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Passive acoustics as a tool to quantify/characterize vessel activity at fish spawning aggregation sites

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ABSTRACT

The vulnerability of fish spawning aggregations (FSA) to fishing pressure has led to seasonal fishing bans for certain aggregating reef-fish species and seasonal or permanent closures of known FSA sites throughout the Caribbean. While discerning the degree of compliance with fisheries regulations is essential in evaluating their success, this information can be scarce when opportunistic surveillance from enforcement vessels is minimal or absent. We used passive acoustic recorders to determine the temporal patterns of vessel activity at three red hind, *Epinephelus guttatus*, spawning aggregation sites off western Puerto Rico with varying levels of protection (Buoy 4: no regulation, Abrir la Sierra (ALS): seasonal closure, and Mona: permanent closure) during the closed (January and February) and open (March) periods for the capture of red hind. We proposed that dynamic vessel sounds (e.g., gear shifting, sudden changes in speed) at known FSA sites and during aggregating periods could be indicative of fishing activity. A band-limited energy detector was used to detect vessel sounds, with detections grouped into discreate vessel events and classified as having only constant vessel sounds or containing dynamic vessel sounds. While most of the vessel events consisted of constant vessel sounds at all sites, events with dynamic vessel sounds were greatest at Buoy 4, followed by ALS and only one detected at Mona. Average events with dynamic vessel sounds were greater during the closed than the open period at Buoy 4, while the opposite was found at ALS, and red hind calling activity was significantly correlated with vessel detections during 3 years at Buoy 4. Results suggest fishers may have been targeting red hind at Buoy 4 despite red hind's seasonal closure, and the site-specific regulations at ALS may have served as a deterrent and divert fishing effort towards other areas. Acoustic records can reveal high-resolution temporal patterns of vessel activity and of events with dynamic vessel sounds, which could be used to infer about fishing activities and complement other surveys to provide estimates of compliance.

1. Introduction

The occurrence of mass aggregations of fish at recurrent times and locations in order to spawn, is a necessary event for the reproduction of certain reef fish species, including some groupers of the family Epinephelidae (Domeier and Colin 1997). In addition to being ecologically important events (which host large numbers of conspecific adult fish at certain times), fish spawning aggregations (FSA) are key events that support the fishery resource associated with coral reef ecosystems (Sadovy et al., 2012; Domeier and Colin 1997). Hence, they are particularly vulnerable to fishing pressure, and have been traditionally exploited by commercial and recreational fishers due to the predictability of aggregations in space and time, and the opportunity to capture many fish over short time periods (Sadovy et al., 2012). Coupled with slow growth and late sex maturation, groupers have been among the most vulnerable aggregating species (Sadovy 1997; Reynolds et al., 2005). The Nassau grouper (*Epinephelus striatus*), for example, which used to be the main grouper species landed in the Caribbean until the mid-1980s, was so heavily fished that the species is considered commercially extinct in some islands (Sadovy 1997).

Yet, even though many reef fish species of commercial value aggregate to spawn, a small portion are effectively protected (Sadovy De Mitcheson et al., 2008). A review of marine managed areas in the Caribbean found that very few no-take marine reserves were specifically designed to incorporate FSA sites within the boundaries (Schärer-Umpierre et al. 2014). In Puerto Rico, the constant decline in landings of

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commercially important reef species (Appeldoorn et al., 1992) and the vulnerability of FSA sites has led to the implementation of seasonal fishing bans for certain species island wide as well as seasonal or permanent closures of confirmed FSA sites (PR DRNA 2010; CFMC 1996). Due to their ecological importance and susceptibility to human-induced degradation, some of these managed FSA sites were designated as Essential Fish Habitats or Habitat Areas of Particular Concern as amendments to the local management plans based on the Magnuson-Stevens Fishery Conservation and Management Act (CFMC 1996). Still, while marine protected areas (MPAs) and seasonal fishing bans are intended to help restore or maintain exploited fish stocks, among other benefits, by restricting the harvesting of part of the fish population in critical habitats (Bohnsack and Ault 1996), the benefits largely depend on the degree of compliance with regulations (Sale et al., 2005; Byers and Noonburg 2007; Bergseth et al., 2015), and inefficient enforcement can undermine these benefits (Sadovy de Mitcheson et al., 2008). Therefore, understanding the extent and patterns of compliance with fisheries regulations is essential in evaluating the success of MPAs, No-Take Zones (NTZ) and seasonal fishing prohibitions (Sale et al., 2005).

Assessing compliance related to vessels activity in MPAs, however, is a challenging task, as it requires the detection of potential poaching events as well as the frequency at which those events occur (Bergseth et al., 2015). Large commercial vessels can be tracked using the U.S. Coast Guard's Automatic Identification System (Hatch et al., 2008); however, the small-scale fishing fleet of Caribbean islands is characterized by small vessels that are not equipped with, nor are they required to have, this technology onboard. The average commercial fishing vessel in Puerto Rico has a length of about 6.4 m and is powered by a single outboard engine (Agar and Shivlani, 2016), which is very similar to most of the privately owned recreational fishing vessels. Information regarding the location or distribution of commercial fishing vessels can only be obtained through systematic surveillance by enforcement agencies or reports by other vessels (Witt and Godley 2007). This information, though, is quite limited especially in the coastal waters of Puerto Rico, where enforcement of fishing regulations is minimal or often absent (Kimmel and Appeldoorn 1992; García-Sais et al., 2008; Marshak and Appeldoorn 2008). Therefore, information on how often vessels frequent an FSA site (protected or not) and what fishing activities occur there (e.g., if fishers are following seasonal closures or not) is rarely available.

A novel and perhaps more efficient way of monitoring vessel activity is by recording sounds generated by vessel engines with the use of passive acoustic recording instruments (Pollara et al., 2017). Recent studies have suggested that soundscapes, and especially anthropogenic sounds, may reflect environmental conditions, biodiversity and human use of critical habitats (Kaplan and Mooney 2015; Simard et al., 2016). Therefore, quantifying the occurrence and intensity of anthropogenic sounds, specifically vessel use, may indicate the potential impact of human activity (by capturing fish aggregating to spawn or by noise affecting their behaviors and reproduction) during the FSA. Although the use of passive acoustic recorders to detect vessel activity was originally employed with military or surveillance purposes, it was first presented in marine conservation studies by Lammers et al. (2008), where they suggested it is a useful tool to monitor vessel activity in protected areas such as marine reserves or sanctuaries, where visual monitoring and access is often logistically challenging. Since then, several studies have used passive acoustics to determine the extent of human activity in tropical reef ecosystems. Sorensen et al. (2010) deployed recorders near an MPA boundary in the Hawaiian Islands to monitor the locations where poaching was most likely to occur. Kaplan and Mooney (2015) used this tool to characterize the diel, weekly, and summer trends in boat sounds at three coral reefs off St. John in the U.S. Virgin Islands, while Simard et al. (2016) quantified boat visitation rates using passive acoustic recorders at four artificial reefs paired with four neighboring natural reef sites in the eastern Gulf of Mexico to measure participant use of those areas. Only recently did a study use acoustic recordings to estimate potential fishing effort of a recreational red snapper (*Lutjanus campechanus*) fishery at offshore artificial reefs based on the sound characteristics of fishing vessels and their temporal patterns (Boyle et al., 2022). As fishing vessels aggregated over the limited area encompassed by the submerged artificial structures, they were able to easily detect sounds indicative of site-specific fishing activity, which revealed reduced fishing effort at unpublished vs. published sites, a decrease in effort as the season advanced, and diel patterns. Yet, no mention has been found in the literature of using this tool to monitor vessel activity nor to quantify the relationship with vessels engaged in potential fishing activity in FSA sites.

Certain characteristics of vessel engine sounds may be associated with a vessel engaged in fishing (Simard et al., 2016; Boyle et al., 2022). We propose that dynamic vessel sounds, such as gear shifting noise, dramatic changes in speed and periods of vessel in idle or neutral position, at known FSA sites and during periods when fish aggregate to reproduce may be indicative of fishing activity, as vessels attempt to maintain their position, after drifting with wind or currents near the shelf-edge when using bottom-lines or when a vessel is tracking SCUBA divers from the surface. This method has also been termed "live-boating" (Boyle et al., 2022). However, this technique has some limitations, as its easier to detect non-compliance with the presence of a vessel that is fishing in an area where no fishing is allowed, like a no-take zone (NTZ) or marine reserve (MR) than to determine if they are catching certain species or using a restricted gear to obtain a legal catch when others are allowed (Bohnsack and Ault 1996). However, if temporal patterns of vessel activity (especially with those that contain dynamic vessel sounds) correlate positively with the time when groupers are expected to aggregate to spawn at a particular site, it is likely that vessels are interacting with spawning stock at the aggregation site when they are most vulnerable. Past aerial surveys done in 2002 and 2003 documented concentrations of fishing vessels at red hind aggregation sites along the western shelf-edge of Puerto Rico for a limited time period and during the expected red hind spawning season (Johnston et al., 2006).

Within this context, the main objective of this study was to determine the temporal patterns of acoustic signatures produced by vessels at three red hind, *E. guttatus*, spawning aggregation sites off western Puerto Rico with varying levels of protection. Temporal patterns of vessel events per day were described across years and between aggregating and non-aggregating periods. Vessel events were classified into two categories: those that had constant vessel sounds and those that had dynamic vessel sounds during the duration of the vessel detection event, and they were used to determine whether vessel events indicative of being engaged in fishing activity (those with dynamic sounds) occurred during site-specific fishing bans. Under the model of high compliance with fishing regulations at aggregations sites, it was predicted (i.e., hypotheses) that the temporal pattern of vessel sounds across all years:

1. Will be different at each aggregation site with different fishing regulations. It was further predicted that vessel events with dynamic sounds would be less frequent in a no-take zone during the area's closed season.
2. Will be different between aggregation and non-aggregation seasons at each site, as the capture of red hind is banned island-wide during a 90-day seasonal closure (December 1 – February 28) regardless of the fishing regulations at a particular site.
3. Will be independent of the temporal trends of red hind calling activity.

2. Methods

2.1. Site descriptions and regulations

Passive acoustic monitoring (PAM) has been ongoing at three FSA sites off western Puerto Rico: Abrir la Sierra (ALS), Buoy 4 and Mona

Island (Fig. 1); to document the presence and calling rates of red hind (Mann et al., 2010; Rowell et al., 2012; Zayas-Santiago et al., 2020) as well as other soniferous grouper (Schärer et al. 2013, 2014) species that aggregate to spawn. Red hind is a protogynous species that forms yearly spawning aggregations at recurrent sites, spawning on a lunar cycle during the months of December through March (Colin et al., 1987; Shapiro et al., 1993; Sadovy et al., 1994). Apart from Mona Island which is a multi-species spawning site (*Mycteroperca venenosa* aggregate from January through May; Schärer et al., 2012), red hind is the only grouper known to aggregate at these multi-species spawning sites. Another reason for choosing these sites is that all three have distinct fishing regulations or levels of protection, different degrees of isolation (distance from coast) and hence different rates of vessel activity were expected.

Abrir la Sierra is a well-studied red hind spawning aggregation site located in the U.S. exclusive economic zone (EEZ) of the western insular shelf of Puerto Rico (Mann et al., 2010; Rowell et al., 2012). This site is one of three seasonally closed MPAs with red hind aggregations off the west coast of Puerto Rico (Fig. 1). This seasonal MPA covers 29.5 km^2 of submerged habitat closed to all fishing from December 1 – February 28 (CFMC 1996), which includes most of the red hind spawning season. Buoy 4 is also located in the EEZ waters approximately 10 km south-southeast of ALS on the same shelf-break zone as ALS. This site is open to fishing year-round, but seasonal bans for certain species apply including a closed season for red hind from December 1 – February 28 (50 FR 622.435, also applies to and compatible with local Puerto Rico regulations: PR DNER 2010) and a ban on conch fishing in federal jurisdiction waters only.

The Mona and Monito Islands are the most distant and isolated islands of the Puerto Rico archipelago (72 km west of P.R.). Together, they form the largest marine natural reserve in Puerto Rican waters, which encompasses 9 nautical miles from the coast of both islands (Schärer et al., 2010). Within this reserve, a permanent NTZ has been established for waters extending up to 1 nautical mile from shore of both islands, which includes most of the insular platform around both islands (PR DNER 2010). The Mona Passage, which divides the Mona/Monito and Puerto Rico insular platforms, is thought to be a biogeographic barrier for some species due to oceanographic patterns and depths found there (>1,000 m; Taylor and Hellberg 2003; Baums et al., 2006).

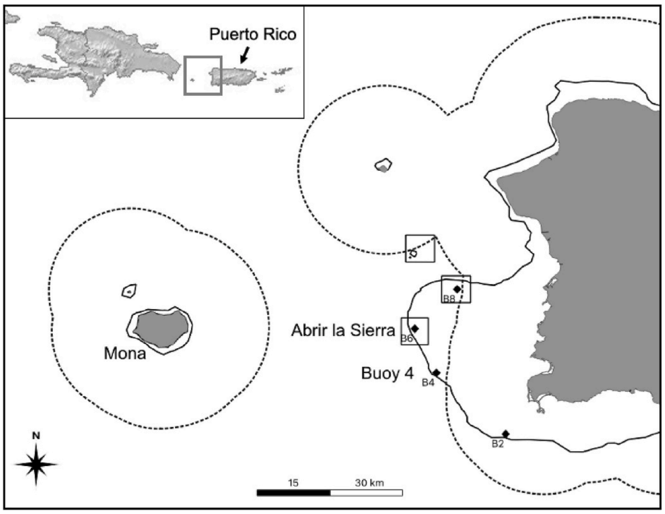

Fig. 1. Deployment sites of acoustic recorders (Buoy 4, Abrir la Sierra, Mona) off western Puerto Rico, the navigational aid buoys (black diamonds), the Exclusive Economic Zone (EEZ) limit (dashed line) 9 nautical miles from shore, the 50-m depth contour (solid line) and the Caribbean Fisheries Management Council (CFMC) seasonal MPAs (squares).

2.2. Acoustic data collection and analysis

Acoustic recordings from three sites were collected with passive acoustic recording units known as digital spectrogram recorders (DSG, Loggerhead Instruments), which are designed to record low frequency ambient sounds. The DSG consists of a hydrophone attached to an enclosed polyvinyl chloride cylinder containing a circuit board with microSD cards (64 or 128 GB) and 24 D-cell alkaline batteries. The hydrophone sensitivity, gain and sampling rate varied among deployments (sensitivity: -179.5 to-180.1 dB re 1 μPa^{-1}, gain: 2–20 dB, sampling rate: 10–44.1 kHz) due to occasional upgrades of hardware and/or firmware of the recording units. A recording schedule of 20 s every 5 min has been consistently used since the first deployments in 2007, as it has been shown to be sufficient to record the soundscape diel variations and conserve enough electrical power for a six-month deployment. Each 20 s recording is generated as a single.wav file (hereon referred to as "sound file") and recorded on microSD cards with a date and time stamp. The recording units have been deployed yearly at each site in December and recovered no earlier than April. The units were deployed yearly from 2016 to 2020 at all three study sites.

Recordings from deployments at ALS, Mona Island and Buoy 4 from 2016 to 2020 were processed to extract, classify and count vessel and fish sounds. Due to equipment failure the units deployed at Mona Island and Buoy 4 did not record during the 2016 and 2018 deployments respectively. A three-month period (January–March) was selected for signal processing from every deployment. This period encompasses two months of the closed season for red hind (January and February) followed by the month of March, when fishing for this species is open at Buoy 4 and the fishing ban at ALS expires, but Mona's NTZ is closed to all fishing year-round.

The first step in the processing of recordings for vessel detection was to apply a band-limited energy detector (BLED) in the sound analysis software Raven (version 1.5). This detects when the energy over a specific frequency bandwidth exceeds a threshold for a specified range of durations. The detector was first tested on nine days (applied per day at a time, as one continuous spectrogram of sound files from 0:00–23:55 AST pasted together end-to-end) that a known commercial fishing vessel (FV; 6.7 m in length, fiberglass hull with two 90-HP four-stroke engines) visited one of the study sites (Buoy 4) for research purposes. The parameter values of the BLED were adjusted to maximize detection probability of FV sounds. A bandwidth of 0.05–1.5 kHz was selected as a previous study showed that typical vessel sounds in Hawaii consisted of low-frequency harmonics (<1.5 kHz) caused by propeller movement (Sorensen et al., 2010), and sporadic geophonic sounds (i.e., from seismic events) and electrical noise of the recording unit are found mostly below 50 Hz (Wenz 1962). While most of the detections did not contain vessel sounds (i.e., sounds produced by underwater currents, whales, fish), it was successful in detecting FV on all occasions it visited the site. Using this detector not only provided a means to process many sound files quickly, but also a way of filtering only those files that were above a minimum specified energy threshold (>9 dB signal-to-noise ratio, 40% minimum occupancy) and therefore only consider vessel events that were relatively close to the recording unit.

The detector, with fixed parameter values, was subsequently applied to all sound files in the same manner as they were for FV, with spectrogram parameter values specified according to the sampling frequency of the unit in each recording season (2016 and 2017: Hann window, 1024 window length; 2018–2020: Hann window, 4096 window length). Each detection on the spectrogram was visually inspected (0–1.5 kHz visible bandwidth) to verify it contained sounds like those produced by vessels, and those that did were noted with their corresponding sound files and time stamp. Detections of known research vessels present at a site were removed from the data set. For every successful vessel sounds detection, we visually and aurally inspected sound files that were adjacent to the detection to estimate the entire length of the vessel's presence (constituting a vessel event), and determine if a vessel event had sound files with only constant vessel sounds (as when a vessel is passing by the recording unit without stopping) or if it contained dynamic vessel sounds (indicative of a vessel that is trying to maintain its position either to target a specific site or to track divers). This was done because some sound files with vessel sounds during a vessel event may not have been detected if they didn't meet the requirements of the parameters established by the BLED. A vessel event was defined as a period lasting from seconds to hours which contained sounds produced by a discrete vessel, which was characterized by its unique acoustical signature. An event could have periods without vessel sounds, such as when the vessel is in idle due to the low amplitude of the sounds generated by the vessel in this state. No limitations were established for the length of a period without vessel sounds during an event. When vessel sounds with a distinct acoustic signature was detected during a vessel event, they were treated as two discrete events.

The main fishing methods for capturing reef fishes, including red hind (hook and line, jigging, multi-hook lines and spearfishing), require the vessel to maintain position by shifting gears often due to the proximity to the shelf-edge and strong surface currents. An example of this can be seen in Fig. 2, which shows the spectrogram of two recordings of fishing vessel FV: one traveling at a constant speed (top; dominant frequency: 72.11 ± 7.45 Hz), and another with dynamic sounds when the vessel was idle or in neutral gear then shifting momentarily to reverse and back to neutral (bottom). It should be noted how vessel sounds are almost undetectable when vessel is in an idle or neutral position due to its low amplitude. According to these characteristics, all vessel events were classified into two categories: constant sounds and dynamic sounds (Table 1). Additionally, vessel events that contained putative anthropogenic sounds (i.e., sounds from the bubbles exhaled by SCUBA divers, spearguns, conch shell hammering) were also noted. Recreational SCUBA diving is rare at these sites since they are located at least 18 km from west coast ports.

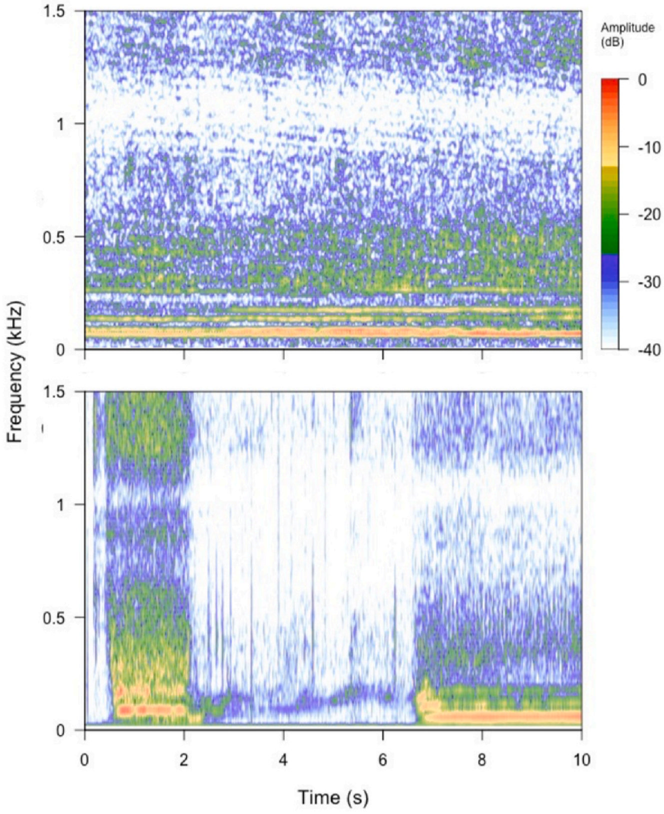

Fig. 2. Spectrograms showing a fishing vessel at constant speed (top) and idle (bottom) with a short burst of shifting into gear (1–2 and 7–10 s). Amplitude is expressed with a relative decibels (dB) color scale. All spectrograms were filtered with a finite impulse response filter (0–1.5 kHz). Spectrogram parameters: Hanning window, 1024 window length, 88% window overlap.

Table 1
Classification criteria for vessel events.

Category	Vessel Event
Constant	Vessel sound is constant throughout the time duration of that event, with no gaps or interruptions in the sound signal.
Dynamic	Vessel sound is not constant throughout the event and contains at least one of the following: i) constant vessel sounds but different dominant frequencies ii) interruption in vessel sounds with gaps in the sound signal iii) dynamic sounds (i.e., gear shifting "pops", actively increasing, or decreasing amplitude)

To assess the performance of the BLED, all the sound files (26 208) from 2016 at Buoy 4 were visually and aurally inspected to determine if they contained vessel sounds (regardless of its intensity). In addition, all the detections that were incorrectly classified by the BLED as having vessel sounds (false positives) were noted during this time-period only. These data were then presented as percentages of successful detections, false positives, false negatives and of the vessel events with dynamic sounds that were successfully detected. The performance of the BLED was only determined for the sound files from 1 year at Buoy 4, due to the similarities in the biophony (i.e., sounds produced by fish, whales and invertebrates), geophony (i.e., sounds generated by seismic events, currents and the breaking of waves at the surface) and anthropophony (i.e., vessels and sounds of human origin) components of the soundscapes among sites, and seasonal changes in the biophony during the months recorded recurred yearly.

Vessel events were organized as monthly averages (number of events per number of days of that month) to detect any temporal differences per month and category, and to compare across years and among sites. Vessel events were also averaged per closed season (January 1–February 28) and open season (March 1–31) to compare between them and compare across years and among sites. To determine if the temporal patterns of vessel activity were independent of those of red hind calling activity, the number of sound files with red hind courtship associated sounds (CAS) found in them during the period of 18:00–19:00 AST was compared against the number of sound files that were detected by the BLED and had vessel sounds for the entire 24 h. This was done per week for each year and site, with Pearson correlation tests between proportions performed per year and site as well. Red hind produce low frequency CAS (50–450 Hz) during reproductive periods, which become more frequent as individuals start to aggregate and increasing until the peak days of the aggregation when spawning is presumed to occur (Mann et al., 2010; Zayas-Santiago et al., 2020). Only 1 h of the day was selected to process recordings for red hind calling activity, as the acoustic activity of red hind is known to be greatest during that time-period (sunset), and interference from vessels or divers is reduced (Colin et al., 1987; Mann et al., 2010; Rowell et al., 2012). Each sound file was visually and aurally inspected for red hind CAS, by generating a spectrogram in Audacity 2.3.3 (0–1 kHz visual bandwidth, Hann window, 1024 window length [2016 and 2017]; 4096 window length [2018–2020]).

Understanding that vessel activity could be influenced by several factors, a Pearson's chi-squared "goodness of fit" test was done for vessel events per category and in total (with all years summed per site) according to the day of the week to determine if vessels had an equal probability of being detected on any weekday. Sea conditions are another factor that influences vessel activity at these offshore sites. Thus, records of wind speed were obtained (NOAA-National Data Buoy Center) from the nearest weather station in Rincón (Station PTRP4; located at coordinates 18.367, -67.251), and significant wave height measurements (NOAA-National Data Buoy Center) from the nearest Waverider buoy (Station 41115; 18.376, -67.28), both located to the northeast of the study locations off western Puerto Rico. Daily averages of wind speed and significant wave height of the diurnal hours of the day (6:00–18:00 AST) were used to perform Pearson correlation tests against daily vessel event counts in total for all years at each site.

3. Results

Processing and analyzing 336 960 sound files (each of 20 s duration), which comprised a total of 1,872 h of acoustic records resulted in 245 vessel events identified at Buoy 4 (average ± SD: 61 ± 30.4 per year), 164 at ALS (33 ± 9.4 per year) and 34 at Mona (9 ± 1.9 per year). Of all vessel events identified, most were classified as having constant vessel sound (Buoy 4 = 64–81% ALS = 56–78% and Mona = 90–100%), since they lacked any dynamic vessel sounds (Mona had only one event with dynamic vessel sounds). Events with only constant vessel sound consisted mostly of a single sound file, and therefore about a single detection on average (Buoy 4 = 1.17–1.38, ALS = 1.00–1.80 and Mona = 1.00–1.75), whereas events with dynamic vessel sounds had more detections per event on average and a greater range as well (Buoy 4 = 2.60–3.55, ALS = 1.82–3.10 and Mona = 1). Sounds of SCUBA divers were commonly associated with events classified as dynamic vessel sounds (Buoy 4 = 57–70%, ALS = 43–55% and Mona = 0%), being the most at Buoy 4 followed by ALS. Other anthropogenic sounds associated with vessel events with dynamic sounds such as use of spearguns and conch-shell hammering sounds underwater (for harvesting queen conch, *Aliger gigas*) were also heard at both ALS and Buoy 4 (Table A.1). Identification of these sounds were based on the authors' knowledge of the acoustic signature of these sounds underwater, as formal measurements and descriptions of these sounds were not attempted for this study, nor were they available in the literature. Possible conch-shell hammering sounds were heard only during one event in January-2016 at Buoy 4 and at least on one event of every year except in 2017 at ALS, mostly during March of 2019 and 2020 (both on 3 occasions respectively). Sounds of possible speargun firing were heard only during an event in February 2016 and another in March 2018 at ALS, but were heard on between one to four events of every year at Buoy 4, with all of them in January except for one in February 2017.

Assessment of the BLED's performance revealed that the detector correctly classified 58% (n = 103) and incorrectly classified 41% (false positives; n = 74) of the total number of detections (n = 177). Based on the number of sound files that were manually identified to have vessel sounds (regardless of its intensity; n = 517), 80% of them were not detected (false negatives). Most of the factors that led to false detections (without vessel sounds) were due to biophonic sounds produced by fish and whales, and to sounds produced when animals established physical contact with the recording unit (e.g., scraping by herbivorous fish). However, the BLED was able to detect 86% (with at least one detection per event; n = 20) of the vessel events that contained dynamic sounds (n = 23).

Average vessel events per month were not the same between sites for each classification category. Events with dynamic vessel sounds showed consistent monthly patterns across all years (Fig. 3; Table A.2). During all years at Buoy 4, events with dynamic vessel sounds were greatest in January than in any other month, with a large decrease observed from January to February, followed by a small decrease or no change (except for a small increase in 2019) from February to March. No consistent pattern was observed for events with constant vessel sounds at Buoy 4 (Fig. 3a). In contrast, events with dynamic vessel sounds at ALS decreased every year from January to February but increased from February to March to values near or above those of January (Fig. 3b). Although this pattern was observed for events with only constant sounds (specifically in 2016, 2017 and 2018), it was not consistent across years. No monthly patterns were observed across years for events at Mona (Fig. 3c).

Average vessel events per closed (January 1–February 28) and open (March 1–March 31) periods showed some consistent temporal patterns across years for events with dynamic vessel sounds, while no patterns were observed for events with constant vessel sounds only at any site (Fig. 4; Table A.3). At Buoy 4, events with dynamic vessel sounds were about five and a half (averaged over all years) times greater during closed than open periods. Meanwhile, the opposite was true at ALS, although with a smaller difference between periods. At Mona, no temporal pattern was observed across years, although events with constant vessel sounds were greater during open than closed periods in 2017 and 2018.

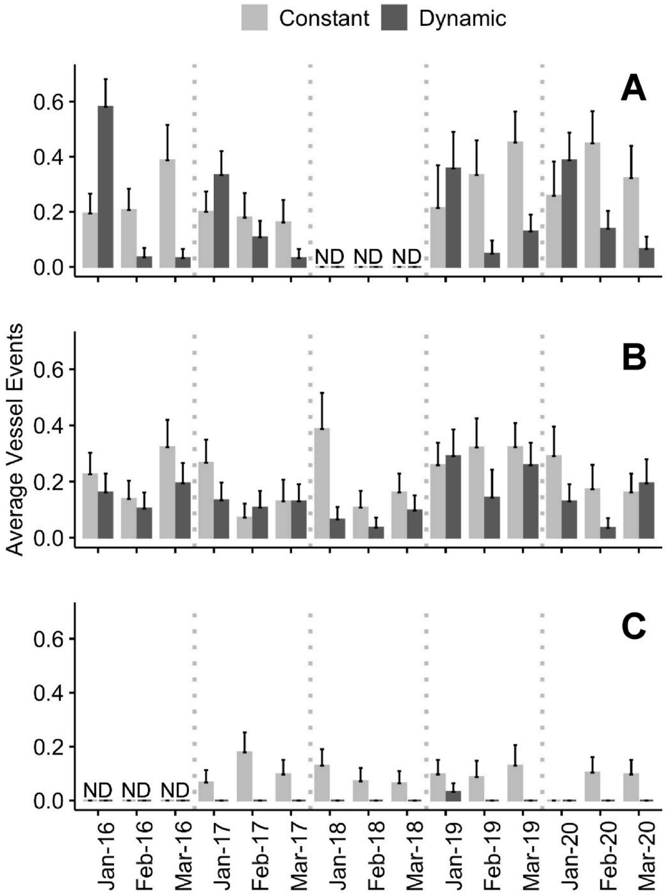

Fig. 3. Average number of vessel events (over the entire 24 hrs of each day) per month (January to March) for 5 years (2016–2020) and classified by type of sound (constant in gray, dynamic in black) at Buoy 4 (A), ALS (B) and Mona (C).

As for determining if temporal trends in red hind calling activity and vessel events were independent, the proportion of sound files with red hind CAS was significantly correlated ($p < 0.05$) with BLED detections of events with dynamic vessel sounds per week at Buoy 4 but only during 2016 ($r = 0.80$), 2017 ($r = 0.62$) and 2019 ($r = 0.65$) (Fig. 5; left), while none were significant at ALS (Fig. 5; right). However, it can be observed visually that at ALS there were periods during almost every year when both proportions had a similar response (increase or decrease), although mainly before week 9, when the seasonal fishing closure at ALS ends and vessel detections increased (Fig. 5; right). Mona was not considered in this comparison as it only contained a single event with dynamic vessel sounds.

Significant ($p < 0.05$) but low negative correlations were found between the number of vessel events in total per day and daily average wind speed, as well as with daily average significant wave height at Buoy 4 ($r = -0.19$ and -0.25, respectively) and ALS ($r = -0.15$ and -0.18, respectively), while no significant correlations were observed with events at Mona. As for the day of the week, on and around weekends (Friday – Monday) had greater vessel events in total than days during mid-week (Tuesday–Thursday) at both ALS and Buoy 4. However, this difference was greater in magnitude at ALS. Pearson's chi-

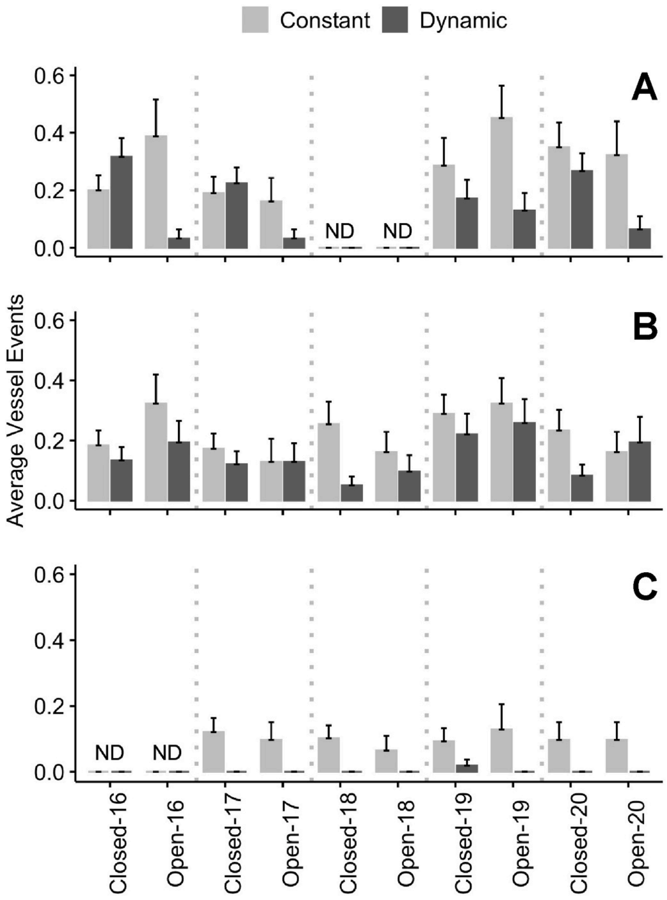

Fig. 4. Average number of vessel events (over the entire 24hrs of each day) per closed season (January 1 – February 28) and open season (March 1 – March 31) and classified by type of sound (constant in gray, dynamic in black) at Buoy 4 (A), ALS (B), Mona (C).

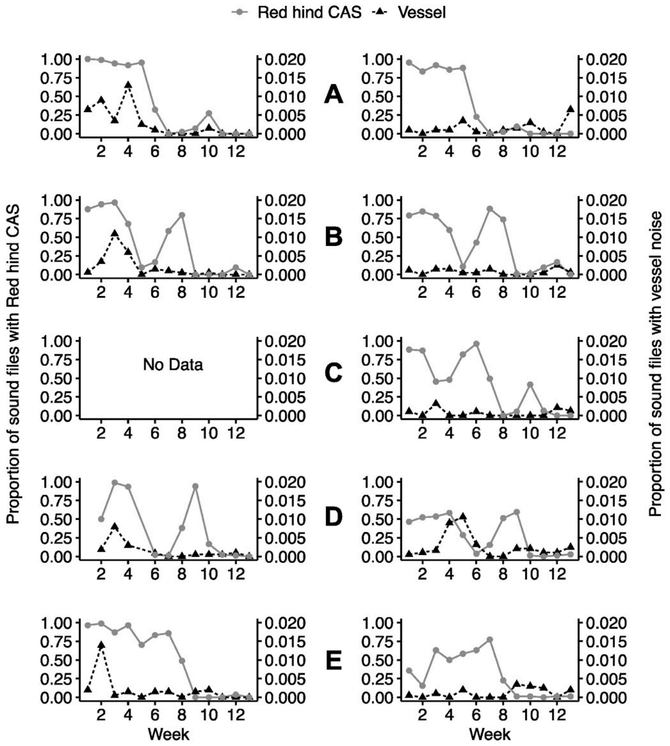

Fig. 5. Proportion of sound files with red hind courtship associated sounds (CAS; gray, circles) and proportion of sound files with vessel sound detections of events with dynamic vessel sounds (black, triangles) per week at Buoy 4 (left) and at ALS (right) during 2016 (A), 2017 (B), 2018 (C), 2019 (D) and 2020 (E).

squared "goodness-of-fit" tests of vessel events in total and per category (with all years summed together), revealed significant ($p < 0.05$) relationships with day of the week only for events at ALS in total ($\chi^2 = 19.828$, df = 6) and those with only constant vessel sounds ($\chi^2 = 22.468$, df = 6).

4. Discussion

Through continuous PAM at FSA sites, we have been able to extract a consecutive long-term, high temporal resolution time series (spanning four to five years) on vessel activity and potential fishing activity that would not have been possible with other methods. Based on the acoustic signal characteristics of sounds produced by vessels (constant sounds or dynamic sounds), we classified detections and quantified activity patterns at important sites with high temporal resolution. In our study, most of the vessel events detected were classified as having constant vessel sounds, with most events of this category consisting of a single detection event, meaning that a vessel in this category likely passed over the recording site without stopping. Although it's possible that these vessels could have been fishing nearby but sufficiently out of range to be acoustically detected, sites such as ALS and Buoy 4 are located in areas where vessels navigate to and from offshore fishing grounds in deeper waters (Tonioli and Agar 2009), which likely contributed to a greater number of events relative to those with dynamic sounds. In addition, as our study sites are located at more than 18 km from shore and nearby ports, the risk involved in reaching these sites (where sea conditions can deteriorate quickly) would almost exclusively be taken by commercial fishing vessels. Events with dynamic vessel sounds, on the other hand, can be associated with vessels actively fishing near the recording unit, as these sounds are indicative of a vessel that is trying to maintain its position relative to the shelf-edge, either to target a specific site or to track divers (Kline et al., 2020; Boyle et al., 2022). Due to this behavior, these events had a longer duration, and therefore a greater number of detections per event, than those with constant vessel sounds. The range of detection for vessel events could not be estimated from the available data. However, based on the findings of Kline et al. (2020), which modeled transmission loss of the sounds from small vessels (<7 m in length and with outboard engines; derived from a simplified form of the passive sonar equation and source levels of small vessels from Barlett and Wilson, 2002), we estimate the maximum range for the BLED to detect small vessels to be approximately 500 m. Although vessel sounds can be received from these vessels at greater distances, our estimate took into consideration the signal-to-noise ratio threshold values established for the detector. Further research is needed to empirically determine the range of detection of small vessels by the BLED.

Our results support our first hypothesis, that vessel events with dynamic sounds would be less frequent in areas with no-take fishing regulations. Indeed, the relatively greater number of events of this category at Buoy 4 than at ALS could have resulted from ALS being seasonally closed to all fishing (December through February) and Buoy 4 having no site-specific fishing regulations. Nevertheless, the presence of events with dynamic vessel sounds at ALS suggests that fishing was occurring there during the seasonal closure. Meanwhile, the lack of events with dynamic sounds at Mona could be due to its distance and isolation from Puerto Rico, in addition to its designation as an NTZ. This suggests that the red hind spawning aggregation site at Mona was not targeted during the recording period.

Organizing vessel events by monthly average revealed temporal patterns and differences among sites, in accordance with our first hypothesis. The consistent trend observed over all years of decreasing dynamic vessel events from January to March observed for Buoy 4 suggests that fishers are possibly targeting a species that aggregates or otherwise has a higher catch rate during January, such as red hind when they are aggregated to spawn. Interestingly, monthly reported landings by commercial fishers from 1996 to 2002 (prior to the establishment of a closed season regulation), showed that red hind landings were greatest in January, followed by February (Ojeda-Serrano et al., 2007). At ALS, the decline in events with dynamic vessel sounds from January to February was also observed but was followed by an increase in events during March when this site is no longer closed to fishing. This could imply that the regulations at ALS and the occasional presence of law enforcement vessels during that time serves as a deterrent and the seasonal closure of ALS has diverted fishing effort towards other areas, which potentially includes Buoy 4 (Marshak and Appeldoorn 2008). Having observed monthly patterns and differences among sites, it was not surprising that results aligned with our second hypothesis, that temporal patterns of average vessel events according to closed (December 1–February 28) and open red hind fishing periods (March 1–31) would be different at each site (although this was observed only for dynamic vessel events).

Our third and final hypothesis, that temporal trends in red hind calling activity would be independent from those of vessel events, held true at ALS but not at Buoy 4. These results suggest that fishers may be targeting red hind at Buoy 4 specifically during the aggregation period (when calling activity is greatest) despite the capture of red hind being prohibited during these months (December 1–February 28). However, it is also possible that some years had aggregation periods that coincided with the weekly patterns of vessel detections observed across years at Buoy 4, since most of the vessel detections occurred between week two and four, and peaks in red hind calling activity occurring the same period. Red hind spawn on a lunar cycle, meaning that the calendar days when spawning aggregations are expected to occur shift every year. In addition, some years can have a single main spawning event while others can have two distinct events of similar magnitude or one being larger in magnitude than the other depending on the timing of the December full moon relative to the date of the winter solstice (Appeldoorn et al., 2015). This was observed in 2017 at Buoy 4, where a peak in red hind CAS around week eight was not reflected by an increase of relative magnitude in vessel detections. However, while in a study by Ojeda-Serrano et al. (2007) almost all interviewed fishers recognized that aggregation events are related to lunar phases, our results suggest that fishers may be targeting red hind during the first weeks of January consistently across years, rather than on specific days relative to the full moon. It should also be noted that the presence/absence of red hind calls doesn't necessarily reflect how many individuals may be present at a particular moment and calling may continue between spawning events due to territorial behaviors in addition to courtship (Zayas-Santiago et al., 2020).

In addition to the dynamic vessels sounds that suggest fishing activity, more than half of these events also contained sounds of bubbles exhaled by SCUBA divers. Although bottom line fishing was reported as the most efficient gear for catching red hind in Puerto Rico between 1995 and 2001 (before the seasonal ban of red hind was implemented), the effort of this fishery has shifted to SCUBA diving. Since the 1990's, the number of commercial fishers classified as SCUBA divers has increased, from 36% in 1996 to 53% in 2002 of the total fishers and reported landings with SCUBA also increased from 14% in 1994 to 31% in 2014 (Matos-Caraballo et al., 2006; Matos-Caraballo and Agar 2010). In the western coast of the island, which hosts the greatest number of commercial divers, diving operations have reported targeting mostly queen conch, spiny lobster, and various reef-fish species (including red hind, *Epinephelus guttatus*) (Agar and Shivlani 2017). Interestingly, the number of events with SCUBA sounds per month mirrored the monthly patterns observed for dynamic sound events. Several of the events with SCUBA sounds also contained signals that resemble sounds of speargun use (occurring mostly at Buoy 4 and almost exclusively during January), suggesting that SCUBA divers were possibly targeting reef-fishes. On the other hand, sounds resembling the hammering of queen conch shells underwater were also heard but were greater at ALS. This is not surprising, as deep-water populations of queen conch located at ALS have been reported by fishers (García-Sais et al., 2008). However, the harvesting of queen conch in federal waters in the US Caribbean (except St. Croix) is banned since 2005 (CFMC/NMFS 2005). Due to low enforcement in these areas, some may risk extracting commercially valuable species that are protected in the EEZ, such as queen conch. For the period between 2016 and 2020, the Puerto Rico Department of Natural and Environmental Resources Fisheries Research Laboratory reported only two law enforcement interventions for either red hind or queen conch at ALS: one in February 2016 for red hind and another in January 2019 for red hind and queen conch, although the degree of enforcement efforts over the years is unknown. Indeed, the presence of law enforcement vessels is a factor to consider that influences fishing activity, as fishery violations may respond to changes in the likelihood of detection. However, low levels of enforcement of fishery regulations in Puerto Rico have been detailed (Kimmel and Appeldoorn 1992).

Another important factor that could have influenced the temporal patterns of detections is sea state, as fishers tend to avoid going out to sea during dangerous conditions due to high wind speeds (greater than 8–10 m/s) or high wave conditions that limit underwater visibility due to swells, and mainly due to the relatively small size of commercial fishing vessel (Agar and Shivlani, 2016). This is common during the months of January–March, when seasonal cold-fronts associated with large swells and above average wind speeds are most frequent. Hence, it's important to consider the risk involved in reaching these offshore aggregation sites (>18 km) from ports and ramps. Our results showed significant negative relationships, although low, between vessel events and average wind speed or significant wave height per day at ALS and Buoy 4 as expected, since these two sites are located on the same shelf edge off western Puerto Rico. Vessel events at Mona showed no relationship with average wind speed or significant wave height, likely due to its distance (74 km) from the main island (where the weather station is located); sea conditions at Mona are known to be different from western Puerto Rico (Torres 2000). All sites, however, are at least 35 km from the nearest weather station, which could have contributed to the low level of correlation, as measured wind speeds or wave height may not always reflect conditions at these sites. Another potential method to estimate sea surface conditions can be through the use of sound produced by surface waves when breaking (Wenz 1962). This sound is produced at specific frequencies and can be easily detected at wind speeds above 7.7 m/s, as per the nearest weather station. However, this would require validation with *in situ* wind speed and wave height measurements, in a subsequent study. Our results were also partly influenced by the preference of boaters and fishermen for certain days of the week (mainly on and around weekends), but only for events with constant vessel sounds at ALS, which may have reflected an increase in recreational fishing (possibly navigating to and from offshore fishing grounds), assuming that they were most likely to use weekends. However, there is no way of acoustically differentiating recreational from commercial fishing vessels in Puerto Rico, as both use the same type of outboard engines.

Based on the results of the BLED's performance, we consider it an adequate method to detect vessel events, provided it be tested, and its parameters be modified accordingly, on a known vessel that represents, or has the characteristics of, the type of vessel that is intended to be detected. Although the percentage of false negatives was high, this was likely an overestimation, as files which were manually identified as having vessel sounds were done so without a minimum amplitude threshold. Furthermore, when grouping sound files with vessel sounds into discreet vessel events, the detector was able to detect almost all the events that contained dynamic sounds. However, we recognize this method has its limitations and drawbacks. First, the size of the vessel could not be determined. Having this ability would be beneficial for sites where vessels of different sizes are frequent, as a vessel's size is often associated with its operational purpose (e.g., fishing reef-associated species, offshore fishing, recreational diving, transportation). Second, biophonic sound sources often caused a false detection, requiring every detection to be manually inspected. Third, sound files adjacent to successful detections with vessel sounds needed to be visually and aurally inspected to determine the duration of the vessel event, and to identify dynamic sounds which were not detected within the event. Nevertheless, and taking these limitations into consideration, the detector provides a means to estimate vessel activity, without having to manually inspect every sound file, and standardized by established thresholds of signal-to-noise ratio parameters.

Despite these considerations, our results showed temporal patterns of events with dynamic vessel sounds that could be used to infer the patterns of fishing activities, which could otherwise not have been provided by opportunistic surveillance by patrol vessels. In the case of MPAs, PAM can be used to indirectly measure compliance within NTZs with total fishing bans, either year-round, or seasonal without a law enforcement presence (Kline et al., 2020; Boyle et al., 2022). Such was the case at ALS, where we could determine with high probability that vessels were fishing in the NTZ during all the years selected for this study, as all fishing practices are prohibited during the 90-day seasonal closure. If we assume that all vessel events with dynamic sounds during the closed season were extracting fish, based on the available data, an average of seven (±1.7 SE) potential violations occurred per year between 2016 and 2020. However, this is likely an underestimate, for recordings were obtained from two (January and February) out of the three-month seasonal closure (December through February), and the closed area is larger than the maximum range for the detection of vessel sounds. Our findings are of great significance to fisheries managers as quantified estimates of compliance (direct or indirect) are not available (to our knowledge) for any of the permanent or seasonally closed MPAs in the U.S. Caribbean. Although compliance and enforcement are often the neglected aspects of fishery management (Branch et al., 2006), the lack of information on compliance with spawning areas protected by law is likely due, in part, to the inherent difficulty of assessing compliance in protected areas (Bergseth et al., 2015), especially those that are remote (Russell et al., 2012), such as ALS. This information is necessary and should be taken into consideration when assessing the efficacy of protected areas, as poaching has been shown to render many MPAs ineffective (Mora et al., 2006; Rife et al., 2013; Edgar et al., 2014; Bergseth et al., 2018). For ALS, we are unable to determine if this is a high or low value of potential violations for the red hind aggregating at this site. However, for purposes of comparison, similar values (9 vessels illegally fishing per month) were obtained from a surveillance camera overlooking an MPA in Australia that was close to shore but far from boat ramps or towns (Harasi et al., 2019). The authors make mention of limited enforcement at that site, and that all the vessels observed illegally fishing were recreational, for which we assume were relatively small and most had outboard engines. On the other hand, a recent study by Iacarella et al. (2021) presented information compiled from 12 studies on the number of non-compliant offenses in 28 MPAs based on enforcement records; they found recorded offenses to be highly variable, with most cases near and some well above a hundred offenses per year (±8 vessels per month), which is on a par with our estimates. However, it's important to consider that estimating non-compliance based on law enforcement records is highly dependent on enforcement effort, which the authors found varied within each MPA and in many cases was not reported. This makes comparisons between locations, and hence with our findings, challenging. Moreover, while records of law enforcement interventions exist in Puerto Rico, they are few and there is limited access to information on the relative effort and expenditure of patrols, and thus their success rate cannot be assessed. Nevertheless, based on the literature, and considering the limited enforcement at ALS, and on the relatively greater number of vessel events with dynamic sounds detected at Buoy 4 (open site), we estimate that there is a moderate level of compliance with the seasonal closure of ALS. Furthermore, our findings suggest that the seasonal closure of ALS may be more effective in protecting the red hind spawning stock by reducing non-compliance, than the seasonal ban on the capture of red hind, which can become ineffective with multiple violators (Charles 2001). Fisher interviews in Puerto Rico have revealed that most are aware of the lack of enforcement and low compliance of regulations and have recommended the strengthening of control and surveillance capabilities to reduce poaching and encourage compliance (Agar et al., 2019). Although it is likely that resources will continue to be limited for enforcement in the future, there are ways that compliance could be improved with limited resources (Russell et al., 2012; Bergseth et al., 2018).

Although it is not possible to directly determine the intentions or the catches from the acoustic records alone, our study shows that for fish that form spawning aggregations at predictable locations and time periods, and are of high commercial value (e.g., red hind), a higher rate of detection of vessels with dynamic sounds (characteristic of a vessel that is fishing and trying to maintain its position) during days of the expected aggregation period suggests a higher probability of impact to the spawning stock. This data, made available by PAM, could support fisheries monitoring programs at FSAs, as many of the world's FSAs lack the resources to design and implement effective management strategies (Erisman et al., 2014). In addition, the methods presented in this study need not be limited to aggregating fish species that are actively soniferous, as temporal trends in fishery-dependent data, if available, could be used to assess comparisons with temporal patterns of vessel activity obtained through PAM. While historical evidence of intense fishing on FSAs is abundant, studies that have attempted to assess vessel activity at FSAs and provide estimates on the degree of potential compliance of regulations related to FSAs (whether by seasonal bans, restrictions on gear and access, or other measures) are lacking. Low compliance and low enforcement levels are mentioned as reasons for ineffective fishery regulations related to FSAs (Nemeth 2005; Luckhurst and Trott 2009; Sadovy de Mitcheson and Erisman 2012; Russell et al., 2012), but claims of non-compliance have been based mostly on researchers' direct observations or personal communications, and don't provide a method to estimate the degree, temporal patterns, or potential of non-compliant behavior. Without this knowledge, it remains difficult to assess compliance and direct enforcement efforts, which could affect the lack of response (i.e., changes in sizes recorded from landings) to the management measures (Sadovy 1994).

The use of PAM to monitor fish and boat activity as conducted in this study have immediate management applications in general, and for Puerto Rico specifically. For the latter, our findings suggest that red hind were being captured during the closed season (and conch in closed areas), to a degree that raises concerns of the potential impact on the red hind spawning stock. Based on the ability to predict the occurrence of spawning aggregations using PAM (Mann et al., 2010; Rowell et al., 2012), we can recommend when enforcement patrols are most needed at the FSA sites off western Puerto Rico, especially those that are outside NTZs. This strategy would maximize the effectiveness of marine patrols, by reducing the costs associated with random patrolling, and by protecting red hind when they are most vulnerable. Furthermore, beyond enforcement purposes, our approach could be used immediately and more broadly to monitor the spatial temporal dynamics of vessel, fishing and diving activity, information that is critical for understanding stakeholder uses of resources across the seascape within a marine spatial planning context, and especially with respect to key conservation areas (Bohnsack and Ault, 1996; Kaplan and Mooney, 2015; Simard et al., 2016).

Future development of this approach, using available technology, will greatly expand the management applications of PAM-based data. Although the methods presented here rely on archival passive acoustic data, real-time acoustic systems are currently in use globally and could potentially serve to detect vessel sounds in real-time and notify patrols standing by, further reducing the costs of at-sea enforcement (Read et al., 2019; Kline et al., 2020). The use of real-time buoys has increased rapidly in recent years, as their technology has improved, and they have shown to be invaluable tools in research and management (Van Parijs et al., 2009). Moreover, our approach could be further enhanced by the availability of artificial intelligence, which could potentially be adapted to learn, detect, and categorize vessel sounds and fish vocalizations (Dufourq et al., 2022; Ibrahim et al., 2018; Wadell et al., 2021), providing near real-time summarized data on fish abundance and potential poaching, which could serve to directly notify enforcement personnel (Chérubin et al., 2020). Additionally, drones could then be deployed to photo-document and identify the suspected vessel, although the use of this technology in fisheries management is still in its infancy (Toonen and Bush, 2020). Artificial intelligence systems could also learn to detect other anthropogenic sounds associated with fishing such as speargun use and conch-shell hammering, thus providing information on potential fishing pressure and poaching during closed seasons or within NTZs.

5. Conclusions

This study evidenced the utility of acoustic records from PAM at FSAs in providing high-resolution temporal patterns of vessel activity in MPAs. Furthermore, we showed that dynamic vessel sounds could be used to infer fishing activity, levels providing estimates of compliance in a seasonal NTZ, and of the potential of fishing during the periods when fish are aggregating to spawn. The use of a band-limited energy detector (BLED) proved adequate to detect vessels automatically, including those with dynamic vessel sounds associated with fishing activity. Although we identified several limitations with this detector, such as false detections caused by biotic sound sources and the inability to estimate vessel size, its ease-of-use through a well-established bio-acoustic analysis program makes it a useful tool for assessing vessel use without the skills needed in running complex detection algorithms in coded language. The spatial and high temporal resolution available with PAM cannot be matched by opportunistic surveillance using patrol vessels or aerial surveys, especially when law enforcement resources are limited. Also, the low effort required in deploying and maintaining acoustic recorders, the ability to record for long time-periods, and the quality of information obtained by a single unit, make them ideal in remote applications. Furthermore, this method could be expanded for a broad range of purposes other than enforcement such as monitoring general vessel activity, diving activity, and estimating fishing pressure in MPAs as well as open areas of interest. Our approach has the potential to be further developed as technology and its accessibility improve, such as the integration of real-time acoustic systems and artificial intelligence to automatically detect and categorize anthropogenic and biotic sounds. Nevertheless, this technique should be a complement to existing methods of evaluating compliance of management strategies designed to protect critical events that sustain local fisheries.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2022.106270.

AppendixSupplementary data

Table A.1
Vessel events with potential conch shell-hammering sounds (for the harvesting of queen conch underwater), and with potential speargun firing sounds.

	Vessel events with potential conch harvesting sounds		Vessel events with potential speargun sounds	
Month-Year	Buoy 4	ALS	Buoy 4	ALS
Jan-2016	3	1	4	0
Feb-2016	0	0	0	1
Mar-2016	0	1	0	0
Jan-2017	0	0	1	0
Feb-2017	0	0	1	0
Mar-2017	0	0	0	0
Jan-2018	No Data	0	No Data	0
Feb-2018	No Data	0	No Data	0
Mar-2018	No Data	1	No Data	1
Jan-2019	0	1	1	0
Feb-2019	0	1	0	0
Mar-2019	0	3	0	0
Jan-2020	0	1	3	0
Feb-2020	0	1	0	0
Mar-2020	0	3	0	0

Table A.2
Average number of vessel events (over the entire 24hrs of each day) per month (January to March) for five years (2016–2020) and classified by category at Buoy 4, ALS and Mona. S.E. = standard error.

Site	Month-Year	Category	Vessel Events average (n)	S.E. (±)
Buoy 4	Jan-2016	Constant	0.19 (6)	0.07
Buoy 4	Feb-2016	Constant	0.21 (6)	0.08
Buoy 4	Mar-2016	Constant	0.39 (12)	0.13
Buoy 4	Jan-2017	Constant	0.20 (6)	0.07
Buoy 4	Feb-2017	Constant	0.18 (5)	0.09
Buoy 4	Mar-2017	Constant	0.16 (5)	0.08
Buoy 4	Jan-2018	Constant	No Data	No Data
Buoy 4	Feb-2018	Constant	No Data	No Data
Buoy 4	Mar-2018	Constant	No Data	No Data
Buoy 4	Jan-2019	Constant	0.21 (3)	0.15
Buoy 4	Feb-2019	Constant	0.33 (7)	0.13
Buoy 4	Mar-2019	Constant	0.45 (14)	0.11
Buoy 4	Jan-2020	Constant	0.26 (8)	0.12
Buoy 4	Feb-2020	Constant	0.45 (13)	0.12
Buoy 4	Mar-2020	Constant	0.32 (10)	0.12
Buoy 4	Jan-2016	Dynamic	0.58 (18)	0.10
Buoy 4	Feb-2016	Dynamic	0.03 (1)	0.03
Buoy 4	Mar-2016	Dynamic	0.03 (1)	0.03
Buoy 4	Jan-2017	Dynamic	0.33 (10)	0.09
Buoy 4	Feb-2017	Dynamic	0.11 (3)	0.06
Buoy 4	Mar-2017	Dynamic	0.03 (1)	0.03
Buoy 4	Jan-2018	Dynamic	No Data	No Data
Buoy 4	Feb-2018	Dynamic	No Data	No Data
Buoy 4	Mar-2018	Dynamic	No Data	No Data
Buoy 4	Jan-2019	Dynamic	0.36 (5)	0.13
Buoy 4	Feb-2019	Dynamic	0.05 (1)	0.05
Buoy 4	Mar-2019	Dynamic	0.13 (4)	0.06
Buoy 4	Jan-2020	Dynamic	0.39 (12)	0.10
Buoy 4	Feb-2020	Dynamic	0.14 (4)	0.07
Buoy 4	Mar-2020	Dynamic	0.06 (2)	0.04
ALS	Jan-2016	Constant	0.23 (7)	0.08
ALS	Feb-2016	Constant	0.14 (4)	0.07
ALS	Mar-2016	Constant	0.32 (10)	0.10
ALS	Jan-2017	Constant	0.27 (8)	0.08
ALS	Feb-2017	Constant	0.07 (2)	0.05
ALS	Mar-2017	Constant	0.13 (4)	0.08
ALS	Jan-2018	Constant	0.39 (12)	0.13
ALS	Feb-2018	Constant	0.11 (3)	0.06
ALS	Mar-2018	Constant	0.16 (5)	0.07
ALS	Jan-2019	Constant	0.26 (8)	0.08
ALS	Feb-2019	Constant	0.32 (9)	0.10
ALS	Mar-2019	Constant	0.32 (10)	0.09
ALS	Jan-2020	Constant	0.29 (9)	0.11
ALS	Feb-2020	Constant	0.17 (5)	0.09
ALS	Mar-2020	Constant	0.16 (5)	0.07
ALS	Jan-2016	Dynamic	0.16 (5)	0.07
ALS	Feb-2016	Dynamic	0.10 (3)	0.06
ALS	Mar-2016	Dynamic	0.19 (6)	0.07
ALS	Jan-2017	Dynamic	0.13 (4)	0.06
ALS	Feb-2017	Dynamic	0.11 (3)	0.06
ALS	Mar-2017	Dynamic	0.13 (4)	0.06
ALS	Jan-2018	Dynamic	0.06 (2)	0.04
ALS	Feb-2018	Dynamic	0.04 (1)	0.04
ALS	Mar-2018	Dynamic	0.10 (3)	0.05
ALS	Jan-2019	Dynamic	0.29 (9)	0.09
ALS	Feb-2019	Dynamic	0.14 (4)	0.10
ALS	Mar-2019	Dynamic	0.26 (8)	0.08
ALS	Jan-2020	Dynamic	0.13 (4)	0.06
ALS	Feb-2020	Dynamic	0.03 (1)	0.03
ALS	Mar-2020	Dynamic	0.19 (6)	0.09
Mona	Jan-2016	Constant	No Data	No Data
Mona	Feb-2016	Constant	No Data	No Data
Mona	Mar-2016	Constant	No Data	No Data
Mona	Jan-2017	Constant	0.07 (2)	0.05
Mona	Feb-2017	Constant	0.18 (5)	0.07
Mona	Mar-2017	Constant	0.10 (3)	0.05
Mona	Jan-2018	Constant	0.13 (4)	0.06
Mona	Feb-2018	Constant	0.07 (2)	0.05
Mona	Mar-2018	Constant	0.06 (2)	0.04
Mona	Jan-2019	Constant	0.10 (3)	0.05
Mona	Feb-2019	Constant	0.09 (2)	0.06
Mona	Mar-2019	Constant	0.13 (4)	0.08
Mona	Jan-2020	Constant	0.00 (0)	0.00

(*continued on next page*)

Table A.2 (*continued*)

Site	Month-Year	Category	Vessel Events average (n)	S.E. (±)
Mona	Feb-2020	Constant	0.10 (3)	0.06
Mona	Mar-2020	Constant	0.10 (3)	0.05
Mona	Jan-2016	Dynamic	No Data	No Data
Mona	Feb-2016	Dynamic	No Data	No Data
Mona	Mar-2016	Dynamic	No Data	No Data
Mona	Jan-2017	Dynamic	0.00 (0)	0.00
Mona	Feb-2017	Dynamic	0.00 (0)	0.00
Mona	Mar-2017	Dynamic	0.00 (0)	0.00
Mona	Jan-2018	Dynamic	0.00 (0)	0.00
Mona	Feb-2018	Dynamic	0.00 (0)	0.00
Mona	Mar-2018	Dynamic	0.00 (0)	0.00
Mona	Jan-2019	Dynamic	0.03 (1)	0.03
Mona	Feb-2019	Dynamic	0.00 (0)	0.00
Mona	Mar-2019	Dynamic	0.00 (0)	0.00
Mona	Jan-2020	Dynamic	0.00 (0)	0.00
Mona	Feb-2020	Dynamic	0.00 (0)	0.00
Mona	Mar-2020	Dynamic	0.00 (0)	0.00

Table A.3

Average number of vessel events (over the entire 24hrs of each day) per closed season (January 1 – February 28) and open season (March 1 – March 31) and classified by category at Buoy 4, ALS and Mona. S.E. = standard error.

Site	Season-Year	Category	Vessel Events average (n)	S.E. (±)
Buoy 4	Closed-2016	Constant	0.20 (12)	0.05
Buoy 4	Open-2016	Constant	0.39 (12)	0.13
Buoy 4	Closed-2017	Constant	0.19 (11)	0.06
Buoy 4	Open-2017	Constant	0.16 (5)	0.08
Buoy 4	Closed-2018	Constant	No Data	No Data
Buoy 4	Open-2018	Constant	No Data	No Data
Buoy 4	Closed-2019	Constant	0.29 (10)	0.10
Buoy 4	Open-2019	Constant	0.45 (14)	0.11
Buoy 4	Closed-2020	Constant	0.35 (21)	0.09
Buoy 4	Open-2020	Constant	0.32 (10)	0.12
Buoy 4	Closed-2016	Dynamic	0.32 (19)	0.07
Buoy 4	Open-2016	Dynamic	0.03 (1)	0.03
Buoy 4	Closed-2017	Dynamic	0.22 (13)	0.06
Buoy 4	Open-2017	Dynamic	0.03 (1)	0.03
Buoy 4	Closed-2018	Dynamic	No Data	No Data
Buoy 4	Open-2018	Dynamic	No Data	No Data
Buoy 4	Closed-2019	Dynamic	0.17 (6)	0.06
Buoy 4	Open-2019	Dynamic	0.13 (4)	0.06
Buoy 4	Closed-2020	Dynamic	0.27 (16)	0.06
Buoy 4	Open-2020	Dynamic	0.06 (2)	0.04
ALS	Closed-2016	Constant	0.18 (11)	0.05
ALS	Open-2016	Constant	0.32 (10)	0.10
ALS	Closed-2017	Constant	0.17 (10)	0.05
ALS	Open-2017	Constant	0.13 (4)	0.08
ALS	Closed-2018	Constant	0.25 (15)	0.07
ALS	Open-2018	Constant	0.16 (5)	0.07
ALS	Closed-2019	Constant	0.29 (17)	0.06
ALS	Open-2019	Constant	0.32 (10)	0.09
ALS	Closed-2020	Constant	0.23 (14)	0.07
ALS	Open-2020	Constant	0.16 (5)	0.07
ALS	Closed-2016	Dynamic	0.13 (8)	0.04
ALS	Open-2016	Dynamic	0.19 (6)	0.07
ALS	Closed-2017	Dynamic	0.12 (7)	0.04
ALS	Open-2017	Dynamic	0.13 (4)	0.06
ALS	Closed-2018	Dynamic	0.05 (3)	0.03
ALS	Open-2018	Dynamic	0.10 (3)	0.05
ALS	Closed-2019	Dynamic	0.22 (13)	0.07
ALS	Open-2019	Dynamic	0.26 (8)	0.08
ALS	Closed-2020	Dynamic	0.08 (5)	0.04
ALS	Open-2020	Dynamic	0.19 (6)	0.09
Mona	Closed-2016	Constant	No Data	No Data
Mona	Open-2016	Constant	No Data	No Data
Mona	Closed-2017	Constant	0.12 (7)	0.04
Mona	Open-2017	Constant	0.10 (3)	0.05
Mona	Closed-2018	Constant	0.10 (10)	0.04
Mona	Open-2018	Constant	0.06(4)	0.04
Mona	Closed-2019	Constant	0.09 (6)	0.04
Mona	Open-2019	Constant	0.13 (5)	0.08
Mona	Closed-2020	Constant	0.10 (3)	0.05

(*continued on next page*)

Table A.3 (*continued*)

Site	Season-Year	Category	Vessel Events average (n)	S.E. (±)
Mona	Open-2020	Constant	0.10 (3)	0.05
Mona	Closed-2016	Dynamic	No Data	No Data
Mona	Open-2016	Dynamic	No Data	No Data
Mona	Closed-2017	Dynamic	0.00 (0)	0.00
Mona	Open-2017	Dynamic	0.00 (0)	0.00
Mona	Closed-2018	Dynamic	0.00 (0)	0.00
Mona	Open-2018	Dynamic	0.00 (0)	0.00
Mona	Closed-2019	Dynamic	0.02 (1)	0.02
Mona	Open-2019	Dynamic	0.00 (0)	0.00
Mona	Closed-2020	Dynamic	0.00 (0)	0.00
Mona	Open-2020	Dynamic	0.00 (0)	0.00

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