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Co-Occurrence Mapping of Disparate Data Sets to Assess Potential Aquaculture Sites in the Gulf of Maine

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ABSTRACT

As the need for aquaculture continues to grow, expansion of marine aquaculture into the coastal ocean and beyond will require an understanding of ocean use and attention to spatial planning with engagement from a variety of industry sectors and stakeholders. The easiest means to site aquaculture will be to demonstrate locations that lack of conflict with exiting industries and ecosystem components. Under this framework, the potential space for aquaculture in a 123,023-km^2 area within the federal waters of the Gulf of Maine was determined by assessing concurrent use by the fishing and shipping industries and also by large pelagic animals (baleen whales and turtles). All three user groups were evaluated for use across seasons, and these data layers were then overlaid to create an index of low use areas that constitute a first pass assessment for where aquaculture would be suitable. The low-use areas (little presence of fishing, shipping and baleen whales and turtles) were focused on Nantucket shoals, and in the central parts of the Gulf of Maine and Georges Bank. A total of 18,778 km^2, or 15.2%, was identified as low-use areas with the closest being 38 km to shore and the farthest being over 240 km from shore. With 46 km being the current outer limit for aquaculture profitability, then only 5,978 km^2, or roughly 5%, is available. In order for aquaculture to be able to find more suitable space, it will need to work cooperatively with the existing users to demonstrate where space can be shared as opposed to being relegated to low-use portions of the Gulf of Maine.

KEYWORDS

Aquaculture site selection; co-occurrence mapping; fishing; GIS; marine mammals; sea turtles; shipping; whales

1. Introduction

Globally, the wild harvest of fish has reached a plateau, yet the demand for this important protein source continues to grow (FAO, 2012). To lessen this gap, aquaculture production has been steadily increasing, and will need to continue to do so. Globally, aquaculture will have to provide up to 117 million metric tonnes by 2050 to meet the needs through increased population demand (Merino et al., 2012). Within the United States, the seafood trade deficit exceeds $10 billion dollars annually, with 50% of the imports being from aquaculture (Kite-Powell et al., 2013). To increase the volume of seafood available for consumers, new production areas on land, offshore, or in marginal areas need to be developed (Froehlich et al., 2017; Tlusty et al., 2000). Production in marginal areas is a less than desirable option because cultured animals tend to experience greater physiological stress, while normal operating rules (e.g., feed tables, estimating waste output) do not apply (Tlusty et al., 2000). Because the ecological boundaries are being pushed, it is difficult to achieve environmentally sound or "sustainable" long-term development in these frontier regions. Land-based production is not a complete solution either, given the financial constraints of the real estate required for large pond operations, as well as closed-loop recirculating technology being fiscally and energetically expensive, (Cao et al., 2013). Furthermore, terrestrial space may not be able to bear a larger allocation to food production, given that 40.5% of all U.S. land is farmland (USDA National Agricultural Statistics Service, 2014), with this value being greater globally (58%, Clay, 2010). Because of the difficulties with frontier regions and inland production, it is necessary to explore the feasibility of more distant and offshore aquaculture production as an opportunity to significantly increase the aquaculture

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output of the United States (Froehlich et al., 2017), as well as globally (Jin et al., 2007).

In anticipating the challenge of increasing distant and offshore aquaculture, this activity needs to be balanced against other spatially competing activities (Kapetsky et al., 2012). The occurrence of multiple users and uses of coastal environments may severely limit the potential sites where aquaculture development can occur without significantly affecting others and causing conflicts between user groups (Silva et al., 2011). Because of these competing uses for space in the oceans, it is imperative to apply marine spatial planning principles, including assessment of the co-occurrence of spatially explicit activities and their compatibility (Cicin- Sain et al., 2005; Kapetsky et al., 2012). This will function to demonstrate up-front that there is adequate space available for aquaculture in suitable areas, and also create a solid understanding of the space, economic, human and ecosystem-service tradeoffs that will occur through appropriate aquaculture siting. By reducing or eliminating the concerns over competition for space, a significant hurdle against the implementation of aquaculture will be removed (Silva et al., 2011), and this will help attract new ventures to the region.

A multitude of ocean activities potentially compete for or augment the spatial demands of aquaculture (Kapetsky et al., 2012; Pérez et al., 2005; Silva et al., 2011). Given the number of concurrent users, the idea of user constraints and overlap in offshore environments need to be explored. While some space restrictions are absolute closed areas, others are proportionally present with regards to season. This analysis focuses on three such proportionately present user groups—fishers, commercial shipping and protected species (baleen whales and turtles). The challenge of these three groups is the disparate nature of the data, including trip reports, automatically collected continuous data, and point observations. Concurrent use was defined by collecting vessel trip reports to characterize fishing effort, real-time shipping data, and observations of marine mammal and turtle distributions. Each was normalized and assessed for the spatial need (amount of time spent at a specific location), as well as the economic valuation of that activity at that location. Location and intensity of each group was charted, and used to tabulate the economic value opportunity costs (displacement of current shipping lanes, loss of whale watching or fishing activity) across the Gulf of Maine. These data were combined to provide the cumulative use assessment, identifying the areas with the least disruption to the identified user groups, and thus the greatest potential for aquaculture siting. The results from this type of study will be the foundation for further exploration of siting of aquaculture in the Gulf of Maine.

2. Methods

2.1. Study area

The study focused on waters in the Gulf of Maine under U.S. federal jurisdiction (Figure 1). State waters, 3 nautical miles (nm, 5.6 km) from the shore in most locations, were not included. Thus the inshore extent was defined as the boundary between state and federal waters. The eastern edge of the study area was defined as the boundary between U.S. and Canadian Exclusive Economic Zones. The offshore limit of the study area was defined as the continental shelf break, at approximately the 200-m depth contour, with the western edge defined arbitrarily as 71°W longitude. This area encompassed 123,023 km^2 total (Figure 1).

2.2. Fishing

2.2.1. Fishing vessel trip reports

The commercial fishing effort and catch summaries for the offshore area in the Gulf of Maine were compiled using Vessel Trip Reports (VTRs) provided by the Northeast Regional Fisheries Statistics Office National Marine Fishery Service. VTRs contain information about the vessel, gear used, species caught, amount landed, amount kept, amount discarded, date sailed, date landed and the general location of the trip. The location of the trip was reported as a single latitude and longitude location or loran coordinates, allowing for georeferencing of each trip report. There were two main iterations of the effort data provided by NOAA, the first was compiled in April 2009 and the location data was based upon the latitude and longitude (or calculated latitude and longitude) of each vessel trip. The second iteration was compiled in December 2010, and geolocated the catch data in accordance with the new federal confidentiality requirements (a minimum of three positions in summary record). These data were summarized based upon statistical areas measuring 10 minutes of latitude (18.5 km) by 10 minutes of longitude (13.5 km, Murawski et al., 2005).

2.2.2. Characterization of fishing effort

The trip-level VTR tables were converted into GIS databases using the latitude and longitude of each record. Only data points within the study area were selected for analysis, as this eliminated erroneous locations outside the area of interest. There was no way to determine erroneous points if they fell within the study area. The high-use and low-use areas of fishing effort were mapped using Kernel Density Estimate (KDE) mapping. KDE is a non-parametric mapping technique that creates a 3-dimensional continuous surface over each point in a dataset (a kernel), summarizes the values over a specified

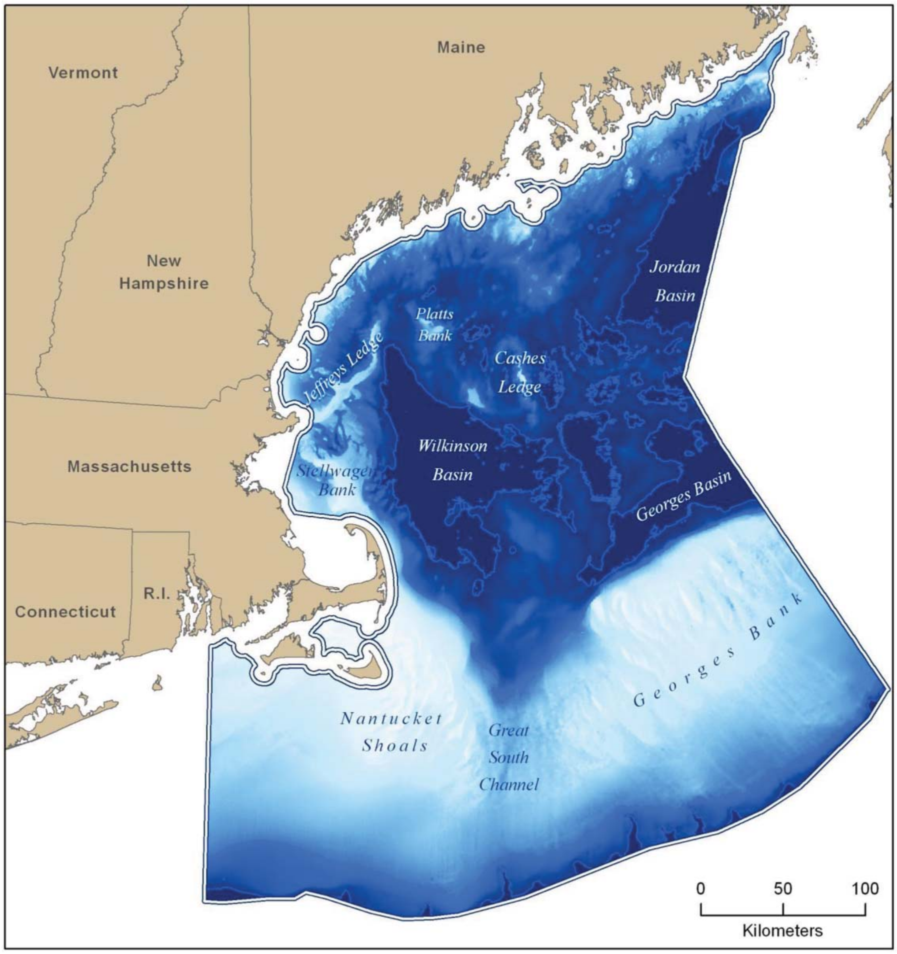

Figure 1. Study area for the aquaculture suitability assessment in U.S. federal waters in the Gulf of Maine, with the major bathymetric features identified.

distance (bandwidth) and reports the result to a geographic area (cell). The trip-level data were mapped using the KDE function (Spatial Analyst, ArcGIS 9.3) with a 5.0-km bandwidth (area to summarize individual kernels) and a 250-m cell size (the areal extent of the results), based upon the recommendations in Bolstad (2008). Each trip-level dataset was mapped according to gear type, season and year to visualize differences between attributes. Fishing data were provided by the Northeast Regional Fisheries Statistics Office National Marine Fishery Service for the years 1998-2009.

2.2.3. Economic analysis of fishing effort

A Net Revenue Economic Model was developed from a 10-year dataset covering the years 1999-2008. This model was created by first summarizing data to a 10-minute statistical area based on the VTR data. Each 10-minute area was identified by a unique code provided by NMFS, which was converted to a latitude and longitude center point for each area.

The conceptual framework for calculating the net revenue from commercial fishing was based on compiling catch and effort data for each spatial location (k) and time period (t). The catch and effort data were then combined with relevant price and cost information to estimate the total revenue and cost at k and t. Finally, location- and time-specific net revenue was obtained by subtracting the total cost from the total revenue.

Specifically, the total gross revenue R at location k and time t was:

$$R_{k,t} = \sum_{s} P_{s,t} Q_{s,k,t} \tag{1}$$

where $P_{s,t}$ was the price (in dollars per pound) of species s at t, and $Q_{s,k,t}$ was the catch (in pounds) of species s at location k and time t. The total cost C at location k and time t was

$$C_{k,t} = \sum_{g} \sum_{n} W_{g,n} D_{g,n,k,t} \tag{2}$$

where $W_{g,n}$ was the unit cost (in dollars per day absent) of gear type g and vessel tonnage class n, and $D_{g,n,k,t}$ was the number of days absent of gear type g and vessel tonnage class n at location k and time t. The net revenue was thus defined as $R_{k,t} - C_{k,t}$. The study covered a ten-year period (1999-2008). The spatial unit was 10-minute square, and the time unit was month.

The commercial fishery catch and effort data were as described above, while fishing cost data were provided by Northeast Regional Fisheries Statistics Office National Marine Fishery Service. Unlike the catch, effort and price data, monthly cost data were unavailable. Cost survey data from recent years were used to construct a representative cost data set for the study period. As noted, the average cost per day was used to estimate the total cost for each 10-minute square. The cost consisted of three components: vessel fixed cost, variable trip cost, and labor (crew) cost. The initial cost data set was constructed using the 2006 trip cost data and the 2006 fixed cost survey data (Jin, 2008a). Because sample sizes were very small for several vessel groups, the resulting average costs were inconsistent across these gear type and vessel size categories. Additional adjustments were made based on Maloof (2001).

2.2.4. Gross revenue and net revenue data

For the study, two final data sets were compiled and mapped: a gross revenue data set based on complete catch records and a net revenue data set based on partial catch and effort records. The second data set did not cover all fishing trips due to NMFS data disclosure restrictions (summary data based on 10-minute squares having at least 3 observations per trip). Monthly data were aggregated to a seasonal total which allowed the most fishing trips to be utilized given the data anonymity restrictions. The resulting net revenue set accounted for over 70% of the total catch value and quantity. Seasons were defined as winter (Dec-Feb), spring (Mar-May), summer (Jun-Aug), and autumn (Sep-Nov).

The net revenue data were provided for each of the 10-minute statistical areas in the Gulf of Maine. To align this modeling effort with the other "heat-mapped" datasets, data were interpolated as the center points of each statistical area using Ordinary Kriging in the Geostatistical Analyst tool (ArcGIS 9.3).

2.3. Ship movements

Data from Automatic Identification System (AIS) real-time ship movements (based on 2- to 8-second sampling and hereafter referred to as shipping) within the Gulf of Maine were donated by Maritime Information Systems, Inc. (Warren, RI; http://www.misdevelopment.com/) for a period covering March 2008 to February 2009. The data were provided in Microsoft SQL Server including positional information as well as information about the vessels. The ships were categorized as being tankers, tug and towing vessels, cargo vessels, passenger vessels, and pleasure craft. These data tables were imported into geodatabase files (ArcGIS 9.3) and converted into a point dataset. Points were selected if they fell within the study area and if the vessel's speed was greater than 0.5 knots (0.9 km/hr). To gain an appropriate understanding of the AIS transits occurring in the Gulf of Maine, the point dataset was subsequently converted to linear tracklines by creating a new field concatenating the Maritime Mobile Service Identity (MMSI) number, date and hour. Consequently, a line was created for each unique concatenated field, which allowed tracks to be compiled for each vessel transiting through the study area without connecting lines from different vessels or dates or for two points not in sequence. The trackline data were then recombined with a vessel type dataset. Similar to the fishing datasets, two datasets were created, the first, based on density of the lines and the second, summarizations to 10-minute statistical areas.

The economic value of the ocean as transit lanes for maritime shipping and other vessel traffic was estimated from the incremental cost to those vessels if they were forced to travel by an alternate (presumably longer) route. Commercial vessels naturally seek the most direct (low-cost) transit route between ports of call. If other uses of a section of the ocean were to preclude vessels from transiting through it, these vessels will incur additional costs that vary with the added distance they have to travel to avoid the "closed" areas.

The cost of closing an area to maritime transits therefore depends on (a) the number and nature of vessels that would use the area if it were not closed, and (b) the incremental distance these vessels must travel given that the area is closed. Each vessel class has a characteristic unit cost per nautical mile of transit depending on the vessel's daily capital and operating cost, and its normal operating speed (Kite-Powell, 2001; US Army Corps of Engineers, 2000).

2.4. Baleen whales and turtles

The goal of this component of the project was to understand the average annual and seasonal distributions of selected marine mammal and sea turtles in the study area. There are at least 20 species of cetaceans (whales, dolphins and porpoises) and 4 species of sea turtles known from the Gulf of Maine region (Cetacean and Turtle Assessment Program, 1982; Ernst, Lovich, 2009; Pittman et al., 2006; Shoop, Kenney, 1992; Waring et al., 2014). The analysis was limited to the more common species of baleen whales and sea turtles—North Atlantic right whale (*Eubalaena glacialis*), humpback whale

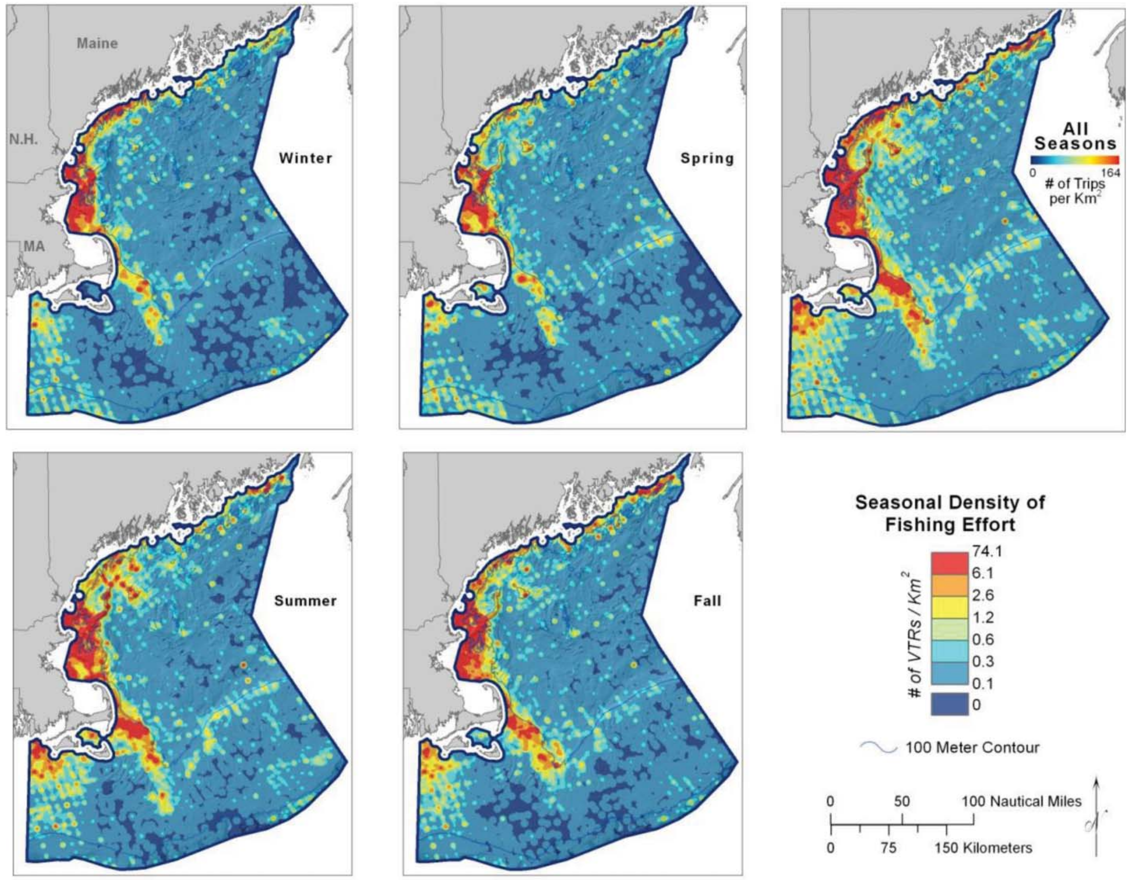

Figure 2. Geographic distribution of fishing effort, combining all years (1998-2009) and all gear types, in the Gulf of Maine study area by season and for all seasons combined.

(*Megaptera novaeangliae*), fin whale (*Balaenoptera physalus*), sei whale (*B. borealis*), minke whale (*B. acutorostrata*), leatherback turtle (*Dermochelys coriacea*), and loggerhead turtle (*Caretta caretta*). Sightings of unidentified sea turtles (most were probably loggerheads) were pooled with the identified sightings together as a single sea turtle species group. All of the whale species except minke whale are listed as Endangered under the U.S. Endangered Species Act; leatherback turtles are classified as Endangered and loggerheads as Threatened.

Rather than use raw sighting data that are biased by the uneven distribution of survey effort, Sightings per Unit Effort (SPUE) data were used as derived from the North Atlantic Right Whale Consortium database archived at the University of Rhode Island (Kenney, 2001). SPUE data are standardized and corrected for effort (see Pittman et al., 2006 for methodological details). Briefly, all aerial and shipboard survey tracks that met standardized criteria (observers on watch, visibility at least 2 nm, sea state of Beaufort 3 or lower) were partitioned across a grid of 5 × 5-minute cells, and the distances surveyed in each cell were calculated and then summed by season and overall. The numbers of individuals sighted for each of the target species or groups were similarly summed by season and overall for each cell. Number of animals sighted divided by distance surveyed (effort) is SPUE, in units of animals per 1000 km of survey effort. Each record in the SPUE data file for each species/group contained the latitude and longitude of the center of the 5 × 5-minute cell, season, kilometers of trackline effort, number of animals, and the SPUE value. The resulting point dataset was a regular spaced grid of points with SPUE values for the annual and seasonal distribution for each species or grouping.

The SPUE analysis created highly variable spatial data depending on the amount of effort and sightings. Since these species are highly migratory, a method was necessary to smooth the local variability in the SPUE data. To do so, the ArcGIS Geostatical Analyst was used to create Ordinary Kriging interpolations (ESRI, 2010) of the distributions of species or species groups from the SPUE point data. Data were projected into an Albers projection (central meridian = 68.8°W; standard parallel 1 = 41.6°N; standard parallel 2 = 43.1°N; latitude of origin = 42.5°N; North American Datum 1983) for the Kriging interpolation. The resultant values were modeled

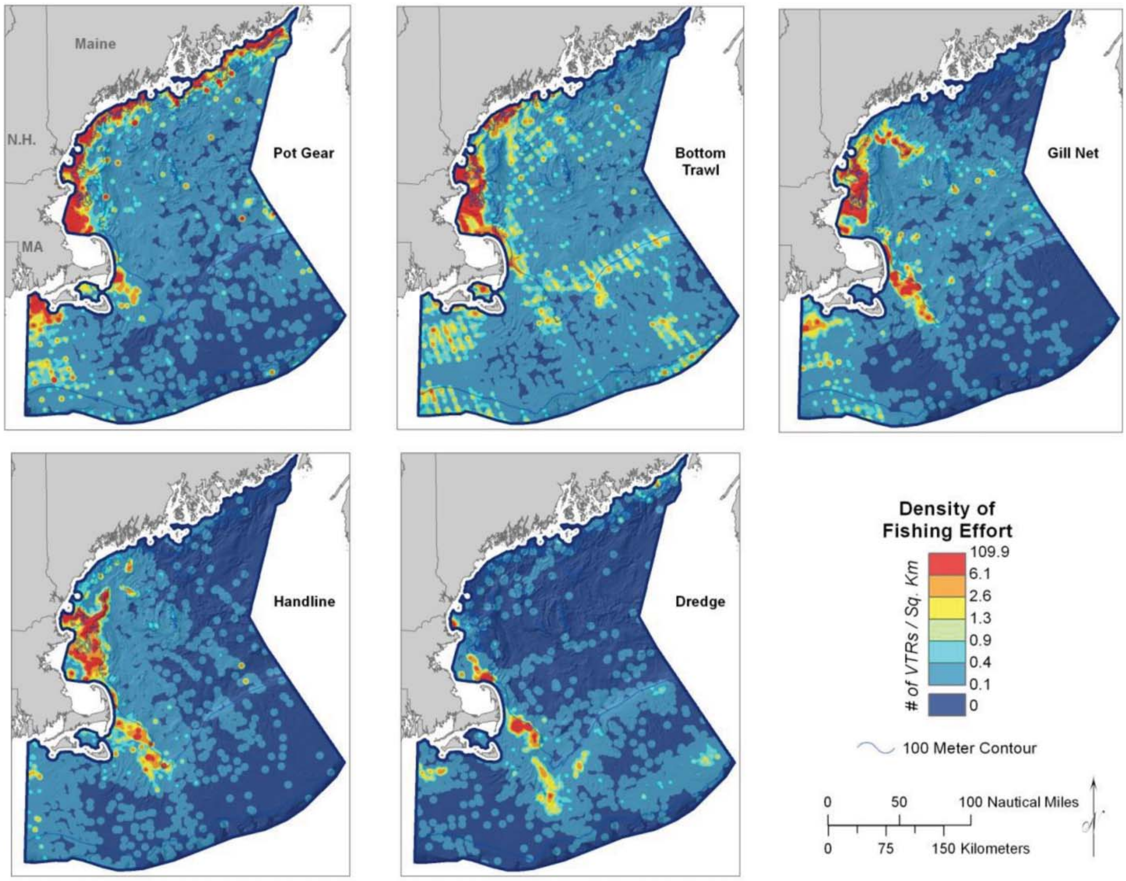

Figure 3. Geographic distribution of fishing effort for the top five gear types in the Gulf of Maine study area, all years and seasons combined.

using a semivariogram (Bolstad, 2008) with adjusted distance weights determined using a sigmoidal function away from the prediction location up to a distance equal to 2 times the major semiaxis (ESRI, 2010; Gribov, Krivoruchko, 2004). The spatial predictions were calculated using a smoothing factor of 1 (the highest) and major and minor semiaxes of 20 km in order to include at least 6 points into the calculations. Kriging distributions were used to show the high- and low-use areas of these species, and were averaged in the 10-minute statistical areas used for the integration of all three datasets.

2.5. Integration of the three datasets

The cumulative use assessment was performed with both a Continuous Distribution (raster) approach and a 10-minute statistical area (vector) approach. The two approaches differed slightly in the datasets used in the analyses, but the biggest difference was the appearance of the results, not the selection of low-use areas.

2.5.1. Continuous distribution method

The data layers combined under this method include the Kriging interpolation of net revenue for fishing, the density of kilometers of vessel tracks for shipping, and the Kriging interpolation of whales and sea turtles. Each dataset was converted to a Z-Score (point value – mean / standard deviation). This technique created a similar scale for all three datasets even if they differed in magnitude. Finally, the three Z-score datasets were summed and visualized as quintiles (20% of data) and converted to a polygon dataset. The lowest 20% of data were selected and the average depth of the seafloor and distance to land for each polygon were summarized, as these factors will affect offshore aquaculture siting decisions. This approach was followed for each season and also for a total across all seasons.

2.5.2. 10-Minute statistical area method

The data layers used to calculate this method include the net revenue for fishing, the MMSI and date counts for shipping, and the average SPUE values from Kriging

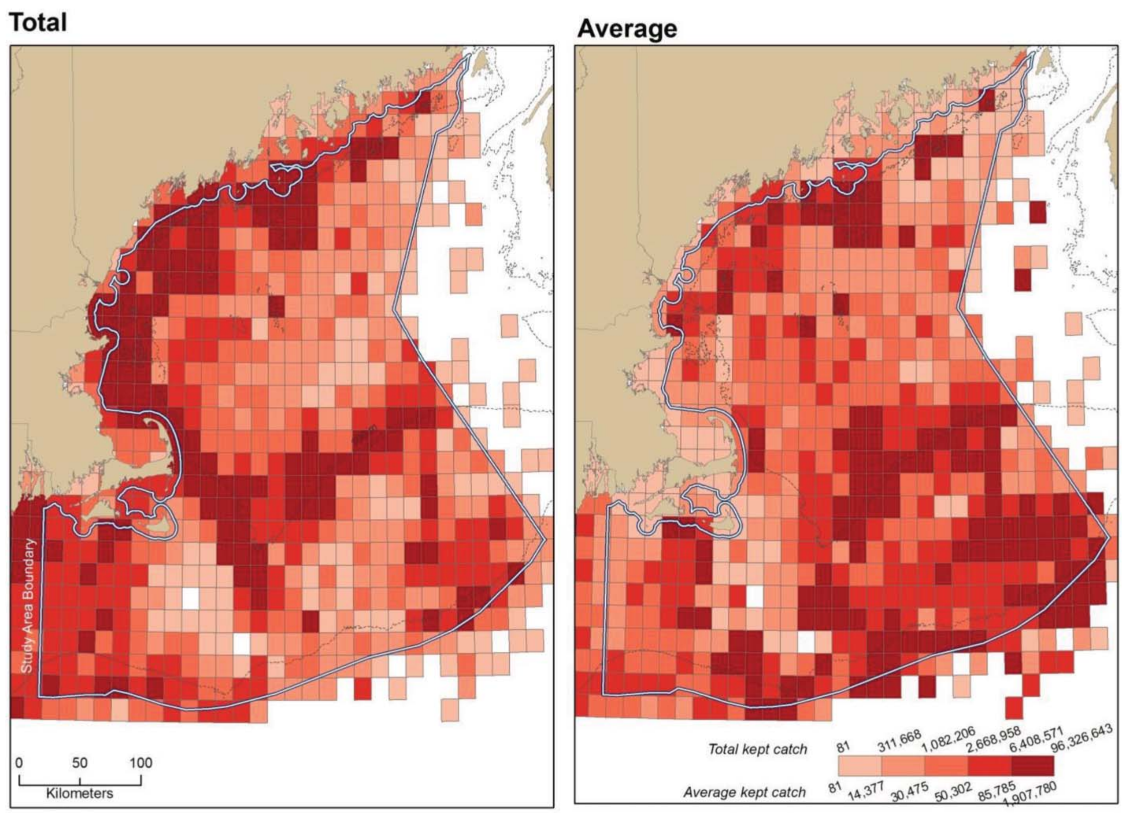

Figure 4. Total and pounds average landed catch in each 10-minute statistical area across years, seasons and gear types.

interpolations for whales and sea turtles. Each dataset was summarized to the 10-minute statistical area, which were also Z-Score normalized. After all three attributes (fishing, shipping and protected species) were normalized they were then summed. This final field was used to symbolize the high- and low-use areas. To gain an understanding of the low-use areas, the lowest 20% of the data was selected and the depth of the seafloor and distance to shore were summarized in the 10-minute statistical areas. This approach was conducted for each season and also for a total across all seasons.

3. Results

3.1. Fishing

The 2000-2008 VTR database contained 559,862 records, of which 353,099 were within the study area boundary. Summer had the highest number of vessel trips followed by fall, winter and spring, respectively (Figure 2). The average number of vessel trips per year was 39,233 (S.D. = 5,442). Most of the fishing effort was near the coast, with some high-use areas following bathymetric contours, especially the 100-m contour from Cape Cod to the Great South Channel and the northern edge of Georges Bank (Figure 2). There was also a high-use area in the western portion of the study area south of Cape Cod. Consequently, the lowest-use areas tended to be in flat areas south of Nantucket Island, in the middle of Georges Bank, and in the central Gulf of Maine to the west of Jordan Basin. The low-use areas incorporate areas closed to fishing.

Pot gear was the most reported fishing gear in the database, followed by bottom trawling and gill nets (Figure 3). The geographic distribution of fishing effort did vary by gear type, but the seasonality of fishing remained relatively constant across gear types with a consistent pattern across years. There was a high level of agreement seasonally and between gear types between the 10-minute statistical area data and the density patterns of VTR data, indicating the data can be combined to assess the economics of the fishery. The total and average amount of fish caught in each statistical area show very different patterns (Figure 4). The total kept catch from 1998-2009 closely resembles the effort, but with some higher emphasis on areas farther offshore due the high catch of bottom trawl gear. The average amount caught per year highlights the trawl gear, but also the dredge gear in the offshore areas. The bottom trawl gear type uses the largest area and with the heaviest intensity (extraction) in the Gulf of Maine study area. Pots and trap use an extensive amount of

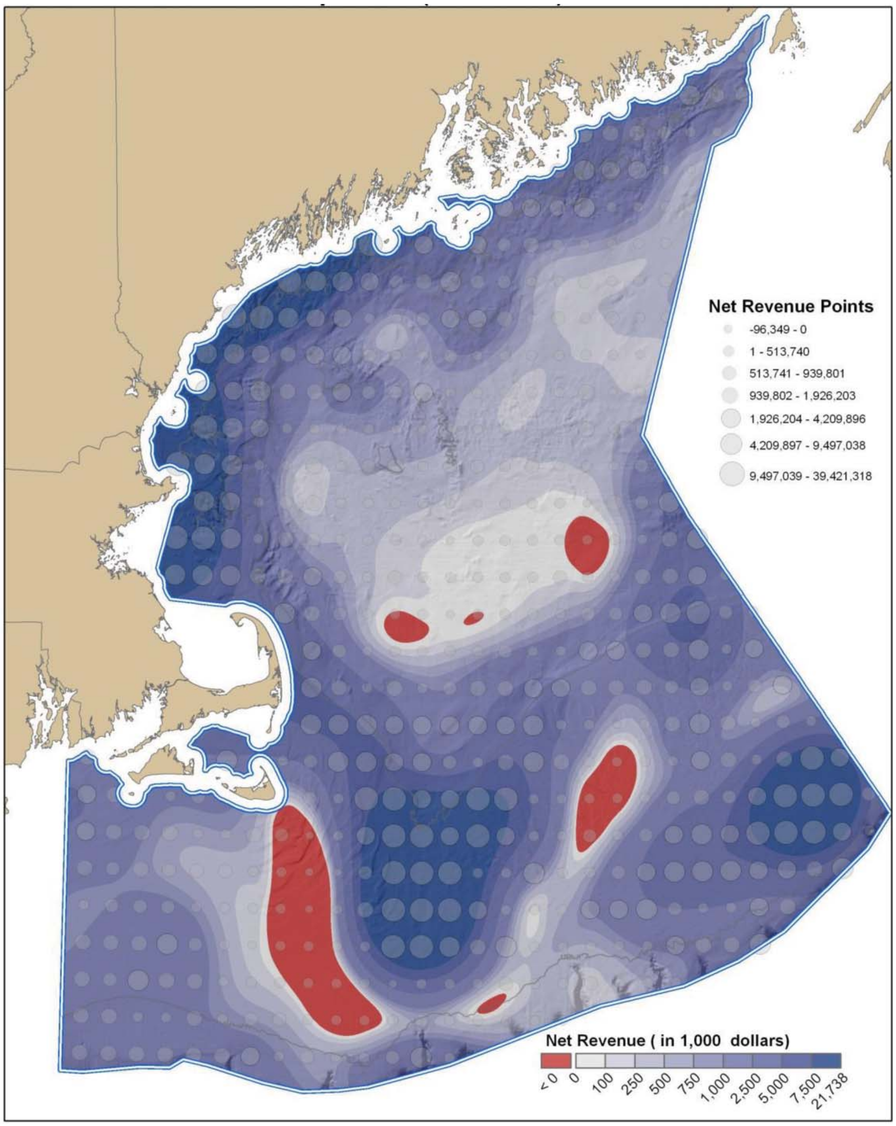

Figure 5. Interpolation of the total indexed fishery net revenue points calculated at the centers of each 10-minute statistical area.

area in the study area, but not to the same levels of extraction (catch).

The total spatially indexed fishery value, integrating the costs and value of all retained catches from all gear types across all seasons and years, shows high values in areas near the coast, as well as in the Great South Channel and the eastern part of Georges Bank (Figure 5). There is not perfect correlation between the value and use analyses (Figure 5 compared to Figure 4). South of Georges Bank and West of Nantucket shoals are used extensively, but their value is lagging.

3.2. Shipping

There were 878,195 records in the point dataset of vessels traveling greater than 0.5 knots and within the study area, which created 8,746 unique vessel transits (same MMSI and date). Of these unique transits, 28.6% (2,502) were tankers, 25.3% (2,214) were tug and towing vessels, 19.7% were cargo vessels (1,722), 8% (697) were passenger vessels and 6% (511) were pleasure craft. The number of AIS transits varied by season, with most being recorded during the summer (2,864), followed by fall (2,503), spring (1,850) and winter (1,529). In addition to there being fewer vessels transiting the study area in the winter, the number of vessel trips may have been also been decreased due to weather changes resulting lower VHF signal reception in the winter.

The general shipping tracks in the Gulf of Maine follow great circle routes or straight-line courses. Most of the vessels were entering or leaving the port of Boston, with many of the vessels also entering and leaving the port of Portland, Maine (Figure 6). The visualizations of the patterns of shipping were similar between the two

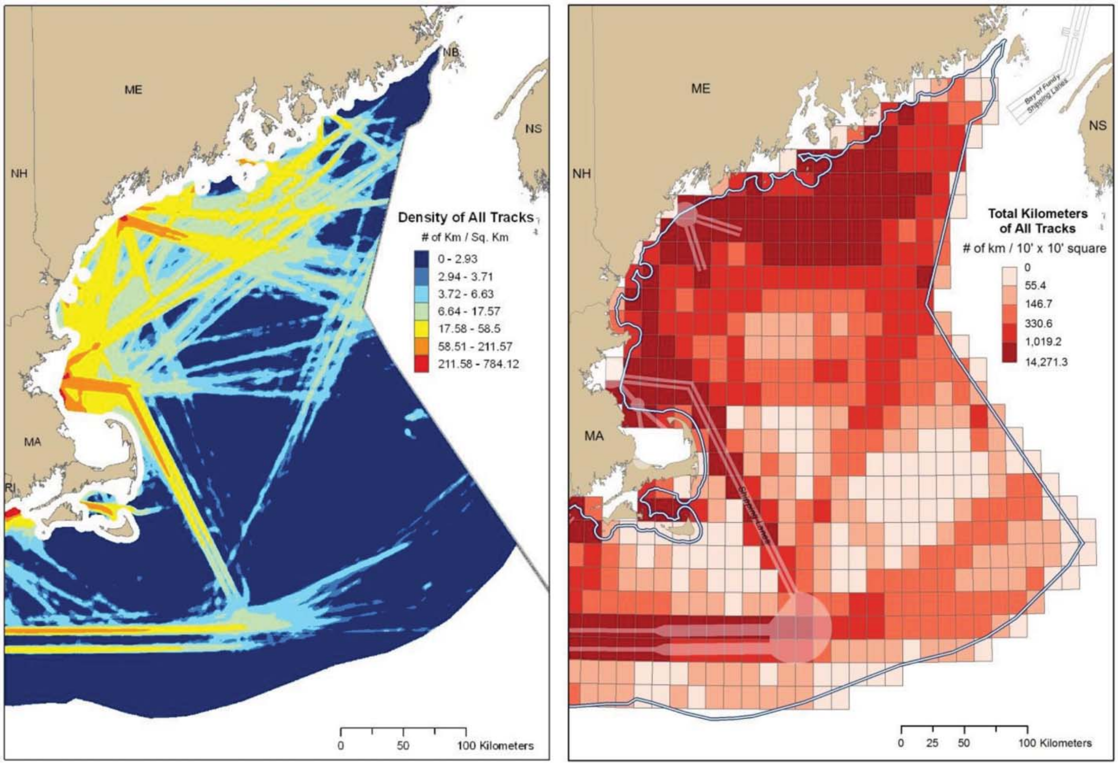

Figure 6. Density of all vessel tracks calculated using kernel density (left) and the summary of total kilometers of trackline per 10-minute statistical area (right). Both methods were used to evaluate the approaches in the overlay of all current uses. The general patterns remain consistent in both approaches.

different methodological approaches (density and 10-minute summaries—Figure 6). The density method more clearly highlights the linear pathways, while the 10-minute summaries provide a clearer assessment of the total tracklines in the study area. The three major low-use areas for shipping were south of Nantucket shoals, north of the Great South Channel, and the northern part of Georges Bank.

3.3. Baleen whales and turtles

There was a total of 1,028,155 km of combined aerial and vessel survey effort reported in the North Atlantic Right Whale Consortium Database from 1978 to 2009. The effort distribution was not even throughout the study area, with most of the effort being focused close to shore. The highest areas of effort were south of Stellwagen Bank and during the spring months (March, April, May).

The Kriging interpolation (Figure 7) highlights the use of bathymetric features by baleen whales and sea turtles in the vicinity of the Great South Channel to the north side of Georges Bank, with some other hot-spot areas around Jeffreys Ledge, Stellwagen Bank and Jordan Basin. The highest relative abundance seasonally was in the summer, followed by fall, spring and winter, respectively. The 10-minute summaries follow the Kriging interpolations, and revealed different patterns for different species of whales and the sea turtles during different seasons (Figure 8).

3.4. Integrated assessment

The integration of the three datasets revealed patterns that mirror the individual datasets. The habitats exploited by both commercial fishermen and marine animals tend to co-occur with the bathymetric contours in the Gulf of Maine. The low-use areas were focused on Nantucket shoals, and in the central parts of the Gulf of Maine and Georges Bank (Figure 9). The comparison between the continuous distribution and the 10-minute statistical area summaries revealed similar patterns, with the continuous dataset representing smoother boundaries between the high- and low-use areas. This continuous approach allows for easier interpretation of the varying highs and lows. The low-use areas were scattered throughout the Gulf of Maine, with large blocks located on Nantucket Shoals and on Georges Bank. The low-use areas closest to shore were on Nantucket Shoals and smaller areas in the northwest and the southern section of Wilkinson Basin. Other areas were located farther offshore near the U.S./Canada boundary line in and around

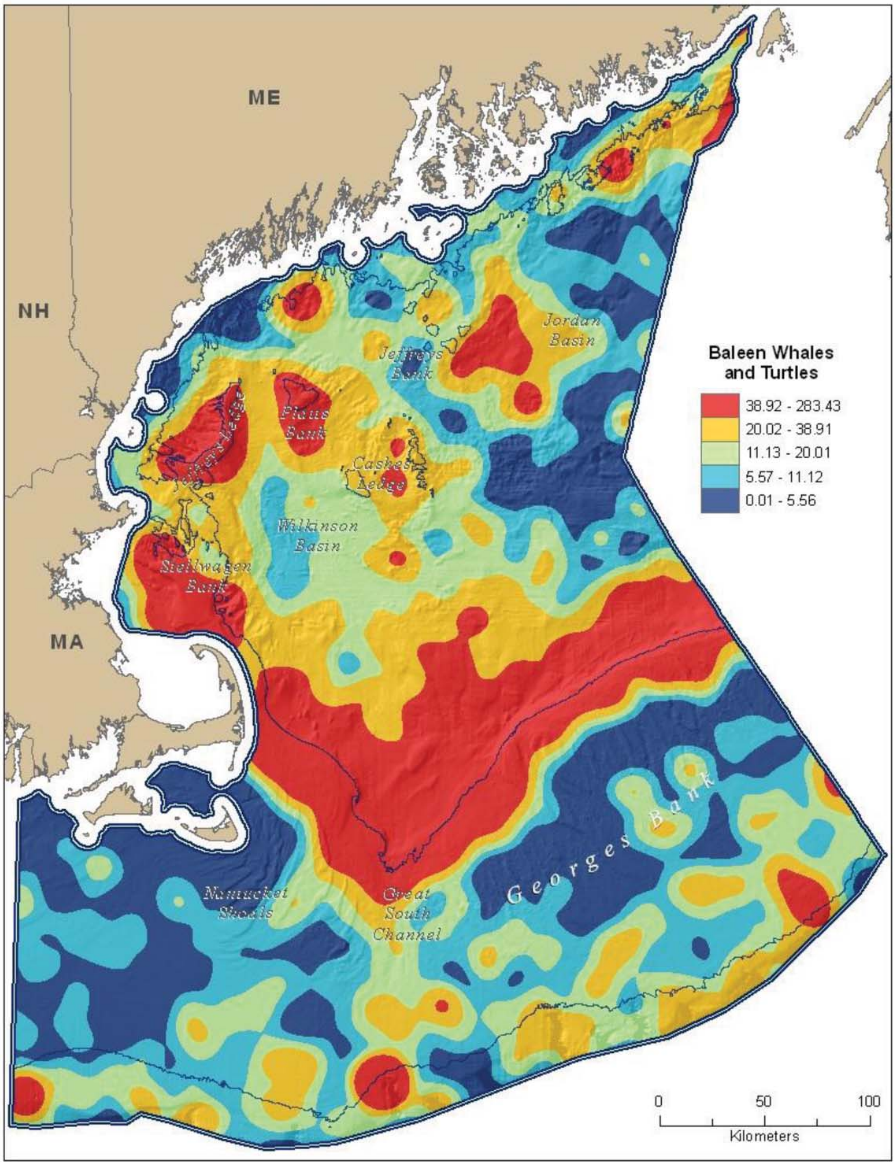

Figure 7. The combined baleen whale and sea turtle habitat use distribution in the Gulf of Maine created by Kriging the 5′x5′ SPUE (animals per 1,000 km of survey effort) distribution across all seasons and years.

Jordan Basin. There is much seasonal variation, with the Great South Channel being less occupied in the summer, and the spring having few areas of very low use (Figure 10).

Overall utility of a site for aquaculture will depend both on reducing conflicts with alternate users of space (see above), the sharing of space, and on the physical parameters of the site. In aquaculture siting, distance to shore and water depth are two critical factors, as they greatly influence operational costs. Each of the low-use areas defined within this study (Figure 9) can be cross-indexed with regards to distance and depth (Figure 11). A total of 18,778.25 km^2 was identified as low-use area (Table 1). Individual low-use areas ranged from an average of 38 km to shore (site #13, Figure 11) to over 240 km from shore (site #11, Figure 11).

4. Discussion

With many human activities expanding into the world's oceans, coordinated regional efforts are essential for minimizing spatial conflicts and assuring that marine resources are not severely depleted (Kapetsky et al., 2012). In addition to aquaculture and fisheries, other uses of the offshore environment include mineral or energy development; recreational uses; shipping channels both designated and de facto; the presence of endangered, threatened or sensitive species; military operations; and

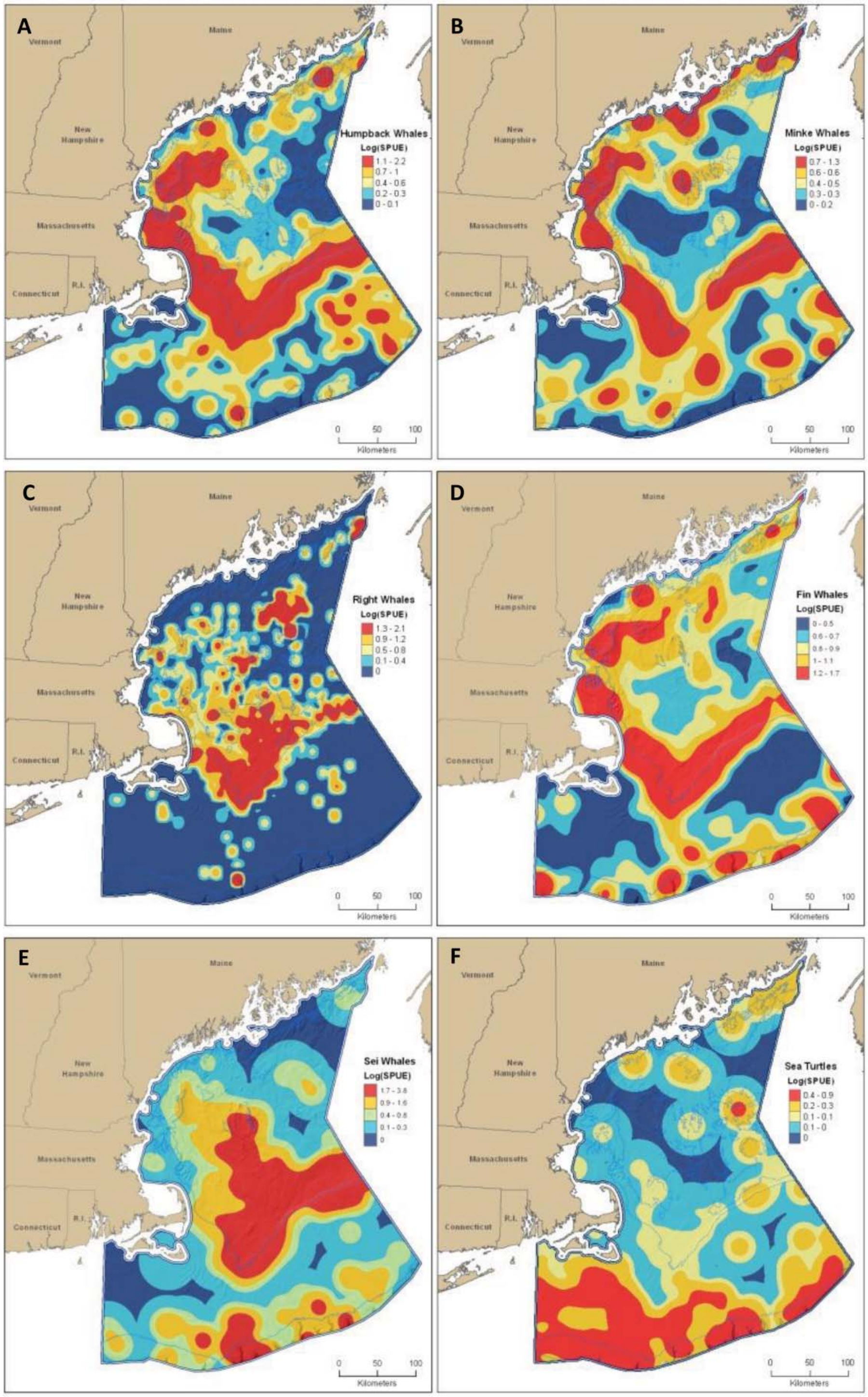

Figure 8. Interpolated SPUE (animals per 1,000 km of survey effort, log-transformed) distributions for humpback whales, minke whales, North Atlantic right whales, fin whales, sei whales, and sea turtles.

development of marine protected areas. Management in the marine environment has been historically focused on a single species, individual sector, or specific activity or concern (Quinn, Collie, 2005; Rosenberg, McLeod, 2005). These management approaches did not consider cumulative impacts or the ecosystem services provided (Rosenberg, McLeod, 2005). Ecosystem-based management (Charles, 2001; Rosenberg, McLeod, 2005) was conceptually developed as a management system that would emphasize protections of ecosystem structure, function and key processes to ensure the long-term delivery of "services," including production of seafood and medicines, nutrient cycling, water purification, coastal protection from storms, moderation of climate and weather,

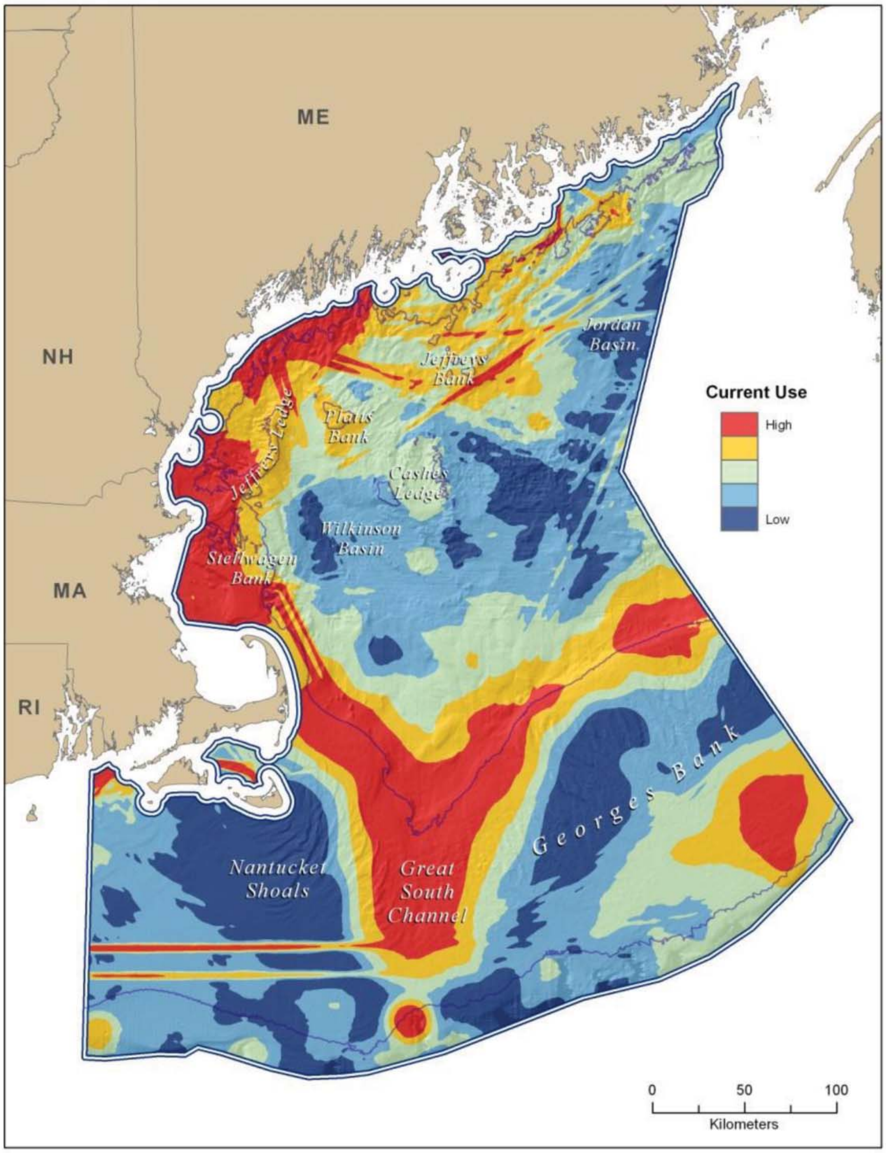

Figure 9. The cumulative use assessment combining marine animals (whales and turtles), shipping and fishing in the Gulf of Maine study area.

recreation and other nonmaterial benefits. An underlying consideration of ecosystem-based management was the interconnections between ecosystem goods and services and human activities and well-being as a means to enable a more coordinated and sustainable management of activities that affect the oceans. The development of such an integrated approach to resolving the spatial issues associated with offshore aquaculture development is necessary to ensure an ecologically intact and economically viable ecosystem. Existing applications of ecosystem-based management plans in the marine environment are relatively few, often do not include all of the guiding principles (Ruckelshaus et al., 2008) and are difficult to implement because of the lack of clear criteria (Crowder, Norse, 2008).

This work describes a way to integrate three fairly disparate data sets (vessel trip report data, AIS data for shipping, and observations of large pelagic animals) into a co-occurrence map. The integration of the fishing, shipping, and marine-animal datasets allows for a view of the high-and low-use patterns of these three activities. The analysis presented here was possible because of the use of Z-scores, which re-ranked each spatially explicit value based upon the distribution of the dataset, which allowed for comparison between disparate datasets. This analysis is limited by the scope and the limitations of the datasets. For example, lobster harvests may be underestimated by relying on VTR data as fishermen that only catch lobster will not report VTR data. Yet the normalization procedure will also help overcome deficiencies of data, provided the deficiency is

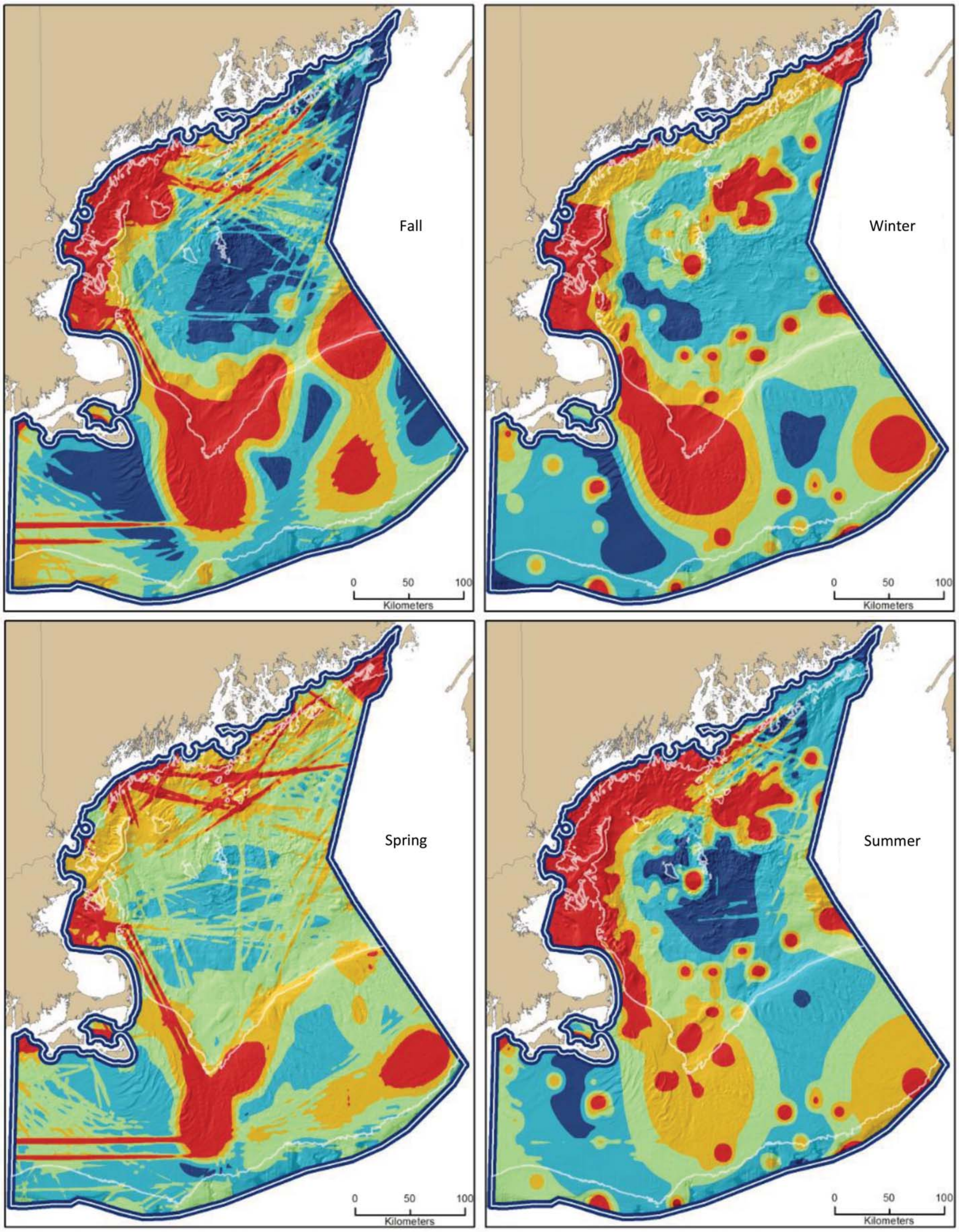

Figure 10. Seasonal cumulative use assessments combining whales and turtles, shipping and fishing in the Gulf of Maine study area. Use is indexed as in Figure 9.

proportional to the data being recorded. Murawski et al (2005) found vessel monitoring system data to be of greater accuracy than the VTR data. However, VTR data appear appropriate for the purposes of determining co-occurrence and available space determination. This co-occurrence mapping also provides a framework of analysis so that additional or improved data could be integrated (Kapetsky, Aguilar-Manjarrez et al. 2012) as it becomes available. This mapping exercise would be a first step toward more comprehensive spatial planning that would include the various requirements of the numerous permitting authorities.

Defining suitable aquaculture areas as being of low use by other user groups (in this case, fishing, shipping, and use by large pelagic animals), then a total of 18778 km^2,

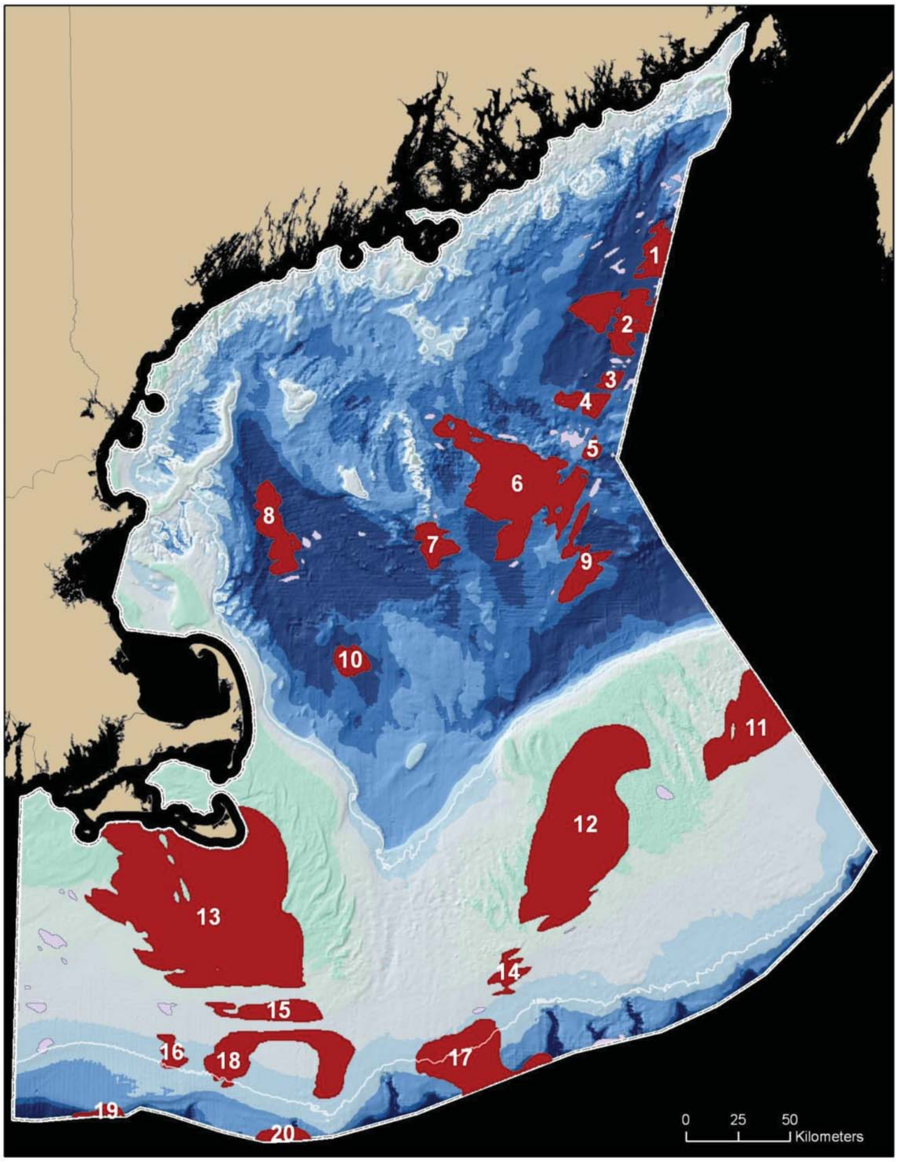

Figure 11. The low-use areas identified from this study (numbered locations). Low-use areas that are shallower and closer to shore will be primary candidates for aquaculture siting. Numbers relate to sites identified in Table 1.

or 15.2% of the total Gulf of Maine, was identified as low-use areas. The closest was 38 km from shore while the farthest was over 240 km from shore. The economics of open-ocean aquaculture production tend to constrain siting from being too far offshore. Jin (2008b) determined that costs will substantially increase beyond a distance of 46.3 km, a value that remains *de rigueur* (Kapetsky et al., 2013). Filtering this analysis for those sites closer than 46 km, there was only a single 5978 km^2 site that had low use characteristics making it suitable for aquaculture production. With only one-third of low-use space occurring within an economically feasible distance from shore, aquaculture growth will be constrained until costs of operating at a distance of greater than 46 km can be reduced. We offer low use areas as a first pass for determining potential aquaculture areas. However, there are areas, such as the approach to Boston Harbor from the Great South Channel where there is much fishing, shipping and protected species activity. The heavy use by all of these groups will create a significant challenge for siting aquaculture here.

This study determined that there are few areas within the Gulf of Maine that have low levels of activity. If aquaculture is to increase in this body of water, it will be necessary for it to co-locate with extant activities. Lobster fishing is the most important fishery in the Gulf of Maine, and this is one of the most amenable fisheries to aquaculture given the stationary nature of the trap gear, and the mobility of the fishing vessels. Spatial management plans will need to ensure that groups amenable to

Table 1. Low-use areas identified in the Gulf of Maine study area (Figure 11), showing size of the area (km^2), average depth (m) and average distance to shore (km).

Site ID	Area	Depth	Distance
1	275.7	225.7	71.1
2	737.0	242.9	82.3
3	85.2	231.0	106.4
4	218.7	192.8	105.8
5	72.7	180.5	126.8
6	2,184.7	191.4	124.6
7	282.0	195.0	114.9
8	518.0	251.9	60.5
9	437.0	190.0	167.4
10	207.7	211.3	56.1
11	1,061.5	58.5	242.3
12	3,542.2	38.9	166.4
13	5,978.2	35.6	38.1
14	195.2	67.5	147.6
15	415.7	67.9	86.9
16	154.2	91.5	105.4
17	1,121.0	134.5	156.6
18	1,069.5	82.8	110.7
19	82.0	169.0	134.7
20	139.5	215.6	145.5

co-occurrence will work cooperatively. Fishermen as well as many of the smaller shipping vessels might provide transportation or logistical support for aquaculture employees, equipment, or feeds. Fish farms that abut navigational corridors provide reliable information on frequency of vessel traffic, sea state and wave climate, weather, and safety. Without such cooperation, the U.S. will miss out on developing aquaculture and continue to lag in seafood production.

When attempting to fit new industries into a crowded ocean, current uses may account for significant portions of the total available space (Pérez et al., 2005). The results here for the Gulf of Maine were more pronounced than those of the Bay of Plenty, New Zealand. There, conflicting uses accounted for 46% of the total space (Longdill et al., 2008), whereas in the Gulf of Maine it accounted for 85%. The low-use areas identified from this analysis serve as a starting point to conduct further analysis, more robust surveys, and additional environmental impact assessments. In addition, the temporal component of these data must be taken into consideration. This is especially true for the fishing activity; some of the areas of low use for fishing are due to closures. If these areas were to reopen, then this area would likely be of much higher use. The role of aquaculture in relationship to fishery closures along with Marine Protected Areas and Essential Fish Habitat designations will also need to be addressed. Potential exists for aquaculture to be associated with closed areas, and appropriate siting may help increase the benefits of these areas (N Sims, pers. comm.).

This study also considered a spatially explicit economic value assessment. In some cases (western Nantucket Shoals, southern edge of George's Bank) space use was heavy without a concomitant increased economic value. Spatial managers will have to determine if they are to maximize the time or profit within the system. Explicit statements of tradeoffs encompassing a broad swath of users can maximize value and minimize user conflict (White et al., 2012).

With the advent of marine spatial planning, this study provides the structure on how to integrate activity and usage data from very disparate sources into a proactive GIS assessment (also see Kapetsky et al., 2013). This is a first step of the decision process on farm siting, and due diligence will need to be upheld to ensure any selected site will be in compliance with all regulatory bodies and zones of exclusion. This technique can be replicated with updated and additional data and could be integrated with other studies, such as the individual state ocean plans or oceanographic assessments for aquaculture feasibility.

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