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MITRE TECHNICAL REPORT

Evaluation of On-Demand Gear Acoustic Interoperability Approaches in the Northeast U.S.

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Executive Summary

The National Oceanic and Atmospheric Administration's (NOAA) National Marine Fisheries Service (NMFS) is mandated by the Marine Mammal Protection Act (MMPA) to reduce the mortality and serious injury of North Atlantic Right Whales (NARW) caused by commercial fishing to below its Potential Biological Removal (PBR) level. To achieve this, U.S. commercial fisheries need to continue to decrease entanglement risk. In areas of high co-occurrence between whales and surface marking systems, seasonal closure areas have been implemented to enforce separation of whales and fishing gear. More recently, closures in the Greater Atlantic Region (Northwest Atlantic from Virginia to Maine) have been modified to be closures to the use of surface marking systems rather than closures to the harvest of lobster, crabs, and other species targeted with fixed fishing gear traditionally marked and retrieved by buoy lines. On-demand fishing, which uses acoustic signaling to communicate with fishing vessels instead of surface marking systems, offers a way to allow fishers to continue to fish without endangering large whales. The Consolidated Appropriations Act of 2023 tasked NOAA with promoting innovative gear research and development to advance state-of-the art technology available to the fishing industry. Currently, there are over a dozen manufacturers who serve this market, each using proprietary acoustic signaling techniques to facilitate communication and retrieval operations with subsurface gear from a surface vessel. To enable large-scale adoption and use of on-demand gear in areas closed to surface marking systems, interoperability between manufacturers must be established. Interoperability is a means for gear of different manufacturers to work together. Without interoperability, enabling large-scale adoption, regulation and enforcement of on-demand fishing in high vessel density and high gear conflict areas is intractable. To date, three different interoperability architectures have been proposed:

A. Proprietary active acoustics, which accomplishes interoperability using a universal cloud database and a universal enforcement deck box

B. An open-source, universal acoustic standard, which requires all manufacturers to adhere to a unified[1] acoustic solution coupled with a universal cloud database

C. An acoustics-only solution, which requires a universal acoustic solution but no cloud database or universal deck box[2]

This work seeks to evaluate the feasibility of these different architectures and recommend a path forward for achieving on-demand interoperability in the Greater Atlantic Region.

The key components of interoperability are gear location marking, gear deployment, and acoustic communication with subsurface devices to facilitate gear retrieval, either by fishers or enforcement. For on-demand gear to replace fixed vertical line fishing at scale, an on-demand interoperability architecture must address multiple factors:

- The gear must satisfy the requirements served by current surface buoys with markings compliant with the Code of Federal Rulemaking Title 50 regulations under the Magnuson-Stevens Fishery Conservation and Management Act or the Atlantic Coastal Fisheries Cooperative Management Act.
- The gear must not present a greater threat to marine life when deployed at scale than that posed by traditional gear.

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[1] In this context, "unified" means that all devices use the same acoustic waveform and communication protocols and work cooperatively, enabling things such as signal brokering and multi-vessel localization of subsurface gear.

[2] The term "universal deck box" denotes a piece of equipment used by enforcement, capable of interacting with on-demand gear from all vendors approved for use in areas closed to surface marking systems.

- Any economic consequences of a proposed interoperability framework must be justified.

The data-driven analysis performed in this work demonstrates that a proprietary active acoustics architecture, which allows manufacturers to retain unique acoustic signaling and achieves interoperability through a universal cloud database and a universal deck box, best meets all requirements for replacing surface buoys and presents the most justifiable path forward towards interoperability in the short term given the uncertainty on how on-demand fishing will scale in the future. More work remains to determine whether, when, and where global positioning system (GPS) marking may be sufficient for gear localization. In areas with a high risk of gear conflict, it is likely that acoustic localization is required, and results in this report suggest that localization through acoustic ranging performed by the gear deploying vessel is a sufficient solution. Geospatial analyses were conducted and showed that the risk of gear conflict is variable within current areas in the Greater Atlantic Region subject to closure and may benefit from acoustic localization to mitigate conflict. Finally, it is demonstrated that the proliferation of on-demand gear with proprietary active acoustics does not pose a threat of marine mammal harassment. Recommendations are made to set bounds on allowable frequency bands and source levels of on-demand gear operation to assist with marine law enforcement operations.

The following recommendations are made for future work:

- More research is needed in areas of low gear placement, low vessel density, low gear conflict, environments with different bathymetry, ocean bottom-types, and depth dependent sound speed profiled to comprehensively identify appropriate interoperability regimes as it applies to regions outside the scope of this report
- Experimentation to quantify the required localization accuracies, signal interference measures and cooperative on-demand fishing at-scale in multiple relevant environments
- Establishment of a universal cloud database, the means to access it in real-time, and the development of a data governance, management, and sustainment plan for it
- Continued development of a geospatial risk analysis to determine whether, where and when acoustic localization would be needed
- Completion of an acoustic modeling toolbox to compare the expected performance of various acoustic communication approaches
- Establishment of an allowable operating frequency range for on-demand gear that will enable development of a universal deck box using a single transducer and a software defined modem (SDM)
- Development of a comprehensive framework to operationalize on-demand fishing, including data standards, data transmission and visualization tools, and rules-based data management system to support near real-time information sharing

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1 Introduction

The North Atlantic right whale (NARW, *Eubalaena glacialis*) is a critically endangered species with approximately 370 individuals remaining [1]. Anthropogenic activities, notably entanglements in commercial fishing gear and vessel strikes, are major contributors to the species' high mortality rate. Vertical lines attached to retrieval buoys that mark bottom set-traps or nets (buoy lines) sit in the water column within whale habitat and pose a significant risk of entanglement [2]. In most years, fishing gear entanglements account for the majority of documented adult NARW mortalities and serious injuries, while the remaining observed adult mortalities and serious injuries are attributed to vessel strikes. The National Oceanic and Atmospheric Administration's (NOAA) National Marine Fisheries Service (NMFS) addresses vessel strike reduction through rulemaking conducted under the authority of the Endangered Species Act (ESA), a challenge not included within the scope of this report. Under the Marine Mammal Protection Act (MMPA), NMFS is required to reduce mortality and serious injury of NARW incidental to commercial fishing to below a stock's Potential Biological Removal (PBR) level. In the case of NARW, NMFS determined that U.S. fisheries needed to reduce the total coastwide entanglement risk by 89%-90% based on data available in 2022 [3]. Regulatory efforts to support recovery strategies on the NARW have included, but are not limited to, implementing seasonal closures to fixed-gear commercial fisheries in areas where NARW are known to congregate and persist, requiring weak rope in fixed-gear fisheries, and requiring fewer buoy lines in trap/pot fisheries where whales and gear co-occur.

Under the take reduction process required by the MMPA, the Atlantic Large Whale Take Reduction Plan was established to reduce deaths and serious injuries of large whales due to incidental entanglement in U.S. commercial fishing gear. This plan introduced seasonal restricted areas in the Greater Atlantic Region, zones where fishing with persistent buoy lines is restricted during certain times of year. However, trap/pot fishers could potentially continue to fish within these closed areas when using on-demand gear, a technology that replaces a persistent buoy line with various devices that can be cued "on-demand" if fishery management plan regulations were modified to allow alternatives to surface gear marking requirements. On-demand gear eliminates the need for persistent lines, significantly reducing entanglement risk for animals like the NARW.

On-demand gear creates an opportunity to support trap/pot and gillnet fisheries while mitigating entanglement risk. In 2022, the Consolidated Appropriations Act (CAA) directed NMFS to promote the "innovation and adoption of gear technologies." Associated Congressional appropriations to NMFS, including the CAA, the Inflation Reduction Act of 2022, and funds directed to New England states through the Atlantic States Marine Fisheries Commission, have accelerated research of on-demand gear development. Further, additional resources were made available through the National Fish and Wildlife Foundation (NFWF) New England Gear Innovation Fund [4]. There are currently over a dozen on-demand gear manufacturers, many of whom have received support through these funding avenues. Several of these companies have leveraged work completed for other active acoustic systems in their catalog (e.g., for applications including petroleum oil field engineering, scientific exploration, and military) for the development of on-demand technologies. Common between these products and on-demand fishing gear is the acoustic signaling methodology to invoke an action – either to communicate information to an underwater system, release a linkage to a buoyant system for surface retrieval, or to facilitate fishing without a vertical line. Given the proprietary nature of development within individual companies and the goal of innovative and diverse solutions that would address the wide range of operational conditions and challenges, acoustic standards were not imposed on developers.

Further, no concerted effort was made upon inception to determine if proprietary acoustic signaling approaches specific to individual companies' products would create problematic situations and whether a universal approach for acoustic interoperability would need to be supported.

The concept of interoperability through universal and unified acoustics is predicated on a single acoustic signaling method shared between separate makes and models of on-demand fishing gear. This approach aims to mitigate signal interference from multiple fishers operating in close proximity, support multi-vessel precision localization of on-demand gear through active acoustics, limit cumulative acoustic emissions through a signal brokering process and reduce potential for lost/ghost gear. To this end, NMFS contracted with the Woods Hole Oceanographic Institution (WHOI) to identify an acoustic interoperability framework to address acoustic interoperability through universal waveform designs and operating schemas. Beyond WHOI, alternative options have been proposed by commercial manufacturers. The review and analysis of these proposals and a discussion of their benefits and trade-offs is the focus of this report.

The MITRE Corporation (MITRE) is under contract with NMFS to serve as a technical evaluator for the currently proposed acoustic interoperability approaches. An effective approach will enable on-demand fishing gear to be deployed at scale within areas subject to fishing closures while protecting the integrity, needs, and future of the fishing industry. This evaluation will inform a comprehensive and effective framework that enhances the sustainability of fishing practices, supports the fishing community, and assesses the impact on marine mammals.

1.1 Overview of On-Demand Gear Interoperability

In the Greater Atlantic Region, the use of on-demand fishing is limited to research with appropriate federal and state permits, including within some Atlantic Large Whale Take Reduction Plan restricted areas. NMFS' Greater Atlantic Regional Fisheries Office (GARFO) authorizes Exempted Fishing Permits (EFPs) that allow for a federally permitted fishing vessel to conduct fishing operations that federal regulations would otherwise prohibit, in this case fishing without surface marking systems. The potential capabilities of on-demand gear systems go beyond the retrieval of gear by the fisher to include the identification and retrieval of gear by enforcement, the recovery of lost gear, and the reduction of gear conflict between fixed and mobile fishers. However, these additional capabilities cannot be realized within the current landscape of on-demand systems. Existing on-demand gear uses an array of uniquely configured acoustic communication systems with a series of proprietary databases or applications for data storage developed or identified by individual gear manufacturers. While the successful retrieval of gear by the gear owner is possible with a proprietary acoustic communication system, the remaining functions of on-demand gear cannot be successfully accomplished practically without a means of data sharing between different manufacturers' devices.

On-demand interoperability has the potential to reduce conflict associated with system communication and data sharing. NMFS' "Ropeless Roadmap – A Strategy to Develop On-Demand Fishing" [5] [6] and the On-Demand Gear guide [7] point toward the need to create a framework for interoperability between on-demand gear manufacturers' technologies to streamline the data storage, acoustic communication, and privacy of on-demand gear data. The lack of a standardized approach to interoperability and data collection risks a disconnect among fixed and mobile gear fishers, mariners, and other stakeholders, preventing them from accessing critical information needed to operate efficiently and safely within fisheries. Further, the proliferation of on-demand gear is dependent on the U.S. government's ability to regulate and permit the use of on-demand systems. To do so, it is likely that the U.S. government will need on-demand systems to communicate with each other and use the same data formats to ensure enforceability and streamline approval and permitting processes

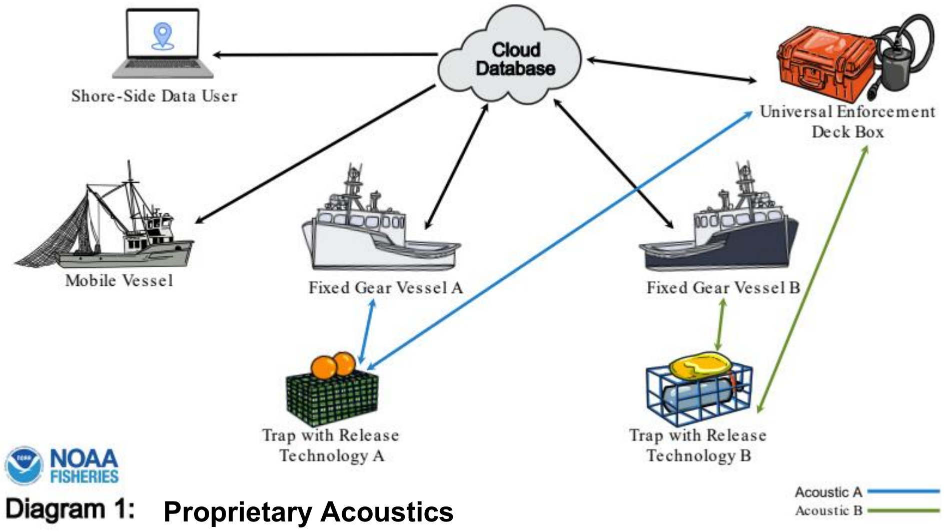
In considering the different levels at which interoperability may be imposed, it is helpful to introduce the basics of how on-demand gear can be positionally marked upon deployment and released to the surface for retrieval. When gear is deployed from a fishing vessel, the vessel's location can be marked by means of a Global Positioning System (GPS) produced measurement. While the gear falls to the ocean bottom, it may drift due to tidal currents, weather, or other environmental factors. Furthermore, once it reaches the ocean bottom, it is not guaranteed that it will remain in a fixed position. Once underwater, localization of subsurface gear can be accomplished by an active acoustic localization technique, introduced in Section 1.3.1.2. In most cases, to retrieve subsurface gear "on-demand" vessels must activate acoustic release mechanisms using acoustic signaling. Put simply, ***interoperability is a means for gear of different manufacturers to work together.*** This can be considered at multiple levels:

- The ability to retrieve location information, derived either from GPS marking or active acoustic localization, from a universal cloud database
- The ability for certain vessels (e.g., enforcement, or fishers purchasing from multiple manufacturers) to localize and release subsurface gear of all manufacturers using proprietary active acoustics and a universal cloud database
- The ability for all vessels to localize and certain vessels to release subsurface gear of any manufacturer using a universal acoustic solution and a universal cloud database
- The ability for all vessels to localize and certain vessels to release subsurface gear of all manufacturers using a universal acoustic solution with no requirement for a universal cloud database

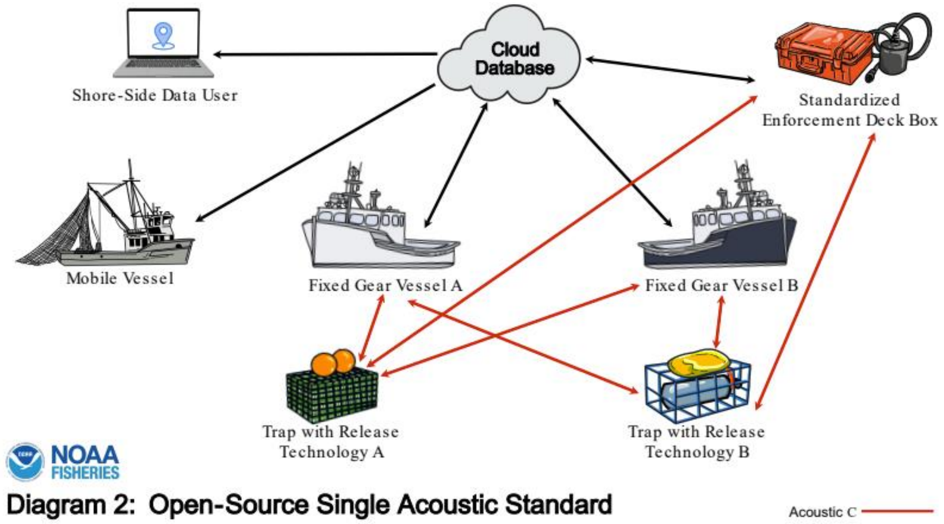
In evaluating the four potential levels of interoperability stated above, without acoustic interoperability achieved through either a universal enforcement deck box or a single acoustic standard, there would be no means for enforcement personnel or other regulators to retrieve subsurface gear. To date, three different on-demand gear interoperability architectures have been proposed, all of which accomplish communication between devices in different ways [4]. In the remainder of this report, the three architectures, summarized in Figure 1, are referred to as:

- Proprietary acoustics, centralized cloud database, and universal enforcement deck box (Option A)
- Open-source single acoustic standard, hereafter referred to as "universal acoustics", and centralized cloud database (Option B)
- Acoustic gear positioning only with an open-source single acoustic standard (Option C)

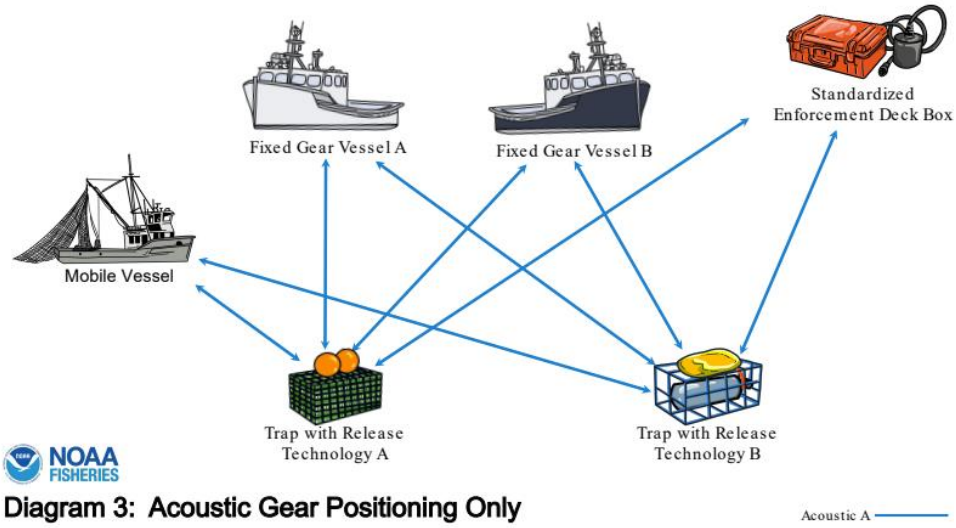
Option A implies that manufacturers can retain proprietary acoustic communication signaling schemes, and that all interoperability requirements would be achieved through communication with a cloud database and a universal enforcement deck box. The universal deck box is currently under development through NFWF funding [4] to consolidate the acoustic signaling equipment from all participating gear manufacturers into a single device for use by law enforcement. The universal deck box will act as a "master key", authorized only for enforcement, by which at-sea retrieval, inspection, and re-deployment will be possible for all participating vendors. This option allows for acoustic interoperability only for enforcement. Option B would require that all manufacturers adopt a universal acoustic solution, and interoperability would be achieved via both acoustics and a cloud database. In this case (as well as Option C), enforcement could use the same standardized hardware available to any fisher, with enforcement functions controlled by software. Neither Option A nor Option B necessarily require acoustic localization – subsurface gear could be GPS marked upon deployment, and that information would be shared on a universal cloud database. Finally, Option C would require all interoperability and gear localization to be accomplished via a single, universal acoustic standard, without a cloud database. Each of these approaches provide different benefits to the fishing, management, and enforcement communities, but they also impose varying degrees of complexity, cost, and potential impact to marine life. MITRE's approach to evaluating the proposed architectures and providing a recommendation for moving forward is summarized in Section 1.3.



(a)



(b)



(c)

Figure 1. Proposed on-demand gear interoperability architectures. (a) describes a multiple acoustic signaling approach, (b) describes a universal acoustic approach through a single open-source standard, and (c) portrays a scenario without a cloud database or wireless connectivity.

1.2 On-Demand Gear Requirements and Considerations

To appropriately replace buoy-marked fixed-gear, on-demand gear must be able to reproduce all functionality of a surface marking system buoy with acceptable performance metrics. Based on stakeholder input on gear location marking methods [8], the primary functionality of a surface buoy is to:

- Allow the detection of subsurface gear by all ocean users from ~0.5 nautical mile (NM) distance
- Alert ocean users to gear presence from a 4-6 NM distance in Federal waters[3]
- Provide accurate information (accuracy depending on environmental conditions) about subsurface gear location
- Act as a standardized non-proprietary identification device for subsurface gear
- Act as a surface connection for fishers and enforcement to retrieve gear at will

Subsurface gear detection at 0.5 NM can be accomplished by either real-time acoustics, or through positional information available on a cloud database (achieved via acoustic localization or GPS surface marking) and visually displayed for the vessel operators. To rely on positional information available on a cloud database, an assumption must be made that ocean users can access that information at operationally relevant times, either through cellular data or an internet connection. This study assumes that internet will be accessible on all vessels that may be affected by on-demand gear soon, which is reasonable based on the rapid adoption of low earth orbit-based satellite internet services by fishers. Subsurface gear detection at 4-6 NM is not reliably achievable using on-demand gear active acoustics, due to the absorption of sound in the ocean at the

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[3] Based on radar-reflector requirements detailed in CFR Title 50 Atlantic Coastal Act (CFR 50 Part 697) [9]

frequencies relevant to on-demand gear (10s of kilohertz [kHz]) and other attenuative properties [10].

Subsurface gear localization can be accomplished by either GPS surface marking, acoustic ranging, acoustic directional ranging, or Successive Acoustic Receive Time (SART) self-localization. Baumgartner et al. [11] provides an overview of these techniques and their expected performances. The requirements for subsurface gear location accuracy depend on anticipated on-demand gear densities and are an open area of research. In 2021, the Workshop on Buoyless Fishing Gear Location Marking Methods [11] reported that a location accuracy of at least 25 feet, or 8 meters, is required for subsurface gear in dense fisheries. This metric was based on interviews conducted with 75 stakeholders throughout government, fishers, Non-Governmental Organizations (NGOs), enforcement, developers, and researchers, and is intended to provide sufficient resolution under the densest current fixed-line fishing conditions, as judged by New England-based inshore and California-based trap/pot fishers. A localization accuracy of 25 ft is a proposed requirement and has been a subject of debate amongst the community [11]. The localization accuracy requirements of on-demand gear are of paramount importance, as there is a direct tradeoff between localization performance and system complexity/cost.

Subsurface gear identification information can be achieved through a cloud database or through direct acoustic communications with gear on the seafloor. Through interaction with a cloud database, gear information is available to anyone with internet and access permission. This underscores the importance of appropriate data governance policies and procedures. Obtaining gear information through direct acoustic communication requires interoperability between the surface and subsea devices. Apart from timed-release gear, all currently commercially available on-demand gear utilize proprietary acoustic communication to transmit information. For ocean-going vessels to communicate with subsurface gear, they must possess the gear manufacturer's complementary surface transducer, which may be either hung off the side of the hull or installed as a thru-hull transducer. For subsea gear of one manufacturer to communicate with surface gear from another manufacturer, they must be acoustically interoperable through a common signaling approach.

Most on-demand gear accomplishes gear retrieval via acoustic communication, timed- or galvanic-release mechanisms, or by manual gear grappling when the acoustic equipment fails. As is the case with retrieving identification information from gear on the seafloor, surface gear must be acoustically compatible with gear on the seafloor to communicate. Enforcement must be able to communicate and retrieve gear on the seafloor produced by all manufacturers. This can be accomplished through a single open-source acoustic interoperability architecture (Options B/C), or through the universal enforcement deck box concept (Option A).

In addition to replacing existing surface-buoy functionality, on-demand gear also has the potential to allow for the following [11]:

- Alert ocean users or enforcement of gear location at any distance
- Control access to sub-surface gear locations and identification information
- Alert gear owners and ocean users of lost or displaced gear
- Provide additional information to enforcement such as time of deployment
- Automatically mark gear deployments and recoveries

With the cloud database proposed in Options A and B, subsurface gear location information is available to anybody with an internet connection and appropriate access. Under these architectures, data governance plans and procedures must be in-place to allow for appropriate access to gear locations and identifying information. It is likely that an appropriate data governance plan would employ varying levels of access to ocean goers depending on their role (e.g. enforcement) and their location (i.e. it may be appropriate for all vessels to locate and identify all subsurface gear within a certain distance of their current position).

Subsurface gear that has moved and been lost without knowledge of the deploying fisher is commonly referred to as “ghost gear”. Ghost gear is a significant concern of both fishers and conservationists, as it represents an economic loss to the fishers and provides a persistent opportunity for marine mammal entanglement. Further, ghost gear poses an ongoing threat as it continues to fish even after being lost, resulting in unmonitored, cryptic mortality of both target and non-target species. Although on-demand gear eliminates the threat of persistent vertical endlines, it can be an order of magnitude more expensive than traditional fixed fishing gear and is therefore a greater concern for economic loss. An acoustic interoperability architecture has the potential to significantly reduce the odds of ghost gear because any vessel with interoperable acoustics could localize any subsurface gear. Without acoustic interoperability, the situation may still be improved by the sharing of gear location markings between fishers and mobile fishing operations.

Some of the primary aims of a universal acoustic solution are to mitigate signal interference from multiple fishers operating in close proximity, support multi-vessel precision localization of on-demand gear through active acoustics, and limit cumulative acoustic emissions through a signal brokering process. To address signal interference from multiple fishers operating in close proximity, some universal acoustic standards propose multi-access modulation schemes. Individual vendors using proprietary acoustics use disjoint frequencies and modulation schemes to mitigate signal interference, but do not necessarily support multi-access. The predicted performance of different modulation schemes in the presence of nearby interfering signals is tied to the ability to retrieve gear at will and is currently under investigation through a follow-on effort. Given the sparse nature of current fixed-gear fishing activity, and the data rates and message durations of the proprietary acoustics used, signal interference is not currently considered a primary compelling point. This could be subject to change if on-demand gear proliferates and frequency- or code-division techniques must be implemented to mitigate interference. The management of cumulative acoustic emissions through signal brokering is tied to regulations on protecting marine life and is addressed in this report.

Automatic gear marking upon deployment and recovery can be accomplished via on-vessel radio frequency communication protocols such as Radio Frequency Identification (RFID) and Bluetooth. This feature is valuable for both fishers and enforcement, as it reduces human workloads and the opportunity for mistakes, and it can act as a safeguard against illegal fishing. Automatic gear marking has been proposed or implemented by interoperability standards proposals and some manufacturers, but it is considered outside the scope of this work.

1.3 Localization Accuracy Requirements

Two divergent solutions have been proposed to achieve on-demand gear interoperability, which are generally described in Figure 1 in Section 1.1. Option A allows manufacturers to retain an acoustic signaling scheme of their choice, with inter-manufacturer interoperability for Office of Law Enforcement (OLE) achieved via a universal enforcement deck box. Alternatively, Options

B and C propose a universal acoustic communications solution that all manufacturers would be required to adopt. A comparison of the tradeoffs between these approaches is presented throughout the remainder of this report.

Determining which of the two divergent interoperability solutions will be sufficient to accomplish the functionality requirements set forth in Section 1.2 is largely predicated on the precision requirement for gear localization. This requirement is dependent on gear density, or the estimated quantity of on-demand fishing gear per square NM of measure, as well as the cumulative fishing level of effort of mobile and ground fishing vessels in that same region. Both factors pose a gear conflict risk to on-demand systems wherein they may be overlapped by other on-demand traps and trawls in dense regions, or intersected by bottom trawling operations from mobile vessel due to inaccuracies in gear marking.

1.3.1 On-Demand Gear Localization Accuracies

There are several different techniques that can be employed to achieve on-demand gear localization; those included in this report are: GPS marking, acoustic ranging, acoustic directional ranging, and SART. For all these techniques, a key consideration is whether they can be accomplished by a single fishing vessel (assumed to be the vessel that deploys the gear), or if they require cooperation amongst multiple vessels. Furthermore, each technique compels a different degree of complexity and cost. This section introduces the different techniques proposed to achieve subsurface gear localization and how their accuracies can be compared against requirements.

1.3.1.1 GPS-only Marking

The least complex and costly solution for interoperable subsurface localization is the use of GPS only markings that are uploaded to a cloud database. GPS marking is a simple technology that is currently available on all fishing vessels with a chart-plotter, where the location of the subsurface gear is assumed to be sufficiently close to the GPS mark. Although simple and low cost, GPS marking suffers from low positional resolution as compared to acoustic techniques due in part to environmental variables as gear transcends the water column, and locations cannot be updated once gear has descended below the ocean surface. This may be adequate in regions with low gear density.

1.3.1.2 Acoustic Localization Techniques

A full description of acoustic localization techniques is beyond the scope of this report, but the techniques proposed in the Workshop on Buoyless Fishing Gear Location Marking Methods [7] are presented here in the context of the accuracy requirements of on-demand fishing.

Acoustic ranging measures two-way travel time between two acoustic transducers to estimate the slant range between the two points. Through a combination of multiple measurements and assumptions about gear depth and ocean-sound speed, the location of the subsurface gear can be derived using pseudo-range multilateration [12]. In the context of on-demand fishing, one transducer is located on the surface, either a thru-hull transducer or a transducer draped over the side of a fishing vessel, and the second transducer is located on the subsurface on-demand gear. When the measurement is performed at four or more separate locations, the depth of the subsurface gear can be derived from available bathymetry data. An assumption of constant sound speed can reasonably be made (for relevant on-demand fishing ranges) based on either temperature measurement capability on on-demand gear or widely available salinity, temperature, and depth data.

Acoustic directional ranging uses one-way travel time and a directional transducer or array at the surface to estimate slant range and bearing between the surface vessel and the subsurface gear. The same multilateration algorithms used for acoustic ranging can then be applied to derive the subsurface gear location. With a properly calibrated thru-hull transducer array, such as the Ultra-Short Baseline (USBL) array solution presented in the FONTUS proposal, directional-ranging can provide improved localization accuracy with fewer measurements as compared to range-only multilateration. Both acoustic ranging and acoustic directional ranging can be performed by a single vessel or multiple cooperative vessels with a common acoustic signaling scheme. Multi-vessel localization increases the likelihood of achieving measurement diversity, a key driver of localization accuracy.

SART uses successive transmissions from a thru-hull transducer on moving vessels to provide localization information to the subsurface gear. After collecting this information from at least two passing ships, the device on the sea floor can estimate its own position. This technique has the benefit of continuously updating its own position and can potentially achieve higher accuracy than ranging-only performed by a single ship. However, it requires a single universal acoustic solution to facilitate transmission of common information from multiple transiting vessels and is reliant on local computations occurring in the processor of the subsurface gear, which is constrained by battery duration.

1.4 Evaluation Overview and Objectives

The ultimate objective of this work is to evaluate the different on-demand gear interoperability architectures proposed by the community and provide a robust discussion of the benefits and limitations of general interoperability measures. Recommendations must balance the complex needs of fishers, enforcement, regulators, and other stakeholders. Further, they must ensure appropriate performance requirements are met with reasonable costs and defensible impact to existing businesses in order to accelerate a solution for fishers to operate in closed areas using on-demand gear.

First, the benefits and constraints imposed by the three proposed interoperability architectures are evaluated. Option C, which is reliant exclusively on acoustics, is eliminated based on lack of compliance against gear marking stipulations detailed in the Code of Federal Rulemaking (CFR) Title 50 as well as lack of necessary involvement with collocated mobile fishing operations.

One of the driving factors in determining what level of interoperability is necessary is the possibility of gear conflict in dense fishing areas or areas with a high likelihood of overlap with mobile fishing activities. This work seeks to assess the likelihood of on-demand gear conflict with both fixed-gear and mobile fishers using an unbiased, data-driven approach. Fixed-gear density is assessed throughout the Northeast Exclusive Economic Zone (EEZ) using data from NOAA's Woods Hole Analysis of Line Entanglement Decision Support Tool (WHALE DST). The likelihood of gear conflict with mobile fishers is assessed using Vessel Monitoring System (VMS) data filtered by declaration code and vessel speed to isolate mobile fishing with bottom-tending gear that could interfere with fixed fishing gear.

A variety of factors must be considered to determine if acoustic interoperability is required for all on-demand gear, such as: predicted internet access, predicted gear density, predicted performance, whether or not an acoustic signaling scheme can meet the functional expectations of current surface buoys, if it can support the potential additional benefits of on-demand gear, the predicted impact to marine life, and the impact to government and fishers. Each of these factors are considered for proposed interoperability standards and existing on-demand gear.

The objectives of this study can be addressed by the following research questions:

1. What are the performance requirements for on-demand gear to replace existing fixed-line gear with surface buoys? Which proposed interoperability architectures meet those requirements?
2. Is acoustic interoperability necessary, or is it sufficient to impose interoperability via alternative mechanisms?
3. Is a universal acoustic solution necessary to achieve acoustic interoperability and meet the performance requirements for on-demand gear to replace existing fixed-line buoys?
4. How do proposed acoustic interoperability architectures align with what is available in today's market?
5. Will the sound emitted by active acoustic on-demand gear adversely impact endangered and threatened marine species?

At this time, the only open-source interoperability architecture with sufficiently described detail for evaluation is FONTUS, proposed by WHOI and expert consultants under NMFS contract [13]. FONTUS is a unified acoustic interoperability architecture, introduced as Option B in Section 1.1. It is a flexible, yet complex, framework that allows for gear localization via either direct acoustic communication or GPS surface marking. FONTUS uses a wideband modulated waveform, discussed in Section 3.3. No current existing gear manufacturers natively support FONTUS, based on a combination of the recency of the proposal as well as system constraints. Funding has been awarded through the New England Gear Innovation Fund to certain vendors to develop this capability [4], and while progress has been made, considerable work remains to fully support FONTUS. The implications of this are discussed throughout the remainder of this report.

The scope of this study focuses on the Northeast U.S., where seasonal restricted areas for NARW protection have been implemented. It is assumed that internet will be accessible on all relevant vessels soon, which is reasonable based on the rapid adoption of low earth orbit-based satellite internet services (e.g., Starlink) by fishers. While a standardized cloud database, such as those implemented by EarthRanger and RMWHub, is required for the proposed interoperability Options A and B, the specifics of that system are considered out of scope for this work.

It's important to note that a multitude of complex factors continue to influence the development and adoption of on-demand fishing gear, and the analysis that follows seeks to provide recommendations toward interoperability forecasted over the next five to ten years. Changes to take reduction measures, the adoption rate of ropeless fishing, and most importantly, the observed performance of proliferated on-demand gear, should influence what the adequate level of interoperability should be in order to sustainably keep fisheries open and reduce takes against the NARW.

2 Methodology Overview

The following subsections will provide an overview of the technical methodology used to answer the research questions posed in Section 1.4. The analyses conducted in this report are derived from data sources at varying levels of sensitivity. All non-public data has been anonymized and is appropriate for a federal government audience. A full discussion of these data sources is provided in 5Appendix A.

2.1 Assessing the Adherence of Interoperability Proposals to On-Demand Performance Requirements

Research Questions

1. *What are the performance requirements for on-demand gear to replace existing fixed-line gear with surface buoys? Which proposed interoperability architectures meet those requirements?*
2. *Is acoustic interoperability necessary, or is it sufficient to impose interoperability via alternative mechanisms?*

To assess the three proposed interoperability architectures introduced in Section 1.1, each option is compared to the requirements stated in Section 1.2. Practical considerations are also discussed to establish benefits and drawbacks. The question surrounding the necessity of acoustic interoperability is addressed through examining the community proposed architectures which share a common feature of using acoustics to interact with and localize others' on-demand gear. This is a minimum necessity for OLE for the adjudication of illegally fished gear but has also been proposed by Baumgartner et. al [11] to precisely localize gear on the ocean floor and provide a means toward the recovery of lost or displaced gear.

Current gear marking requirements mandate identifying information unique to the gear owner and visible from a distance; these attributes must remain for on-demand gear but will be facilitated through different means, such as acoustic communication and digital chart-plotter integration. Uncertainties specific to fixed-gear must also be considered. For example, a surface buoy may not precisely denote the location of underwater gear residing on the ocean floor. That same level of error in location accuracy should be used to provide context to the errors associated with surface marking and underwater localization procedures facilitated through active acoustics for on-demand gear. As discussed in Section 1.2, the 25 ft positional accuracy requirement proposed by Baumgartner et al. [11] has been a point of contention in the community. This work estimates the positional accuracy of various methods using all available objective data sources in following sections. These accuracies are then compared to the positional accuracy of current fixed-line surface buoys.

2.2 Examining Interoperability vs. a Universal Acoustic Solution

Research Question

3. *Is a universal acoustic solution necessary to achieve acoustic interoperability and meet the performance requirements for on-demand gear to replace existing fixed-line buoys?*

To determine the merits of allowing proprietary acoustics (Option A) versus mandating a universal acoustic solution (Option B) to satisfy the gear marking requirements set forth in Section 1.2, a comparison of the tradeoffs between these architectures is presented in Section 3.1 and 3.2.

When considering the technical differences between the two proposed architectures with respect to the requirements set forth in Section 1.2, determining which solutions are sufficient is largely predicated on the precision requirement for gear localization, which is in turn dependent on the risk for gear conflict**.** To adequately describe this risk metric geospatially, MITRE explored a new approach to determine relative risk of gear conflict based on empirical data that takes into account the complexity of varying fisheries. A seasonal gear conflict risk map was constructed from data sourced from the WHALE DST fixed-gear fishery layer [14] and VMS telemetry of mobile fishing activities operating within the same seasonal time frame between 2019 to 2021. Further detail on the available data and limitations is addressed below in Section 2.2.1 and Section 3.5.

Section 3.2.1 and the following subsections describe initial results where gear conflict may occur based on the effort taken to combine these disparate geospatial statistics toward a risk map. The implications of this risk inform where localization accuracy may be paramount and thus, where acoustic localization of subsurface gear may be required. A full description of the geospatial risk study performed in this work is presented in 5Appendix B.

2.2.1 Geospatial Gear Conflict Analysis

In this section, a novel methodology for developing a data-driven gear conflict risk map is described to identify areas by low, moderate, elevated, and high levels of probabilistic gear conflict based on fixed-gear density and mobile fishing activities. Gear conflict risk maps aim to determine where high-precision gear localization might be necessary for sustainable interoperable fishing, in addition to finding lower risk areas where GPS-only on-demand gear marking may be sufficient. Fixed-gear density and fishing vessel activity are the two variables used to generate the gear conflict risk maps, and processing is applied to isolate fishing effort based on project, plan, and gear type information contained within the VMS declaration code glossary [15]. Selections of gear type codes include dredge (“D”), midwater trawl (“M”), purse seine (“S”), and bottom trawl (“W”). Plan codes for surfclam, ocean quahog, and mussel permits (“SCO”) along with squid, mackerel, and butterfish (“SMB”) were also included, agnostic to gear type declaration. In addition, plan and program codes “SES-SAA”, “SES-SCA”, and “SES-SWE” were included to capture activity from scallop permit vessels with special access area, limited access, and state waters exempted program codes. All these selections are then filtered by the reported “derived speed” field of each VMS report to isolate activity between 0.01 – 4.0 knots, representative of fishing effort and not mooring or transiting. The VMS data used herein is considered largely representative of the bulk of licensed commercial fishing with reporting requirements in the Northeast. However, these records are incomplete, as they do not include fisheries without VMS reporting requirements. The majority of fishing efforts in non-VMS mobile fisheries, such as summer flounder, black sea bass, scup, and whiting, is accounted for by vessels that are required to have VMS due to other federal permits (e.g., groundfish or scallop permits). These vessels declare out of their VMS fishery when targeting non-VMS fisheries, with approximately 90% of the effort in these fisheries captured through VMS data using “Declare Out of Fishery” (DOF) codes. DOF declarations with gear type listed as one of the above categories are included in this analysis, leaving an estimated 10% of vessels unaccounted for in this analysis based on estimates provided to MITRE by GARFO.

VMS reporting was selected in years that coincide with fixed-gear fishery layer data reporting from WHALE DST between March 2019 to December 2021, which represents the most recent timeframe before lobster fishery vertical line closures were implemented. Within that timeframe, months that coincide with vertical line restrictions in regions of the Northeast include February to April for the South Island Restricted Area and October through January for Lobster Management Area (LMA1). The methodology is based on fusing the fixed-gear density and vessel activity geospatial data across common coordinate points in time to generate a gear conflict risk map. More information on methodologies for generating the fixed-gear density and vessel activity maps can be found in Appendix 5A.5.

To generate the gear conflict map, relative risk of gear conflict was calculated over averaged seasonal vertical-line closure months across the Northeast EEZ, with risk thresholds corresponding to the 95th percentile from the statistical distributions of gear density and mobile fishing activity averaged over the three years considered in this study. Figures for these geospatial distributions are available in Appendix A.5 for averaged fixed-gear density and averaged VMS telemetry. Given the geographic sparsity of the datasets, thresholds were selected that would isolate areas of both gear density and mobile vessel activity higher than 95% of the entire area of regard. From the thresholds set by these distributions, geospatial regions are labeled with respect to different risk levels as: a) ‘No-Data’, b) ‘Low Risk’, c) ‘Moderate Risk’, d) ‘Elevated Risk’, and e) ‘High Risk’. The assignment of areas to risk levels is summarized in Table 1. Any area without available fixed-gear or VMS telemetry data is labeled as ‘No-Data’.

Table 1. Summary of gear conflict risk assignments based on statistic thresholds.

Risk Level	**95th Percentile of Fixed-Gear Density**	**95th Percentile of Mobile Vessel Activity**
Low	Below	Below
Moderate	Below	Above
Elevated	Above	Below
High	Above	Above

Following the extraction of the thresholds and the gear conflict risk regions, seasonal gear conflict maps were generated. Grid cell locations without numerical values for fixed-gear density values were not considered. These regions are color-coded as ‘No-Data’ and can be observed broadly in figures within Section 3.2.1.

2.2.2 Subsurface Gear Localization Accuracy Requirements

In 2021, Baumgartner et al. [11] presented a summary of survey results that indicated 25 ft positional accuracy should be a requirement for the widespread adoption of on-demand gear. This is a strict level of localization precision and to date, work has not been done to assess where this type of requirement may be valid and where less accurate positional estimates may be sufficient. A better understanding of localization accuracy needs within zones likely to adopt on-demand gear offers an opportunity to determine what localization techniques are necessary to meet requirements.

To do this, the study assessed the distribution of relative risk of gear conflict within the areas likely to adopt on-demand gear, such as a region subject to seasonal vertical line closures. The aim of the study is to understand where a stringent 25-ft requirement may be necessary to mitigate gear conflict based on available geospatial fishery data and assess how common those conditions are in representative closed areas. The geospatial analysis method explored in this work and its efficacy is presented in Section 3.2.1.

Following the geospatial analysis, the positional accuracy of various gear localization techniques is evaluated in comparison to the 25 ft requirement. The goal of this analysis is to determine what type of localization technique is necessary to meet stringent requirements in areas with significant risk for gear conflict.

2.3 Evaluating the Compatibility of Interoperability Proposals with Existing On-Demand Gear

Research Question

4. *How do proposed acoustic interoperability architectures align with what is available in today's market?*

The various interoperability proposals all require some level of technological development to support implementation. Vessels involved in on-demand fishing must be able to resolve and communicate gear marking locations through real-time wireless connectivity, either with cellular access or satellite internet. Subsurface fishing gear may be required to facilitate acoustic localization procedures and reproduce acoustic signaling techniques described in the universal acoustic communication proposal FONTUS [13]. The adaptation of existing on-demand gear to meet these requirements is non-trivial, and in some cases, may be prohibitive to implement all together based on technical complexity and cost.

The proprietary acoustics interoperability framework portrayed in Figure 1 Option A may be acceptable if OLE is enabled to provide at-sea interdiction of on-demand fishing gear through a universal deck box, and existing gear can support an acoustic localization solution, such as acoustic ranging, under current functionality.

A single open-source acoustic standard architecture, portrayed Figure 1 Option B, enables an increased set of capabilities over separate acoustic approaches, which include precision localization through standardized signaling and a means to recover lost or displaced gear through that same method. To support these additional capabilities, which are predicated on a unified, wideband acoustic signal, significant technological redevelopment of many existing on-demand systems may be necessary. An analysis of current specifications sourced from vendor-provided information is compared against the specifications of FONTUS in Section 3.3 to show that two of the four acoustic on-demand system manufacturers who provided detailed information in response to MITRE's Request for Information (RFI) will currently not be capable of reproducing the broadband acoustic signal that FONTUS is designed around due predominantly to differences in system bandwidth.

Additionally, it is recognized that wideband acoustic signaling protocols, such as FONTUS, offer improved communication performance over narrowband solutions in multi-path environments, perhaps resulting in more efficient gear retrieval. Work is currently underway to construct an acoustic modeling toolbox to evaluate the effectiveness of various proposed signaling schemes in various ocean environments.

Finally, an important consideration when comparing Options A and B is the resulting cost, both in terms of required government investments and the resulting cost increase to end users. To evaluate the financial and operational impact of adopting a universal standard, MITRE issued a second RFI inquiring about the internal investments required to adopt a universal standard and how such adoption would affect the system costs for end users. To simplify the data collection, MITRE requested that each company focus on how the cost adaptation would apply specifically to FONTUS. Throughout the process, MITRE clarified that the use of FONTUS in this analysis does not imply any decision regarding its implementation.

The specific questions asked in MITRE's cost analysis RFI were:

1. *What type of internal investment would need to* be *made to implement FONTUS?*
2. *What is your current market price? How much do you anticipate this price decreasing with manufacturing-at-scale? How would the implementation of FONTUS impact the cost for end users?*

As a metric of cost comparison, two scenarios were considered based on the architectures described for proprietary acoustics with interoperability through a universal deck box (Option A) and for an open-acoustic standard (Option B) with wide industry adoption. In the first scenario, the NFWF award of $1.383M for the development of the universal deck box [4] was used as an initial investment cost and each unit was assigned a notional cost of $100k each. Given that the universal deck box does not exist as a product, $100k was chosen as a conservatively high estimate. In the second scenario, an investment of $1.175M was awarded to each vendor who responded to the RFI, which is commensurate with the funding made available for interoperability of on-demand gear through the 2023 NFWF New England Gear Innovation Fund [4]. In this scenario, this was assumed to be a U.S. government investment. It is worth noting that this award is smaller than the amounts stated by vendors as necessary for redevelopment in the RFI, which are intractable to consider for the purpose of a fair comparison. RFI responses were used to assess nominal increases of 150% to the sale prices of existing gear, resulting in a cost burden to end users. Conservatively low estimates of sale price increases were used. Thus, the cost analysis of the proprietary acoustic scenario is likely an overestimate, and the universal acoustic scenario, likely an underestimate.

2.4 Assessing the Impact of Acoustic On-Demand Signaling on Marine Life

Research Question

5. *Will the sound emitted by active acoustic on-demand gear adversely impact endangered and threatened marine species?*

Under both the ESA and the MMPA, NMFS has developed acoustic criteria to assess the potential for underwater sound to harass marine mammals and other protected marine life [16]. The NMFS acoustic criteria provide thresholds for non-impulsive, intermittent sources of which active acoustic on-demand fishing gear may be generally characterized; levels above these thresholds may cause negative effects ranging from onset of behavioral disturbance to onset of physical injury in the protected species. An important factor in the operation of on-demand fishing gear is to ensure that acoustic emissions from regular communication and signaling activity do not approach a significant probability of exceeding these criteria for species outside of the immediate vicinity of the signaling devices. Before NMFS approves on-demand acoustic signaling devices for use on a broad scale, they must characterize the expected emission levels and their impacts on protected species to determine whether an interoperability standard which governs emission rates is necessary. The FONTUS proposal offers a brokering system where gear position is localized for some time period and after which no further signaling to or from that gear occurs outside of normal on-demand fishing operations to retrieve and deploy said gear. This system ensures that each piece of gear signals with a designed emission rate that may never exceed the defined maximum within a period of time, and, as a result, offers a means to control cumulative emissions within a temporal and geospatial extent.

To understand if such a control measure is needed for compliance, models of both cumulative instantaneous and time-averaged acoustic emissions from on-demand fishing gear under worst-case and representative operation were created in an example vertical-line restricted area. This study includes a representation of realistic gear specifications, such as source level and duty cycle, as well as environmental parameters local to the zone of analysis. The acoustic environment is modeled with a ray-tracing program, BELLHOP [17], to derive transmission loss coefficients across a statistical sample of fishery conditions. From this information, a non-coherent sum of sound pressure levels across a range of operating scenarios is presented to determine if cumulative levels approach the NMFS' acoustic criteria. This finding serves as the basis to determine if limitations on acoustic emissions made possible by an interoperability proposal are necessary toward the protection of marine life or if current gear operating without coordination does not exceed acoustic criteria for non-impulsive intermittent sources.

2.4.1 Evaluating Acoustic Emissions

All on-demand gear using active acoustic transmitters have characteristic frequencies of operation as well as a transmitting source level, in units which describe the calculated physical sound pressure level in the underwater environment 1 meter away from the source. Based on descriptions and acoustic criteria provided by NMFS [16], these can be characterized as non-impulsive, intermittent sound sources given the limited duty cycle much of this equipment employs. The frequency range under consideration is 7 kHz to 160 kHz, which encompasses the audible range for low-, high-, and very high-frequency cetaceans and pinniped groups as well as fishes and sea turtles. All acoustic on-demand fishing gear functions within this boundary and therefore its risk to these species is subject to evaluation and assessment. NMFS' current underwater marine mammal Level B behavioral harassment threshold of 160 dB, for intermittent sound sources, is the limiting sound pressure level this evaluation is based on, though additional comparisons are included for 150 dB and 175 dB behavioral disturbance for fishes and sea turtles respectively. These thresholds are based on instantaneous sound pressure levels, not cumulative time-averaged emissions. Cumulative time-averaged emission criteria exist for "impulsive" and "continuous" sound sources, which on-demand gear does not fall under. The various interoperability proposals have no impact on instantaneous pressure levels from individual sources. However, they could decrease spatially cumulative instantaneous levels under the worst-case scenario of dense source accumulations emitting simultaneously, and they could lower time-averaged cumulative emissions as well.

To evaluate the spatially cumulative instantaneous and time-averaged emissions of on-demand gear in representative conditions, 500 acoustic sources were distributed within the South Island Restricted Area. This number was chosen based on available data from the WHALE DST fixed-gear fishery layer and is likely a conservative overestimate of a dense deployment of on-demand gear within a fishery. A notional distribution of sources is portrayed in Figure 2, where the white dots represent the coordinate location of an emitting piece of acoustic on-demand gear. These units are distributed according to a random Poisson process to simulate geospatial clustering common within fisheries.

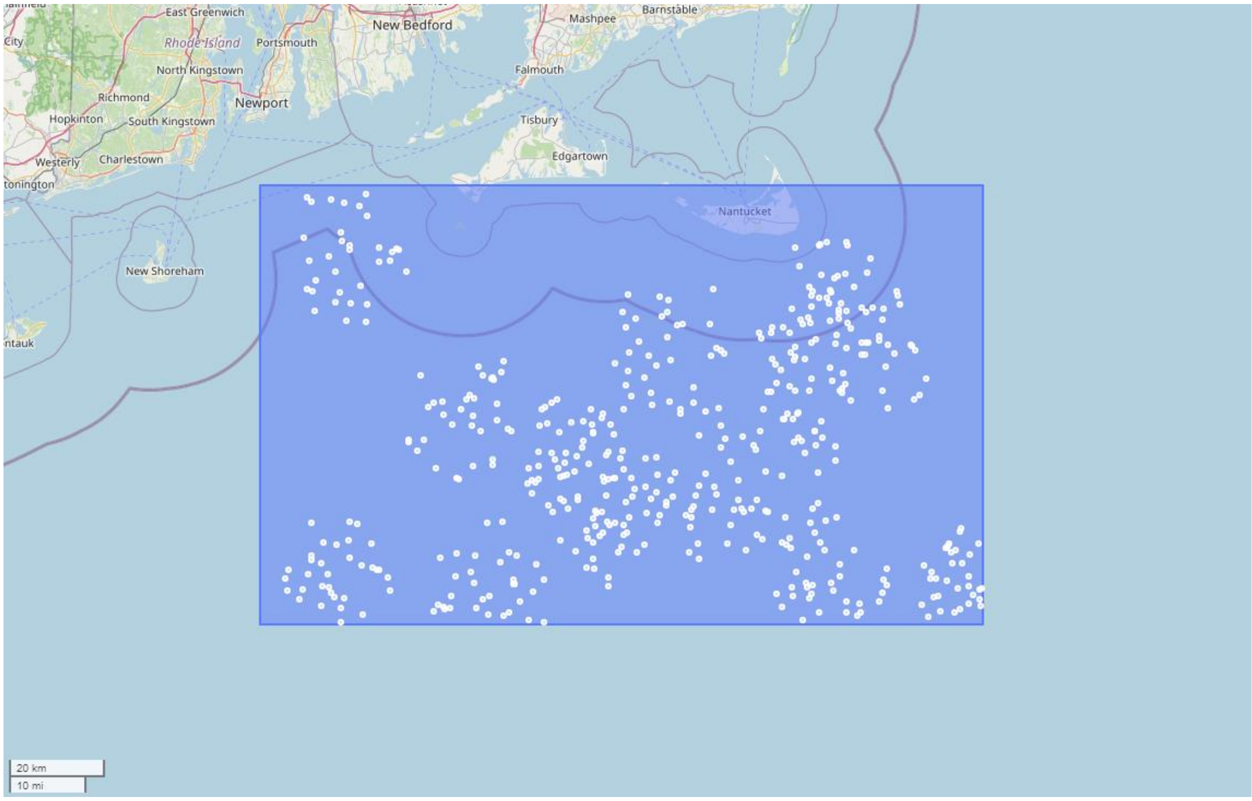

Figure 2. A notional representation of N=500 sources distributed according to a Poisson process within the South Island Restricted Area.

The full emissions analysis is provided in detail in Appendix C, while key results are presented in Section 3.4 and the procedure used to produce those results is summarized here. For each acoustic source, propagation was calculated along the four cardinal directions. Sources were placed both 1 meter from the surface, chosen to represent characteristic thru-hull transducers, and 1 meter from the bottom, to represent subsurface gear. Given the relatively flat bathymetry and consistent acoustic properties throughout the area, the differences observed across the region, and between the surface and bottom sources, were small. For simplicity, the stochastic β coefficients defined in Appendix C were derived from a single source location, shown to be representative of an average gear placement within the region. The deviation caused by different levels of boundary interaction and propagation loss due to channel geometry and sound speed profiles result in a standard error on the order of ± 3 dB per source.

Source distributions within the South Island Restricted Area were calculated using a Poisson distribution, as shown in Figure 2. The Poisson distribution is based on multiple random centroids meant to represent dense fishing, notionally informed by biomass distribution and other social factors. In this case, a total of 500 emitting sources were considered.

Results were then generated for two scenarios: continuous emissions and time-averaged emissions according to a notional signaling limit of 120-seconds worth of active transmit time over a 24-hour period, a conservative overestimate given the limited duty cycle of these devices. The first scenario is indicative of the worst-case situation in which 17.75 kHz sources with a root-mean-square (RMS) source level of 183 dB re. 1 μPa at 1 meter emit continuously over the 24-hour duration of analysis. The NMFS behavioral thresholds are evaluated against these results. The second scenario is representative of a notional signaling scheme in which a cumulative 120-seconds worth of source emission is non-coherently time-averaged over the analysis period. These parameters were selected from an industry survey, shown in Table 4, as those corresponding with the ‘loudest’ acoustic characteristics from real gear: a combination of the highest source level, lowest frequency, and longest duty cycle. This scenario represents the emissions that FONTUS seeks to manage through signal brokering. Leveraging the solution for emission at a specified location derived in Appendix C, both the worst-case and time-averaged cumulative decibel level is computed throughout the area of analysis. In both scenarios, acoustic emissions are plotted in units of dB re. 1 μPa^2 at standoff distances of 5- and 10-meters from the distributed sources as colormap across the region. Histograms showing statistics and the percentage of cells exhibiting a specific sound pressure level are shown in Figure 19 and Figure 46.

3 Results and Discussion

This section presents the results generated in this study, answering the five research questions detailed in Section 1.4.

3.1 On-Demand Requirements and Interoperability Proposals

Research Questions

1. *What are the performance requirements for on-demand gear to replace existing fixed-line gear with surface buoys? Which proposed interoperability architectures meet those requirements?*
2. *Is acoustic interoperability necessary, or is it sufficient to impose interoperability via alternative mechanisms?*

To be considered for adoption, an interoperability proposal must conform with the requirements set forth in Section 1.2. The three architectures proposed by the community are evaluated against those requirements and summarized in Table 2 which has been adapted from the 2021 report, "Workshop on Buoyless Fishing Gear Location Marking Methods" [11]:

Table 2. Gear marking requirements versus three proposed interoperability architectures.

Requirement	Option A Proprietary Acoustics	Option B Universal Acoustic Standard	Option C Acoustic Gear Positioning Only
~0.5 NM detection	✓	✓	✓
4-6 NM presence alert	✓	✓	✗
Accurate[4] subsurface localization	✓	✓	✓
Non-proprietary subsurface gear identification	✓	✓	✓
Surface connection for gear retrieval	✓	✓	✓

Based on the requirements for on-demand gear to replace fixed-line surface buoys, it can immediately be seen that the adoption of an active acoustic-only positioning system will not be able to replicate the gear alert range (interpreted as 4-6 NM in [11]), currently achieved via the required radar-reflector for federal waters based on radar-reflector requirements detailed in CFR Title 50 Atlantic Coastal Act (CFR 50 Part 697) [9], Fisheries Conservation and Management Act (CFR 50 Part 648) [18], and the MMPA (CFR 50 Part 229) [19]. Furthermore, and perhaps more importantly, Option C requires the adoption of active acoustic positioning by all users that may overlap in time and space with subsurface on-demand gear. The implication of this is that mobile fishing vessels would be required to install and operate thru-hull acoustic positioning transducers,

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[4] Note that "accurate" subsurface localization is a subjective metric that is addressed in following sections.

which is an asymmetric burden on an industry that will not be subjected to vertical line-restrictions established to protect large whales and will not be fishing with on-demand gear.

In summary, some level of acoustic interoperability is required to achieve all the requirements for on-demand gear to replace existing fixed-line surface buoys. The information available indicates that these requirements can be satisfied using either proprietary acoustics (Option A) or a universal acoustic solution (Option B).

3.2 On-Demand Gear Localization Assessment

Research Question

3. *Is a universal acoustic solution necessary to achieve acoustic interoperability and meet the performance requirements for on-demand gear to replace existing fixed-line buoys?*

The interoperability and performance requirements for on-demand gear are driven by the proximity between gear from different fishers and the potential for gear conflict. As described in Section 1.3, these are represented by localization accuracy requirements, and any other potential benefits of a universal acoustic solution are not tied to the requirements presented in Section 1.2. Single open-source acoustic interoperability standards offer the ability to perform multi-vessel cooperative subsurface acoustic localization, with improved accuracy over surface GPS markings and single-vessel acoustic localization. This section evaluates the accuracy of various localization techniques in the context of gear density and the likelihood of gear conflict in areas where on-demand gear is likely to be employed.

Under current requirements in the Greater Atlantic Region, the position of trap/pot and gillnet fixed-gear is represented by a surface marker (e.g., buoy) constrained to the true underwater position of the gear by a vertical line. This system permits some level of inaccuracy in that under current and tidal influence, the position of the surface marker will displace, forming a watch circle over time which contains the true position of the underwater gear. In areas of sparse gear placement and low levels of interfering mobile ground fishing operations, this relative inaccuracy may not be problematic, although further research is needed to fully understand how on-demand gear localization may play a part in interoperability in these areas. In areas of high gear density and/or subject to high gear displacement (due to weather or levels of trawling and dredging from mobile fishing vessels), gear conflict may occur. On-demand gear location accuracies must be at least as accurate as current surface marker accuracies in these areas.

In 2021, Baumgartner et al. [11] summarized survey results suggesting that a 25 ft positional accuracy should be mandated for the widespread adoption of on-demand gear. Understanding localization accuracy requirements in areas likely to adopt this gear is crucial for identifying the necessary techniques to meet these standards and ultimately reducing the risk of mobile fishers inadvertently damaging or destroying fixed-gear lacking surface buoys or other fixed-gear fishers deploying gear on top of existing gear. To address this, it is essential to identify potential areas of conflict where there is dense fixed-gear, high levels of mobile fishing activity in the presence of fixed-gear, and where these two scenarios significantly overlap. The study evaluated the proportion of high and elevated relative risk of gear conflict within the Northeast U.S., focusing on areas subject to seasonal closures. The initial results and efficacy of the geospatial analysis are detailed below.

After the geospatial analysis, the accuracy of various subsurface gear localization techniques are examined. A key consideration for each technique is whether it can be executed by a single fishing vessel (assumed to be the one deploying the gear) or if it requires collaboration among multiple vessels. The complexity and cost associated with each technique are discussed.

3.2.1 Geospatial Analysis and Results

As described in Section 2.2.1, the thresholds for identifying risk regions were derived from the 95th percentiles of the VMS and WHALE DST statistical distributions averaged over a three-year period of activity between March 2019 through December of 2021. The percentile was chosen based on analysis that much of the northeast U.S. EEZ is sparse, with little fixed-fishing gear seasonally present in offshore regions and clustered mobile fishing activity. Thus, this percentile corresponds to 10.31 pieces of fixed-gear per square nautical mile and 30.61 fishing hours per square nautical mile. The thresholds used in this study are notional, and, going forward, may be assigned in a manner that better reflects on-demand gear spacing and empirical conflict rates when sufficient observation has taken place. That is, if for example there are actual reported "gear conflict incidents" that provide the corresponding "fixed-gear density" and "fishing-vessel-activity" values at the times those incidents happened, it could be highly likely to assign more realistic thresholds for these two parameters in determining these risk regions. The resulting 2-dimentional (2D) histogram plot can be seen in Figure 3 with the identified risk categories highlighted according to Table 1.

Assigning these discretized gear conflict risk levels to data available in the Northeast EEZ yields the results shown in Figure 4, Figure 6, and Figure 6, which represent seasonal variability between an averaging period of February 1 to April 31, May 1 to September 30, and October 1 to January 31 of 2019-2021, with the former and latter periods corresponding to the months of vertical line closure for South Island Restricted Area and Lobster Management Area 1 (LMA1) respectively. The Massachusetts Restricted Area and Great South Channel were under active closure during the time that fixed-gear density data was gathered (2017- 2021) and as a result, fixed-gear density is not reflected in the data and results from these regions will not be included in this analysis. From visual inspection, both maps are largely occupied by regions characterized by ‘no-data’ (purple) and ‘low risk’ (blue) labels, but significant ‘elevated risk’ (orange) and some ‘high risk’ (red) cells occur persistently across seasons in inshore Gulf of Maine. An isolated look at this region is provided in Figure 7 and Figure 9 for Spring and Fall/Winter seasons respectively. A comprehensive examination of multispecies broad stock areas [20] within the Northeast EEZ and their respective gear conflict threat levels is provided in Appendix A.5.

Statistics on the percentage of square nautical miles evaluated at each risk level throughout inshore Gulf of Maine (Broad Stock Area 1) are given in Figure 10. Percentages and area totals for each risk level are shown for seasonal averages in this area between (a) February – April, (b) May – September, and (c) October – January for data given between 2019 – 2021.

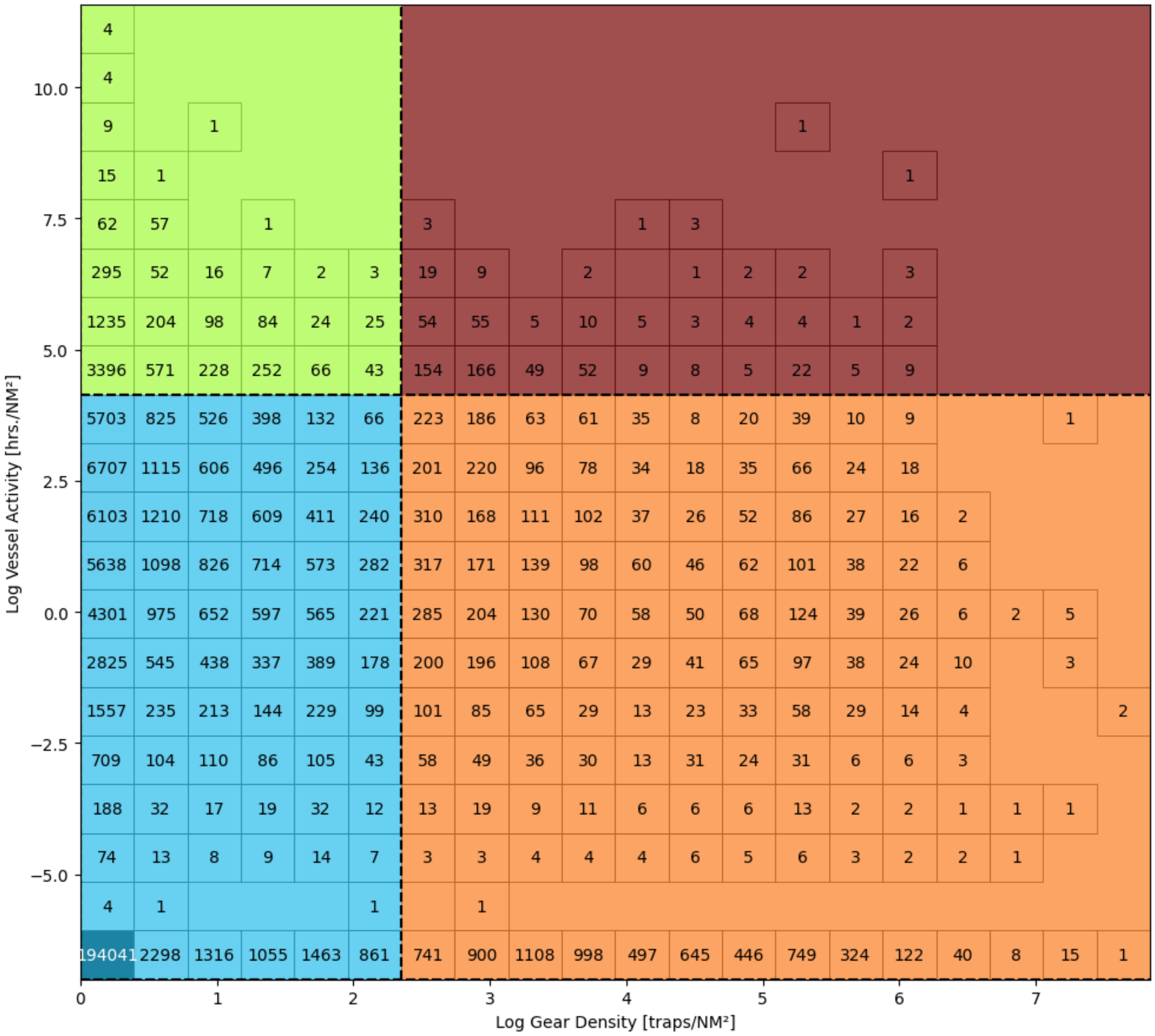


Figure 3. 2D histogram of fixed-gear density and vessel activity collected in the Northeast EEZ and averaged between March of 2019 through December of 2021. 95th percentile thresholds discretize the histogram according to risk level: 'low risk' (blue), moderate risk’ (green), ‘elevated risk’ (orange), and ‘high risk’ (red). Square nautical mile counts corresponding to logarithmic gear density and logarithmic fishing activity are printed within each histogram bin.

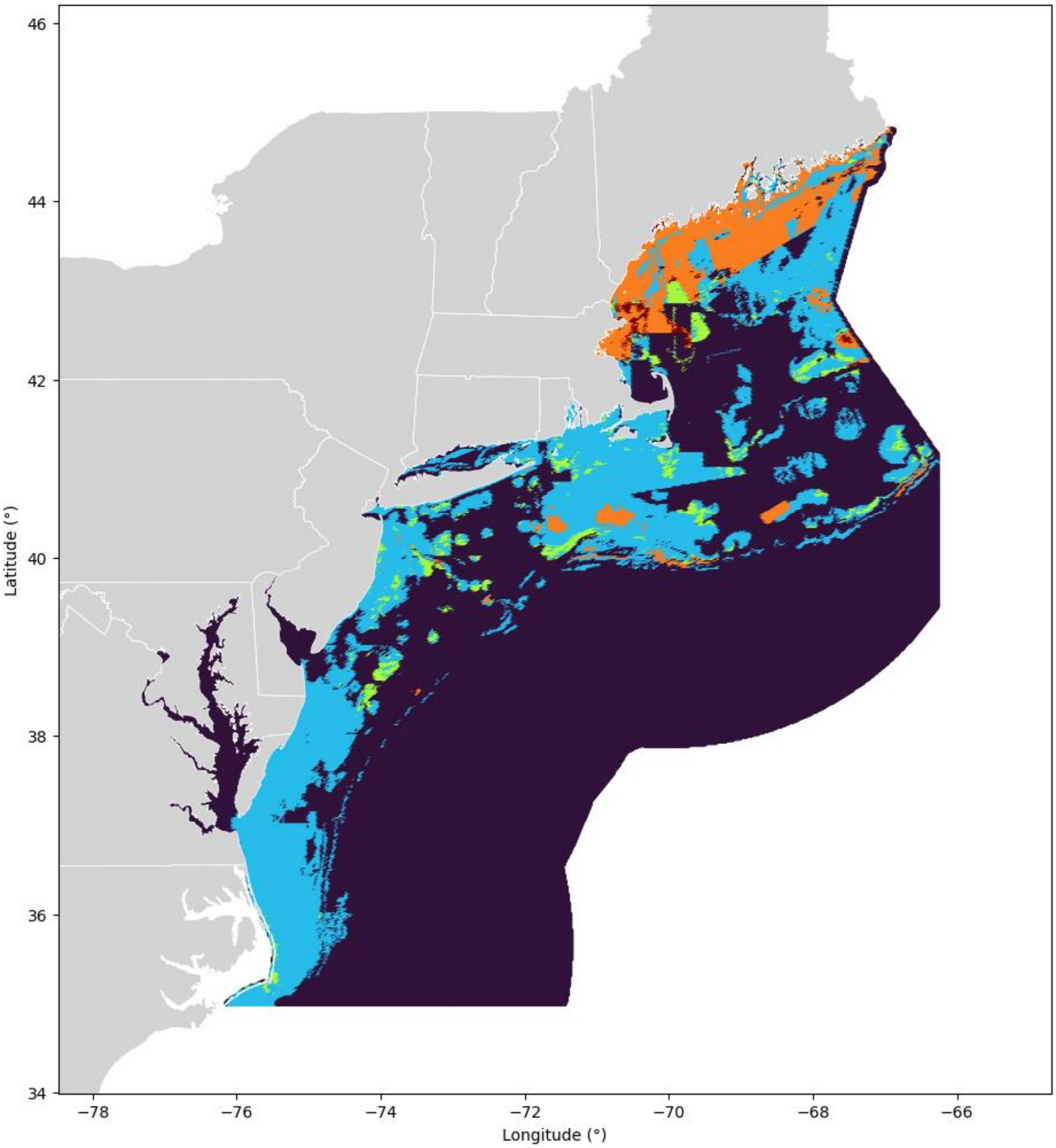


Figure 4. Gear conflict risk levels, color-coded as 'no-data' (purple), 'low risk' (blue), 'moderate risk' (green), 'elevated risk' (orange), and 'high risk' (red) shown through the northeast EEZ based on fixed-gear density and mobile fishing activity averaged between the months of February - April from 2019 – 2021.

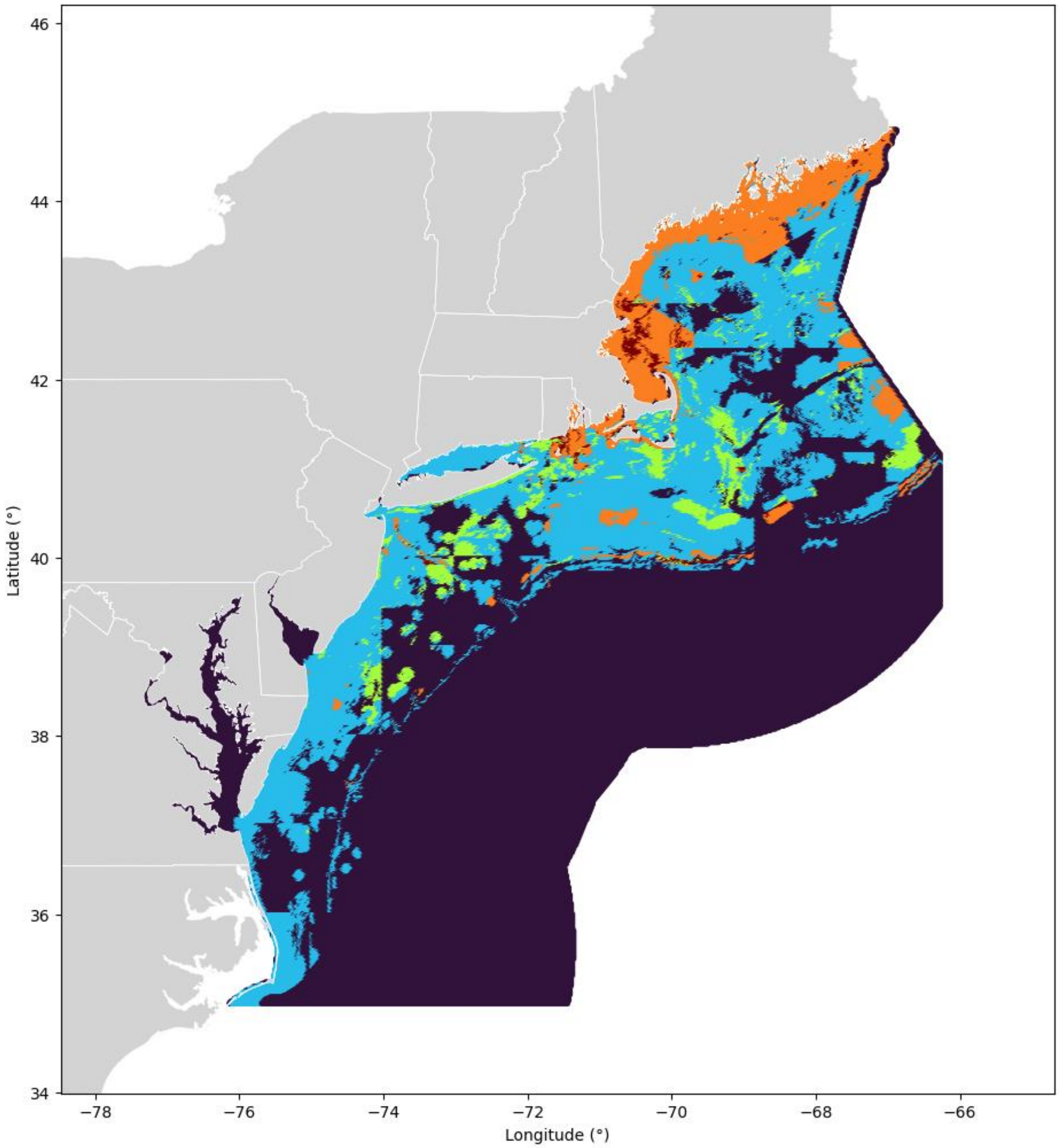


Figure 5. Gear conflict risk levels, color-coded as 'no-data' (purple), 'low risk' (blue), ‘moderate risk’ (green), ‘elevated risk’ (orange), and ‘high risk’ (red) shown through the northeast EEZ based on fixed-gear density and mobile fishing activity averaged between the months of May - September from 2019 – 2021.

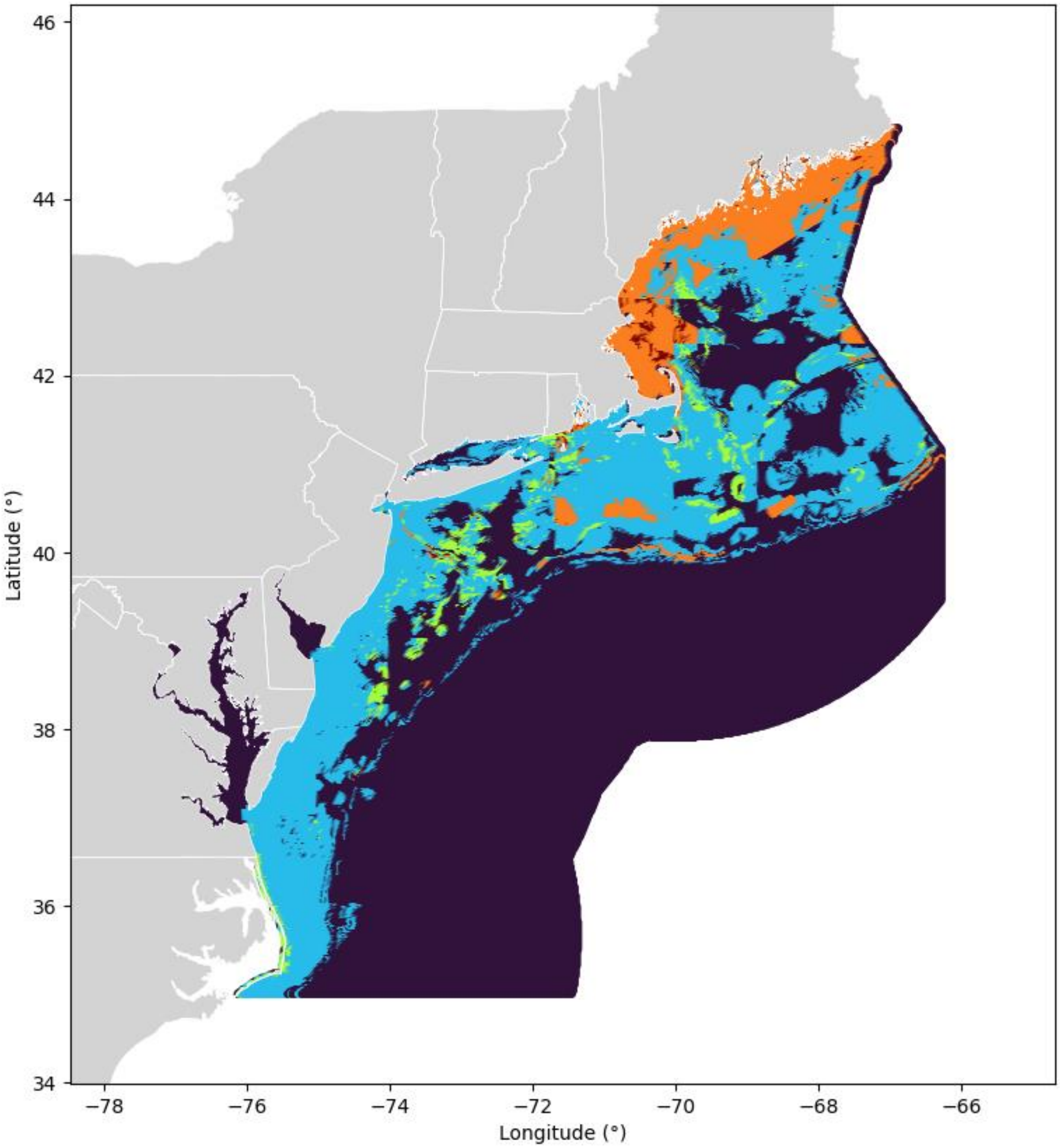


Figure 6. Gear conflict risk levels, color-coded as 'no-data' (purple), 'low risk' (blue), 'moderate risk' (green), 'elevated risk' (orange), and 'high risk' (red) shown through the northeast EEZ based on fixed-gear density and mobile fishing activity averaged between the months of October - January from 2019 – 2021.

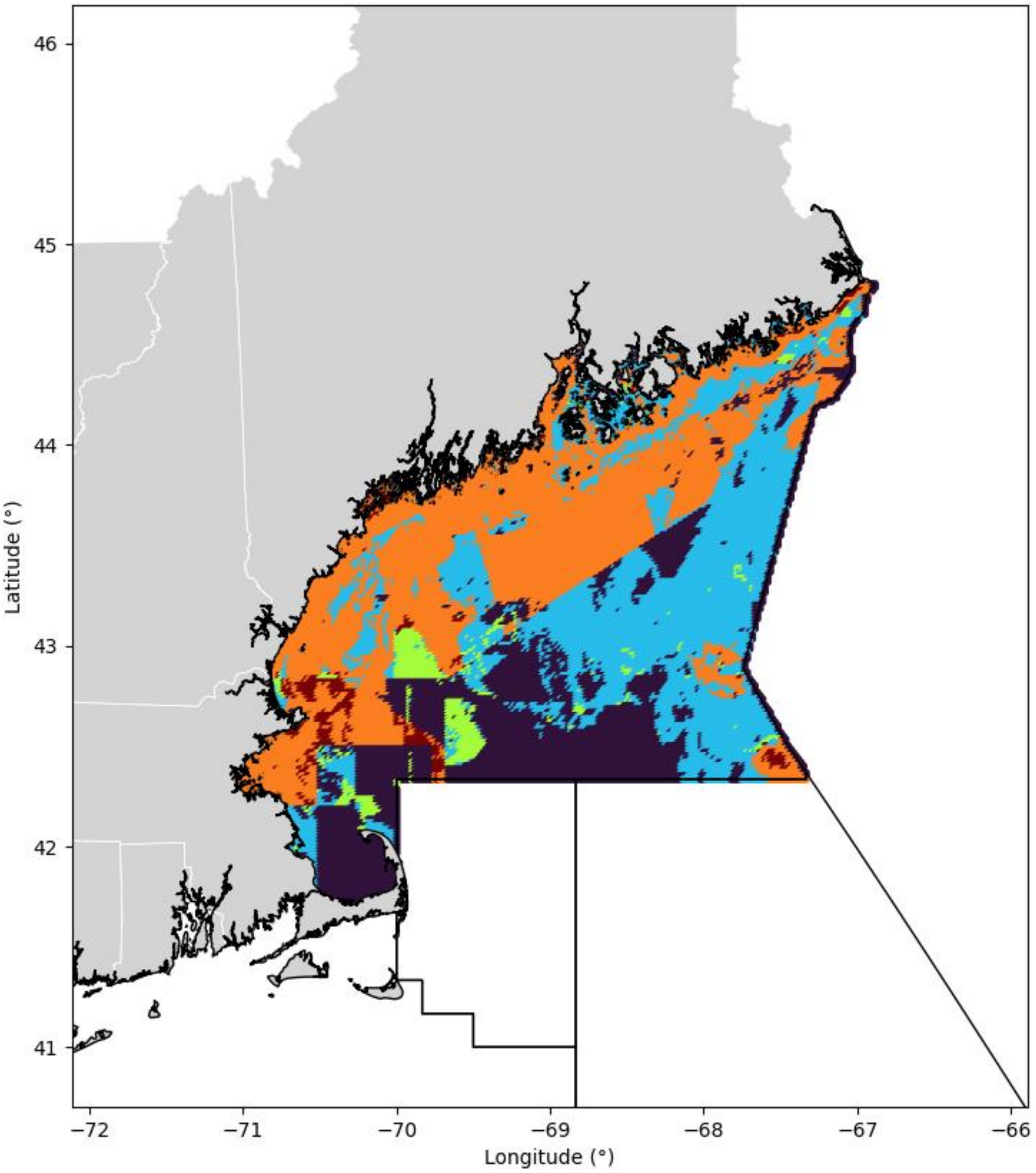


Figure 7. Gear conflict risk levels, color-coded as 'no-data' (purple), 'low risk' (blue), ‘moderate risk’ (green), ‘elevated risk’ (orange), and ‘high risk’ (red) shown in inshore Gulf of Maine (Broad Stock Area 1) averaged between the months of February - April from 2019 – 2021.

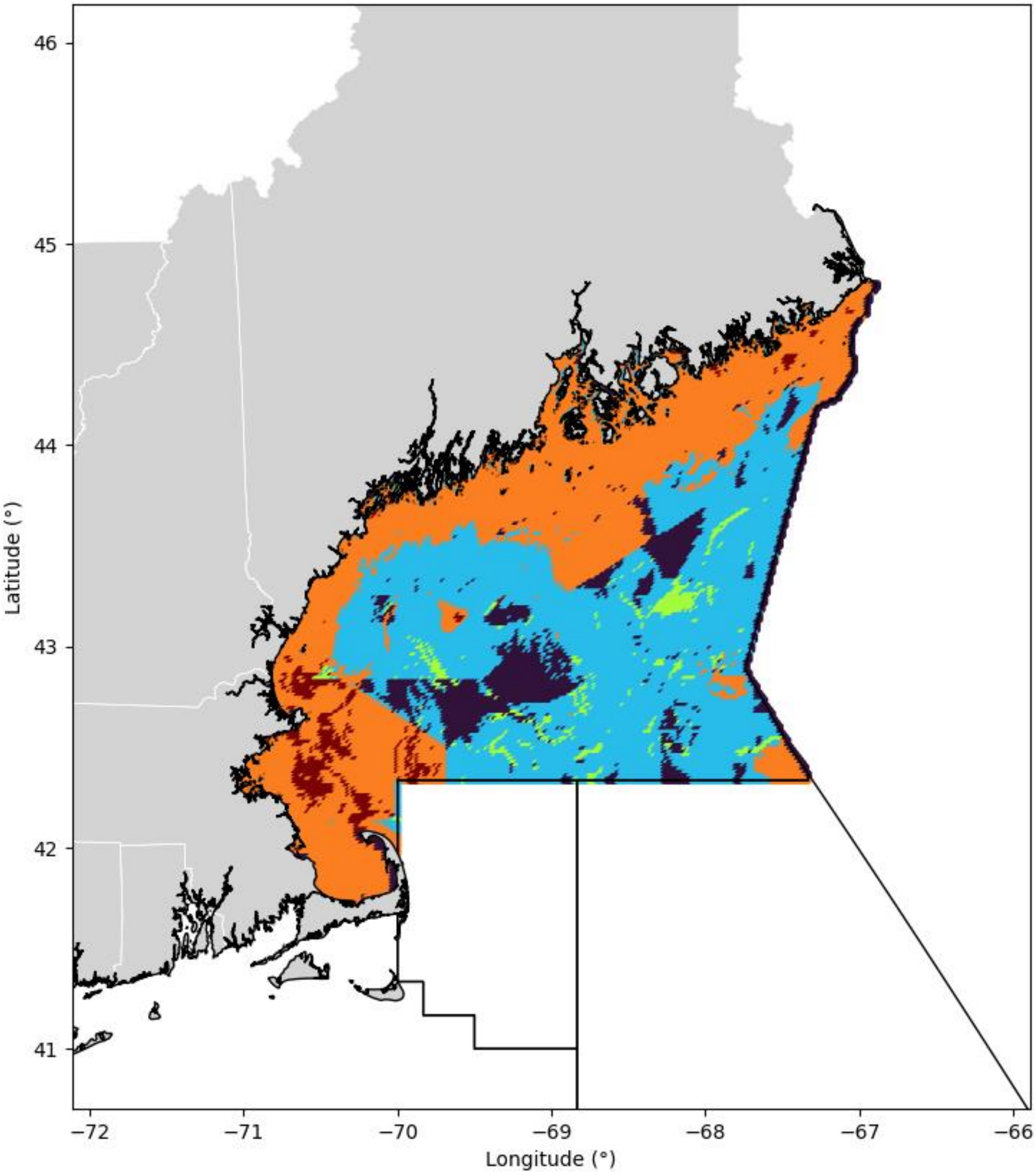


Figure 8. Gear conflict risk levels, color-coded as 'no-data' (purple), 'low risk' (blue), ‘moderate risk’ (green), ‘elevated risk’ (orange), and ‘high risk’ (red) shown in inshore Gulf of Maine (Broad Stock Area 1) averaged between the months of May - September from 2019 – 2021.

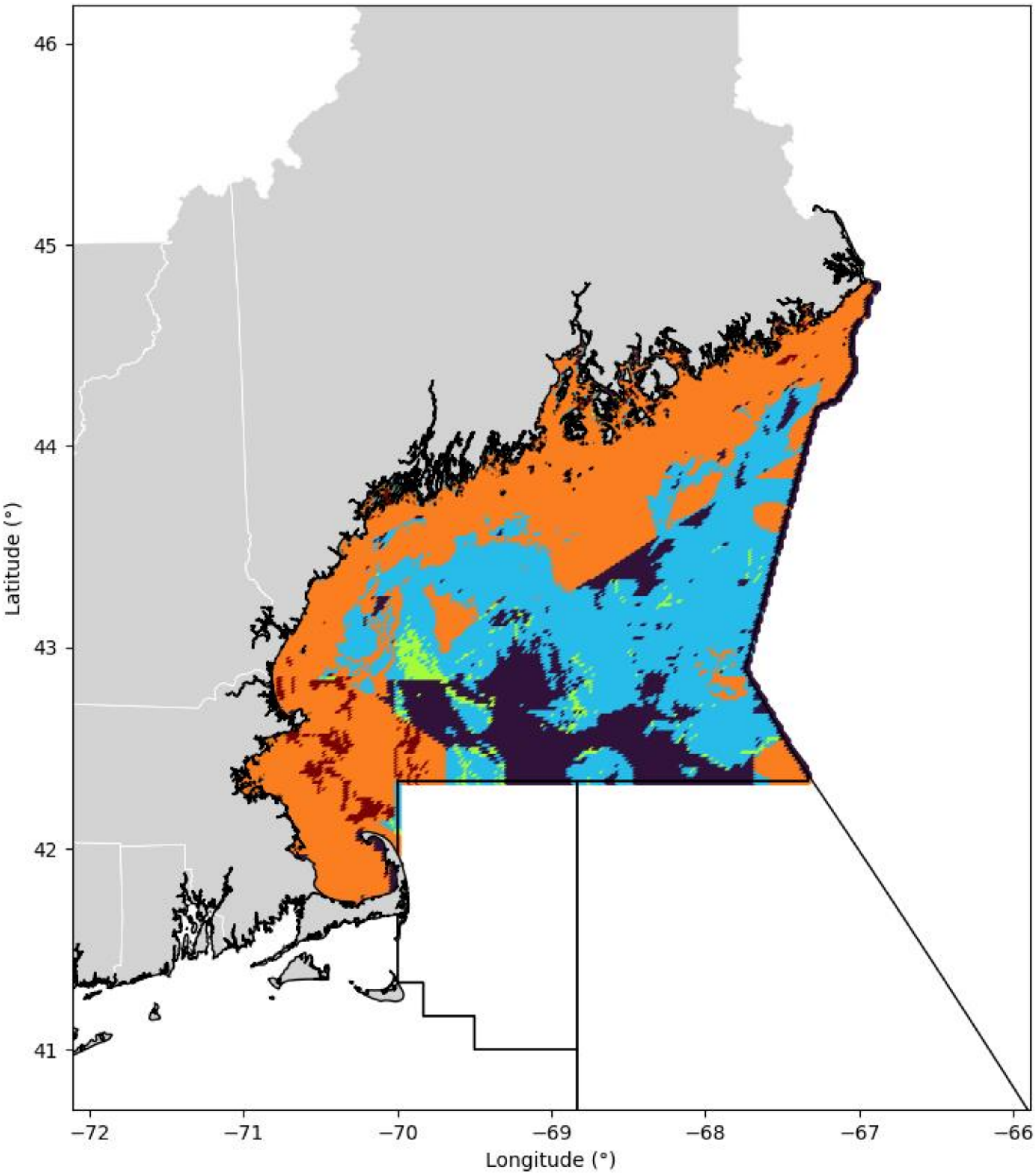
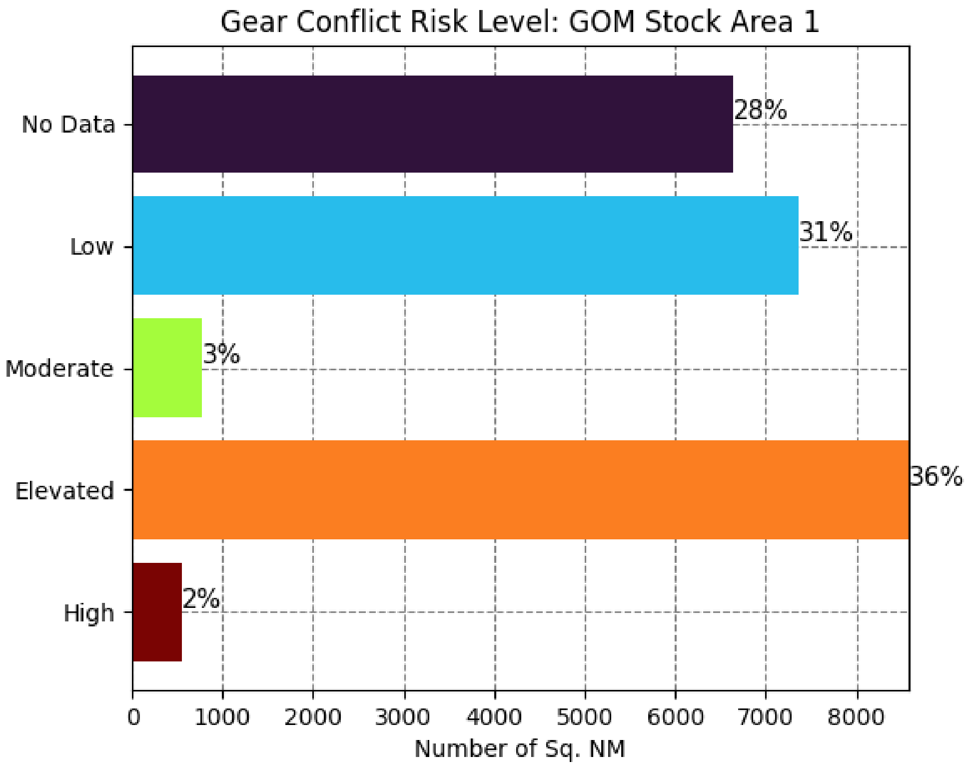
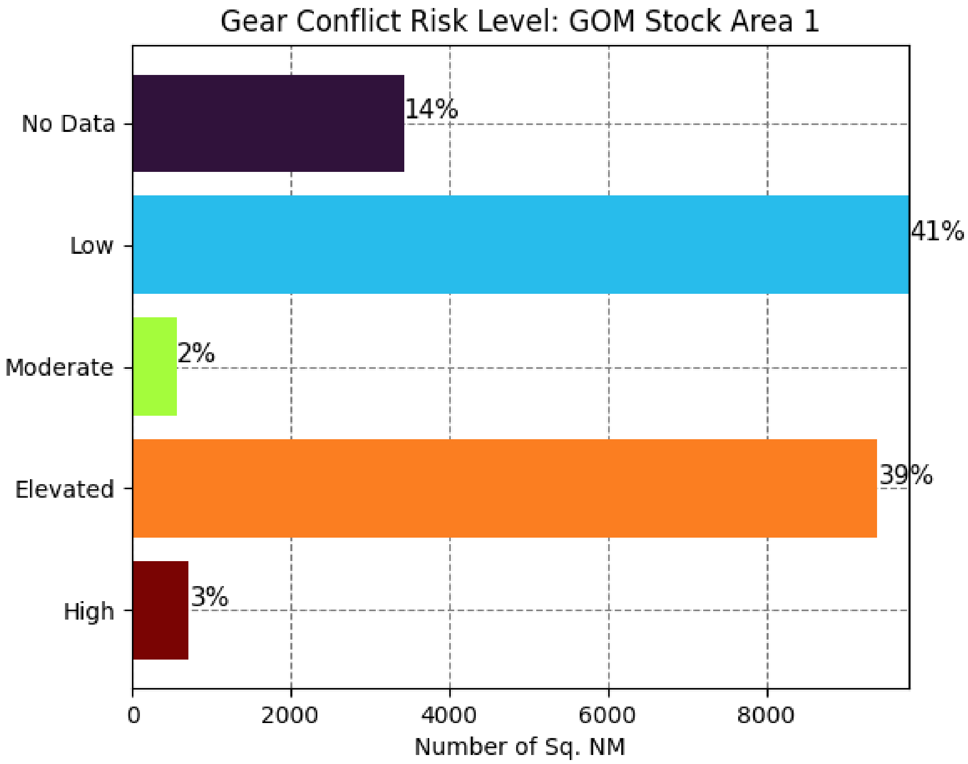


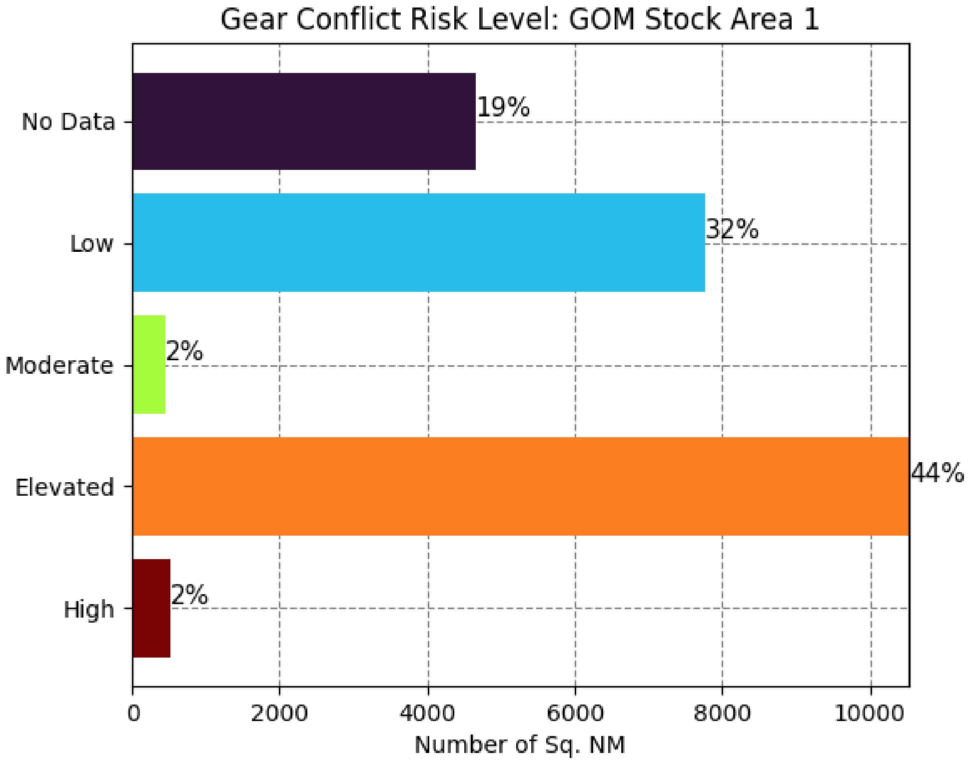
Figure 9. Gear conflict risk levels, color-coded as 'no-data' (purple), 'low risk' (blue), ‘moderate risk’ (green), ‘elevated risk’ (orange), and ‘high risk’ (red) shown in inshore Gulf of Maine (Broad Stock Area 1) averaged between the months of October - January from 2019 – 2021.


Gear Conflict Risk Level: GOM Stock Area 1
No Data
Low
Moderate
Elevated
High
28%
31%
3%
36%
2%
0
1000
2000
3000
4000
5000
6000
7000
8000
Number of Sq. NM

(a)


Gear Conflict Risk Level: GOM Stock Area 1
No Data
Low
Moderate
Elevated
High
14%
41%
2%
39%
3%
0
2000
4000
6000
8000
Number of Sq. NM

(b)



(c)

Figure 10 Gear conflict risk percentages of total square nautical miles Broad Stock Area 1 between (a) February – April, (b) May – September, and (c) October – January for data given between 2019 – 2021.

Analysis of Figure 10 indicates areas of 'elevated' risk between the seasonal averaging periods of 36-44% – over 10,000 square nautical miles. 'High' risk areas comprising 2% make up less than 1,000 square nautical miles but constitute a higher percentage of area than any other broad stock area analyzed in Appendix A-6.

Two of the four vertical-line restricted areas within the broad stock areas analyzed above and shown in Figure 11 were evaluated with respect to their gear conflict risk maps. These closure zones, and the corresponding months for each of the two analyzed zones, are presented below in Figure 12 and Figure 13. Both the South Island Restricted Area and (LMA1) Restricted Area were implemented after 2021, so data obtained before that time period was used to quantify the relative risk of gear conflict in the area.

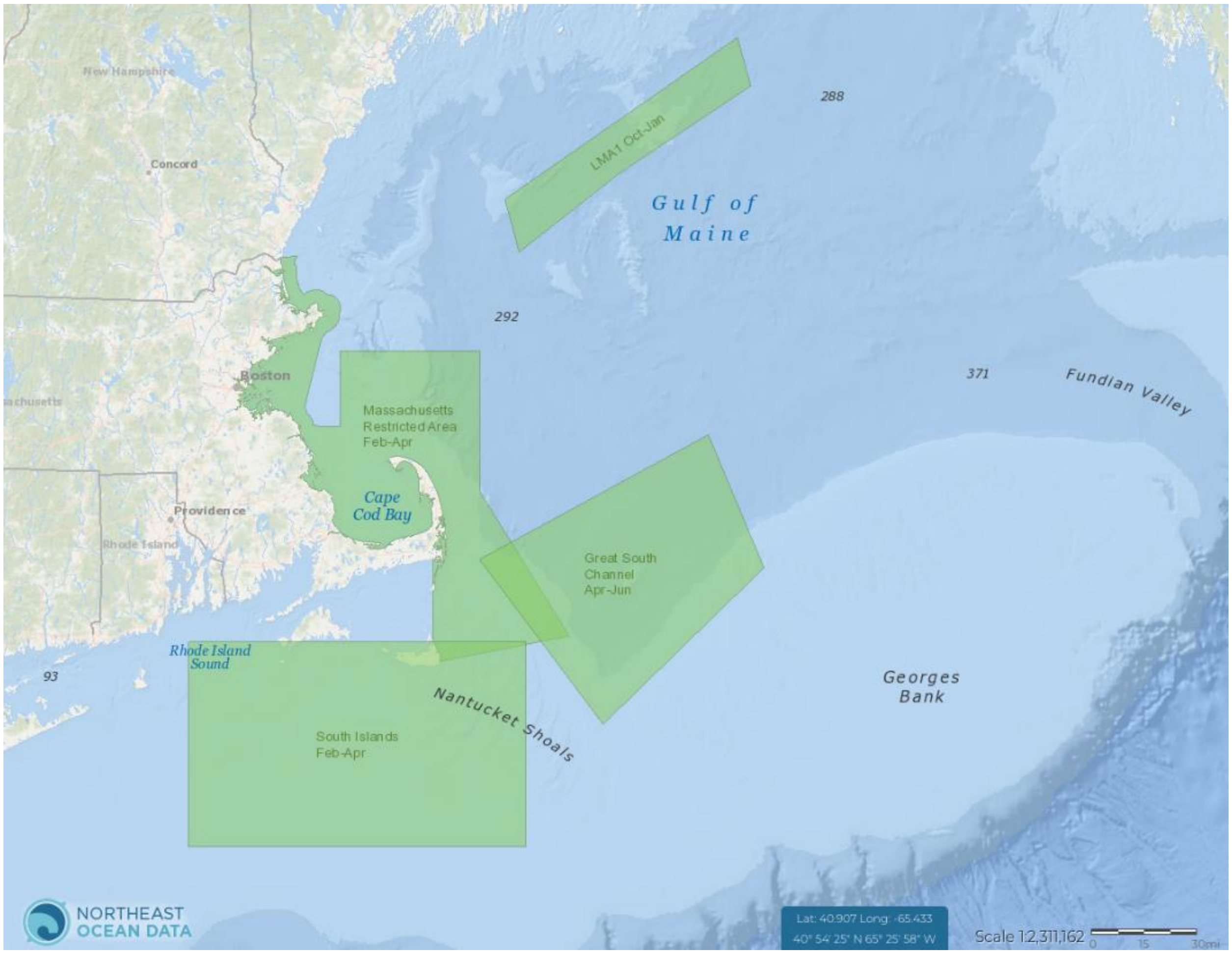


Figure 11. Regional map of Gulf of Maine and Georges Bank showing seasonal vertical line restrictions in South Islands Restricted Area (February to April), Great South Channel (April to June), Massachusetts Restricted Area (February to April), LMA1 (October to January) [21]

As with the broad stock areas, the averaged gear conflict risk maps for both the South Island Restricted Area and LMA1 were computed using the averaged data for both fixed-gear density and vessel activity during the months when vertical line restrictions were in place for each area. These averaged gear conflict risk maps for the two closure zones with gear density data can be seen in Figure 12 and Figure 13 below. Percentages and area totals for each risk level are shown in Figure 14.

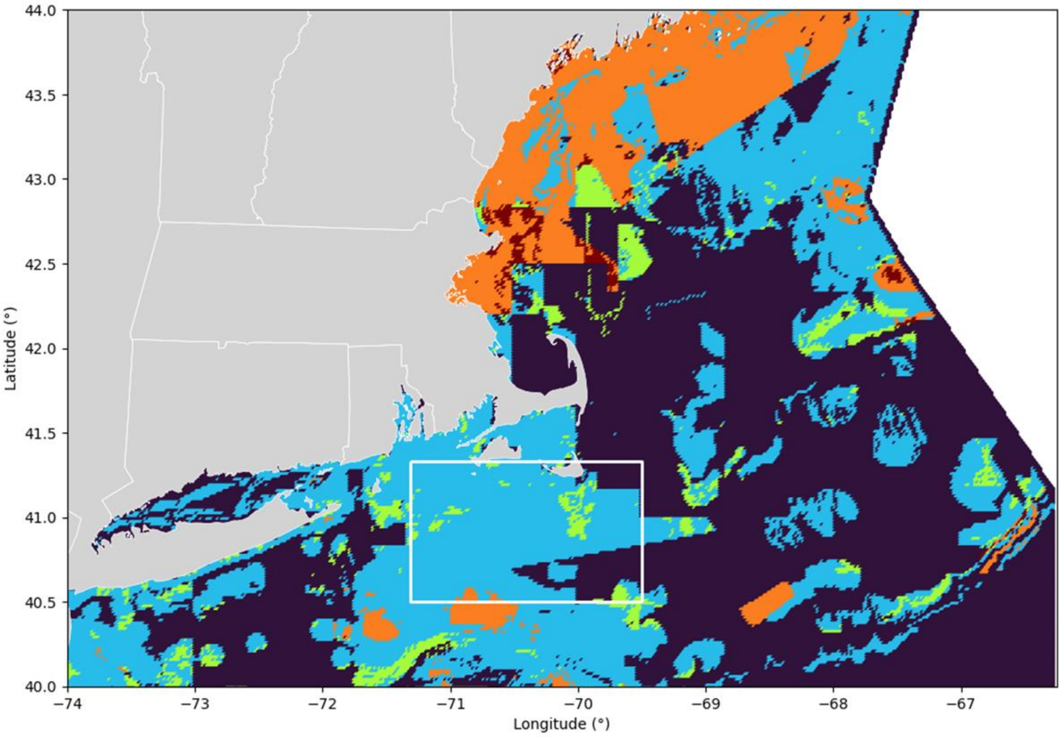


Figure 12. Gear conflict risk levels, color-coded as 'no-data' (purple), 'low risk' (blue), ‘moderate risk’ (green), ‘elevated risk’ (orange), and ‘high risk’ (red) shown the for South Island Restricted Area (Feb - Apr) highlighted in white and surroundings.

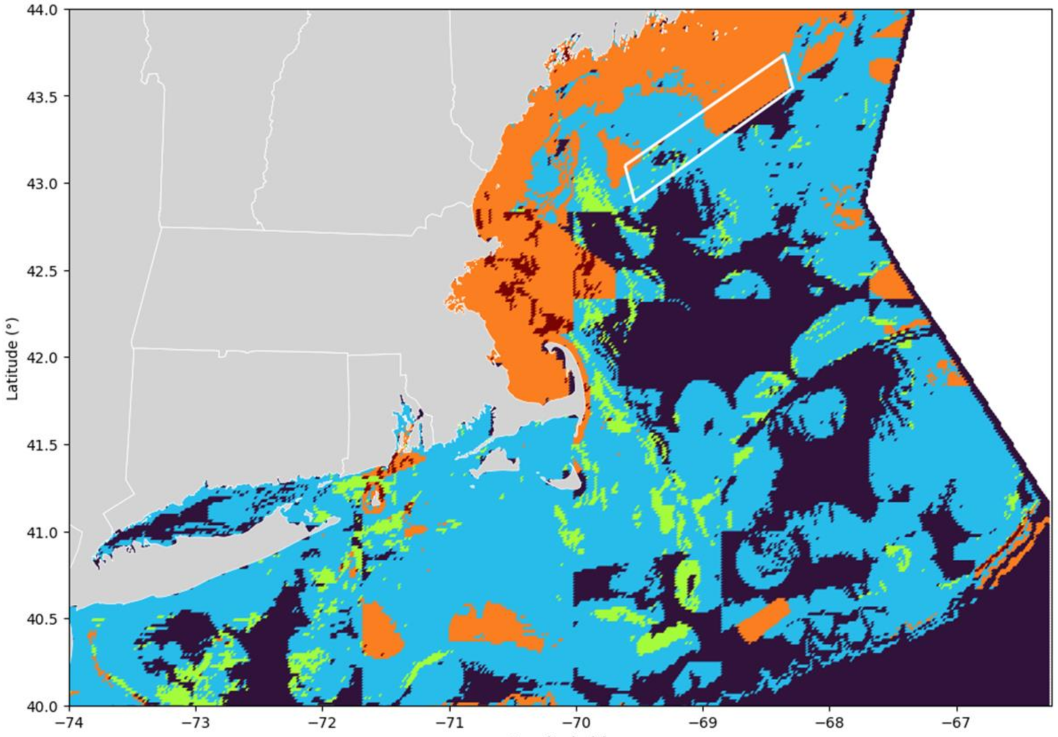
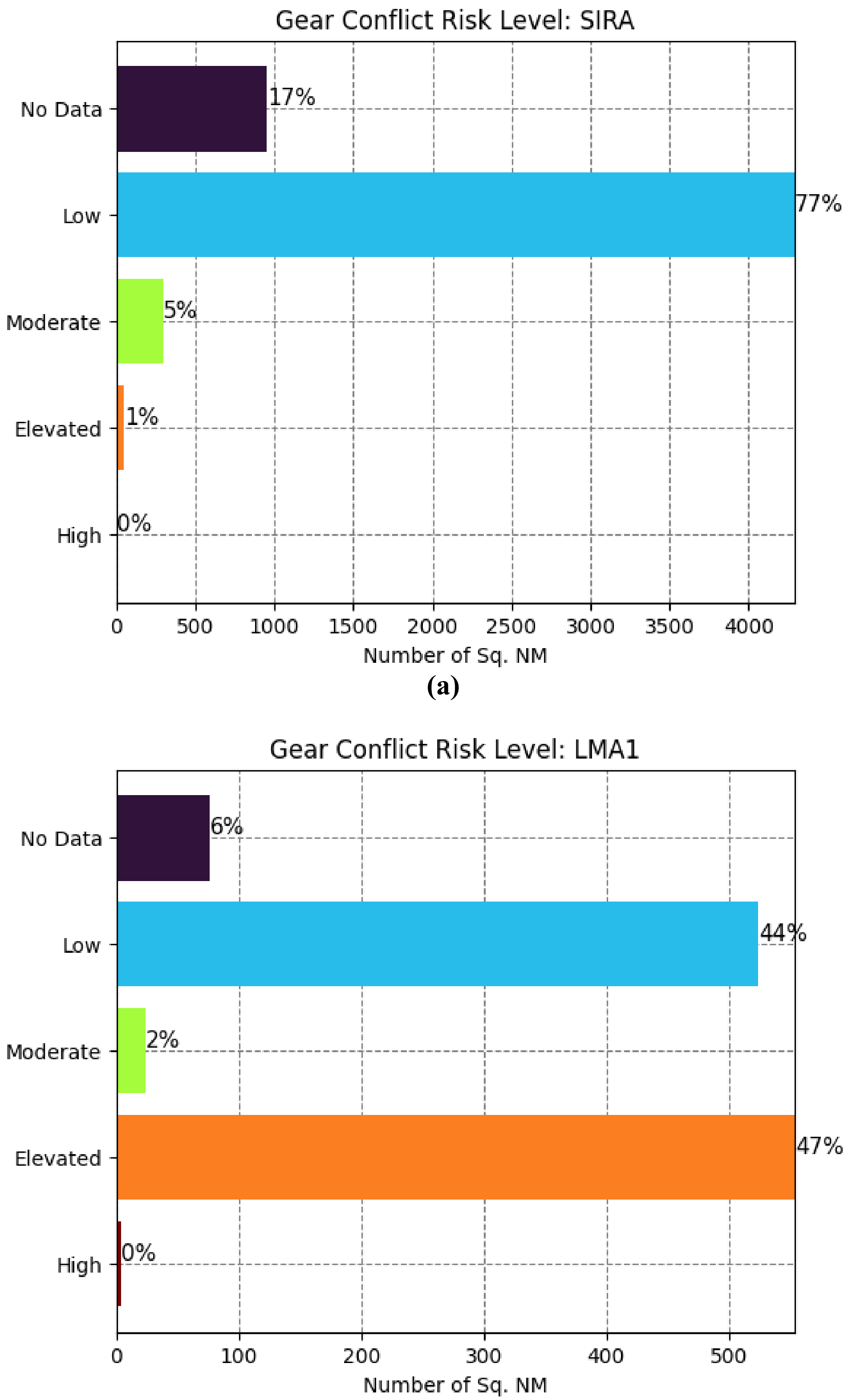


Figure 13. Gear conflict risk levels, color-coded as 'no-data' (purple), 'low risk' (blue), ‘moderate risk’ (green), ‘elevated risk’ (orange), and ‘high risk’ (red) shown the for LMA1 (Oct - Feb) highlighted in white and surroundings.



(a)

(b)

Figure 14. Gear conflict risk percentages of total square nautical miles in (a) South Island Restricted Area between February – April and (b) LMA1 between October – January for data given between 2019 – 2021.

Analysis of the percentages shown in Figure 14 indicate that the South Island Restricted Area is comprised of an overwhelmingly large ‘low’ gear conflict risk area, at 77% and over 4,000 square nautical miles. In this region, ‘elevated’ and ‘high’ risk labels make up less than 1% of the total area. The LMA1 Restricted Area shows a predominantly ‘elevated’ level of gear conflict risk, comprising 47% of the total area and over 500 square nautical miles. Interpreting these results, possible conclusions may be drawn as to what level of accuracy is necessary for gear location marking. For example, in the South Island Restricted Area, gear density is sparse and mobile fishing operations are largely below the assigned risk thresholds. It is possible that GPS surface marking of on-demand gear may suffice in this region whereas within LMA1, with its prevailing ‘elevated’ level of gear conflict risk, acoustic localization may be required to achieve the most precise accuracy metric and prevent gear conflict. Current measures to consolidate fixed fishing gear and assign a minimum number of traps per trawl as specified in the Atlantic Large Whale Take Reduction Plan [22] may mitigate issues due to dense gear emplacement, but further observation is required. More information about how the gear density map was derived from fixed-gear density and vessel activity data can be found in Appendix A.

3.2.2 Localization Accuracy Assessment

To determine what localization techniques may be required in areas at elevated or high risk of gear conflict, a localization accuracy assessment of GPS-only marking and various acoustic localization techniques is presented in this section. Definitive conclusions are not drawn based on a lack of sufficiently rigorous data for the accuracy of existing surface markers, GPS-marking, and acoustic localization techniques.

3.2.2.1 GPS-only Marking

The subsurface localization solution that is the least complex and costly is the use of GPS-only markings. This section examines a previous study of GPS marking-only precision and errors and attempts to trace those errors to contributing factors such as tidal currents. The errors presented in the prior study are significantly greater than 25 ft, meaning GPS marking is likely insufficient in areas at risk of gear conflict.

NFWF funded a study through Commercial Fisheries Research Foundation (CFRF) [23] to assess the gear tagging application “Trap Tracker” for its potential in helping reduce use of vertical buoy lines in fixed-gear fishing through logging GPS tags of gear placement locations. In the study report, the authors find that the error between tagged and actual gear locations is 68.96 ± 44.63 meters and speculate that if this is the baseline uncertainty for Trap Tracker’s gear location marking, then it and other approaches with similar baseline error are not suitable for use in high-effort areas. The authors explore the correlation between the observed errors and several environmental factors, such as sea state and soak time, but find no clear correlations in the results. It should be noted that the errors presented in the report and portrayed here are based on the marked difference between deployment and haul locations and not the true location of the gear on the ocean floor. As such, the influence from the following stated factors may be present on both the deployment and retrieval of the gear and future testing should aim to quantify subsurface gear displacement through acoustic positioning or other more accurate means.

The present aim of this report is to examine potential sources of error with GPS-only approaches and use that error budget to better understand the observations in the NFWF/CFRF report, inform potential follow-on study approaches, and ultimately inform (in part) decisions of what gear marking approach may be suitable in a given scenario (where and when).

One potential source of error is the precision of a GPS receiver itself. Not all consumer GPS devices have the same accuracy, varying in ability to reduce location error through satellite lock counts, assumed motion models, and other means. A potentially beneficial facet of future study would be a side-by-side comparison of logged locations of the system with a trusted, high-performance GPS receiver.

A second source of error inherent to the problem space is tidal currents. A notional model of how currents affect gear location marking errors is illustrated in Figure 15. In this model, the vessel and the traps (in this case single) move with the currents, which are uniform throughout the water column. A typical example of current forecasts for the areas of interest is shown in Figure 16, where peak-to-peak current speeds vary with tidal cycle from ± 1.0 knot (0.5 m/s), or 0.7 knots rms (0.4 m/s). If a GPS tag is created exactly at the location the gear is placed at the surface, and the trap descends at 1.0 m/s (this will vary by gear configuration), then the root mean square placement error owing to tidal currents will be 0.4 m/m depth. For example, in 50 m of water the root mean square displacement error will be 20 m. Note that the direction of tidal currents will vary with both location and tidal phase.

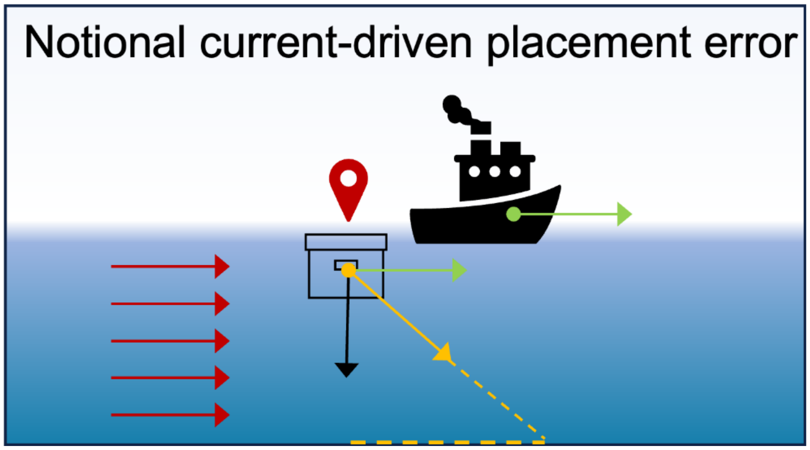


Figure 15. Notional model for current-driven gear placement errors. Red vectors are tidal current, and green vectors are resulting gear and vessel drift. Red pin is location of GPS marking. Black arrow is gear descent. Yellow vector is net gear motion, and yellow dashed line is gear overall placement uncertainty.

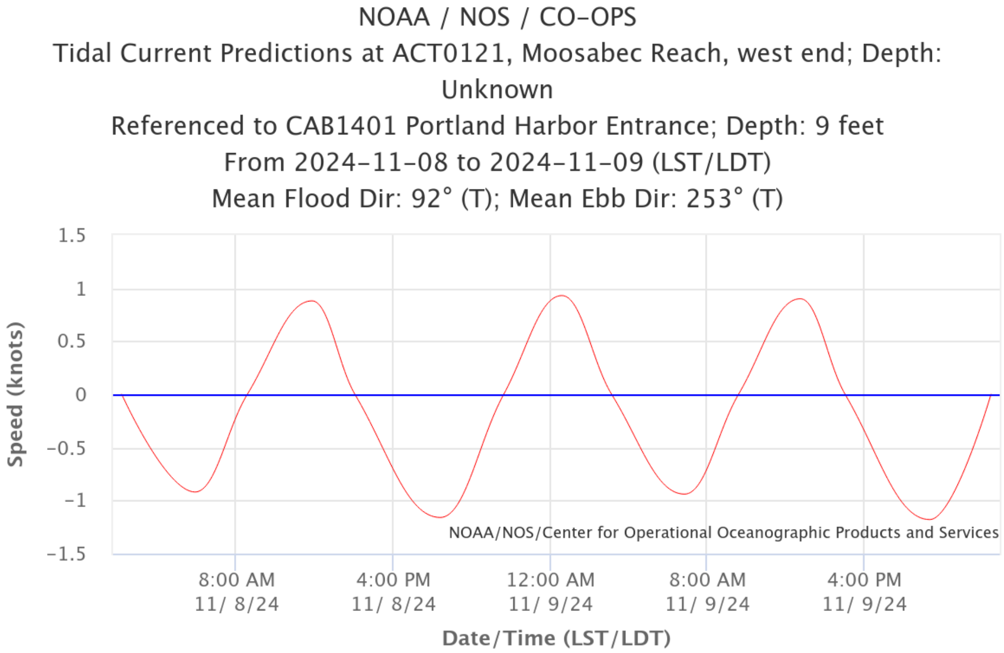


Figure 16. Example NOAA tidal current forecast [24].

A future study of GPS-only gear marking will benefit from the inclusion of a means and plan to survey locations of placed gear when they reach the bottom, for instance through acoustic survey, to track the gear's drift during placement. Additionally, location errors reported in easting and northing, rather than just by range, will lend further insights into the sources of systemic gear marking errors. Given the magnitude of the mean and standard deviation location errors, as well as poor control over test variables that are physically unrelated to gear displacement (e.g., GPS-receiver error), a similar study with greater levels of control should be repeated for better insight into surface marking location discrepancies.

3.2.2.2 Acoustic Localization Techniques

In areas of elevated gear conflict risk, such as inshore Gulf of Maine shown in Figure 7 and Figure 9, it is likely that the accuracy of GPS-marking will be insufficient due to uncertainties detailed in Section 3.2.2.1. Thus, an acoustic localization capability should be a requirement of any proposed interoperability standard in areas where gear conflict rates necessitate it.

Derived from work originally conducted by Baumgartner et al. [11] comparing various options for acoustic localization, the benefits and drawbacks of each technique are summarized in

Table 3 below. SART is not considered here in detail as it is de-emphasized by the authors of the original study as a solution due to application constraints and complexities for on-demand fishing [13].

Table 3. Summary of benefits and drawbacks of proposed acoustic localization techniques.

	Benefits	Drawbacks
Ranging	• Simplest and lowest cost acoustic option • Does not require common acoustic signaling • Computations can be performed onboard vessels or in the cloud • Only requires one vessel	• Likely requires a thru-hull acoustic transducer • Requires multiple measurements at different locations which may require concerted effort • Accuracy can be compromised in certain geometries
Directional Ranging	• Improved accuracy over range-only in certain cases • Requires fewer measurements than range-only • Does not require common acoustic signaling • Only requires one vessel	• Requires a potentially expensive directional thru-hull acoustic solution • Requires complex calibration for accuracy
SART	• Lower cost as compared to directional ranging • Limits acoustic transmissions through brokering performed by the subsurface gear • Likely achieves better accuracy than single-vessel ranging by improving measurement geometries from multiple vessel tracks	• Requires measurements from multiple vessels, necessitating a universal acoustic solution • Requires additional processing to be performed by subsurface gear

The FONTUS authors revisit and endorse multiliterate localization through both acoustic ranging and directional ranging in their open-standard proposal via a comprehensive simulation exploring the effect of geometry, stochastic error, and localization effort between two independent vessels [13]. In this study, an open-standard acoustics architecture is considered between two interoperable vessels - one deploying gear and the other transiting in the region – to analyze localization accuracy resolved under this scenario. Figure B-7 from [13] portrays the resultant accuracy of these scenarios in order to assess the benefits of multiliterate and directional multi-vessel ranging.

Within that study, the results for the acoustic ranging simulation indicate that the average positional error achieved under the worst-case geometries, when all measurements are performed along the same line of bearing between the surface vessels and the subsurface gear, is approximately 24 meters +/- 12 meters with a standard timing error of 1 millisecond on position estimates. This error, however, quickly decreases with increased angular diversity between measurement locations.

3.2.2.3 Single-Vessel Acoustic Localization

While the study presented in Section 3.2.2.2 examines localization accuracy with two interoperable vessels conducting the measurement survey, there is no reason why this study and its results could not be reinterpreted for a single vessel both deploying the gear and performing all localization range measurements toward multilateration of a final subsurface gear position. In [11], this approach is deemphasized as a possibility because it would require survey effort on behalf of an individual fisher, which is not a practical undertaking during normal fishing operations. Though in this interpretation of the results, the simulation of gear position error calculated in [13] suggest that only modest angle diversity is required on part of an individual fisher to geolocate underwater gear with accuracy comparable to multi-vessel cooperative localization. This would require a maneuver off a single bearing angle by 20 degrees or more to achieve a sub-8-meter average position error according to Figure B-7 from [13], which may be modest enough to require no additional effort on behalf of a fisher in the midst of trawl deployment operations. These results support a finding that between relative angles of 20 to 170 degrees off bearing, and 200 to 350 degrees off bearing, a single vessel using a separate acoustic signaling scheme could achieve high localization precision using multiliterate ranging only.

The geospatial analysis conducted in this work indicates that high-resolution location measurements of subsea gear would be warranted in localized areas where gear conflict may occur, and that these conditions may be satisfied by single vessels performing acoustic ranging assuming trawl deployment, or overall trawl length, permit it without additional survey effort on behalf of the fisher. Results derived in Section 3.2.1 identify inshore Gulf of Maine as having significant levels of ‘elevated’ and ‘high’ gear conflict risk, suggesting that in this region above all others, acoustic localization may be necessary. Information provided by the Maine Lobsterman’s Association on characteristic trawl lengths within this location, specifically Zone’s A through G, which have minimum trap counts dictated by the Atlantic Right Whale Take Reduction Team [25], was gathered across a region of 14 zones and subzones within. From this survey, 8 out of 14 regions fish trawls less than 700 meters, and 13 out of 14 regions fish trawls less than 800 meters (approximately half a mile in length). This leaves only Zone B/Swan’s Island with characteristic trawl lengths greater than half a mile (878 meters), suggesting that in all other areas a single fisher may be able to communicate with either end of a trawl simultaneously. This finding is of note because while federal requirements dictate a maximum trawl length under 1.5 miles [9], the comparatively modest length of trawls fished, and thus modest range to each subsurface on-demand unit, in this high density area may allow for highly accurate multilaterate localization without any survey effort undertaken by the fisher. In this situation, similar to the case of a single endline/on-demand unit trawl, the normal vessel maneuvering after deployment of the second endline may introduce enough angular diversity between the vessel and both underwater on-demand units that the location can be resolved with the high levels of accuracy suggested in [13]. This suggestion assumes that all on-demand gear can support half a mile of range at minimum, and while that is the threshold in the FONTUS specification, it may not be ubiquitous to all vendors under all fishing conditions.

3.2.3 Localization Analysis Summary

In Section 3.2, a geospatial analysis was presented which showed that gear conflict risk varies dramatically both across and within fisheries. In the majority of the South Island Restricted Area, gear conflict risk is low and GPS marking may be a sufficiently accurate solution. However, inshore Gulf of Maine has large areas of ‘elevated’ and ‘high’ gear conflict risk, where acoustic localization is likely necessary. A summary of the localization capabilities of existing on-demand gear is provided in Section 3.3.3.

Definitive conclusions are not drawn in this work based on a lack of quality data for the accuracy of existing surface markers, GPS-marking, and acoustic localization techniques. Furthermore, the thresholds used in the geospatial analysis should be rigorously defined prior to any location-specific requirements being set.

It should be stated that both the multi-vessel localization scheme proposed in FONTUS, and the MITRE single-vessel suggestion outlined above, will require the installation of a thru-hull transducer. This modification will be necessary for measurements to happen in-situ with fishing or transiting activities, as there can be no expectation that fishers will undertake the multiple measurements necessary for localization without automated orchestration. This recommendation presumes the performance of the thru-hull transducer is at least as effective as the current temporary deployment strategies, but this assumption should be validated with empirical trialing.

More experimental work remains to be done to quantify the accuracy of various localization techniques relative to traditional surface markings, but the current data suggests sufficiency in a single-vessel acoustic ranging approach rather than multi-vessel localization employing a universal acoustic standard in the predominant region where areas of elevated and high gear conflict risk occur. Recommendations are made for follow-on work in Section 4.5.

3.3 Compatibility of Existing On-Demand Gear with FONTUS

Research Question

4. *How do proposed acoustic interoperability architectures align with what is available in today's market?*

This section examines the configuration and readiness of existing on-demand systems including patent-pending Ropeless Systems, Edgetech, Sub Sea Sonics, and Teledyne in the event of acoustic standard implementation. Note that this is not a comprehensive list of existing on-demand gear systems but rather a majority group of acoustic subsystem developers who responded to an RFI query issued by MITRE in January 2024, the template of which is provided in 5Appendix D Table 10. It is of interest to understand the impact that standard implementation may have on any existing system, so as not to render them obsolete and reduce the number of products and market selection that may effectively serve fishers, and by proxy NMFS, in the event of a fishery closure. Existing systems are effective, designed to respond to the needs of users and optimized around endurant and repeated operations in undersea environments. If an on-demand standard is implemented, current systems will have to adapt to meet the requirements of said standard. This is true not just for the case of a universal, multi-access acoustic solution, such as the specification given in FONTUS, but also for any interoperability proposal which requires cloud connectivity or a universal deck box. These concepts only exist as prototype systems today and realization will include development challenges as they are implemented at scale. Both a cloud database and a universal deckbox, however, are less disruptive to existing acoustic on-demand systems than the potential effects of implementing a universal acoustic signaling scheme across all makes and models of on-demand gear. For the purpose of understanding the impact of implementation of a universal acoustic standard, a specification comparison of the FONTUS standard as it compares to current on-demand systems is presented in Table 4. The FONTUS system is used in this comparison scenario not because it is the only possible path forward, but because it has been identified as the most developed standard with the highest potential for deployment. This comparison helps to illustrate the existing gaps in technology readiness necessary to support FONTUS implementation.

Table 4. Existing System Specifications versus FONTUS v1.0 Requirement

Vendor Name	**Ropeless Systems, Inc.**	**EdgeTech**	**Sub Sea Sonics**		**Teledyne**	**FONTUS v1.0 Requirement**
Product Name	*Ropeless RISER™*	*5112 On-Demand System*	*AR 50AA*	*AR 60E*	*ATM900/ UCM903 Modem*	*N/A*
Communication System	Half Duplex	Half Duplex	Half Duplex	Half Duplex	Half Duplex	Half Duplex
Modulation	PSK	BFSK-PPM	MF-PPM	MF-PPM	MFSK	FH/BFSK
Acoustic Localization Support	Directional Ranging	Ranging	Ranging	Ranging	Directional Ranging	Variable
Message Length [s]	.008s - .032	13.772	1.0	1.0	1.3	2.0
Center Frequency [kHz] Downlink	24	17.75	35.714	35.714	25	25
Center Frequency [kHz] Uplink	24	24.5	35.714	35.714	25	25
Bandwidth [kHz]	12	0.4	Not Specified	Not Specified	5	7.52
Narrow or Broadband?	Broad	Narrow	Narrow	Narrow	Broad	Broad
Transmit Source Level Uplink 1Vrms in.	176 dB	178 dB	151 dB	171.5 dB	Not Specified	Variable
Transmit Source Level Downlink 1Vrms in.	176 dB	176 dB	181.5 dB	181.5 dB	Not Specified	Variable
Max Transmit Source Level Uplink	Not Specified	183 dB	Not Specified	Not Specified	183 dB	N/A

Vendor Name	Ropeless Systems, Inc.	EdgeTech	Sub Sea Sonics		Teledyne	FONTUS v1.0 Requirement
Max Transmit Source Level Downlink	Not Specified	176 dB	Not Specified	Not Specified	173 dB	N/A

3.3.1 Comparison of Frequency Response Requirements

A major divergence between much of the existing gear outlined in Table 4 and the FONTUS proposal occurs due to the broadband frequency response requirements of FONTUS. As discussed in detail within Section 1.2, this interoperability approach is contingent upon a single acoustic signaling technology between different makes and models of gear and would require all active acoustic on-demand gear to be able to reproduce the waveform specific to FONTUS. FONTUS requires half-duplex communication, meaning both surface and subsurface acoustic components must be able to transmit and receive acoustic signals, though not simultaneously. All gear surveyed herein supports half-duplex communication. An examination of center frequency, bandwidth, and broadband versus narrowband classification yields the most insight into the challenge for existing gear to comply with FONTUS requirements. These attributes are characteristic of a device's frequency response, which is limited by the physical hardware components and describes the sensitivity of a certain system toward reproduction of acoustic signals across a frequency range. While three out of the four vendors, and four out of the five models, of on-demand gear are within close frequency proximity (< 1 kHz) of the 25 kHz requirement of FONTUS, two of the vendors, and three models of gear, cannot attain the bandwidth requirement of 7.52 kHz. While the Teledyne ATM900 does not meet or exceed the bandwidth requirement, they have been active in augmenting their system to reproduce FONTUS [4] and are considered within acceptance criteria.

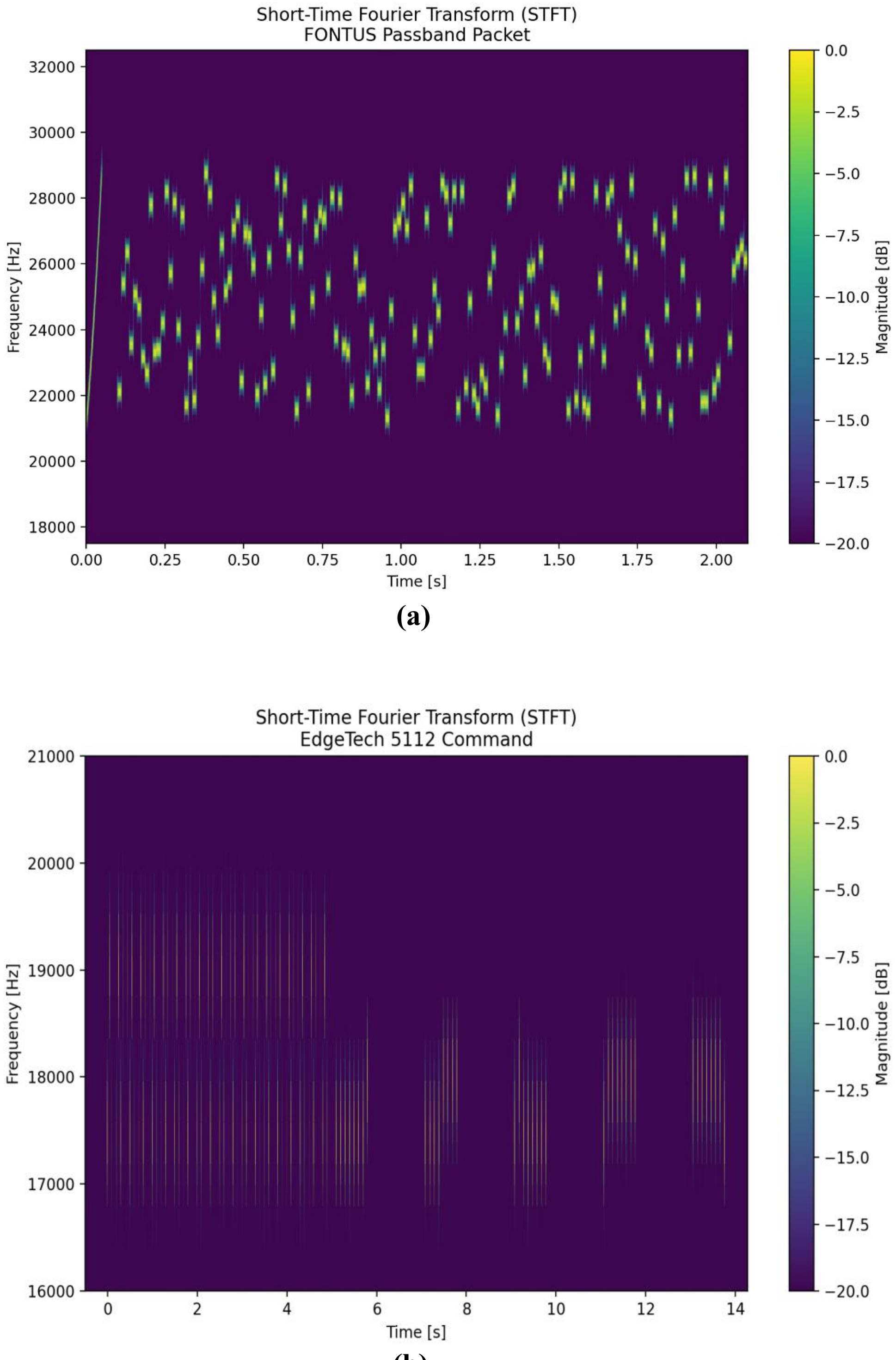
Three models from EdgeTech and Sub Sea Sonics may be considered narrowband systems based on the criteria that their bandwidth is much less than their center frequency of operation. This is a key difference and potential inhibiting factor toward adoption of the FONTUS universal acoustic signaling approach on this gear. Several factors may limit simplistic modification of these systems to adapt a broadband signaling approach. The quality-factor of the acoustic transducer used, bandwidth of the implemented electronic filtering, physical base-banding circuitry, sample rates of the analog-to-digital converters, and digital signal processing integrated circuits may all pose limitations in these systems. Further consideration must be given to design factors around the efficiency and battery life of resonant, narrowband systems that would have to be entirely reconsidered if adoption of a broadband acoustic waveform was mandated. While MITRE has not done a detailed engineering analysis to prove that these systems cannot be readily modified, direct discussions with on-demand gear manufacturers have supported that inference.

3.3.2 Comparison of Modulation Approaches

FONTUS uses a low-data rate signaling method known as Frequency Hopping/Binary Frequency Shift Keying (FH/BFSK) non-coherent modulation to facilitate the coded multi-access approach necessary for universal acoustic signaling in a challenging underwater environment. This approach will not be described in detail within this report, but, importantly, all modulation schemes defined within Table 4 are designed to transmit information, such as on-demand gear marking data, through an encoded bit-sequence and certain methods are more effective than others. Broadband modulation approaches, such as FH/BFSK, are designed to overcome a signal corrupting effect, known as multipath, within an acoustic channel. This physical phenomenon is due to the reflection of a propagating acoustic signal with boundaries in the underwater environment, commonly the air-water interface and the seafloor. The interaction with these boundaries will result in specular reflection of the acoustic signal along a ray path or perpendicular to a line of constant phase from an advancing wavefront, eventually intersecting at a receiver location with some amount of delay time corresponding to the accumulated distance traveled compared to the direct path of propagation from the source. The primary advantage afforded by broadband FH/BFSK in a strong multipath environment, such as a littoral fishing area with a rocky seabed, is through the frequency diversity of the modulated signal, which limits interference from a prior bit within an information bitstream. Narrowband modulation approaches, such as those implemented on EdgeTech and Sub Sea Sonics, address this phenomenon with long guard times between symbols to reduce the risk of interference, resulting in a longer overall message time.

A visual comparison of the normalized signaling differences between the proposed FONTUS waveform and an EdgeTech 5112 command sequence is available in Figure 17 to illustrate the difference in total utilized bandwidth. These two waveforms were chosen as representative examples of broadband and narrowband modulation approaches, respectively. At the time of this report, a comparative study of the performance of the two waveform styles is being done through a follow-on effort.

Both Ropeless Systems, Inc. and Teledyne offer gear with the requisite bandwidth and similar coded multi-access modulation schemes to presumably support FONTUS. While adoption of a universal acoustic standard should not be considered trivial, their operating principles are similar to FONTUS, and it is reasonable to believe that implementation is readily attainable.



(a)

(b)

Figure 17. The Short-Time Fourier Transforms (STFTs) of (a) a FONTUS passband signal centered at 25.0 kHz over a duration of 2-seconds and (b) an EdgeTech 5112 Command alternating around a center frequency of 17.75 kHz after the signal preamble over a 13.772-second duration.

3.3.3 Comparison of Acoustic Localization Support Capability

The FONTUS proposal does not mandate a single localization capability, but rather supports a variable scale of solutions, from GPS-only marking discussed in Section 3.2.2 to directional ranging through a USBL array, as one example. This system is meant to scale with requirement, cost, and gear conflict risk of the fishery where on-demand gear is being fished. Because there is no defined requirement put forth by the FONTUS standard, and GPS-only marking does not require any form of acoustic signaling to support, this subsection will focus on what current manufacturers can support, not where they diverge from the proposal. Across all four manufacturers surveyed, their current offerings of acoustic gear support range query or directional range query operations. In principle, this is achieved by sending a range request message from a topside transducer to a piece of subsurface gear which replies upon receipt of the message. The propagation delay between when this message is sent and when it is received, minus any pre-determined processing latency, corresponds to twice the ambiguous radial distance when multiplied by the average channel sound speed. This relative measurement of slant range can be transformed to an absolute position on a geographic coordinate system using the vessel's navigation unit. Outlined in Section 1.3.1.2, and further supported in Section 3.2.2.2, multiple reports of slant range sampled by a single vessel may be fused through a process of multilateration to resolve an object's position in a geographic coordinate system given input from the vessel's navigation unit. The fact that all manufacturers surveyed support this capability offers a way forward for implementation of an acoustic localization approach using separate acoustic signals specific to each vendor.

Additional information is available through a bearing angle estimate supported by both the Ropeless Systems, Inc. Ropeless RISER™ and Teledyne array equipment. These systems require multi-channel processing to resolve a direction of arrival estimate of an acoustic signal impinging on a receiver, such as a range response arriving from a subsurface unit to a thru-hull USBL. While this capability allows for the use of only a single observation to resolve a position, the analysis by Baumgartner et al. [13] found that even modest errors inhibit accurate localization for source to receiver ranges greater than 0.125 NM. In addition, cost generally scales inversely with error, so the higher accuracy USBLs are often more expensive. While some benefit may be achieved from the use of a directional ranging solution, their technical merits are not substantiated by analysis applicable to on-demand fishing, and two of the four surveyed manufacturers do not support this capability.

In areas subject to high gear conflict risk, based on results in Section 3.2.1, acoustic localization is likely necessary to achieve the precision required to ensure accurate gear location marking. By means detailed in Section 3.2.2.2, all of the acoustic vendors can support this process today with the addition of measurement fusion capability available either as part of the notional Central Command Unit (CCU) suggested in FONTUS [13], or through a cloud-supported solution where measurements are transmitted to an onshore processing unit and a position is computed and disseminated in near-real time. Both Ropeless Systems and EdgeTech may already possess this capability in their respective gear location repositories, and if this utility can be established for the other manufacturers, acoustically localized-positions may be shared through the cloud on a central repository to all fishers operating in a dense region not suitable for GPS-only marking.

3.3.4 Cost Analysis of Existing Vendors Adopting a FONTUS-Compliant System

A key consideration when comparing different proposed interoperability architectures is the cost required to adopt them. To estimate the cost of adoption for either Option A or Option B, an analysis was conducted as described in Section 2.3 with multiple discussions with each vendor initiated by the questions provided in the template of which is provided in 5Appendix D Table 11. Given the sensitivity of cost information, anonymized RFI data is presented in Table 5. Responses varied significantly, both in terms of the required investments to implement FONTUS and the cost impact to end users. Currently, system costs range from $1.2-$7k. Based on data from the RFI responses, FONTUS compliant system costs could range from ~$2.7 - $32k assuming the current market price specific to each vendor, the estimated increase provided by each vendor, and with adjustment for manufacturing at scale.

Table 5. Anonymized responses to MITRE's cost analysis RFI from existing on-demand gear manufacturers.

Vendor	A	B	C
Required Investment to Implement FONTUS	$35M	$1.7M-3M	$80k-150k
Current Market Price	$4.8k	$1.2k	$5k - $7k
Price Increase to End User Cost of FONTUS Compliant System	600%	150-233%	~0%
Price Decrease if Manufactured at Scale	5%	10%	2-10%

The cost analysis RFI yielded many insights to what FONTUS adoption may look like. One is the dramatic differences in the estimated investments required to implement FONTUS. Manufacturers with large existing on-demand gear market shares, and who currently provide more affordable gear than other vendors, provided higher estimates for required investments and larger price increases to end users. While some of this could be due to the need to overhaul major internal investments in manufacturing, it is noteworthy that both manufacturers A and B suggested that their estimates were based on tracked development costs for their own proprietary gear and as such have historical precedent in the requirements and costs around new product development. Given the significant differences between the fundamental components of some existing systems and the requirements to host FONTUS, as detailed in Section 3.3.1, it is reasonable to believe that significant reinvestment and costs at the manufacturer-level will be realized from the supply chain, to manufacturing, to testing prior to validation of the product.

Another insight gleaned from the RFI is the time that would be required to implement FONTUS. Only vendor C stood out as being prepared to adopt FONTUS, and this was represented in their modest required investments, negligible impact to end users, and the fact that they have been funded through the 2023 NFWF New England Gear Innovation Fund [4] for the development of interoperable on-demand gear. It should be noted that this vendor's system is expensive compared to the cheapest options on the market. Other companies estimated up to eight years of development time required to implement FONTUS or another wideband acoustic standard. Finally, there was explicit unwillingness raised by some companies with respect to adopting FONTUS or other acoustic standards under the pretense that they would not be willing to tie their company's reputation to the performance of a standardized waveform that they had no part in developing. Follow-on work is currently underway to examine the effectiveness of different waveforms through a modeling effort.

Results from the cost analysis described in Section 2.3 are presented below. One scenario was evaluated for each interoperability Option A and B. Note that these scenarios were created for the purpose of fair and equitable comparison between the two options. These scenarios evaluate the cost of acoustic gear alone, and do not account for additional development, integration, and operational costs for things such as the universal cloud database.

3.3.4.1 Vendor Proprietary Acoustics Cost Analysis

Estimates of the East Coast OLE fleet, including those not responsible for fixed-gear enforcement, with requirement to possess a universal deck box are approximately 100 total [26]. Combining the initial NFWF award of \$1.383M for the development of the universal deck box with a notional cost of \$100k per unit results in a total government investment of \$11.383M required for this scenario.

3.3.4.2 Universal Acoustic Standard Analysis

Across the three manufacturers, an average gear cost increase of 150% was considered for Vendors A and B accounting for FONTUS adoption. No increase was applied to Vendor C due to their RFI response. Gear costs were discounted for manufacturing at scale based on the RFI responses (5% for Vendor A, 10% for Vendor B, and 6% for Vendor C). Across these three manufacturers, new costs total \$11.40k per unit for Vendor A, \$2.7k for Vendor B, and \$5.64k for Vendor C (chosen as the average of the vendor-provided range).

We now consider the impact of market size on the overall cost. Based on the byproduct of research conducted on the creation of the Fixed-gear Fishery Layer (FGFL) [27], prior to the Take Reduction Plan enactment, a maximum number of endlines, and thus, total possible on-demand units, was estimated to be 230,312. This estimate is reasonably proportional to the total issuance of federal and state lobster permits that have been granted [28], along with a maximum allowable count of traps per permitted fisher, and characteristic pots per trawl with 2 on-demand units per trawl. Derived from the FGFL, a sum total of 8,400 endlines were present in the Massachusetts Restricted Area, LMA1 Restricted Area and South Island Restricted area. Using this count as an effective lower bound of 3.65% of the total market, we arbitrarily assign an upper bound of 10% market for on-demand gear to comprise a range of cost possibilities. This range results in a total market opportunity between 8,400 to 23,031 on-demand units. Computing the difference between the cost of the cheapest gear currently available (Vendor B, \$1.2k per unit) and the adjusted price of that same manufacturers offering when considering the necessary adjustments (\$2.7k), a total between \$12.60M to \$34.55M in additional cost is incurred. This notional scenario uses the lowest possible market cost figure from the gear surveyed in Table 5, but recalculating the same scenario with Vendor A's gear (adjusted to \$11.40k per unit), the difference totals between \$55.44M - \$152M.

If federal funding awards were again granted for open-standard adoption, an additional \$1.175M per vendor should be considered in this calculation as well. If all three of the vendors surveyed in this section receive this award, and if the additional cost incurred is between $12.6M and $152M, a total expenditure range of $16.1M to $155.5M would result. Note that no additional costs borne by manufacturers for FONTUS development were included in this analysis.

3.3.4.3 Summary

In summary, results from this RFI suggest that the implementation of FONTUS or another similar universal acoustic standard would reduce market participation in both the short and long term and lead to significant cost increases to end users, even using conservative estimates which likely overestimate the required number of universal deck box units and underestimate the lower end of adjusted costs for on-demand gear with universal acoustic signaling capability. Key takeaways from the two cost analysis scenarios are summarized in Table 6.

Table 6. Summary of the cost analysis scenarios evaluated in this work.

Scenario	Cost per Unit	Estimated Government Investment	Estimated Cost Range to End Users	Total Estimated Cost Range
Vendor Proprietary Acoustics (Option A)	$100k	$11.4M	$0	$11.4M
Universal Acoustic Standard (Option B)	$2.7k	$3.5M	$12.6M - $34.6M	$16.1M - $38.1M
	$11.4k	$3.5M	$55.4M - $152M	$58.9M - $155.5M

3.4 Acoustic Emissions Effect on Marine Life

Research Question

5. *Will the sound emitted by active acoustic on-demand gear adversely impact endangered and threatened marine species?*

A previously unanswered question regarding the scaled operation of on-demand gear is what effect, if any, the acoustic emissions have on local marine life when used in regular fishing operations. A hypothesized benefit of open-source acoustic standards such as FONTUS is the ability to regulate cumulative acoustic emissions through a cloud brokering system, and this work seeks to assess the necessity of such a strategy. An analysis is presented here based on environmental data within the South Island Restricted Area, which was chosen to be a representative closed zone for potential on-demand gear operation. Key results are presented in this section for conciseness and clarity, but the full analysis is included in Appendix C.

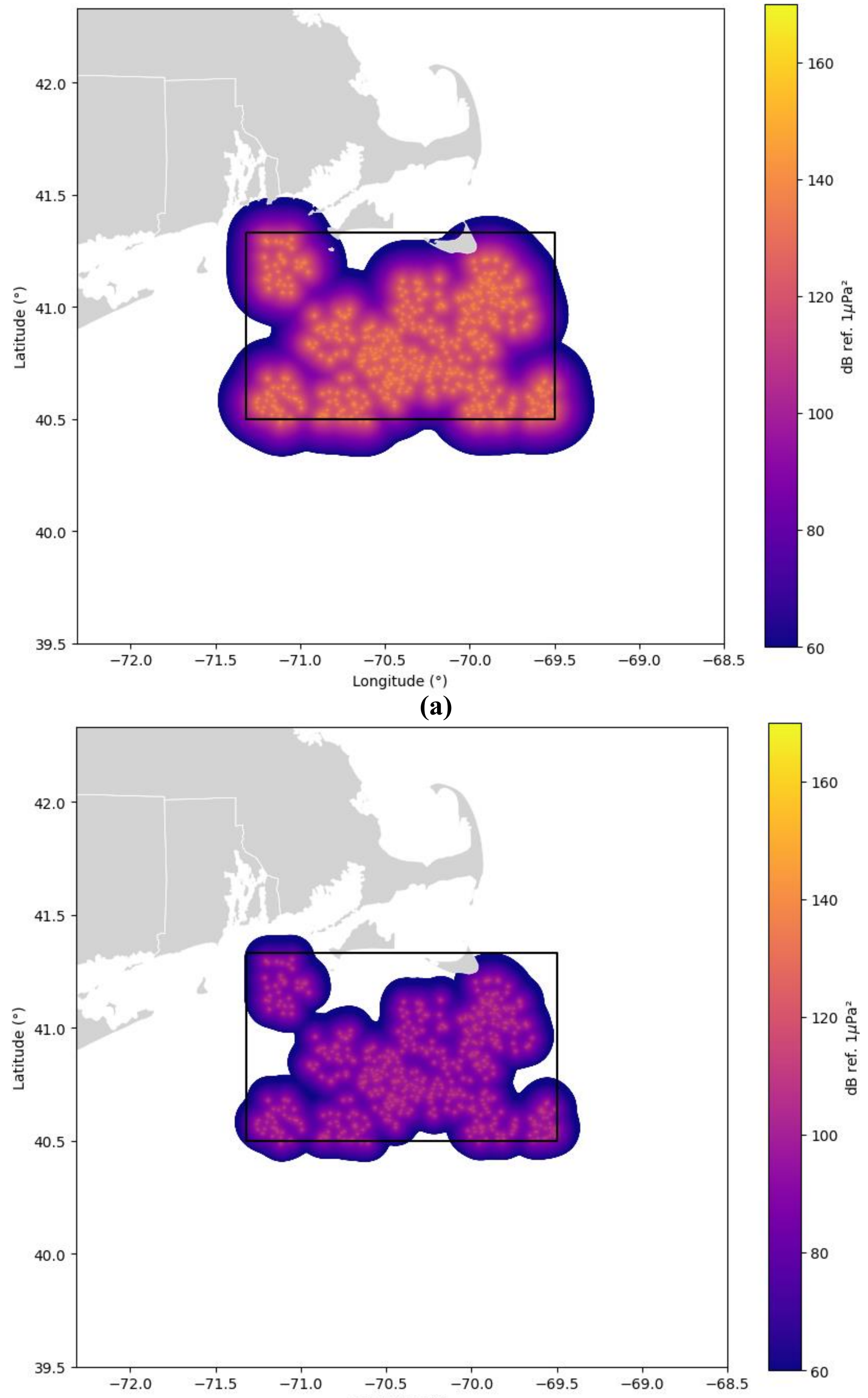
Acoustic models were constructed in the South Island Restricted area with inputs derived from randomly placed source locations, as described in Appendix C. Given the relative uniformity within the South Island Restricted Area, and the sound speed profile sampling resolution described in Appendix A.4, results were consistent across the region and single depth and sound speed profiles were used in the analysis presented here.

3.4.1 Evaluating Acoustic Emissions

Following the process introduced in Section 2.4.1 and described in detail within Appendix C, solutions were computed for the worst-case, continuous emission scenario and results are presented at a 5-meter standoff distance from the distributed sources. This strictly hypothetical situation seeks to demonstrate total radiated sound pressure levels from on-demand gear that is transmitting constantly, and likely, far in exceedance of any requirements of frameworks proposed in Section 1.1. The accumulation is the result of the spatial contribution from all sources. At each point, all emitters are considered and in the 24-hour case, they are persistently contributing at each point. The 120-second case considers the same spatial distribution, but they are attenuated by the time averaging described in Equation C.7. In both cases, the period is considered over a 24-hour averaging window. The modeled received sound pressure levels within the South Island Restricted area shown in Figure 18 (a) were predicted to be between the maximum level of 169.9 dB re. 1 μPa^2 at 5 meters from the source location, and a lower limit of 60 dB re. 1 μPa^2, representing the ambient acoustic noise floor in the frequency band of interest [29]. Signals from active acoustic on-demand gear below this level would be masked by the noise within the underwater environment and therefore, are considered inconsequential for the purpose of the study. Due to the non-coherent nature of the summation, each source acts as a point intensity function and local maxima are correlated with the source location. Computing the time-averaged value defined in Equation C.7 yields the results shown in Figure 18 (b). In the time-averaged emissions scenario for a duty cycle of 120-seconds over a 24-hour period, the reduced maximum level is 141.4 dB re. 1 μPa^2 for the same geospatial distribution of sources.

Analysis of the distribution of received sound pressure levels for the scenarios considered herein suggests that the received sound pressure level between an ambient noise floor of 60 dB re. 1 μPa^2 and the scenario maximum follows a log-normal distribution. This hypothesis is supported by the histograms shown in Figure 19, which portray both the worst-case and cumulative distributions and are truncated below the ambient noise floor limit of 60 dB re. 1 μPa^2. The data distributions are plotted as percentage of cell values within the binned received sound pressure levels to provide a statistical representation of cumulative acoustic levels across the entirety of the analysis region. The modal values are 123.9 dB re. 1 μPa^2 for the continuous emission scenario and 95.1 re. 1 μPa^2 for the averaged 120-second emission scenario.

Median values are 113.3 dB re. 1 μPa^2 and 84.8 dB re. 1 μPa^2 for the continuous emission scenario and 120-second emission scenario, respectively. This reduced median value set is partially due to the heavy-tailed distribution of analysis cells with source sound pressure contribution below the acoustic ambient noise floor. Under the worst-case continuous emission scenario, a very small percentage of area exists above the 150 dB behavioral disturbance threshold for fishes, and an even smaller amount exists above the 160 dB threshold for cetaceans, as evident in Figure 19. To illustrate this more clearly, the sound pressure level map shown in Figure 20 is filtered to show values greater than or equal to 150 dB re. 1 μPa^2. This visualization shows that sound pressure levels in excess of the minimum behavioral disturbance level of 150 dB are localized to regions in the immediate vicinity of the sources. Given the relatively high frequency of these devices, the presence of strong acoustic absorption and attenuation from near-spherical spreading loss works to confine the propagation range of on-demand gear. It should be noted that these levels will be present for any configuration of on-demand gear transmitting at the chosen source level of 183 dB, and any interoperability architecture would not affect that.



(a)

(b)

Figure 18. (a) Sound pressure level maps calculated at 5-meters from a Poisson distribution of sources operating as continuous emitters and (b) cumulative emissions when emitting for 120-seconds per day.

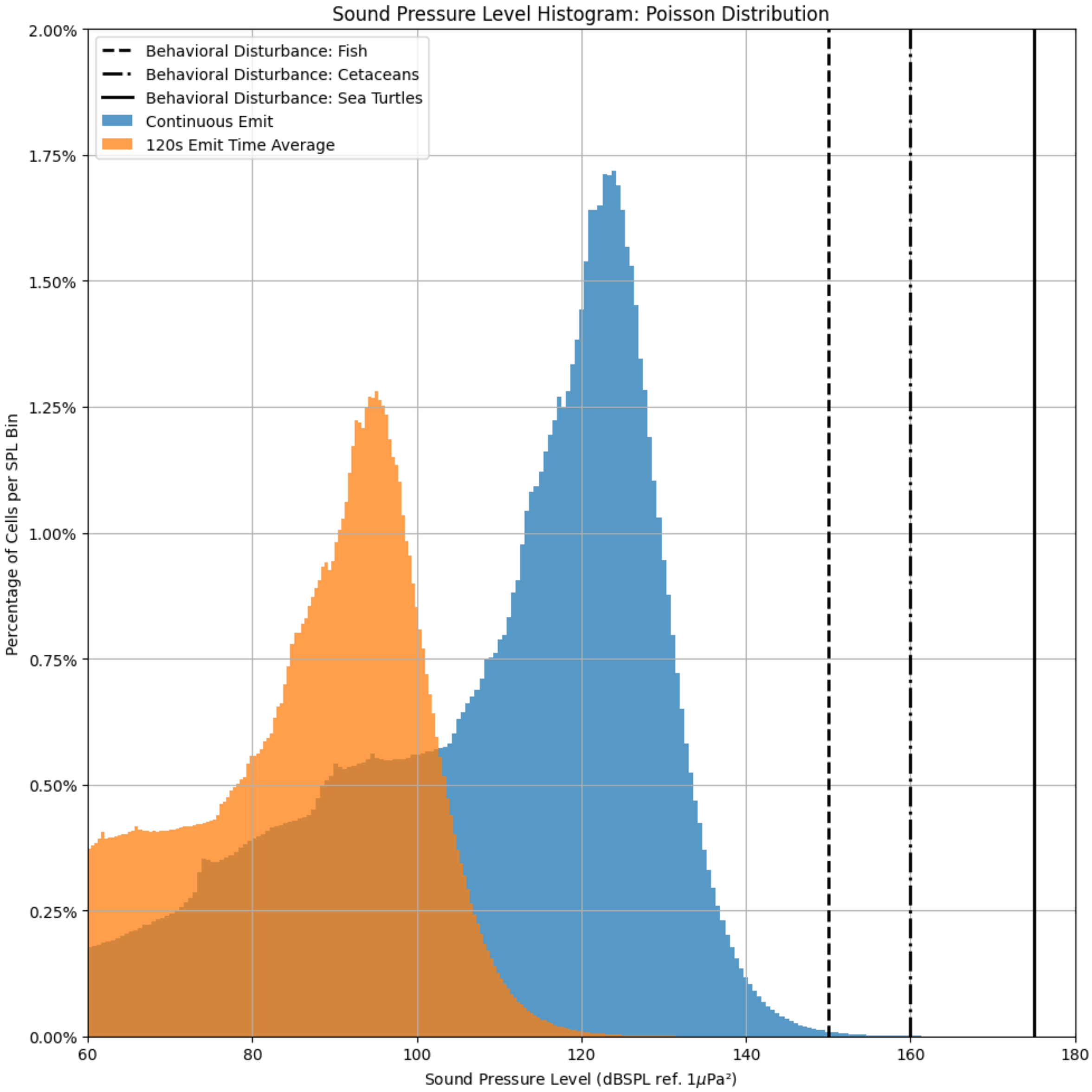


Figure 19. A histogram showing sound pressure level accumulations for a Poisson distribution of N=500 sources distributed within the South Island Restricted Area and measured at a 5-meter range. Cumulative distributions are shown for the continuous emission scenario and the time-averaged emissions from a 120-second per day emission scenario. Behavioral onset threshold levels, relevant for comparison to the blue data, are plotted for fishes, cetaceans, and sea turtles.

In the cases analyzed, maximum levels exceed NMFS' behavioral harassment onset thresholds only very near to the sources. Results discussed within this section were computed at 5-meters from the source location placed 1 meter offset from the seafloor. A receive pressure model at a reduced distance of 10 meters from the source location is included in Appendix C for completeness.

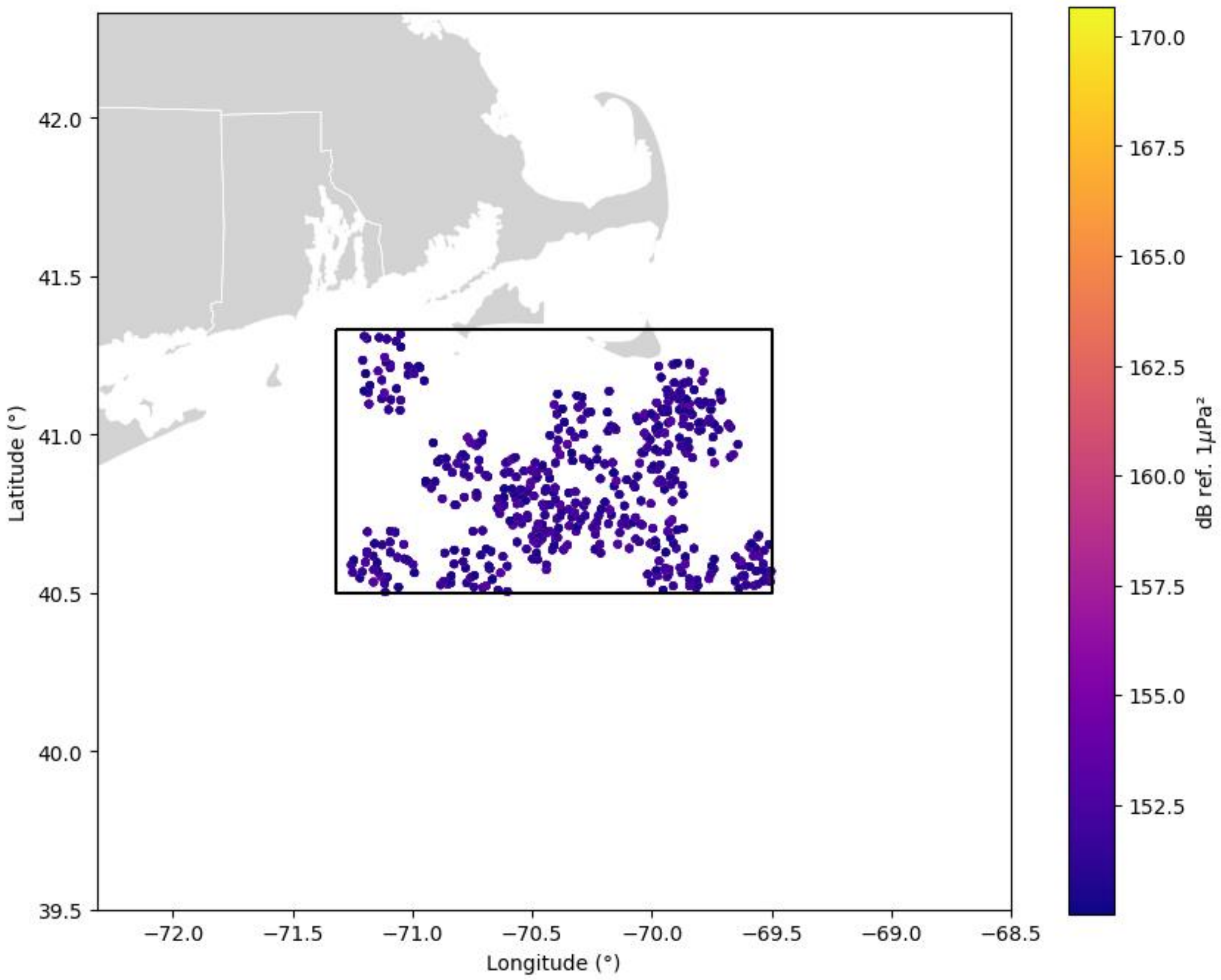


Figure 20. Sound pressure level map for levels greater than or equal to 150 dB calculated at 5-meters from a Poisson distribution of sources operating as continuous emitters.

Source levels greater than, or frequencies lower than the nominal values used in this study (183 dB SPL re.1 µPa at 1m and 17.75 kHz) will result in increases to the emissions calculated here. Despite these possible increases, it stands to reason that even under unrealistic emission rates, close proximity depths, and maximal source levels, cumulative emissions from on-demand fishing gear will not pose a significant threat to exceed the marine animal behavioral harassment onset thresholds. When operated at rates, distances, and levels characteristic of fishing, received sound pressure levels are significantly below threshold values. With this, the emission control measures offered in FONTUS do not seem to be a strong rationale for a single open-source acoustic standard. For completeness, additional analysis should be performed in other regions with differing bathymetry, ocean bottom-types, and depth dependent sound speed profiles, but the results of this study within the South Island Restricted Area find cumulative emission levels to be non-problematic and not something to control through an interoperability standard.

3.4.2 Acoustic Emissions Summary

Results shown in this section demonstrate that on-demand gear will exceed NMFS behavioral disturbance thresholds only in the vicinity of the source, and that no proposed interoperability architecture would change that. Given the frequency at which on-demand gear operates, sound pressure levels are attenuated and absorbed away from the sources and do not result in significant spatial accumulation when multiple sources are present. Cumulative time-averaged emissions, which interoperability proposals such as FONTUS seek to mitigate through signal brokering, are not tied to regulations and were shown to have a modal value of approximately 95 dB in this conservative analysis. This level of cumulative time-averaged emission is not considered problematic and therefore, any attempt to reduce its impact is not considered a driving factor for the choice of an interoperability architecture.

3.5 Summary of Evaluation Limitations

This report endeavors to provide an objective technical evaluation of interoperability proposals given information currently available. The field of on-demand gear and related technology used to support ropeless fishing is nascent and, as such, the state-of-the-art continues to progress at a rapid pace. Major developments in technology, legislation, and conservation efforts may require further analysis or reconsideration of the findings herein.

A presumption of necessity for compliance with current laws was used to frame this analysis. Namely, gear marking requirements defined in CFR Title 50 [16] [17] [18], the Magnuson-Stevens Fishery Conservation and Management Act, and the Atlantic Coastal Fisheries Cooperative Management Act, as well as NMFS' current marine mammal acoustic thresholds set the maximum requirements that an interoperability standard must achieve in this analysis. This context framing was used to characterize universal acoustic solutions, such as FONTUS, as potentially more stringent than necessary given that separate acoustic approaches could presumably achieve all current federal rules and facilitate interoperability. This raises the question: what measures should be mandated for interoperable, on-demand fishing, and what measures are performant? While it may be true that the FONTUS waveform design is theoretically superior and more robust to multi-path environments than some vendor-proprietary signaling approaches, is that level of performance necessary to implement on-demand fishing?

The risk in meeting the FONTUS standard potentially entails a higher increase in investment relative to currently functioning on-demand systems, with little empirical evidence of increased value in terms of improvement in localizing gear. The result of this may increase costs to end users, permanently alter the competitive landscape in the market of on-demand fishing gear, and limit the number of viable vendor systems available. If performance remains a significant impediment to the acoustically separate interoperability suggestions provided herein, NMFS's role in mandating requirements outside the scope of current regulations should be considered. To date, accurate projections of ghost gear proliferations due to on-demand fishing gear are not available. With a better understanding of ghost gear rates due to on-demand gear, a more comprehensive cost and tradeoff analysis can be performed. At a substantial level, lost gear and conflict incurred from ghost gear may outweigh the large initial investment toward an open acoustic standard but further analysis is necessary to substantiate that with cost figures. Furthermore, the dynamics of on-demand gear under a large displacement event, such as a storm, are poorly understood and if large area gear displacement poses a problem, a universal acoustic standard may be the necessary solution.

A significant motivation of universal acoustic interoperability proposals, such as FONTUS, is gear localization in dense fisheries or areas subject to high gear conflict risk. Surveys and interviews with fishers conducted by Pew Charitable Trusts, WHOI, and Canadian Wildlife Federation [30] suggested a preference for an 8-meter maximum resolution standard for these situations, which subsequently justifies ranging through multiple independent fishing vessels using universal acoustics. Work performed in Section 2.2.1 of this report attempted to address gear conflict risk at scale by assigning statistical thresholds based on quartile divisions to classify risk levels within a fishery. In both cases, further evaluation is necessary to determine causal sources of error in gear location marking at statistical levels. Given limited sample interviews in the survey work, and frequentist statistics described within this report, subsequent studies of gear marking error and conjunction with mobile fishing vessels would help to provide a Bayesian understanding of where to set risk thresholds in terms of pieces of gear and mobile fishing activity per square NM. Current data sourced from the WHALE DST fixed-gear fishery layer is uniformly distributed based on the resolution of reporting methods and going forward, a much more realistic understanding of on-demand gear placement may be available if a cloud interoperability solution of gear marking is implemented. Fusing this realistic reporting with VMS telemetry would improve the gear conflict map product presented within this report, but for now, data is based on historical distributions and not the reality of on-demand fishing. An additional complication is presented in the data collection period for the fixed-gear fishery layer; 2019-2021 coincided with the COVID-19 pandemic which had a profound effect on commercial fishing. This analysis was performed with the data provided by NMFS, but if the fixed-gear fishery layer is recomputed for a more typical time period, results may vary.

The analysis in Section 3.4 on compatibility of existing on-demand gear with FONTUS is based on both current gear capabilities and operating procedures as well as FONTUS version 1.0 requirements. It is highly likely that both proprietary gear, as well as the FONTUS standard, improve through continued development and at-sea testing. At the time of publication for this report, the FONTUS standard is only just starting to be implemented on actual manufactured on-demand gear. Findings through this implementation may reshape requirements and, similarly, challenges under repeated at-sea operations may persuade current vendors to adopt more robust acoustic signaling methods suitable for challenging multi-path environments subject to dense fishing. If these improvements result in wideband signaling adoption, the universal acoustic approach from FONTUS should be reconsidered, particularly if localization and ghost gear remediation remain open issues. In addition, ongoing work is investigating the performance of the various signaling approaches, in the presence of multipath, typical noise environments, and other gear that may be erroneously commanded by the misinterpretation of a signal transmitted by a fisher in proximity.

Finally, the acoustic emissions analysis is based both on current specifications of on-demand fishing gear as well as the NMFS current marine mammal acoustic criteria [16]. A change to gear capabilities (i.e., increased source level, lower operating frequency) would require a revised analysis, although, given the wide margin between estimated levels described in Section 3.4, vendor desire to maintain gear battery endurance, and the current minimum threshold level for marine mammal behavioral harassment onset, this is not a significant risk and likely not something that will need to be controlled or brokered through an open standard interoperability approach. However, if behavioral onset thresholds were to be lowered for any of the infraorder and species considered within the NFMS thresholds, this analysis and the conclusions it offers will need to be reconsidered.

4 Summary and Conclusions

To meet the requirements of a proliferated ecosystem of on-demand gear, with the goal of replacing fixed-line fishing with surface buoys in closed areas, interoperability standards are needed. This report examined the merits of various proposed interoperability architectures to meet those requirements and provide the basis for a sustainable long-term solution.

4.1 Proposed Architecture Tradeoffs

Requirements for on-demand gear to replace surface buoys can be satisfied by either proprietary acoustics and a universal deck box, or a universal acoustic solution, as illustrated in Figure 1 Options A and B. Both architectures require the establishment of a universal cloud database for storing gear information and location but achieve acoustic interoperability in different ways. Given that a cloud database is required, ensuring consistent and reliable on-water internet or cellular access should be considered a top priority.

The proposal of an acoustics-only standard (Option C) was eliminated based on two factors: its inability to achieve detection ranges commensurate with radar reflectors under certain requirements outlined within CFR Title 50 [9], [18], [19], and its requirement for the mobile fishing fleet to adopt acoustics onboard their vessels. In comparing a universal acoustic solution (Option B) to an ecosystem of proprietary acoustics (Option A), several benefits and drawbacks were identified which have been presented below in Table 7:

Table 7. Benefits and Drawbacks of Proprietary vs. Universal Acoustic Standards – underlined items are specific to FONTUS and the multi-vehicle localization it enables

	Potential Benefits	**Potential Drawbacks**
Proprietary Acoustics with Universal Deck Box (Figure 1 Option A)	• Quicker adoption timeline • Asymmetric cost benefit (incurred by enforcement) • Less expensive than FONTUS (Section 3.3.4) • Diversity of marketplace choice • Less disruption to existing market • Less initial regulatory burden • Existing gear is sea-tested	• Potential for gear conflict risk in high-density geospatial zones • Less consistency in acoustic performance between vendors • Vendor lock based on thru-hull transducer installation • Unproven acoustic signal interference performance • Less frequent gear position updates
Universal Acoustic Standard (i.e., FONTUS or similar) (Figure 1 Option B)	• Improved ghost gear localization • Better subsurface localization capability • Acoustic signaling developed from a proven signaling approach (JANUS) • Performant and multi-access acoustic signaling benefits • Consistent acoustic performance between collocated fishers • Breaks vendor lock for thru-hull transducer installation	• Significant hardware reinvestment by vendors • Higher cost to the end user • Limits consumer choice • Requires development of a complex cloud brokering agent for cooperative vessel tasking • Requires complex calibration for accuracy in certain cases

Analysis presented in Section 3.1 indicates that the minimum requirements of on-demand gear do not currently compel a universal acoustic solution. However, an open-standard acoustic architecture (Option B) may still be a better solution for the community, especially if issues specific to on-demand gear are observed to be prolific. A discussion is presented here which explains the benefits and drawbacks of a universal acoustic architecture, in the context of whether these justify regulation through a single standard. In addition to the requirements that on-demand gear must satisfy to replace fixed-line surface buoys, additional benefits are made possible by the cooperative nature of the acoustic signaling approach. As originally suggested in the FONTUS proposal, a key benefit of an open acoustic standard is localization and recovery of ghost gear. With a single acoustic standard, subsurface gear could be localized by receiving transmissions from any passing vessel equipped with an on-demand thru-hull transducer. With interoperability achieved through proprietary active acoustics, ghost gear could only be localized by ships equipped with compatible acoustics, who are actively looking for the gear. An important distinction should be made that the proposed ghost gear mitigation benefit is not currently stipulated under fixed fishing gear requirements under federal rulemaking. Currently, more work is required to determine the magnitude of the predicted ghost gear problem and whether it justifies the adoption of a single standard.

In the absence of a single standard, benefits such as the ability to recover ghost gear could also hypothetically be increased using proprietary active acoustics. When gear has been lost, information available in the cloud database could provide quantifiable data on the time period in which the gear could have been moved by mobile fishing activities or recovered by another fisher. In the case of gear being moved by mobile fishing vessels, Automatic Identification System (AIS) or VMS reported telemetry mandated for some commercial fishing operations could be sourced by OLE, or other groups given permission to adjudicate gear conflict, to determine the most likely vector of gear displacement. This could then be used to trigger a guided search for the gear, which could be performed by any vessel equipped with a compatible on-demand thru-hull transducer (either fishers with gear from the same manufacturer or OLE with a universal deck box). At this time, this responsibility is outside of the domain of typical OLE enforcement practices but is being presented here as an option made possible by reporting technology.

Aside from potential opportunities related to ghost gear recovery, it is possible that the adoption of proprietary active acoustics will create an environment that becomes difficult for regulators and enforcement to service. Without any standardization of acoustic communication protocols, a universal deck box must be developed, manufactured, and deployed on the appropriate enforcement vessels. Given the asymmetric nature of the problem (less than 100 East coast enforcement vessels responsible for fixed-gear vs. thousands of fishing vessels that may adopt on-demand gear [26]), it is reasonable to place the burden of interoperability on regulators and enforcement instead of the fishing community and manufacturers. However, some regulations must be put in place to prevent the diversity of proprietary communication protocols in an unbounded manner. For example, if it is required that all manufacturers must transmit within a specific band-limited frequency range, the universal deck box concept could remain tractable through the implementation of a single thru-hull acoustic transducer and a software defined modem that could be updated wirelessly according to a software release schedule for proprietary acoustic gear development.

By issuing a universal acoustic standard, communications and localization performance could be well-characterized in a variety of conditions relevant to on-demand gear. It is well-known that wideband communication protocols, such as the FH/BFSK modulation proposed in FONTUS and other signaling methods of certain proprietary on-demand gear detailed in Table 4, may be able to achieve superior performance to the narrowband protocols employed by other on-demand gear manufacturers at lower peak source levels. However, if the cumulative levels of louder narrowband signals fall below the behavioral disturbance threshold levels as suggested in 3.4.1, it is reasonable to weigh the costs and benefits between a more accurate positioning system against a sufficient and more affordable solution. Technical analysis of this concept is introduced in the preceding sections and will be completed in 2025.

Finally, in the absence of a universal acoustic solution, there is an implied risk of vendor lock for fishers. If a fisher has a selection of subsurface gear and their vessel is outfitted with surface gear from manufacturer A, it will be difficult or costly for them to adopt gear from manufacturer B. The intent of the universal deck box concept is to create a single system that is interoperable with any manufacturer's gear. It seems reasonable to suggest that a version of this system could be made commercially available to any fisher who wishes to future-proof against potential vendor lock. This variant would not allow ubiquitous access to other fisher's gear as in the case of OLE but rather, be capable of reproducing the proprietary acoustic signaling for all participating vendors. Such an innovation would eliminate the need for multiple thru-hull transducers supporting different proprietary manufacturers.

For on-demand active acoustic systems to replace traditional surface systems in terms of providing fishing gear location information and a means for retrieval without causing acoustic impacts on marine life, this tradeoff analysis currently supports an adoption of Option A, proprietary acoustics supported by a universal cloud database and a universal deck box, for acoustic interoperability. This conclusion is subject to change if empirical data on impediments such as gear conflict and ghost gear recovery prove to be an issue with scaled on-demand gear in dense fishing areas.

4.2 Acoustic Emissions Conclusions

Given concerns about the proliferation of on-demand gear posing a threat to marine life by acoustic emissions, an analysis was conducted to estimate the total cumulative emissions of dense on-demand gear deployment in a closed area on marine mammals. Results showed that even under the most extreme conditions (i.e., all gear emitting all the time), the acoustic emissions do not represent a threat for harassment of marine life, outside of their immediate vicinity, based on current marine mammal behavioral harassment threshold. Based on the specifications from our modeling scenario (i.e., a 183 dB source level at 17.75 kHz), statistical modal levels in the simulated region at 5-meters range from the distributed sources total 123.9 dB re. 1 μPa^2. This value is significantly lower than the 150 dB behavioral disturbance threshold for fishes and 160 dB marine mammal behavioral harassment threshold. While the source level of any individual piece of gear exceeds either of these thresholds, cumulative levels fall far below and as such, are likely not important to regulate through an open acoustic standard as proposed in FOTNUS. While earlier studies have observed reduced acoustic signaling between cetaceans when exposed to echo sounder emissions [31], on-demand gear emits at significantly lower duty cycle than representative echo-sounders and acoustic navigation aids that most fishing vessels are already equipped with. These sources, along with acoustic releases and communication modems, have been deemed *de minimis* in prior studies examining the effect of common emitters on marine life [32]. Therefore, any benefit of lower emissions achieved by a universal acoustic solution was not found to be necessary.

4.3 Gear Localization Recommendations

The localization analysis is intended to provide a geospatial understanding of how different fisheries may demand different interoperability requirements, particularly when it comes to gear localization. However, more work is needed to determine the acceptable level of relative risk within a closure zone or restricted area and how that informs specific requirements for subsurface gear localization accuracy and thus the acoustic techniques required.

The risk regions were assigned in a statistical manner to test the validity of this method. The number of risk regions can be extended, and the thresholds that are extracted in a data-driven manner can be also assigned in a more deterministic manner, using actual reported "gear conflict incidents" that provide the corresponding "fixed-gear density" and "fishing-vessel activity" values at the times those incidents happened. This approach could assign more realistic thresholds for these two parameters in determining these risk regions.

The preliminary results presented in this report indicate that the proposed method holds promise for enhancing the understanding of localization accuracy requirements in areas likely to adopt on-demand gear. This approach provides an opportunity to identify the specific localization techniques necessary to meet these requirements. By implementing the improvements discussed in the paragraphs above, this assessment can be expanded to incorporate future restricted areas if developed or across the entire northeast coastline of the U.S. This expansion will facilitate the development of location-specific subsurface gear localization accuracy requirements, thereby avoiding the need for strict universal requirements.

In terms of subsurface gear localization techniques, the results from this report suggest that GPS only marking is likely insufficient in areas with a risk of gear conflict. Initial results from the geospatial analysis conducted showed that areas of high or elevated conflict risk exist within current seasonal restricted areas. In instances where acoustic localization is required, it was found that acoustic ranging is likely a sufficient solution, which all vendors surveyed have the capability to perform, though with the notable complication of thru-hull transducer requirement to perform measurements in-situ. More work remains to be done to conclusively determine where, when, and what kind of localization should be required for on-demand fishing.

4.4 Requirement Considerations

The choice of a proprietary acoustics interoperability architecture comes with a risk for regulation difficulties, which can be mitigated by setting frequency and power bounds for on-demand gear. By establishing an allowable frequency band of operation (e.g., 17-40 kHz), the government can bound the requirements of a universal deck box device to something that can be achieved using a single acoustic source and power amplifier, controlled by an SDM. This type of system could be continuously updated via software and would not require any hardware changes to accommodate interoperability with new devices. Taken together, these requirements would enable large-scale feasibility without the adoption of a single universal acoustic solution, fostering consumer choice and preventing the disruption of existing business.

4.5 Future Work Recommendations

To finalize and substantiate recommendations for acoustic interoperability and localization requirements and regulations, the following additional work is recommended:

- Establishment of a universal cloud database and the development of a data governance, management, and sustainment plan for it
- Evaluation of satellite internet access throughout the fixed-gear and mobile fishing fleet
- Continued development of a geospatial risk analysis to determine where and when acoustic localization will be required
- Experimentation to quantify the localization accuracies of GPS marking, acoustic ranging, and directional ranging in multiple relevant environments
- Completion of an acoustic modeling toolbox to compare the expected performance of various acoustic communication technologies for on-demand gear developers and interoperability proposers to use
- Establishment of an allowable operating frequency range for on-demand gear that will enable a universal deck box to use a single transducer and an SDM
- Development of a comprehensive interoperable framework to operationalize on-demand fishing, including the acoustic communication and data standards, data transmission and

visualization tools, and rules-based data management system to support near real-time information sharing

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Appendix A Data Sources

The data sources leveraged across the analyses presented in this report include the following:

A.1 Mobile Fishery Data

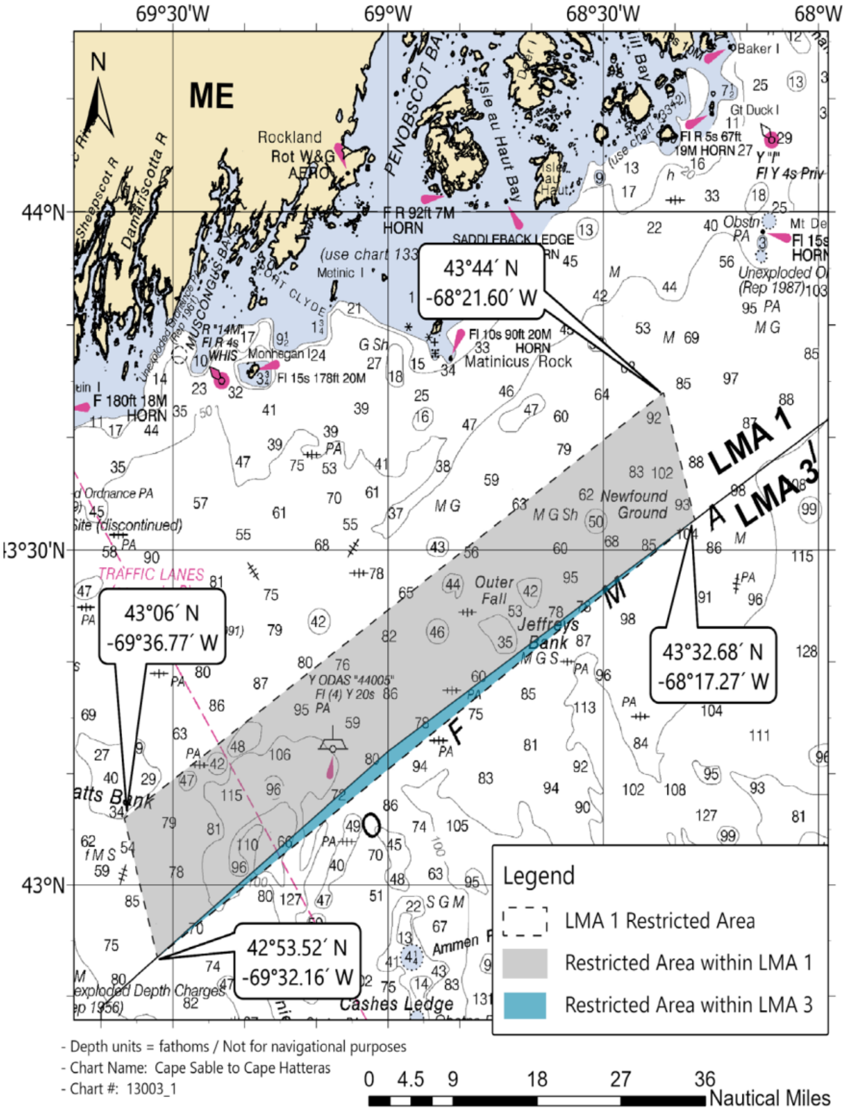
The mobile fishery data used in this work correspond to the VMS telemetry data. VMS is a satellite-based surveillance system to monitor the location and movement of commercial fishing vessels [33]. Through filtering of vessel telemetry data and declaration codes describing program plan, program, and gear type, the surveillance system provides quantitative information about mobile fishing operations [15]. Details on the specific components of the declaration codes used to filter the data are provided in Section 2.2.1. The VMS telemetry data consists of sampled data acquisition times, speed, and location information (latitude/longitude) of the vessels throughout their fishing trips. In addition to these data attributes, declaration (fishing type) of the fishing vessels is also present within the VMS data. In this work, we used the VMS telemetry data to generate monthly vessel activity maps which are then utilized in the generation of gear conflict risk maps. The VMS data used in the vessel activity map generation were from 2019 to 2021.

A.2 Fixed-Gear Density

WHALE DST, which was developed by NMFS, has the objective of evaluating and comparing management options that reduce entanglement risks of large whales in commercial fixed-gear fisheries [14]. The WHALE DST aims to generate estimates of baseline co-occurrence between whales and gear. Additionally, it provides quantitative information about the associated risk of the gear. For these estimations, the WHALE DST requires fishery inputs as data layers. One of these inputs is the gear map, which is a data layer with the fishing gear density (represented by a gear fished metric) throughout the estimation model adapted in the WHALE DST. The fixed-gear density data used in this work was obtained from the fishing gear density input layer of the WHALE DST. The years involved in the retrieval of the gear density data varied by fishery subgroup to capture the most representative data of the current fishery and consisted of monthly estimates of fixed-gear density per square NM.

A.3 Vertical Line Closures

The MMPA and ESA require NMFS to take actions to reduce the risk of human-caused mortality and serious injury to help the endangered NARW species recover. The two primary threats to adult right whales are vessel strikes and entanglements in commercial fishing gear. To address vessel strikes, NMFS implemented a vessel speed regulation that imposes speed limits on vessels greater than 65 feet in identified seasonal management areas. To address the threats caused by commercial fishing, the MMPA requires that NMFS establish a Take Reduction Team to develop a Take Reduction Plan with the goal of reducing mortality and serious injury due to fixed-gear gillnet and trap/pot commercial fishing in U.S. waters to below PBR. The Atlantic Large Whale Take Reduction Plan currently requires the use of weak links or weak ropes, sinking groundline, gear marking, seasonal restricted areas, and a minimum number of traps per trawl [22]. The ropes, which are also known as vertical lines, connect the buoys on the sea surface to the fish traps on the sea floor. These vertical lines pose a significant entanglement risk to NARW [34]. Areas that restrict the use of persistent buoy lines in areas and at times of year where right whales are likely to be present are the most effective way to reduce the entanglement risk. An example vertical line restricted area (LMA1) can be seen in Figure 21. In this work, we computed gear conflict risk maps for two seasonal restricted areas, including LMA1, which are introduced in detail in Section 3.2.1.



- Depth units = fathoms / Not for navigational purposes
- Chart Name: Cape Sable to Cape Hatteras
- Chart #: 13003_1

Figure 21. LMA1 and LMA3 vertical line restricted areas

A.4 Underwater Environmental Parameters

For our acoustic modeling efforts, we utilize several geospatial datasets to create detailed profiles of various ocean and environmental parameters. These datasets are accessed via Network Common Data Form (NetCDF) format files. These files are specifically designed for array oriented scientific data, making them ideal for accessing large-scale geospatial information. The geospatial datasets used for modeling fall into three categories: bathymetry datasets, sediment datasets, and ocean environmental datasets. Bathymetry datasets are used to create bottom profiles of the seafloor which describe the seafloor depth in relation to mean sea level. Sediment datasets are used to collect information on sediment grainsize, porosity, and sediment thickness which affect various geoacoustic properties. Ocean environmental datasets are used to collect the average salinity and temperature of the water which are used to create sound speed profiles for acoustic wave propagation.

A.4.1 Bathymetry Parameters

Bathymetry, or maps of ocean depth, are used to provide the bottom boundary location for ocean acoustic propagation modeling. Bathymetric datasets map coordinates to depth values which indicate the distance from the sea surface to the seafloor. Bathymetry is most commonly mapped in one of two ways:

a) Through shipboard surveys using single beam and multibeam echosounders (often described as a 'direct' method) where the measured time of echoes from the seafloor are converted to distance through knowledge of the speed of sound
b) Indirectly from satellite radar altimetry measurements of the height of the air-sea boundary, where differences in observed ocean surface height from that of an equipotential surface are used to infer gravitational anomalies, and these anomalies are then transformed into estimates of depth. Satellite measurements have much coarser resolution, and occasionally miss important features (e.g., underwater mountains).

There are several global bathymetry compilations that are derived from several sources including both shipboard surveys and satellite measurements. As of 21 June 2024, the percentage of the ocean floor that has been mapped from shipboard surveys using echosounders is 26.1% [35]. From the perspective of acoustic propagation model, where acoustic wavelengths vary from a few meters to a few centimeters, it is helpful to understand the underlying spatial resolution of these compilations. The following data sets are available online and provide varying levels of global coverage and spatial resolution.

Table 8. Spatial coverage and resolution of bathymetry datasets

Bathymetry Dataset	Coverage	Resolution	Notes
General Bathymetric Chart of the Ocean (GEBCO)	Global	15 arc-seconds	---
NOAA National Center for Environmental Information (NCEI) Coastal Relief Map	United State Coastlines	1 arc-seconds	---
NOAA NCEI Earth Topography (ETOPO) 2022	Global	15 arc-seconds	Includes data from other compilations including GEBCO 2022

Table 8 shows characteristics and limitations of some of the data sources surveyed. It is worth noting that 15 arc-seconds is the equivalent of about 450 meters.

Note that in coastal environments, especially near estuaries, areas with large tidal currents, and regions that are periodically dredged, bathymetry can be dynamic - in these cases, take care with potential data source staleness.

The datasets described in this section reference horizontal datum to WGS84 and vertical datum Earth Gravitational Model (EGM) 2008. The Office of Geomatics at National Geospatial Intelligence Office (NGA) defines EGM as a set of geopotential coefficients used in a spherical harmonic expansion to create a global potential surface to coincide with Mean Sea Level (MSL) [36].

A.4.1.1 GEBCO

The GEBCO_2022 Grid is a global terrain model for ocean and land, providing elevation data, in meters, on a 15 arc-second interval grid of 43200 rows x 86400 columns, giving 3,732,480,000 data points. The data values are pixel-center registered i.e. they refer to elevations, in meters, at the center of grid cells [37].

GEBCO is available to download at:
https://www.gebco.net/data_and_products/gridded_bathymetry_data/

A.4.1.2 NCEI Coastal Relief Maps

NOAA's NCEI has compiled a collection of bathymetric data into Coastal Relief Models (CRMs) at 1 arc-second resolution (~30 meters) that are available for most of the U.S. coast and are downloadable as NetCDF's which is our preferred method for accessing the data. It's important to note that while the coastal relief maps offer the best bathymetric resolution, they only offer coverage within the U.S. EEZ [38].

NCEI CRMs are available to download at:
https://www.ncei.noaa.gov/products/coastal-relief-model

A.4.1.3 ETOPO

The Earth Topography (ETOPO) dataset is a comprehensive, seamless, gridded topographic and bathymetric bare-earth elevation repository. ETOPO is specifically designed to provide full global coverage, making it an invaluable resource for coastal hazard and tsunami modelers. However, its utility extends beyond these applications, serving as a foundational dataset in scientific papers, data products, and references worldwide [39].

ETOPO is released as a global earth surface elevation file, consisting of 288 individual tiles, each covering a 15x15 degree area (latitude/longitude) at a high resolution of 15-arc-seconds. These tiles are available in NetCDF formats, ensuring accessibility and compatibility with various analytical tools. The dataset can be downloaded from NCEI at: https://www.ncei.noaa.gov/products/etopo-global-relief-model.

A.4.1.4 Sediment Parameters

Ocean floor sediment databases are scarce, the process of collecting the data needed to create a large-scale database can be time and cost intensive. However, there are two databases which provide valuable sediment parameters useful for acoustic modeling. The NCEI's global ocean sediment thickness grid (Globsed version 3), and the United States Geological Survey's usSEABED databases.

A.4.1.5 usSEABED

usSEABED is the collaborative product of the U.S. Geological Survey (USGS), the University of Colorado, and other partners. The usSEABED database contains six point coverages of known sediment samples, inspections, and probes from the usSEABED data collection for samples collected within the U.S. EEZ [40].

The database is a compilation of data collected over multiple decades at various locations in the US EEZ. Given the extreme variability of sediment composition, the database is not uniformly grided at specific arc second resolutions. Instead, it contains data at any location where samples have been taken and processed. This means that there can be multiple datapoints for a single location.

In addition to seafloor surface samples the usSEABED database contains core samples that provide insight into the layered composition of seafloor sediments. This provides information needed to calculate the compressional and shear sound speeds as well as attenuation through ocean floor sediments.

The two parameters we are using from the usSEABED database are the sediment mean grainsize and sediment porosity. The sediment grainsize values in the database are in units of phi (φ) which are a negative log base 2 conversion of sediment diameter in millimeters

$$\varphi = -\log_2(diameter)$$

usSEABED is available for download at:
https://www.usgs.gov/programs/cmhrp/science/accessing-usseabed

A.4.1.6 Globsed

GlobSed version 3 is a comprehensive global 5-arc-minute total sediment thickness grid designed to map the sediment distribution across the world's oceans and marginal seas. Version 3 incorporates new data and covers a larger area than previous models, resulting in a 29.7% increase in estimated total oceanic sediment volume [41].

GlobSed allows the user to determine the ocean floor basement. The ocean floor basement, often referred to as the "basement" in geological terms, is the layer of solid rock beneath the sediments on the ocean floor.

GlobSed is available for download online at:
https://www.ngdc.noaa.gov/mgg/sedthick/

A.4.2 Ocean Parameters

Calculation of sound speed is performed through either the Mackenzie Equation or the Thermodynamic Equation of Seawater 2010. The parameters needed to calculate the sound speed are the temperature, salinity, and their corresponding depth in the water column. The World Ocean Atlas conveniently provides all three parameters.

A.4.2.1 World Ocean Atlas

The World Ocean Atlas (WOA) [42] is a comprehensive collection of objectively analyzed, quality-controlled means of various ocean parameters, including temperature, salinity, oxygen, phosphate, silicate, and nitrate. These means are derived from profile data in the World Ocean

Database (WOD) and are periodically updated by NCEI. The WOA serves multiple purposes, such as creating boundary and initial conditions for ocean models, verifying numerical simulations, and corroborating satellite data [43].

A distinctive feature of the WOA is its three-dimensional structure, which includes values of ocean parameters at various depths. This allows for a detailed representation of the ocean's vertical profile, providing insights into how parameters change with depth.

The WOA23, initially released in October 2022, contains the 1991–2020 climate normals of global ocean temperature and salinity at selected standard depths. These fields were generated to complement the recently released U.S. Climate normals and were updated as part of the full February 2024 release. According to the World Meteorological Organization (WMO), a "normal" is defined as the 30-year average of data for a particular variable, calculated for a uniform time period. Normals provide long-term means for initializing models, conducting environmental studies, and validating in situ observations.

The WOA offers three resolution options: ¼ degree, 1 degree, and 5 degrees.

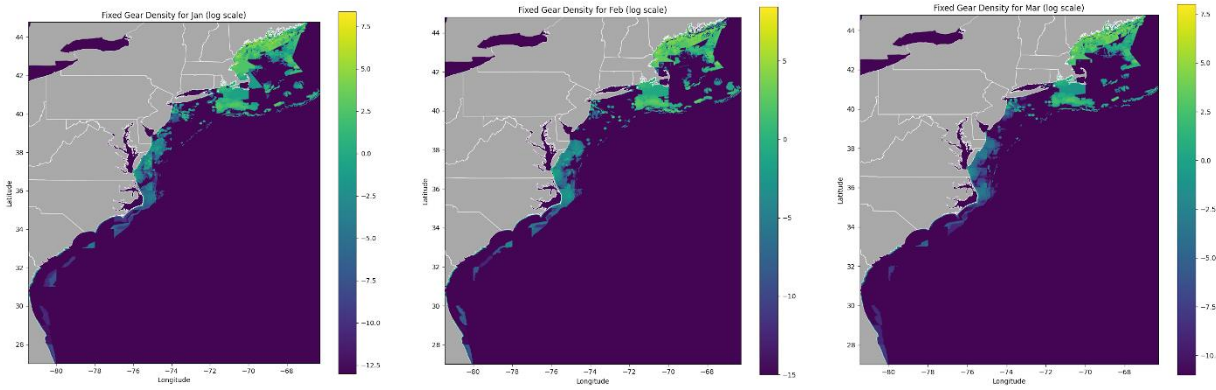
A.5 Gear Conflict Risk Methodology

A.5.1 Fixed-Gear Density Map

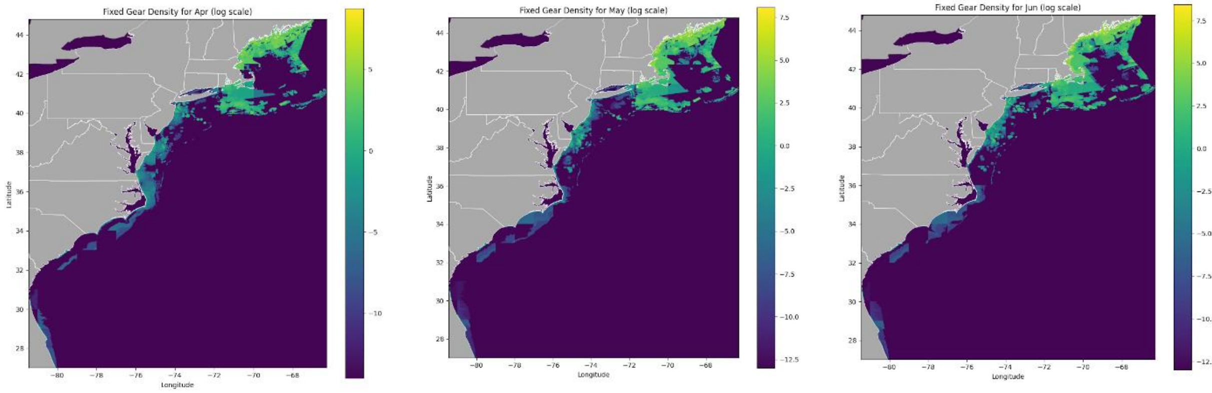
Fishing effort and catch data from WHALE DST were originally sourced from federal databases maintained by the Northeast Fisheries Science Center (NEFSC) and Southeast Fisheries Science Center (SEFSC), as well as state-level data from the Atlantic Coastal Cooperative Statistics Program (ACCSP). These datasets are derived from fisher logbook reports, which summarize trip details such as gear type, fishing location, and effort. The spatial data provided in these reports is often coarse, with vessels typically reporting a general region of activity or, in some cases, a single coordinate to represent the broader fishing area. When vessels change gear or move between Statistical Reporting Areas, separate effort records are logged for each segment of the trip. The analysis focused on identifying the location, timing, gear type, and species landed during fishing trips [14]. The data consists of gear density values in spatial resolution of 1 square NM cells. In addition to fixed-gear density values, locations of each fixed-gear density value in latitude and longitude coordinates are available. The data corresponds to monthly averaged fixed-gear density values across variable years for each fishery subgroup (representing the most current fishing behavior). From the fixed-gear density values and their latitude/longitude locations, the latitude and longitude resolution is 0.01666667 degrees. The fixed-gear density data also indicated the minimum and maximum latitude and longitude values which are [27.00833, 44.79166] for latitude and [-81.45833, -66.27499] for longitude, respectively.

Using the lower and upper latitude and longitude coordinates and the resolution of 0.01666667 degrees, a reference grid coordinate system is formed to generate the monthly fixed-gear density maps. With the formed grid coordinate system, for each month, a matrix that has the same size of the grid coordinate system is initialized. We then inserted the fixed-gear density values in the matrix at the designated coordinate locations (latitude/longitude), which resulted in the monthly fixed-gear density maps. The unit in each grid cell of the fixed-gear density map is “total number of traps or nets deployed in a month per square nautical mile”. For better visualization, logarithmic scale is used in map generation. Due to the use of the logarithmic scale, the grid cells in the map that have no data values are set slightly to a lower value than the lowest measured fixed-gear density value in the map.

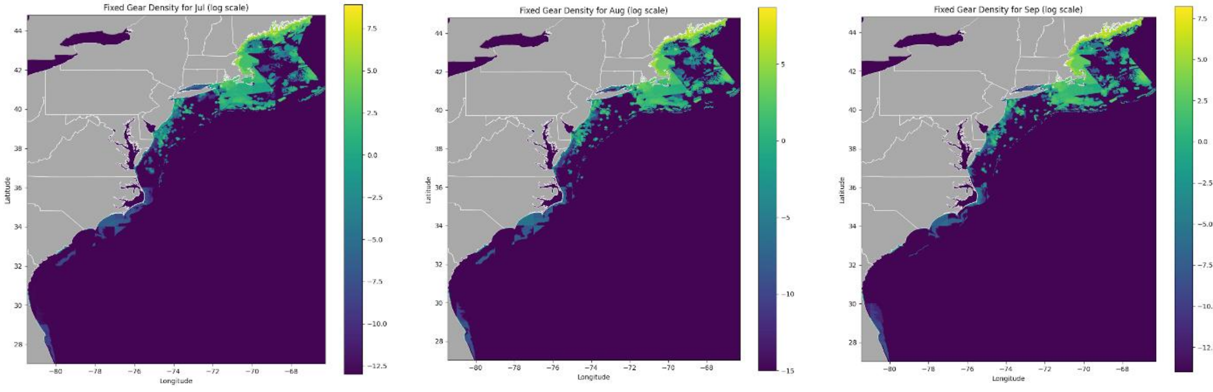
Figure 22 shows the resultant monthly fixed-gear density maps. In the monthly maps, the color bar next to each map helps to identify which grid cell locations (latitude/longitude) have higher fixed-gear density values where brighter grid cells indicate locations with higher fixed-gear density. Figure 23 and Figure 25 portray seasonal fixed-gear density between Feb - April 2019 – 2021 and Oct – Jan 2019 – 2021 respectively, representing an average of total trap/pot and gillnet count per square nautical mile in logarithmic scale.



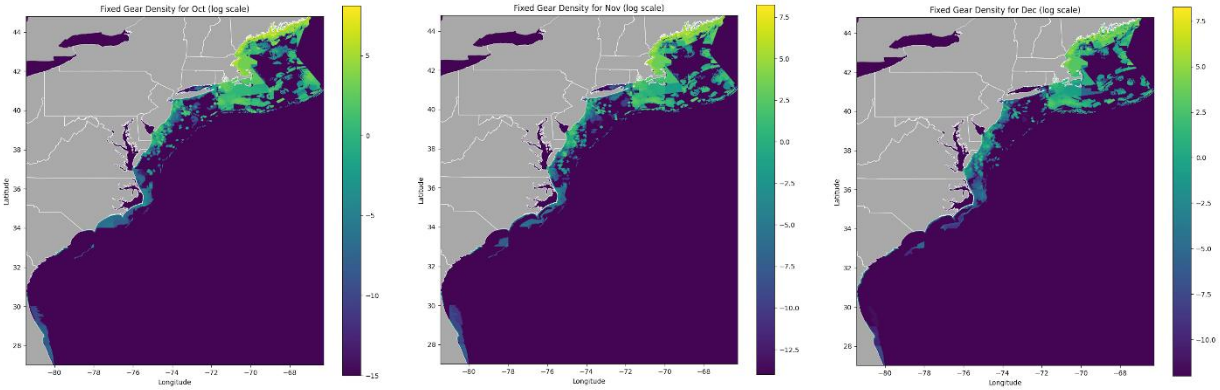
(a) January (b) February (c) March



(d) April (e) May (f) June



(g) July (h) August (i) September



(j) October (k) November (l) December

Figure 22. Monthly fixed-gear density maps representing an average of total trap/pot and gillnet count per square nautical mile.

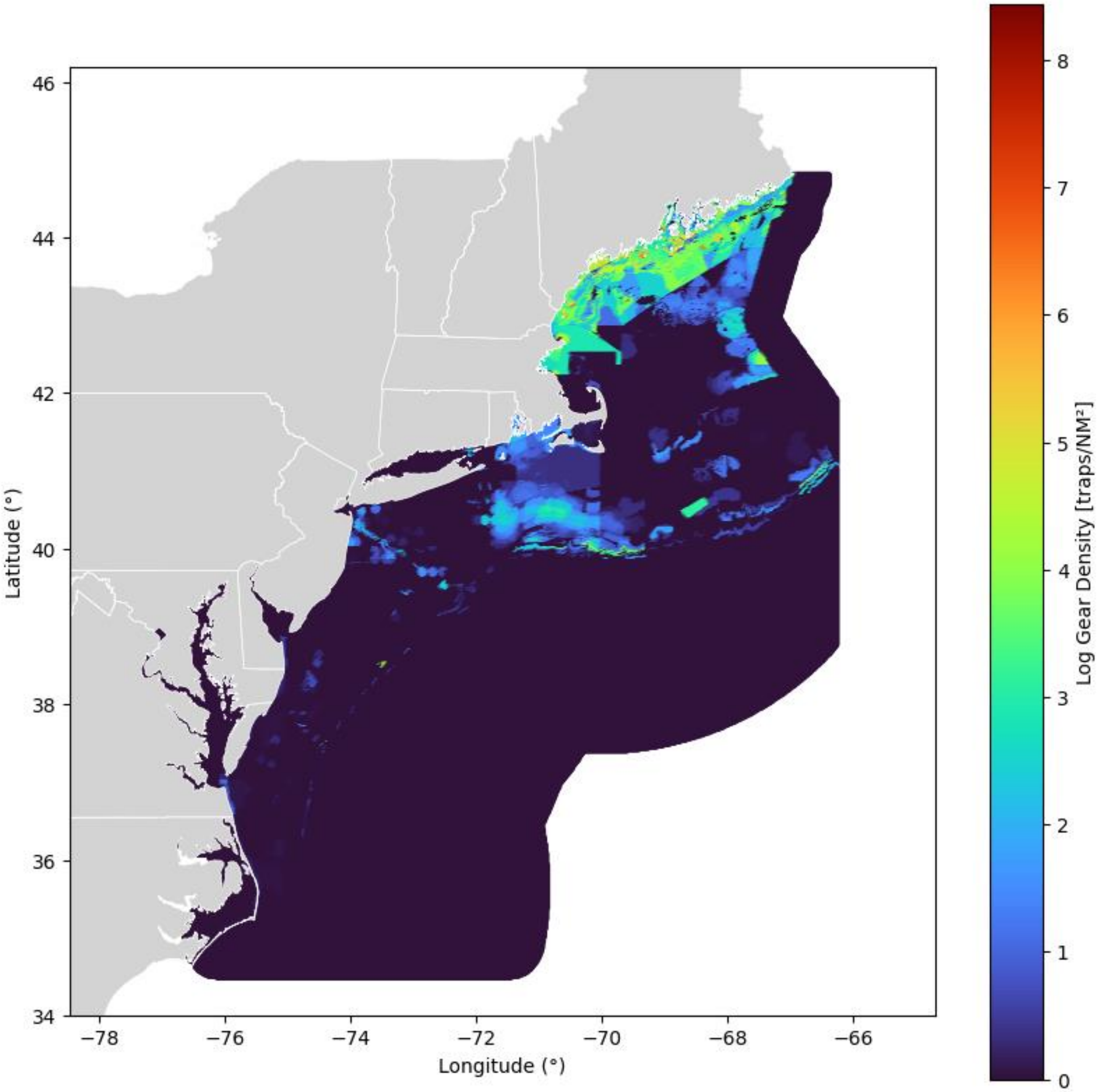


Figure 23. Seasonal fixed-gear density representing an average of total trap/pot and gillnet count per square nautical mile between February - April 2019 – 2021 in logarithmic scale.

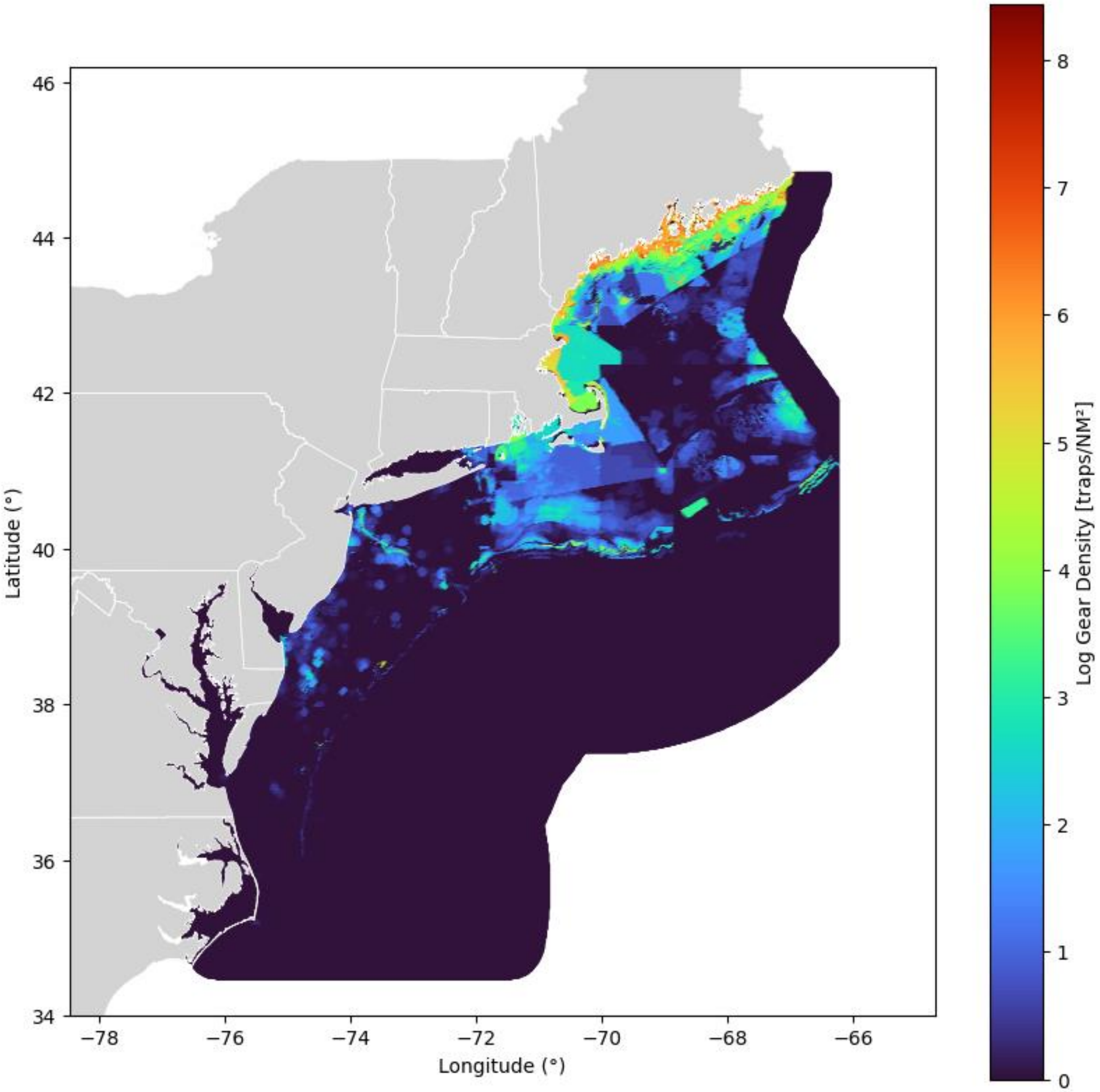


Figure 24. Seasonal fixed-gear density representing an average of total trap/pot and gillnet count per square nautical mile between May - September 2019 – 2021 in logarithmic scale.

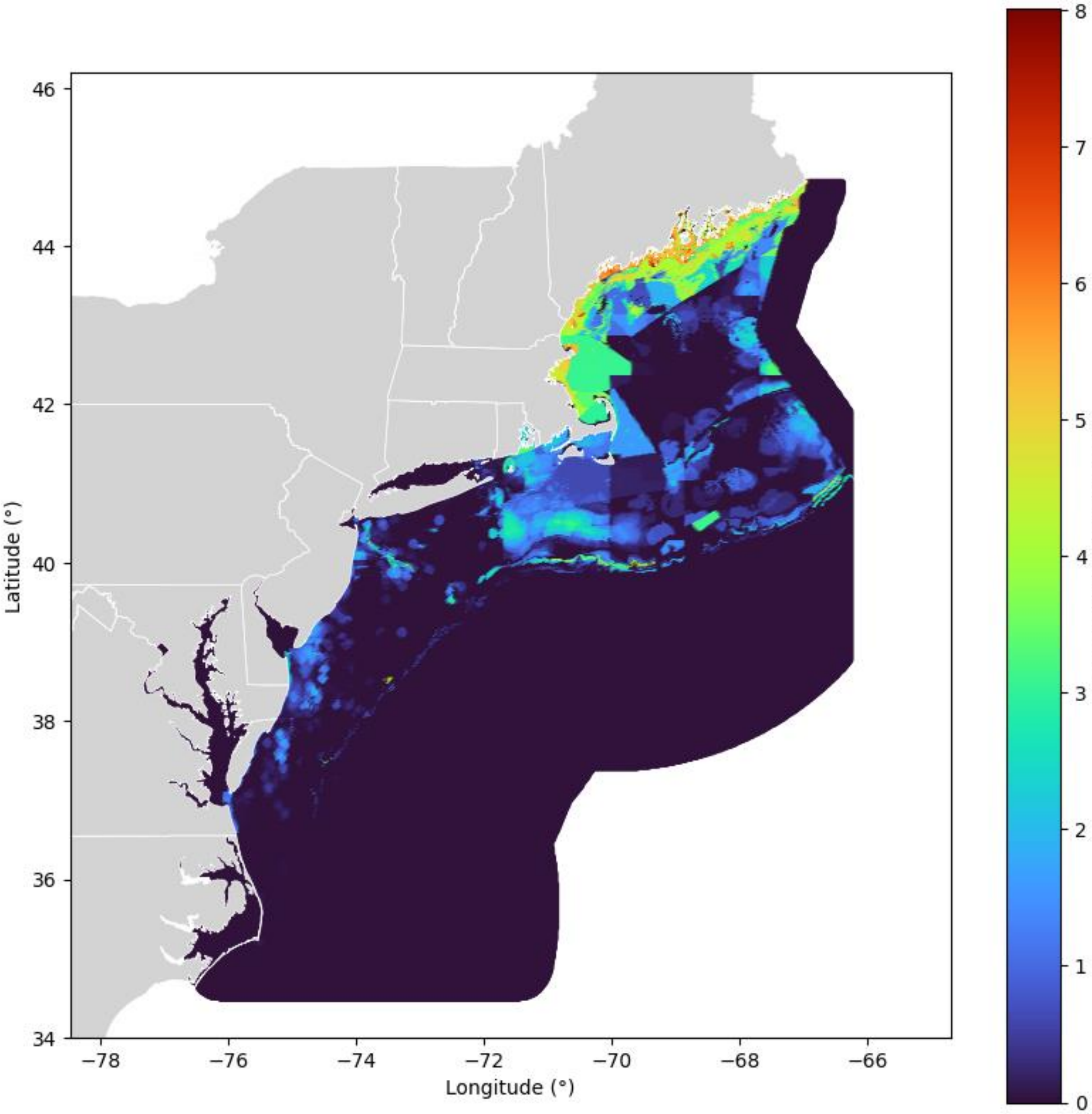


Figure 25. Seasonal fixed-gear density representing an average of total trap/pot and gillnet count per square nautical mile between October - January 2019 – 2021 in logarithmic scale.

A.5.2 Vessel Activity Map

VMS telemetry data are used for extracting the fishing vessel activity which is then transformed into fishing vessel activity map. The VMS telemetry data consists of sampled data acquisition times, speed and location information (latitude/longitude) of the fishing vessels throughout their trips. For generating a gear conflict risk map using vessel activity information together with fixed-gear density, we are interested in the fishing times only of the vessels during their trips. This is because a gear conflict happens when a mobile fishing vessel is performing fishing activity close to fixed-gear. To retrieve the corresponding VMS telemetry data for fishing activity only, declaration code and speed filters are introduced. Sourced from the VMS declaration code glossary [15], the gear type codes include dredge ("D"), midwater trawl ("M"), purse seine ("S"), and bottom trawl ("W"). Additionally, plan codes for surfclam, ocean quahog, and mussel permits ("SCO"), as well as squid, mackerel, and butterfish ("SMB"), were incorporated without regard to specific gear type declarations. Furthermore, plan and program codes "SES-SAA," "SES-SCA," and "SES-SWE" were included to account for activities from scallop permit vessels operating under special access area, limited access, and state waters exempted program codes. The VMS telemetry data samples with vessel speed values that are between 0.01 knots and 4 knots are included only in the vessel activity map generation. The lower limit speed filter value is set to 0.01 knots, slightly above 0, since a considerable number of telemetry data samples consist of a speed value of 0, which is considered as no fishing activity. For the upper speed limit in the filter, a value of 4 knots is used, since any vessel speed value above 4 knots is considered as potential transiting. In the vessel activity map generation, other than vessel speed, no other specific filtering has been applied with respect to the fishing vessels' declaration (fishing type) and all the fishing vessels of any fishing type with VMS data have been used.

For consistency and ease in fusing the two sources of information to create a gear conflict risk map, the fishing vessel activity map is generated on a monthly time scale using the same grid coordinate system of the fixed-gear density map. The unit of each grid cell in the resultant vessel activity map is "total number of *fishing* hours".

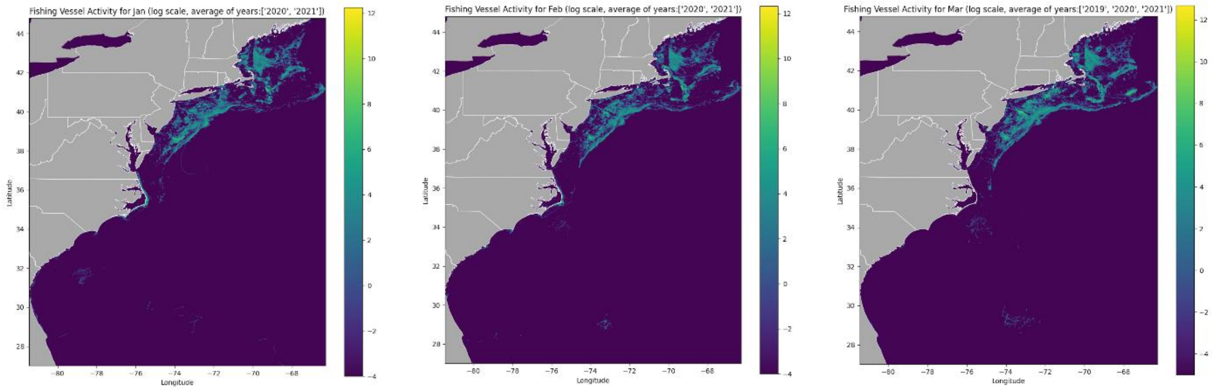
The logic in forming the fishing vessel activity map from the telemetry data is based on first grouping the telemetry data with respect to unique fishing permits for the year and month of interest. We considered using unique permit in the grouping process instead of using vessel's name since there could be multiple fishing vessels with the same name in the telemetry data. For each unique permit, the speed filter is applied to the vessel's telemetry data to extract the total fishing hours for each vessel spatially. The data blocks with consecutive times in the telemetry data are identified first. Following that a matrix that represents the fishing activity for the individual vessel with the unique permit is formed by incrementing the values at the corresponding grid cell locations by the total amount of extracted fishing time. The same process is then repeated for all fishing vessels with unique permits. A vessel activity map is then generated that consists of the sum of all the individual vessel activity values. Table 9 outlines the steps of the fishing vessel activity map generation.

Table 9. Vessel Activity Map Generation

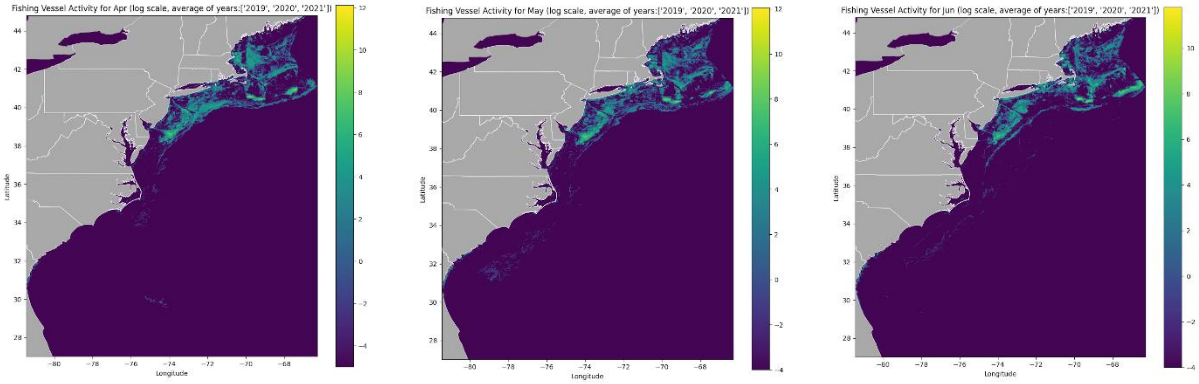
```
Retrieve the reference coordinate grid system (latitude, longitude) from the fixed-gear density map
Create an empty matrix to store the "vessels_activity" values (same size as the reference grid) and initialize it to zero (the zero values will correspond to no vessel activity)
Read the VMS telemetry data for the month/year of interest
Find all unique permits (each unique permit corresponds to a unique vessel)
For each unique permit (or fishing vessel)
    Create an empty matrix to store the "single_vessel_activity" values (same size as the reference grid) and initialize the matrix to zero
    Filter the telemetry data based on the fishing vessel speed (4 knots >= speed >=0.01)
    Find data blocks with consecutive timesteps in the filtered telemetry data
    For each data block that consists of consecutive telemetry data points
        Retrieve the timestamps of the data block and their corresponding lat/lon coordinates
        For each telemetry data point in the data block
```

```
        Identify the grid cell location where the telemetry data point falls into using its lat/long
        Increment "single_vessel_activity" at the identified grid cell location by the timestamp difference
    Increment "vessels_activity" by "single_vessel_activity"
```

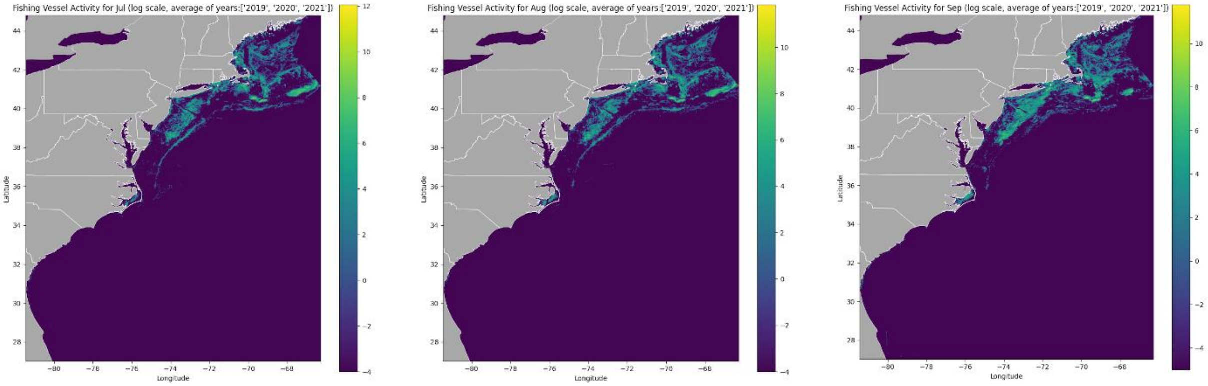
Figure 26 shows the resultant vessel activity maps for each month of the year. The average of three years of VMS telemetry data (2019, 2020, and 2021) are considered when forming the monthly vessel activity maps between March 2019 to December 2021. When plotting the vessel activity maps, like fixed-gear density map, logarithmic scale is used to better visualize the vessel activities in a wide varying range of values. The grid cells in the map that have no data values are set slightly to a lower value than the lowest calculated vessel activity value so that a smooth plot in logarithmic scale can be generated. In the monthly maps in Figure 26, the color bar next to the maps helps to identify which grid cell locations have the highest vessel activity where brighter cells indicating higher vessel activity. Figure 27 and Figure 29 portray seasonal fixed-gear density between Feb - April 2019 – 2021 and Oct – Jan 2019 – 2021 respectively, representing an average of fishing hours per square nautical mile in logarithmic scale.



(a) January (b) February (c) March



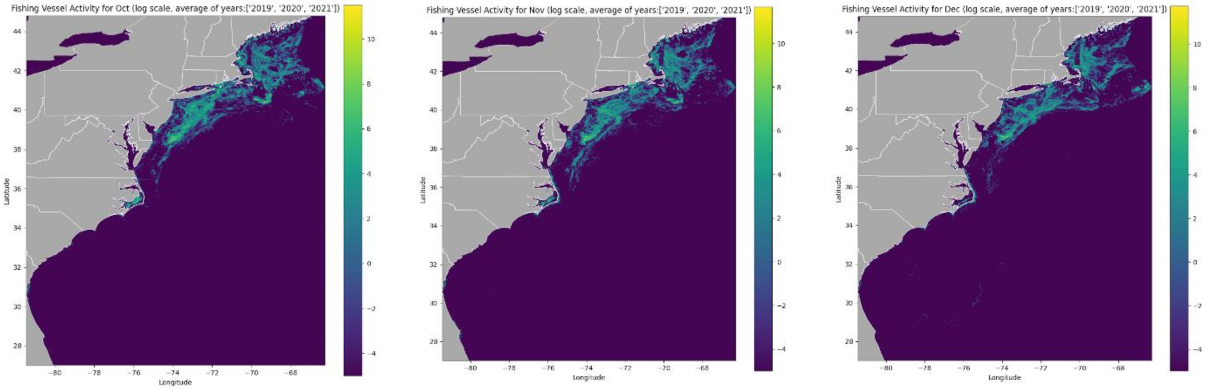
(d) April (e) May (f) June


Fishing Vessel Activity for Jul (log scale, average of years:['2019', '2020', '2021'])

Fishing Vessel Activity for Aug (log scale, average of years:['2019', '2020', '2021'])

Fishing Vessel Activity for Sep (log scale, average of years:['2019', '2020', '2021'])

(g) July (h) August (i) September


Fishing Vessel Activity for Oct (log scale, average of years:['2019', '2020', '2021'])

Fishing Vessel Activity for Nov (log scale, average of years:['2019', '2020', '2021'])

Fishing Vessel Activity for Dec (log scale, average of years:['2019', '2020', '2021'])

(j) October (k) November (l) December

Figure 26. Fishing vessel activity maps (monthly)

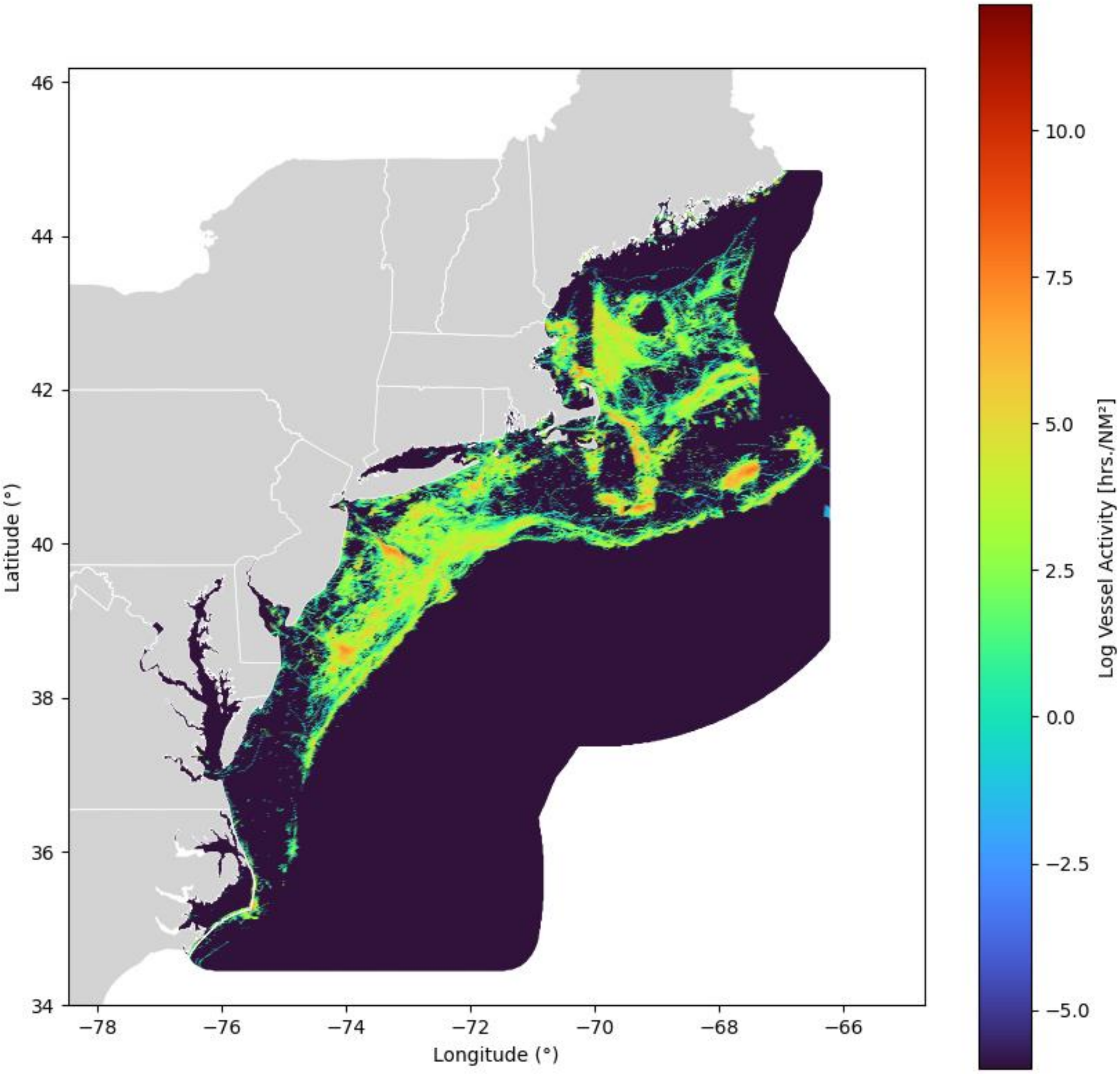


Figure 27. Seasonal vessel activity representing an average of fishing hours per square nautical mile between February - April 2019 – 2021 in logarithmic scale.

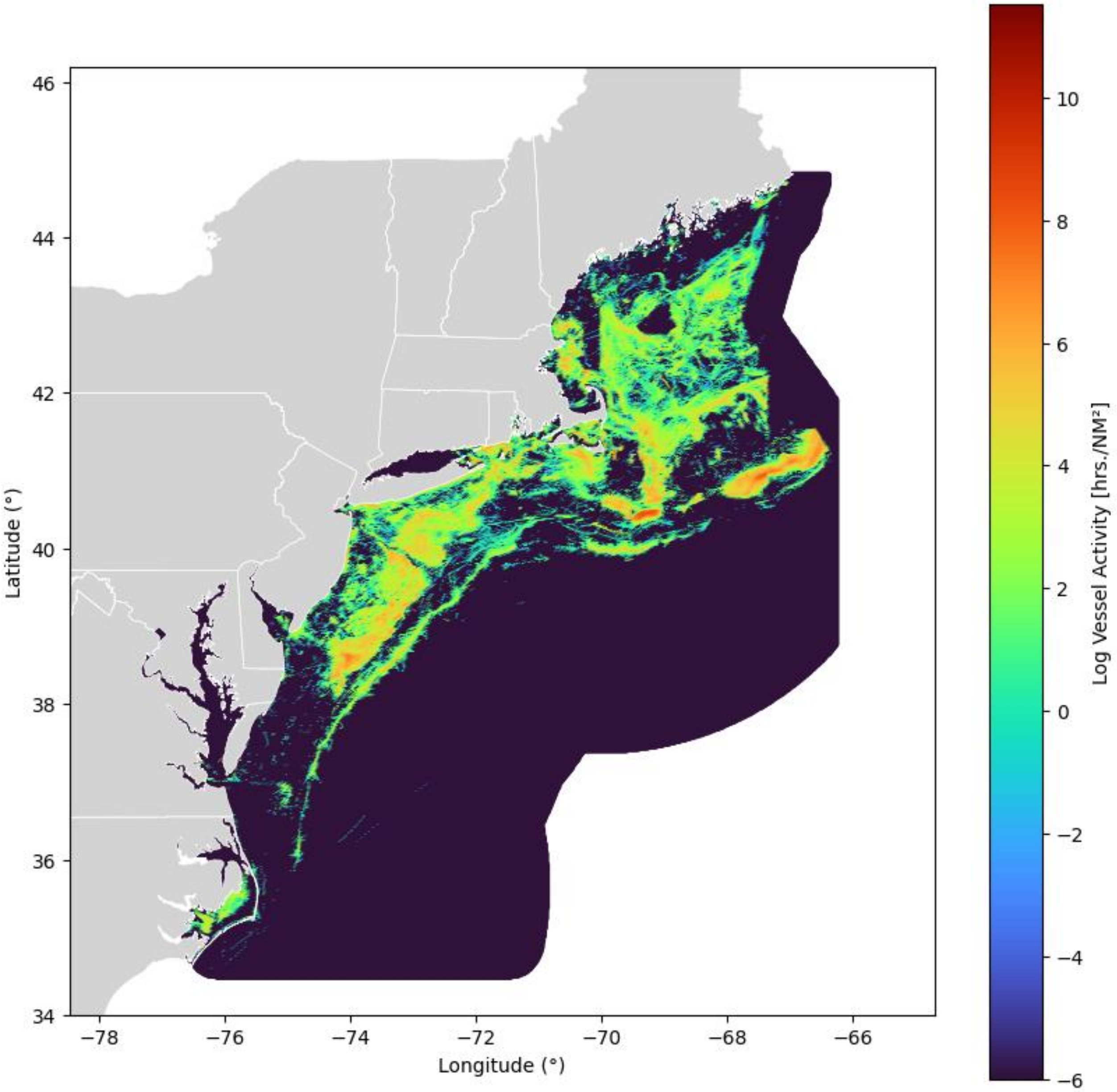


Figure 28. Seasonal vessel activity representing an average of fishing hours per square nautical mile between May - September 2019 – 2021 in logarithmic scale.

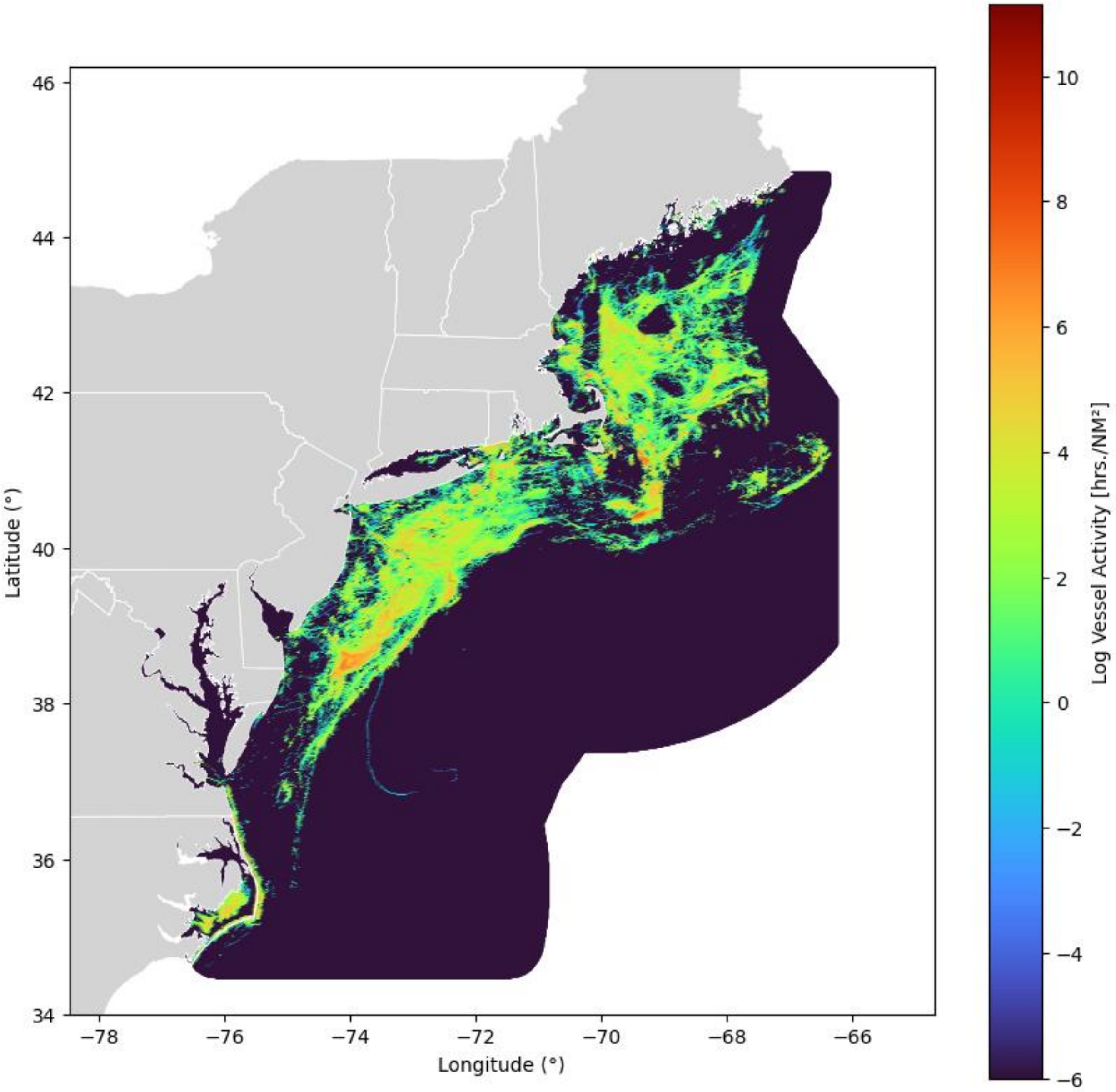


Figure 29. Seasonal vessel activity representing an average of fishing hours per square nautical mile between October - January 2019 – 2021 in logarithmic scale.

A.5.3 Determining Thresholds for Gear Conflict Risk Maps

This subsection introduces the gear conflict risk map generation methodology that fuses the information in the monthly fixed-gear density and vessel activity maps. In the gear conflict risk map generation methodology, the first step is to generate one-dimensional histograms of the fixed-gear density and vessel activity values separately to identify thresholds for each of the two parameters. These thresholds are then used to partition the 2D space of the fixed-gear density and vessel activity into four different gear conflict risk regions. In the data-driven methodology for extracting these two thresholds, for data, the average of all 12 months of fixed-gear density and vessel activity map data with respect to the years of interest is used. The fixed-gear density and vessel activity values in logarithmic scale are used in the histogram analyses and the values included in the histogram analysis correspond to the common grid cells that contain measurements for both fixed-gear density and vessel activity. The histogram plots for the fixed-gear density and vessel activity can be found in Figure 30. The 95th percentile was used to identify the thresholds to generate the risk maps, which are also highlighted in Figure 30 with dashed-red lines. The threshold for fixed-gear density was found to be 2.3325 log-gear density per square nautical mile and 3.421079958153013 for vessel fishing activity in base units of log-vessel activity per square nautical mile.

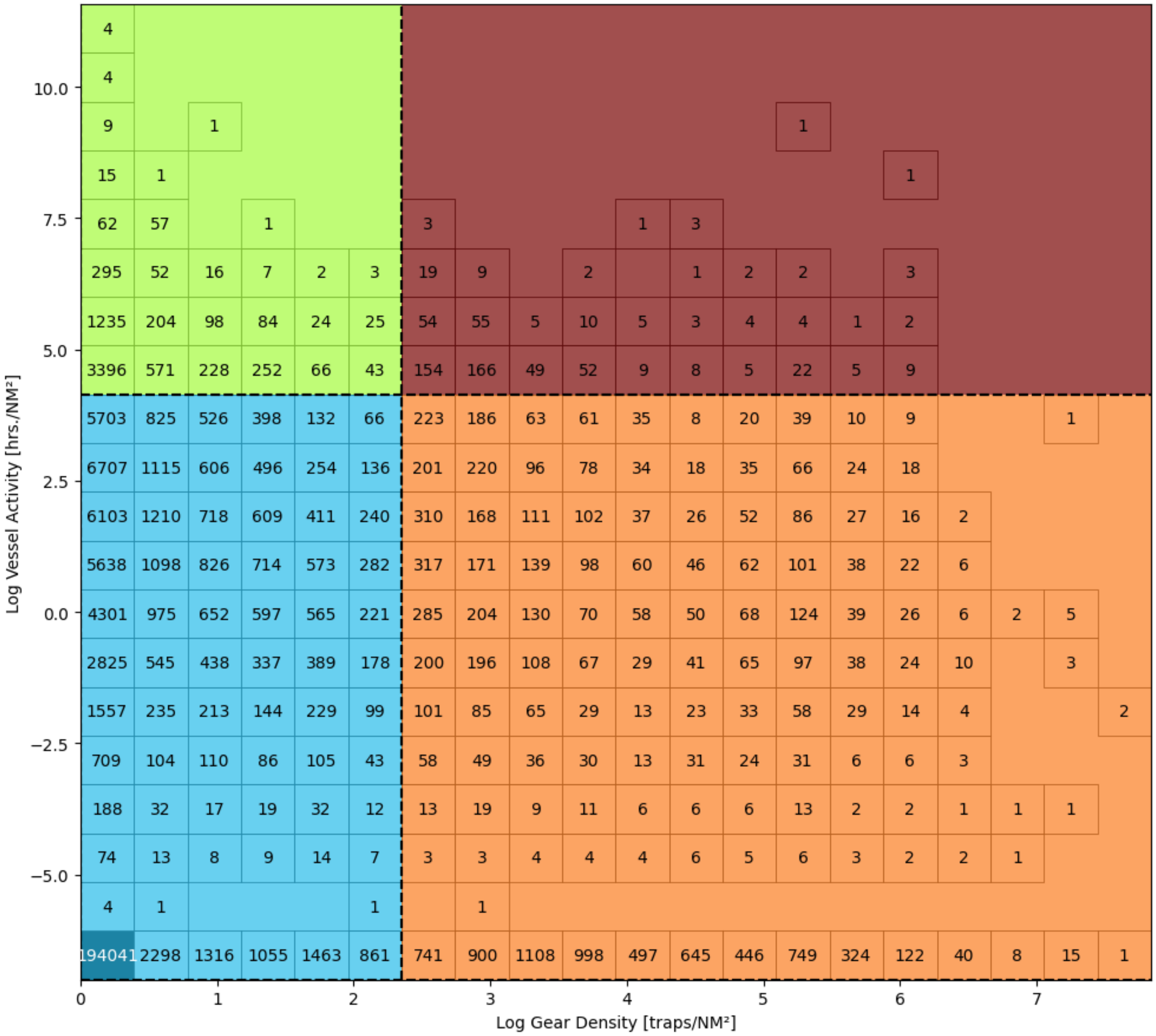


Figure 30. 2D histogram of fixed-gear density and vessel activity collected in the Northeast EEZ and averaged between March of 2019 through December of 2021. 95th percentile thresholds discretize the histogram according to risk level: 'low risk' (blue), moderate risk' (green), 'elevated risk' (orange), and 'high risk' (red). Square nautical mile counts corresponding to logarithmic gear density and logarithmic fishing activity are printed within each histogram bin.

The extracted thresholds for the two parameters together with the assigned four risk regions in the 2D space can be visualized using a 2D histogram plot. The 2D space, which consists of fixed-gear density and vessel activity values on the two axes, are partitioned into four regions using the two extracted thresholds that can be seen with dashed black lines in Section 3.2.1 and reproduced here above in Figure 30.

A.6 Data Descriptive Statistics

Includes high-level descriptive statistics to highlight important characteristics of the data such as geographic location, completeness, types of vessels, etc.

A.7 Additional Information about Data Sources

Underwater acoustic modeling is a complex challenge and understanding the environment is crucial for solving high-frequency, shallow-water acoustics problems [44]. Physical properties of the water and sediment must be known such as the salinity and temperature of the water column and seafloor sediment mass density, grainsize, porosity, etc. From the physical properties of the water and seafloor, acoustic properties such as sound speed, attenuation, and acoustic impedance can be estimated. With this information, acoustic problems can be addressed and properly modeled, as the equations of motion and boundary conditions for the acoustic field are well understood [44].

Our software, developed in Python, leverages the xarray library, which offers powerful tools for efficiently searching and manipulating data within these NetCDF files. Xarray, allows users to easily extract values for specific environmental parameters at single locations or across multiple locations. When a location falls between the gridded values provided by the datasets, we employ cubic interpolation. This method is chosen for its ability to deliver smooth and accurate estimates, which are crucial for the precision required in our modeling efforts.

Given the large size of the original datasets, we select subsets from the databases to focus on specific regions of interest. This sub setting allows us to perform interpolation over areas of interest without the computational overhead of processing the entire dataset. By narrowing down to relevant subsets, we can ensure that our interpolation and modeling efforts are both efficient and effective.

This approach not only ensures accurate environmental profiles but also provides flexibility and efficiency, accommodating both individual point queries and broader spatial analyses. By integrating high-resolution geospatial data with advanced computational tools, we can support a wide range of environmental applications and analyses.

Creating Sound Speed Profiles

A sound speed profile is the term used to describe the speed of sound in the water column at specific depths. Sound speed profiles are used by acoustic modeling software to predict the propagation of sound in simulated environments. Sound speed profiles are calculated using the data from WOA, specifically the temperature and salinity at various depths within the ocean. Using the data from the WOA sourced during the effective vertical line restricted season (February – April), sound speed profiles are created using either the Mackenzie equation [45] or Thermodynamic Equation of Seawater 2010 (TEOS-10) implemented via the Gibbs Seawater Python (GSW-Python) library [46].

Appendix B Geospatial analysis

Following the extraction of the thresholds and the gear conflict risk regions, we generated seasonal gear conflict risk maps. We considered only the grid cell locations that have numerical values for fixed-gear density values in the map generation. A zero value is considered for vessel activity in the grid cell locations that have numerical data for the fixed-gear density parameter but do not have any numerical data for the vessel activity when forming the gear conflict maps. The resultant seasonal gear conflict maps can be seen in Figure 4 and Figure 6 in Section 3.2.1. Analysis of the broad stock areas, in addition to the results for inshore Gulf of Maine, are portrayed below.

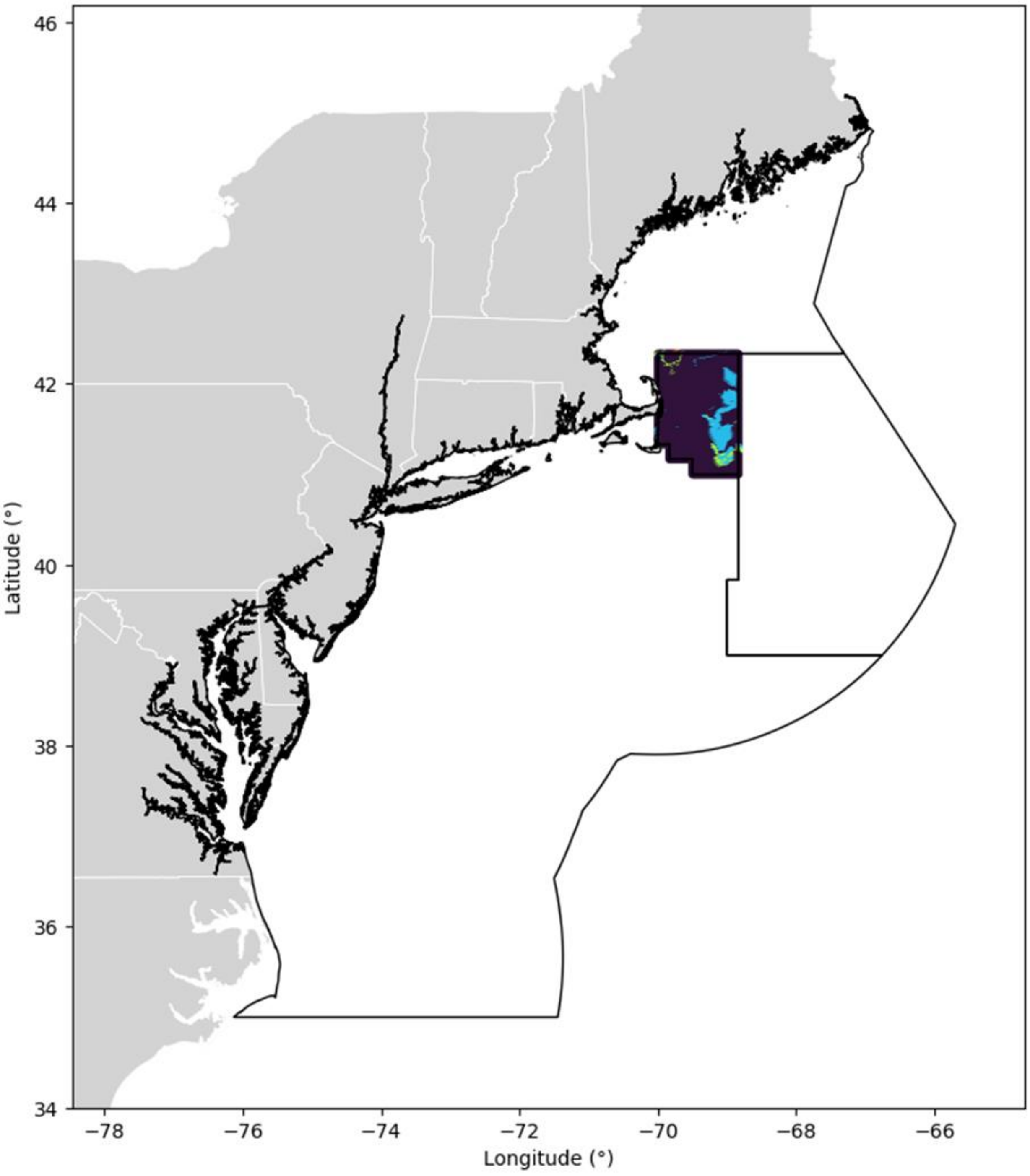


Figure 31. Gear conflict risk levels, color-coded as 'no-data' (purple), 'low risk' (blue), ‘moderate risk’ (green), ‘elevated risk’ (orange), and ‘high risk’ (red) shown in Broad Stock Area 2 averaged between the months of February - April from 2019 – 2021.

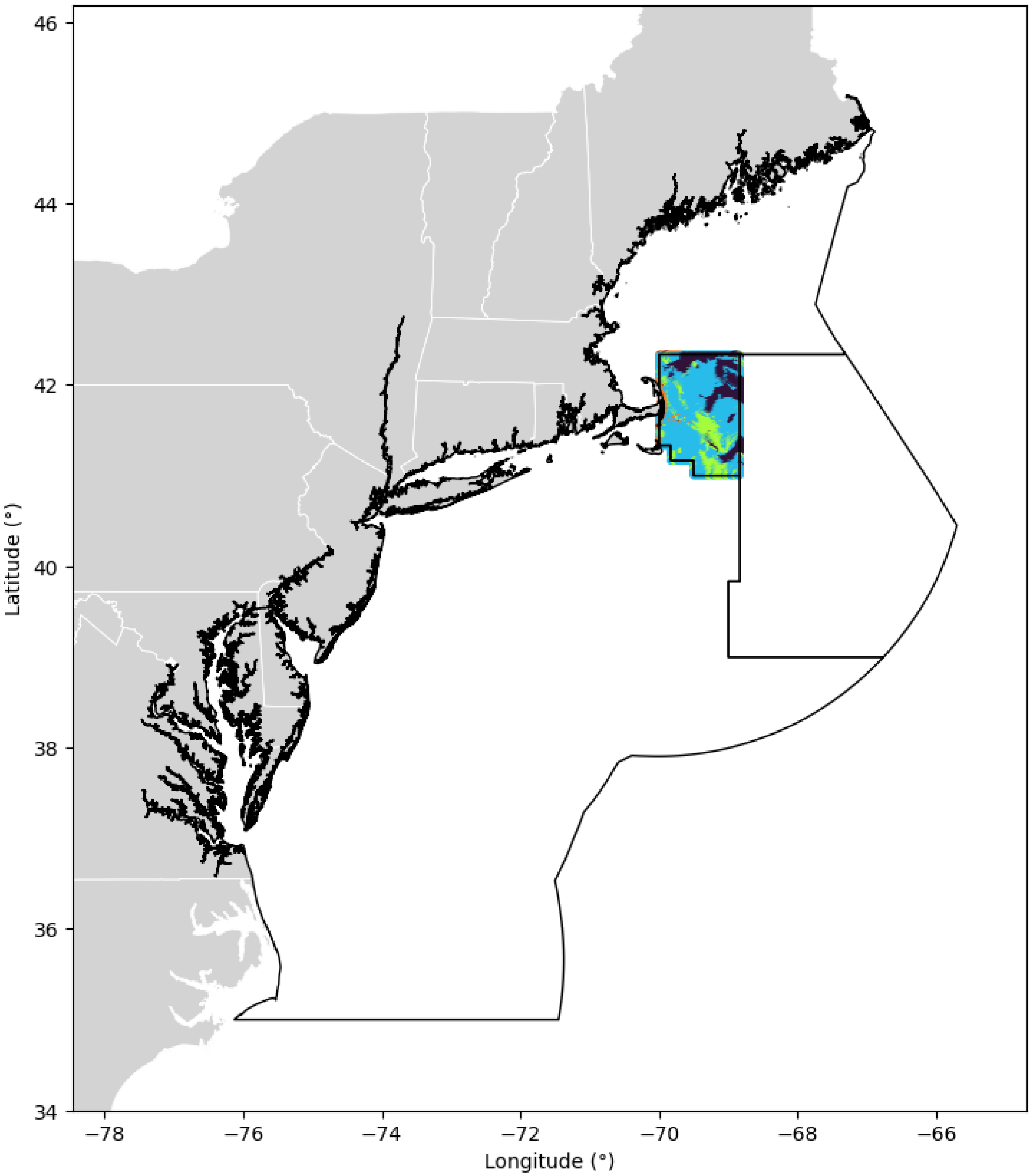


Figure 32. Gear conflict risk levels, color-coded as 'no-data' (purple), 'low risk' (blue), ‘moderate risk’ (green), ‘elevated risk’ (orange), and ‘high risk’ (red) shown in in Broad Stock Area 2 averaged between the months of May - September from 2019 – 2021.

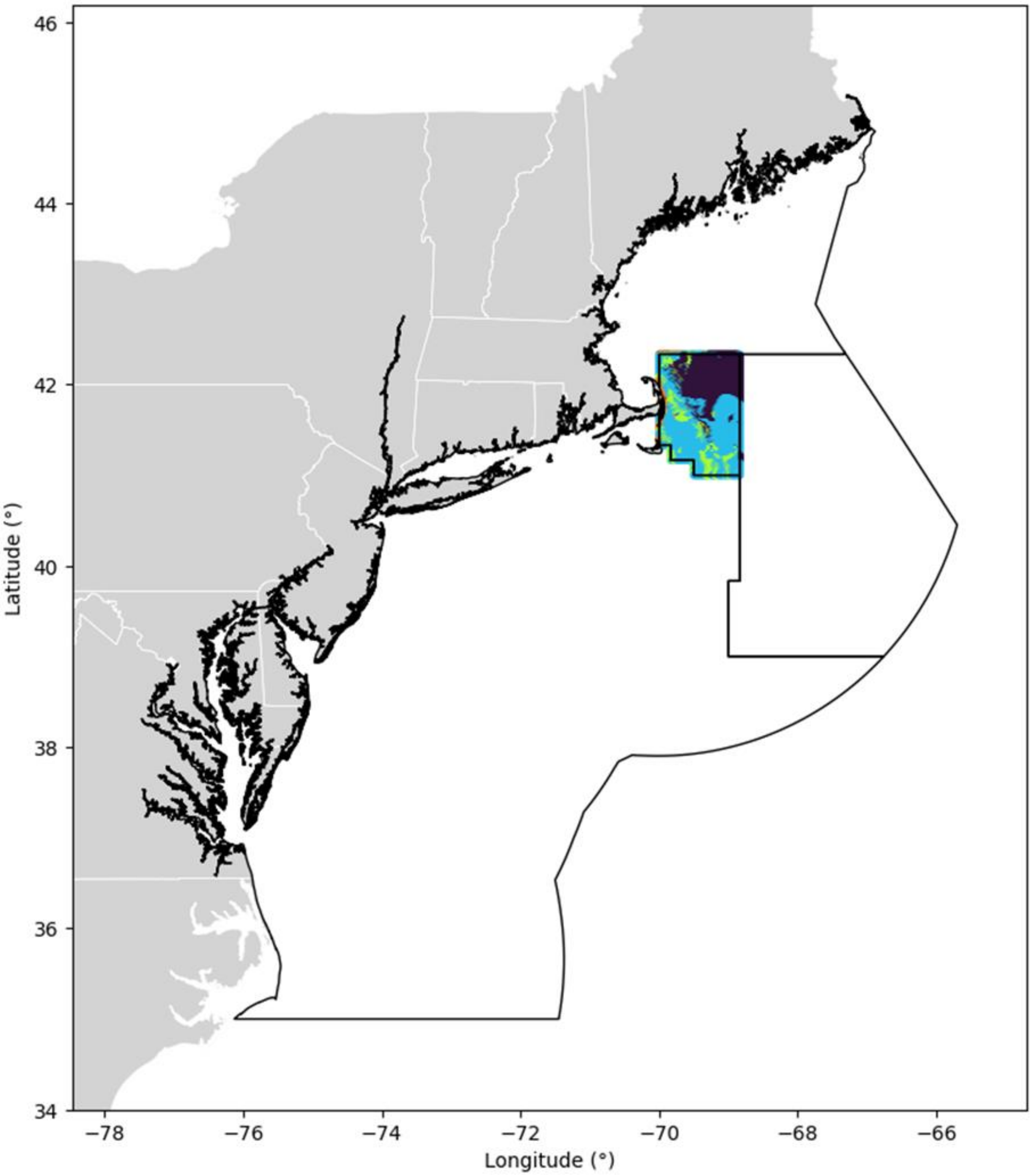
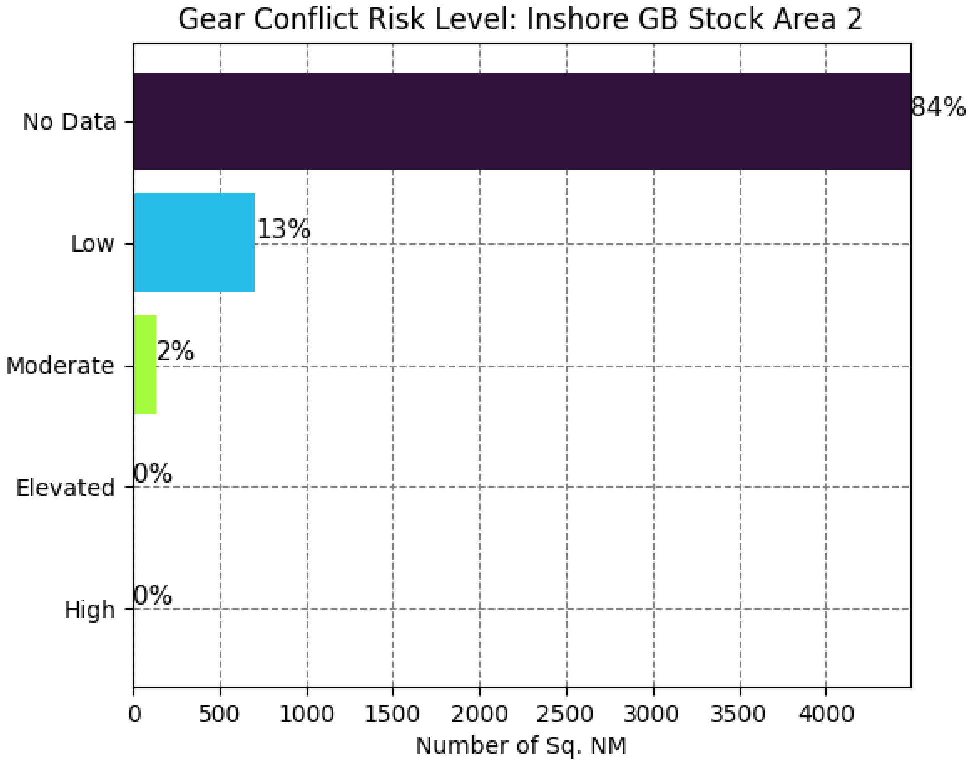
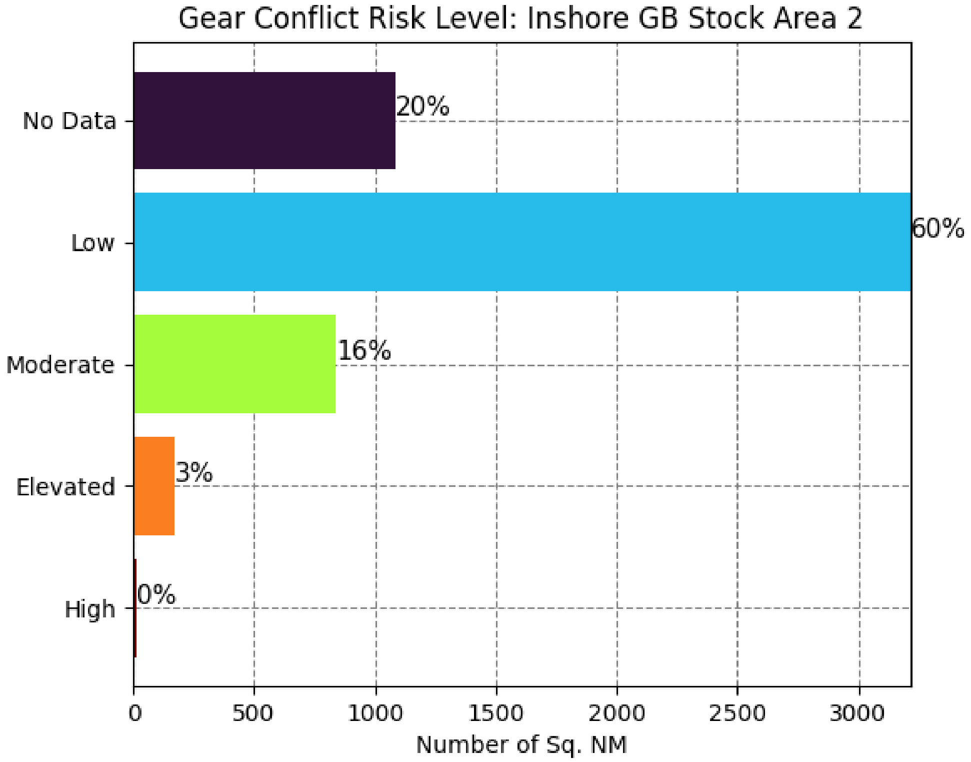


Figure 33. Gear conflict risk levels, color-coded as 'no-data' (purple), 'low risk' (blue), 'moderate risk' (green), 'elevated risk' (orange), and 'high risk' (red) shown in in Broad Stock Area 2 averaged between the months of October - January from 2019 – 2021.

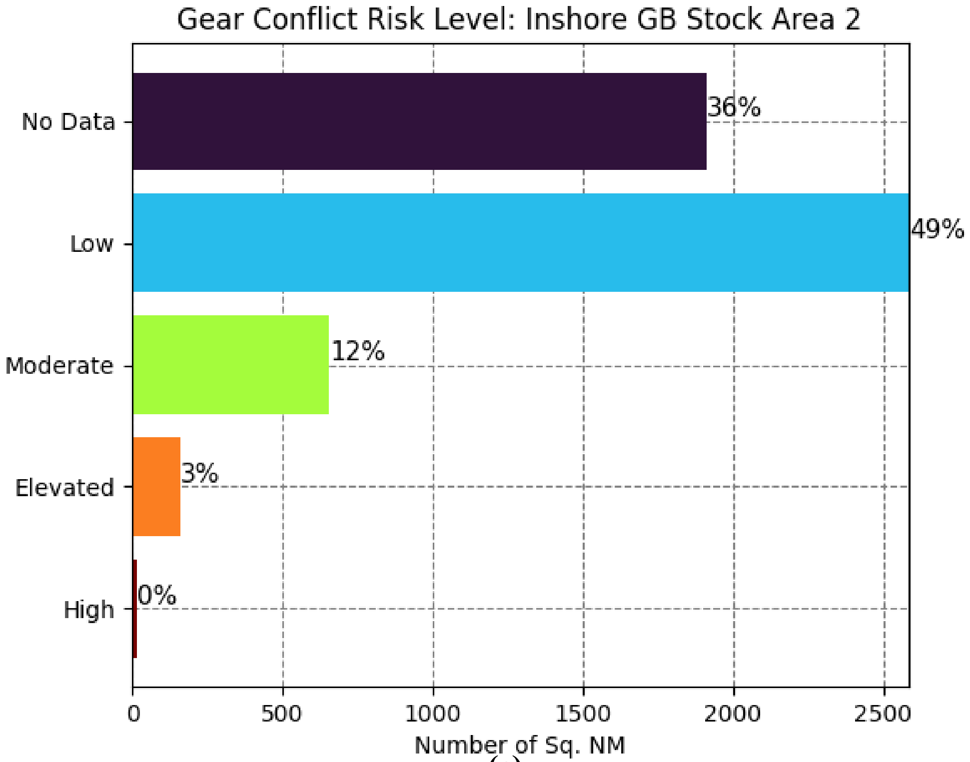
Statistics on the percentage of square nautical miles evaluated as 'no-data' (purple), 'low risk' (blue), 'moderate risk' (green), 'elevated risk' (orange), and 'high risk' (red) shown in inshore George's Bank (Broad Stock Area 2) are given in Figure 34. Percentages and area totals for each risk level are shown for seasonal averages in this area between (a) February – April and (b) October – January for data given between 2019 – 2021.


Gear Conflict Risk Level: Inshore GB Stock Area 2
No Data
Low
Moderate
Elevated
High
84%
13%
2%
0%
0%
0
500
1000
1500
2000
2500
3000
3500
4000
Number of Sq. NM

(a)


Gear Conflict Risk Level: Inshore GB Stock Area 2
No Data
Low
Moderate
Elevated
High
20%
60%
16%
3%
0%
0
500
1000
1500
2000
2500
3000
Number of Sq. NM

(b)



(c)

Figure 34: Gear conflict risk percentages of total square nautical miles Broad Stock Area 3 between (a) February – April, (b) May – September, and (c) October – January for data given between 2019 – 2021.

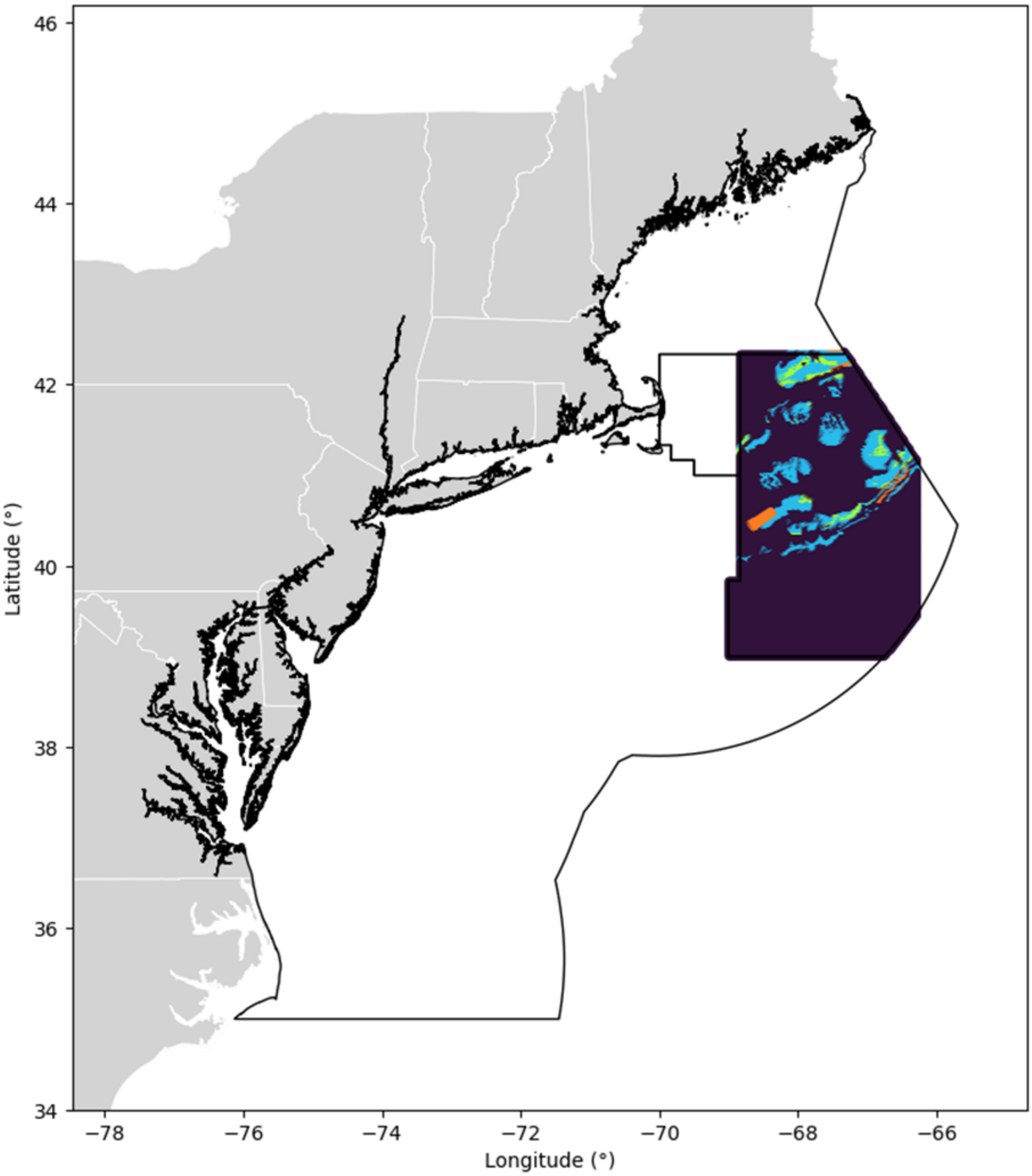


Figure 35. Gear conflict risk levels, color-coded as 'no-data' (purple), 'low risk' (blue), 'moderate risk' (green), 'elevated risk' (orange), and 'high risk' (red) shown in Broad Stock Area 3 averaged between the months of February - April from 2019 – 2021.

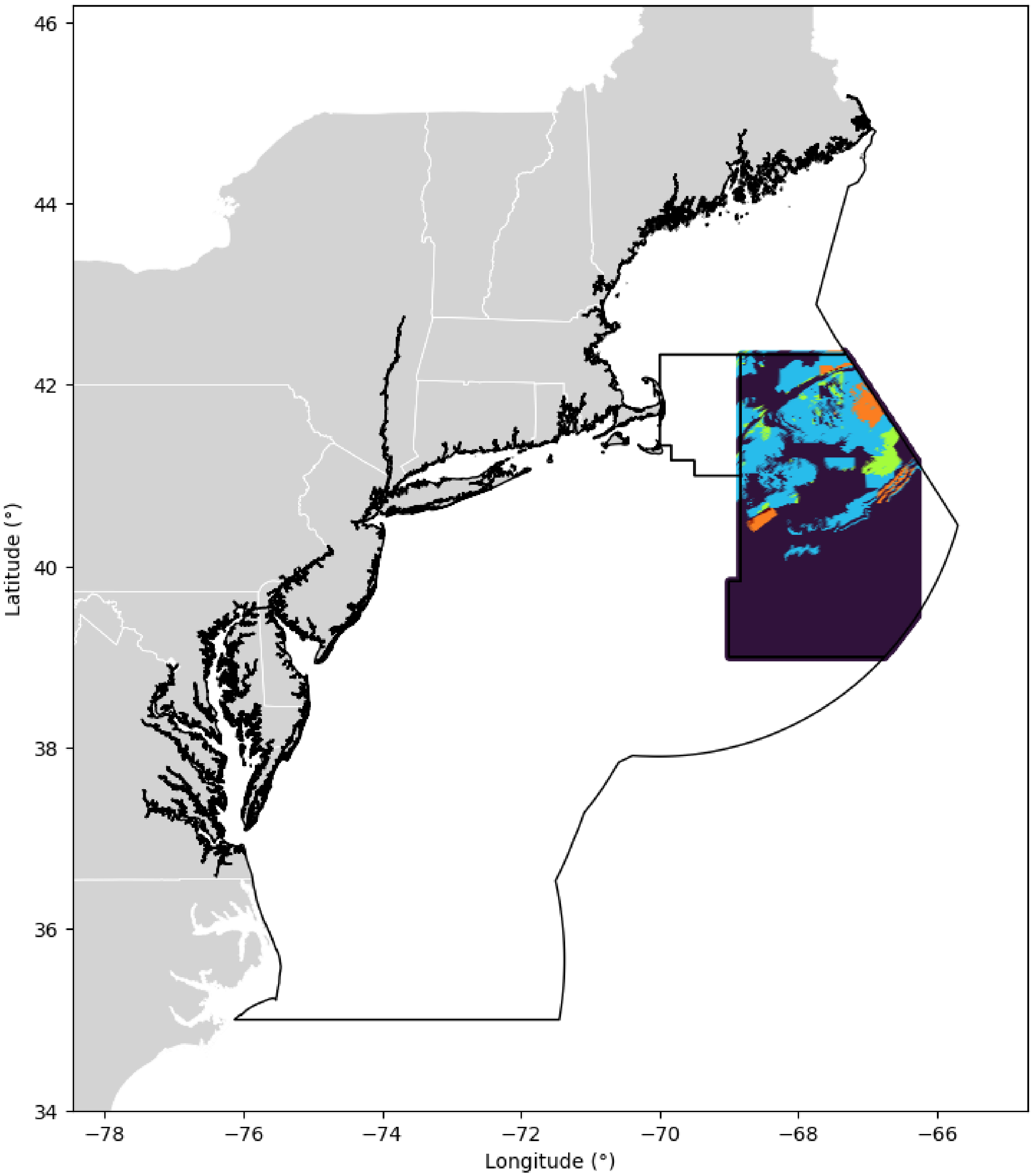


Figure 36. Gear conflict risk levels, color-coded as 'no-data' (purple), 'low risk' (blue), ‘moderate risk’ (green), ‘elevated risk’ (orange), and ‘high risk’ (red) shown in Broad Stock Area 3 averaged between the months of May - September from 2019 – 2021.

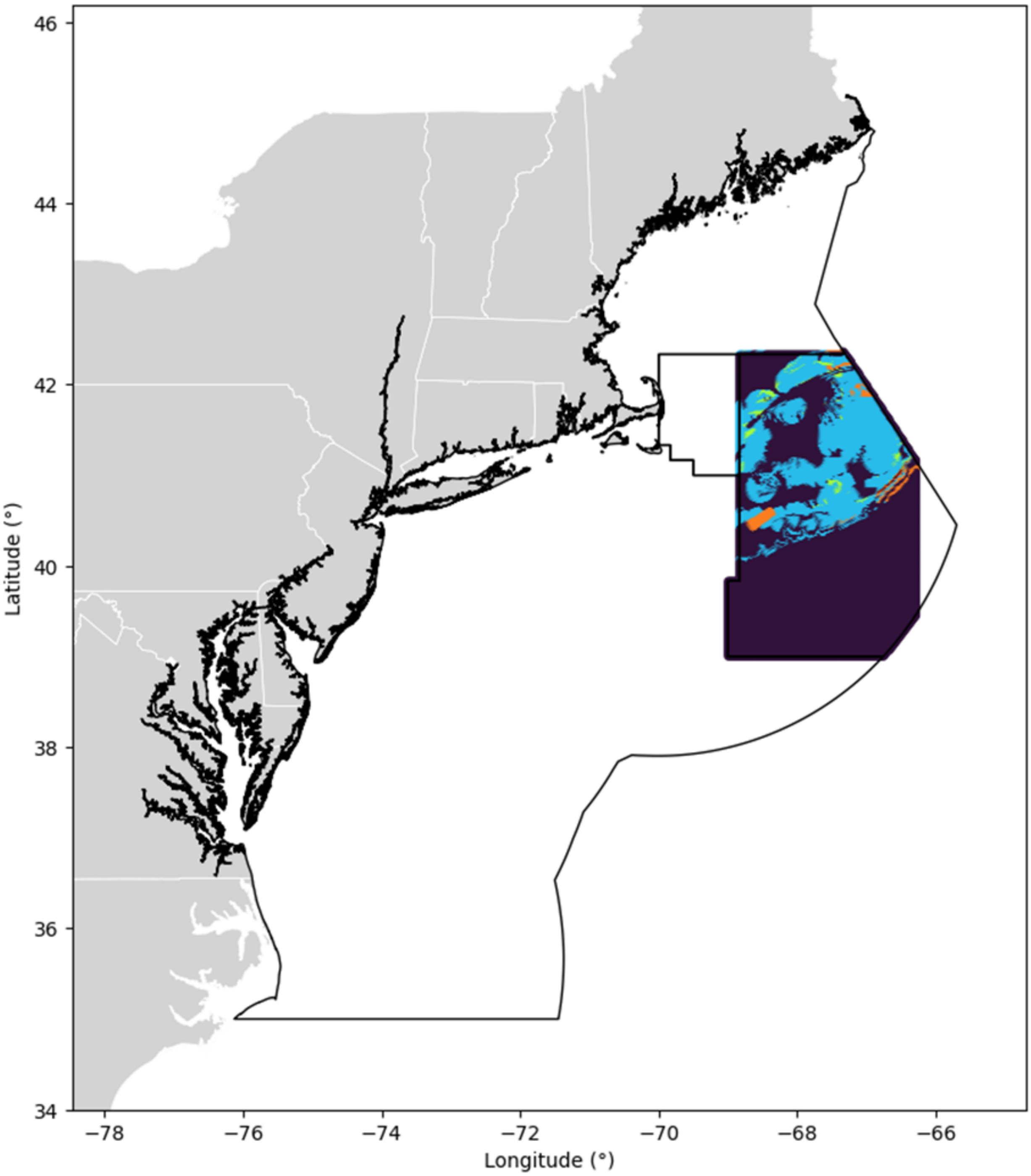
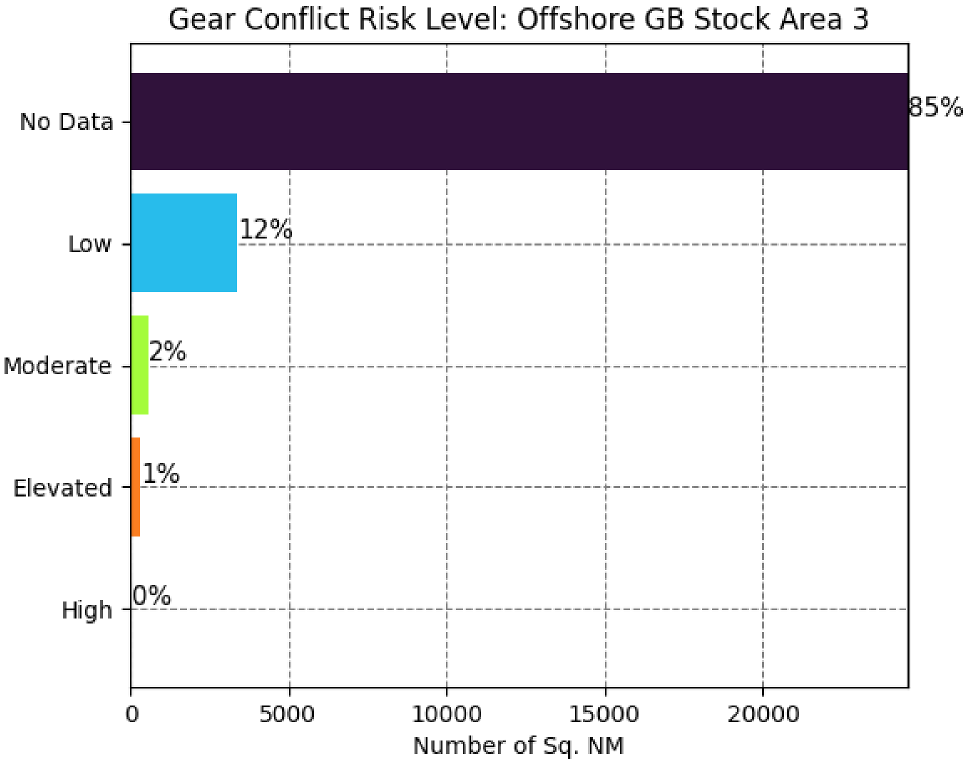
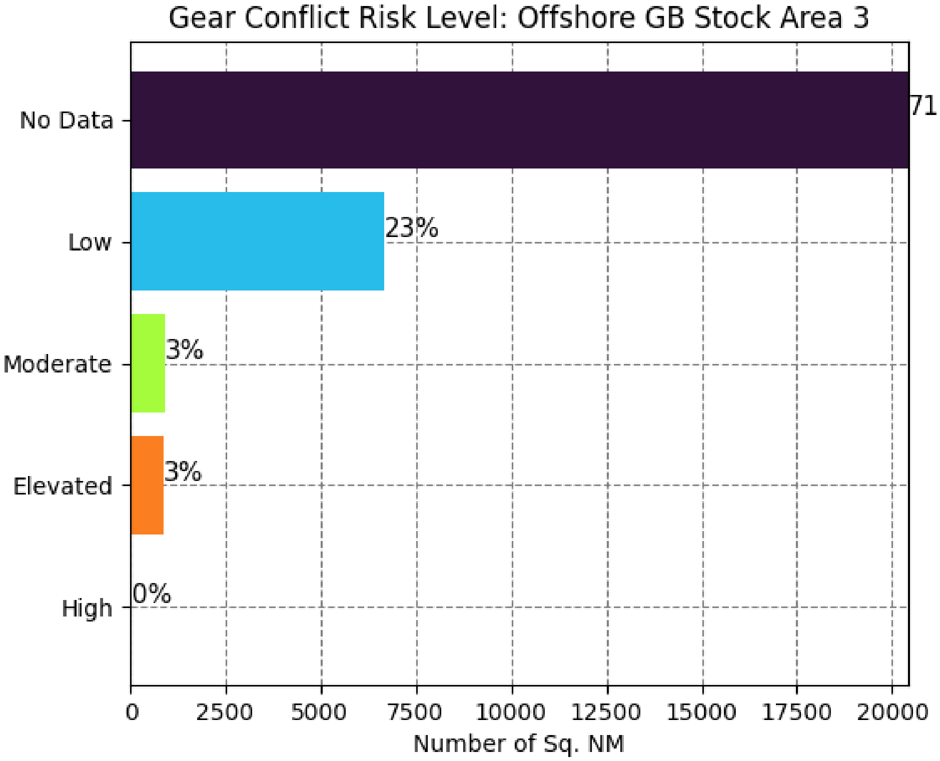


Figure 37. Gear conflict risk levels, color-coded as 'no-data' (purple), 'low risk' (blue), 'moderate risk' (green), 'elevated risk' (orange), and 'high risk' (red) shown in in Broad Stock Area 3 averaged between the months of October - January from 2019 – 2021.

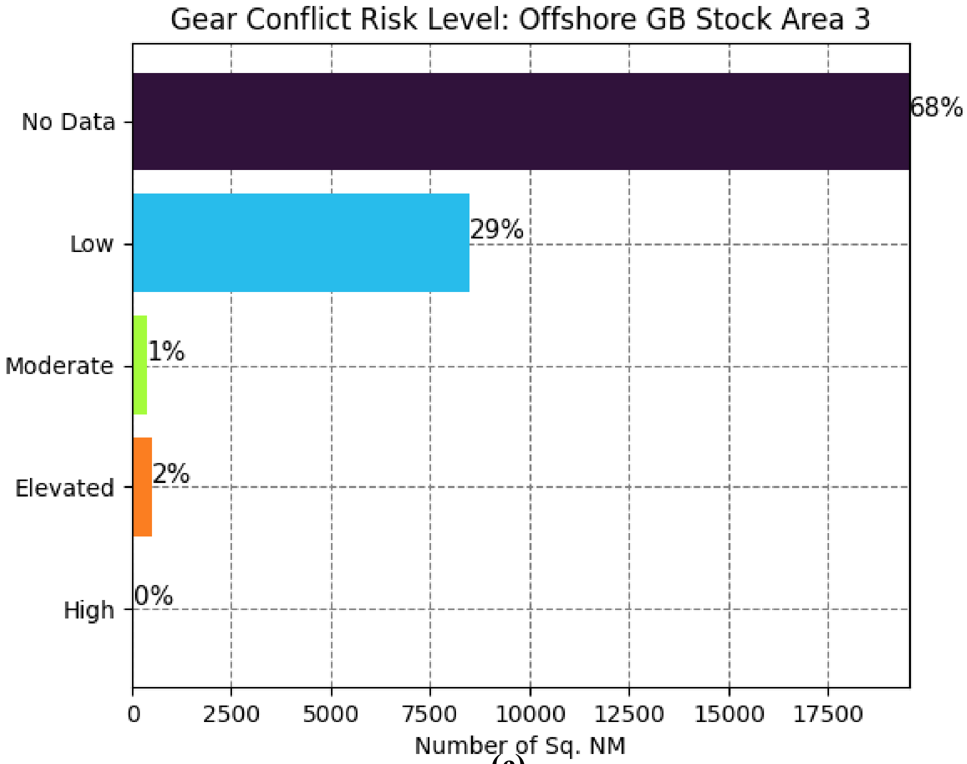
Statistics on the percentage of square nautical miles evaluated as 'no-data' (purple), 'low risk' (blue), 'moderate risk' (green), 'elevated risk' (orange), and 'high risk' (red) shown in offshore George's Bank (Broad Stock Area 3) are given in Figure 38. Percentages and area totals for each risk level are shown for seasonal averages in this area between (a) February – April and (b) October – January for data given between 2019 – 2021.


Gear Conflict Risk Level: Offshore GB Stock Area 3
No Data
Low
Moderate
Elevated
High
85%
12%
2%
1%
0%
0
5000
10000
15000
20000
Number of Sq. NM

(a)


Gear Conflict Risk Level: Offshore GB Stock Area 3
No Data
Low
Moderate
Elevated
High
71%
23%
3%
3%
0%
0
2500
5000
7500
10000
12500
15000
17500
20000
Number of Sq. NM

(b)



(c)

Figure 38. Gear conflict risk percentages of total square nautical miles Broad Stock Area 3 between (a) February – April, (b) May – September, and (c) October – January for data given between 2019 – 2021.

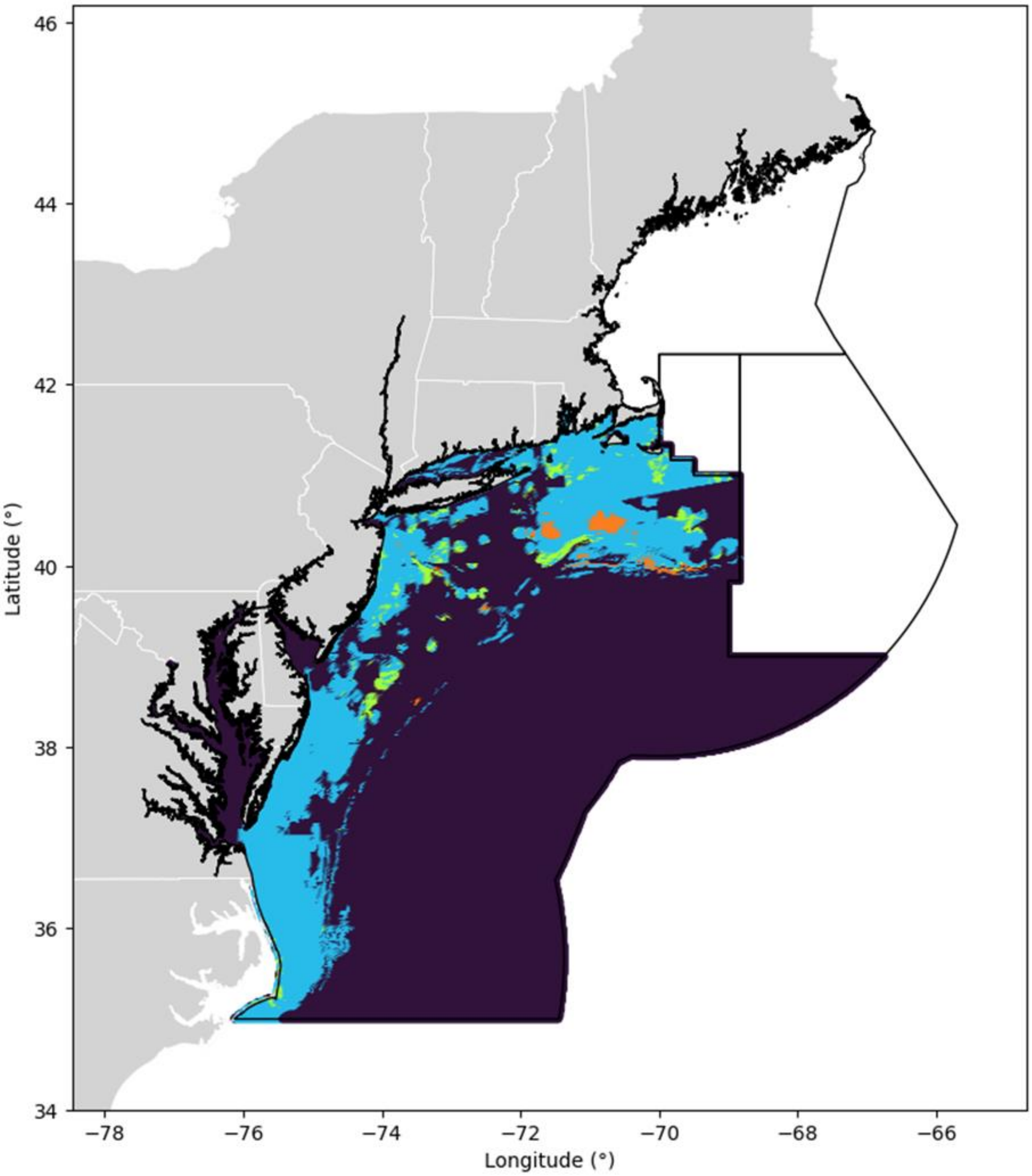


Figure 39. Gear conflict risk levels, color-coded as 'no-data' (purple), 'low risk' (blue), ‘moderate risk’ (green), ‘elevated risk’ (orange), and ‘high risk’ (red) shown in Broad Stock Area 4 averaged between the months of February - April from 2019 – 2021.

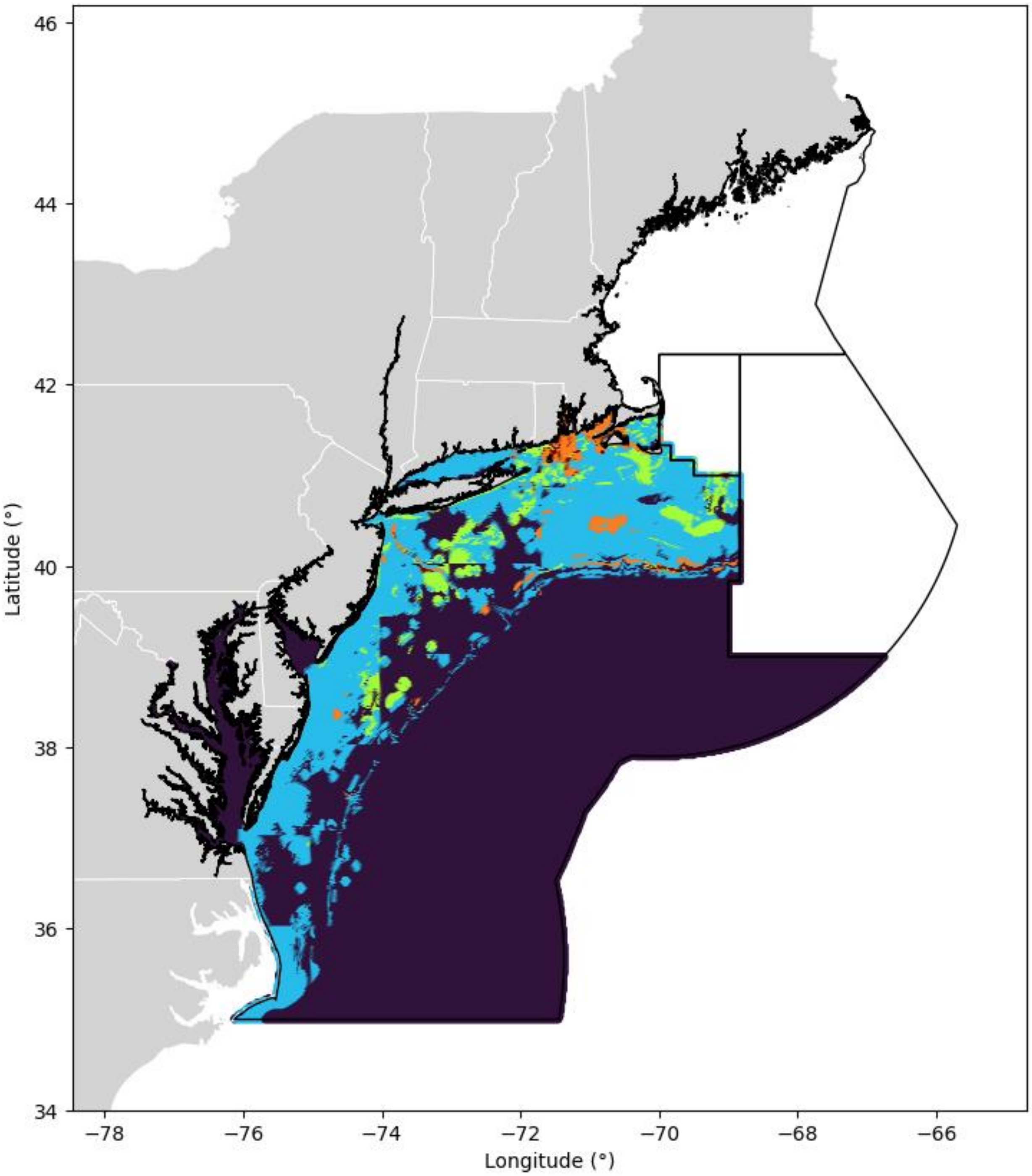


Figure 40. Gear conflict risk levels, color-coded as 'no-data' (purple), 'low risk' (blue), ‘moderate risk’ (green), ‘elevated risk’ (orange), and ‘high risk’ (red) shown in Broad Stock Area 4 averaged between the months of May - September from 2019 – 2021.

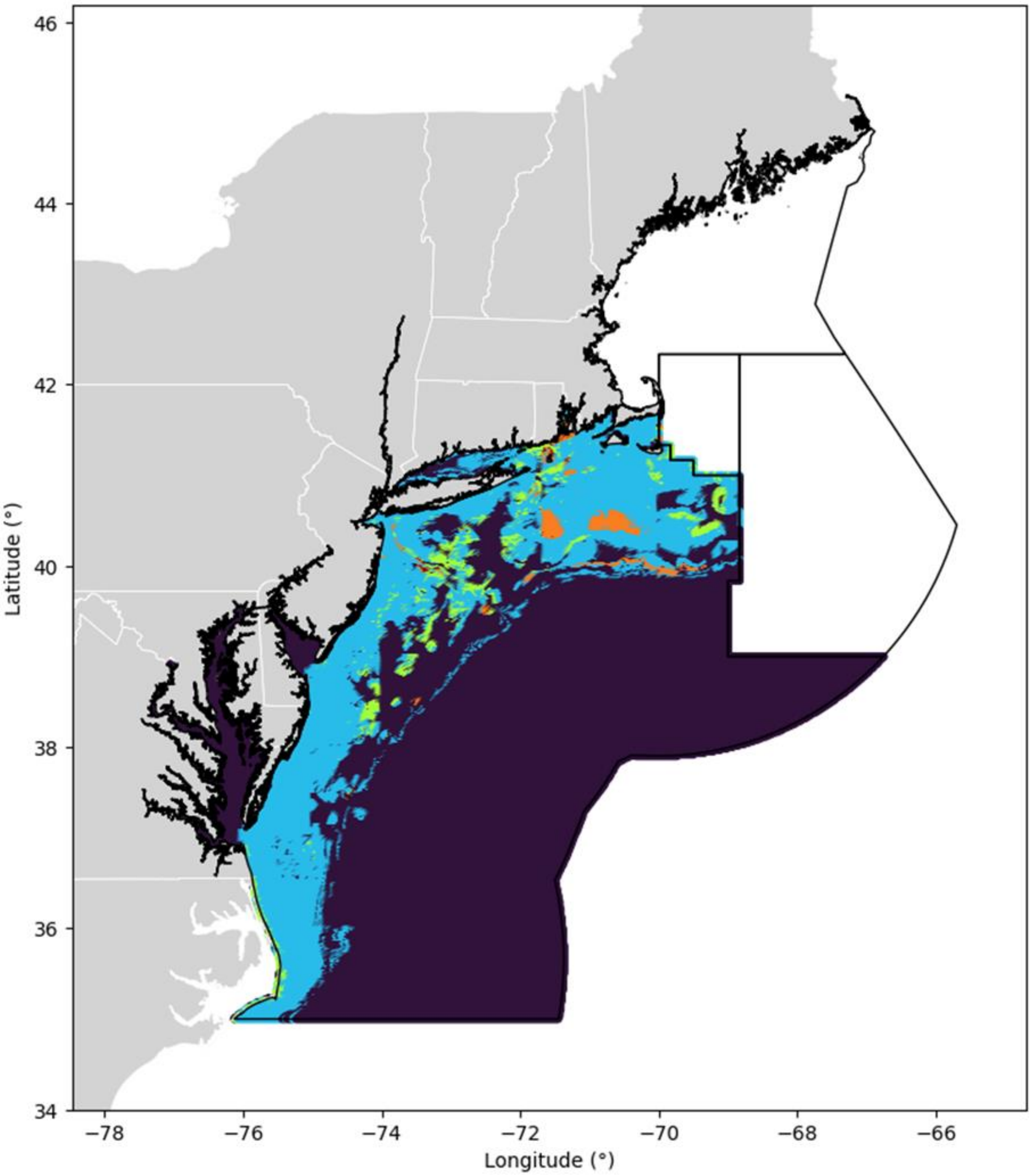
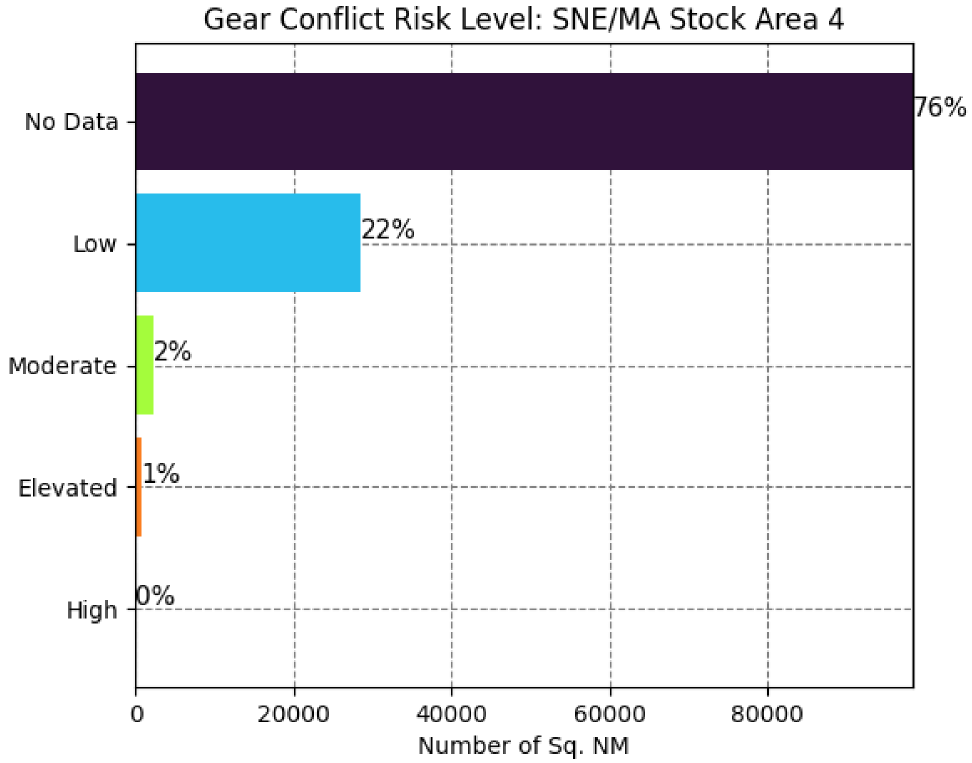
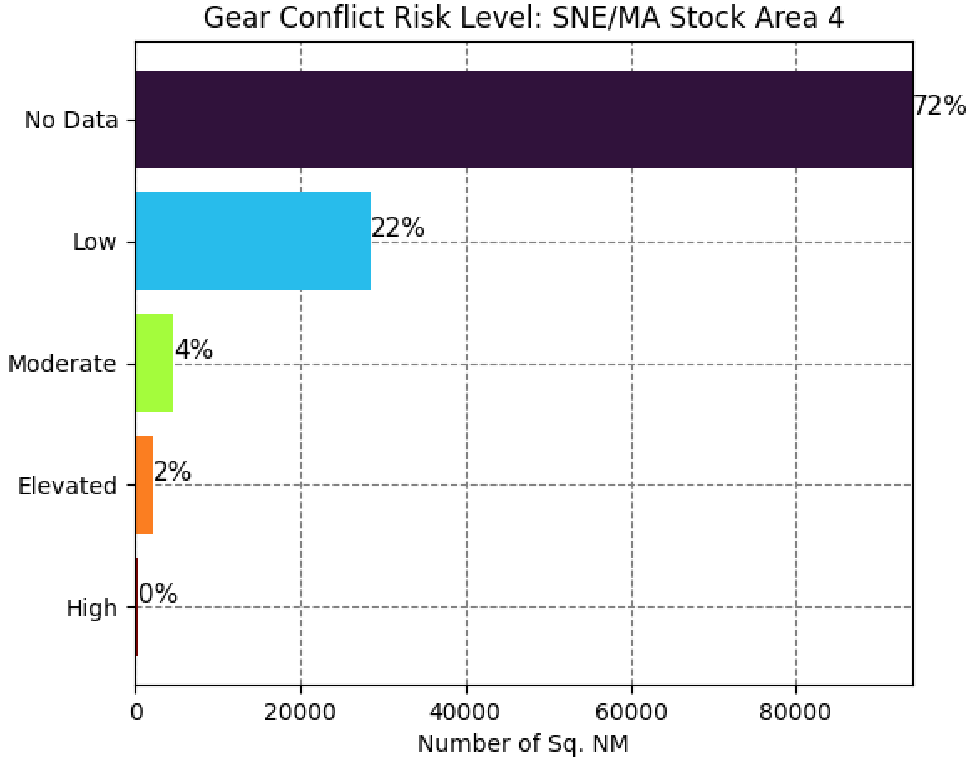


Figure 41. Gear conflict risk levels, color-coded as 'no-data' (purple), 'low risk' (blue), ‘moderate risk’ (green), ‘elevated risk’ (orange), and ‘high risk’ (red) shown in in Broad Stock Area 4 averaged between the months of October - January from 2019 – 2021.

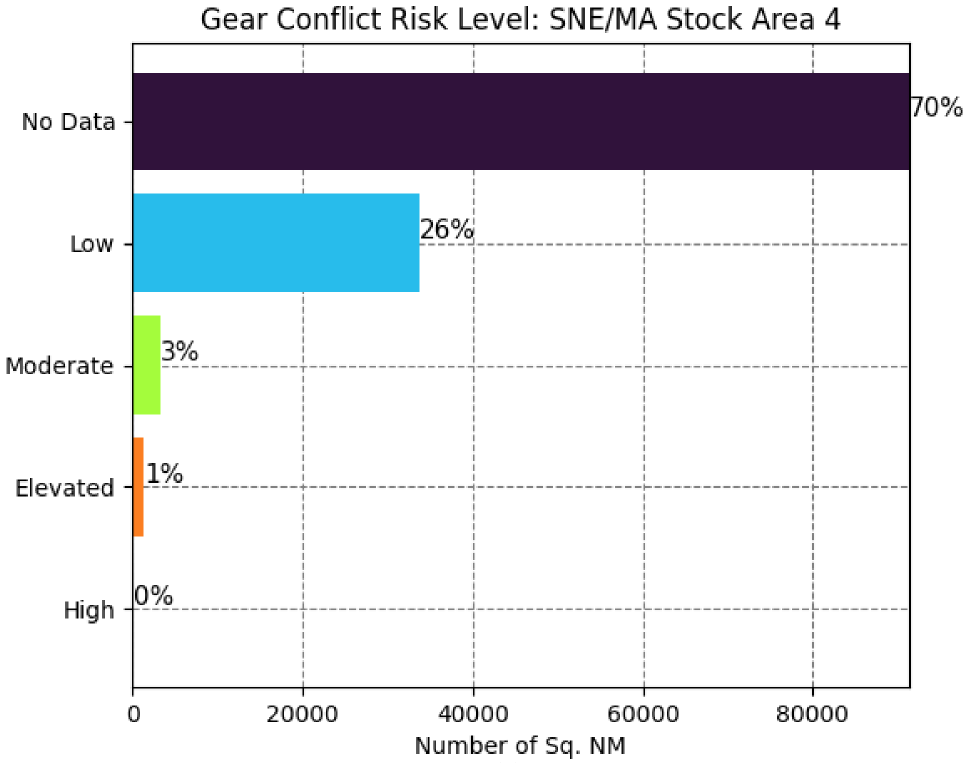
Statistics on the percentage of square nautical miles evaluated as 'no-data' (purple), 'low risk' (blue), ‘moderate risk’ (green), ‘elevated risk’ (orange), and ‘high risk’ (red) shown in southern New England (Broad Stock Area 4) are given in Figure 42. Percentages and area totals for each risk level are shown for seasonal averages in this area between (a) February – April and (b) October – January for data given between 2019 – 2021.


Gear Conflict Risk Level: SNE/MA Stock Area 4
No Data
Low
Moderate
Elevated
High
76%
22%
2%
1%
0%
0
20000
40000
60000
80000
Number of Sq. NM

(a)


Gear Conflict Risk Level: SNE/MA Stock Area 4
No Data
Low
Moderate
Elevated
High
72%
22%
4%
2%
0%
0
20000
40000
60000
80000
Number of Sq. NM

(b)



(c)

Figure 42. Gear conflict risk percentages of total square nautical miles Broad Stock Area 3 between (a) February – April, (b) May – September, and (b) October – January for data given between 2019 – 2021.

With the exception of the inshore George's Bank (Broad Stock Area 2) region through the October to January time period, all other geospatial zones of analysis are dominated by 'No Data' classification, indicating little fixed-gear present within that region based on input from WHALE DST. 'Elevated' and 'high' risk labels comprise 3% or less in each of the total areas represented, indicating that in general, these regions are sparse and that the primary region of concern for gear conflict risk is within inshore Gulf of Maine (Broad Stock Area 1) as represented by Figure 7, Figure 8, and Figure 9.

Appendix C Acoustic Emissions Analysis

A previously unanswered question regarding the scaled operation of on-demand gear is what effect, if any, the active acoustic emissions have on local marine life when used in regular fishing operations. An analysis is performed here based on environmental data within the South Island Restricted Area, which was chosen to be a representative closed zone for potential on-demand gear operation.

C.1 Methodology

Given a proliferation of active acoustic on-demand fishing gear emitting with a duty cycle defined by utilization and interoperability, a cumulative sound pressure level over a spatial and temporal range may be estimated. This quantity is described as an averaged received sound pressure level at any point in an underwater environment from the physical emissions of frequency-limited acoustic communication devices, such as on-demand gear modems or transponders. The generation of underwater sound from any one of these devices propagates away from the source and through the environment where it is attenuated according to geometric spreading laws and absorption, which depends on the frequency and seawater properties. The relationship between the source sound pressure level and frequency, and the magnitude of the combined effects of spreading and absorption (defined cumulatively as transmission loss) predict the amount of signal excess at any point away from the transmitting source. A multitude of sources emitting with a random but statistically describable schedule will combine non-coherently at any point in the underwater channel to yield a combined metric in terms of decibel sound pressure level with reference to 1 micropascal. By assuming that the frequency content is the same across a non-coherent array of M sources, Equation C.1 describes the non-coherent contribution at a position vector $\vec{x}$ from an array of sources positioned at $\vec{x}_m$.

$$p(\vec{x}|\vec{x}_M) = \left[\sum_{m=1}^{M}\left[\beta_0 \cdot \sqrt{p_{SEL,m}} \cdot e^{-\alpha(f)(|\vec{x}-\vec{x}_m|)} \cdot (|\vec{x}-\vec{x}_m|)^{\beta_1}\right]^2\right]^{\frac{1}{2}} \qquad (C.1)$$

$$|\vec{x}-\vec{x}_m| = \sqrt{(x-x_m)^2 + (y-y_m)^2 + (z-z_m)^2} \qquad (C.2)$$

The source level is described in Equation C.3 by the sound exposure level metric p_{SEL} based on acoustic standard ISO 18405:2017 [47]. Derived from the decibel measure of source level with reference to p_o, or an underwater reference pressure of 1 micropascal, integration of the time-varying pressure $p(t)$ over the signal period T yields the mean linear sound pressure level over the duration of emission.

$$p_{SEL} = \frac{1}{T}\int_0^T 10^{\frac{\sqrt{2}SL}{10}}dt = \frac{1}{T}\int_0^T p(t)^2 dt \qquad (C.3)$$

This metric may vary across M sources according to the source level for each source positioned at location $\vec{x}_m$ in a 3-dimensional cartesian space. The absolute difference between the evaluation position $\vec{x}$ and an emitter located at $\vec{x}_m$ given in Equation C.2 is the range between receiver and source respectively, on which several important parameters depend. The product of range and the frequency-dependent absorption rate $\alpha(f)$ is the first significant loss term in Equation C.1, which accounts for a reduction in signal energy at a range away from the emitter according to physical loss processes in the underwater environment. Described by François and Garrison [48] in Equation C.4 as three cumulative terms describing Boric Acid contribution, Magnesium Sulphate contribution, and pure water contribution respectively, the absorption rate increases proportional to frequency.

$$\bar{\alpha}(f) = \frac{A_1 P_1 f_1 f^2}{f_1^2 + f^2} + \frac{A_2 P_2 f_2 f^2}{f_2^2 + f^2} + A_3 P_3 f^2 \tag{C.4}$$

The A_i and P_i coefficients in Equation C.4 depend on parameters of the underwater acoustic channel, namely salinity, temperature, acidity, and depth of the seawater. Relaxation frequencies f_i are described in kilohertz and the resultant sum $\bar{\alpha}(f)$ is given in units of dB/kilometer which must be converted to linear units of Neper/kilometer to achieve the value $\alpha(f)$ in Equation 2.1. Broadly speaking, lower frequency signals will propagate further in an underwater environment due to the reduced effects of absorption loss which increase proportional to frequency squared. For this study, absorption rates are relevant for frequencies between 15 to 40 kHz and may be considered a scalar value when the source signal bandwidth relative to the source center frequency satisfies the narrowband assumption, $BW/f_c \ll 1$, where BW and f_c are the signal bandwidth and center frequency, respectively.

Geometric spreading loss and boundary interactions account for the other major attenuative factors for propagating acoustic emissions in an underwater channel. These terms are described in the β_i coefficients of Equation C.1, where β_0 encapsulates loss from absorptive boundaries, such as the water-sediment interface, and β_1 describes inverse-power law attenuation due to the geometric dilution of energy as a wavefront propagates outward from an emitting source. This loss factor is constrained between values of $[-2 - 1]$ which bound the range between spherical spreading loss and cylindrical spreading loss, with empirical loss values for an underwater channel typically existing somewhere in-between. The absolute difference between the evaluation position $\vec{x}$ and an emitter located at $\vec{x}_m$ raised to the power β_1 determines the attenuation of the signal over range.

Both β_i coefficients are functions of the environmental conditions within the underwater domain and as such, may be derived from computational models of source distributions in representative environments which capture sound speed profiles, bathymetry, boundary conditions, and source positions. The acoustic ray-tracing software BELLHOP [17] was employed to efficiently calculate these values by numerically solving for the spatial distributions of pressure within an underwater environment from a statistical sample of sources distributed within a fishery. A notional distribution of sources is portrayed in Figure 45 (a) where the white dots represent the coordinate location of an emitting piece of acoustic on-demand gear. These units are distributed according to a random Poisson process to simulate geospatial clustering common within fisheries.

By sampling a statistically significant number of source locations under conditions representative of the environment, a stochastic β_i coefficient may be derived where the geometric spreading loss component varies according to a multivariate log-normal distribution as described in Equation C.5.

$$\beta_i \sim Lognormal(\boldsymbol{\mu}, \boldsymbol{\Sigma}) \tag{C.5}$$

Deriving the mean value for this distribution is contingent upon solving a nonlinear least-squares problem to derive an inverse power-law description of the averaged transmission loss within the range of analysis points. This minimization procedure is described in Equation C.6 which states the least-squares problem for minimization as a function of the difference between a power-law distribution and values calculated computationally using BELLHOP given as a function of range $\widehat{TL}(r_i)$.

$$minimize \sum_{i=1}^{N}\left(\left[\overline{\beta_1}\, log_{10}(r_i) + \overline{\beta_0}\right] - \widehat{TL}(r_i)\right)^2 \qquad (C.6)$$

After optimization, $\overline{\beta_\iota}$ terms – which represent the decibel values of the linear β_i terms – are allowed to vary randomly within Equation C.1 with variance based on distribution statistics denoted in Equation 2.5. This approach allows for a convenient statistical representation of transmission loss factors within an underwater acoustic channel that would otherwise be computationally infeasible to run in BELLHOP.

The geospatial area for analysis is discretized into a raster grid for computation at latitude/longitude points and a non-coherent summation of sound pressure level is calculated at each point based on the influencing factors described above and detailed in Equation 2.1. This value is computed for both realistic emitting times and a worst-case scenario of high-duty cycle transmission to generate a conservative estimate of instantaneous and cumulative emissions on a temporal scale. Results are presented in Section 3.4 for analysis confined within the bounds of the South Island Restricted Area vertical line closure. Source levels and operating frequencies are assumed from the information provided in Section 3.3 to produce a geospatial map of received sound pressure level at any point within the region of analysis.

Source distributions within the South Island Restricted Area were calculated for both uniform and Poisson distributions, with the Poisson distribution case shown in Figure 45 (b). In each case, a total of 500 emitting sources were considered. The uniform distribution is assumptive of no causality behind source distribution whereas the Poisson distribution is based on multiple random centroids meant to represent dense fishing notionally informed by biomass distribution and other social factors. In both cases, the latitude and longitude extent of the region is discretized into 1 million cells of spatial resolution 0.00187° in longitude and 0.000833° in latitude. With source positions described by the two random distributions, and receive points positioned at the resolution increments and approximate midwater depth from the source position, Equation C.2 may be solved for the range matrix from each source to each resolution cell. This factor is essential in determining the propagation distance and absorption length necessary to compute the cumulative acoustic emission level given in Equation C.1.

Results were then generated for two scenarios: continuous emissions and time-averaged emissions according to a notional signaling limit of 120-seconds worth of active transmit time over a 24-hour period. The first scenario is indicative of the worst-case scenario in which 25 kHz sources at a defined level of 183 dBSPL ref.1 μPa at 1m emit continuously over the 24-hour duration of analysis. This represents the worst-case scenario for instantaneous sound pressure levels, which are the basis for the regulation of non-impulsive intermittent sources. The second scenario is representative of a notional signaling scheme in which a cumulative 1-minute worth of source emission is non-coherently time-averaged over the analysis period. These parameters were determined from an industry survey, shown in Table 4. Leveraging the solution for cumulative emission at a specified location from Equation C.1, the time-averaged decibel level may be computed according to Equation C.7.

$$\langle p(\vec{x}|\vec{x}_M)\rangle = 10\log_{10}\left(\frac{p(\vec{x}|\vec{x}_M)^2}{p_0^2}\right) + 10\log_{10}\left(\frac{t_{emit}}{T_{24}}\right) \qquad (C.7)$$

Here, the variable t_{emit} is set to 120-seconds and T_{24} is 86,400-seconds. p_0^2 is the square of the reference pressure taken as 1 μPa^2.

C.2 Results

Sourced from bathymetry and ocean parameter datasets specific to a location as described in Appendix A.4, depth profiles over range and depth-dependent sound speed profiles shown in Figure 43 were provided as input parameters to a BELLHOP simulation. The inclusion of these sampled data provides a realistic basis for simulation of transmission loss within a region but represent averaged characteristics rather than instantaneous values. This fact contributes to a level of uncertainty within the modeled result which should suffice to represent characteristic acoustic properties of an underwater environment while not being specific to the precise placement of any one single piece of on-demand gear.

By modeling source positions and receiver locations across this range, transmission loss may be computed as a spatial function of the acoustic channel as it varies across latitude and longitude.

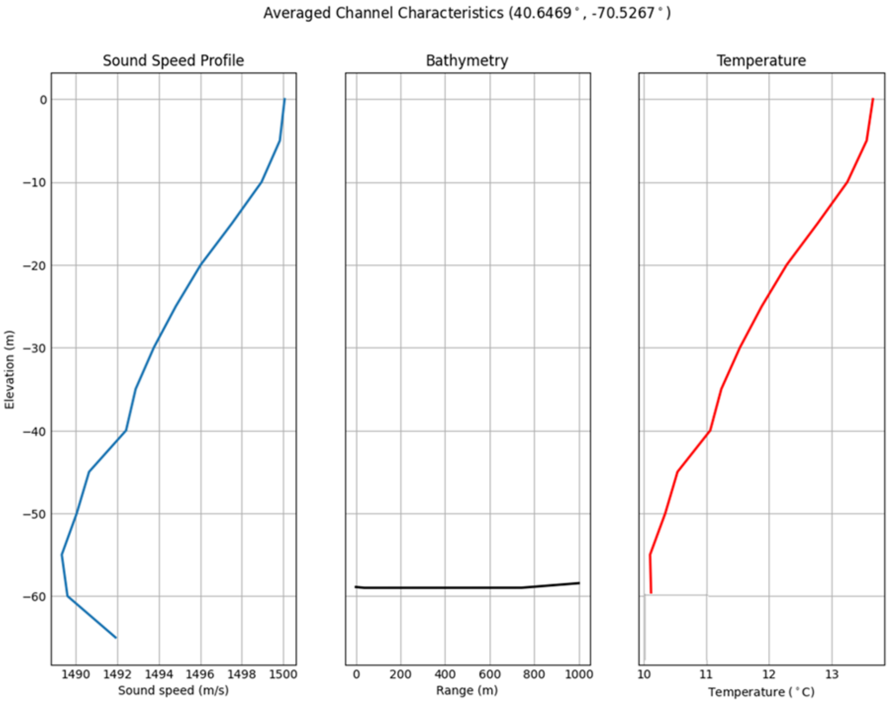


Figure 43. Annually averaged channel characteristics at a location within the South Island Restricted Area.

Sample points were selected across this region based on a uniform random distribution and transmission loss was calculated for each of these points across a 1-kilometer range away from each source along bearing lines corresponding to four cardinal directions.

This sampling approach, depicted in Figure 44, provides as an approximation on the geometric spreading loss and boundary interaction factors for each source. The power-law approximation of this transmission loss, based on β_i coefficients derived according to the approach detailed in Section C.1, is optimized against the linearized and averaged transmission loss computed along bearing lines for each source at mid-water depth relative to each source position, according to Equation C.6. The deviation caused by different levels of boundary interaction and propagation loss due to channel geometry and sound speed profiles results in a standard error on the order of ± 3 dB per source.

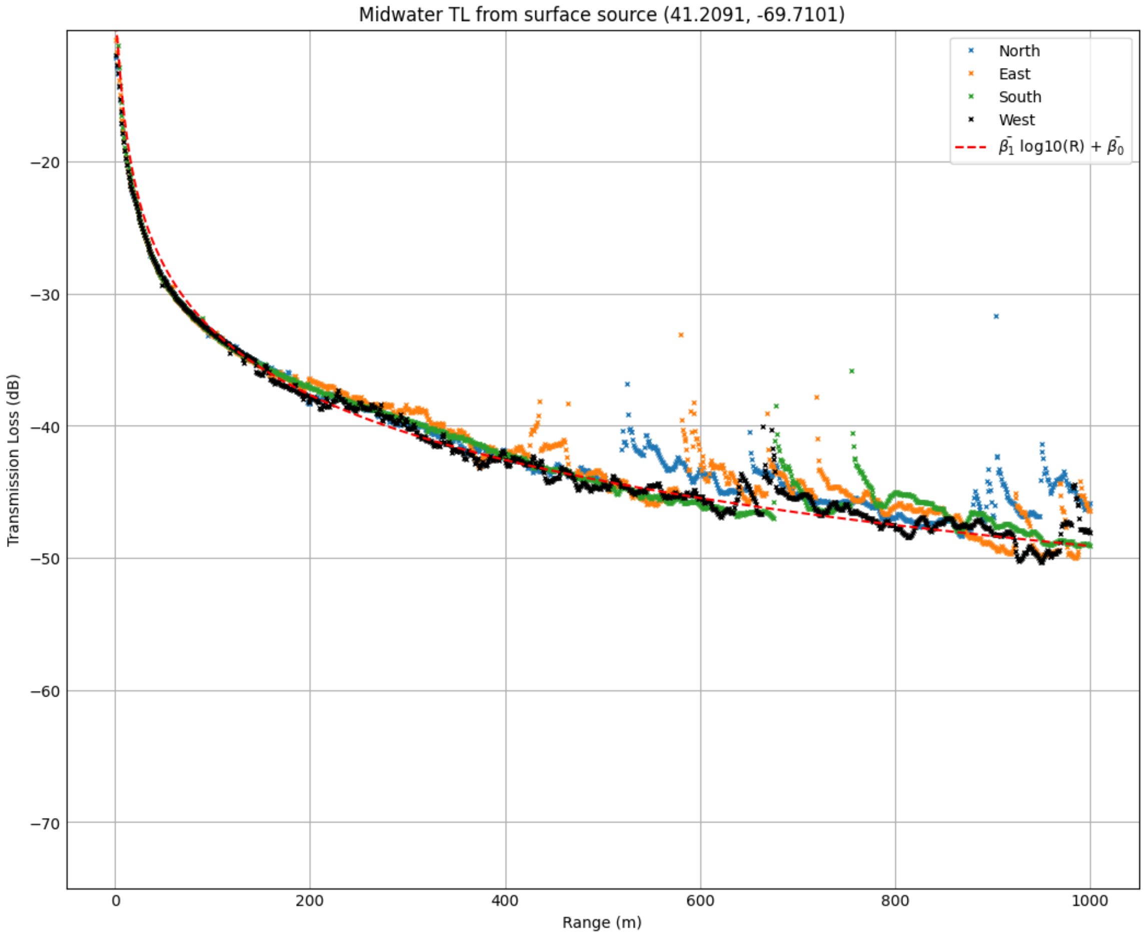


Figure 44. Transmission loss sampled across a constant depth over 1 kilometer range in four cardinal directions from the source origin. A model of the average transmission loss across the cardinal directions is presented here in the dashed red line.

This behavior is statistically captured in Equation C.5 which allows loss values to fluctuate according to a log-normal distribution based on results computed across the geospatial region of analysis. The stochastic β_i terms are included in Equation C.1 for calculation of cumulative non-coherent sound pressure level at any point in space.

Source distributions within the South Island Restricted Area are shown for both random uniform and Poisson distributions in Figure 45 (a) and (b), respectively. In each case, a total of 500 emitting sources were considered. The uniform distribution is assumptive of no causality behind source distribution whereas the Poisson distribution is based on multiple random centroids meant to represent dense fishing notionally informed by biomass distribution and other social factors. In both cases, the latitude and longitude extent of the region is discretized into 1 million cells of spatial resolution 0.00187° in longitude and 0.000833° in latitude. With source positions described by the two random distributions, and receive points positioned at the resolution increments and approximate midwater depth from the source position, Equation C.2 may be solved for the range matrix from each source to each resolution cell. This factor is essential in determining the propagation distance and absorption length necessary to compute the cumulative acoustic emission level given in Equation C.1.

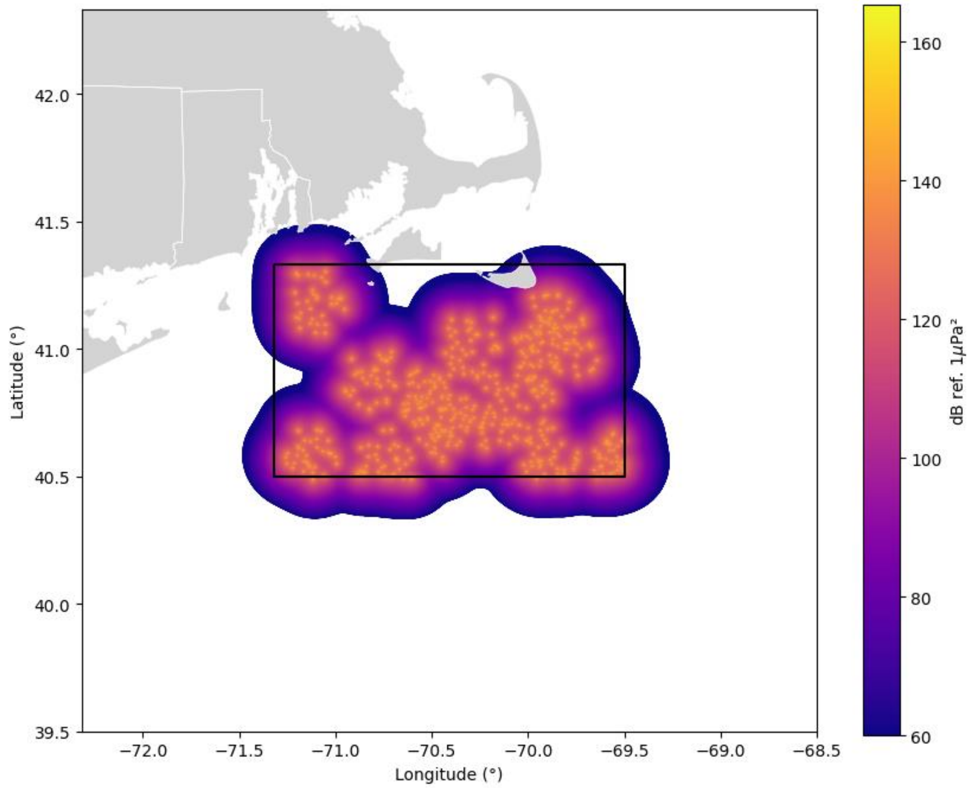
Results were then generated for two scenarios: continuous emissions and time-averaged emissions according to a notional signaling limit of 120-seconds worth of active transmit time over a 24-hour period.

The first scenario is indicative of the worst-case scenario in which sources at a defined level of 183 dBSPL re.1 µPa at 1 m emit continuously over the 24-hour duration of analysis. The second scenario is representative of a notional signaling scheme in which a cumulative 2-minutes worth of source emission is non-coherently time-averaged over the analysis period. Leveraging the solution for cumulative emission at a specified location from Equation C.1, the time-averaged decibel level may be computed according to Equation C.8.

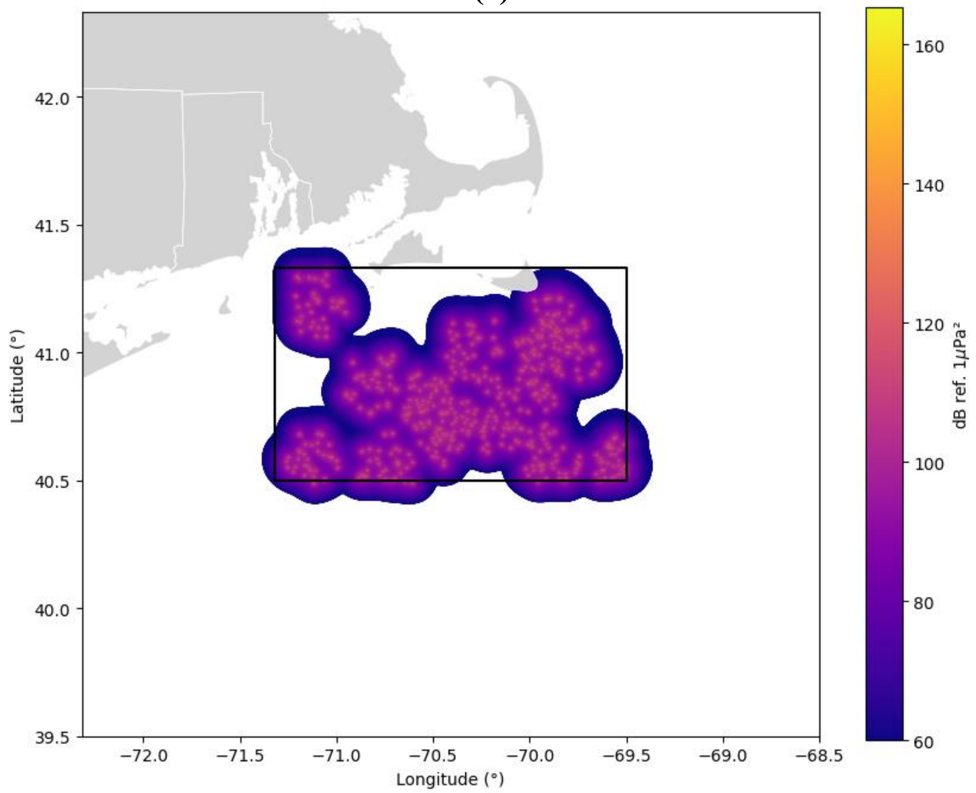
$$\langle p(\vec{x}|\vec{x}_M)\rangle = 10\log_{10}\left(\frac{p(\vec{x}|\vec{x}_M)^2}{p_0^2}\right) + 10\log_{10}\left(\frac{t_{emit}}{T_{24}}\right) \qquad (C.8)$$

Here, the variable t_{emit} is set to 120-seconds and T_{24} is 86,400-seconds. p_0^2 is the square of the reference pressure taken as $1\ \mu Pa^2$.

The solution for a standoff range of 5-meters was presented in Section 3.4.1 and a follow-on analysis for a standoff range of 10-meters is shown below computed for the worst-case, and continuous emission scenario. Results presented in Figure 45 (a) show received sound pressure levels between 165.3 dB re. 1 µPa^2 and a lower limit of 60 dB re. 1 µPa^2, representing the ambient acoustic noise floor in the frequency band of interest. Computing the time-averaged value defined in Equation C.8 yields the results shown in Figure 45 (b). Due to the non-coherent reduction in received sound pressure level over the 24-hour period, the reduced maximum level is 136.7 dB re. 1 µPa^2 for the same geospatial distribution of sources.



(a)



(b)

Figure 45. (a) Sound pressure level maps calculated at 10-meters from a Poisson distribution of sources operating as continuous emitters and (b) emitting for 120-seconds per day.

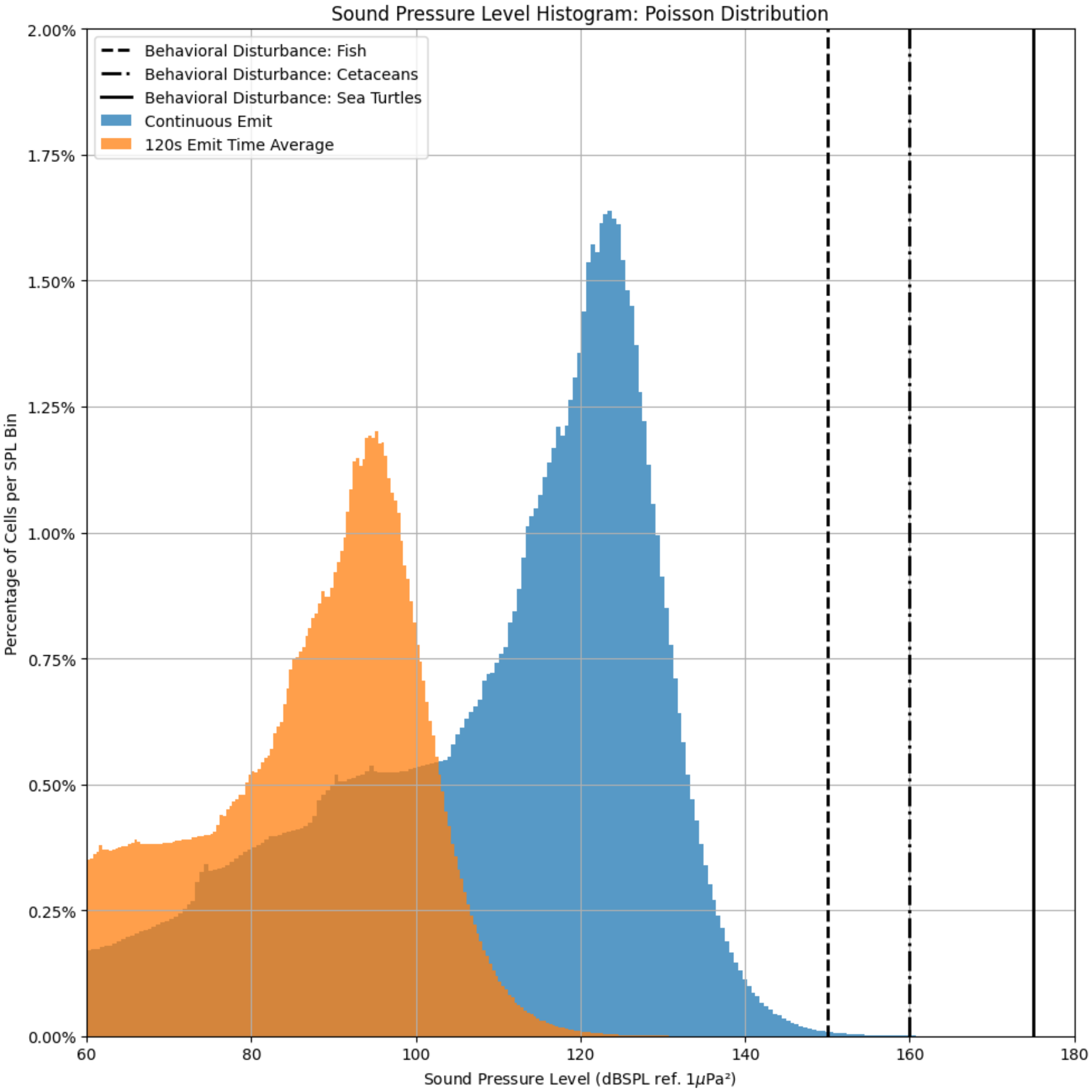


Figure 46. A histogram showing sound pressure level accumulations for a Poisson distribution of N=500 sources distributed within the South Island Restricted Area and measured at a 10-meter range. Distributions are shown for the continuous emission scenario and the 120-second per day emission scenario. Behavioral onset threshold levels are plotted for fishes, cetaceans, and sea turtles.

Histograms shown in Figure 46, portray both the worst-case and cumulative distributions for the 10-meter standoff scenario and are truncated below the ambient noise floor limit of 60 dB re. 1 μPa^2. The data distributions are plotted as percentage of cell values within the binned received sound pressure levels to provide a statistical representation of cumulative acoustic levels across the entirety of the analysis region. The modal values are 122.9 dB re. 1 μPa^2 for the continuous emission scenario and 95.1 re. 1 μPa^2 for the averaged 120-second emission scenario. The number of cells at these modal densities is decreased from the 5-meter standoff analysis presented in 3.4.1 Figure 19 but the sound pressure level value remains near constant between analyses. Neither the 5- nor 10-meter receiver standoff scenarios justify the need for an interoperability standard to control or broker acoustic emissions based on these findings.

Appendix D Vendor RFI Forms

Table 10. Vendor Technical Specification RFI Template

ID	Vendor Name		
	Product Name		
System Operation Specs	Communication System (select one): 1. Simplex 2. Half-Duplex 3. Full Duplex		
	Modulation or Signaling Scheme(s)		
	Message Length(s) [s]		
	Duty Cycle [%]		
	Max. Number of Addressable Devices within Range at Once		
	Design Operating Point: [In-Band SNR[‡], Pcmr[§], Pfa[¶]]		
	SNR-Dependent Receiver Operating Characteristic (ROC)*		
		Downlink[#] Hardware	**Uplink[♠] Hardware***
Hardware System Specs	Center Frequency [Hz]		
	System Half-Power Bandwidth [Hz]†		
	Transmit Source Level Frequency Response [dB re. 1 µPa/1Vrms @ 1m]		
	Max Transmit Source Level [dB re. 1 µPa @ 1m]		
	Receiver Sensitivity Frequency Response [dB re. 1 V/1 µPa]		

	Transmit Beamwidth – Horizontal, Vertical [Degrees]		
	Receiver Beamwidth - Horizontal, Vertical [Degrees]		
	Transmitter Sampling Rate [Hz]*		
	Receiver Sampling Rate [Hz]*		
	Analog-to-Digital Converter Dynamic Range [bits]*		

* If available

† Based on the transfer function response of the entire device (i.e. electronic filters, transducer bandwidth, ADC sample rate)

[‡] In-Band SNR: Signal-to-Noise Ratio specified in decibels (dB) within the system half-power bandwidth

[§] Pcmr: Probability of Correct Message Received specified as a percentage

[§] Pfa: Probability of False Alarm specified as a percentage

[#] Downlink Hardware: Defined as components of the shipboard system

[♠] Uplink Hardware: Defined as components of the subsea system

Table 11. Vendor Interoperability Cost Estimation RFI Template

We are looking for insights into the following questions:

1. What type of internal investment would need to be made to implement FONTUS?
2. What is your current market price? How much do you anticipate this price decreasing with manufacturing-at-scale? How would the implementation of FONTUS impact the cost for end users?

*Please include estimated dollar amount where it is possible to do so.

Appendix E Abbreviations and Acronyms

Acronym	**Definition**
°C	Celsius
2D	Two-Dimensional
ACCSP	Atlantic Coastal Cooperative Statistics Program
AIS	Automatic Identification System
CAA	Consolidated Appropriations Act
CCU	Central Command Unit
CFRF	Commercial Fisheries Research Foundation
CRM	Coastal Relief Models
dBSPL	Decibel Sound Pressure Level
EEZ	Exclusive Economic Zone
EFPs	Exempted Fishing Permits
EGM	Earth Gravitational Model
ESA	Endangered Species Act
ETOPO	NOAA NCEI Earth Topography
FGFL	Fixed-Gear Fishery Layer
FH/BFSK	Frequency Hopped Binary Frequency-Shift Keyed
GARFO	Greater Atlantic Regional Fisheries Office
GEBCO	General Bathymetric Chart of the Ocean
GPS	Global Positioning System
GSW-Python	Gibbs Seawater Python
kHz	Kilohertz
m	Meter
m/s	Meter per second
MITRE	The MITRE Corporation
MMPA	Marine Mammal Protection Act
ms	Millisecond
MSL	Mean Sea Level
NARW	The North Atlantic Right Whale
NCEI	National Center for Environmental Information
NEFSC	Northeast Fisheries Science Center
NetCDF	Network Common Data Form

NFWF	National Fish and Wildlife Foundation
NGA	National Geospatial Intelligence Office
NGOs	Non-governmental organizations
NM	Nautical miles
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
OLE	Office of Law Enforcement
PBR	Potential Biological Removal
PPM	Pulse Position Modulation
RFI	Request for Information
RFID	Radio Frequency Identification
RMS	Root-Mean Square
SART	Successive Acoustic Receive Time
SDM	Software Defined Modem
SEFSC	Southeast Fisheries Science Center
STFT	Short-Time Fourier Transform
U.S.	United States
USBL	Ultra-Short Baseline
USGS	U.S. Geological Survey
VMS	Vessel Monitoring System
WHALE DST	Woods Hole Analysis of Line Entanglement-Decision Support Tool
WHOI	Woods Hole Oceanographic Institution
WMO	World Meteorological Organization
WOA	World Ocean Atlas
WOD	World Ocean Database