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Use of video monitoring to quantify spatial and temporal patterns in fishing activity across sectors at moored fish aggregating devices off Puerto Rico

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Summary: A key challenge in small-scale fisheries that use moored fish aggregating devices (mFADs) is the ability to accurately quantify multi-sector fishing activity through fishery-independent methods. Here, we present a novel fishery-independent assessment of multi-sector fishing activity associated with a newly developed open access mFAD programme off San Juan, Puerto Rico. We identified three fishing sectors (recreational, charter and commercial) and 158 individual fishing vessels that routinely operated in the vicinity of the mFADs. The results indicate that daytime fishing activity varied by time of day, day of week, location and sector. During fishing tournaments, the data revealed that fishing activity increased threefold; across monitoring periods, for-hire charter vessels were the most consistent day-to-day user segment, and recreational activity peaked on weekends. Our study represents a new technique for rapidly identifying and detecting multi-sector fishing activity near mFADs and highlights the potential to gather comparable data wherever mFADs are deployed. The results are used to discuss how this technique can be used to assess the performance of mFADs to identify sector overlap and guide management in determining deployment patterns and facilitate the design of cost-effective surveys to estimate mFAD vessel activity, and potentially catch, of mFAD-associated species.

Keywords: fish aggregating devices; fishery-independent survey; video monitoring; small-scale fisheries; recreational fisheries; Caribbean Sea.

Uso de video para cuantificar los patrones espacio-temporales de la actividad pesquera de los distintos sectores en los Sistemas de Agregadores de Peces de Puerto Rico

Resumen: Un reto crucial en las pesquerías artesanales que utilizan los sistemas de agregadores de peces fijos (mFAD, por sus siglas en inglés) es el poder cuantificar con certeza la actividad pesquera multisectorial a través de métodos independientes de la pesca. En este estudio presentamos un innovador análisis independiente de la pesca para la actividad de pesca multisectorial asociada a los nuevos mFAD establecidos en Puerto Rico. Se identificaron 3 sectores pesqueros (recreacional, de alquiler y comercial) y 158 embarcaciones que rutinariamente pescaban alrededor de los mFAD. Los resultados muestran que la actividad pesquera diurna variaba por hora del día, día de la semana, lugar y sector. Durante torneos de pesca la actividad pesquera se triplicó, a lo largo de los periodos evaluados los botes de alquiler mostraron mayor consistencia por día y la actividad recreativa aumentó durante el fin de semana. Nuestro estudio plantea una nueva técnica para identificar rápidamente y detectar actividad multisectorial pesquera cerca de los mFAD y resalta el potencial de tomar datos comparables en otros lugares donde se coloquen los mFAD. Los resultados se utilizan para discutir cómo esta técnica puede ser utilizada para evaluar la ejecutoria de los mFAD, identificar solape de uso por varios sectores y guiar las decisiones en cuanto a los patrones para colocar los mFAD y facilitar el diseño de estudios costo efectivos para estimar la actividad de embarcaciones y el potencial de captura de peces alrededor de los mFAD.

Palabras clave: sistemas de agregadores de peces; estudios independientes de pesca; evaluaciones utilizando video; pesquería artesanal; pesquería recreativa; mar Caribe.

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INTRODUCTION

Floating objects moored in coastal areas are commonly used to attract pelagic fishes to improve catch rates. Their use was first recorded in the second-century Roman poem *Halieutica* (Taquet 2013). Simple structures, such as bamboo rafts held in place by a stone ballast, have been used in the Mediterranean, Japan (e.g. tsukegi rafts) and the Indo-Pacific (e.g. Malaysia, unjang devices; Philippines, payaos devices; Indonesia, rumpon devices) to target a variety of species (e.g. thunnids, scombrids and coryphaenids) that naturally aggregate near floating objects (Matsumoto et al. 1981, Dempster and Taquet 2004). By the late 1950s, moored and drifting structures used to aggregate and capture fish were discussed scientifically as fish attracting or fish aggregating devices (FADs) (Galea 1961, Gooding and Magnuson 1967). Moored and drifting FADs (mFADs and dFADs) are now commonly utilized by all major fishing sectors (e.g. industrial, semi-industrial, artisanal and recreational) throughout all tropical and sub-tropical regions of the ocean (Taquet 2011, Fonteneau et al. 2013, Gershman et al. 2015). While industrial fleets that utilize dFADs are required to report associated catch and effort to regional fishery management organizations, comparable quantitative estimates of mFAD catch and effort do not exist, and while thought to be a fraction of those associated with dFADs (Dempster and Taquet 2004), the figures are still substantial due to the sheer magnitude of use around the world (Itano et al. 2004, Taquet 2013).

In the 1980s, mFAD (hereafter FAD) programmes in the U.S. Caribbean Sea (i.e. Puerto Rico and United States Virgin Islands) (Feigenbaum et al. 1989, Friedlander et al. 1994) favoured recreational and artisanal sectors (Guyader et al. 2013). Use among artisanal fisheries expanded to Guadeloupe, Martinique, Dominica and locations in the southern Caribbean Sea throughout the early 1990s (Diaz et al. 2007, Taquet 2013) and, since then, it is unknown whether use has remained constant or continued to expand. Within the last decade, however, there has been a dramatic increase of recreational FAD use in the Dominican Republic (e.g. Casa de Campo and Punta Cana), commonly overlapping with established artisanal FAD sites (Bareuther 2016), and within the last three years Puerto Rico and the United States Virgin Islands have initiated new open-access FAD programmes, following the Hawaiian model (Holland and Jaffe 2000), which has led to a re-emergence of recreational FAD use and an increase in multi-sector overlap at these sites. Despite the quantity and broad distribution of FAD programmes active throughout the Caribbean Sea, quantitative assessments of temporal and spatial FAD use are needed but lacking, though there are clear management issues (Sidman et al. 2015) that require such an assessment.

The FADs in Puerto Rico are moored in deep water (mean depth ± standard deviation: 448.0±135.7 m) and aggregate myriad open water species that have been identified in standardized scuba diving surveys (e.g. carangids, scombrids, coryphaenids, istophorids, thunnids and carcharhinds) (Merten unpublished data). The species most often targeted and subsequently caught near these FADs, as determined through online and direct communication catch surveys, are dolphinfish, blue and white marlin, sailfish, wahoo and various tuna species (e.g. blackfin and yellowfin tuna); it is not known whether juvenile sharks observed at the FADs during dives (*Carcharhinus falciformis*) are targeted or caught as bycatch (Merten unpublished). Across sectors, pole and troll methods using ballyhoo, hook and line with live bait, vertical jigging and spearfishing are the main fishing strategies, yet estimates of how frequently these fishing techniques are used at the FADs, their proximity to the FADs and their relative catch success are lacking. Quantifying when and how fishers target fish at the FADs can aid fishery managers to better assess FAD use patterns and gear-specific fishing mortality.

In Puerto Rico, there are 23882 registered vessels (http://www.marinetitle.com/boat-registration/PR-Puerto-Rico.htm accessed 8/16/2017). The majority of the vessels are likely recreational but the exact number is unknown (pers. comm. Puerto Rico Office of the Navigational Commissioner). It is estimated, however, that there are 12 for-hire charters (https://fishingbooker.com/charters/search/, accessed 8/16/2016) and 75 registered commercial vessels active in the area near the FADs (e.g. Manati to Loiza) (pers. comm. Daniel Matos, Puerto Rico, Dept. of Natural and Environmental Resources). While funds are being spent to deploy FADs for these vessels, data are not being collected to assess use patterns (e.g. by time, season or sector), so resource managers cannot evaluate how FADs are used across sectors (private, charter and commercial) within a temporal and spatial context. Gathering robust calculations of FAD use is critical in order to address FAD management at different temporal and spatial scales and to determine the most cost-effective approaches to properly assess catch (i.e. when, where and who to sample) and the impact FAD use is having on exploited stocks. In Haiti and Dominica, where recreational fisheries are not prolific, fishery-dependent data (e.g. surveys and interviews) suggest average FAD use in Haiti ranged from 3 to 4 boats (maximum of 16) fishing on the same FAD at any given time at most locations (Vallès 2015), while in Dominica 15 to 20 boats were seen fishing the same FAD during some trips 5. However, these estimates do not characterize multi-sectoral use, and as they were short-term, they did not fully quantify variations in use over space and time. Use of FADs

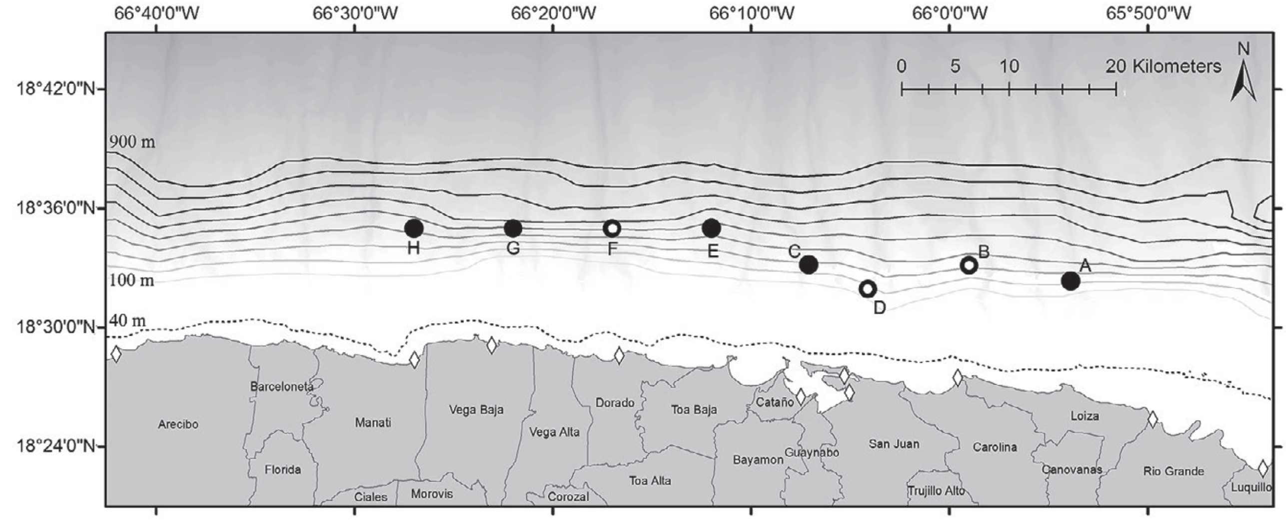

Fig. 1. – FADs were deployed in a linear array from Loiza to Manati off San Juan, Puerto Rico. White circles within a black oval indicate the location of time-lapse cameras; white diamonds indicate the locations of marinas, docks or boat ramps where vessels access the ocean; municipalites along the north coast of Puerto Rico are labelled by name.

could be considerably higher where there is a greater incidence of multi-sector overlap, as in Puerto Rico.

The purpose of this study was to provide a fishery-independent assessment of FAD use of an open access FAD array deployed off San Juan, Puerto Rico, during the first year of the programme. This study sought to address who visited the FADs (e.g. which sectors, individual charters and individual fishermen) and in what temporal and spatial frequency, and what fishing methods were used. The results are used to evaluate temporal and spatial FAD use patterns to identify sector use and help management determine future use practices and deployment patterns, and to discuss the costs and benefits of video versus traditional survey methods for estimating vessel activity, and potentially catch, of FAD-associated species.

METHODS

Study setup and data management

In 2015, the Government of Puerto Rico (PR) deployed eight spherical steel FADs (147 cm diameter). The FADs were moored in a line that spanned approximately 60.06 km from Loiza to Manati; individual FAD depths are as follows: FAD A, 305 m; FAD B, 402 m; FAD C, 349 m; FAD D, 260 m; FAD E, 550 m; FAD F, 600 m; FAD G, 598 m; FAD H, 520 m (Fig. 1). The FADs were close to shore (7.44-12.24 km) and from 5.72 km (C-D) to 9.24 km (B-D) apart (Fig. 1).

Time-lapse cameras were programmed (Supplementary material, Table S1) and mounted at the base of the mast on three of the FADs nearest the two largest ports in the study area and nearest an active boat ramp (FAD B, Cangrejos; FAD D, San Juan; FAD F, Dorado boat ramp) (Fig. 1). The cameras were left to record for as long as the batteries lasted (Duration: 20.7±2.4 d) before they were retrieved. There were four monitoring periods (I, 8/29/2015-9/19/2015; II, 10/2/2015-10/20/2015; III, 1/29/2016-2/22/2016; IV, 6/14/2016-7/5/2016); not all sites were monitored in each period (Table 1). No cameras were stolen or tampered with during the study. At the time of the first camera deployment, the FADs had been moored for 87 (FAD F), 133 (FAD B), and 235 days (FAD C).

Vessel labelling and nomenclature

Every recorded day (0530-1930) was imported into video editing software (FCPX v10.2.3) and labelled image by image for presence or absence of vessels. Images with vessels were then classified following these steps: (1) the first image of a vessel proximal to a FAD where distinct features could be identified (i.e. vessel make and model, vessel name and unique vessel attributes) was saved to an archive (i.e. as a reference image) and given a unique label to allow that vessel to be cross-identified if it occurred in subsequent images; (2) reference images were cross-identified with each subsequent vessel image throughout the entire dataset; (3) images with vessels present, but not close enough to allow cross-identification or unique identification, were physically labelled as unknown vessels (i.e. to allow the presence and absence of unknown vessels to be calculated); (4) certain ship types (e.g. tankers, cargo vessels, cruise ships and sailboats) were excluded from the database and never labelled because their size and behaviour were easily distinguished from those of fishing vessels. All labelled vessels were assumed to be fishing vessels and engaged in some form of fishing (e.g. searching, trolling, hand-lining, jigging, drifting, free-diving, running, setting lines, following birds, tying up to the FAD or passing the FADs were all categorized as apparent fishing activities). All apparent fishing vessel activities were described in three ways: per vessel, sector or as a whole (number of images, average amount of time present per day and visits per day).

All labelled vessels were categorized according to three sectors. Charter vessels were identified from experience and using the web (www.fishingbooker.com, accessed 08/10/2016). Commercial fishing vessels were identified from experience or when vessel owners identified themselves as commercial fishermen when submitting catch reports via an online survey (https://www.surveymonkey.com/r/QM27BXN). All vessels that were not labelled as a charter or commercial fishing vessel were labelled as recreational, including spearfishing vessels. All labelled vessels that had outboard engines and lacked cabins with multiple levels were designated as small (i.e. approximately 5 to 8 m); all vessels with inboard engines and presence of cabins with multiple levels were designated as large (i.e. 8 to >20 m); size designations were not given to unknown vessel types.

Analysis and statistics

The metadata from each video were imported into Microsoft Excel ver.2013. Within Excel, timestamps were converted to a particular format (YYYY-MM-DD HH:MM:SS) and all data were imported into Google BigQuery (https://cloud.google.com/bigquery), which was used to sort, bin and analyse the data.

Time series data were categorized by time of day (TOD: a, early am, 0530-0859; b, late am, 0900-1229; c, early pm, 1230-1559; d, late pm, 1600-1930), by day of week (DOW: Monday, 1; Tuesday, 2; Wednesday, 3; Thursday, 4; Friday, 5; Saturday, 6; Sunday, 7) and whether there was a distinct event associated with the day (e.g. holiday, tournament or none) for each monitoring period per FAD. Data were analysed in R studio version 0.99.903. Comparisons of activity between FAD locations were only considered with full recording days and when all FADs were recording simultaneously. The association of vessel activity with the factors TOD and DOW was considered using a logistic regression model (Bretz et al. 2011). We fitted a logistic regression that includes both main effects and an interaction effect of TOD and DOW. For TOD_i = 1,..,4, DOW_j = 1,..,7, and photo index t=1,…,n

$$\text{logit}(y_{i,j,k}) = \beta_0 + \beta_1 TOD_{i,t} + \beta_2 DOW_{j,t} + \beta_3 (TOD*DOW)_{i,j,t}$$

where $y_{i,j,k}$ is the probability that a vessel is detected at TOD_i, DOW_j and photo index t. All inference was conducted at 5% significance. In this model, TODa and DOW1 were treated as the common reference groups, with which the rest of the TOD/DOW combinations were compared. To control familywise error rate while investigating vessel activity relative to each combination of TOD and DOW, simultaneous confidence intervals were constructed using a contrast matrix.

For $c_j=(c_{0,j},\ldots c_{p,j})$, $\beta=(\beta_0,\ldots \beta_p)$ our j=1,...,m null hypotheses are: $H_j{:}c_j^T\,\beta=0$.

Vessel activity, in terms of average vessel visits per day, was then compared by distinct day, looking solely at days when official fishing tournaments were held over weekends (n=7) versus non-tournament weekends (n=38) using a chi-square analysis.

Range detection

To test vessel range detection, one of the cameras used during this study was redeployed on FAD B but with internal time calibrated to the time of a handheld GPS (Garmin s76) and video operation set to continuous. The vessel used was a 20’ centre console with dual outboards and dual outriggers (height of centre console above the water, 2.4 m; freeboard aft, 0.6 m; length of outriggers, 3.9 m). The vessel was then oriented to the direction of the camera and slowly motored away while waypoints were taken frequently. The waypoints were plotted in ArcMap v.10.4.1. and matched to the time associated with the images.

FAD proximity

All images for labelled vessels were visually classified based on FAD proximity relative to reference images acquired from range detection (Supplementary material, Fig. S1). There were three designations: adjacent (<70 m), close (~70-132 m) and far (>132 m) from a FAD. In addition, each image classified for proximity was labelled based on fishing mode. There were three fishing modes: spearfishing, drift fishing (i.e. troll and pole live baiting, vertical jigging, hand-lining and fly fishing) and trolling. Data were then analysed cumulatively and by large and small vessels in R.

Movements

Individual vessel dynamics were examined to calculate the total number of images, time spent per day, daily visits, re-visitation times (e.g. time between successive appearances at a single FAD on the same day, between days, months, weeks or FAD locations) and movement time between FADs. Revisits were defined as any visit greater than 30 minutes apart.

FAD catch composition

Catch reports gathered from an online survey from FADs that overlapped with camera deployments were tallied and compared with the imagery for matches. These data were used to relate preliminary catch quantity and composition while vessels fished the FADs.

Cost-benefit analysis

A qualitative cost-benefit analysis was conducted between the video monitoring technique and traditional port, phone, mail and web-based survey (PPMW) techniques (personal communication QuanTech, Inc.). All surveys were assessed based on the costs associated with personnel and methods and the benefits of each approach.

RESULTS

A total of 158 unique vessels were characterized in 150 days recorded by the cameras from 29 August 2015 to 5 July 2016. When considering only full days

Table 1. – Time-lapse cameras were deployed on three FADs during different times of the year off San Juan, Puerto Rico. [1] No. vessel days is the number of days that a single fishing vessel was not detected at each respective FAD; *r, vessels that were cross-identified and matched between monitoring periods and repeatedly visited; *t, vessels that were cross-identified and matched as transient between FADs during a monitoring period.

FAD	Monitoring start date	Monitoring end date	Full days	No. vessel days[1]	Total images	Vessel images	Detection rate	Vessels classified	Vessel movements (r/t*)	Early visit	Late visit
F	8/30/2015	9/18/2015	20	0	33600	1746	5.2%	56	n/a	0542	1740
F	10/3/2015	10/19/2015	17	0	28560	709	2.5%	20	11r	0547	1715
F	1/30/2016	2/16/2016	18	5	30240	215	0.7%	10	7r	0747	1625
B	1/30/2016	2/21/2016	23	2	38640	744	1.9%	31	10t	0701	1618
D	1/30/2016	2/20/2016	22	4	36960	1126	3.0%	35	10t	0617	1823
F	6/15/2016	7/3/2016	19	9	31920	188	0.6%	4	3r	0741	1519
D	6/15/2016	7/4/2016	20	1	33600	954	2.8%	7	7r/3t	0716	1745

recorded, a total of 139 days captured 233520 images. Overall, data were collected over 81 calendar days or 22.1% of the year. The maximum number of days during a monitoring period in which no vessels were captured on camera was 9; only the first two deployments had at least one vessel captured every day (Table 1). The earliest and latest vessel visit were at 0542 and 1823, respectively (Supplementary material Fig. S2: #1 and #2). In terms of catch quantity and composition, 69 online catch reports from 32 different fishing vessels overlapped with camera deployments but only 20% were matched to camera data. Cumulatively, vessels reported 188 dolphinfish, 8 blue marlin, 3 white marlin, 1 king mackerel, 1 yellowfin tuna and 5 wahoo caught in association with a FAD. Of these, 38 dolphinfish, 1 blue marlin, 1 king mackerel, 1 yellowfin tuna and 1 wahoo were matched to vessel occurrences in the camera data.

Cumulatively, the vessel detection rate for full recording days was 2.4% (n=5680) but varied by FAD location and time of year (Table 1). The unknown vessel detection rate was 0.7% (n=1127). Overall, 76% of all full days recorded (47 d) had at least one image in which a vessel could not be identified or labelled for matching. By TOD, the proportion of unknown to classified vessel images increased from 17% in the early morning to a peak of 35% in early afternoon, before decreasing to 20% at the end of the day. By FAD, there were significant differences in the number of images with unknown vessels (chi-square: P<0.001); when examined by the amount of time unknown vessels were present, FAD D had significantly more time than FAD B and FAD F (ANOVA: P<0.05) (Fig. 2).

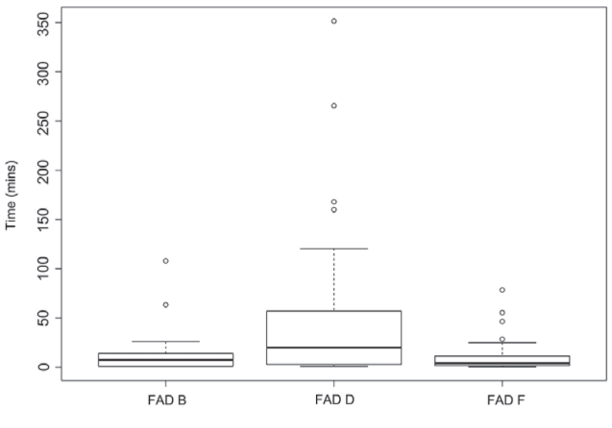

Fig. 2. – Cumulative presence (minutes/d) of vessels that could not be cross-identified or classified at FAD B, D and F off San Juan, Puerto Rico.

Table 2. – Results of a two-way analysis of variance comparing vessel effort by time of day and day of week off San Juan, Puerto Rico.

Source of variation	DF	SS	MS	F	P
TOD	3	35	11.64	498.05	<0.001
Day	6	36	5.96	255.03	<0.001
Interaction	18	16	0.86	36.93	<0.001
Error	233492	5458	0.023		

Temporal variation

Vessel activity varied significantly by TOD and DOW (logistic regression: P<0.001). Table 2 summarizes the effects of TOD and DOW on vessel activity using a two-way analysis of variance. According to simultaneous confidence intervals, the probability of detected vessel activity was highest on Friday, Saturday and Sunday during late morning (0900-1229) (Fig. 3). During tournaments, average vessel visits per day was 2.93 times greater than non-tournament weekends (chi-square: P<0.001; mean±sd: 9.42±4.50 vessels/d versus 3.21±2.34 vessels/d, respectively). Vessels were always detected during tournament weekends (range: 5-16 vessel visits/d), while only during non-tournament weekends were no vessels detected (range: 0-9 vessel visits/d).

Table 3 reports the average time and number of vessels observed at each FAD over time. The longest time series was for FAD F. Here, the number of cumula-

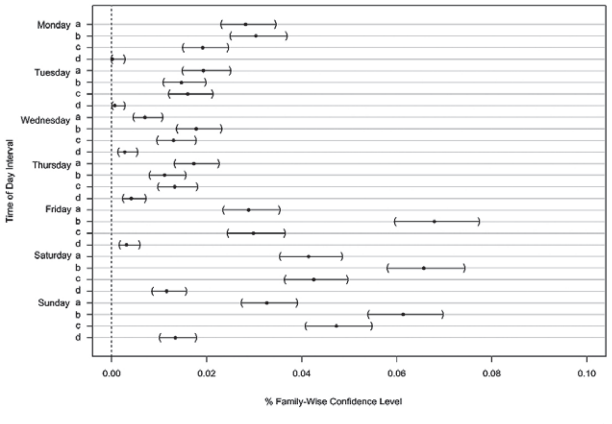

Fig. 3. – Simultaneous familywise confidence intervals (P<0.05) for the probability of vessel presence by day of week and time of day interval in chronological order (early am to late pm: a to d) at moored FADs off San Juan, Puerto Rico.

Table 3. – Cumulative vessel presence in terms of hours per day and vessel visits per day for all monitoring periods by FAD off San Juan, Puerto Rico.

Monitoring start and end date	Days (#)	FAD F		FAD D		FAD B	
		(hrs/d)	(vessels/d)	(hrs/d)	(vessels/d)	(hrs/day)	(vessels/d)
8/30/15 – 9/18/15	20	2.56±1.93	4.04±2.53	-	-	-	-
10/3/15 – 10/19/15	17	1.67±2.00	1.58±1.50	-	-	-	-
1/30/16 – 2/16/16	18	0.52±0.81	1.68±1.79	1.75±2.37	4.47±4.64	0.98±1.23	3.31±3.09
6/15/16 – 7/3/16	19	0.19±0.30	1.50±0.78	1.12±1.25	2.00±1.32	-	-

tive vessel hours per day was highest during the first monitoring period and decreased by 93% throughout the study period. Vessel visits per day, however, while initially high, levelled off at a consistent vessel visit rate, with an overall reduction of 63% from the first monitoring period to the last. A similar but lower trend was seen at FAD D between periods three and four, with vessel hours per day and visits per day dropping by 46% and 66%, respectively. Across FADs, vessel duration/d and number/d was 44%-70%, and 25%-65%, greater at FAD D than at FAD B and F, respectively. During the last monitoring period, while the number of vessel visits per day was nearly the same at FAD D and FAD F, the amount of hours spent was nearly six times lower at FAD F.

Fishing sector variation

The proportion of vessel types, classified by size or sector, varied by TOD (chi-square: P<0.001) (Fig. 4). Small recreational fishing vessels predominately visited the FADs early, along with small commercial vessels. Commercial vessels decreased in proportion from a peak in the early morning. Lastly, the proportion of large and small vessels classified and documented at FAD D was nearly the same. At FAD B, the number of large vessels was nearly the same as at FAD D, but far fewer smaller vessels were detected. At FAD F, 2 to 6 times more small vessels were classified and detected than at the other FADs.

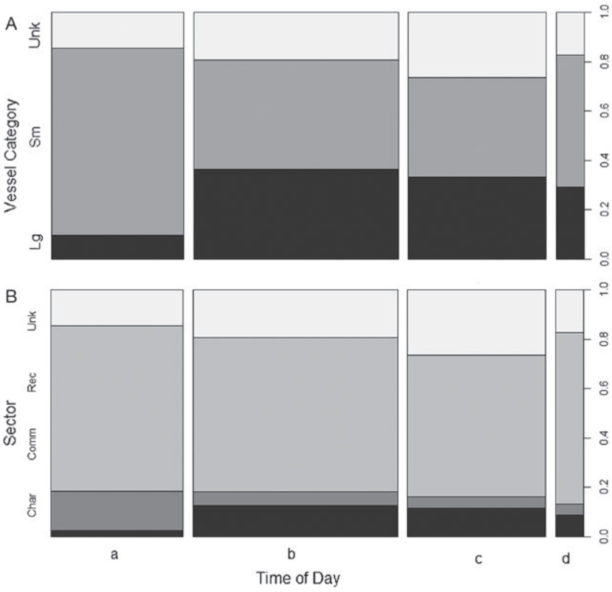

Fig. 4. – Association of (A) vessel category and (B) sector to detected vessel presence by time of day off San Juan, Puerto Rico. The rectangle height determines the frequency of (A) vessel category and (B) sector association; width determines the frequency of time of day. (A) Labelled from top to bottom (Unk: vessel unclassifiable; Sm: small vessel; Lg: large vessel) (B) Labelled from top to bottom (Unk: vessel unclassifiable; Rec: recreational; Comm: known and likely commercial vessels; Char: known charter vessels); (time of day = a, early am (0530-0859); b, late am (0900-1229); c, early pm (1230-1559); d, late pm (1600-1930)).

Vessels that were only detected on one day (103 vessels or 64.7% of the total) represented 25.5% of all vessel detections and were mostly detected on weekends (65.5%). The majority (57.3%) of these vessels were small recreational, followed by large recreational (31.1%), and then small commercial fishing vessels (11.6%). Vessels detected more than six days (=10 vessels or 6.2% of total) represented 23.7% of all vessel detections and were detected consistently across all days of the week. Of these vessels, five were recreational, four were charter and one was a commercial fishing vessel.

Range detection

Range detection was calculated as 492 m. Within 30 m, detailed vessel attributes were distinguishable and classifiable. At 70 m, detailed attributes were no longer classifiable but larger features such as the presence of outriggers, the centre console, and the colour of the outboards and hull were still detectable. At 132 m, the vessel was still clearly visible as a centre console and other features, such as the black outboard engines could be seen. At locations greater than 132 m, the vessel was still detectable but only as a moving object on the horizon.

FAD proximity

Cumulatively, labelled images (n=4553) showed vessels far (>132 m, 45%; n=2038) and near (70-132 m, 30%; n=1353), rather than close to the FADs (<70 m, 25%; n=1162). Among these images, observed fishing modes were troll (73.7%), drift (23.8%) and spearfishing (2.5%). When images were examined by large (n=1593) and small vessels (n=2960) there were significant differences in both proximity and fishing mode (chi-square: P<0.001) (Fig. 5). Large vessels operated mostly far from the FADs (64.8%). In terms of fishing mode, large vessels predominately trolled (95.5%), rarely drift fished (4.5%), and never engaged in spearfishing. For small vessels, there were no significant differences in distribution of activity (chi-square: P=0.1016) while detected near the FADs. There were, however, significant differences in fishing mode (chi-square: P<0.001), with small vessels primarily trolling

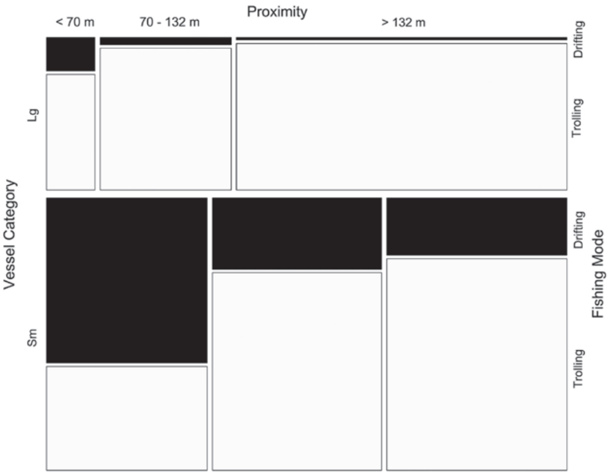

Fig. 5. – Cumulative association of vessel category, operation proximity and fishing mode to detected vessel presence at moored FADs off San Juan, Puerto Rico. The rectangle height determines the frequency of fishing mode association; width determines the frequency of operation proximity.

near and far from the FADs, but also engaging in drift fishing which began close to the FADs.

Movements

Only 11.6% (n=19) of the detected vessels moved between monitored FADs during the monitoring periods; 4.2% (n=7) of the vessels were detected moving between FADs on the same day (all FAD D to B=9.24 km); and only one vessel moved between FAD D and B each day during three separate visits. The least amount of time between FAD visits on the same day was 22 min; the greatest was 262 min. Movements from FAD D or FAD B to FAD F were not detected on the same day, but one vessel did move between FAD F and FAD D (=23.36 km) during the same monitoring period.

Across all monitoring periods, 27 vessels revisited a FAD more than once on the same day. In total, there were 111 repeat events (FAD F, n=55; FAD D, n=37; FAD B, n=19) (74.41±56.79 min).

Cost-benefit analysis

Table 4 presents the results of the cost-benefit analysis. All survey methods require computers and special software to store and analyse data. Video monitoring is the only fishery-independent method and is the cheapest to conduct over short time frames; costs of video monitoring will increase over time due to the need to curate, store and analyse very large datasets. It is expensive to set up PPMW surveys, making them impractical for short study durations. In addition, participation is voluntary, so there may be a chance of reporting bias, but these techniques do not rely on remote monitoring equipment which can malfunction, be stolen, tampered with or obscured by objects (Supplementary material Fig. S5: #3 and #4). Of all of the techniques, port sampling is the most expensive and requires the greatest amount of staff training, transportation to and from sites, and time in the field to survey fishermen, but can result in very detailed trip profile and vessel information from respondents.

Table 4. – Costs and benefits of video versus traditional survey techniques for one three-week camera deployment in the study region from Loiza to Manati, Puerto Rico; No., number; $F, field; $D, desk.

Survey Method	No. (#)	Personnel Salary[A] (USD/hr)	Field[1] (hrs)	Desk[2] (hrs)	Method Cost	Resources	Data Size (gb)	Technique Pros	Cons
Video	2F 1D	$45F[X] $45D[X]	3	40	$2070[C] ($5000)[D]	Boat; FAD; Camera; SD card; Batteries	7	in situ; programmable; potential for automation; potential for web streaming; easily comparable to other locations with FADs	Potential lens obstruction or field of view issues; need batteries or power source; need demographic data from other data sources
Port	11F 3D	$35F $60D	880[B]	520	$70000[C] ($15000)[D]	Forms; Clipboards; Pens; Transportation	1	Obtain more information about trip profiles and boats	Only public access sites are sampled; no data from boats at private docks
Phone	4D	$60D	N/A	260[E]	$18000[C] ($8000)[D]	Phone service; Office space	2	Easy for domestic calls; reach people at private access sites and those that fish odd hours	Difficult and expensive to call internationally; low response rates without pre-notification
Mail	3D	$60D	0	270[F]	$24750[C] ($8000)[D]	Printer; Postage	3	Reach people at private access sites; no valid phone number or e-mail needed	Printing and mailing surveys is expensive; need valid addresses
Web	1D	$100D	0	170	$18000[J] ($11000)[D]	Web domain; Web server; E-mail licence	2	Can target entire study group; once developed, reused for little cost	No contact or data without valid emails

[A] Average salary for field biologists and office employees at QuanTech Inc; [B] Each site is visited every day for 4 hours; [C] Cost includes hourly costs and other direct costs such as supplies; [D] One time cost to train staff and develop survey protocol; [E] Hours to survey based on a sample size of 1000 registered vessels over a one-week period to ask about trips from a three-week period; [F] Hours to survey based on a sample size of 1000 registered vessels by mail asking about trips from a three-week period; includes time required to design paper surveys; [H] Cost to print and mail an advanced letter, survey, reminder postcard and second survey for non-respondents; [J] Cost to register domain, develop web survey, lease web server space and maintain survey for 2 months; [X] Based on salary for lead author to conduct this study; [1] Approximate time needed for deploying and retrieving the equipment in the study area on 1 FAD; [2] Approximate time needed to store, process, analyse and acquire results from one camera deployment.

DISCUSSION

This fishery-independent assessment of multi-sector fishing activity relative to an open access FAD array off San Juan, PR, is the first such study using video monitoring. Generally, activity was highest during late morning, on weekends, near major ports and during fishing tournaments. Ocean access influenced FAD fleet activity composition, and the results showed differences in FAD exploitation by TOD, DOW, fishing mode and proximity to the FADs by sector and size of vessel. This approach illustrates how video techniques can be used to generate high-resolution data useful for describing spatio-temporal trends in activity relative to a fixed structure in the ocean. This methodology has the potential to be extended beyond monitoring moored FADs to other features of interest, such as coastal marine reserves or ports of interest.

However, this study also had a number of limitations. First, while sampling was done over the course of a full year, data were not collected continuously and were unevenly distributed between locations, so they did not allow seasonal or interannual comparisons, time scales that FAD use may vary on. Additionally, these data were collected during the first year of a new programme and the results could be inflated due to fishers' interest in moving offshore, whether for commercial or recreational purposes, to target pelagic species as new FADs were deployed (Table 1). On the other hand, these data can be used as a baseline to assess whether future use expands or contracts following this initial period of interest. In the future, the use of infrared cameras with a motion sensor, equipping all FADs with cameras, and the use of vessel tracking systems could fill the gaps in this study of whether FADs are fished at night, in addition to better quantifying variation in FAD use and frequency of FAD visitation per day. In addition, cameras should be deployed in conjunction with underwater sonar to assess simultaneous fishing activity and fish school size and presence. Adapting this study to include any or all of these techniques could lead to more detailed information on FAD fleet–fish behaviour.

Spatio-temporal trends in activity

Activity varied significantly by TOD during this study. Generally, daytime activity began just before sunrise (e.g. civil twilight), increased through the late morning, and then decreased steadily through the early and late afternoon. Reynal et al. (2015) observed that activity around FADs in Martinique and Guadeloupe varied during the day depending on target species and gear-type, with sub-surface and surface trolling lines, vertical jigging and spearfishing most used during the day to target pelagic fish (e.g. billfish, tuna and dolphinfish). These results are consistent with those of the present study observed through catch data matched to vessel occurrences at the FADs. At night, swordfish and blackfin tuna were caught using deep-set buoy gear and deep trolling (~30 m) techniques (Reynal et al. 2015), respectively, gears and techniques that went unobserved during this study. To obtain a complete picture of activity around FADs, future studies should consider recording both day and night. By gathering continuous camera data, TOD could also be coded by sunrise and sunset to facilitate interpretation of a TOD effect across seasons.

Activity varied significantly by DOW during this study. It was highest on weekends and during fishing tournaments, where vessel visits per day increased threefold. In other Caribbean locations with FADs, such as Dominica and Haiti, large recreational fishing sectors (e.g. private recreational fishermen and charter boats) do not exist in the same concentration as in PR (Appeldoorn et al. 2006, Sidman et al. 2015, Vallès 2015). Therefore, fleet dynamics observed by DOW may be different. In the Dominican Republic (DR), however, recreational fishing vessel presence and routine tournaments around Punta Cana and Casa de Campo are likely to match, if not exceed, FAD activity observed in PR. The reason is that FADs in DR are owned by private commercial fishermen, so recreational activity is additive to any consistent commercial activity. In PR, the FADs are open-access, so activity patterns may be more variable (Sidman et al. 2015). In the future, the use of video sampling could lead to comparative studies in activity patterns between different FAD locations throughout the Caribbean Sea, which would improve upon local and regional assessments of FAD fishery dynamics and potential impacts on shared stocks.

Activity varied significantly by sector. Large charter and recreational vessel activity peaked during late morning (0900-1230), while smaller commercial and recreational vessel activity peaked during early morning (0530-0859) (Fig. 4). In addition, early morning mid-week peaks in activity were due to small commercial and recreational vessels. Charter vessels visited the FADs consistently throughout the week, while recreational vessels preferred weekends. For FAD visitation, however, when compared these sectors were nearly equivalent in terms of total use. On a per vessel basis, one charter was detected 24% of total days recorded (19 days), suggesting that if results were collected continuously for a year, the operation would log around 87 days on the water. Eleven months (November 2016 to September 2017) of vessel tracking data collected after this study showed that this same vessel took 94 trips (Merten unpublished), supporting the use of camera data to estimate yearly individual vessel trip counts. While vessel tracking data can acquire consistent daily data streams for individual vessels, the cost and practicality of tracking all vessels is likely not possible wherever FADs exist. Video sampling, however, is a quantified sampling strategy (Nazir et al. 2017) for independently assessing fleet dynamics and can be useful in situations where expensive vessel tracking and fishery-dependent survey techniques are not feasible.

Movements

During the study, fewer daily movements were detected between FADs than in repeat occurrences at the same FAD, results that suggest vessels utilize FADs

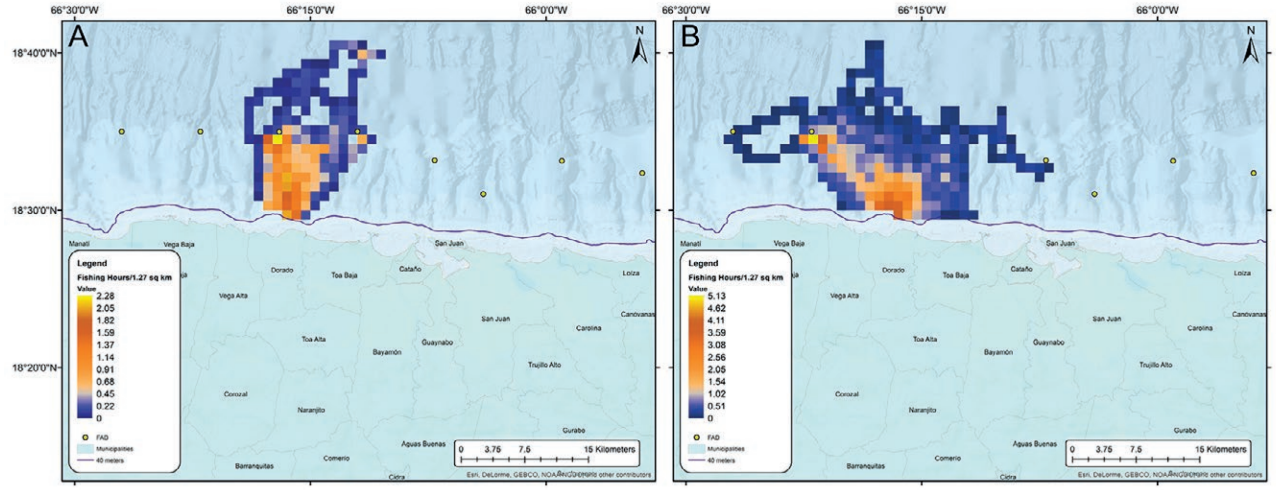

Fig. 6. – Fishing hours (A) before (10/25/2016-1/16/2017) and (B) after (1/17/2017-5/14/2017) the loss of two FADs nearest vessel A's home port of Dorado, Puerto Rico.

closest to their home port. In Guadeloupe, Guyader et al. (2013) found that five FAD fleet segments and their involvement in FAD fisheries were highly dependent on harbour-FAD proximity in an attempt to minimize cost and maximize ease of access. Here, only 7 vessels were detected moving longitudinally between FAD B and D (9.24 km) on the same day, yet no vessels were detected moving between FAD F and FAD D or B. In total, 27 vessels were observed to revisit the same FAD more than once per day, and some vessels several times, which suggests that vessels may concentrate their activity near FADs closest to their home port. Supporting evidence of this comes from vessel tracking data that show that a vessel preferentially shifted its fishing effort after two FADs were damaged and lost nearest the vessel's home port (Fig. 6). The loss of the FADs extended the range of the vessel involuntarily. Based on these observations, visits from vessels to FADs from popular fishing ports outside the immediate study area (e.g. Arecibo, west of Manati; and Fajardo, east of Rio Grande) are likely but infrequent given the cost of travel and difficulty of access. Future research should address whether FADs outside of the immediate San Juan area (e.g. FADs A, G, and H) are utilized less in terms of hours of activity and visits per day, but also by fewer different vessels than FADs B, C, D, E, and F (e.g. FADs within 30 km of San Juan Bay). The results here suggest there would be differences (Table 3). This becomes important when gauging FAD performance based on overall visit rate or number of distinct vessel visits, with the latter representing increased fishing opportunities for more vessels in the context of an open access FAD programme.

On a per FAD basis, ocean access determined FAD activity dynamics. At FAD D, the vast majority of repeats (81%) occurred within an hour. At FADs F and B, half of the repeats were greater than an hour apart. Points of entry at these locations are a boat ramp and a shallow channel that periodically shoals (Atkins 2012), respectively (Fig. 1). FAD D is the closest to the largest port in this region and the only one that can safely moor large vessels with considerable drafts. Interestingly, small vessels were classified most at FAD F and large vessels most at FAD D. In addition, results show differences in incidence of images with unknown vessels by FAD location, with FAD D having the greatest number of images and amount of time per day with vessels active in the vicinity but not approaching within a classifiable range. While the incidence of unclassifiable vessels is a major limitation of video monitoring, the information is still useful for showing consistent fishing activity in the area (Supplementary material, Fig. S2: #3), which is helpful when trying to gauge the concentration of activity over small spatial scales. This becomes important to prevent the placement of a FAD in a location known to support reproductive dynamics (e.g. spawning) of fish populations.

Cost-benefit analysis

Video monitoring represents a new method for quantitatively sampling fishing vessel activity which has costs and benefits when compared with traditional PPMW techniques (Table 4). Generally, video data represent a great technique for gauging FAD activity on short time scales, but on longer time scales it should be incorporated with other survey techniques. Ultimately, the combination of PPMW survey techniques with video sampling could prove very useful for gathering more detailed results of fishing dynamics near FADs. Indeed, the combination of video and web-based techniques here allowed catch quantity and composition to be related to vessel activity at the FADs.

Management and future research priorities

One of the motivating factors for this work was that the new method and information obtained would have direct application for describing spatio-temporal fishing activity relative to FADs in other locations. Video monitoring provided insights into FAD fishing activity down to the level of an individual vessel, information that can be used to improve FAD rules and regulations, better understand FAD fishing activity, better determine FAD deployment locations, and structure surveys that minimize costs but maximize the potential to approximate FAD catch and effort in the future.

Given the results of this study, local management agencies [e.g. the Caribbean Fisheries Management Council and the Department of Natural and Environmental Resources (DNER)], and fishing marinas should consider introducing additional questions to established port and tournament-sampling strategies in order to better evaluate FAD use patterns and performance. For example, management agencies could place an emphasis on quantifying the frequency of gear types being used at the FADs, and marinas that host fishing tournaments can determine whether fish were caught within a mile of a FAD during their tournaments. Gathering these types of data and comparing them with in situ camera data can provide FAD performance values that, when combined with catch, can be used to justify the need and longevity of the programme in PR (or any other location where FADs exist). This could also be useful for quantifying the performance of individual FADs, in terms of both activity levels and catch success, to better determine the amount, spacing and proper location to deploy FADs in the future.

Given the noticeable differences in sector use by TOD and DOW, another strategy could be to manage the daily timing of FAD fishing by sector to realize the full productivity of all sectors [i.e. maximize catch of locally sourced seafood (commercial sector; early am); maximize the opportunity of catching billfish (charter fleet; late am to sunset); and maximize fishing opportunities (recreational fleet; late am to sunset)]. This could take the form of separate licensing by sector and allocating specific fishing days and times based on the type of licence purchased (Guyader et al. 2013). Another option that may help increase FAD productivity is to limit daytime fishing activity to early afternoon (e.g. 1600-1730: the period of the day with the lowest fishing activity levels) to allow for a period of stock rebuilding and recruitment.

The technique described herein has potential to be compared with the co-occurrence of FAD fish biomass and diel movements of fish (e.g. scombrids, coryphaenids, istophorids and thunnids) targeted at the FADs. Multi-frequency echo sounder buoys are commonly used on dFADs by industrial fishermen to estimate the amount of fish biomass by depth based on signal intensity at a FAD (Lopez et al. 2014). If similar instruments are deployed on FADs equipped with video cameras, the amount and change in biomass of fish aggregating around the FADs (Freon and Dagorn 2000, Girard et al. 2004) could be related to fishing activity. In addition, fishing activity could be compared with the diel movements of fish at FADs (see, Dagorn et al. 2007, Taquet et al. 2008, Whitney et al. 2016) and compared with catch reports to allow estimates of when specific species may be more vulnerable to fishing. These strategies could provide fishers with information to adapt fishing strategies by TOD and managers to estimate fishing mortality and biomass depletion.

It is important that future research incorporate fishery-dependent socio-economic and catch data simultaneously with in situ vessel detection to provide a more complete picture of the FAD fleet dynamics and performance in this region; these techniques can be scaled up and applied to any location where FADs exist. The most economical surveys to add would be phone-and web-based surveys. Lastly, in order to realize the full benefits of this fishery-independent survey technique for FAD management, it is important to increase recording time, automate the detection of vessels through image recognition (Elias et al. 2016) and link cameras to the web (Nazir et al. 2017) to better understand seasonal fleet dynamics, fishing activity trends and institute near real-time compliance of local and regional fishing regulations to ensure sustainable development and use of FADs in the US Caribbean and beyond.

ACKNOWLEDGEMENTS

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SUPPLEMENTARY MATERIAL

The following supplementary material is available through the online version of this article and at the following link: http://scimar.icm.csic.es/scimar/supplm/sm04730esm.pdf

Table S1. – Camera type, power source and setup used in this study.

Fig. S1. – A camera was redeployed to conduct a range test to determine approximately how far a vessel in an image was from the FAD. Image (1) is a vessel that is 70 metres from the FAD; Image (2) is the same vessel 132 m from the FAD. These photos were used to determine the proximity of vessels to the FADs.

Fig. S2. – Clockwise from upper left: (1) Vessel #55 earliest buoy visit 0542; (2) Vessel #143 latest buoy visit 1823; (3) Yellow arrows indicate highest number of vessels present in single image; all were unclassifiable and designated as unknown; (4) tanker.

Fig. S3. – Clockwise from upper left: (1) Vessel #89 known charter vessel trolling; (2) Vessel #132 likely recreational vessel trolling named "g_yacht_blue_pin_strips_dbl_window"; (3) Vessel #9 known commercial vessel trolling; (4) Vessel #23 likely recreational vessel drift fishing with handlines named "g_blank_boat".

Fig. S4. – Clockwise from upper left: (1) Vessel #69 likely recreational spearfishermen with spears and floats visible; (2) Vessel #12 known commercial vessel with gaff in hand; (3) Vessel #19 likely recreational vessel jigging and drift fishing with sargassum present; (4) Unknown vessel trolling away from the buoy with a fish visible (it appears to be a dolphinfish) in the foreground.

Fig. S5. – Clockwise from upper left: (1) Vessel #50 present in squall; this vessel was named "g_very_sm_lowris_centercons"; (2) Vessel #57 shown tying up to buoy F; (3) Example of image with vessel and birds blocking a portion of the field of view; (4) Example of image with vessel with a bird blocking a greater portion of the field of view.

Fig. S6. – Clockwise from upper left: (1) Unknown vessel present with foggy lens and bird present; (2) A dolphinfish is present in the lower left portion of the image; (3) An unidentified tern bird with a fish in its beak; (4) An unidentified marine animal.

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Use of video monitoring to quantify spatial and temporal patterns in fishing activity across sectors at moored fish aggregating devices off Puerto Rico

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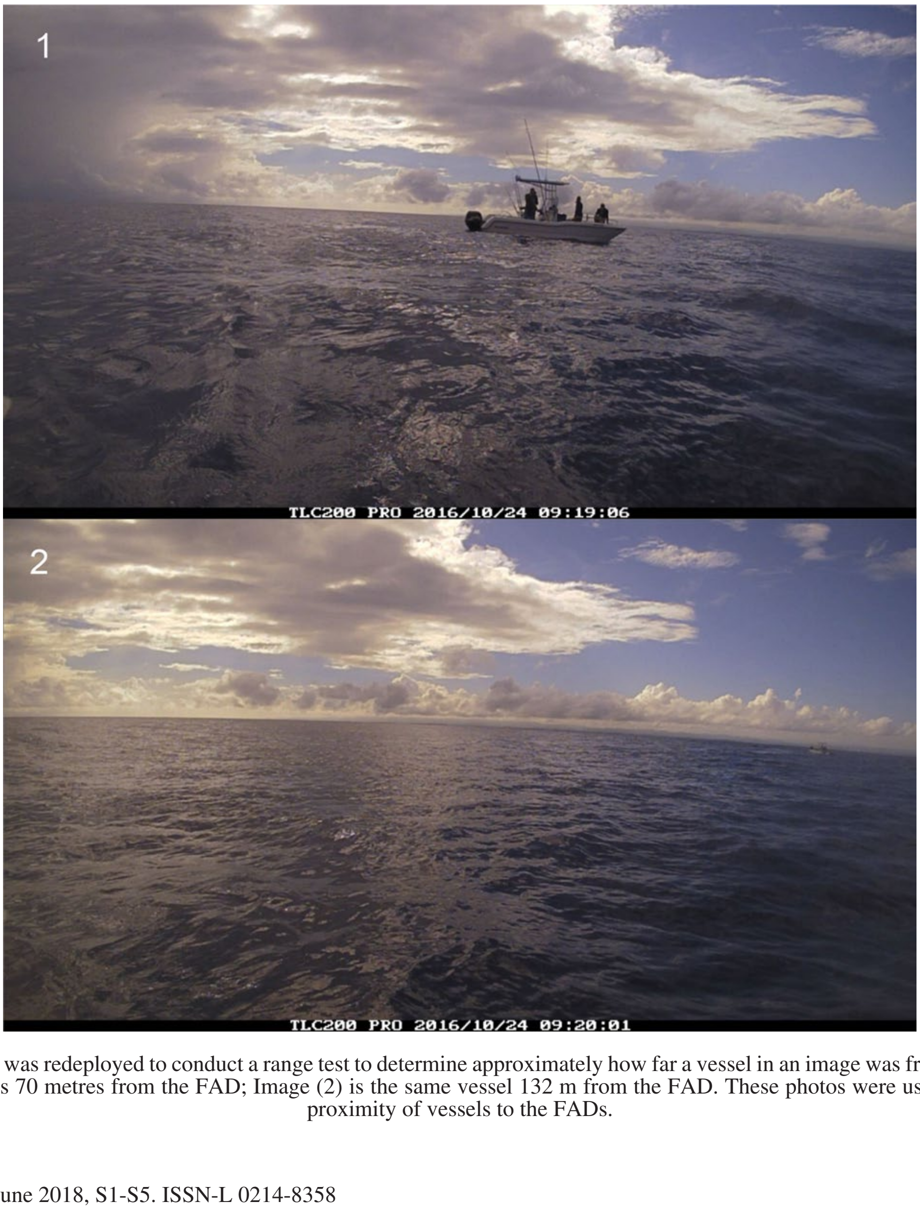
Nilda Jimenez

Supplementary material

Table S1. – Camera type, power source and setup used in this study.

Make and Model	Brinno TLC Pro 200
Power Source	(4) AA lithium ion batteries
Frame Rate	30 frames per second
Image Time Interval	1 image every 30 seconds
Time-lapse Video Format and Resolution	.AVI & 1280 x 720 pixels
Field of View and Focal Length	112º & 19 mm (35 mm equivalent)
Timer off	1930-0530
Timer on	0530-1930
Timestamp	on
White Balance	auto
Image Quality	best
Scene	twilight
HDR	high
Exposure	n/a
Saturation	n/a
Contrast	n/a
Sharpness	n/a
Low Light Recording	on
Set Date & Time	local internet time in deployment region
LED	Off
Band Filter	None
Housing	ATH 120 Weather Resistant Housing
Memory	32 gigabyte SD card
Additional Protection	Plastic roof and duct tape
Mounting	12” hose clamps and two industrial cable ties



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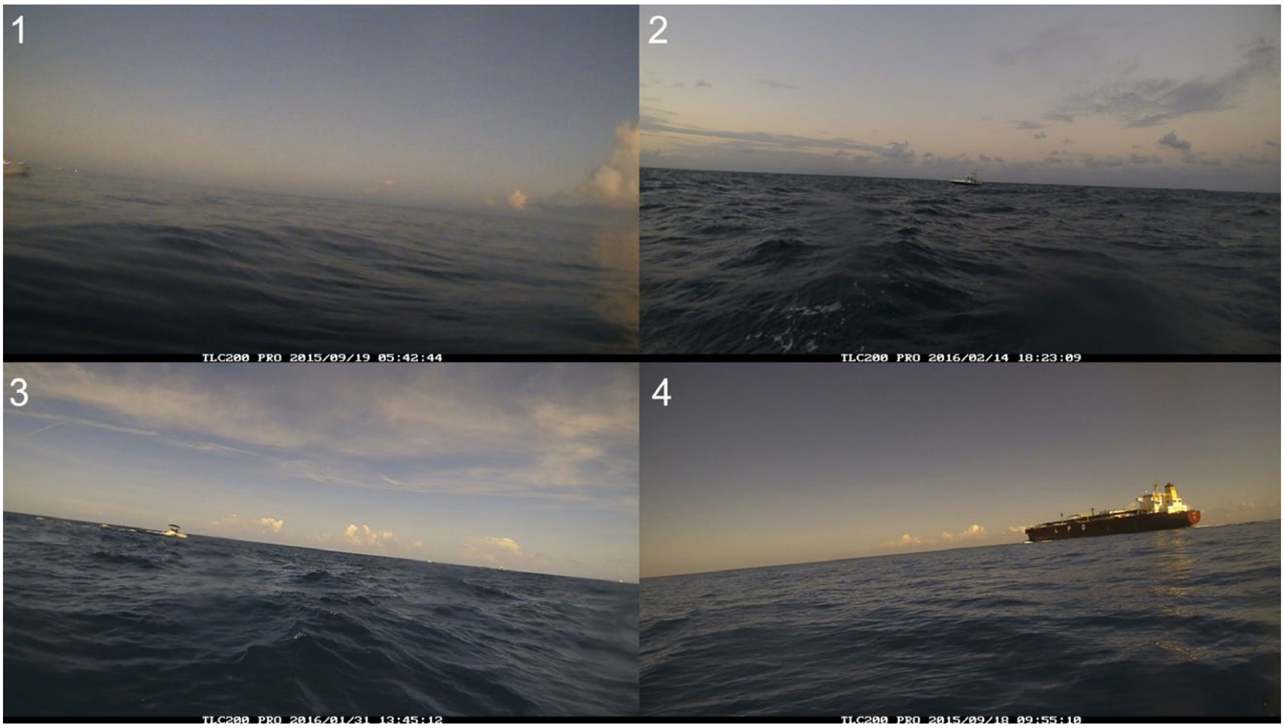

Fig. S2. – Clockwise from upper left: (1) Vessel #55 earliest buoy visit 0542; (2) Vessel #143 latest buoy visit 1823; (3) Yellow arrows indicate highest number of vessels present in single image; all were unclassifiable and designated as unknown; (4) tanker.

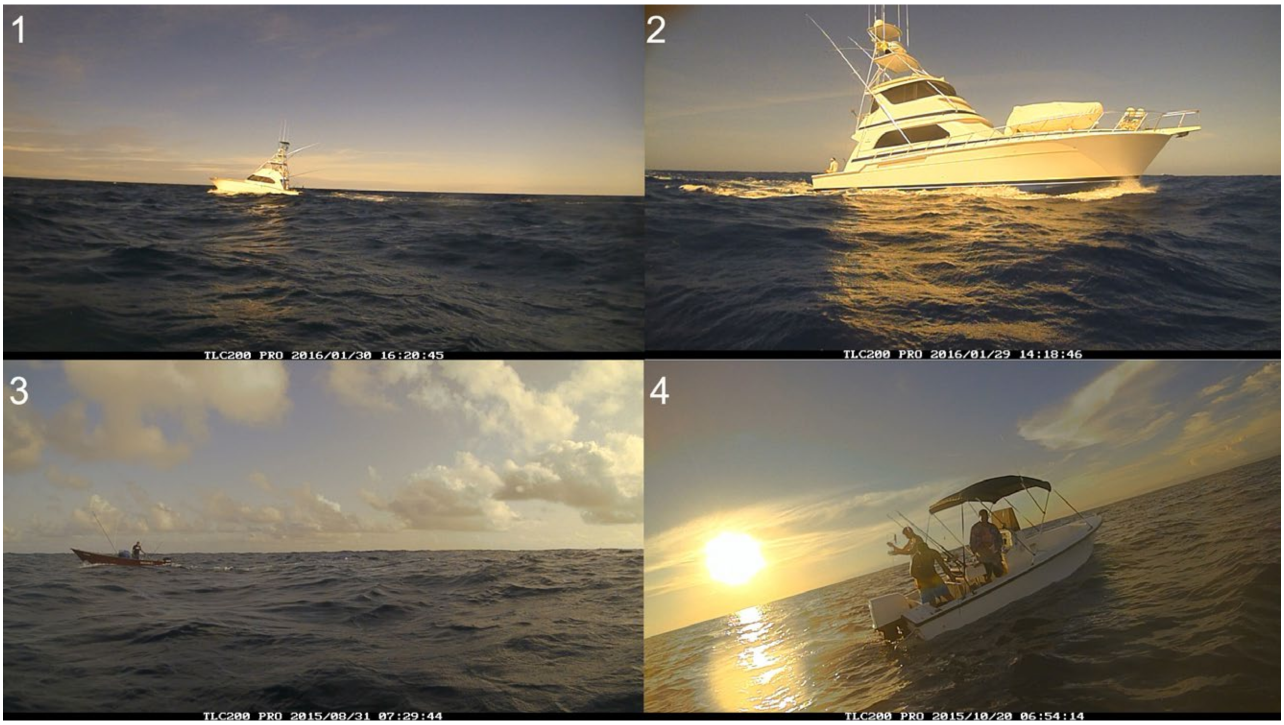

Fig. S3. – Clockwise from upper left: (1) Vessel #89 known charter vessel trolling; (2) Vessel #132 likely recreational vessel trolling named “g_yacht_blue_pin_strips_dbl_window”; (3) Vessel #9 known commercial vessel trolling; (4) Vessel #23 likely recreational vessel drift fishing with handlines named “g_blank_boat”.

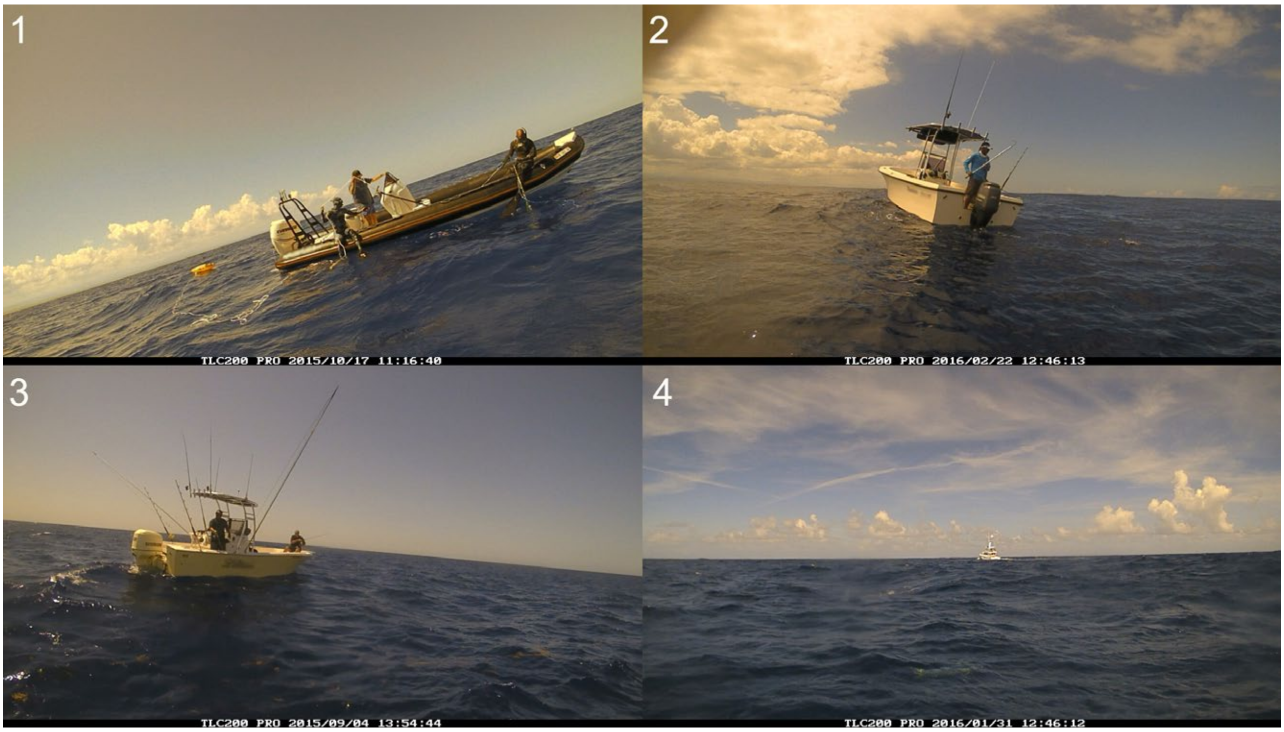

Fig. S4. – Clockwise from upper left: (1) Vessel #69 likely recreational spearfishermen with spears and floats visible; (2) Vessel #12 known commercial vessel with gaff in hand; (3) Vessel #19 likely recreational vessel jigging and drift fishing with sargassum present; (4) Unknown vessel trolling away from the buoy with a fish visible (it appears to be a dolphinfish) in the foreground.

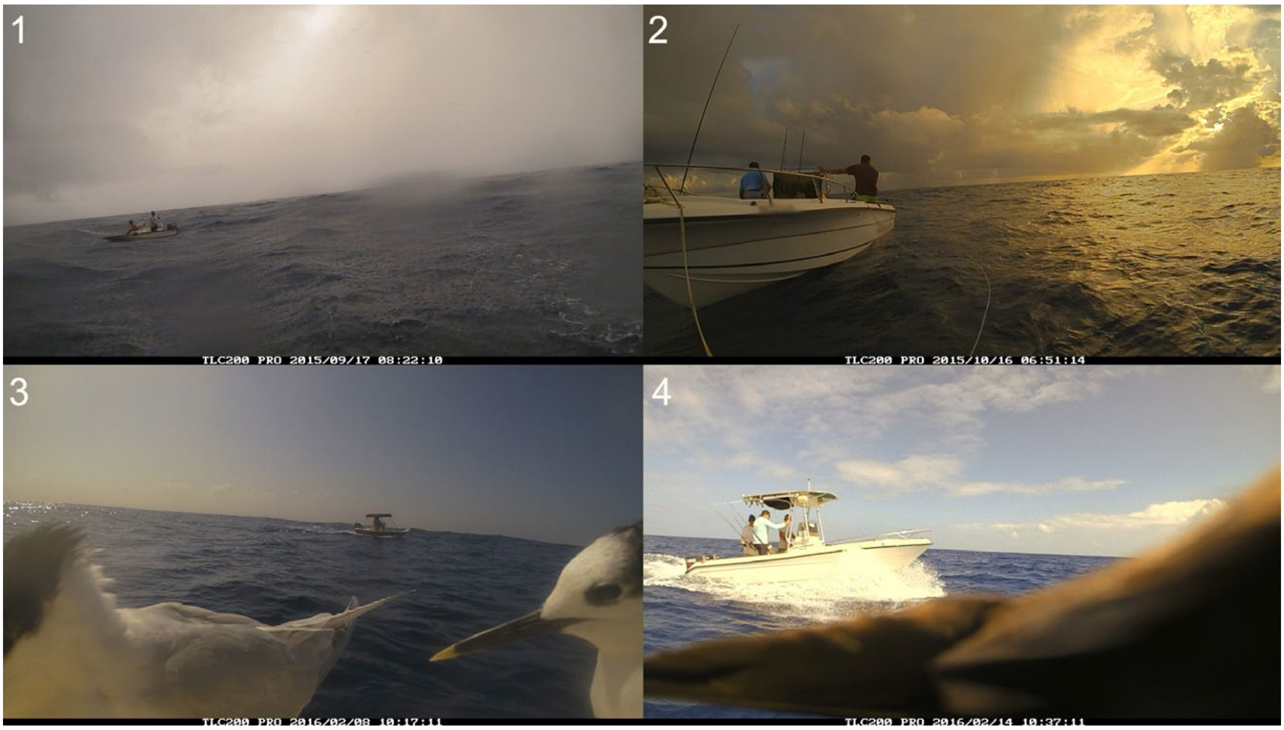

Fig. S5. – Clockwise from upper left: (1) Vessel #50 present in squall; this vessel was named “g_very_sm_lowris_centercons”; (2) Vessel #57 shown tying up to buoy F; (3) Example of image with vessel and birds blocking a portion of the field of view; (4) Example of image with vessel with a bird blocking a greater portion of the field of view.

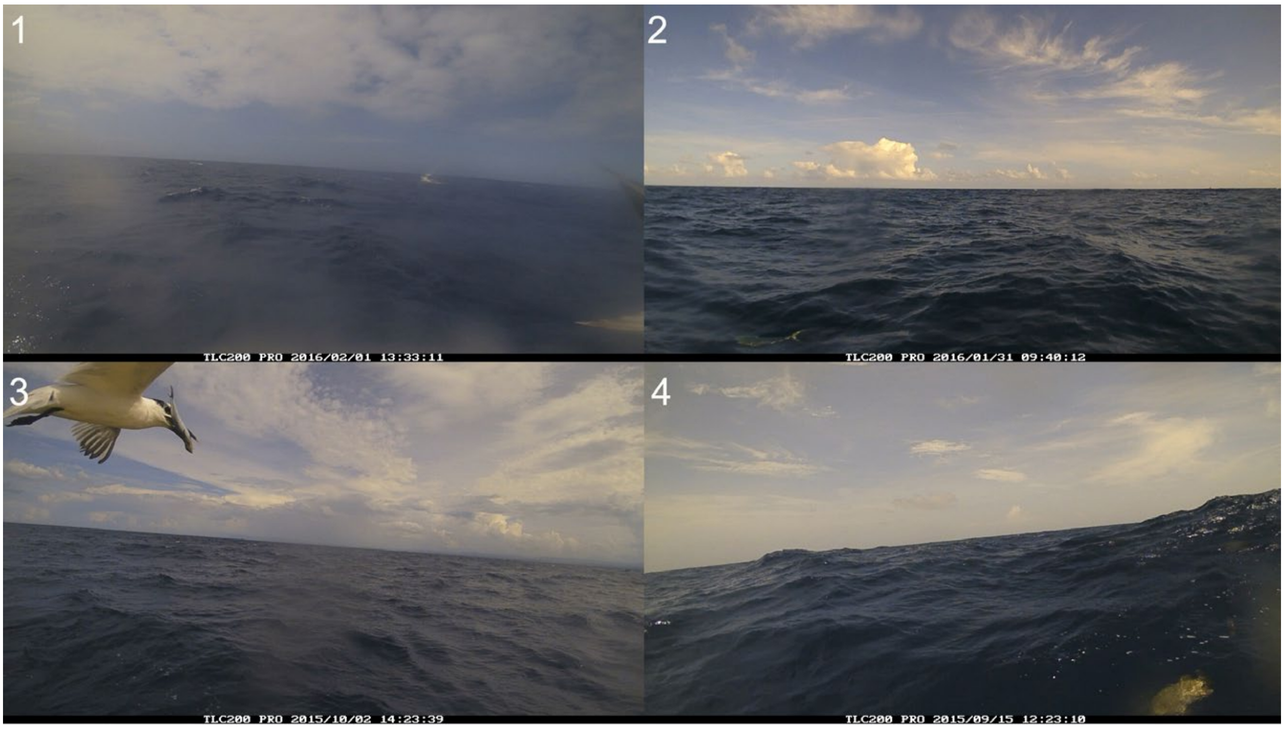

Fig. S6. – Clockwise from upper left: (1) Unknown vessel present with foggy lens and bird present; (2) A dolphinfish is present in the lower left portion of the image; (3) An unidentified tern bird with a fish in its beak; (4) An unidentified marine animal.