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Increase in Dolphinfish (*Coryphaena hippurus*) Fishing Success Off the North Coast of Puerto Rico during Hurricane *Leslie*

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ABSTRACT—Documenting how storms and environmental variability affect the population dynamics, trends, and abundance of dolphinfish (*Coryphaena hippurus*) on short temporal scales is important for improving dolphinfish resource monitoring, conservation, and management. Here, a multifaceted technique was used to document an abrupt increase in fishing success among small-scale fishing sectors off the north coast of Puerto Rico during the 2018 Hurricane *Leslie* event. Seven datasets were used to document this event, and each provided substantiating information, but the combination of vessel catch and effort and seven-day averages of floating-algae density (FD), derived from the satellite-based alternative floating algae index (AFAI) imagery, present the newest technique to monitor dolphinfish fishing success on short and near-real time scales. Results revealed vessel effort and FD co-occurrence, with several vessel tracks within FD coverage of .01%–0.4%. Catch records from outings confirmed landings of dolphinfish from *Sargassum* and during the episode, 87% of total dolphinfish catch occurred at *Sargassum* habitat, with the remaining associated with nearby fish aggregating devices (FADs). Scuba visual census and fish tracking provided additional evidence of dolphinfish abundance and movements associated with *Sargassum* and nearby FADs. The combination of these methods provided a new technique to support insight into documenting changes in fishing success for dolphinfish, a key pelagic fishery. Expanding the spatiotemporal coverage of these methods could lead to the underpinnings of robust dolphinfish (and other pelagic fish, e.g., tuna and billfish) resource monitoring, improving data collection, and enhancing regulatory and data reporting compliance among small-scale fisheries.

Weather systems have been found to cause economic loss due to equipment destruction (Buck 2005; Solis et al. 2013) and loss of time at sea (Agar et al. 2020) to commercial and recreational fisheries throughout the world. Hurricanes can be particularly disruptive by destroying maritime infrastructure (e.g., entire fleets, docks, marinas, boat ramps, and ports) (Ingles 2008) leading to a decrease in revenue generated by fisheries where storm impacts occur. For example, the commercial grouper industry in the Gulf of Mexico experienced

an estimated \$927,000 USD immediate loss of revenue between 2005 and 2009 due to hurricanes (Solis et al. 2013). In Puerto Rico and the U.S. Virgin Islands, Hurricanes *Irma* and *Maria* caused an estimated loss of \$17.8 USD million, excluding post-harvest impacts, to small-scale fisheries (SSFs: recreational, charter, and artisanal) around Puerto Rico (Agar et al. 2020).

Coastal marine animals and habitats (e.g., salt marshes, mangroves, coral reefs) can also suffer impacts from large flooding events that cause excessive

inundation of estuarine nurseries (Paerl et al. 2001) as well as powerful currents that have been known to carry fish away from their natal habitat as well as destroy reef structures (Adams 2001). However, storms are natural processes that help to maintain species diversity, abundance, and biomass in coastal habitats. For example, studies suggest an enhanced abundance of marine species following hurricane events, such as plankton and fish abundance within Chesapeake Bay following Hurricane *Isabel* in 2003 (Roman et al. 2005). Following Hurricanes *Irma* and *Maria*, *Gnathia marleyi*, a marine isopod, near Puerto Rico and the U. S. Virgin Islands, experienced an increase in genetic diversity through greater dispersal and gene flow (Pagán et al. 2020). For marine sea turtles, Dubois et al. (2020) found that years with high numbers of hurricanes corresponded to shorter dispersal distance for hatchlings within the first 6 months of life. Documenting examples of how storms and environmental variability affect the population dynamics, trends, and abundance of marine species is important to improve conservation management and resource monitoring. Yet, there are few examples of how hurricanes or changes in environmental factors over short-time frames impact pelagic finfish species such as dolphinfish (*Corphyaena hippurus*). Indeed, there are examples that document changes in large-scale movement trends in their preferred offshore habitat, *Sargassum* (Wang and Hu 2016; Wang et al. 2019; Johns et al. 2020). However, trends in movements of this habitat and its effects on the population dynamics of dolphinfish are lacking, information that can be useful for establishing more dynamic pelagic resource data collection, compliance, and management strategies for both the species and small-scale pelagic fisheries.

Geographic Information Systems (GIS) proves to be a useful tool in predicting the outcome of significant storms on communities (Taramelli et al. 2010) as well as measuring the overall aftermath in relation to both urban development and natural ecosystems (Rifai et al. 2021). Remote sensing has also been used to determine ecosystem disturbances as a result of hurricane damage. For example, Sentinel-2 and Landsat-8 multispectral data were used to assess the aftermath of Hurricane *Maria* in 2017 on the vegetation of Puerto Rico and Dominica (Hu and Smith 2018). Another instance of the utilization of remote sensing to assess forest damage is noted in Wang et al. (2010), who used

moderate resolution imaging spectroradiometer (MODIS) to evaluate the effects of Hurricane *Katrina* on the associated impacted land region. Conversely, there is a lack of methodology and subsequent information to assess the effects of major storms on pelagic ecosystems including the distribution and abundance of *Sargassum* and finfish species that utilize it for habitat (e.g., dolphinfish, yellowfin tuna (*Thunnus albacares*), blue marlin (*Makaira nigricans*), and wahoo (*Acanthocybium solandri*). In the context of SSFs, the ability to evaluate and even predict episodes of changes in the spatio-temporal distribution of *Sargassum* and pelagic fish abundance can help resource managers assess increases or decreases in fishing effort and catch and enforce compliance (check bag limits and minimum sizes) and monitoring (catch records) relative to state and regional fishing regulations.

Over the past decade, given improvements in remote sensing technologies, near and real-time data information systems, recreational and artisanal sectors have become more attune to fish predicting and forecasting technology (e.g., FishTrack, SiriusXM Marine, ROFFS, and Hilton Fish Forecasting) that highlight the occurrence of environmental attributes such as chlorophyll-a, sea surface temperatures, salinities, and sea level pressures, to predict the abundance of key recreationally and commercially important pelagic fish (e.g., dolphinfish, yellowfin tuna, blue marlin, and wahoo) at sea (Cooke et al. 2021). However, information that confirms the presence of habitat features (e.g., *Sargassum*) and fishing success near to or distant from these features is lacking. While there are many studies that have documented fishing catch and effort by large-scale commercial purse seiners that utilize near or real-time sonar attached to fish aggregating devices (FADs) to investigate school sizes and fish abundance (Lopez et al. 2014; Gershman et al. 2015; Lennert-Cody et al. 2018), similar studies with SSFs have not been explored. This could be due in part to lack of access to vessel monitoring and reliable catch reports from small-scale fishing fleets, lack of fishing vessel-validated remote sensing and environmental data that confirm changes in pelagic habitat occurrence and distribution, and coincidence of overlap with a weather feature (e.g., hurricane) which may induce changes in ocean pelagic habitat and fish distribution and angler fishing success.

The purpose of this study is to present a technique

used to assess an abrupt increase in dolphinfish fishing success and subsequent catch among SSFs sectors off the north coast of Puerto Rico during the Hurricane *Leslie* event. Results are used to discuss how coupling several data collection techniques and methods can aid in gathering data on fishing success before and after changes in distribution of pelagic habitat (e.g., *Sargassum*), which can benefit small-scale fishery success and improve pelagic resource management, data collection, and monitoring on near-real time scales.

MATERIALS AND METHODS

Storm data collection and analysis

Hurricane track data for *Leslie* (active from: September 22, 2018, to October 14, 2018) were obtained from National Oceanic Atmospheric Administration's (NOAA) National Hurricane Center (2020). Storm data were plotted using ArcMap v10.7.1 (ArcMap) and annotated using Photoshop CS4.

Meteorological and Oceanographic Data Collection and Analysis

Meteorological (wind direction and speed at 10-minute intervals) as well as oceanographic data (hourly wave heights, direction and period) were collected from the NOAA's National Data Buoy Center (Station 41053) between September 1, 2018, and November 2, 2018, three weeks before and after the storm event (Weeks 1: 9.1.2018–9.7.2018; 2: 9.8.2018–9.14.2018; 3: 9.15.2018–9.21.2018; 4: 9.22.2018–9.28.2018; 5: 9.29.2018–10.5.2018; 6: 10.6.2018–10.12.2018; 7: 10.13.2018–10.19.2018; 8: 10.20.2018–10.26.2018; 9: 10.27.2018–11.2.2018). Using Microsoft Excel version 2011 (MS Excel), timestamps were converted from coordinated universal time (UTC) to Atlantic standard time (AST) and all datasets were catalogued by week. Hourly descriptive statistics (average and standard deviation) were compiled for meteorological and oceanographic data. Due to island-based diurnal effects on wind patterns along the north coast of Puerto Rico (Jury 2011a), and the close proximity of Station 40153 to the coast (0.4 km offshore), wind strength and direction values are presented as weekly averages that incorporated only midnight to noon for each day throughout the time period. However, for data visualization, all data were converted to natural logarithms, and aggregated into 6 hour means using Google BigQuery (<https://cloud.google.com/bigquery>).

Vessel catch and effort data collection and analysis

Methods were developed to collect daily catch (i.e., landings) and effort data from charter, recreational, and commercial vessels around Puerto Rico (SSFs), with an emphasis on catch and effort adjacent to fish aggregating devices (FADs) deployed in the Puerto Rico FAD system ($n = 10$), using Pelagic Data Systems (PDS) vessel tracking devices (<https://www.pelagicdata.com/details#hardware>). Vessel monitoring began in October 2016, but only catch and effort data from September 1 to November 2, 2018, the time before and after the Hurricane *Leslie* event, were analyzed from all vessels ($n = 10$) and their trips ($n = 89$) in the study region. During this period, only two FADs (FAD F coordinates: 18.583 North; 66.283 West; FAD K: 18.4883 N; 65.6867 W) were active. Catch data were catalogued using MS Excel and aggregated by vessel, trip, and week. Vessel effort was aggregated similarly but data were accessed from the PDS application program interface and plotted using ArcMap. All vessel points over the continental shelf break (< 40 m) were deemed transitory movements between port and offshore fishing grounds and were filtered out of the analysis. Any trips where the vessels indicated they were targeting bottom fish species were also filtered out ($n = 2$). Any dolphinfish tagged and released ($n = 38$) during an outing ($n = 5$) were considered non-landed catch, and were included as catch. Anglers did not report discards other than the aforementioned tag releases.

Analysis, conducted using R version 4.0.3, included a paired t-test to compare FAD and non-FAD associated dolphinfish catch (number of fish landed) by week. In addition, an analysis of variance (ANOVA) of trip success by week, a binary variable defined as a trip that resulted in the catch of at least one dolphinfish or not, was run with individual boat ($n = 10$) and catch categories (none = 0 individuals; low = 1–5; medium = 6–15; or high = > 16) as interaction terms. To examine which weeks were statistically different for trip success, a Tukey's Honestly Significant Difference (Tukey's HSD) test was run. Fishing effort was standardized by the amount of time (in hours) vessels were fishing offshore (equal to or north of 18.49° North or the latitudinal start of offshore fishing grounds) and summed per week for the period. Catch per unit effort for dolphinfish and other additional catch (i.e., yellowfin tuna, blue marlin, wahoo) were standardized per

outing hour by vessel (for outing hours equal to or north of 18.49° North) and summed among vessel outings by week (e.g., dolphinfish weekly CPUE: Amount of dolphinfish catch divided by trip hours per individual vessel outing summed across all vessel outings by week).

Visual census data collection and analysis

In 2016, methods to assess fish presence at three FADs (FAD ID, latitude × longitude, Depth; FAD B, 18.5523 × -65.9834, 402 m; D, 18.5324 × -66.0685, 260 m; F, 18.58333 × -66.28333, 600 m) deployed along the north coast of Puerto Rico were developed. A total of 28, 25-minute, standardized dives were conducted from October 2016 to October 2018. Three divers worked together on each dive; one diver tallied species composition, size, and abundance, another recorded video of marine life present, and a third was the safety diver. The survey protocol included the following steps for each survey: A. Divers entered the water ~50–75 m away and did a quick surface assessment (at 0 m scanning to ~10 m) then swam towards the FAD for three minutes (min) only assessing fish species on the side of the FAD to which divers approached; B. While at the FAD at the surface (0 m), scan to 15 m (the marking at 15 m on the FAD provided the depth gauge), and in every direction surrounding the FAD for three minutes; C. Descend slowly to 15 m while counting intransitant and extrantant species (0 to 15 m scanning out to 25 m) for three minutes; D. At 15 m, scan to 30 m below and out 25 m counting and assessing any fish schools or individuals for six minutes; E. Ascend to surface slowly (15 to 0 m scanning out to 25 m) for three minutes; F. While at the FAD at the surface (0 m), scan to 15 m for three minutes; G. Swim away from the FAD to 50–75 m away (at 0 m scanning to ~10 m) in the opposite direction in which divers originally approached the FAD for three minutes. Using these methods, sampling 0 to 15 m was done twice per survey: once from above and once from below for each side of the FAD. Here, only data on dolphinfish presence and absence during surveys are presented.

Fish tagging data

Conventional dolphinfish tagging data ($n = 392$; 60.87 ± 11.37 cm FL) from the Dolphinfish Research Program™, a volunteer-driven international tagging program for dolphinfish, were acquired from 2015 until 2018 for the north coast of Puerto Rico and the

United States Virgin Islands. Anglers marked dolphinfish with plastic dart tags (Hallprint®, South Australia, Australia; individually numbered external 15.2 cm orange polyethylene streamer) and noted whether releases were near (< 1.6 km) or distant from (> 1.6 km) from FADs deployed in the Puerto Rico and Virgin Islands FAD systems. Anglers also noted whether *Sargassum* was present or absent when fish were tagged and recaptured. All anglers received guidance on tagging procedures which are outlined in Merten et al. (2014). From these releases, 10 dolphinfish (65.65 ± 8.12 cm FL) were recaptured between 2015 and 2018. These fish ranged at liberty from the same day tagged up to 42 days post-release.

Remote sensing data collection and analysis

Seven-day averages of floating-algae density (FD, in terms of percent of algae area cover), derived from satellite-based alternative floating algae index (AFAI) imagery collected by the Moderate Resolution Imaging Spectroradiometer satellite sensors, were acquired for the eastern Caribbean Sea from September 1 to November 2, 2018, from the satellite-based *Sargassum* Watch System (SAWs) (https://optics.marine.usf.edu/cgi-bin/optics_data?roi=ECARIB¤t=1), over the same time-frame as outlined in the catch and effort section above. Raster images (.png) were imported into ArcMap and georeferenced to the extent associated with each file (23.0 N × -75 W by 10 N × -60 W) and then focused on a region of interest around the Greater Antilles (20.0 N × -68 W by 18.5 N × -64.5 W). For each raster, a value of 0.1 indicates 0.1% surface area coverage in that location. The density is calculated using the method described in Wang and Hu (2016). Overlaid on each weekly projection are the heading of surface currents from the Hybrid Coordinate Ocean Model (HYCOM) with Navy Coupled Ocean Data Assimilation (NCODA) Global 1/12 degree analysis (GLBa0.08/expt_91.2) (<https://www.hycom.org/dataserver/gofs-3pt0/analysis>) and resampled for the last day of each weekly time period. The arrowhead of the current vectors depicts direction and vector size and positively corresponds with predicted surface current strength. For Week 8, the week with the highest recorded catch, a composite *Sargassum* distribution map was generated from Sentinel-2 satellite data. The procedure to generate *Sargassum* distribution maps from Sentinel-2 satellite data contains six steps. The procedure is similar to

that for MODIS (Wang and Hu, 2016) but adjusted to remove sensor-specific noise and other artifacts (Wang and Hu 2020). First, Sentinel-2 Level-1 data collected over the study region (20.0 N \times -68 W by 18.5 N \times -64.5 W) from 10/20/2018 to 10/26/2018 were downloaded from the PlanetScope, Inc. (<https://developers.planet.com/docs/data/sentinel211c/>). Second, the Level-1 data were processed using the ACOLITE software (version 20190326) (Vanhellemont and Ruddick 2016) to generate Rayleigh-corrected reflectance (Rrc, unitless), from which floating algae index (FAI) images were generated (Hu, 2009). Third, noise was reduced, and clouds were masked using the procedure described by Wang and Hu (2020). Fourth, after removing noise and clouds in FAI images, *Sargassum* features were extracted based on the FAI spatial contrasts (Wang and Hu 2020). Fifth, for each pixel classified as *Sargassum*, the fractional coverage was calculated through spectral unmixing (Wang and Hu 2020). Lastly, all 10-m pixels were aggregated to 1-km grids, where in each grid the *Sargassum* density (% cover) was calculated as the weighted arithmetic mean from all pixels (Wang and Hu 2016).

Vessel tracking data aggregated by week were overlaid on georeferenced *Sargassum* FD maps to identify the incidence of presence and absence of vessel activity near *Sargassum* features. Matches were defined as any location where vessel tracking data were present over, defined as co-occurrence, or near (within ten kilometers = length or width of one pixel), defined as proximity, colored pixels. One pixel in the AFAI images equals 100 square kilometers. Given the higher resolution nature of the Sentinel-2 images, proximity was equal to the pixel size of one square kilometer. Lastly, the headings of vessel tracks were qualitatively examined relative to HYCOM currents as in general alignment or skewed.

RESULTS

Meteorological and oceanographic data

On September 22, 2018, the low pressure associated with *Leslie* formed 2,777.63 kilometers (km) east-northeast of San Juan, Puerto Rico, and meandered as a weak tropical low and depression until September 26, when *Leslie* was upgraded to a tropical storm (Fig. 1). *Leslie* quickly intensified on September 27 to near hurricane strength and began to slowly move west-southwest toward Puerto Rico for six days undergoing de-

re-intensification. On October 3, *Leslie* strengthened to a hurricane and remained nearly stationary for 24 hours about 1,547.11 km east-northeast of Puerto Rico before slowly moving north for 36 hours. On October 6, the storm headed east but did not accelerate toward the eastern Atlantic Ocean until October 11.

The lowest average wind speeds (9.5 ± 5.5 kilometers per hour (kph)) recorded during the study period were predominately from the south ($154.58^\circ \pm 44.66^\circ$) and occurred during Week 5. Week 5 also had the highest average wave heights (1.99 ± 0.54 meters (m)) and wave period (13.21 ± 2.15 seconds (s)) with swell predominately from the northeast ($25.37^\circ \pm 5.95^\circ$) (Appendix 1). Due to the proximity of *Leslie* to Puerto Rico when the storm formed, storm-associated swell first arrived late on September 22. Due to the storm's persistence northeast of Puerto Rico, wave heights and periods remained elevated until October 12 (Appendix 1). Extended periods of southerly winds occurred five times during the monitoring period, with the longest event lasting eight days which began during Week 5.

Fishery-independent data

Visual census

Standardized scuba dive surveys included linear transects (range: 78.12–266.96 m) to and away from the structures (e.g., FADs, *Sargassum*) or within the open ocean (i.e., epipelagic zone). Overall, 88% of dolphinfish observed during dive surveys occurred from October 10th to October 19th, 2018 (Table 1). Water clarity varied throughout surveys. In October 2018, there were days when the visibility was 30 m. There were also noticeable differences in water stratification during the surveys. The upper water column (0–15 m) was cloudy during spring and summer dives, with a clear layer below. In October 2018, there was no water column stratification, and the visibility was the highest of all the dive surveys.

Remote sensing

Vessel tracking data were overlaid on the MODIS-based *Sargassum* FD maps and 15 co-occurrences and 11 proximity estimates were derived. All matches, however, were confined to offshore areas at least 25 km from shore (Fig. 2). When vessels only operated closer to shore (< 25 km) (Fig. 2, subpanels B and C) no co-occurrences were detected but the extent of several trips were proximal to the lowest detected cell

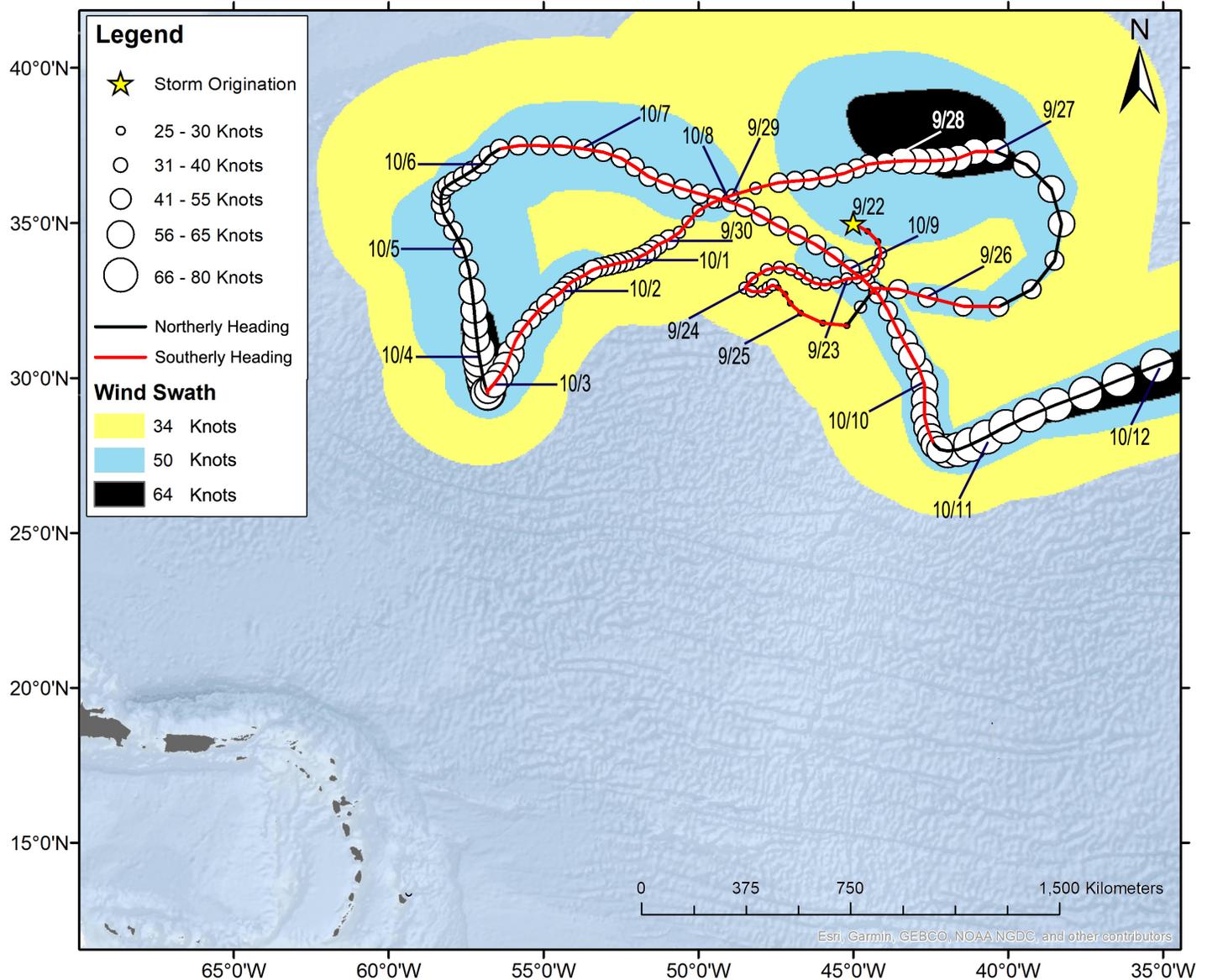


FIG. 1. *Leslie* origination (yellow star) and track from September 22, 2018, until movement toward the eastern Atlantic Ocean on October 12, 2018. Northerly (black line segments) and southerly (red line segments) headings indicate the direction of movement and the extent of storm (>34 knots: light yellow), tropical storm (> 50 knots), and hurricane force (> 64 knots: black) winds. Hurricane force winds formed before 10/3/2018 and continued until the middle of 10/4/2018 as the storm was nearly stationary at its closest approach to the northeastern Caribbean Sea.

coverage. At these locations, tracks indicated horizontal movement aligned with HYCOM vectors. Similarly, there were no co-occurrences detected for two consecutive weeks (Fig. 2, subpanels F and G) yet vessels did move offshore into cell coverage with some tracks indicating alignment with HYCOM vectors. For Weeks 2–5, 8, and 9, portions of vessel tracks were in alignment with HYCOM vectors. During Weeks 1, 6, and 7, the lowest alignment with HYCOM vectors was observed. During Weeks 1–3, the highest FD coverage

was detected proximal to vessel tracks which showed horizontal alignment with current vectors.

A Sentinel-2 *Sargassum* FD map (Week 8) resulted in vessel-sargassum matches in areas close to shore (< 8 to 16 km) (Fig. 3). For this same week the MODIS-based *Sargassum* FD map (Fig. 2, subpanel H) did not produce any co-occurrences or proximity matches. The Sentinel-2 map resulted in four co-occurrences and two proximity estimates with vessel tracking data close to shore.

TABLE 1. Event details associated with standardized scuba dive surveys of fish aggregating device (FAD) or *Sargassum* lines from October, 2016, to October, 2018. ^x = Dive conducted at a location where a FAD was no longer present; Sar = Sargassum line.

Dives (#)	Date	FAD or Dive Location	Start Times	Average Distance (m)	Dolphinfish (#)
3	10/24/2016	A; B; D	845; 1040; 1212	125.89	0
3	10/26/2016	A; B; D	851; 1036; 1215	173.84	0
3	10/27/2016	A; B; D	847; 1033; 1208	133.39	0
3	10/28/2016	A; B; D	855; 1048; 1213	212.68	0
2	4/20/2017	D; C	823; 1100	194.57	0
2	4/21/2017	C; D	825; 1154	216.34	0
2	8/14/2017	B; F	1015; 1158	111.57	0; 10
3	10/10/2018	B ^x ; D ^x ; F	923; 1059; 1245	266.96	22; 0; 3
3	10/11/2018	D ^x ; Sar; F	749; 959; 1119	123.46	0; 0; 15
3	10/12/2018	F; Sar; D ^x	830; 1105; 1310	196.38	25; 1; 0
1	10/19/2018	F	820	78.12	1

The *Sargassum* FD maps indicated more algae coverage in the first four weeks followed by a lower amount detected during Week 5. In Weeks 6 and 7, the *Sargassum* FD maps indicated very little algae coverage. During Weeks 8 and 9, a greater quantity of algae was detected, similar to the coverage observed in Week 5.

Fishery-dependent data

Vessel catch and effort

During the period, ten vessels embarked on 89 fishing trips and recorded catch of 700 dolphinfish (Table 2). By boat, there were significant differences in the amount of catch per trip (chi-square: $P < 0.001$). In addition, pairwise comparisons revealed significant differences in trip success by week (Tukey HSD: $P < 0.001$). From Week 1 through Week 4, vessels embarked on 42 trips of which 18 resulted in no catch. There were no statistical differences in catch success between Weeks 1 and 3 ($P = 0.004$), Weeks 2 and 4 ($P = 0.013$), and Weeks 3 and 4 ($P = 0.066$). From Weeks 5 through 9, of 47 trips, only three resulted in no catch. There were significant differences in trip success when comparing Weeks 1 through 4 to Weeks 5 through 9 (Tukey HSD: $P < 0.001$). The incidence of vessel catch per trip was highest in Week 5 and just over half (50.5%) of recorded dolphinfish catch occurred in Week 5 and Week 8. Furthermore, total catch per trip hours summed by week

for all vessels for dolphinfish and other pelagic fish (i.e., yellowfin tuna, blue marlin, and wahoo) increased from less than five during Weeks 1 and 2 to above 20 during Week 5, and remained higher than 10 for the remainder of the period (Fig. 4). For vessels that embarked on trips from Weeks 5 to 9, each vessel recorded their highest catch per trip. Pairwise catch success comparisons were not significantly different for Week 5 through 9. Overall, significantly more dolphinfish (85.3%) were caught away from and unassociated with moored FADs during the period (T-Test: $P < 0.05$).

In terms of vessel effort, the total number of vessel trips per week was highest for Week 1 ($n = 15$) and lowest for Week 5 ($n = 5$) (Table 2; Fig. 4). For vessel hours by latitude, effort gradually shifted offshore through the period with weekly latitudinal averages lowest for Weeks 2 through 4, and highest for Weeks 5 through 9 (Fig. 5). However, Week 1 was similar to Week 6. Across all weeks, vessel effort was aggregated the most near 18.58° North (N), followed by 18.49° N, 18.51° N, then in two to four degree increments beginning at 18.62° N (Fig. 5).

Conventional tagging data

In total, 23% of all dolphinfish tagged occurred during the time period examined. Furthermore, October 2018, had the highest number of dolphinfish tag deployments (15%; $n = 59$) when compared to all other months from 2015 through 2018. In addition, the ma-

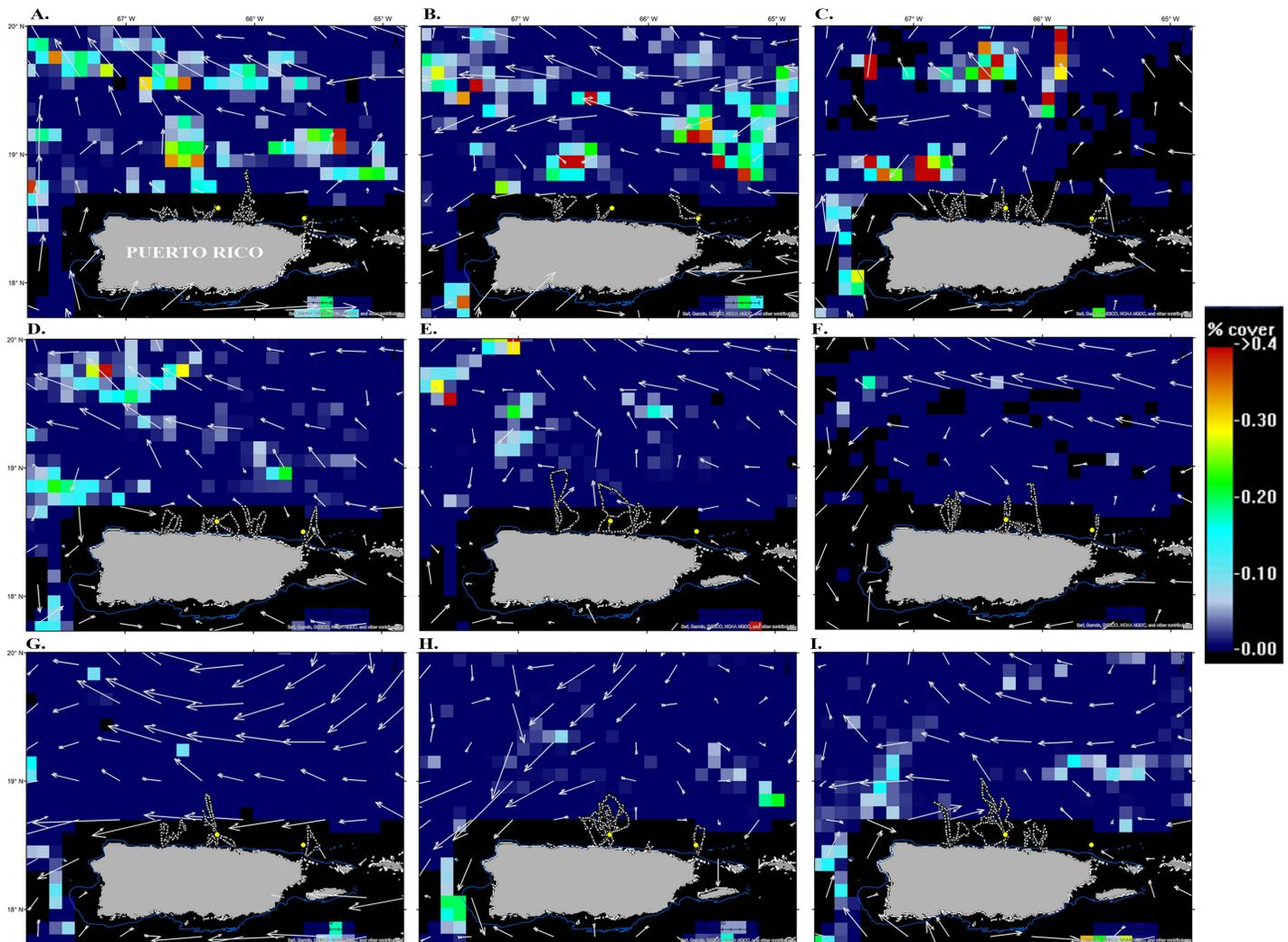


FIG. 2. Weekly vessel tracking points (white dots) and seven-day average of floating-algae density (FD) (derived from MODIS observations) are displayed along the north coast of Puerto Rico over 9 weeks from (A.) September 1, 2018, to (I.) November 2, 2018. The locations of active fish aggregating devices (FADs) deployed in the Puerto Rico FAD system (yellow ovals) along with the 40 m depth contour (blue line) are shown. Hybrid Coordinate Ocean Model (HYCOM) with Navy Coupled Ocean Data Assimilation (NCODA) Global 1/12 degree analysis current vectors (gray arrows) are displayed for the last day of each weekly time period. The arrow head of the current vectors depicts direction and vector size and positively correspond with predicted surface current strength. Please refer to the text in the paper for the exact dates of the weekly time periods. FD and HYCOM data were acquired from the satellite-based *Sargassum* Watch System (SaWS).

majority of dolphinfish recoveries (60%; $n = 6$) occurred during September and October 2018. Five of those were tagged and released at FADs with *Sargassum* present; one was tagged at a FAD without *Sargassum* present. Four were recovered unassociated with a FAD of which two were reported as caught near *Sargassum*. When these positions are compared with the Sentinel-2 FD map, recovery locations were near detected algae cell coverage. The other two were recovered at FADs (Table 3).

DISCUSSION

The combination of the methods and datasets used in this study allowed for fine-scale dynamics in pelagic habitat, dolphinfish and additional catch, and fishing sector (artisanal, charter, and recreational) activity to be revealed before, during, and after Hurricane *Leslie* impacted the north coast of Puerto Rico. While *Leslie*'s track was unusual, given that the storm remained within Puerto Rico's swell window for 20 days, the occur-

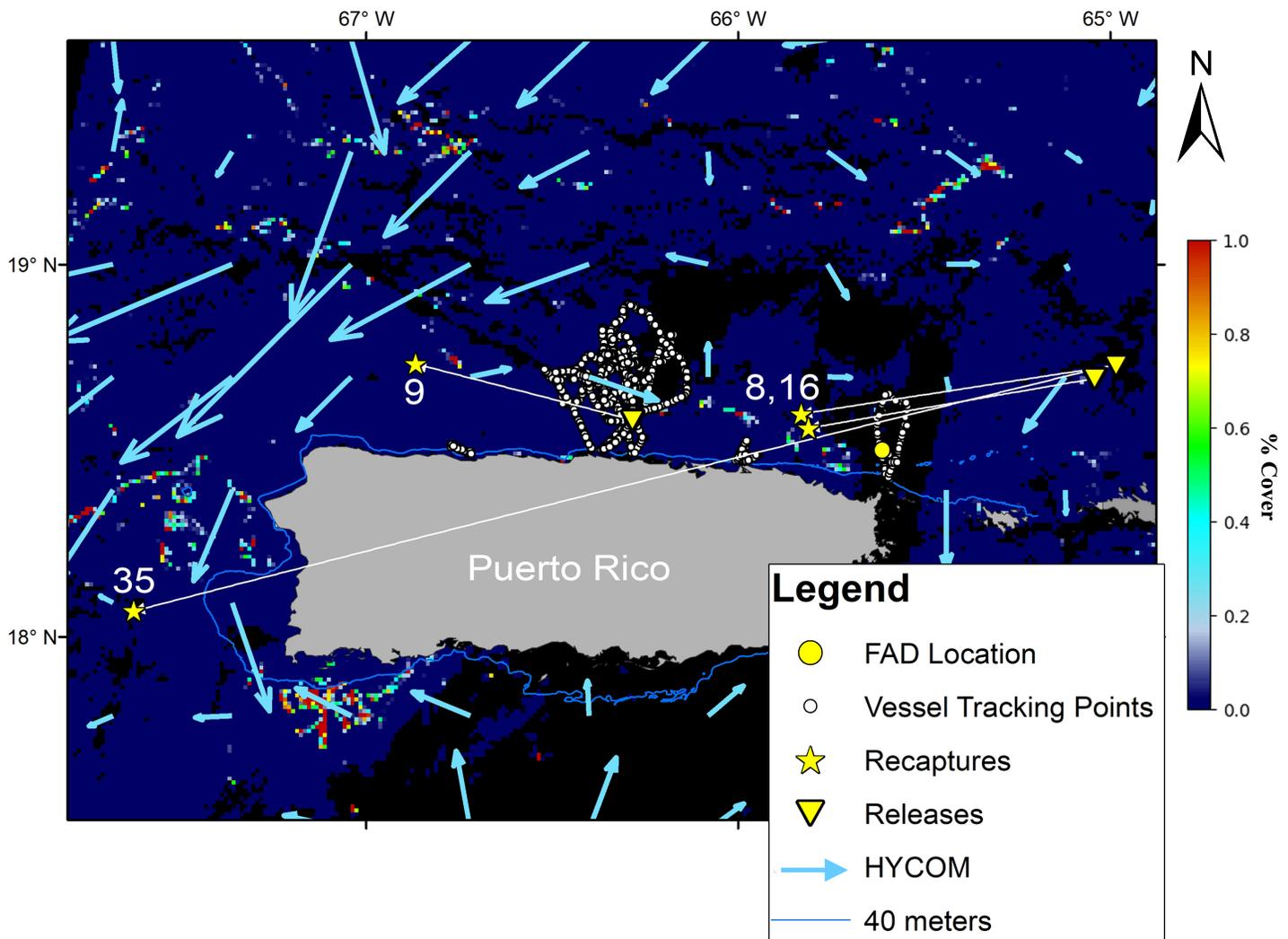


FIG. 3. Composite *Sargassum* density map generated from Sentinel-2 observations with vessel tracking points (white dots) from October 20, 2018, to October 26, 2018. The locations of active fish aggregating devices (FADs) deployed in the Puerto Rico FAD system (yellow ovals) and 40-m depth contour (blue line) are shown. Dolphin-fish tagging sites (yellow triangles) and recapture locations (yellow stars) that correspond with this week are included along with days at liberty. Hybrid Coordinate Ocean Model (HYCOM) with Navy Coupled Ocean Data Assimilation (NCODA) Global 1/12 degree analysis current vectors (blue arrows) are displayed for the last day of the time period. The arrowhead of the current vectors depicts direction and vector size and positively corresponds with predicted surface current strength.

rence of similar storm tracks, persistence of eddies or other wind episodes, when combined with the methods documented through this study, can serve as the underpinnings for dynamically assessing offshore resources and the interplay between SSF sectors in a fishery management and data collection context. Below we discuss caveats and additional methods that can be explored to improve dolphin-fish, and pelagic fishery monitoring, during similar episodes

Meteorological and oceanographic data

In a SSF context throughout the Caribbean Sea and

tropical Atlantic, the extraordinary yearly and recurring accumulations of *Sargassum* since 2011 (Wang et al. 2019; Johns et al. 2020) are opportunities to investigate how these episodes impact fishing success. However, there is little research or examples of how SSFs are affected by these events. We used the anomalous Hurricane *Leslie* episode to pinpoint a period to investigate how SSFs were affected by an influx in accumulation of *Sargassum* combined with optimal fishing conditions (i.e., minimal sea state).

Hurricane *Leslie's* storm track was unusual given that it lingered northeast of Puerto Rico for nearly three

TABLE 2. Fishing vessel trips and catch matrix for fish aggregating device (FAD: F) associated or non-FAD (X) associated landings for the top four pelagic species (#1 (dolphinfish (*Coryphaena hippurus*)), #2 (yellowfin tuna (*Thunnus albacares*)), #3 (blue marlin (*Makaira nigricans*)), #4 (wahoo (*Acanthocybium solandri*)) caught by week from September 1, 2018, to November 2, 2018. Total trips (T) taken and overall catch (C) is included by week and vessel. Boat ID bold: commercial; italics: charter; normal: recreational). $\sum T + C$ = summation of trips and catch. Summation of catch includes species #1, #2, #3, then #4; $\sum F$ = summation of fad associated catch; $\sum X$ = summation of non-fad associated catch. F and X are provided relative to species #1–#4.

Boat ID	Week 1		Week 2		Week 3		Week 4		Week 5		Week 6		Week 7		Week 8		Week 9		Total	
	T	C	T	C	T	C	T	C	T	C	T	C	T	C	T	C	T	C	T	C
2830	F 3	0,5	3	1,9	2	0	2	18,0	1	0	1	1,1,1	3	28	3	20	0	0	17	49,15,1
X	0	0	0	0	0,0,1	2,0,1	30	0	0	43	120	0	0	0	0	0	0	0	157,0,2	
871	F 0	0	0	0	0	0	0	0	3	10	0	0	4	0	0	0	0	0	14	
X	0	0	0	0	0	0	1	13	26	0	0	0	0	0	0	0	0	0	39	
2017	F 0	0	0	0	0	0	0	0	0	0	0	0	8	1	0	0	1	0	8	
X	0	0	0	0	0	0	0	0	0	0	0	0	0	0	36	0	1	34,1	70,1	
2286	F 0	0	0	0	1	14	0	1	6,1	0	0	0	0	0	0	0	1	0	20,1	
X	0	0	0	0	16	0	1	111,1	0,1	0	0	0	0	0	0	0	1	30,0,0,5	157,2,0,5	
2287	F 3	0	0	0	3	0	2	0	0	0	1	0	0	0	1	0	4	0	14	
X	0	0	0	0	0,0,1	2,1	0	2,1	8,0,1	0	0	0	0	0	0	0	2,0,0,1	0	12,1,2,1	
3177	F 2	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	1	0	0	
X	0,1	0	0	0	0	0	0	0	22	1	1	0	0	0	2,0,0,1	0	1	1,0,0,1	26,1,0,2	
1076	F 1	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	
X	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	
1135	X 1	0	1	0,1	0	0	1	0,1	0	0	1	6,2,0,1	1	1	2	19	0	0	7	26,4,0,1
865	X 0	0	0	0	1	9,1,0,1	1	0,1	1	11	1	0	2	19	1	0	2	5	9	44,2,0,1
1968	X 5	11,0,1	3	11,0,2	3	12,0,1	1	0	0	0	4	25,0,3	1	4,0,1	0	0	2	11	19	74,0,8
$\sum T+C$	15	14,6,1	8	13,10,2	10	38,1,3,1	9	36,3,1	5	187,1	13	83,4,3,1	9	50,1,2	9	197,0,0,1	11	83,1,0,7	89	700,26,12,10
$\sum F$	2,5	1,9	0	32,0,1	0	16,2,1	21,1,1	20	0	92,17,3,0										
$\sum X$	12,1,1	12,1,2	37,1,3,1	4,3	187,1	67,2,2,1	29,0,1	177,0,0,1	83,1,0,7	608,9,9,10										

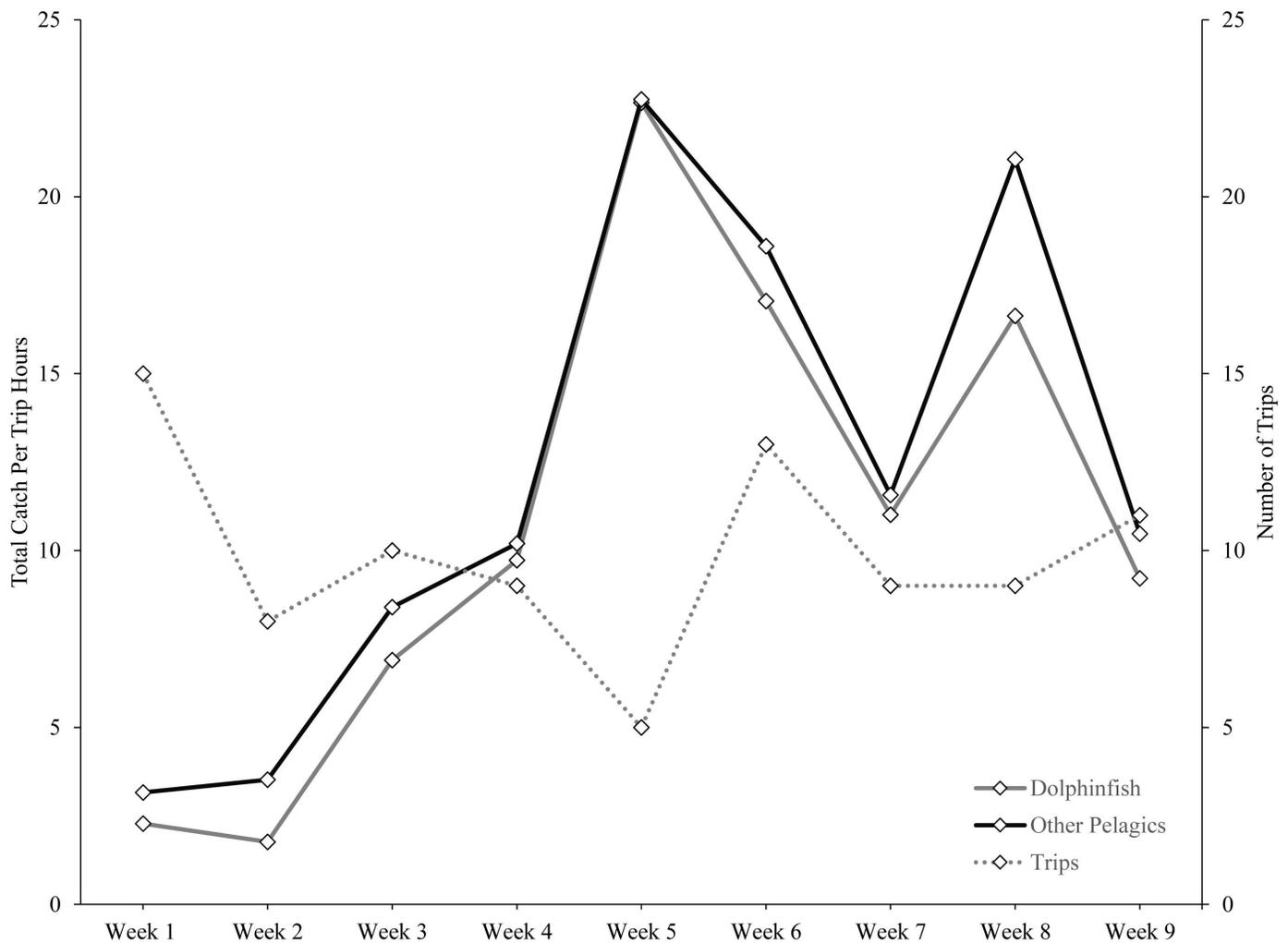


FIG. 4. Total catch per trip hours for dolphinfish (grey line) and other pelagics (yellowfin tuna, blue marlin, wahoo) by week monitored off the north coast of Puerto Rico from September 1, 2018, to November 2, 2018. The total number of trips per week (dotted grey line) is also included.

weeks within 1,550–2,500 kilometers, a proximity that imparted a major influence on the island's north coast winds and swell pattern. Given the position of the storm, it imparted consistent southerly winds along the north coast of Puerto Rico; when combined with longer interval northeast swell, this made for a calm sea state conducive for offshore fishing. In addition, prolonged periods of south to southeasterly winds off the north coast of Puerto Rico may promote northward Ekman transport and cooler SSTs which may support higher fishery productivity (Jury 2011b). Future studies should incorporate additional data collection on sea surface temperature during time of catch for participating vessels as well as assimilate remote sensing SST data for comparison to *in situ* measurements. Similarly, data on chlorophyll *a* should be collected and incorporated into the analysis, which could be compared to *in situ*

measurements of turbidity from underwater time lapse cameras mounted to fish aggregating devices off San Juan, Puerto Rico. Incorporating SSTs, Chlorophyll *a*, and turbidity information can be used in conjunction with the additional datasets and methods discussed below to quantitatively assess SSF productivity.

Fishery-independent data

Visual census

Visual census surveys were good for identifying intransigent and extrantant species (fish close to the FADs or structures) but not for circumnavigant species (fish patrolling within 500–1,000 m around the FADs or structures), similar to results from other visual census work in the pelagic environment (Gaertner et al. 2008; Taquet et al. 2008). Despite this caveat, as noted by Gaertner et al. 2008, visual census surveys can

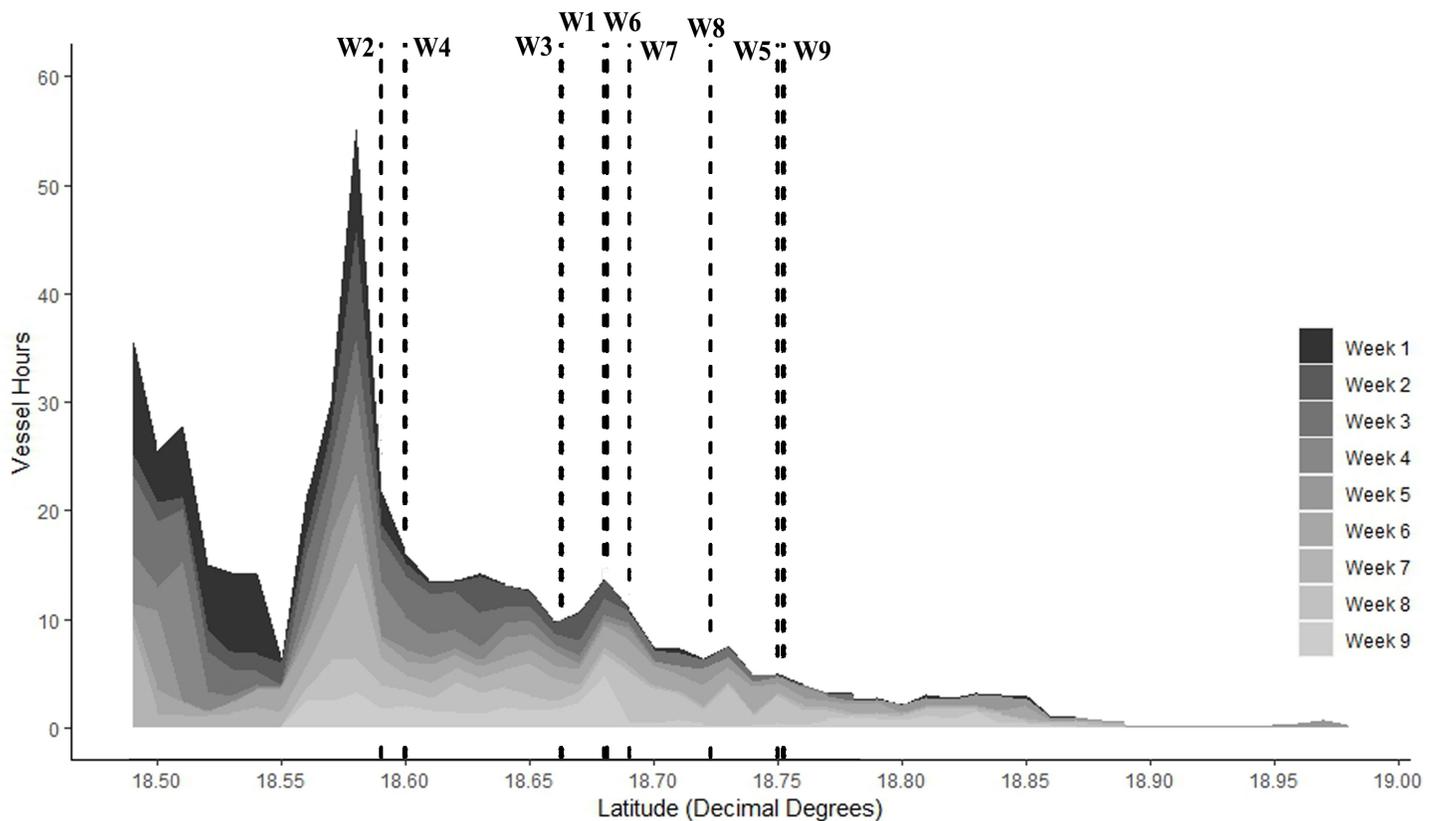


FIG. 5. Vessel hours by latitude (Decimal Degrees North) categorized by week monitored off the north coast of Puerto Rico from September 1, 2018, to November 2, 2018. A total of ten vessels were monitored. Dashed black lines equal weekly vessel hour latitudinal means.

provide reproducible fishery-independent information to monitor pelagic fish communities at FADs or Sargassum habitat. Including the use of underwater cameras that record time-lapse imagery could augment monitoring of offshore marine species and could produce large point estimates of species diversity and abundance. While cameras could eliminate the negative effect that divers may have on large and elusive pelagic predators, cameras are limited in terms of field of view, angle, and depth perception, especially given poor water clarity which was observed during spring and summer dives. As mentioned above, camera data could also be used to assess the turbidity of water masses, which could be coupled with additional remote sensing data to augment the analysis of coastal pelagic fisheries.

Remote sensing

Due to the coarse resolution, there are often data gaps in nearshore waters (out ~24 miles) in the MODIS-based *Sargassum* FD maps available from SaWS, which lead to no matches of vessels at any habitat features nearshore. In several of the weeks examined, vessel headings in nearshore waters indicated movement

along currents, *Sargassum* lines, and frontal boundaries, which are headings parallel to the predominate east-northeast trade winds in this region. To identify vessel use of *Sargassum* habitat nearshore, the use of the finer-resolution Sentinel-2 imagery is a promising approach. For the week examined with Sentinel-2 imagery (Week 8), several co-occurrences and proximity estimates were detected. Vessel catch and effort reports confirmed the presence of *Sargassum* habitat and *Sargassum* associated fish catch. Given that many SSF vessels operate more nearshore than offshore in this region, using higher resolution Sentinel-2 imagery to pinpoint habitat use is a priority, but there are other remote sensing data products that can potentially be used in the future. Wang and Hu (2021) and Zhang et al. (2022) showed success in mapping *Sargassum* in nearshore waters with other high-resolution images from Landsat-8 and PlanetScope/Dove sensors. Given the extensive spatio-temporal nearshore coverage of Sentinel-2, Landsat-8, and PlanetScope/Dove imagery, coupling vessel tracking data and catch reports with *Sargassum* FD maps produced with these high-resolution images could be very helpful to improve monitoring of off-

TABLE 3. Dolphinfish conventional movement records for dolphinfish released in the study area from 2015 through 2018. Distances correspond to minimum straight-line distances. The nearest tag and final locations are provided. DAL: Days at liberty; PR: Puerto Rico; USVI: United States Virgin Islands; FAD = Fish Aggregating Device. Distance (km); Rate (km/day). DR: Dominican Republic.

Tag #	Tagged (mm. dd.yyyy)	Recaptured (mm.dd.yyyy)	DAL	Distance	Rate	Tagging Site	Final Location
25713	8/10/2017	8/11/2017	1	14.17	14.17	USVI FAD	USVI FAD
25718	8/9/2017	9/20/2017	42	589.66	14.03	USVI FAD	Puerto Plata, DR
34878	8/11/2018	8/11/2018	0	0.003	0.003	USVI FAD	USVI FAD
34878	8/11/2018	8/12/2018	1	0.003	0.003	USVI FAD	USVI FAD
34942	9/17/2018	9/17/2018	0	0	0	USVI FAD	USVI FAD
36043	9/18/2018	10/23/2018	35	288.22	8.23	USVI FAD	Mona Passage, PR
36046	10/8/2018	10/24/2018	16	131.93	8.24	USVI FAD	North of Loiza, PR
34400	10/10/2018	10/14/2018	4	0.08	0.02	FAD F	FAD F
34379	10/12/2018	10/21/2018	9	84.20	9.35	FAD F	North of Camuy, PR
36058	10/16/2018	10/24/2018	8	82.42	10.30	USVI FAD	North of Loiza, PR

shore fishing resources to pinpoint periods of low and high abundance of migratory coastal pelagics and SSFs dynamics.

For outings offshore, co-occurrence and proximity matches occurred in all but two of the weeks examined, showing the utility of MODIS-based *Sargassum* FD maps available from SaWS. The benefit of using this product to identify habitat features is the ease of data access and data coupling. The *Sargassum* FD maps can be downloaded and imported into any geospatial software to compare and contrast vessel habitat use. This can provide a rapid assessment of offshore habitat use and prompt further analyses with higher resolution data. When coupled with local and regional weather data, additional insights can be gleaned from the analysis. For example, beginning in Week 5, an extended period of southerly winds and smooth seas occurred off the north coast of Puerto Rico. From Week 5 through Week 9, this weather pattern led many of the monitored vessels to extend their outings further offshore into areas conducive for matching with MODIS-based *Sargassum* FD maps. However, if vessels do not extend their range further offshore, analyses should focus more on Sentinel-2 data than SaWS.

Fishery-dependent data

Vessel catch and effort

With the advent of low-cost technology, and ease of installation associated with the PDS tracking devices,

this study demonstrated the benefits of utilizing volunteer vessel catch and effort data among SSFs due to the high level of details it can provide. Studies in other parts of the world are utilizing similar technology and methods to study the distribution of anchored FADs (Widyatmoko et al. 2021) and to determine fleet and fisher characteristics at different landing sites on a national scale (Metcalf et al. 2016). As with those other studies, due to a limited number of tracking devices available, devices are only provided to vessels that volunteer to participate so results do not encompass the entire fleet. In addition, tracking devices fail, so there are staggered start times and dates when vessels begin in the program. During this study, however, none of the devices failed and all maintained strong signals during the period examined. Despite these drawbacks, boats outfitted with devices and continuously monitored, even given low samples sizes as is the case with our examination, can return significant insights into offshore fishing conditions and catch success. For example, over the nine-week period examined, 700 dolphinfish were reported as landed with a general increase in catch through the first half of the monitoring period and the vast majority of the total catch was unassociated with nearby FADs (Table 2). These observations point to a large influx of *Sargassum* related catch, which was confirmed with remote sensing data, that would not have otherwise been detected unless vessels were being monitored to this degree.

Fish tagging data

Conventional tag and recapture data on dolphinfish provided additional data on the presence of *Sargassum* when fish were recaptured by vessels not participating in the vessel catch and effort component. This led to a match with the Sentinel-2 *Sargassum* distribution map during the week of the event with the highest recorded catch among monitored vessels. Here, the fishery-dependent nature of conventional tagging data was valuable to further determine the presence of *Sargassum* during the Hurricane *Leslie* event. While conventional tag and recaptures methods to determine fish habitat utilization is not the only fish tracking method, it is the most cost effective. Satellite and acoustic tracking data, however, could provide geolocation, and active tracking estimates, respectively, which could show interesting habitat use patterns (Merten et al. 2016; Whitney et al. 2016), but these are expensive to implement on short-time frames and require the hardware to be readily available. Collectively, fish movement work provides essential ground truthing to *Sargassum* distribution maps as well as aids in determining additional fishing effort relative to pelagic habitat or fish aggregating devices.

CONCLUSIONS

We found that the combination of several datasets, methods, and our voluntary vessel catch and effort program can provide high-quality information to support significant insight into variability of fishing success for coastal pelagic fisheries such as the dolphinfish fishery. This multi-faceted approach to dolphinfish monitoring drew benefits from each described method and dataset. Without the vessel catch and effort data, however, the signal of higher fishing success for dolphinfish during this period could not have been observed as clearly. Yet, it is necessary to state that the observed increase in fishing success is also likely due to the innate behavior of dolphinfish to aggregate and remain associated with floating or stationary objects in the ocean for short-time frames. Taquet et al. (2007) documented dolphinfish to remain with drifting objects in the Indian Ocean for 15 days but similar results for the species are lacking for the WCA. However, as documented with this study, a dolphinfish was recaptured at the same stationary FAD off Puerto Rico after four days at liberty, and several times on the same day or after a day, between a series of

stationary submerged FADs north of St. Thomas, United States Virgin Islands (Table 3). Nonetheless, despite the tendency for dolphinfish to aggregate at *Sargassum* or FADs, vessel catch and effort data during the period examined were unique comparative to previous results that returned low fishing success at *Sargassum* or FADs in the same region, observations that suggest Hurricane *Leslie* as well as other environmental factors contributed to the period of heightened fishing success.

The visual census and fish movement data showed a signal but not nearly as clear until the vessel catch and effort data were examined by week and relative to *Sargassum* distribution maps, meteorological, and oceanographic data. Based on our study, dynamically assessing fishing success for coastal pelagic resources relative to habitat among small-scale fisheries is possible and can aid in providing useful information for better compliance of local and regional fisheries regulations during periods of heightened fishing success of pelagic fish such as dolphinfish.

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APPENDIX 1. Natural logarithm of (A) wave direction (grey) and wave period (black); as well as (B) wind direction (black) and wind speed (grey) for nine weeks beginning September 1, 2018, and ending November 2, 2018.

