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Integration of Multiple Data Types to Document Spatial Effort in a Recreational Fishery for Highly Migratory Species in Relation to Offshore Wind Development

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ABSTRACT

The expansion of offshore wind interests in US waters has raised concern over potential adverse impacts to fisheries activity and productivity. Yet evidence-based platforms for assessing those impacts are lacking for many recreational fisheries. We demonstrate how data from a federal fishery survey (Large Pelagics Intercept Survey [LPIS]), cooperative tagging programs, and the direct survey of recreational fishermen can be used to characterize the spatial extent of baseline (pre-construction) effort in a recreational fishery that targets highly migratory fishes (HMS) in US territorial waters of the Atlantic, Gulf of Mexico, and Caribbean. To document the location of effort, LPIS catch data and tag, release, and recapture (CTR) records from four cooperative tagging programs were independently aggregated onto a grid of offshore wind lease blocks. An online survey of recreational fishermen was also executed to assess the spatial extent of effort in relation to a Draft Call Area (DCA) in the Gulf of Maine region. Collectively, the LPIS and CTR data described widespread recreational fishing effort for HMS, including within and around the majority of existing and planned offshore wind lease areas. Responses to the online survey revealed more widespread effort within the Gulf of Maine DCA than both the LPIS and CTR data, but some respondents may have overrepresented true levels of fishing effort. Our results demonstrate the need for multiple data types to comprehensively assess offshore wind impacts on the recreational HMS fishery and to inform marine spatial planning in regions into which offshore wind energy development may be expanded.

1 | Introduction

Growing concerns over adverse impacts of climate change have initiated global expansion of renewable energy technologies (Olabi and Abdelkareem 2022). In the United States (US), policies established under the Federal Sustainability Plan have set aggressive goals for reducing carbon emissions and initiated, among other things, plans to develop 30 GW of offshore wind capacity in US waters by 2030. To begin to meet these goals, large portions of ocean off the US east coast and in the Gulf of Mexico have been sited and/or leased for offshore wind farm development, and there is intent for further development in many regions. Although rooted in the desire to mitigate climate change, plans for such rapid and widespread industrialization of the ocean have sparked concern among many ocean user groups related to potential adverse impacts of wind turbine siting, construction, and operation on marine fauna, threats to biodiversity, and negative interactions between existing ocean industries and offshore wind activities (Gill et al. 2020; Wang et al. 2024). To complicate matters, offshore wind development off portions of the northeast US has progressed faster than the establishment of monitoring programs aimed at objectively assessing its impacts on wildlife, fish, and fisheries.

Perceived threats to the fishing industry from offshore wind development have been a point of great debate and speculation and resulted in the formation of advocacy groups and the initiation of lawsuits seeking to halt or delay construction activities or obtain compensation mitigation for lost fishing opportunities. Given this contention, there is a dire need for fisheries monitoring in and around offshore wind project areas to establish evidence-based platforms for assessing actual effects on fishing activity and productivity at both local and regional scales (Gill et al. 2020). Effective fisheries monitoring relies on the existence of baseline fisheries data that document the nature, magnitude, and spatial extent of fishing effort prior to offshore wind activity, which serve as the standard to which post-construction fishing activity can be compared. In US commercial fisheries, baseline effort data documenting both the location and magnitude of fishing effort are generally available because of existing fishery management reporting requirements that have been in place at the state, federal, and international levels for decades. However, similar information from recreational fisheries is scarce or even absent because of the lack of reporting requirements for most species and/or the inability of existing effort surveys to collect fine-scale information on the location of effort. This dearth of data makes evidence-based assessment of offshore wind impacts on recreational fisheries more challenging and necessitates the exploration of alternative data streams and scientific approaches that can provide insights into the location and magnitude of recreational fishing activity before and after offshore wind farm construction (DePiper et al. 2023).

In this paper, we demonstrate multiple pathways for collecting baseline information on recreational fishing effort in relation to offshore wind activity, focusing on an extensive fishery for medium pelagic, large pelagic, and highly migratory species (e.g., billfishes, sharks, and tunas, collectively referred to as HMS; see species outlined in McCandless et al. 2023) that is largely managed by the National Marine Fisheries Service (NMFS) HMS Management Division. This fishery, annually valued at more than $510 million USD (Hutt and Silva 2019), operates throughout coastal and offshore waters of the US Atlantic, Gulf of Mexico, and Caribbean and in 2022 involved participation by upwards of 27,000 permitted vessels representing both the charter (~4000 permits) and private (~23,000 permits) angling communities (NMFS 2023). Effort is primarily exerted in offshore, federal waters thereby exposing fishing activities to potential impact from the wind energy industry. Although the benefits of offshore structures to the recreational HMS fishery in the US Gulf of Mexico are well documented (Dugas, Guillory, and Fischer 1979; Snodgrass et al. 2020), there are concerns that offshore wind development may disrupt certain fishing tactics (e.g., trolling in dense wind turbine generator arrays; MADMF 2019) and/or displace forage or predatory species from traditional fishing areas (McCandless et al. 2023). Despite these concerns, potential interactions between HMS recreational fishing effort and offshore wind have only been assessed across a small portion of the fisheries' footprint (e.g., Kneebone and Capizzano 2020; Davis and Kneebone 2023), and no formal analyses have been conducted to compare HMS distribution and offshore wind lease areas (e.g., Friedland et al. 2021; Hendon et al. 2024).

Information on recreational effort for HMS in the US Atlantic and Gulf of Mexico is estimated by a series of regional data collection programs that are collectively part of the NOAA Fisheries Marine Recreational Information Program (MRIP). In general, these regional surveys are designed to estimate total recreational catch and effort by species and region in support of fishery management. Because MRIP surveys were not designed to inform marine spatial planning, most do not collect fine-scale information (i.e., geographic coordinates) on the location of fishing effort. However, the Large Pelagics Intercept Survey (LPIS), a seasonal (June through October) dockside intercept survey of private and charter vessels who participate in the recreational HMS fishery in the waters from Maine through Virginia, does collect detailed spatial data on the location of trips and catch. These spatially linked effort data have been used to assess how recreational effort for some HMS has shifted because of climate change (e.g., Crear et al. 2023) and have value for monitoring potential changes in the northeast US recreational HMS fishery resulting from offshore wind activity. Nonetheless, as the LPIS was not designed to assess the impacts of offshore wind, its data may be insufficient to adequately monitor fine-scale changes in the fishery resulting from the sequential construction of individual and/or adjacent offshore wind lease areas. Furthermore, the persistent lack of fine-scale location information on recreational HMS fishing effort outside the LPIS region leaves a void of data where HMS fishing effort and offshore wind interests coexist.

To supplement and expand upon the data collected by the LPIS in the northeast US, we analyzed information collected by cooperative fish tagging programs and from direct surveys of recreational anglers to better characterize the spatial extent of baseline (preconstruction) regional fishing effort. Cooperative tagging programs focused on HMS have been in existence for decades and were largely designed to collect information on species distribution and movements in partnership with the fishing industry (see Scott, Prince, and Goodyear 1990; Kohler and Turner 2001; Ortiz et al. 2003). Through this partnership, fishermen routinely deploy and recover tags during their normal fishing operations and collect vast amounts of spatiotemporal data on the location and timing of catch (i.e., dates and coordinates of tag releases and recaptures), which by extension provide a minimum representation of their spatial fishing effort (Hilborn 1990). Angler surveys are also widely used to estimate recreational fishing effort (McCluskey and Lewison 2008; Parnell et al. 2010; Brownscombe et al. 2019) and were conducted to investigate historical effort in the Gulf of Maine region in relation to a Bureau of Ocean Energy Management (BOEM) offshore wind Draft Call Area (DCA). In this study, compiled data were analyzed both independently and synergistically to demonstrate how the spatial extent of baseline recreational fishing effort for HMS can be characterized and to illustrate the value of multiple data types when evaluating interactions between the recreational fishing and offshore wind industries in US waters.

2 | Methods

2.1 | Study Area

To demonstrate our methodology, we characterized the spatial extent of recreational fishing effort for HMS throughout all US waters of the Atlantic Ocean, Gulf of Mexico, and Caribbean (Puerto Rico and the Virgin Islands) (Figure 1). To determine the individual and collective utility of multiple data types as descriptors of effort, we focused analyses off the northeast US, roughly from Virginia to Maine, where offshore wind activities are underway and additional construction is imminent. Emphasis was placed on the Gulf of Maine region as it is the only region of the US Exclusive Economic Zone that currently has representation from all three data sources examined (LPIS, tagging data, and online effort survey).

2.2 | NMFS Large Pelagics Intercept Survey (LPIS) Data

Direct data on recreational fishing effort for HMS in the northeast US was obtained by downloading publicly available records generated by the LPIS. The LPIS is managed and executed from Virginia to New Hampshire by the Fisheries Research Group of QuanTech Inc. (Rockville, MD) and in Maine by the Department of Marine Resources (DMR) and collects detailed information on recreational effort and catch for the estimation of total recreational catch by species. Within each state, the LPIS operates at specific access sites and the number of monthly

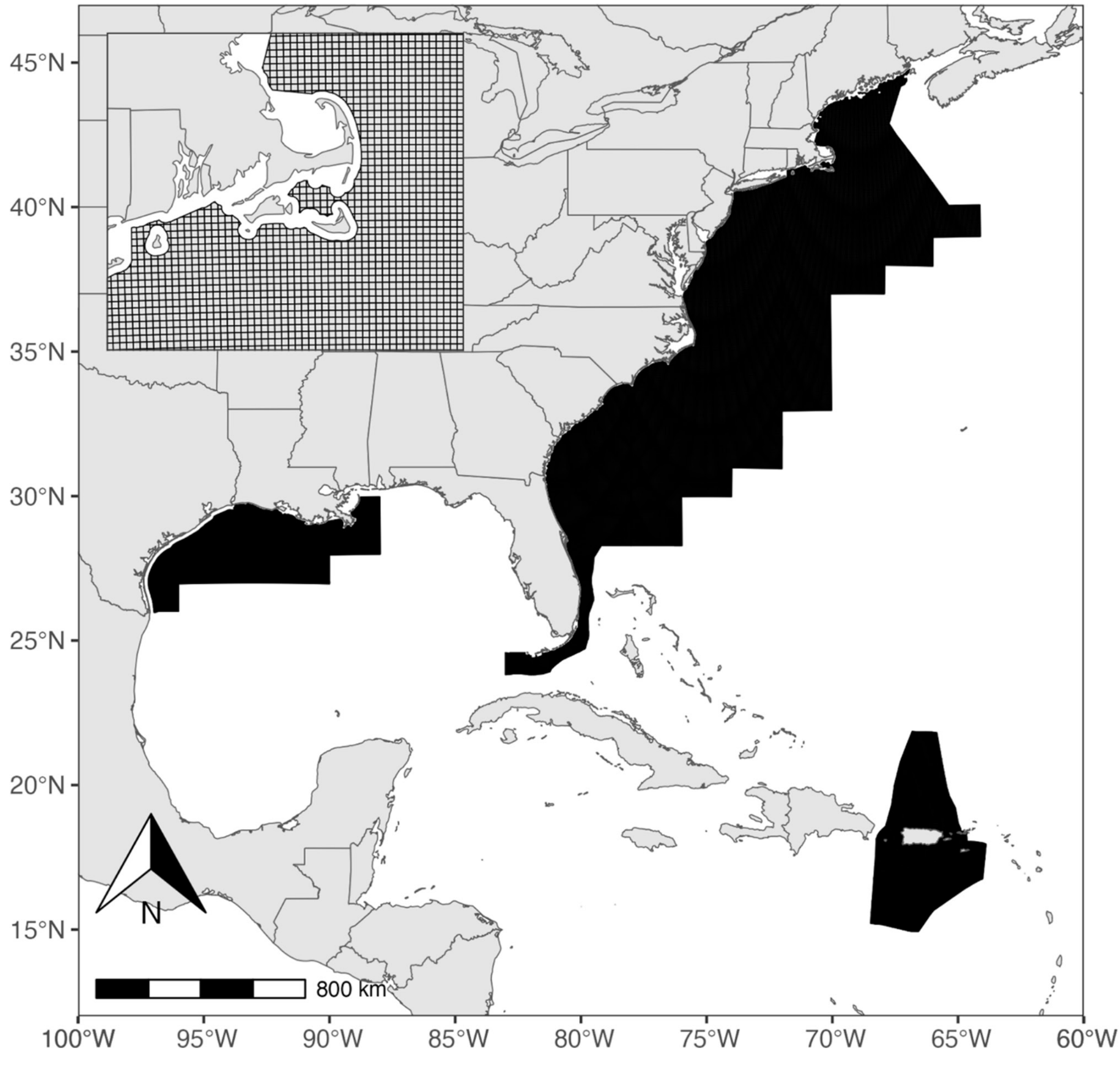

FIGURE 1 | Map showing the geographic range of the grid (black shaded area) over which recreational fisheries-dependent data from the Large Pelagics Intercept Survey and conventional tag, release, or recapture records were interpolated. The grid, shown at higher resolution in the inset map, was based on Bureau of Ocean Energy Management Outer Continental Shelf Lease Blocks existing throughout the Atlantic and Gulf of Mexico and cells with similar dimensions (4.8 × 4.8 km) created for this study around Puerto Rico and the Virgin Islands.

sampling assignments at each site has been adjusted over time to achieve a consistent number of intercepted trips across states, months (June to October), and years (Crear et al. 2023). For this analysis, data from the LPIS were used to investigate the number of recreational trips and total recreational catch throughout the survey area from 2002 to 2022 (2022 was the last year for which data were available at the time of analysis). Data sourced from the LPIS included the following trip level information: the date (month and year) of the trip, the state and county where the intercept survey occurred (i.e., the port of origin for the trip), the reported fishing location (latitude–longitude coordinates), the target species, and the reported catch by species. Of note, the LPIS has an established list of fixed coordinates that are assigned by default whenever a respondent testifies to fishing in a general or named location (e.g., Coxes Ledge off southern New England, Hudson Canyon, Norfolk Canyon, etc.). LPIS data analyzed herein were publicly available, but NOAA Fisheries does not endorse or assume responsibility for the way they were used in this study.

2.3 | Cooperative Tag, Recapture, or Release (CTR) Data

To supplement the effort data obtained from the LPIS and to document baseline recreational HMS fishing activity beyond the LPIS region, historical records representing conventional tagging, recapture, or release (i.e., catch and release but without a tag deployment) events of HMS occurring solely aboard recreational vessels using rod and reel from 1954 to 2022 were compiled from several groups/entities that maintain active volunteer tagging programs in the US Atlantic, Caribbean, and Gulf of Mexico. Those groups included the NMFS Cooperative Shark Tagging Program (Apex Predators Program, Narragansett, Rhode Island), NMFS Southeast Fisheries Science Center Cooperative Tagging Center (Miami, Florida), The Billfish Foundation (Ft. Lauderdale, Florida), and the Dolphinfish Research Program (Newport, Rhode Island). For the purposes of this analysis, data were filtered to include only records that were reported by recreational fishermen, and it was assumed that a tagging, recapture, or documented release event was an indirect indicator of effort because the event had to have involved fishing activity from an angler or vessel to occur. For some records, CTR data auditors interpolated coordinates for tag, recapture, and release records that indicated approximate capture locations or coastal cities or towns, such as “20 miles south of Martha's Vineyard” or “Miami.” Following this logic, the compilation of CTR records originating from the recreational sector serves as a direct proxy for the location of fishing effort and, for multiple reasons, a relative proxy for the magnitude of catch in both space and time. For example, each year only a portion of the recreational sector participated in cooperative tagging programs and the percentage of participants changed over time. Unlike the LPIS data, CTR records also only represent recreational fishing trips with positive catches and do not contain any information on trips on which no HMS were caught or on which HMS were caught but not tagged. Accordingly, CTR records were not used to estimate the number of recreational trips occurring in space and time. Information requested from CTR providers included the date, the species, and the location (latitude–longitude coordinates) of each capture event.

2.4 | Online Effort Survey

In addition to information provided from the LPIS and CTR datasets, an online survey was created by the Maine DMR to allow fishermen the opportunity to self-characterize fishing effort for HMS in the Gulf of Maine over recent decades (for details on the survey design and instructions see Davis and Kneebone 2023). The survey, built using the ArcGIS Survey123 platform, was released on December 7, 2022, and consisted of nested questions relating to spatiotemporal fishing effort in and around the then-current Gulf of Maine BOEM DCA for wind development (Table 1). Links to the survey were emailed to 4643 subscribers of the State of Maine “General Recreational Fishing” direct government notification system on December 7, 2022, and again on January 13, 2023. This notification list was determined to most closely overlap with HMS fishermen in the DMR database, as the State did not have authority to send a targeted email to federal HMS permit holders. The survey was also hyperlinked on the DMR website and social media pages and advertised through email correspondence with members of the Atlantic Bluefin Tuna Association and through a post on the *On The Water* Magazine website (https://www.onthewater.com/help-minimize-offshore-wind-development-impact-on-fisheries). Fishermen were able to submit responses anonymously until the survey closed at 23:59 on February 24, 2023, after being active for 80 days. Software settings in ArcGIS Survey123 used browser cookies to limit one submission per respondent (IP address).

As part of the survey, respondents were provided a digital nautical map and asked to draw polygons around areas in which they fished. Respondents could draw multiple polygons to best reflect the spatial extent of their effort and for each polygon were asked to identify the decade(s) in which effort was exerted and the targeted specie(s) of interest. Individual polygons from each respondent were saved as shapefiles and were later imported into ArcGIS Pro (version 2.8.7) for spatial analysis.

2.5 | Analysis

All fisheries-dependent data retrieved from the LPIS and CTR sources, although assumed to have already been examined for quality control by their provider, were filtered for inaccuracies or duplicate records. For instance, provided locations from records that intersected with inland portions of US Atlantic states or territories were removed. Entries among CTR sources were also filtered for duplicate records according to their identification number, species, year and month of capture, and location (latitude–longitude coordinates). Entries with no species or location information were also removed from the analysis. All analyses were performed in the R Statistical Environment (version 4.3.1; R Core Team 2023).

Given the broad geographic extent of the recreational HMS fishery (see NMFS 2023), fisheries-dependent data were aggregated over a grid based on the BOEM Outer Continental Shelf (OCS) lease blocks established throughout US waters of the Atlantic Ocean and Gulf of Mexico. This grid was chosen because the OCS blocks represent the framework by which BOEM designs offshore lease areas. Thus, assessment effort

TABLE 1 | Questions asked of fishermen in the online survey focused in the Gulf of Maine.

Question	Resulting outcome	Choices
Parent 1. Did you fish for HMS in the Gulf of Maine during the years 2010 to 2021?	Yes—Child 1a No—Parent 2	Yes; No (select one)
Child 1a. How many years during 2010–2021 did you fish for HMS in the Gulf of Maine?	Any—Child 1b	1; 2; 3; 4; 5; 6; 7; 8; 9; 10; 11 (select one)
Child 1b. During 2010–2021, what is the average number of days you fished for HMS in the Gulf of Maine each year?	Any—Parent 2	1–10 days; 11–20; 21–30; 31–40; 41–50; 51–60; 61–70; 71–80; 81–90; 91–100; 101–110; 111–120; 121+ (select one)
Parent 2. Did you fish for HMS in the Gulf of Maine during the years 2000 to 2009?	Yes—Child 2a No—Parent 3	Yes; No (select one)
Child 2a. How many years during 2000–2009 did you fish for HMS in the Gulf of Maine?	Any—Parent 3	1; 2; 3; 4; 5; 6; 7; 8; 9; 10 (select one)
Parent 3. Did you fish for HMS in the Gulf of Maine during the years 1990 to 1999?	Yes—Child 3a No—Parent 4	Yes; No (select one)
Child 3a. How many years during 1990–1999 did you fish for HMS in the Gulf of Maine?	Any—Parent 4	1; 2; 3; 4; 5; 6; 7; 8; 9; 10 (select one)
Parent 4. Did you fish for HMS in the Gulf of Maine during the years 1980 to 1989?	Yes—Child 4a No—Parent 5	Yes; No (select one)
Child 4a. How many years during 1980–1989 did you fish for HMS in the Gulf of Maine?	Any—Parent 5	1; 2; 3; 4; 5; 6; 7; 8; 9; 10 (select one)
Parent 5. Recognizing that you may target HMS in multiple locations within a year, or even in a given day/trip, using the map below please circle the areas that you fished.	Any—Child 5a	Respondents were able to draw their fishing area(s) on a nautical map. There was no limit to the number of fishing areas that could be drawn by each participant. Child Questions 5a and 5b were asked for each unique fishing area identified.
Child 5a. What HMS did you target when fishing this area?	Any—Child 5b	Bluefin Tuna; Sharks (mako, common thresher, blue, porbeagle); Other (billfish, mahi mahi) (select one or multiple)
Child 5b. During what time frame(s) did you fish this habitat?	Any—Question 6	2010–2021; 2000–2009; 1990–1999; 1980–1989 (select one or multiple)
Question 6. What fishing methods did you typically employ when targeting HMS in the Gulf of Maine?	Any—Question 7	Anchoring; Casting (run and gun); Drifting; Harpoon; Trolling (select one or multiple)
Question 7. What type of HMS permit do you currently (or most recently) hold?	Any—Question 8	Angling; Charter/Headboat; General; Harpoon (select one or multiple)
Question 8. In what state is your home port located in?		Maine; New Hampshire; Massachusetts; Rhode Island; Connecticut (select one)

Note: Child questions were asked only if respondents answered "Yes" to the related parent question. Choices represent the possible answers fishermen could choose from in their response as well as instructions for how many to select.

in individual OCS cells would match the resolution used by BOEM to construct lease areas. Shapefiles of OCS blocks clipped to the US Submerged Lands Act boundary on the shoreward side (2304 ha per standard block) were obtained for the Atlantic and Gulf of Mexico regions at: https://www.boem.gov/oil-gas-energy/mapping-and-data. Electrical transport cable lines associated with some lease areas were removed from the shapefiles prior to analysis. BOEM has yet to publicly release OCS blocks associated with US territories of the Caribbean, thus, a grid with cell sizes of similar dimension to that of BOEM's OCS blocks (4.8 km × 4.8 km) was created within the US maritime limits and boundaries around the waters of Puerto Rico and the Virgin Islands to permit comparable aggregation of data in the US Caribbean. The grid was created using a shapefile of the maritime limits and boundaries (available at https://nauticalcharts.noaa.gov/data/us-maritime-limits-and-boundaries.html) and the st_make_grid function in the R package *sf* (Pebesma and Bivand 2023), which built the grid relative to the lower left (southwest) extent of the shapefile (latitude: 14.92819, longitude: −68.48189). Each grid cell/OCS block ($n = 67{,}514$) was assigned a unique identifying number, and all cells from the Atlantic, Gulf of Mexico, and

US Caribbean were grouped into a single geodatabase with an NAD83 projection, referenced hereafter as the OCS grid (Figure 1).

LPIS trip level data and CTR records were individually analyzed over the OCS grid to characterize effort and catch data over all cells. To examine the location of HMS fishing effort on a finer scale, each LPIS trip/catch and CTR record was aggregated onto the OCS grid to examine total effort (LPIS: number of trips and total catch by species and target species; CTR: number of capture events by species) by grid cell. Aggregation (rather than plotting raw locations) was necessary because of data confidentiality requirements of some of the data providers. Plots were created to visually demonstrate the relative amount of recreational fishing effort documented in each grid cell for all HMS by the LPIS and CTR records. When appropriate, bin sizes used in plots were determined using Jenks Natural Breaks. To compare the spatial extent of fishing effort documented by the LPIS and CTR data, the number of grid cells containing effort and total catch by species or species group was calculated for each source over its full time series. To permit a relative comparison between the two data types, summaries were also created for the CTR data over 2002–2022 (i.e., the LPIS period) as well as only in the LPIS region, which was defined as the region north of the southern-most intercepted LPIS trip (35.96°N; 19,869 cells). To compare effort identified by the LPIS and CTR records occurring within BOEM offshore wind lease areas in existence throughout the LPIS region ($n = 28$ lease areas) as of June 6, 2024 (Figure S1), the number and proportion of grid cells containing effort in each lease area was calculated using data from both the 1954–2022 and 2002–2022 time periods. A one-way analysis of variance was used to examine whether the LPIS and CTR records identified effort in a similar number of grid cells across the lease areas across the two time periods. Pairwise comparisons were made with a Tukey's Honestly Significant Difference (HSD) test and significance was accepted at $p < 0.05$. Shapefiles of the offshore wind lease areas were downloaded at https://www.boem.gov/renewable-energy/mapping-and-data.

Responses to the online survey from HMS recreational fishermen regarding fishing effort in the Gulf of Maine DCA were downloaded from ArcGIS Survey123 and analyzed to quantify the location and magnitude of fishing effort during the 2010–2021 period. This period was chosen as it represents the most recent years of fishing effort and coincides with the execution of the LPIS. To calculate conservative estimates of the number of fishing days per year, the minimum number of days was chosen from the selected range (i.e., 1–10 days = 1 day, 11–20 days = 11, and 21–30 days = 21) and summed over all respondents

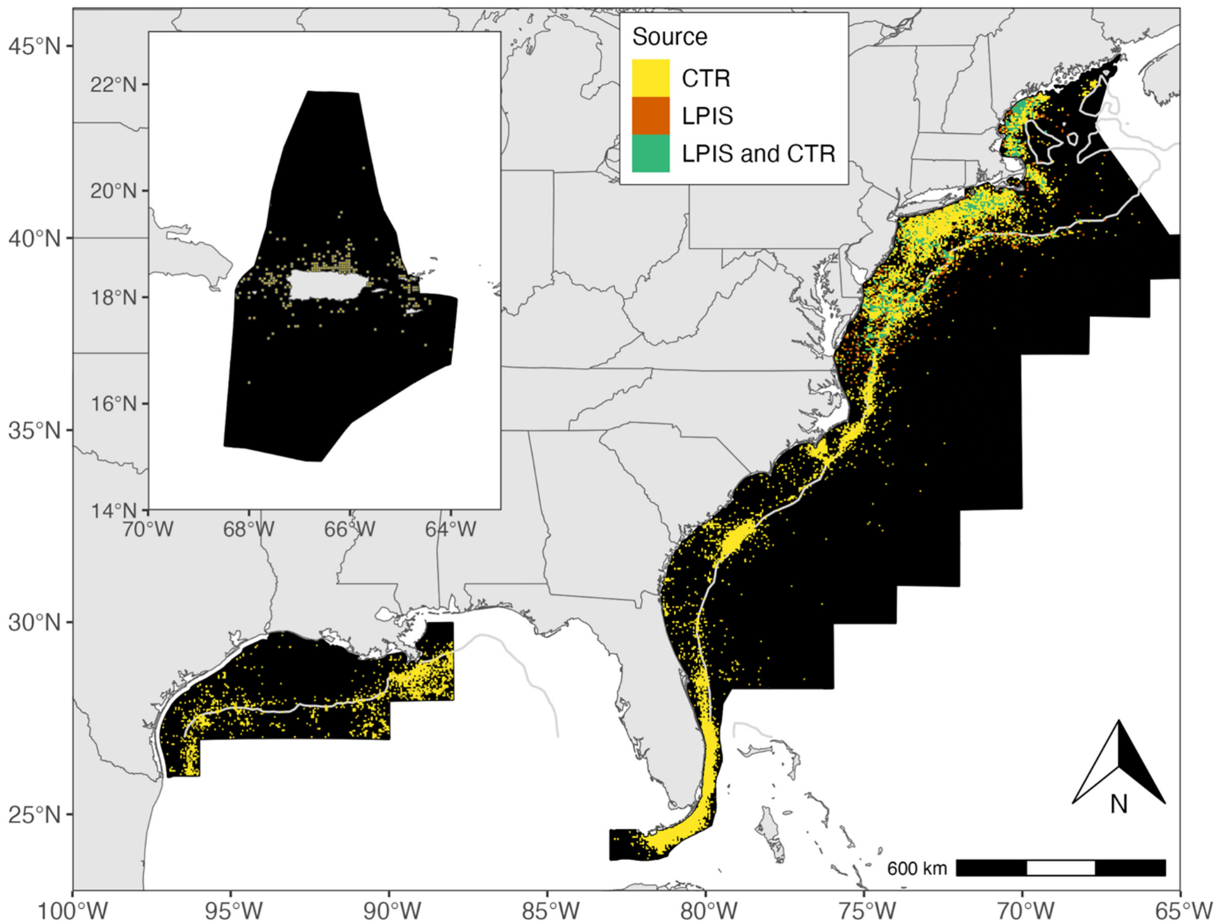

FIGURE 2 | Locations within the Outer Continental Shelf grid (black area) where recreational fishing effort for highly migratory species was identified based on Large Pelagic Intercept Survey (LPIS) and cooperative tag, release, or recapture (CTR) data from 2002 to 2022. Cells are color coded based on whether effort was described solely by catch records from the LPIS, solely by CTR records, or by both data sources (LPIS and CTR).

(Kneebone and Capizzano 2020). To quantify spatial fishing effort, shapefiles of respondent-drawn polygons were overlaid on the OCS grid. Any grid cells with overlapping polygon bounds, including cases of partial overlap, were considered when addressing the spatial extent of fishing effort. In cases where a respondent submitted multiple polygons, their reported minimum number of HMS fishing days per year was evenly divided among the fishing areas. Cumulative spatial effort within the Gulf of Maine DCA was summarized by minimum annual trip days using Jenks Natural Breaks. To enable a spatial comparison between the location of effort identified by survey respondents and by the LPIS and CTR databases within the DCA, data from each source representing effort from 2010 to 2021 were overlaid and plotted.

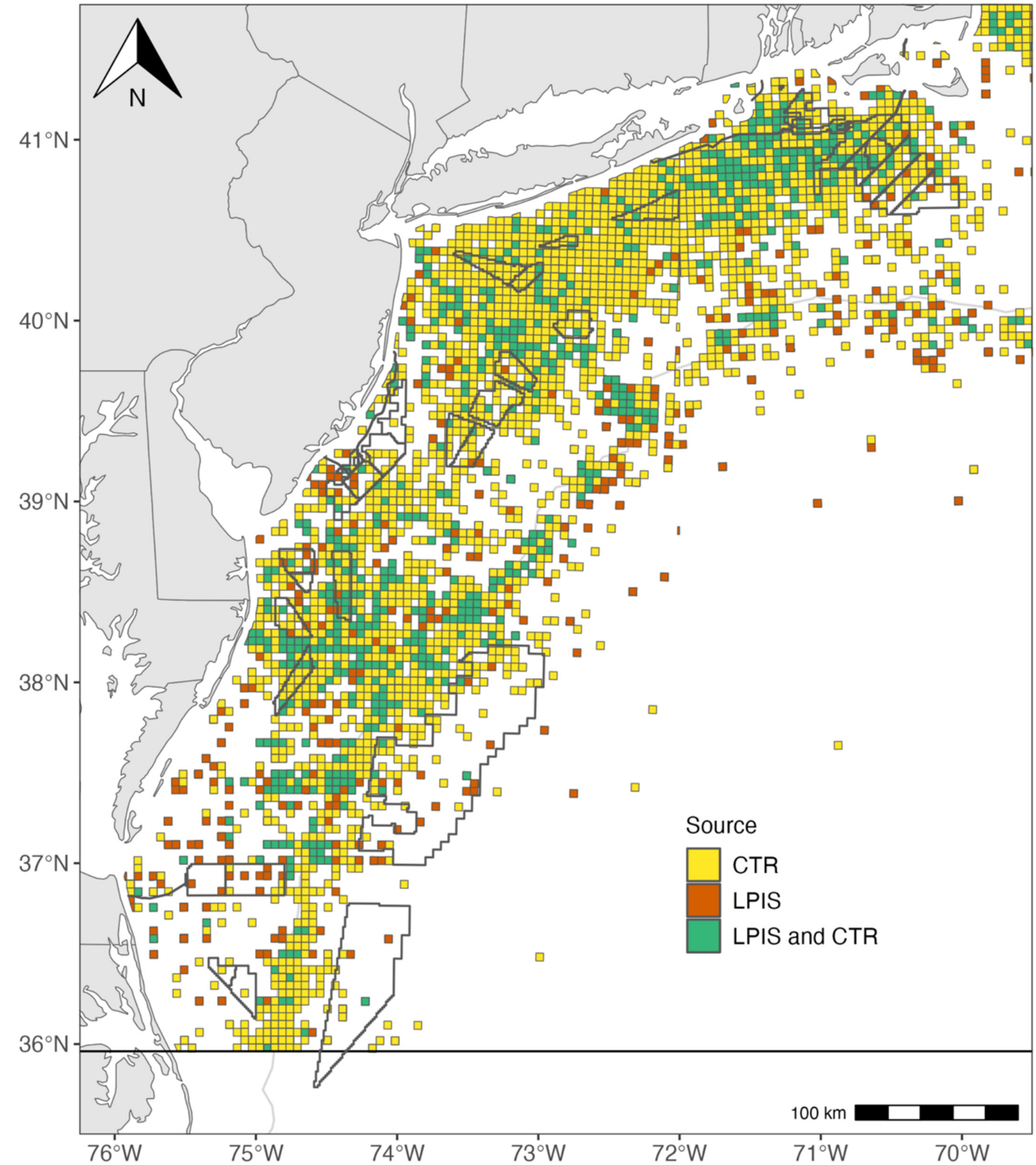

FIGURE 3 | The location of recreational fishing effort for highly migratory species within the mid-Atlantic and southern New England region of the Outer Continental Shelf grid documented from 2002 to 2022. Cells are color coded based on whether effort was described solely by catch records from the Large Pelagics Intercept Survey (LPIS), solely by cooperative tag, release, or recapture (CTR) records, or by both data sources (LPIS and CTR). Bureau of Ocean Energy Management offshore wind lease areas or planning areas are mapped to demonstrate overlap between space used by the wind and recreational fishing industries. Grid cells with no data are not shown. Horizontal black line represents the southern boundary of the LPIS region.

3 | Results

3.1 | LPIS and CTR

From 2002 to 2022, a total of 43,035 trips occurring within 1203 of the 19,869 (6.1%) OCS grid cells in the LPIS region (Virginia to Maine) were intercepted (Figures 2–4). More than half of these trips targeted tunas, including bigeye tuna (*Thunnus obesus*), albacore tuna (*Thunnus alalunga*), yellowfin tuna (*Thunnus albacares*), skipjack tuna (*Katsuwonus pelamis*), bluefin tuna (*Thunnus thynnus*), and "Any tuna." Directed billfish (17.5%) and shark (11.1%) trips were also documented, with all other targets representing < 5% of total trips. Collectively, intercepted trips captured a total of 280,310 fish representing 32 individual HMS and seven HMS groups (Table 2, Figure 4; Table S1).

A total of 247,544 CTR records were compiled over the OCS grid from 1954 to 2022 (Table 2, Figures 2–4). Records involved the

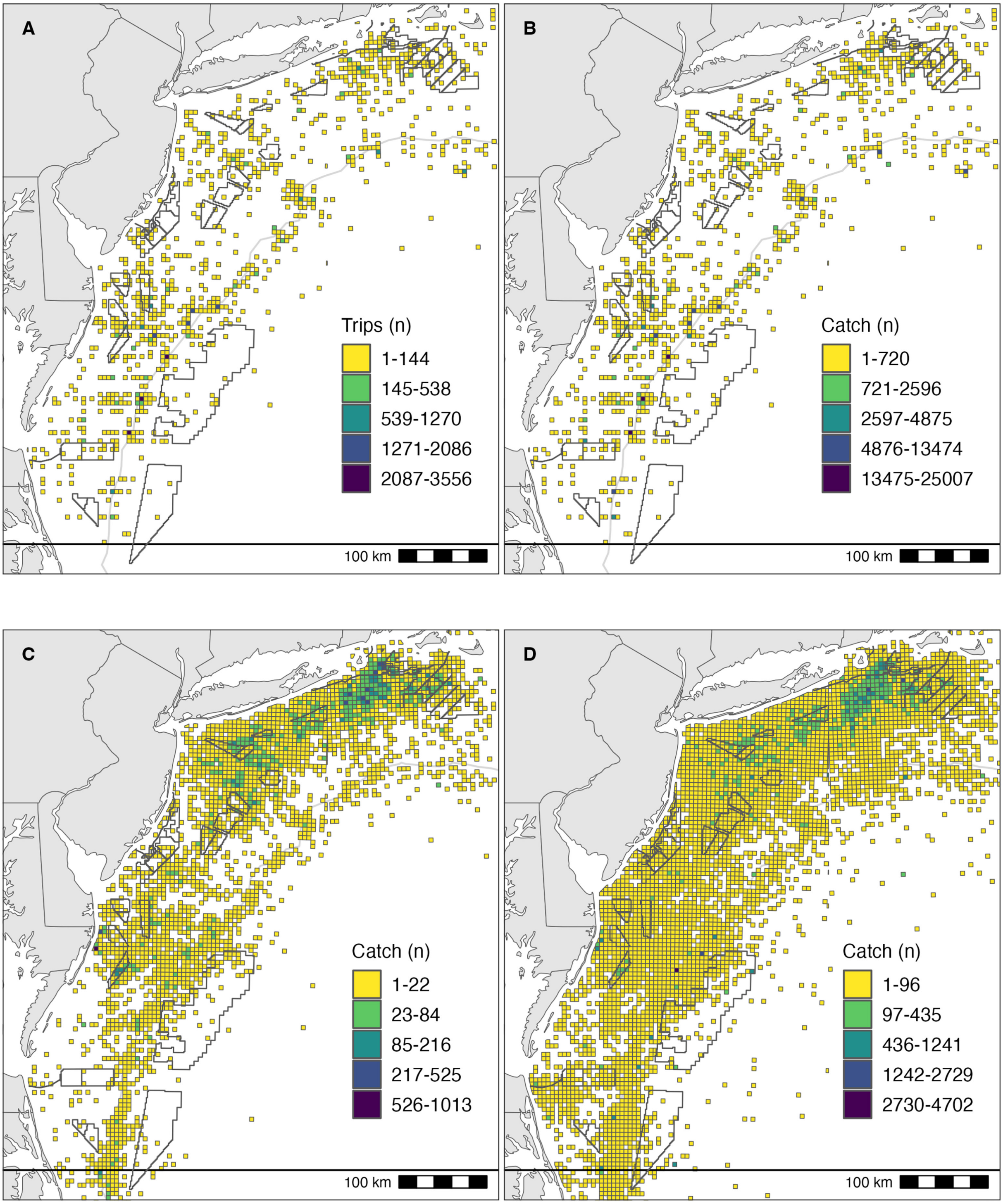

FIGURE 4 | Relative levels of recreational fishing effort for all highly migratory species within the mid-Atlantic and southern New England region of the Outer Continental Shelf grid documented by the Large Pelagics Intercept Survey from 2002 to 2022 (A,B), and cooperative tag, recapture, or release records from 2002 to 2022 (C) and 1954 to 2022 (D). Bin sizes were established using Jenks Natural Breaks.

TABLE 2 | Summary of metrics describing recreational fishing effort for highly migratory species in the Outer Continental Shelf (OCS) grid based on the Large Pelagics Intercept Survey (LPIS) and cooperative tag, release, or recapture (CTR) databases.

		Number of			
Source	Time period	Catch records	OCS grid cells	Species	Species groups
CTR	1954–2022	247,544	10,359	46	6
CTR	2002–2022	75,388	6985	45	6
CTR (LPIS region)	2002–2022	35,383	3196	35	6
LPIS	2002–2022	280,310	1203	32	7

Note: The number of OCS grid cells represents the total number of cells in which effort was identified by the data source in the specified time period. Catch records indicate the total number of fish caught. See Table S1 for a list of individual species and species groups.

capture of 46 individual HMS and six HMS groups with blue shark (*Prionace glauca*), Atlantic sailfish (*Istiophorus albicans*), white marlin (*Kajikia albida*), bluefin tuna, and mahi mahi (*Coryphaena sp.*) collectively representing 78% of the total observations (Table S1). Over the full time series (1954–2022), effort occurred in 10,359 of 67,514 (15.3%) OCS grid cells. During the period in which the LPIS was occurring (2002–2022), a total of 75,388 catch records were compiled for 45 individual HMS and six HMS groups over 6985 of the 67,514 OCS cells (10.3%). Within the LPIS region and period (2002–2022), effort was identified in 3196 of the 19,869 cells (16.1%) representing 35,383 catch records of 35 HMS and six HMS groups (Table 2).

During 2002–2022 and within the LPIS region (19,869 cells), effort was identified by both LPIS and CTR records in 818 cells (4.1%), whereas the LPIS identified effort in 385 cells (1.9%) where no CTR effort was recorded and CTR records identified effort in 2378 cells (12.0%) where no effort was recorded by the LPIS (Figures 2 and 3). Widespread effort was identified in relation to BOEM lease areas by both the LPIS and CTR records (Table 3, Figure 4). Data from the LPIS documented recreational fishing effort for HMS in 25 (89.3%) of the 28 BOEM leases occurring in the LPIS region. CTR records from 1954 to 2022 identified recreational fishing effort in all lease areas, whereas CTR records spanning 2002 to 2022 identified effort in 27 of 28 lease areas (96.4%). Overall, the LPIS identified effort in a significantly lower percentage of total grid cells in each lease area (range: 0%–50%, mean ± sd: 18 ± 13%) than CTR records during both the 1954–2022 (range: 26%–100%, mean ± sd: 87 ± 20%) and 2002–2022 (range: 0–100, mean ± sd: 59 ± 32%) periods (Tukey's HSD: $p < 0.05$).

3.2 | Online Survey and Data Convergence

A total of 58 recreational HMS fishermen responded to the online survey (response rate of email recipients = 1.3%) and testified to having fished within the Gulf of Maine DCA for at least 1 year during 2010–2021. Fishermen reported holding either an Atlantic HMS Angling ($n = 21$) or Charter/Headboat ($n = 37$) permit and originated from Maine ($n = 15$), New Hampshire ($n = 10$), or Massachusetts ($n = 33$). These respondents reported fishing an average of 43 ± 38 (mean ± sd) days per year during the period, for a cumulative total minima of 2548 days per year. Respondent drawn polygons ($n = 68$) representing the areas in which they exerted fishing effort ranged from 64.1 to 135,864.3 km^2 (mean ± sd: 20,412.9 ± 31,847.3 km^2; median: 8276.0 km^2) (Figure 5A). Reported fishing grounds were not always entirely within the bounds of the Gulf of Maine DCA, and in some cases only marginally overlapped with the DCA (Figure 6). Of the DCA cells with reported fishing effort, approximately 50.1% ($n = 1032$ cells) were claimed as being used by five or less participants, whereas only 1.7% ($n = 35$ cells) were used by half or more of respondents (Figure 5B). In total, the submitted polygons partially or fully overlapped with 2061 of the 2114 cells (97.5%) of the Gulf of Maine DCA (Figure 7). During 2010–2021, the majority (98.0%) of LPIS trip and catch effort in the Gulf of Maine occurred outside of the DCA. However, there was documented effort from 100 trips and 96 catch events within 17 (0.8%) grid cells of the Gulf of Maine DCA. Trips in the DCA were conducted by fishermen from Massachusetts ($n = 21$ trips), Maine ($n = 71$ trips), and New Hampshire ($n = 8$ trips), holding both HMS Angling ($n = 29$ trips) and Charter/Headboat ($n = 71$ trips) permits. A total of 158 CTR records within 48 (2.3%) DCA grid cells occurred during 2010–2021 (Figure 7). Five cells (0.2%) in the DCA had documented effort from all three data sources (online survey, LPIS, CTR).

4 | Discussion

Marine recreational fishing effort is growing in the US (Ihde et al. 2011; Shertzer et al. 2019), yet the effects of offshore wind development on recreational fishing are poorly understood and will likely vary based on geographic location, angler perspective and behavior, and associated impacts to target species and fishery access (ten Brink and Dalton 2018; Gill et al. 2020; Smythe, Bidwell, and Tyler 2021; Chaji and Werner 2023). To begin to fill this knowledge gap, evidence-based platforms are needed to monitor effects on fishing activity and productivity at both local and regional scales. However, offshore wind activity off portions of the northeast US has already outpaced the development of monitoring programs specifically designed for recreational fisheries, thereby creating a dependency on historical data, angler retrospective accounts, and existing monitoring platforms to understand baseline (preconstruction) effort. To complicate matters, existing state and federal fishery monitoring programs often do not collect sufficient fine-scale information on the location of effort, which is necessary to understand historical trends in effort, identify geographic shifts in effort over time, and evaluate whether observed changes may be because of offshore wind activities or other factors (e.g., climate change; Crear et al. 2023). We demonstrate how multiple data types collected using different methods and under different objectives can be synthesized to characterize baseline spatial effort of a large recreational fishery targeting HMS and compare how

TABLE 3 | Total number of Outer Continental Shelf grid cells occurring within existing offshore wind lease areas in which highly migratory species fishing effort was identified based on the Large Pelagics Intercept Survey (LPIS) and the full and LPIS time period truncated time series of cooperative tag, release, or recapture (CTR) databases.

Lease number	Total cells in lease	LPIS 2002–2022	CTR 1954–2022	CTR 2002–2022
OCS-A 0482	22	7(32)	20(91)	9(41)
OCS-A 0483	29	4(14)	18(62)	0(0)
OCS-A 0486	40	6(15)	38(95)	33(83)
OCS-A 0487	37	16(43)	37(100)	36(97)
OCS-A 0490	23	4(17)	20(87)	14(61)
OCS-A 0497	12	1(8)	11(92)	2(17)
OCS-A 0498	49	7(14)	44(90)	19(39)
OCS-A 0499	31	0(0)	26(84)	10(32)
OCS-A 0500	53	17(32)	53(100)	53(100)
OCS-A 0501	30	6(20)	27(90)	25(83)
OCS-A 0508	23	0(0)	6(26)	1(4)
OCS-A 0512	30	3(10)	30(100)	29(97)
OCS-A 0517	28	10(36)	25(89)	24(86)
OCS-A 0519	11	2(18)	9(82)	5(45)
OCS-A 0520	44	15(34)	44(100)	32(73)
OCS-A 0521	42	10(24)	39(93)	24(57)
OCS-A 0522	38	5(13)	30(79)	14(37)
OCS-A 0532	33	9(27)	32(97)	10(30)
OCS-A 0534	25	9(36)	25(100)	24(96)
OCS-A 0537	25	1(4)	24(96)	19(76)
OCS-A 0538	23	4(17)	23(100)	19(83)
OCS-A 0539	34	4(12)	34(100)	25(74)
OCS-A 0541	21	2(10)	20(95)	15(71)
OCS-A 0542	25	2(8)	23(92)	12(48)
OCS-A 0544	15	2(13)	15(100)	15(100)
OCS-A 0549	28	1(4)	16(57)	5(18)
OCS-A 0559	18	0(0)	5(28)	2(11)
OCS-A 0561	18	9(50)	18(100)	17(94)

Note: Numbers in parentheses represent the percent of total cells in each lease area that contained fishing effort.

the data types cumulatively and independently describe effort in relation to existing offshore wind lease and planning areas. Because of the accelerated pace of offshore wind development off the northeast US, we focused our demonstration of the approach on this region and encourage future studies to be conducted focusing on offshore wind development in other regions, such as the Gulf of Mexico. Furthermore, our approach is flexible to match any spatial area or temporal period of interest and to focus on HMS as a complex or individual target species.

Analysis of LPIS and CTR records revealed extensive recreational fishing effort for HMS throughout the US Atlantic, Gulf of Mexico, and around Puerto Rico and the Virgin Islands. Within the LPIS region (i.e., Maine to Virginia) and period (2002–2022), LPIS records indicated effort occurred in 1203 total OCS grid cells, 818 (68.0%) of which also contained effort described by the CTR records. Within this same period and geographic range, CTR records described effort across 3196 total OCS grid cells, 166% more than described by the LPIS. Within the LPIS region, the CTR records also documented effort in more BOEM lease areas and in more

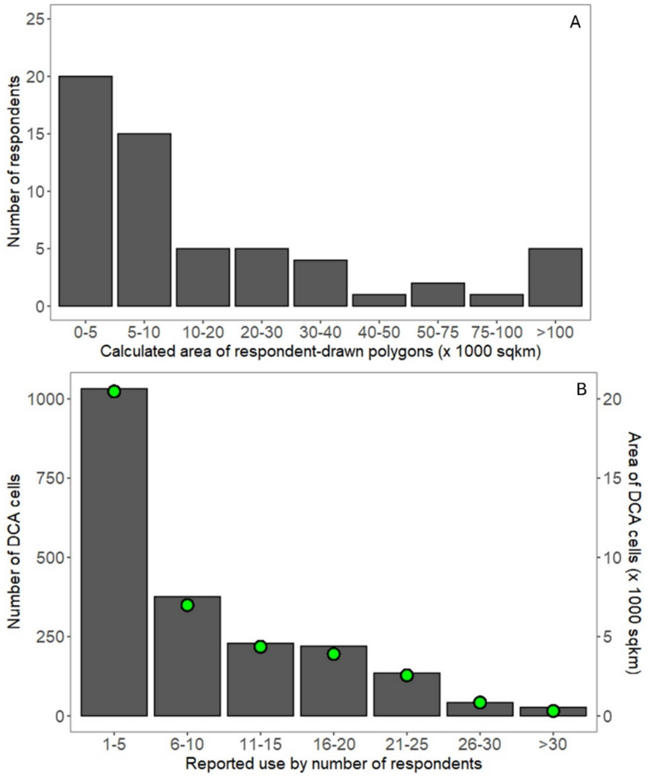

FIGURE 5 | The number of online survey respondents who indicated exerting recreational fishing effort for highly migratory species over various spatial extents within the Gulf of Maine (A) and the relative spatial extent of reported effort within the Gulf of Maine Draft Call Area (DCA) (B). In A, bins represent the total area of polygons drawn by respondents to describe the area they fished when targeting highly migratory species in the northeast US from 2010 to 2021. For respondents who identified multiple polygons, the area of all polygons was combined. In B, columns represent the number of cells in the DCA, whereas green points represent the area of those DCA cells, as not all cells within the DCA were standard size (4.8 × 4.8 km).

grid cells within those lease areas than the LPIS, including in four lease areas that had no intercepted trips throughout the LPIS time series. Collectively, these discrepancies demonstrate the value of the CTR records for obtaining a more complete assessment of the spatial extent of recreational fishing effort throughout a region and with respect to existing and planned offshore wind lease areas. Outside the LPIS region, CTR records perhaps represent the best-available and most comprehensive data demonstrating historical effort in the HMS recreational fishery, given the absence of state or federal fishery monitoring programs that collect fine-scale information on the spatial extent of effort.

Large discrepancies in the spatial extent of recreational HMS fishing effort in the Gulf of Maine DCA were identified when comparing the results of the online survey of anglers and available LPIS and CTR records over the period of 2010–2021. Respondents to the online survey reported exerting recreational HMS fishing activity in nearly 97.5% of the Gulf of Maine DCA. However, LPIS and CTR records indicated fishing effort only occurred in 0.8% and 2.3% of cells in the DCA, respectively. There are several potential factors influencing this vast difference in apparent effort, perhaps the greatest of which relates to the spatial extent of the polygons some survey respondents created to document their fishing effort. Although around 50% of fishermen described exerting effort over areas less than 10,000 km^2 within the Gulf of Maine, roughly 20% of respondents created polygons that covered more than 30,000 km^2 and around 7% created polygons > 100,000 km^2 that extended beyond the Gulf of Maine region as far south and west as western Long Island, inclusive of land. Although it is possible that these respondents did exert effort over a broad geographic extent over a decadal period, it is unlikely they exerted continuous effort throughout all the designated area. Thus, the drawn polygons likely grossly overreport the actual area fished and should be considered a bounding box of their area of effort as opposed to a representation of actual areas fished within it. It is also important to keep in mind that CTR data only represent the locations of reported catch and may not truly reflect the total area fished by the recreational fleet. With respect to the LPIS in Maine, dockside surveys are typically confined to areas west of Penobscot Bay, and a substantial portion of HMS fishing in the Gulf of Maine region is carried out from personal residences or docks that are difficult or impossible for surveyors to access. Together with Maine's large and complex coastline, which can prolong the travel time between ports, the number of intercepted trips may therefore be insufficient to adequately characterize the spatial extent of recreational HMS fishing effort in the Gulf of Maine region. The relative paucity of CTR records in the Gulf of Maine, perhaps because of the smaller number of species available for tagging (e.g., only five of the 46 species had records in this region), may also contribute to the low levels of effort documented throughout the region.

Despite the potential value of fishermen's testimonials in understanding recreational fishing effort in areas with few or no LPIS or CTR records, numerous caveats must be considered when interpreting self-characterized effort data. In our survey of Gulf of Maine anglers, respondents were asked to identify the locations they fished over the period of 2010–2021 to capture interannual variability in fish distribution (and related fishing activity) throughout the region. However, it is possible that some respondent's recollection of their efforts over such a protracted period was inaccurate and may have led to over or under representation of the actual area they fished. Selection of the period over which fishermen are asked to reflect upon past effort should therefore achieve a balance between being long enough to capture the natural dynamics of the fishery (i.e., temporal variability) while not extending so far back in time that it leads to inadvertent or biased misrepresentation of effort (Lewin et al. 2021). It is also possible that misunderstanding or misinterpretation of the instructions provided with the survey resulted in inaccurate responses to specific questions. For example, several recreational anglers reported confusion or difficulty with the use of the mapping interface required to draw polygons around areas where they exerted fishing effort (question 5) and were either unable to complete the survey in its entirety or submit their survey altogether. Aside from resulting in a reduced amount of data, these obstacles could have resulted in respondents drawing single, large polygons that covered vast extents of area rather than drawing multiple independent polygons that characterized their effort in specific geographic areas. It is also possible that respondents deliberately enlarged the amount of area fished to demonstrate greater spatial effort in an attempt to deter offshore wind development or achieve greater consideration for financial mitigation for lost fishing opportunities due to offshore wind activity. The overall response rate to our survey was low (< 2%) and

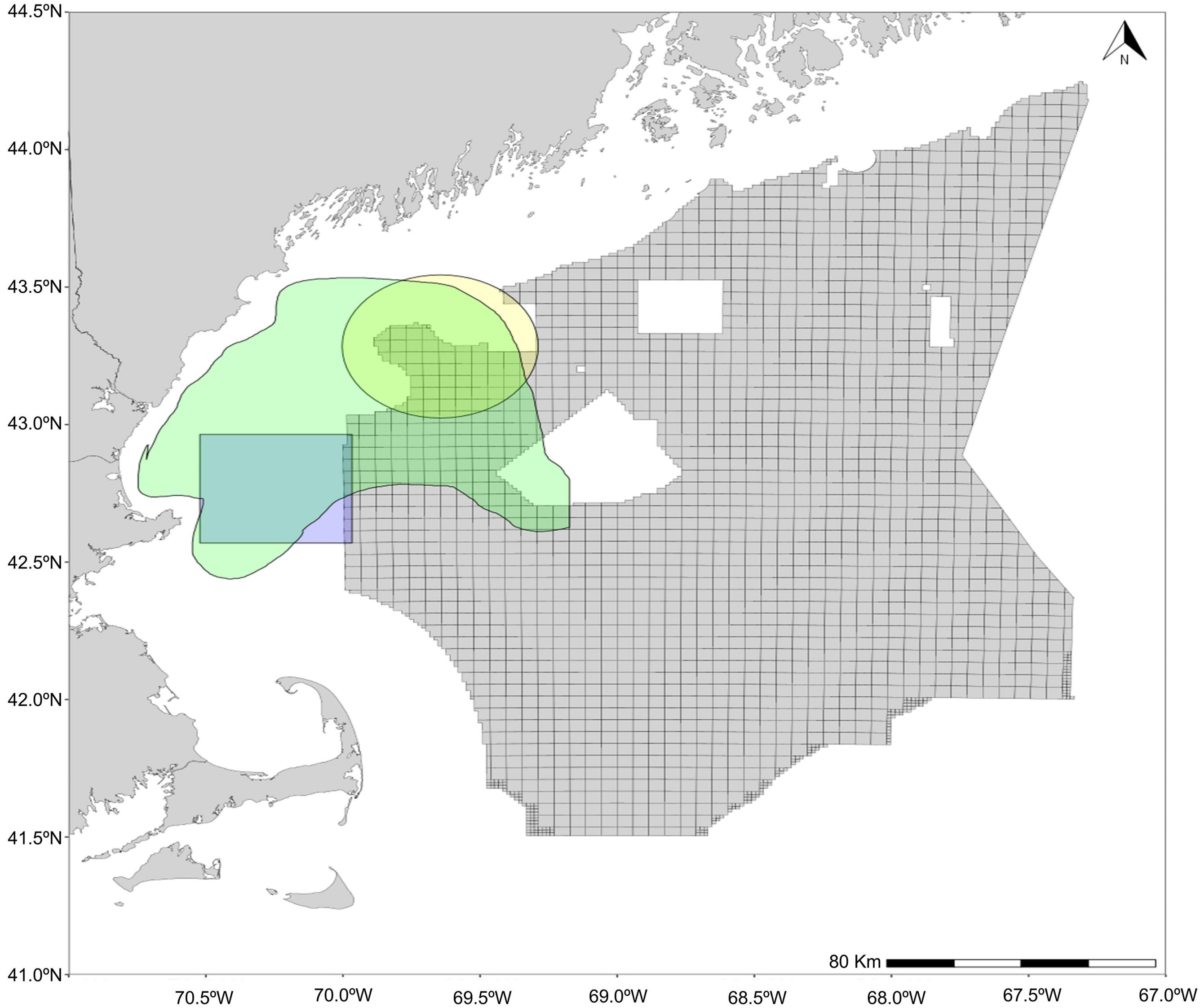

FIGURE 6 | Example of three independent and anonymous respondent-drawn polygons provided during the online survey to demonstrate the spatial extent of their recreational fishing effort from 2010 to 2021 in relation to the Gulf of Maine Draft Call Area (gray grid cells). Areas covered by each polygon were 1990.2 km^2 (blue), 2628.2 km^2 (yellow), and 9542.3 km^2 (green). The polygons shown were selected for display at random, and do not necessarily represent the shape, size, or location of other respondent submissions.

e-mail surveys are likely to contain age biases (Wallen et al. 2016). Taken together, these considerations underscore the need for future offshore wind-related surveys of recreational fishing effort to include additional distribution mediums (e.g., mailed, in person, or phone interviews), detailed information on the intent of the survey, disclosure of who will use the data collected by the survey, carefully thought-out questions, explicit instruction related to the completion of those questions, and adequate levels of technical support to assist with the completion of the survey. Focus groups or direct in-person interviews of anglers may also be beneficial for collecting data in the appropriate context, conveying the intent of the survey, and reaching fishermen who have difficulty responding to computer-based surveys (e.g., DeCelles et al. 2017).

The LPIS and CTR records provided extensive insight into recreational fishing effort for HMS across multiple regions, but it is important to disclose some of the nuances associated with the use of these data to approximate effort. First and foremost, neither the LPIS nor cooperative tagging programs were designed specifically to inform marine spatial planning. Thus, the level of precision of their trip or catch level location data may not allow for the assessment of fine-scale or localized (e.g., km scale) impacts from the construction and operation of individual wind farms. Similarly, the latitude–longitude coordinates associated with LPIS trips and CTR capture events may not always accurately reflect the exact location in which fishing effort occurred because of the need to interpolate coordinates when fishermen reported fishing in named or approximate locations (e.g., "Coxes Ledge," "20 miles south of Martha's Vineyard," or "Miami"). Although approximated locations are valuable for assessing recreational effort on a broad or regional scale, their value is diminished when attempting to assess effort over a small scale, such as between two adjacent lease areas. For example, the default LPIS-assigned coordinates to trips testified to have occurred on

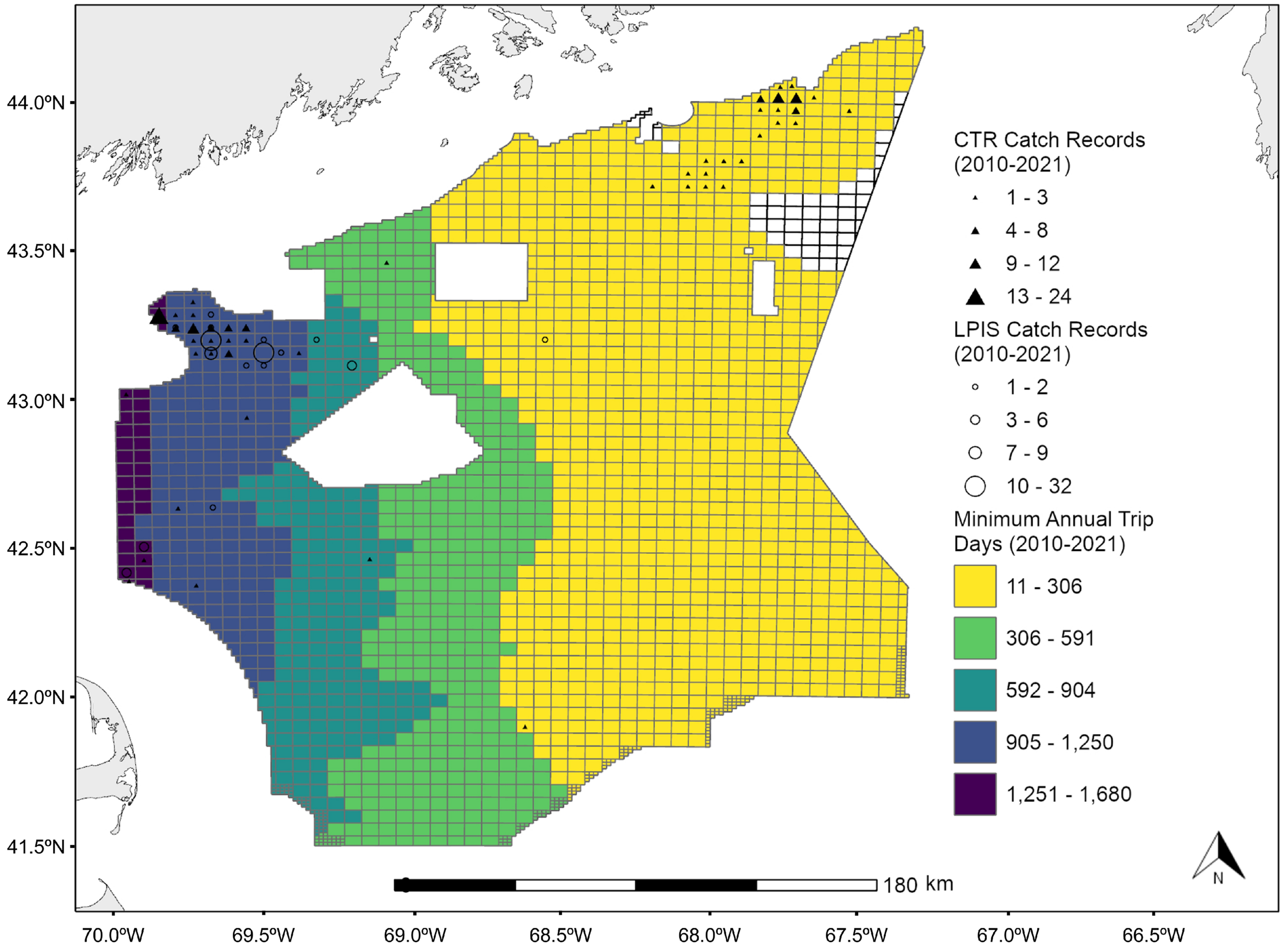

FIGURE 7 | Spatial comparison of recreational fishing effort for highly migratory species throughout the Gulf of Maine Draft Call Area (DCA) during 2010–2021. The number of Large Pelagics Intercept Survey (LPIS) and cooperative tag, release, or recapture (CTR) catch records are plotted in the cell in which they occurred. Cells are color coded based on the cumulative number of fishing days respondents to the online survey testified to fishing within the DCA based on polygons drawn in response to parent question 5. Blank cells represent areas with no effort.

Coxes Ledge, a large complex bottom habitat in southern New England whose boundaries extend throughout two lease areas (OCS-A-0486 and 0517; Figure S1) as well into areas outside of any lease area, fall within OCS-A 0517. Thus, any LPIS trip testified to have occurred on "Coxes Ledge" (without explicit mention of exact geographic coordinates) was assigned to have occurred in this one lease area, even though it could have occurred in OCS-A-0486 or completely outside the boundary of any lease area. Furthermore, because the LPIS collected location data to the nearest minute of latitude and longitude, a resolution three to four times coarser than that of individual cells in the OCS grid, it is possible that effort may have been over or underestimated in some grid cells that were respectively aligned or unaligned with the degree minute spatial grid. This scenario may be one reason why the LPIS identified effort across comparatively fewer cells within BOEM lease areas. Collectively, these shortcomings accentuate the need for monitoring platforms that allow for the collection of more accurate and precise data on the location of fishing effort (e.g., decimal degrees or degrees minutes seconds), particularly in areas with numerous adjacent offshore wind leases that are simultaneously under construction or in operation.

Although the intent of this study was to demonstrate how LPIS and CTR data can be used qualitatively to document the spatial extent of baseline recreational fishing effort for HMS, there is opportunity to analyze these time series quantitatively to assess temporal shifts in fishing effort over time and in relation to individual species, regions, and external factors. Recently, Crear et al. (2023) aggregated LPIS catch data over a 0.25° grid and used spatiotemporal models to examine shifts in the location of HMS catch from 2002 to 2019. Results indicated that significant northward latitudinal shifts in the location of catch have occurred for numerous species correlated with increasing sea surface temperatures throughout the northeast US region. Temporal shifts in the timing of catch during the survey period (June to October) were also identified for numerous species, where the predicted day of the first 25% of catch occurred earlier in more recent years of the time series because of the presence of warmer water earlier in the fishing season. CTR records have also been used to document northward shifts in tiger shark (*Galeocerdo cuvier*) distribution in response to sea surface temperature (Hammerschlag et al. 2022) and could be analyzed across more HMS to investigate shifts in the location where individual species were tagged or recaptured over time. In the context of offshore wind, the ability of the LPIS and CTR records to identify climate-induced shifts in regional species distribution and fishing effort is particularly valuable given the need to discriminate between environmental (climate) and offshore wind-related impacts in fisheries monitoring (Hogan et al. 2023). As LPIS and CTR records become available during years of large-scale offshore wind farm construction and operation, additional efforts will be required to evaluate the extent to which these data can be used to identify changes in the location of effort because of offshore wind activities while also accounting for climate effects.

The ability to monitor impacts to recreational fishing from offshore wind could be enhanced with techniques or technologies that permit the collection of high-resolution effort data over small spatial extents, such as within or around active offshore wind projects. Smartphones may hold great value for monitoring both the location and magnitude of effort given their ability to relay information on the geographic location of the user (e.g., DePiper et al. 2023) and the growing number of applications built to monitor catch (reviewed by Venturelli, Hyder, and Skov 2017; Cooke et al. 2021). However, their utility is contingent upon the willingness of recreational fishermen to use applications and consistently report their location and catch, both of which have been identified as limitations of smartphone-derived effort metrics (Midway et al. 2020; Johnston et al. 2022). Systematic visual surveys of fishing effort in and around offshore wind areas using time lapse photography (Signaroli, Lana, and Alós 2024), aerial surveys (Ma et al. 2018), or drone surveys (Dainys et al. 2022) may also be effective monitoring platforms if conducted over all stages of offshore wind project activities (e.g., preconstruction, construction, and operations). However, as demonstrated by this study, the use of multiple, complementary monitoring methods will likely yield the most accurate and comprehensive information on interactions between recreational fishing and offshore wind activities and will also provide increased opportunity for data validation through comparison of trends identified by each method (Ma et al. 2018).

5 | Conclusions

The recreational fishery for HMS in the US Atlantic, Gulf of Mexico, and Caribbean occurs in numerous locations where offshore wind activity is proposed, planned, or underway, yet there has been little attention paid to identifying and monitoring potential interactions between the industries. We demonstrate how fisheries-dependent data from a federal fisheries survey (LPIS), cooperative tagging programs, and the direct survey of recreational fishermen can be used independently and synergistically to document the spatial and temporal extent of recreational fishing effort for HMS over vast regions and in relation to existing offshore wind lease or planning areas. Off the northeast US from Virginia to Maine, the spatially linked effort data collected by the LPIS provided the foundation for documenting baseline levels of recreational fishing effort. However, analysis of CTR records and testimonials from recreational fishermen revealed additional effort in locations not captured by the LPIS, thereby accentuating the value in using multiple data types or scientific approaches to achieve the most comprehensive characterization of fishing effort. Outside of the LPIS region or in states where its coverage is only partial, CTR records and directed surveys of regional effort are of heightened value for assessing historical levels of effort, and in many cases may be one of the only available sources to estimate recreational fishing effort. Given their long time series, both the LPIS and CTR records hold value as the basis for long-term monitoring platforms, but improvements should be made to increase accuracy of reported location of effort. Additional techniques and technologies should be implemented and used in concert with existing fisheries-dependent time series data to achieve a comprehensive assessment of offshore wind impacts on the recreational HMS fishery and to inform marine spatial planning in regions into which offshore wind energy development may be expanded.

Author Contributions

JK, MD, and ESO designed the study. ESO, CMT, PC, and WM provided cooperative tagging data from their respective programs. JK, MD, RK, CC, and EK performed the analyses. JK composed the manuscript with assistance from MD and ESO. All authors reviewed and provided editorial comments.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data from the cooperative tagging programs may be available upon reasonable request to the tagging program. The Large Pelagics Survey data used in this study are publicly available at http://fisheries.noaa.gov/recreational-fishing-data/recreational-fishing-data-downloads.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.