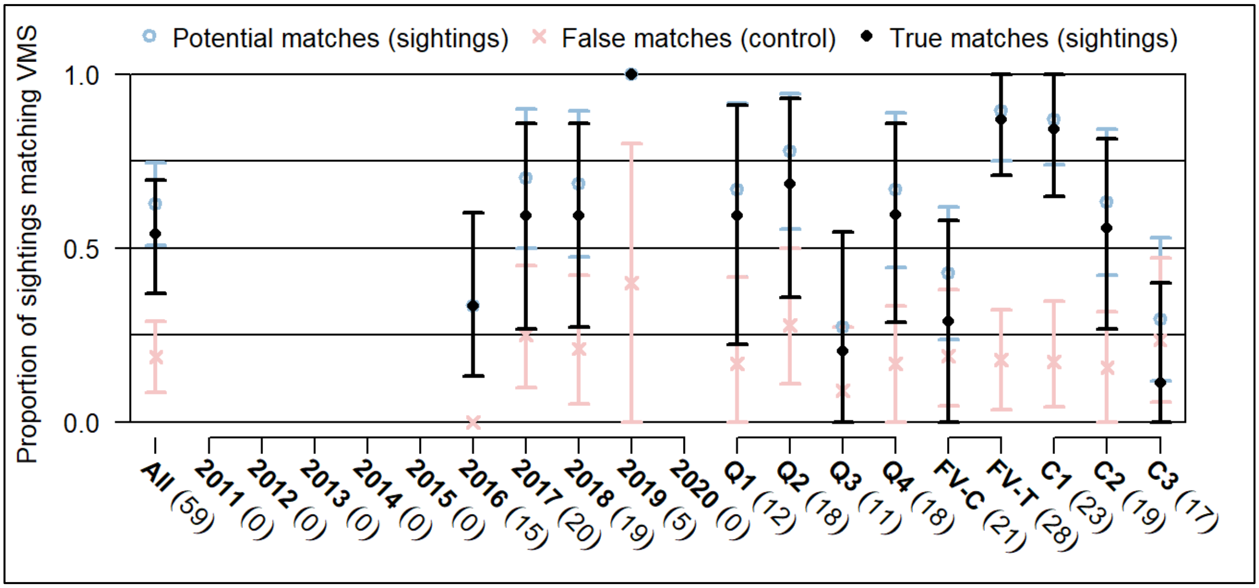

Figure 14. Proportion of sightings matching VMS (mean and 95% CI) for NYSERDA data pooled by year, quarter, vessel type, and spatial cluster (with sample sizes).

CCS Fishing Vessel Sightings Matched to VMS

Overall, only 6% (CI: ±1%) of the CCS vessel sightings were considered true matches with VMS tracks after accounting for the expected number of false matches (Figures 15 and 16). None of the analyzed subsets had a favorable value of >50% matched. For 2019, lower numbers of potential matches for CCS sightings than for CCS control resulted in an estimate of 0% true matches. The CI sizes were favorable (<25%) for all except the Q3 subset, which had the lowest sample size (n=43).

There was an unfavorably large amount of interannual (0%–13%), seasonal (2%–%35), vessel type (2%–8%), and spatial (4%–21%) variation among subsets. This resulted in distinct (non-overlapping) CIs for 2016/2019 (lower) or 2018/2020 (higher) and other years, Q2 and other seasons, FV-C and FV-T, and cluster 2 and other clusters.

The subset with the maximum proportion of matched sightings was Q3 at only 35%.

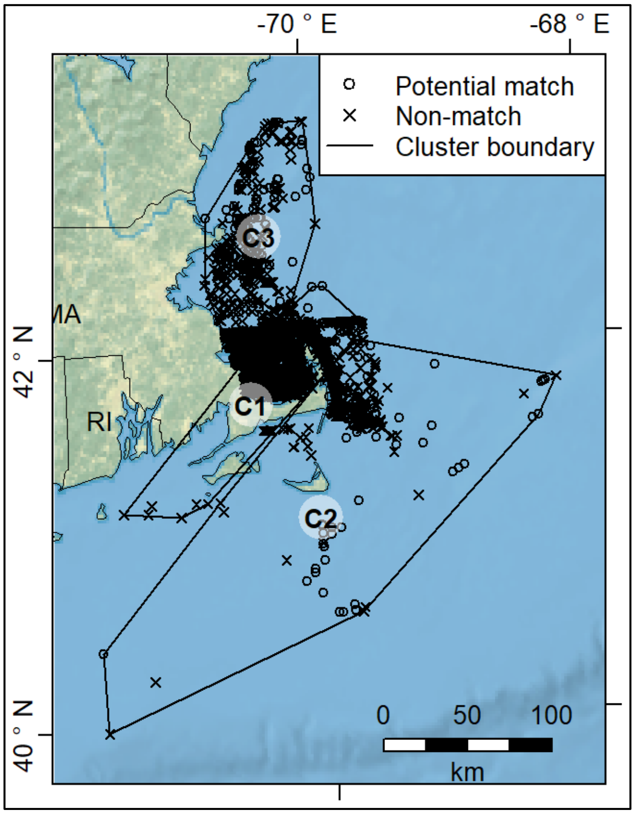

Figure 15. Potential matches of CCS sightings and VMS tracks.

C1–C3 = clusters

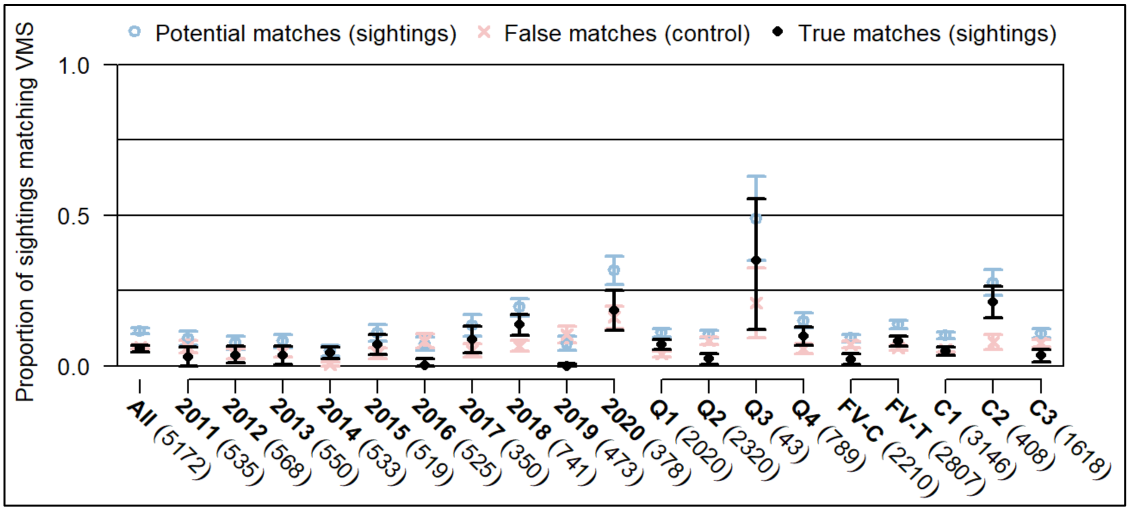

Figure 16. Proportion of sightings matching VMS (mean and 95% CI) for CCS data pooled by year, quarter, vessel type, and spatial cluster (with sample sizes).

EcoMon Fishing Vessel Sightings Matched to VMS

Overall, only 30% of the EcoMon vessel sightings were considered true matches with VMS tracks after accounting for the expected number of false matches (Figures 17 and 18). The CI for this estimate was 17%–42%. None of the analyzed subsets of EcoMon data had a favorable value of >50% matched. The CI sizes were unfavorable (>25%) for all subsets except 2013 and cluster 1. The CI value of zero for 2013 was an artifact of 0% matched sightings size (n=8).

Interannual (0%–33%), seasonal (25%–35%), and spatial (8%–47%) variation was substantial but did not result in distinct CIs (excluding 2013).

The subset with the maximum proportion of matched sightings was cluster 2 at only 47%.

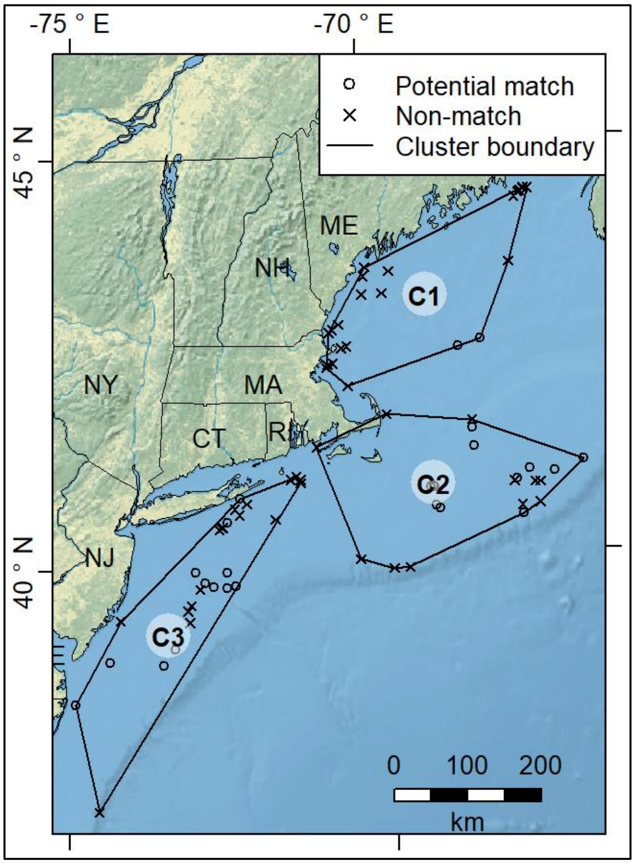

Figure 17. Potential matches of EcoMon sightings and VMS tracks.

C1–C3 = clusters

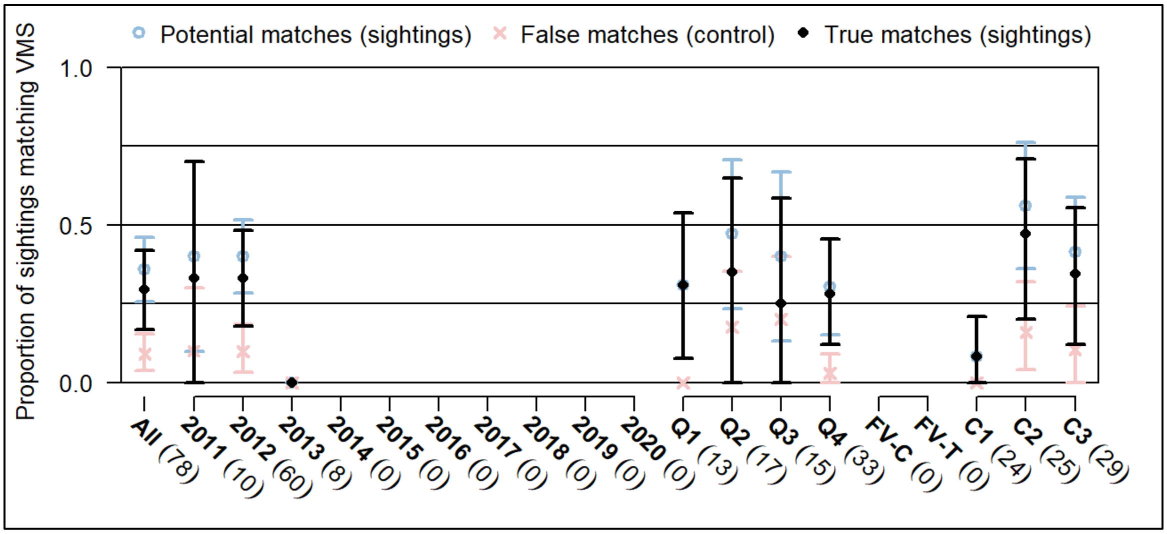

Figure 18. Proportion of sightings matching VMS (mean and 95% CI) for EcoMon data pooled by year, quarter, vessel type, and spatial cluster (with sample sizes).

Stellwagen Fishing Vessel Sightings Matched to VMS

Overall, only 17% of the Stellwagen vessel sightings were considered true matches with VMS tracks after accounting for the expected number of false matches (Figures 19 and 20). The CI for this estimate was 9%–26%. None of the analyzed subsets of Stellwagen data had a favorable value of >50% matched. The CI sizes were unfavorable (>25%) for some data subsets (2015, Q2, Q3, and spatial clusters 1 and 3), and otherwise favorable. However, CI values of zero were artifacts of 0% matched sightings for 2012 (n=3) and Q1 (n=9).

Even without considering 2012, there was an unfavorably large amount of interannual (5%–41%) variation, resulting in distinct (non-overlapping) CIs for 2014 and 2015. Seasonal (0–29%) and spatial (14%–22%) variation was substantial but did not result in distinct CIs (excluding Q1).

The subset with the maximum proportion of matched sightings was 2015 at only 41%.

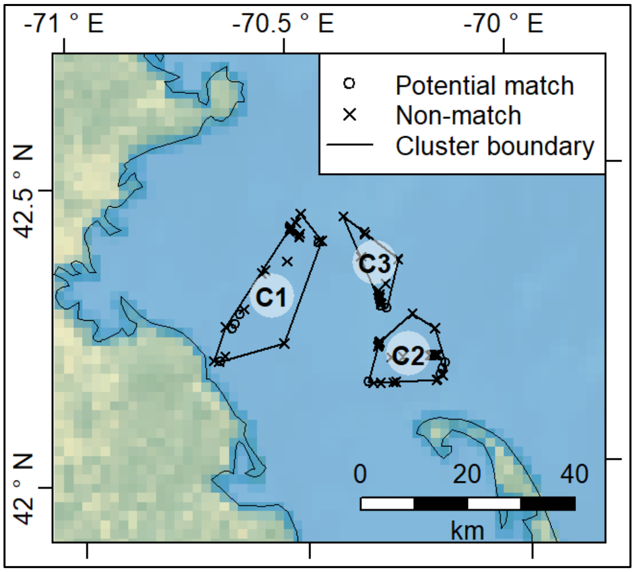

Figure 19. Potential matches of Stellwagen sightings and VMS tracks.

C1–C3 = clusters

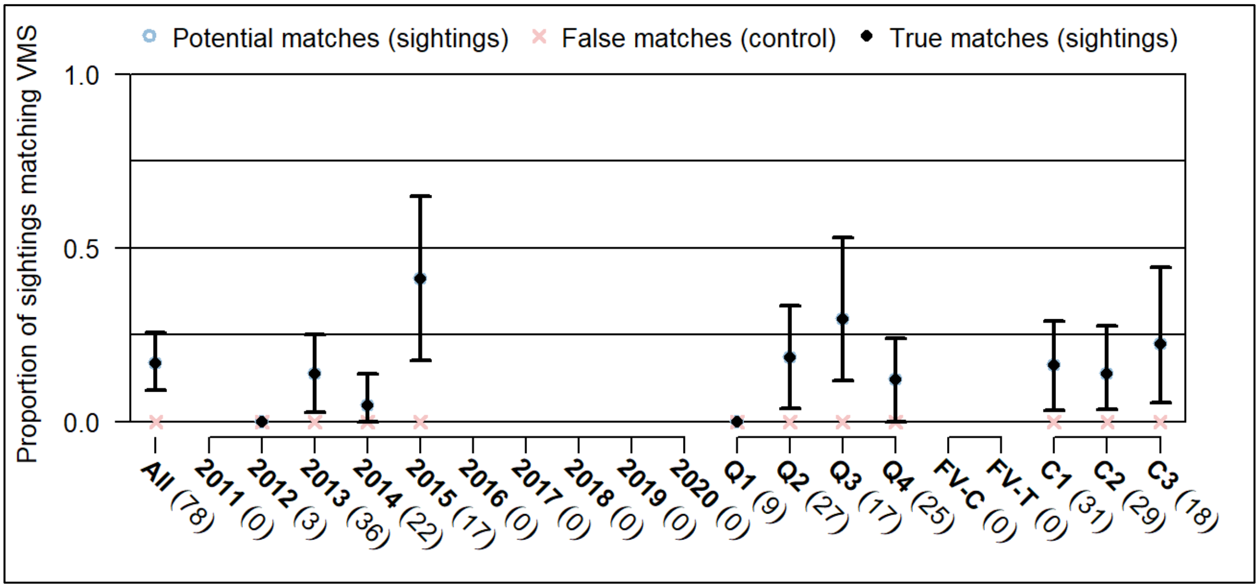

Figure 20. Proportion of sightings matching VMS (mean and 95% CI) for Stellwagen data pooled by year, quarter, vessel type, and spatial cluster (with sample sizes).

Herring Survey Fishing Vessel Sightings Matched to VMS

Overall, only 13% (CI: ±5%) of the herring survey fishing vessel sightings were considered true matches with VMS tracks after accounting for the expected number of false matches (Figures 21 and 22). None of the analyzed subsets of herring data had a favorable value of >50% matched.

The CI sizes were unfavorable (>25%) for all subsets except 2012, Q4, and cluster 1. The CI of zero for cluster 1 was an artifact of 0% matched sightings (n=20). Interannual (5%–27%), seasonal (8%–17%), and spatial (0%–44%, including 2012) variation was substantial but did not result in distinct CIs.

The subset with the maximum proportion of matched sightings was 2011 at only 27%.

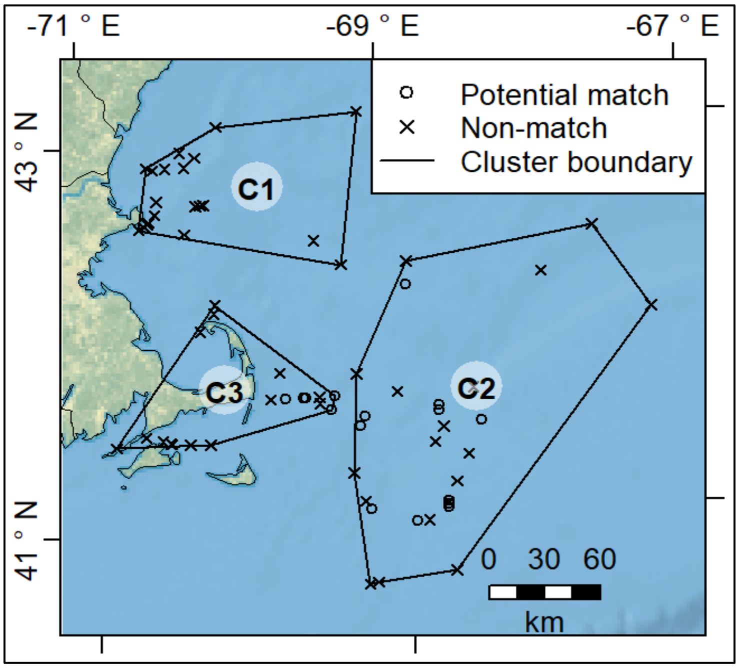

Figure 21. Potential matches of Herring sightings and VMS tracks.

C1–C3 = clusters

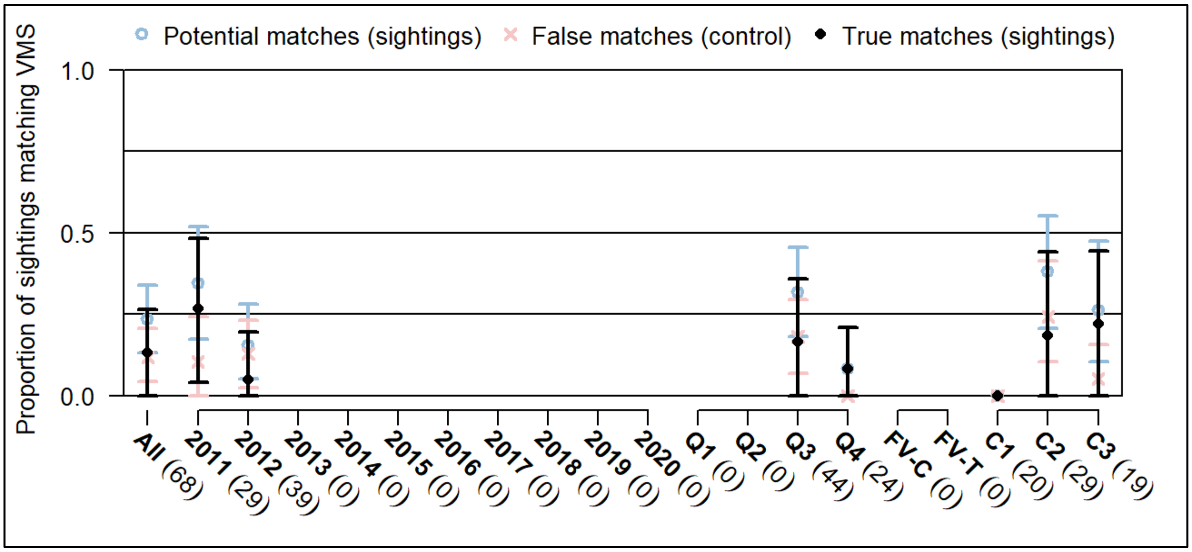

Figure 22. Proportion of sightings matching VMS (mean and 95% CI) for Herring data pooled by year, quarter, vessel type, and spatial cluster (with sample sizes).

3.1.3 Proportion of Vessels Matched by Dataset in the Southeast Region

Two large datasets were from the Southeast region: EWS-North (from North Carolina to northern Florida) and EWS-South (from Georgia to southern Florida) (Tables 2 and 3; Figure 23).

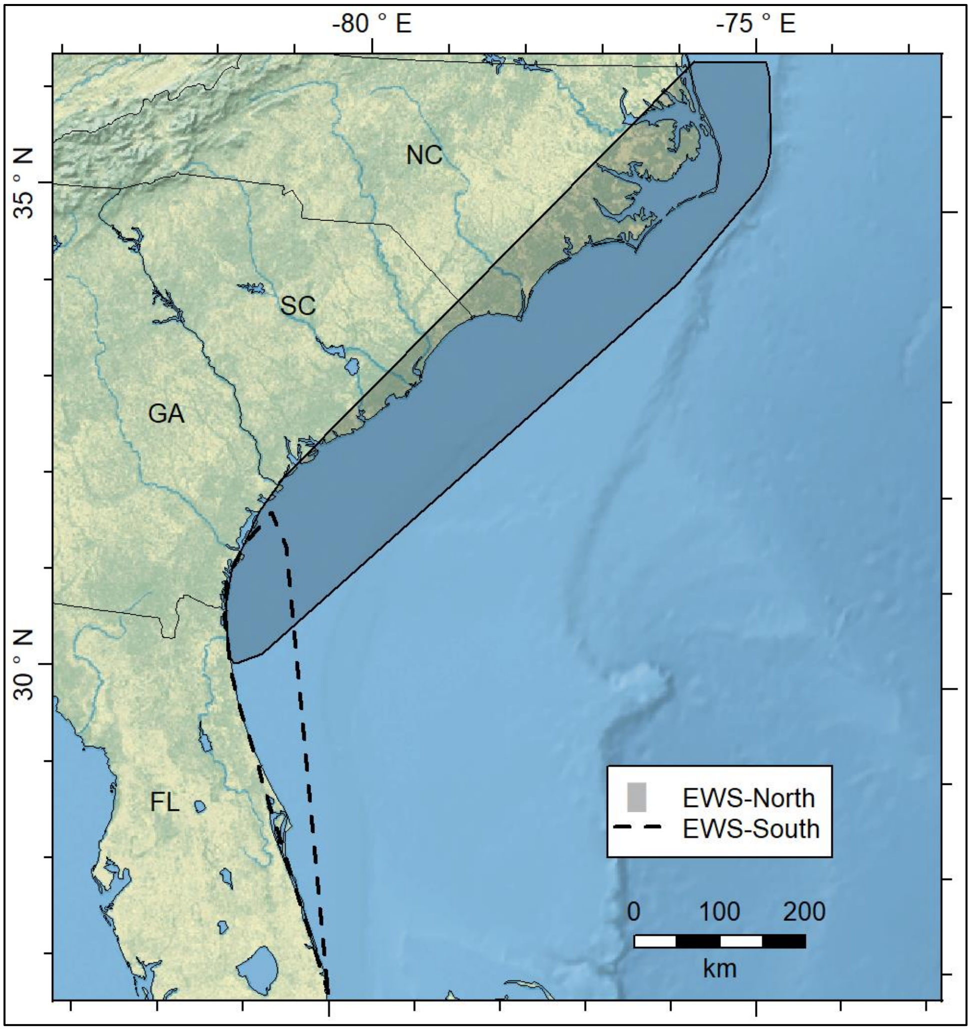

Figure 23. Spatial extent and overlap of wildlife survey data in the Southeast region.

In these surveys, the identified fishing vessel types consisted of 91%–93% shrimpers, 3%–5% crab/lobster vessels, and 4% head boats. All Southeast surveys and survey data subsets (year, quarter, vessel type, or spatial cluster) had low proportions of corrected matches with VMS. The highest estimated mean for any subset was 6%. Consequently, further details on spatiotemporal patterns with VMS are only summarized in abbreviated form in Appendix B. Comparisons of EWS-North and EWS-South with AIS are presented by dataset below.

EWS-North Fishing Vessel Sightings Matched to AIS

Overall, only 10% (CI: 8%–13%) of the EWS-North vessel sightings were considered true matches with AIS tracks after accounting for the expected number of false matches (Figures 24 and 25). None of the analyzed subsets of EWS-North data had a favorable value of >50% matched. The CI sizes for all subsets were favorable (<25%).

There was an unfavorably large amount of seasonal variation (3%–13%), resulting in distinct (non-overlapping) CIs for Q1 and Q2. Interannual (5%–11%), vessel type (16%–12%), and spatial (6%–11%) variation was small and did not result in distinct CIs.

The subset with the maximum proportion of matched sightings was Q1 at only 13%.

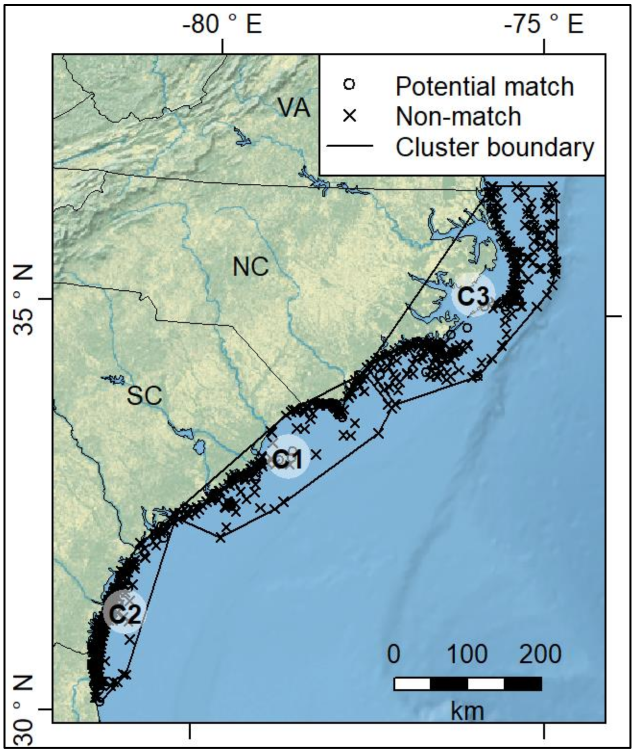

Figure 24. Potential matches of EWS-North sightings and AIS tracks.

C1–C3 = clusters

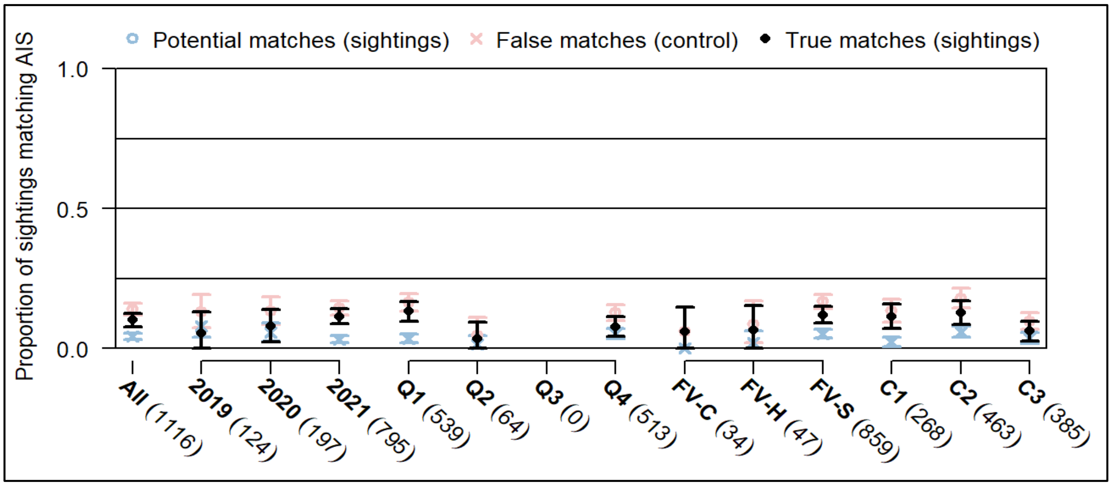

Figure 25. Proportion of sightings matching AIS (mean and 95% CI) for EWS-North data pooled by year, quarter, vessel type, and spatial cluster (with sample sizes).

EWS-South Fishing Vessel Sightings Matched to AIS

Overall, only 7% (CI: 4%–9%) of the EWS- South vessel sightings were considered true matches with AIS tracks after accounting for the expected number of false matches (Figures 26 and 27). None of the analyzed subsets of EWS-South data had a favorable value of >50% matched. For 2021 and Q4, lower numbers of potential matches for CCS sightings than for CCS control resulted in an estimate of 0% true matches. The CI sizes for all subsets were favorable (<25%).

There was an unfavorably large amount of interannual (0%–11%), seasonal (0%–11%), and vessel type (0%–7%) variation among subsets. This resulted in distinct (non-overlapping) CIs for 2019/2020 and 2021, Q1 and Q4, and FV-H and FV-S. Spatial variation (6%–9%) was small and did not result in distinct CIs.

The subset with the maximum proportion of matched sightings was Q1 at only 11%.

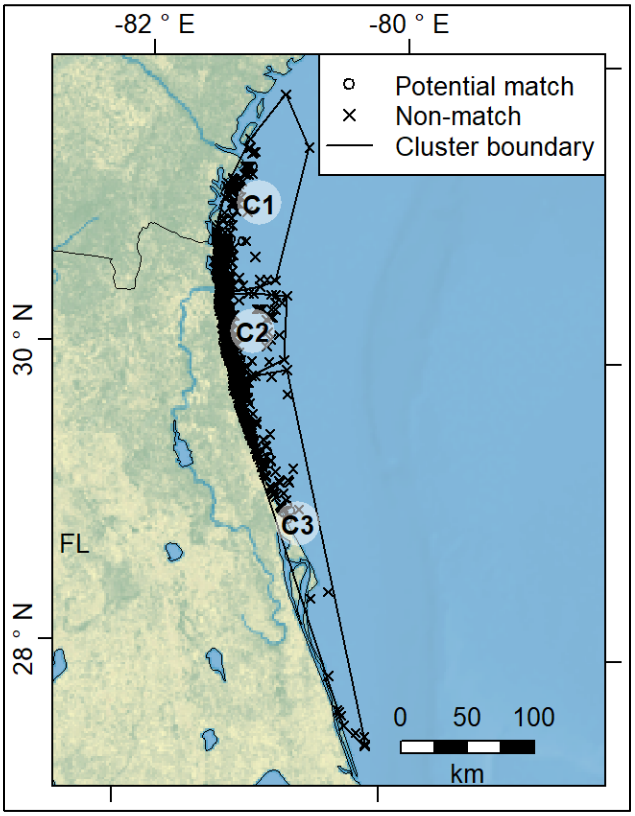

Figure 26. Potential matches of EWS-South sightings and AIS tracks.

C1–C3 = clusters

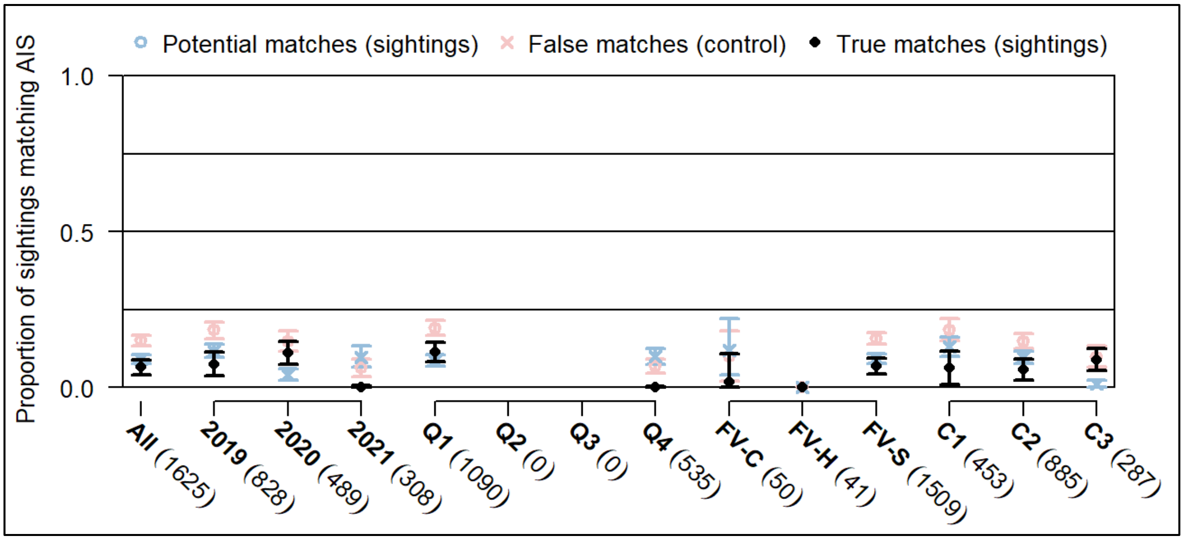

Figure 27. Proportion of sightings matching AIS (mean and 95%) for EWS-South data pooled by year, quarter, vessel type, and spatial cluster (with sample sizes).

4. Discussion

4.1 Suitability of a Correction Factor

This study sought to determine if vessel sightings from wildlife surveys could be matched to fishing vessel tracking data to correct or improve estimates of vessel activity derived from tracking data alone. The criteria used to evaluate suitability of the potential correction factor were high matched proportion (i.e., only a minority of vessels needs to be inferred rather than observed), low uncertainty (i.e., narrow CIs in estimates), and low spatiotemporal variability (i.e., consistency in estimates among years, seasons, and subregions). Unfortunately, overall results indicate that no subsets of survey data were identified where all three evaluation criteria were favorable for the use of the matched proportion metric as a correction factor for either AIS- or VMS-based fishing activity estimates. Few sightings could be matched to AIS or VMS tracks for a majority of datasets; the ones that could had large uncertainty, and there was a large amount of inconsistency among years, seasons, and subregions of the analysis. Consequently, use of the matched proportion of vessel sightings from wildlife surveys as a correction factor is not recommended for any survey datasets or subsets.

Overall, there was strong evidence that only a small proportion of fishing vessel sightings was consistent with vessel tracking data. This result alone indicated that use of the correction factor was not advisable. With few exceptions, mean estimates of matched proportion were consistently <50% and therefore unfavorable for use in improving estimates of vessel activity. In fact, the matched proportions in the Northeast region with AIS tracks, and in the Southeast region with VMS, were so low that the analyzed combinations of datasets appeared to be fundamentally incompatible and could be matched for only 6% or less of vessels. Only NYSERDA sightings compared to VMS had an overall match rate over 50% (and a few years, seasons, and clusters also had suitable match rates). This finding was not simply due to the fact that the positional uncertainty of the NYSERDA data (approximately 10 m) was smaller than for any of the other datasets. While moderate or better precision (≤2.5 km) was required to detect high proportions of matches, additional precision did not seem to have a large effect. Instead, the results suggested that moderate precision was generally sufficient to identify potential matches and that non-matches occurred due to sighted vessels that were not tracked by AIS or VMS. For example, there was no indication that datasets of moderate precision, such as NNE and NEA, had substantial numbers of sightings that could have been shifted from non-matches to matches, given increased precision. In fact, sightings with nearest VMS vessels slightly above the 5-km match threshold were similarly rare for NYSERDA, NNE, and NEA (3% of sightings for 5.0–7.5 km; Figure 6). Consequently, the proportion of sighted vessels tracked by VMS really appears to be higher in the NYSERDA survey area than in the nearby NNE and NEA areas, with the caveat that uncertainty for NYSERDA was quite large (Figure 14).

Uncertainty in mean estimates, measured as the size of the 95% CI, was generally favorable only in cases with sample sizes of vessel sightings >50 and in some cases with very low matched proportions. For example, even though NYSERDA had acceptably high mean estimates, it had low sample sizes in all subsets of data that were considered (n=5–28), and nearly all of them had unacceptably large ranges in CIs. Use of a correction factor with large uncertainty is inadvisable. In fact, there was only one subset of data with both a favorably large mean and favorably small uncertainty. This was for VMS matches with 2015 NEA sightings.

The case of VMS matches with 2015 NEA sightings illustrates the importance of the third criterion, spatiotemporal variability. For unknown reasons, the 51% ± 12% CI for 2015 NEA/VMS was notably higher than mean estimates for other years and for the overall 2011–2020 period (19% ± 3%). This is highly problematic, because a VMS-based estimate of 2011–2020 fishing activity corrected using the 2015 matched proportion could still be substantially too low (19% / 51% is approximately 37% of the correct value), whereas a VMS-based estimate of 2015 fishing activity, adjusted using the 2011–2020 matched proportion, could be much too high (51% / 19% is approximately 268% of the correct value). In this case, the third evaluation criterion was not met because the CI for 2015 was distinctly different from one or more other years (non-overlapping). Indeed, across all surveys, low uncertainty for a particular year, quarter, or spatial cluster was often associated with the same cluster being distinct from other years, quarters, or clusters. Consequently, interannual, seasonal, and spatial variability were each problematic in three to four of the five large surveys (n>1,000), with respect to VMS matches in the Northeast and AIS matches in the Southeast.

An additional concern regarding the use of wildlife survey data to improve fishing activity estimates was that spatiotemporal patterns were often inconsistent across datasets. For example, even though the NNE and NEA surveys overlapped in time and space, NNE had the fewest VMS matches in 2015, whereas NEA had the most VMS matches in 2015. Similarly, the NNE spatial cluster with the fewest VMS matches was the one farthest to the south, while the EcoMon cluster with the fewest VMS matches was the one farthest to the north. Such inconsistencies suggest that there are very different and unknown biases affecting values among the datasets. A correction factor even for the same location and year might need to be very different depending on the dataset it is based upon.

One consistent pattern was a higher proportion of VMS matches with FV-T sightings than with FV-C sightings in all wildlife surveys with vessel type information (NNE, NEA, NYSERDA, and CCS). This should not come as a surprise, since FV-T vessels are generally associated with fisheries that were subject to mandatory VMS monitoring, whereas the crab and lobster fishing vessels were not (OLE 2022, 50 C.F.R. § 648.10). Nevertheless, the estimated proportion (or uncertainty) of matched FV-T sightings was still unfavorable for all four surveys.

4.2 Influences on Matches

In order for a true match to be inferred, several conditions needed to be met. First, the sighted vessel had to be outfitted with vessel tracking equipment. Since AIS transceivers were not mandatory for vessels <65 ft (80 Fed. Reg. 5282 [March 2, 2015]), and VMS transceivers were only mandatory for specific categories of fishing permits (OLE 2022), a substantial fraction of sighted fishing vessels may have been exempt from AIS/VMS tracking. Most importantly, neither the Southeast region lobster/crab and shrimp fisheries (with the exception of South Atlantic rock shrimp) nor open-charter head boats required VMS (OLE 2022), which is consistent with the almost complete lack of VMS matches in this region. In contrast, approximately 65% of 2011–2020 commercial fishing vessels in the Northeast had permits for fisheries that required VMS (NOAA Greater Atlantic Regional Fisheries Office 2024). Only about 15% of 2019–2021 commercial fishing vessels in the Northeast were ≥65 ft in length (NOAA Greater Atlantic Regional Fisheries Office 2024), although for FV-T, the percentage was likely much higher (Orphanides and Magnusson 2007). In any case, many commercial vessels operating on the continental shelf are <65 ft in length, partially explaining the low proportion of matches with AIS. That a large proportion of vessels were not required to use AIS and/or VMS made it unlikely that the first criterion of linking half the sightings to wildlife surveys was achievable from the outset, except perhaps for VMS in the Northeast. Second, AIS/VMS transceivers needed to be operating as intended for a true match to be identified. Anecdotally, fishing vessels sometimes obscure their true position, for example, by running AIS transceivers in low-power mode (Shepperson et al. 2018) or otherwise tampering with monitoring equipment (King et al. 2009). Further, the requirement for using AIS extends only to 12 nautical miles from shore (80 Fed. Reg. 5282 [March 2, 2015]), but 27% of sightings in the Northeast sightings (and 1% in the Southeast) were located beyond this limit. Third, and problematic for AIS only, the transmitted messages needed to be received and archived by either a terrestrial base station or satellite. Among the available AIS tracks, gaps of sufficient duration to dramatically affect matching were rare. However, some matches may have been missed due to such gaps, especially beyond 100 km offshore. Fourth, the estimated synchronous locations of the sighting and the AIS/VMS track needed to be <5 km from each other despite the positional imprecision of those estimated locations. For some survey datasets, this appeared to be the exception rather than the rule. Fifth, the sighting location needed to be >5 km from the nearest tracked vessels at the control time (same time of day, either 1 week before or after the sighting). Otherwise, the false match to the control data point would essentially cancel out the potential match with the sighting. Additional issues that could not be ruled out include the mistaken identification of other vessels as commercial fishing vessels, and data errors such as timestamps with incorrect formatting.

While the lack of VMS matches in the Southeast region is easily explained by most FV-C, FV-S, and FV-H vessels being exempt from VMS tracking, it was less clear what caused the lack of AIS matches in the Northeast, especially for FV-T. Even if only 15% of overall Northeast fishing vessels were ≥65 ft in length (NOAA Greater Atlantic Regional Fisheries Office 2024), a higher percentage of FV-T vessels was expected to have this size. Approximately one-third of bottom trawl vessels and two-thirds of mid-water trawl vessels in the Northeast were ≥65 ft in length as recently as 2004 (Orphanides and Magnusson 2007), 12 years before AIS became required equipment on vessels of that size. Such vessels should have been outfitted with AIS and yielded higher FV-T match rates if their AIS messages were consistently archived. The extremely low proportions of matches could be explained by a combination of messages not being received due to the technical limitations of AIS and messages not being broadcast in the first place.

4.3 Precision of Vessel Location Estimates

The precision of vessel sighting position estimates varied among surveys, and the precision of interpolated positions along tracks varied between AIS and VMS tracking systems. The threshold for potential matches was defined as 5 km to accommodate the expected combined positional errors from interpolated VMS coordinates (approximately 2.5 km) and moderately precise survey sightings (approximately 2.5 km), while minimizing false matches with control datasets. The conspicuous peaks in NNE, NEA, and NYSERDA sightings with VMS vessels at <2.5-km distance (i.e., dropping to control levels somewhere between 2.5 and 5 km) were consistent with this expectation. While these peaks collectively represented a minority of sightings, their presence provides strong evidence for 5 km being an appropriate threshold value with which to identify some true matches in moderate (or higher) precision datasets. Among the datasets for which precision was not known a priori, only Stellwagen had a peak at <2.5 km, suggesting a similar level of precision, and only EcoMon had a peak at 2.5–5 km, suggesting a slightly lower level of precision still compatible with the 5-km threshold.

For other datasets, the lack of conspicuous peaks at 0–5 km suggests that spatial precision may not have been compatible with the 5-km threshold. Moreover, the lack of peaks anywhere <30 km suggests that some datasets were simply not suitable for identifying true matches, irrespective of the chosen distance threshold. Note that there must always be a nearest AIS/VMS tracked fishing vessel to any location no matter the distance, whether or not that location matches a vessel sighting. Consequently, any increase in threshold must add to false matches as well as potential matches. With it being essentially impossible to determine true matches with certainty, using the difference between sightings and control sightings was an attempt to provide unbiased evidence for true matches (i.e., the proportion of identical vessels at the sample level).

Lack of precision in sighting locations should not be interpreted as reflecting negatively on the survey programs themselves. Observations of fishing vessels were not a primary objective in any of the considered wildlife surveys. In fact, the trade-off between collecting data on vessel observations and focusing on priority objectives resulted in the NNE survey dropping vessel observations from their survey protocol altogether after 2016.

4.4 Additional Sources of Unquantifiable Bias

It is also important to recognize additional sources of bias or characteristics of the data that limited the scope of the analysis. Most notably, wildlife surveys were conducted only during daylight hours, and therefore the temporal scope was not relevant for approximately half of each day, when boats can go elsewhere. It is also possible that weather conditions may affect wildlife surveys and fishing vessel operations differently, and this could vary from survey to survey and from fishery to fishery. Wildlife surveys may not go out and/or fishing vessels may use different grounds during hazardous seas. Even the timing of market fluctuations in the price of seafood or other factors may provide a greater incentive for noncompliance or risk at different times during the study, independent of the year or seasonal divisions that we examined, resulting in temporal bias in AIS/VMS compliance or choice of fishing grounds. Finally, the use of sighting locations at exactly 7 days before or after actual sightings as the control for false matches may have resulted in overestimation or underestimation of true matches. For example, weather conditions during sightings were definitely suitable for wildlife survey and fishing vessel activity, but conditions may have been worse 1 week earlier or later. Note that adjusting for expected false matches did not majorly affect the results (Tables 2 and 3).

4.5. Recommendations for Future Surveys

While the analysis did not yield robust correction factors for fishing activity estimates, based on the results, there are some recommendations for collecting and analyzing vessel observations from wildlife surveys in the future. With respect to matching vessel tracking data, it was important for sightings to have moderate spatial precision (≤2.5 km uncertainty). For example, declination angles used to achieve moderate precision for the NNE survey were obtained directly from NOAA and then merged with the NARWC database version of NNE data for the benefits of standardized formatting and additional quality control performed by NARWC. Without the additional declination angle data, matches with NNE would have been underestimated as even much less common. Other visual aerial surveys besides NNE and NEA likely also recorded additional data that could be used to refine sighting position estimates, and future surveys should do so to facilitate this type of analysis. Regarding the trade-off between higher numbers vs. higher precision of sightings, larger sample sizes of moderate precision sightings (NNE and NEA) were more informative than smaller sample sizes of higher precision sightings (NYSERDA). This indicates that for the benefit of related studies, future surveys of at least moderate precision should prioritize increasing effort over increasing precision. However, surveys using digital imagery have benefits besides high precision that could be leveraged by alternative analysis approaches. For example, images could be used to validate fishing vessels, determine which ones are of a size required to use AIS, and perhaps identify vessels subject to VMS monitoring from the presence of certain types of gear or catch. This additional information could potentially support better statistical inferences about the distributions of vessels without AIS/VMS tracks based on the distributions of those with such tracks. However, spatial and temporal patterns in the distributions of vessels with and without AIS/VMS tracks may or may not be closely related.

Standardizing and documenting survey effort pertaining to fishing vessels should also be a priority. For most of the analyzed datasets, it was unclear whether observers had consistently recorded vessel observations. While the matching analysis presented here did not assume or depend on consistent effort, other analysis approaches may have been feasible, potentially resulting in less uncertainty, if this assumption were reasonable. While lack of consistent effort among the available wildlife survey data made it difficult to meaningfully augment or fill in gaps in the AIS/VMS data, more could be learned from future opportunistic vessel observation data, given better assurance that boats are consistently recorded by all observers. For example, vessel sightability could be estimated per unit of survey effort. Then, the number and sequence of sightings along a survey transect with known effort could be directly compared to expectations based on vessel tracking data. Since this approach could take into account both sightings without matching tracks, and tracks without matching sightings, it may result in reduced bias and uncertainty of match rate estimates. Despite these potential improvements, it seems likely that low AIS/VMS coverage and high spatiotemporal variability would still be problematic, if the presented match rate estimates are correct.

4.6. Conclusion

This study underscores that fishing vessel distributions cannot be inferred by AIS/VMS data alone. Gaps in coverage are expected for various reasons, most importantly, the lack of VMS monitoring requirements for some fisheries, and the lack of AIS requirements for vessels <65 ft in length. The analysis of independent sightings of fishing vessels from wildlife surveys suggested that both AIS and VMS records included variable but generally small fractions of those vessels. To the extent that wildlife survey data are representative of overall fishing vessel distribution, AIS/VMS coverage appears to be quite low. Unfortunately, the available data were not sufficient to fully address spatiotemporal patterns in coverage. Larger sample sizes, consistent identification of fishing vessel types, and more precise vessel location estimates would improve the ability to estimate AIS/VMS coverage from wildlife survey data.

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Appendix A: Results by Northeast Dataset for AIS

NEA Fishing Vessel Sightings Matched to AIS

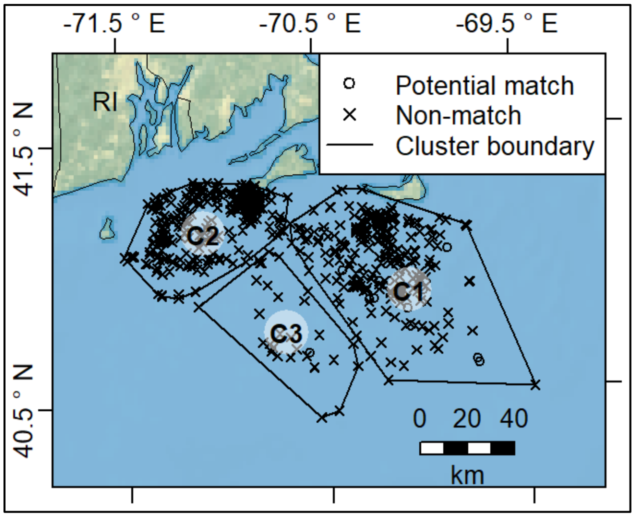

Figure A1. Potential matches of NEA sightings and AIS tracks

C1–C3 = clusters

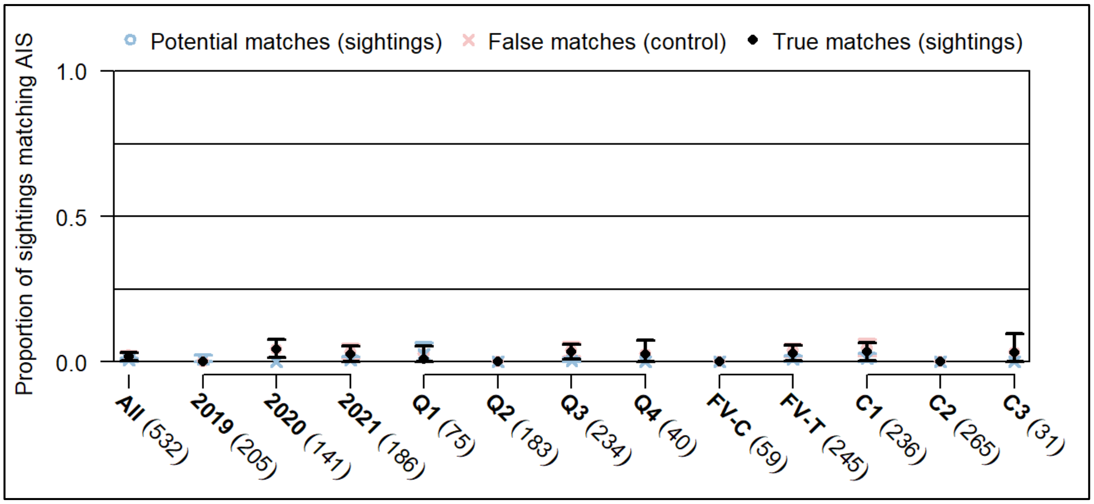

Figure A2. Proportion of sightings matching AIS (mean and 95% CI) for NEA data pooled by year, quarter, vessel type, and spatial cluster (with sample sizes).

CCS Fishing Vessel Sightings Matched to AIS

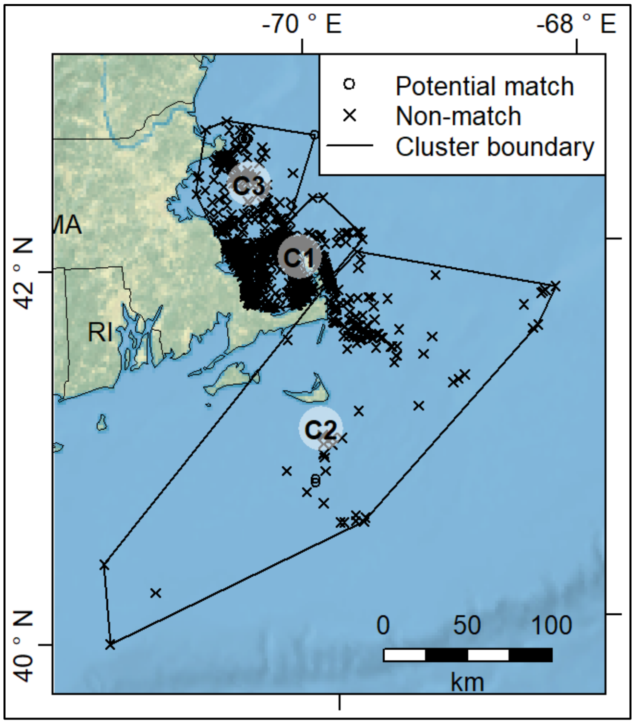

Figure A3. Potential matches of CCS sightings and AIS tracks.

C1–C3 = clusters

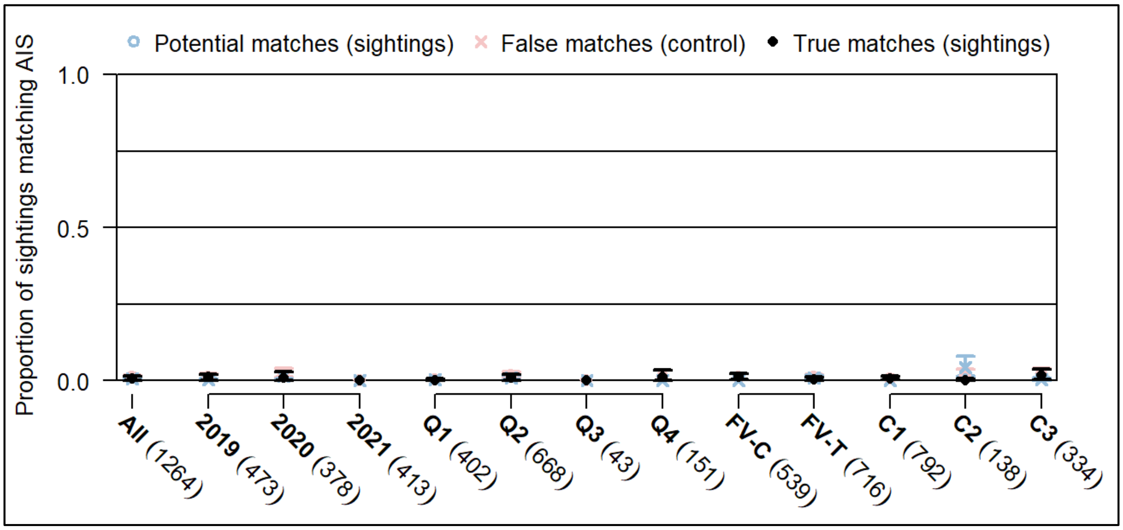

Figure A4. Proportion of sightings matching AIS (mean and 95% CI) for CCS data pooled by year, quarter, vessel type, and spatial cluster (with sample sizes).

Appendix B: Results by Southeast Datasets for VMS

EWS-North Fishing Vessel Sightings Matched to VMS

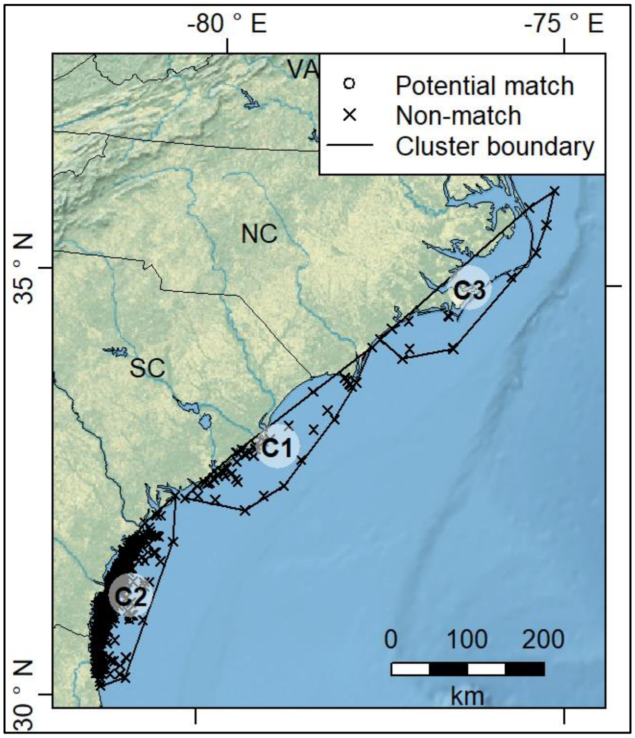

Figure B1. Potential matches of EWS-North sightings and VMS tracks.

C1–C3 = clusters

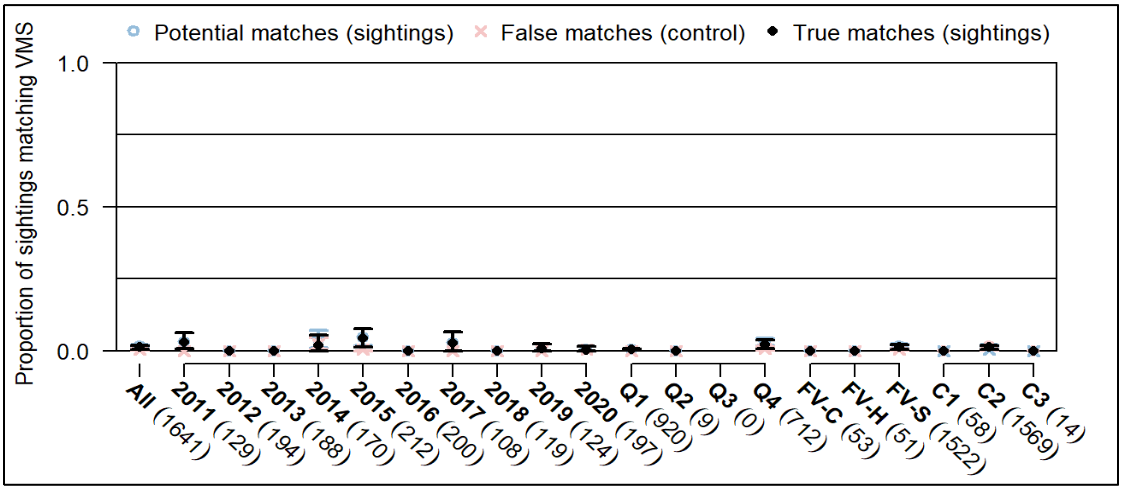

Figure B2. Proportion of sightings matching VMS (mean and 95% CI) for EWS-North data pooled by year, quarter, vessel type, and spatial cluster (with sample sizes).

EWS-South Fishing Vessel Sightings Matched to VMS

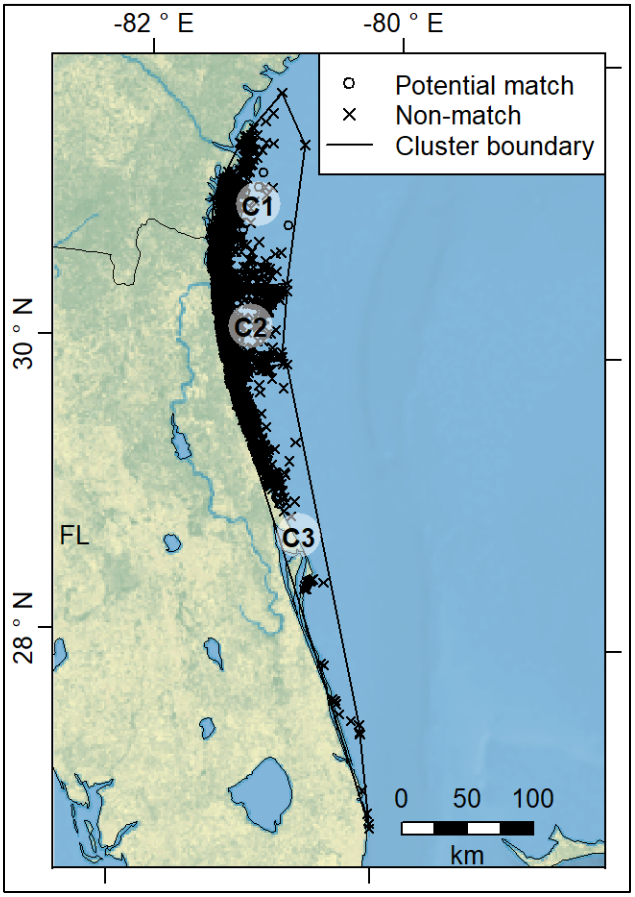

Figure B3. Potential matches of EWS-South sightings and VMS tracks.

C1–C3 = clusters

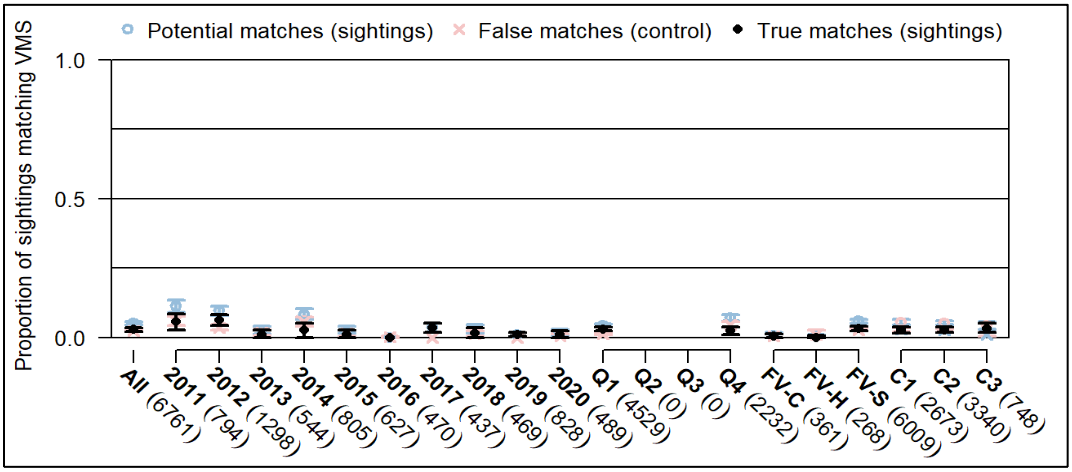

Figure B4. Proportion of sightings matching VMS (mean and 95% CI) for EWS-South data pooled by year, quarter, vessel type, and spatial cluster (with sample sizes).

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