

Paired passive acoustic and gillnet sampling reveal the utility of bioacoustics for monitoring fish populations in a turbid estuary

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Estuaries worldwide provide critical habitat to many ecologically and socioeconomically important fish species. However, the high turbidity and strong environmental gradients inherent to many estuaries make the monitoring of fish populations a challenging task. To assess the health and diversity of local fish populations, resource managers often employ fisheries-independent sampling methods, which result in valuable population assessments, but suffer from low-temporal resolution and high rates of mortality. Passive acoustic monitoring (PAM) provides a near-continuous, non-invasive means for monitoring soniferous fish activity over extended periods, but its utility for quantifying entire fish communities is largely untested, especially in turbid estuaries. Here, we use synchronized acoustic and gillnet sampling at 51 locations in the Mission-Aransas Estuary (TX), across two sampling seasons to test correlations between acoustic indices and gillnet catch. Positive correlations were observed between gillnet catch and sound pressure levels in both broadband (50–22050 Hz) and low-frequency (50–2500 Hz) bands. Additionally, sciaenid calling activity was positively correlated with sciaenid catch during the spring, when most spawning activity occurs. Our results indicate that PAM can be used to monitor the relative abundances of fish in Gulf of Mexico estuaries and beyond, although this is subject to species identity and seasonal dynamics.

Keywords: bioacoustics, community monitoring, estuarine soundscapes, fisheries, fish sounds.

Introduction

Estuaries in the Gulf of Mexico (GoM) provide critical habitat to some of the region's most economically and ecologically important species. Indeed, many fish species that inhabit estuaries throughout the Gulf form the basis of highly lucrative recreational fisheries (NOAA, 2018), annually drawing thousands of anglers to the region. In addition to their economic value, fish occupy multiple trophic levels, often within the ontogeny of a species, and play an essential role in shaping estuarine trophic dynamics (Matlock, 1987; Peters and McMichael, 1987; Lycxkowski-shultz *et al.*, 1988; McMichael and Peters, 1989; Elliott and Hemingway, 2002; Whitfield *et al.*, 2022). Thus, the health of fish communities is tightly intertwined with the health of estuarine ecosystems and the economic well being of surrounding human populations, resulting in a strong need to monitor the health of fish populations through time.

The turbid nature of estuaries in the GoM generally requires the use of fisheries-independent, extractive sampling techniques to monitor fish populations. Along the Texas coast, the Texas Parks and Wildlife Department (TPWD) has been monitoring the abundance and size of estuarine consumer species since the mid-1970's, using a combination of bottom trawl, seine net, and gillnet techniques to compile regional population assessments (Martinez-Andrade *et al.*, 2005). These records are critical for elucidating long-term trends in the health of local fish populations. Many of the techniques, however, are resource and labour-intensive and are only implemented on a monthly or seasonal basis. Thus,

current TPWD monitoring provides data at a relatively low temporal resolution, which may fail to detect early warning signs or abrupt community shifts caused by episodic disturbances that often impact the region. Additionally, the currently implemented methods are highly invasive, and can result in mortality across target and non-target species and, in some cases, small-scale damage to bottom habitat (Sparks-McConkey and Watling, 2001; Lewison and Crowder, 2007; Althaus *et al.*, 2009; Gale *et al.*, 2013; Veneranta *et al.*, 2018). Although population level impacts of such sampling methodologies are typically small, estuarine ecosystems and resource managers in the GoM could benefit from complimentary, less-invasive techniques that provide high-resolution, longitudinal data on the health of local fish communities.

One promising avenue is passive acoustic monitoring (PAM). PAM refers to the capture and analysis of sounds emanating from an environment to gain insight into ecosystem health and function (Pijanowski *et al.*, 2011a; Lindseth and Lobel, 2018). In the marine realm, submersible recorders are used to non-discriminately record all sounds within a pre-determined frequency range. These devices are non-invasive and can continuously record marine soundscapes for weeks to months during a single deployment (Lindseth and Lobel, 2018; Rowell *et al.*, 2019). The sounds captured by acoustic recorders include vocalizations of soniferous mammals, fish, and invertebrates (biophony), anthropogenic noises (anthrophony; e.g. motorized vessels or dredging activity), and geophysical noises (geophony), including the sounds of rain and wave action (Pijanowski *et al.*, 2011b; Harris and

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Radford, 2014; Merchant *et al.*, 2015; Monczak *et al.*, 2019). Sound production is widespread among fish species in the GoM and is often tightly associated with courtship and spawning. This is particularly relevant for fish belonging to the family Sciaenidae (drums and croakers; Mok and Gilmore, 1983; Gilmore, 2003; Ramcharitar *et al.*, 2006; Fine and Parmentier, 2015; Montie *et al.*, 2016, 2017; Parmentier and Fine, 2016), which are some of the region's most economically important species. Sciaenids utilize the shallow bays and inlets of GoM estuaries as nursery and spawning grounds, often filling estuarine soundscapes with choruses of drums and knocks during spawning seasons (Saucier and Baltz, 1993; Rooker and Holt, 1997; Geary *et al.*, 2001; Winner *et al.*, 2014; Biggs *et al.*, 2018). Thus, the detection of sciaenid vocalizations can provide information concerning their presence and behaviour in the immediate vicinity, as well as the reproductive health of local populations. This represents invaluable information for GoM fisheries management, even if no precise estimates of abundance, density, or standing stock can be derived from PAM.

A recent focus in marine soundscape ecology is testing the relationship between bioacoustic metrics (i.e. values of biologically relevant acoustic indices) and species diversity or abundance, which has yielded mixed results. For example, paired visual and acoustic surveys in Panama revealed positive relationships between low-frequency (25–1000 Hz) power spectral density (PSD) and cryptic fish abundance and species richness, but no significant relationships between low-frequency PSD and mobile fish abundance and species richness (Staaterman *et al.*, 2017). Similarly, on coral reefs in Hawaii and French Polynesia, certain bioacoustics indices in low-frequency bands were positively correlated with fish abundance or density (Kaplan *et al.*, 2015; Freeman and Freeman, 2016), and acoustic complexity index (ACI) in the low-frequency band (20–2000 Hz) showed a positive relationship with fish biodiversity (Bertucci *et al.*, 2016). However, many other indices were uncorrelated with visual estimates, suggesting that relationships between bioacoustic and community health indices are highly variable depending on the nature of the assessed metrics, and the location, habitat, and fish community composition in the study area. Nevertheless, many of these studies have used visual techniques for comparative assessments, a method that is impractical in highly turbid in-shore habitats such as estuaries throughout the GoM. This highlights the need for paired studies testing the relationships between acoustic and extractive methods in systems where low visibility negates the use of visual surveys.

We combined passive acoustic and fisheries-independent gillnet collections to test the utility of PAM for monitoring fish communities in shallow, turbid estuaries in the GoM. Our specific research objectives were to (1) identify and compare environmental drivers of gillnet catch (a proxy for overall fish abundance) and fish calling activity in the Mission-Aransas Estuary (MAE), TX, (2) test relationships between gillnet-derived measures of fish abundance and biodiversity and bioacoustic parameters, and (3) investigate the effect of seasonal differences in fish vocalization activity on this relationship. In completing these objectives, we aimed to identify useful acoustic proxies for fish abundance and biodiversity in a southeast Texas estuary, while providing guidance on the utility of a methodology that can be broadly applied by researchers in the GoM and beyond.

Methods

Study site and design

The MAE is a microtidal estuary located on the Gulf Coast of Texas. The estuary is fed by two rivers, the Mission and Aransas Rivers, and connected to the GoM by the Aransas shipping channel and a series of natural inlets. The estuary is composed of four major bays (Aransas Bay, Copano Bay, Mesquite Bay, and St. Charles Bay) and a series of adjacent minor bays that harbour a mosaic of benthic habitat types, including seagrass beds, sandy bottom, soft sediment, and subtidal and intertidal oyster reefs, which range in depth from a few inches nearshore to tens of metres in the centre of the main shipping channel. The MAE experiences sustained and acute climatic disturbances such as steadily increasing water temperatures, highly variable freshwater influx and abrupt salinity changes, freeze events, tropical storms, and hurricanes that impact fish distribution and community composition (Fuiman, 2018; Patrick *et al.*, 2020; Bolser *et al.*, 2023). Additionally, many modification efforts occur to maintain important ecosystem services (e.g. oyster reef enhancement and restoration efforts) and commerce (e.g. dredging to maintain, widen, or deepen shipping channels). These characteristics render the MAE a highly dynamic study system, in which the monitoring of important fisheries species is a vital challenge.

To test relationships between bioacoustic condition and fish abundance and biodiversity, paired collections were carried out at 51 locations in the MAE over two TPWD sampling seasons (spring and fall; Figure 1a and b). Paired sampling at each site included a multi-sized gillnet stretched out perpendicular to the shoreline and an acoustic recorder placed 50 m from the centre of the gillnet. Average gillnet soak time was ~12 h, while acoustic files were collected and analysed over a 24-h period. The longer acoustic sampling period was chosen to capture a full diel cycle of fish calling activity at each location to (1) minimize the effects of variation in gillnet set time relative to peaks in fish calling activity, and (2) ensure the acoustic detection of species that vocalize more readily, or are more detectable, during daylight hours. A total of 26 paired samples were collected during the spring sampling season between 11 April 2021 and 16 June 2021, and 25 paired samples were collected during the fall sampling season between 14 September 2021 and 15 November 2021.

Gillnet sampling

Gillnets were deployed within 1 h of sunset and collected no later than 4 h after sunrise the following day. The gillnets used for the study measured 182.9 (L) x 1.2 (H) m and were composed of four 45.7 m continuous panels of monofilament webbing with stretched mesh sizes of 152, 127, 102, and 76 mm. The end of the net with the smallest mesh size was anchored to the shore. The net was then extended into the bay and anchored with the largest mesh size farthest from shore. Buoys were attached to the top of the gillnet to ensure the net was stretched through the water column, though the weight of the lead line anchored the net to the bottom of the bay when water depth was greater than net height. Immediately after deploying the nets, water depth, GPS points, and hydrological data were collected, including turbidity (Hach 2100 N Turbidimeter), salinity, dissolved oxygen, and water temperature (YSI Pro 2030), at each site. Water depth and hydrological data were collected again prior to gillnet retrieval the

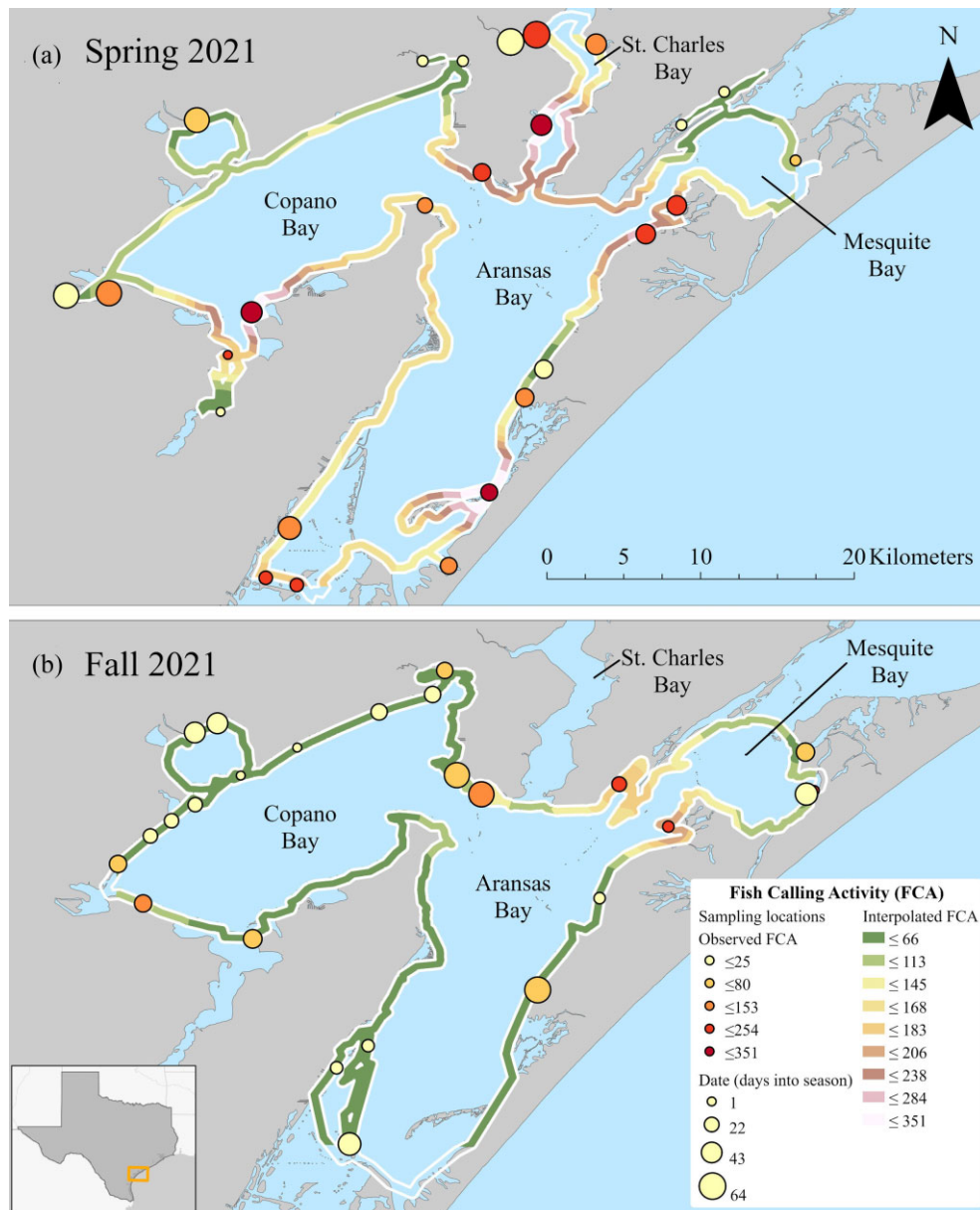


Figure 1. Fish sound production in the MAE during the (a) Spring 2021 and (b) Fall 2021 gillnet sampling seasons. Circles represent sampling locations and are coloured based on the calling activity observed during the 24-h sampling period and sized to reflect the date they were sampled (days into the sampling season). Smaller circles indicate locations that were sampled early in the season, while larger circles indicate locations that were sampled later in the season. The continuous underlying layer represents fish calling activity calculated using inverse distance weighted interpolation.

following morning. All fish >5 mm in total length were counted and identified to the lowest taxonomic unit. Vocalizing (i.e. soniferous) species were verified with existing literature curated in the www.FishSounds.net (Looby *et al.*, 2022) online database. Counts of sound-producing fish species were then summed to generate measures of soniferous fish catch for each site. For a more detailed description of TPWD gillnet sampling methodology, see Martinez-Andrade (2018).

Acoustic collections and analyses

Loggerhead Instruments Snap recorders fitted with hydrophones (sensitivity: -170 dBV re $1 \mu\text{Pa}$; High-Tech, Inc., HTI:96 min) were set adjacent to the gillnets within 15 min of gillnet deployment to collect acoustic data. The Snaps were mounted vertically to PVC pipe and placed in water depths

between 1.5 and 3 m, with a minimum of 0.66 m of water above the hydrophone. Acoustic recorders digitalized sound files at a sampling rate of 44100 Hz and recorded a 1-min sound file every 10 min (10% duty cycle). Recorders were collected no sooner than 36 h after deployment to ensure at least 24 h of acoustic data collection at each sampling site. Upon retrieval, acoustic files were downloaded and recorders were serviced for reuse during the subsequent sampling weeks.

All sound files were aurally and visually reviewed in Raven-Pro (1.6.3) to identify samples with significant anthropogenic noise (e.g. vessel noise) or mechanical noise (e.g. debris rubbing against the hydrophone). Files affected by either source were removed from further analysis. The remaining sound files collected during the first 24 h of recording were analysed to generate measures of sound pressure level (SPL) and ACI in both broadband (50–22050 Hz) and low-frequency

(50–2500 Hz) bands. SPL measures the root-mean-square average amplitude of sounds captured in a recording, reported in dB relative to 1 μ Pa for aquatic studies (Kinsler *et al.*, 1999). ACI, originally developed to quantify avian calling activity, measures variability in sound intensities captured in an audio recording (i.e. differences in acoustic intensity across frequency bands and time) and has been investigated as an acoustic proxy for biodiversity in terrestrial and marine systems (Pieretti *et al.*, 2011; Fuller *et al.*, 2015; Bertucci *et al.*, 2016). Broadband measures encompass all biophony, anthrophony, and geophony captured by the acoustic recorder. The low-frequency band was selected to specifically target low-frequency vocalizations generated by fish, especially species in the family Sciaenidae. SPL was calculated for each 1-min sound file using data calibrated for hydrophone sensitivity and gain with the *PAMGuide* package (Merchant *et al.*, 2015) in MATLAB and then averaged over the 24-h acoustic sampling period (averaged in the linear domain and then converted back to dB). ACI was calculated for each 1-min sound file using the *seewave* package (Sueur *et al.*, 2008) in R and then averaged over the same 24-h period to generate a single acoustic measure for each site. In all cases, measures were calculated using a Hamming Fast Fourier Transform window of 1764 samples (25-Hz frequency resolution) and a 50% overlap.

A subsample of the sound files (~50%) was manually scored for fish calling activity. Specifically, every other sound file collected during the first 24 h of sampling (i.e. one sound file every 20 min) was reviewed for each species or unique vocalization type detected in each sound file, and calling activity was scored using the following scoring system: 0 = no calls; 1 = single call; 2 = multiple, non-overlapping calls; 3 = multiple overlapping calls (i.e. chorusing; Luczkovich *et al.*, 2008; Monczak *et al.*, 2017, 2019). Scores were then summed for each species and 24-h sampling period to generate one summed calling activity score per location. For some analyses, species scores were combined by family or group of interest (e.g. sciaenid fish). If sound files were removed due to significant unwanted noise, interpolated values were generated by averaging the scores of the nearest three sound files collected before and after the removed sound file, then rounding to the nearest integer. For example, a string of values 2, 3, X (removed sound file), 3, 2, 3, would result in an interpolated score of $X = 3$ ($(16/6 = 2.67)$, with 2.67 being rounded up to 3). Measures of phonic richness (Lamont *et al.*, 2022) were then calculated for each site by counting the number of unique vocalization types detected during the 24-h review period.

Finally, we also employed a more targeted approach to determine SPL values that are appropriate for testing species-level relationships. We chose spotted seatrout (*Cynoscion nebulosus*) as the target species because of their relative high presence in both the gillnet and acoustic collections, and their importance as a local recreational species. SPL was calculated for the frequency band between 250–500 Hz—the frequency band that best encompasses *C. nebulosus* vocalizations in the MAE (Biggs *et al.*, 2018)—and averaged over a 4-h window between 18.00 and 22.00 h. This window was determined as the best-fit for capturing *C. nebulosus* vocalization activity by summing *C. nebulosus* calling activity by site and hour of day, averaging the values by hour of day, and plotting the results to examine when the peak(s) occurred (Supplementary Figure S1).

Analytical procedures

Maps displaying seasonal vocalization activity in the MAE were generated using ArcGIS Pro (2.6.0, Esri 2020). GPS coordinates collected during gillnet deployment were imported into ArcGIS Pro and displayed using the NAD 1983 UTM Zone 14 N projected coordinate system. Summed calling activity values were then added for each sampling location. The inverse distance weighted IWD interpolation tool was then used to generate a raster layer for each sampling season (i.e. spring 2021 and fall 2021). Sampling locations served as the input feature, with summed calling activity values serving as the Z-value field (values to be used for interpolation). The resulting continuous layer was clipped to a 300 m buffer of the MAE coastline to generate the final maps (Figure 1a and b).

Generalized additive models (GAMs) were used to investigate significant environmental drivers of total gillnet catch and summed calling activity, as there was an *a priori* expectation that the relationships would be non-linear. Error distributions and link functions for each GAM were determined by assessing the distribution of the dependent variable, and the fit of preliminary models. We used collinearity analysis to identify and remove highly correlated environmental predictors prior to model fitting by calculating Pearson's correlation coefficients between predictors. If the correlation coefficient between two predictors was >0.7 , the predictor that shared a weaker relationship with the dependent variable was excluded from the initial model (Leathwick *et al.*, 2006; Grüss *et al.*, 2018; Bolser *et al.*, 2020). Once highly correlated predictors were removed, GAMs with the remaining hydrological data were fit for SPL measures, total fish calling activity, and gillnet catch using the *gamm4* package in R (version 4.1.2; Wood *et al.*, 2013). All models included a tensor product smooth fitted to eastings and northings, $te(X, Y)$, to account for spatial variation in the data not associated with hydrological predictors. Hydrological predictors in the final model were selected using an iterative protocol outlined by Bolser *et al.* (2020). Initial GAM results were investigated to identify significant predictors (p -values < 0.05) with estimated degrees of freedom values >0.9 . These predictors were retained and used to refit GAMs. The process was repeated until only significant predictors with EDF > 0.9 remained, at which point it was determined the final model. Spatial tensor product smooth terms were retained in all models, regardless of values of EDF or significance.

Once final GAMs were fit, model residuals were assessed for independence from the linear predictor, uniformity, overdispersion, and outliers using the DHARMA package (Wood, 2011) and *gam.check()* function (Wood, 2011) in R (Supplementary Figures S2.2–S6.2 and S2.3–S6.3). A bootstrapping approach was then used to ensure Spearman rank correlation coefficients between GAM predictions and observed data were significantly different from zero >1000 iterations (Bolser *et al.*, 2023).

We used generalized linear models (GLMs) using the *glm* function in the “stats” package (R core team, 2021) in R to test relationships between bioacoustics indices and gillnet measures. Here, our *a priori* expectation was that the tested variables would show linear relationships. Modelled relationships included: (1) low-frequency SPL and total catch, (2) low-frequency SPL and soniferous catch, (3) low-frequency SPL and sciaenid catch, (4) low-frequency SPL and total calling activity, (5) broadband SPL and total catch, (6) broadband

Table 1. Acoustic properties of detected vocalizations.

	Species	Sound type	Dominant frequency (Hz)	Duration (ms)	Repetition rate (calls/sec)
(1)	Hardhead catfish <i>A. felis</i>	knocks/percolating	855–930 (895 ± 27.7)	16–30 (23 ± 6.1)	11.1
(2)	Silver perch <i>B. chrysoura</i>	cluck/knock	665–1170 (895 ± 161.0)	24–37 (32 ± 4.7)	4.6
(3)	Spotted seatrout <i>C. nebulosus</i>	grunt	250–620 (440 ± 137.8)	100–310 (186 ± 64.5)	1.6
		purr	350	1180	
(4)	Atlantic croaker <i>M. undulatus</i>	knocks/drumming	1030–1170 (1088 ± 43.5)	14–22 (17 ± 2.5)	26.9
(5)	Gulf toadfish <i>O. beta</i>	boatwhistle	390–600 (500 ± 67.8)	335–459 (405 ± 37.7)	0.3
(6)	Black drum <i>P. cromis</i>	croak	225–315 (263 ± 29.7)	237–507 (348 ± 95.7)	0.2
(7)	Unknown	croak	315–690 (584 ± 156.9)	34–155 (61 ± 52.3)	2.3

The table was compiled using 10 examples of each vocalization type. Dominant frequency and duration values are reported as ranges (mean ± SD). Repetition rates were calculated using successive sounds thought to be produced by a single individual.

SPL and soniferous catch, (7) broadband SPL and sciaenid catch, (8) seatrout band SPL and spotted seatrout catch, (9) broadband SPL and total calling activity, (10) total calling activity and total catch, (11) total calling activity and soniferous catch, (12) sciaenid calling activity and sciaenid catch, (13) spotted seatrout calling activity and spotted seatrout catch, (14) black drum calling activity and black drum catch, (15) low-frequency ACI and species richness, (16) low-frequency ACI and soniferous species richness, (17) low-frequency ACI and total calling activity, (18) phonic richness and species richness, and (19) phonic richness and soniferous species richness. For each GLM, error distribution and link function were determined by looking at the distribution of the dependent variable and analysing preliminary model fits. GLMs generated using continuous dependent variables (e.g. broadband SPL, low-frequency SPL, and low-frequency ACI), were fitted with gaussian or gamma error distributions. GLMs using discrete, count data (e.g. phonic richness and calling activity) were fitted with Poisson or negative binomial error distributions. Models fitted with data containing many zeros (e.g. calling activity data), were checked for zero inflation using the *performance* package in R (Lüdecke *et al.*, 2021). If zero-inflation was detected, models were refit using zero-inflated error distributions. We also used GLMs to determine potential effects of sampling date on fish abundance or vocalization activity within seasons. Specifically, we tested the effect of the number of days into the sampling season against total gillnet catch and fish calling activity (summed over the 24-h acoustic observation period) for each season. Full information regarding all model structures and results are provided in the Supplementary Materials (Supplementary Table S1).

Finally, we used principal component analyses (PCAs) to examine fish calling activity and gillnet catch composition across seasons, habitat types (Figure 5), and regions (Supplementary Figure S7). Fish counts by species and sampling location were used as the input for the gillnet catch PCAs, while summed calling activity sorted by species and sampling location were used as the inputs for calling activity PCAs. To test whether acoustic or gillnet catch differed across habitats, NOAA habitat shapefiles were imported into ArcGIS Pro and 300 m buffers were set up around each sampling point and spatially joined to the underlying habitat map. The dominant habitat type in each buffer was then chosen for each sampling location. Sampling points were also sorted based on the bay system they were located in (i.e. Aransas Bay, Copano Bay, Mesquite Bay, or St. Charles Bay). Points in minor Bay systems were grouped with the closest major bay points. For

example, samples collected in Carlos Bay (adjacent to Mesquite Bay), were grouped with samples collected in Mesquite Bay due to their geographic proximity. As with habitat types, these regional assignments were used to determine differentiation across locations in the ordination.

Results

Acoustic measures

Average broadband (50–22050 Hz) SPL values for the spring of 2021 sampling season ranged from 92.3 to 110.0 dB re 1 µPa with a mean of 102.5 ± 5.3 (SD) dB re 1 µPa. Average low-frequency (50–2500 Hz) SPL measures for the spring season ranged from 88.9 to 106.4 dB re 1 µPa with a mean of 99.4 ± 5.0 dB re 1 µPa. Average broadband SPL values observed during the fall 2021 sampling season were comparable to those observed during the spring ranging from 92.5 to 112.3 dB re 1 µPa and a mean of 102.6 ± 7.6 dB re 1 µPa. Average low-frequency SPL values for fall 2021 were also similar to those observed in the spring, ranging from 86.9 to 110 dB re 1 µPa and with a mean of 99.6 ± 8.7 dB re 1 µPa.

Average ACI values during the spring 2021 sampling season ranged from 188.4 to 334.9 with a mean of 232.3 ± 41.3. During the fall 2021 sampling season, average low-frequency ACI values were slightly lower and less variable, ranging from 184.1 to 306.3 with a mean of 217.6 ± 29.4. Phonic richness ranged from 0 to 5 during the spring sampling season, and from 0 to 4 during the fall months. The average phonic richness value for the spring sampling season was 2.7 ± 1.5, while the average phonic richness for the fall season was 2.1 ± 1.0.

Seven unique vocalization types were identified during the study (Table 1, Figure 2, Supplementary Material sound files). Calls from *Pogonias cromis* (black drum), *Bairdiella chrysoura* (silver perch), *Cynoscion nebulosus* (spotted seatrout), *Opsanus beta* (gulf toadfish), *Ariopsis felis* (hardhead catfish), and an unidentified croaking organism were detected during the spring sampling season. The same fish were detected during the fall sampling season with the exception of *B. chrysoura* and *P. cromis*. *Micropogonias undulatus* (Atlantic croaker) were only detected during the fall months. The summed calling activity for all detected species in the spring ranged from 0 to 351 per site (over the 24-h observation period) with an average of 127.5 ± 108.9. Summed calling activity in the fall was considerably lower, ranging from 0 to 200 per site with an average of 49.8 ± 64.3. Summed calling activity for sciaenid species ranged from 0 to 99 per site with an average of 13.0 ± 20.7 during the spring sampling season. Sciaenid

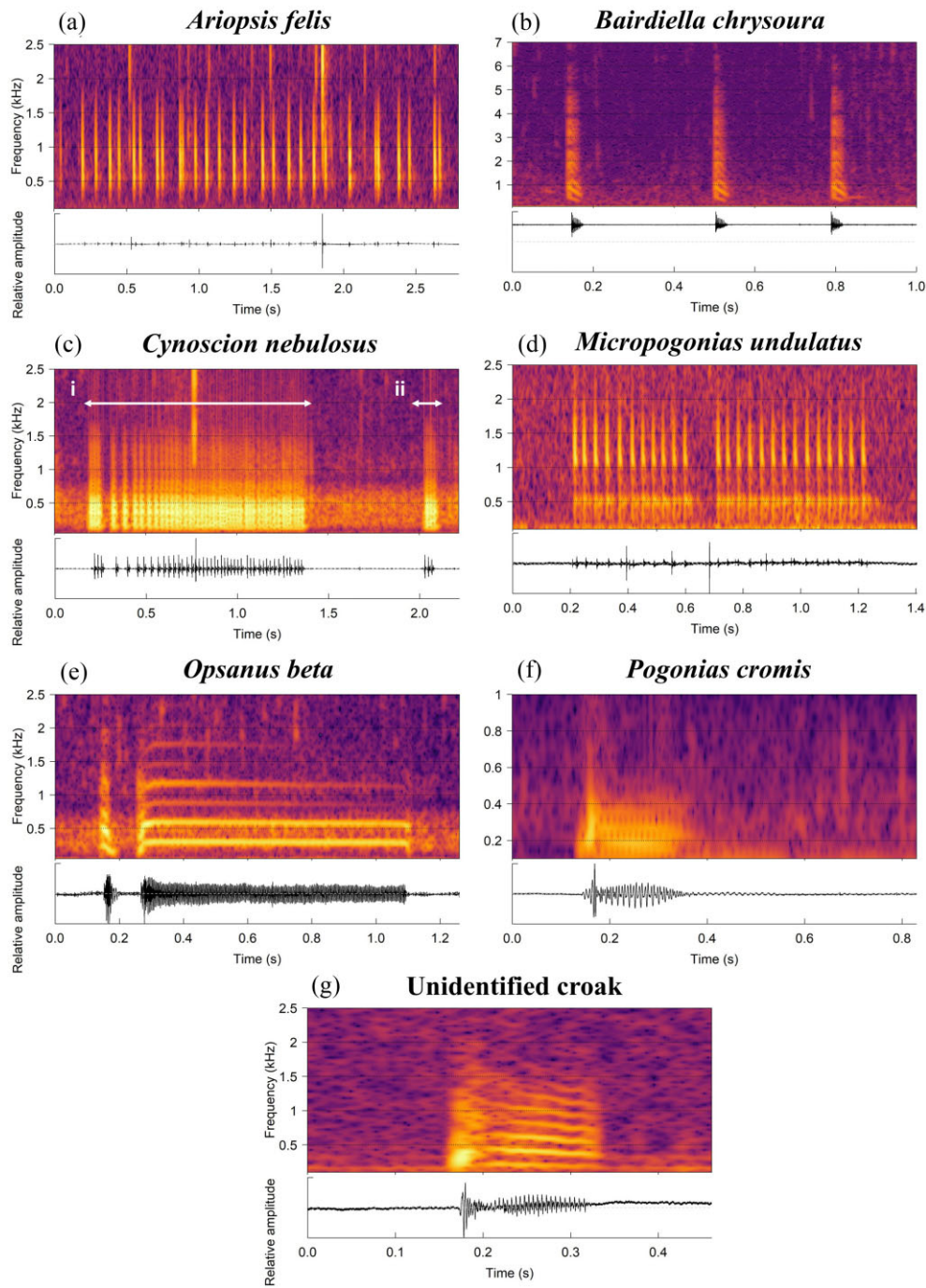


Figure 2. Spectrogram and waveform examples for each species or sound type detected, including (a) *A. felis* percolating/knocks, (b) *B. chrysoura* clucks/knocks, (c) *C. nebulosus* (i) purr and (ii) grunt, (d) *M. undulatus* knocks, (e) *O. beta* boatwhistle, (f) *P. cromis* knock, and (g) a croak from unidentified organism. In the spectrograms (top), yellow indicates higher power and purple indicates lower power.

calling activity was lower during the fall months, ranging from 0 to 24 per site with an average of 2.2 ± 5.3 .

Spatiotemporal trends in calling activity

Fish calling activity was relatively high throughout the MAE during the spring months with most interpolated values ranging between 145 and 351. Spring calling activity hotspots were identified in south Copano Bay, St. Charles Bay, and northeast and southeast Aransas Bay (Figure 1a). Sampling locations in south Copano Bay, St. Charles Bay, and northeast

Aransas Bay were near oyster reef habitat and characterized by high *O. beta* and *A. felis* calling activity. The hotspot in southeast Aransas Bay had high calling activity by species belonging to the family Sciaenidae, especially between the hours of 18.00 and 23.00. Calling activity during the fall months was comparatively low throughout most of the estuary (Figure 1b). During this time, most interpolated values were <66 . Relative hotspots for the fall sampling season were identified in west Mesquite Bay and north Aransas Bay. Both calling activity hotspots for the fall 2021 sampling season

Table 2. Summary of GAMs testing for effects of environmental variables on acoustic indices and catch from gillnet samples.

Dependent variable	Adjusted R^2 (CI)	Error distribution (link function)	Significant predictors	EDF	F statistic	Chi. sq.	p -value
Acoustic monitoring							
Broadband SPL	0.410 (0.235–0.674)	Gamma (log)	Spatial tensor term	7.6	3.032		0.008
			Dissolved oxygen	1.0	5.684		0.001
Low-frequency SPL	0.379 (0.215–0.607)	Gamma (log)	Dissolved oxygen	1.1	5.323		<0.001
			Water temperature	1.1	2.346		0.006
			Salinity	0.9	1.085		0.047
Fish calling activity	0.215 (0.008–0.508)	Tweedie (log)	Spatial tensor term	4.8	2.400		0.043
			Water temperature	1.0	2.767		0.003
			Dissolved oxygen	0.9	1.591		0.016
Gillnet sampling							
Total catch	0.277 (0.110–0.561)	Negative binomial (log)	Spatial tensor term	4.7		17.165	0.007
			Dissolved oxygen	1.0		8.062	0.002
Soniferous catch	0.350 (0.165–0.764)	Negative binomial (log)	Dissolved oxygen	1.1		17.170	<0.001
			Spatial tensor term	4.7		25.070	<0.001

Significant predictors for each model are listed by relative importance (see Supplementary Figures S2–S6). EDF are estimated degrees of freedom and indicate curvature in the model fit.

were characterized by high *A. felis* calling activity throughout the day.

Relationships between sampling date, and total gillnet catch and fish calling activity were evaluated using negative binomial (log link function) GLMs. We did not observe significant relationships between total gillnet catch and days into sampling season for spring ($p = 0.825$, pseudo $R^2_{ML} = 0.001$) or fall ($p = 0.197$, pseudo $R^2_{ML} = 0.067$) sampling seasons (Supplementary Figure S8). Additionally, relationships between fish calling activity and days into sampling season were non-significant for both spring ($p = 0.314$, pseudo $R^2_{ML} = 0.022$) and fall ($p = 0.875$, pseudo $R^2_{ML} = 0.001$) seasons (Supplementary Figure S9). These results indicate that sampling date did not have any predictable effects on the observed fish abundance and vocalization activity within season.

Environmental predictor selection and GAM results

Pearson's correlation coefficients did not show values >0.7 between hydrological or spatial predictors (i.e. dissolved oxygen, water temperature, salinity, turbidity, eastings, or northings). Thus, all predictors were included in the GAMs. For acoustic measures, broadband SPL, low-frequency SPL, and fish calling activity GAMs showed adjusted R -squared values >0.2 . For gillnet measures, total catch and soniferous catch resulted in GAMs with adjusted R -squared values of 0.277 (CI: 0.110–0.561) and 0.350 (0.165–0.764), respectively (Table 2). Dissolved oxygen, salinity, and temperature were retained as significant predictors for the low-frequency SPL GAM. Water temperature and dissolved oxygen were retained in the fish calling activity GAM. Only dissolved oxygen was retained as a significant predictor in the broadband SPL, total gillnet fish catch, and gillnet soniferous fish catch GAMs. Spatial variables (i.e. eastings or northings) were found to be significant predictors of broadband SPL, fish calling activity, total gillnet fish catch, and gillnet soniferous fish catch, but not of low-frequency SPL.

Dissolved oxygen, salinity, and water temperature had positive marginal effects on all dependent variables, with similar curve shape (Supplementary Figures S2.1–6.1). This suggests that changes in SPL, fish vocalization activity, and fish abundance in gillnets are affected by the same environmental factors, which are primarily associated with seasonal change.

Acoustic vs. gillnet measure GLMs

GLMs were used to investigate relationships between sound levels and gillnet catch. Of the relationships tested, six were significant: (1) low-frequency SPL (50–2500 Hz) and total catch ($R^2 = 0.254$), (2) low-frequency SPL and soniferous catch ($R^2 = 0.232$), (3) low-frequency SPL and sciaenid catch ($R^2 = 0.358$), (4) broadband SPL (50–22050 Hz) and total catch (pseudo $R^2_{ML} = 0.225$), (5) broadband SPL and soniferous catch (pseudo $R^2_{ML} = 0.248$), and (6) broadband SPL and sciaenid catch (pseudo $R^2_{ML} = 0.306$). Seasonal interactions were found between broadband SPL and sciaenid catch, and between low-frequency SPL and sciaenid catch (Figure 3c and Supplementary Figure S10c). No seasonal interactions were found between broadband frequency SPL and total catch nor soniferous catch, or between low-frequency SPL and total catch nor soniferous catch (Figure 3a and b and Supplementary Figure S10a and b). Here, positive relationships were observed between low-frequency SPL and total catch, as well as soniferous catch. Positive relationships were also observed between broadband SPL and total catch, as well as soniferous catch. Additionally, there were positive relationships between SPL (both broadband and low-frequency) and sciaenid catch, although effect sizes were larger during the fall sampling season relative to the spring season (Figure 3c). Finally, the relationship between SPL (250–500 Hz, averaged between 18.00 and 22.00 h) and spotted seatrout catch was non-significant (pseudo $R^2_{ML} = 0.076$).

We also found significant relationships between fish calling activity and gillnet catch in fish belonging to the family Sciaenidae, specifically (1) sciaenid calling activity and sciaenid catch, and (2) spotted seatrout calling activity and spotted seatrout catch. Seasonal interactions were identified in both cases, where calling activity had a positive relationship with gillnet catch during the spring sampling season and a slightly negative relationship during the fall sampling season (Figure 4).

Gamma GLMs were used to test the relationships between low-frequency (50–2500 Hz) ACI and both species richness and soniferous species richness. Neither of these relationships were found to be significant. The relationships between phonic richness and both species richness and soniferous catch species richness were also tested using Poisson GLMs. Neither of these relationships were statistically significant.

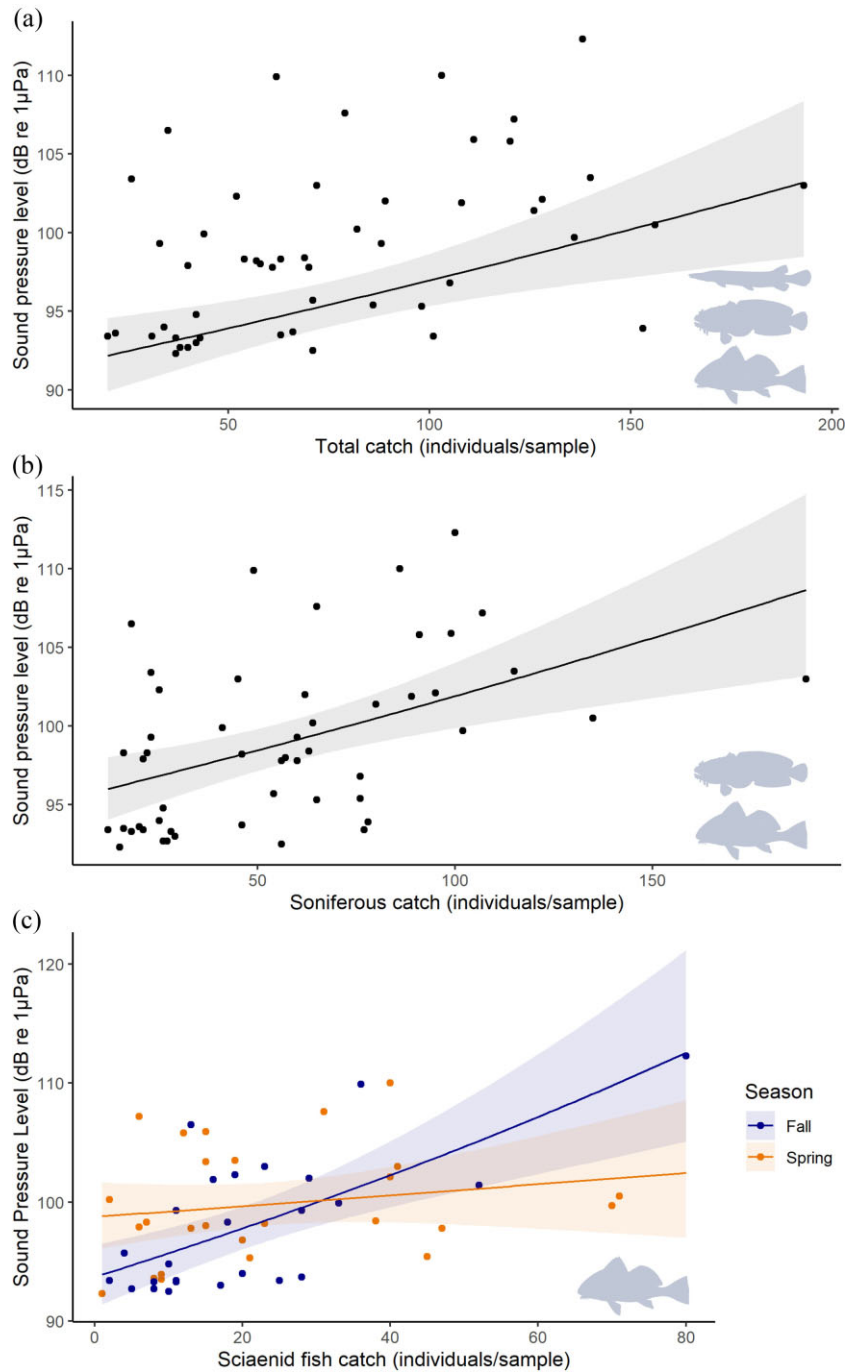


Figure 3. GLM results showing the relationship between (a) broadband SPL and total catch, (b) broadband SPL and soniferous fish catch, and (c) broadband SPL and catch of fish belonging to the family Sciaenidae. Dots represent the raw data, while lines and ribbons represent the model fit and 95% confidence intervals. The two colours in (c) indicate a significant effect of season on the relationship between sciaenid catch and SPL.

Significant relationships were identified between some acoustic indices. Significant seasonal interactions were found between both low-frequency and broadband SPL, and total calling activity. Here, SPL (low-frequency and broadband) shared positive relationships with total calling activity during the spring sampling season and slightly negative relationships during the fall sampling season (Supplementary Figures S11 and S12). There was no significant relationship found between low-frequency ACI and total calling activity (Supplementary Table S1).

Multivariate analysis of fish communities

Of the 26 locations sampled during the spring 2021 sampling season, 17 were classified as seagrass habitat, 8 were classified as wetlands, and 1 was classified as oyster reef habitat. Of the 25 locations sampled during the fall 2021 sampling season, 10 were classified as seagrass habitat, 10 were classified as wetlands, 3 were classified as oyster reef habitat, and 2 were classified as soft sediment habitat. The PCAs for gillnet and acoustic data showed substantial differentiation across the first two axes, with 27% and 21% of the variability

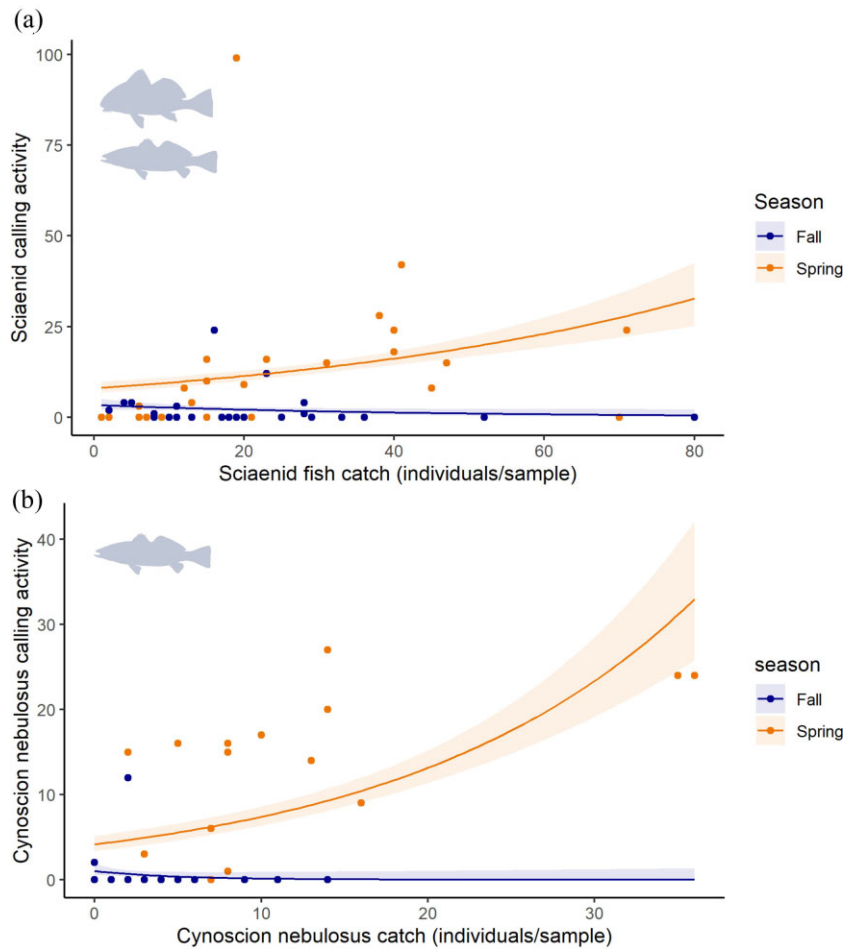


Figure 4. GLM results displaying relationships between (a) sciaenid calling activity and sciaenid catch and (b) *C. nebulosus* calling activity and catch. Dots represent the raw data, while lines and ribbons represent the model fit and 95% confidence intervals, respectively.

explained across PC1 and PC2, respectively, for the acoustic PCA and 31% and 18% of the variability explained across PC1 and PC2, respectively, for the gillnet PCA (Figure 5). Seagrass and wetland convex hulls were considerably larger during the spring season compared to the fall sampling season for both the acoustic community (i.e. collection of vocalizations quantified over a 24-h period) and gillnet community PCAs, suggesting that both communities were more variable during the spring months relative to the fall months. Both PCAs show considerable overlap between habitat types within season, but separation of communities in the same habitat type between seasons. For example, the gillnet catch in wetland habitats during the spring months displayed substantial overlap with the catch in seagrass habitats in the spring, but there was little overlap between gillnet catch in the wetlands during the spring and fall months. Seasonal differences in acoustic community composition appear to be largely driven by observations of *M. undulatus* during the fall sampling season and observations of *B. chrysoura*, *C. nebulosus*, and *O. beta* during the spring sampling season. Similarly, seasonal differences in gillnet catch composition appear to be influenced by observations of *M. undulatus* during the fall sampling season and observations of *A. felis* and *C. nebulosus* during the spring sampling season.

Discussion

PAM provides a promising method for assessing the health and function of fish communities in turbid estuarine systems. However, the relationships between bioacoustic indices and data obtained from extractive methods have rarely been tested, especially in turbid, nearshore environments such as the estuaries of the GoM. We show that PAM is useful for assessing biodiversity in soniferous fish, spawning activity in sciaenid species, and the relative abundance of mobile fish in shallow estuaries in the GoM, revealing clear relationships between several acoustic indices and gillnet sampling data in paired samples. Furthermore, PAM mirrored extractive sampling results by showing strong seasonal differences in the fish communities across habitats. Thus, our study suggests that PAM can function as a complementary technique to the fisheries-independent data collected by local wildlife agencies to continuously monitor some of the region's most ecologically and economically important fish.

Drivers of gillnet catch and bioacoustic indices

Bioacoustic parameters (i.e. SPL, calling activity) were influenced by water temperature, salinity, and dissolved oxygen, while gillnet catch was largely driven by levels of dissolved

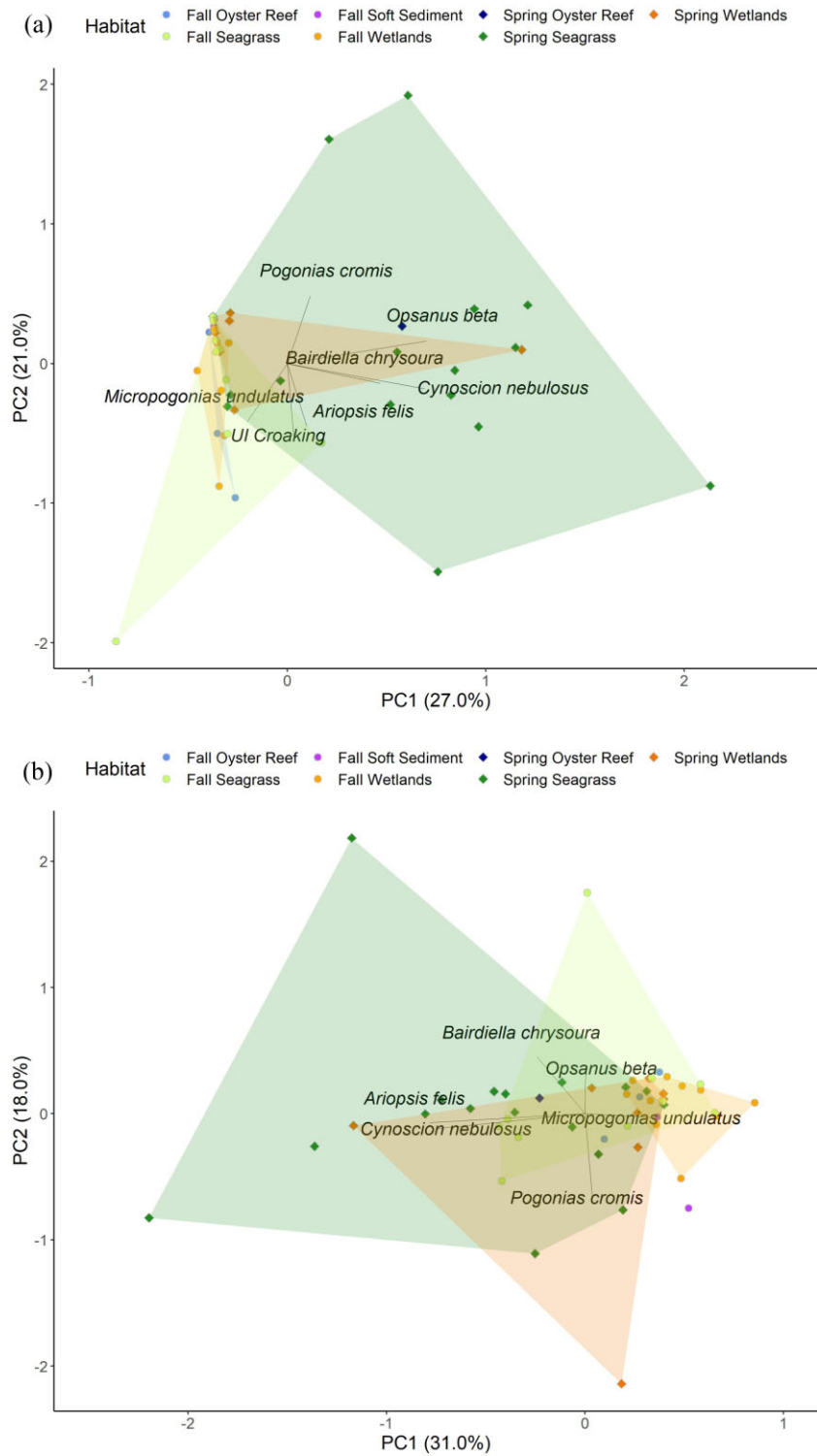


Figure 5. PCA ordination for (a) acoustic and (b) gillnet communities of fish observed vocalizing by habitat type and season. Dots represent individual sites, shaded areas represent the convex hull polygons for habitat-season groupings, and dashed lines depict species loadings.

oxygen. Water temperature is an important proximate cue associated with spawning seasonality in many fish species (Lowerre-Barbieri *et al.*, 2011; Wootton and Smith, 2014), triggering both movement (Dando, 1984; Potter *et al.*, 2015) and vocalization activity (Fish and Mowbray, 1970; Guest and Lasswell, 1978; Gilmore, 2003; Locascio and Mann, 2008) in fish across GoM estuaries. Thus, it is intuitive that this

proximate cue of spawning seasonality influences summed vocalization activity, and sound levels in the MAE. Our findings also support previous studies that have shown water temperature to be an important driver of fish calling phenology in estuarine systems in the GoM and eastern United States (Locascio and Mann, 2011; Rice *et al.*, 2016, 2017; Monczak *et al.*, 2017, 2019). Furthermore, water temperature can

modulate fish calling activity within seasons during acute disturbance events that induce sudden shifts in water temperature (Biggs *et al.*, 2018; Boyd *et al.*, 2021), and there is evidence for broad positive correlations between water temperature and sound levels, especially in low-frequency bands (Ricci *et al.*, 2016; Mueller *et al.*, 2020). Although dissolved oxygen levels and salinity are not considered primary cues for spawning seasonality in the GoM, the occurrence of extreme values can present physiological challenges to marine fish (Kramer, 1987; Brauner *et al.*, 2012). Thus, one might also expect the positive relationships observed between these environmental variables and both gillnet catch and bioacoustics measures.

The PCA results indicate that seasonal differences in acoustic and catch composition override habitat- or bay-specific patterns. In other words, acoustic and gillnet catch composition of detected vocalizing species were more similar between bays or habitats within season than communities in the same bays or habitats across seasons. This further emphasizes the importance of seasonal spawning activity in governing the calling activity and movement of many estuarine-dependent fish. Red drum (*S. ocellatus*), for example, use estuaries in the GoM as nursery areas, emigrate to nearshore habitats upon maturation, and eventually return to estuarine inlets or mouths to spawn (Pearson, 1928; Peters and McMichael, 1987; Murphy and Taylor, 1990; Winner *et al.*, 2014). Similarly, Atlantic croaker (*M. undulatus*) recruit to estuarine habitats as juveniles and migrate offshore to spawn as adults (Pearson, 1928; Anderson *et al.*, 2018), while other soniferous species (e.g. black drum, spotted seatrout, and silver perch) remain in estuaries for most of their ontogeny, but form aggregations in estuarine bays, inlets, or nearby offshore habitats to spawn (Pearson, 1928; Simmons and Breur, 1962; Tabb, 1966; Osburn and Matlock, 1984; Holt *et al.*, 1985; Saucier and Baltz, 1993). These reproductive behaviours likely change the seasonal community composition and fish calling activity on a system-wide scale. Thus, high inter-seasonal variation in the spawning activity of soniferous species found in the MAE (and its drivers) could help explain the observed multivariate differentiation across seasons in both acoustic and gillnet catch composition.

Seasonal fish vocalization activity and behavioural context

The composition of fish calls, and their behavioural context, varied strongly throughout the study. The biological soundscape during the spring sampling season was characterized by widespread calling activity in *A. felis*, *C. nebulosus*, and *O. beta*, and more sporadic calling activity in *B. chrysoura* and *P. cromis*. Spawning activity in all five species in the GoM overlaps, at least partially, with the spring sampling season (Supplementary Figure S13; Nieland and Wilson, 1993; Brown-Peterson and Warren, 2001; Brown-Peterson *et al.*, 2002; Grammer *et al.*, 2009; Anderson *et al.*, 2018; Pensinger *et al.*, 2021). Calling activity in *C. nebulosus* and *B. chrysoura* mostly occurs as chorusing (i.e. simultaneous, overlapping calls generated by groups ranging from a few individuals to hundreds of individuals) during the evening hours, and occurs exclusively for courtship and spawning (Mok and Gilmore, 1983; Luczkovich *et al.*, 2000; Gilmore, 2003). Conversely, *P. cromis* produce sounds outside of courtship and spawning, for example, as a fright response to capture (Locascio and Mann, 2011; Tellechea *et al.*, 2011). Male toadfish in the genus

Opsanus vocalize to attract females to their nest sites and during displays of territoriality (e.g. as warnings to rival males or while egg-guarding; Gray and Winn, 1961; Breder, 1968; Thorson and Fine, 2002). Thus, toadfish calls are only loosely tied to specific spawning activities and have often been observed outside of peak spawning season (Tavolga, 1958; Gray and Winn, 1961). Therefore, most, but not all calling activity during the spring sampling season can be attributed to spawning.

In the fall season, the biological soundscape was dominated by *A. felis* calls, with interspersed observations of *M. undulatus* and *C. nebulosus* vocalizations. Both *M. undulatus* and *C. nebulosus* have peak spawning seasons that extend into the fall sampling season (Supplementary Figure S13). The spawning season of *C. nebulosus* extends from mid-March through September in the GoM (Brown-Peterson and Warren, 2001; Brown-Peterson *et al.*, 2002), which helps explain the low number of calling observations in the fall relative to the spring. While the *M. undulatus* spawning season overlaps with much of the fall sampling season, this species is generally thought to spawn offshore (Warlen, 1982; Diaz and Onuf, 1985; Krahforst, 2010; Anderson *et al.*, 2018). Previous studies have shown that vocalization activity in *M. undulatus* is often tied to reproduction, but can also be used to signal distress or for conspecific communication (Connaughton *et al.*, 2003; Fine *et al.*, 2004; Gannon, 2007). Thus, the detected vocalizations may be associated with spawning, communication, capture by predators, or gillnet entanglement. The first scenario is notable as it would suggest that some individuals forgo offshore migration to spawn in inshore habitats in the MAE. Indeed, female *M. undulatus* in spawning phase (with hydrated oocytes) were previously found in the Chesapeake Bay estuary, supporting the notion that some spawning occurs in estuaries (Barbieri *et al.*, 1994). For *A. felis*, the spawning season does not overlap with the fall sampling season (Supplementary Figure S13; Pensinger *et al.*, 2021), but sound production in catfish (Order Siluriformes) has been associated with fright responses, social behaviour, and has even been suggested as a crude form of echolocation in *A. felis* (Tavolga, 1971, 1976; Kaatz and Lobel, 1999; Fine and Ladich, 2003), which may explain their detection during non-spawning months. It is worth mentioning that catfish species utilize two primary mechanisms for producing sound, stridulation (i.e. rubbing of hard structures), and the sonic vibration of the swimbladder or adjacent parts, with many species capable of both (Tavolga, 1962; Fine and Ladich, 2003). Stridulation is frequently used during disturbance responses, suggesting a mechanistic differentiation in sound production (Kaatz, 1999; Fine and Ladich, 2003). Most sounds assigned to *A. felis* in our study (e.g. knocking and percolating sounds) were considered non-stridulatory, which may help determine the behavioural context of most sounds to social or navigational behaviours rather than stress responses (possibly associated with gillnet capture).

Overall, these results prompt cautious interpretation of fish vocalizations detected with PAM. During both sampling seasons, PAM was a reliable method for detecting the presence of soniferous fish, including species that are under-sampled using the fisheries-independent gillnets employed in this study (e.g. *B. chrysoura* and *O. beta*). In some species (e.g. *C. nebulosus*, *B. chrysoura*, and *P. cromis*), calling activity matched expected spawning timelines for the region, suggesting that their acoustic detection is a reliable indicator of spawning activity

(i.e. most, but not all, of the vocalizations detected are likely attributed to spawning). Conversely, calling activity in *A. felis* and *M. undulatus* was mismatched in time or space with their expected spawning behaviour. Thus, in these species, passive acoustic detection is not a reliable indicator of spawning activity. It is, therefore, important to understand the life history and behaviour of detected species when using calling activity for monitoring purposes.

Utility of bioacoustics monitoring in turbid, marine environments

The positive relationships between SPL measures and gillnet catch suggest that sound levels could be a reliable acoustic proxy for fish abundance in the MAE. Of the 38 species captured in gillnets during the study, 18 are known to be soniferous (47.4%), which provides an intuitive basis for the observed relationship: higher abundances of fish lead to higher vocalization activity and, in turn, higher sound levels. This is further supported by the positive relationships observed between fish calling activity and sound levels during the spring months (Supplementary Figures S11 and S12). One noteworthy result, however, was the seasonal interaction between SPL (broadband and low-frequency) and sciaenid catch, where effect sizes were found to be higher during the fall sampling season (Figure 3c and Supplementary Figure S10c). As discussed previously, vocalization activity in sciaenid fish is tightly correlated with spawning activity, and of the sciaenid species observed, most spawn in the spring (Nieland and Wilson, 1993; Brown-Peterson and Warren, 2001; Brown-Peterson *et al.*, 2002; Grammer *et al.*, 2009; Anderson *et al.*, 2018). One might, therefore, expect to see sound levels positively correlated to sciaenid catch (a proxy for abundance) during the spring months. One possible explanation for this result lies in the non-discriminant nature of SPL measures. SPL measures the average amplitude of all biotic and abiotic sounds in the specified frequency range. Thus, sounds from wind, precipitation, and outside sources of biological noise (e.g. snapping shrimp and other fish species) could have confounded the results, leading to the weakened effect of sciaenid catch on sound levels during the spring sampling season. Though meteorological drivers of noise (i.e. wind, precipitation) and shrimp snaps were not quantified during this study, fish calls produced by non-sciaenids were significantly higher in the spring (average counts per site: spring = 114.4 ± 99.6 , fall = 47.6 ± 61.6 ; Wilcoxon rank-sum test: $p = 0.010$) during which time counts of non-sciaenid vocalizations shared a strong positive correlation with broadband ($R^2 = 0.397$, $p < 0.001$) and low-frequency SPL ($R^2 = 0.424$, $p < 0.001$).

In contrast, the significant relationships between sciaenid calling activity and catch exhibited a more predictable seasonal interaction. Indeed, sciaenid calling activity was positively correlated with sciaenid catch in the spring months, and spotted seatrout catch and calling activity yielded a strong positive correlation during the spring sampling season. These findings suggest that SPL may be more useful to monitor relative abundances at broad taxonomic scales (e.g. total fish catch or soniferous fish catch), while calling activity is better suited to monitor relative abundance at fine taxonomic scales (i.e. family or species level, such as sciaenid fish catch or spotted seatrout catch). Given the socioeconomic and ecological value of these species, the promise of reliable, continuous, and

non-extractive monitoring provides an enticing new avenue for fisheries surveys.

Mobile fish biodiversity was not correlated with ACI in our study. This may be related to several features of estuarine soundscapes. Snapping shrimp (family Alpheidae), for example, are widespread in estuaries in the GoM, and have been shown to greatly influence ACI levels with their impulsive, broadband snapping sounds (Bohnenstiehl *et al.*, 2018). Furthermore, during fish chorusing events, individual calls blend together to form a virtually continuous signal, which may mask other biological sounds, including the individual calls of conspecifics and heterospecifics (Amorim *et al.*, 2015; Parsons *et al.*, 2016; McWilliam *et al.*, 2018), which reduces ACI values despite the presence of a wide range of sounds. Finally, shallow estuaries are subject to substantial geophysical noise that could influence ACI values. While we removed files with overbearing anthropogenic and mechanical noise, variations in abiotic noise (e.g. wind or precipitation) could have influenced ACI values resulting in a lack of correlation between ACI and observed fish biodiversity. For the reasons listed above, we advise caution when measuring and interpreting ACI values in shallow coastal marine environments and believe it is important to develop acoustic indices that more adequately measure diversity in biological sound production in these acoustically complex systems.

Similarly, fish biodiversity was not correlated with phonic richness. Measures of phonic richness are constrained by the sensitivity of the recording devices (i.e. whether we can detect sounds produced by organisms in the area) as well as our knowledge of the vocalizations produced by local organisms. For example, many fish calls are similar in their spectral characteristics (Tricas and Boyle, 2014), which could result in the grouping of similar sounds from different species, and an underestimation of phonic richness. On the other hand, many species are capable of producing multiple sounds that vary, sometimes dramatically, in their spectral characteristics (Fish and Mowbray, 1970; Mok and Gilmore, 1983; Gilmore, 2003; Parmentier *et al.*, 2010, 2019). Thus, phonic richness may only provide a rough proxy for soniferous organism diversity, which could weaken the tested relationships. Finally, our study used only gillnet techniques for collecting fish. Gillnets come with inherent sampling bias as they target mobile fish of sizes that allow for capture in the gillnet mesh. This excludes many benthic-associated fish, as well as fish that are too large or small for capture. As such, relationships between phonic richness and biodiversity may strengthen if multiple techniques are used to survey local fish biodiversity.

Caveats and limitations

While PAM provides a promising technique for fish monitoring in the GoM, it is not without limitations. One potential caveat to our result is the possibility that some of the sounds recorded may be distress calls resulting from gillnet entanglement. Indeed, a few vocalizations observed during the manual review of sound files were preceded by crackling or banging noises, which may be attributed to gillnet capture. While these occurrences were rare, they may have inflated bioacoustics measures compared to acoustic surveys conducted in the absence of gillnets. Nevertheless, the clear lack of an axiomatic relationship between gillnet catch and SPL or calling activity suggests that there was no systematic bias arising from nearby gillnet deployment and entanglement. Furthermore, most

calling activity observed in the study was consistent with natural (i.e. undisturbed, or unimpeded) calling patterns described in the scientific literature. In sciaenid fish, for example, chorusing was observed between dusk and the early morning hours, with little calling activity occurring outside of their expected spawning hours. While placing recorders farther from the source (i.e. gillnet) may have ensured that vocalizations from stress due to entanglement do not bias the results, we sought to ensure strong spatial overlap between acoustic and gillnet sampling domains, and staggered temporal sampling was logistically unfeasible. However, we encourage future studies to consider trade-offs between spatial overlap and possible inflation in bioacoustic measures.

One of these considerations (and a reason for our intention to deploy receivers close to the gillnets) is underwater sound attenuation. Our sampling was performed across shallow coastal habitats in the MAE, where depths rarely exceed 2 m. Shallow water sites such as these have been demonstrated to readily attenuate low-frequency sounds (Urlick, 1983; Biggs and Erisman, 2021), and many sampling sites were characterized by benthic habitats known to attenuate sound (e.g. seagrass beds and soft-bottom habitats; Urlick, 1983; Wilson *et al.*, 2013). These conditions likely reduced the detection range of low-frequency biological sounds (including vocalizations of many soniferous fish), influencing all bioacoustic indices investigated. All sites investigated were similarly shallow, ensuring that depth-driven differences in sound attenuation did not confound the results. We would, however, encourage future studies to also target deeper parts of estuaries as (1) it would allow farther propagation of low-frequency sounds and (2) these areas are often targeted by sciaenid fish as spawning habitat.

Finally, we advise researchers to consider sampling duration in future comparative studies. In the present study, we compared acoustic measures collected over a 24-h period to catch data collected overnight (~12 h). While we consider the 24-h acoustic sampling period necessary to capture local diel patterns in fish calling, as well as call diversity in our system, averaging SPL over a longer period may influence the results. For example, soundscapes in the MAE typically exhibit diel patterns where fish calling activity and SPL increase during evening chorusing hours. Thus, calculating mean SPL during the overnight gillnet soak period may lead to higher values of SPL compared to those calculated over a 24-h period. Further, while investigating the relationship between SPL and *C. nebulosus* catch, we calculated mean SPL over a 4-h sampling window, which was species-relevant, but shorter in duration than the gillnet sampling. As a result, fish caught in the nets after peak chorusing hours could have confounded the results, leading to the non-significant result observed. Thus, we encourage using shorter duration gillnet soaks to investigate relationships between SPL and the abundance of species that engage in predictable evening chorusing.

Conclusions

Our study highlights the utility of PAM for monitoring the biodiversity of soniferous fish, spawning activity in sciaenid species, and the relative abundance of mobile fish in shallow estuaries in the GoM. Although PAM comes with its own set of drawbacks, it clearly complements fisheries-independent sampling techniques in its ability to non-invasively monitor fish populations through time and detect the presence of

undersampled soniferous species. Further, given the low maintenance costs of acoustic monitoring, PAM can overcome the limited temporal replication that plagues traditional fisheries monitoring techniques. This may prove particularly useful in the GoM, which is impacted by many natural and anthropogenic pulse disturbances. Future comparative assessments of the relationship between acoustic variables and visual or extractive surveys across locations, habitats, and conditions may strengthen our ability to broadly implement PAM for fish monitoring as relationships are subject to differ with local biology, habitat, anthropogenic use, and geophysical characteristics. We are optimistic that PAM can aid the assessment of estuarine fisheries, especially as passive acoustic technologies and our understanding of sound production in fish species are poised to grow over the next few years.

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Data availability

Summarized acoustic and gillnet catch data, as well as example fish vocalizations are available as Supplementary Material. Data used for acoustic-gillnet analyses are available via figshare: https://figshare.com/articles/dataset/gillnet_acoustic_data_csv/22747016.

Conflict of interest

The authors have no conflict of interest to declare.

Supplementary material

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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Author contributions

PS Jr conceived the project, collected acoustic data, analysed the data, and wrote the first draft of the manuscript. SB helped develop the project, guided data analysis, and contributed to manuscript writing and revisions. ZO led TPWD's Aransas Bay Ecosystem team in gillnet data collections and contributed to manuscript writing and revisions.

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