Analyzing Long-Term Changes in Soundscapes Using Power Spectral Band Sums

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Contents

Abstract

Various species of fish make sounds (individually and in choruses) while mating and for aggressive encounters. Recording the sounds of fishes in mixed-species choruses has been done for 26 years in Pamlico Sound, North Carolina, USA. But

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the changing contributions of the various fishes to the soundscape that varies diurnally, seasonally, and over 20 years have not been characterized. Multiple passive acoustic recording systems have been used to make these recordings at a variety of locations. After calibrating these recording systems, an analysis of the soundscape was performed using power spectral band (PSB) sums, which sum the acoustic energy in frequency bands associated with known soniferous fish species. The analysis reveals some interesting patterns related to fish ecology: (1) sound production occurs after sunset with a nightly peak in sound pressure levels; (2) there is a seasonal increase in the power spectral band sums, correlated with increasing water temperatures; and (3) species in the Sciaenidae family have distinct periods of sonic activity. The temporal progression of these species in their spawning areas was plotted using PSB sums. Examples are presented of these soundscapes and descriptions of the changes observed in the soundscapes from samples taken over 20 years (1997–2018).

Keywords

Passive acoustic monitoring · Estuary · Spawning · Sciaenidae

Introduction

Various species of fish make sounds (individually and in choruses) while mating and during aggressive encounters (Mok and Gilmore 1983; Rountree et al. 2006). For more than 20 years, passive acoustic monitoring of the estuarine soundscapes has been used to understand the behavior and seasonal occurrence of fishes that produce sounds (Luczkovich et al. 1999, 2008; Sprague et al. 2000). Sounds that are recorded in estuaries in North Carolina are mainly due to fishes in the drum family (Sciaenidae). These fishes produce nocturnal choruses of varying intensity. The chorusing is associated with spawning activity (they are advertisement calls made by males). But the entirety of the data has not been examined for patterns indicating that the sound intensity measured in the same month or season varies across multiple years.

Therefore, it is the objective in this retrospective to investigate the following questions:

1. How does the chorusing vary geographically in the soundscape (using the focal year 1998)?
2. How does the chorusing change temporally within a year (using the focal year 2006)?
3. How does the chorusing change across years (focal years of 2006, 2017, and 2018)?

Calibration of Hydrophones and Recording Systems

Three different recording systems were used, and each one is different in hydrophone sensitivity and recording system frequency response (Table 1). They spanned a range of purchase costs: $200 each ($370 corrected for inflation in 2023, using the tool at https://www.usinflationcalculator.com/) for the East Carolina University Sonobuoy with an analog cassette recorder, $5000 each for the Loggerhead LARS digital recorder (an equivalent model called Snap made by Loggerhead, Inc. costs $3995 in 2023), and $10,185 each (purchased in 2015, $ 11,300 in 2023) for the icListen smart digital hydrophone (Ocean Sonics, Inc.). A float collar, 50-m cable, battery pack, and Lucy instrument control software (V4) were also used with the icListen hydrophone, which raised the cost of the system to $22,308 in 2015 ($28,626 in 2023). A description of each system follows.

ECU Sonobuoys

These sonobuoys were constructed at East Carolina University and consisted of a Gulton GLN-9190 hydrophone (−174 dB re 1 V/μPa sensitivity) connected to a Sony TCM 313 cassette recorder and a timing circuit (Luczkovich et al. 2008). The hydrophone output was recorded on a cassette audiotape (TDK D Type I normal-bias 90 min) for long-term storage and analysis. This recorder system was programmed to be powered on at intervals (30 min or 60 min) selected by the user. After powering up, the cassette recorder made ambient soundscape recordings that were 90 s duration, then shut off until the next power-on interval. A talking clock announced the local time at the start of each recording. Tape recordings with successive intervals lasted for 12–24 h, after which the sonobuoy was recovered and redeployed with new a tape.

Loggerhead LARS

This recording system has an HTI 96-min hydrophone with a sensitivity of −164 dB re 1 V/μPa and a frequency range of 10 Hz−10 kHz. Digital recordings were made using a Dell Axim and the Loggerhead Pocket PC software application. The calibration procedures for the Dell Axim (LHCal.exe) were followed according to the manufacturer using a signal generator as the input. The HTI 96-min hydrophone

Table 1 The passive acoustic hydrophone recording systems and frequency responses of each system used

Recording system	Hydrophone sensitivity	System frequency response
ECU Sonobuoy	−174 dB re 1 V/μPa	30–2000 Hz
Loggerhead LARS	−164 dB re 1 V/μPa	10 Hz–10 kHz
Ocean Sonics icListen HF	−171 dB re 1 V/μPa	10 Hz–200 kHz

sensitivity specification was used (−164 dB re 1 V/μPa). A calibration adjustment was made (+175.5 dB was added to normalized LARS recordings to convert the file sample values to μPa for displays and analysis in Python).

Ocean Sonics icListen HF

This is a “smart” hydrophone (Ocean Sonics model SB2-ETH) with digital recording and hydrophone combined in a single unit. Calibration was provided by the manufacturer (Calibration certificate C3154). This hydrophone has a sensitivity of −171 dB re 1 V/μPa and a system response frequency of 10 Hz–200 kHz. The float collar was used to suspend the icListen in the water column, which allowed the hydrophone to remain neutrally buoyant 1 m above the bottom. The float collar was attached to an anchored cage where the battery pack was cabled to the hydrophone.

Calibrations of the Three Hydrophone Systems

Although the three recording systems each had calibrations based on hydrophone sensitivities, the same sounds were recorded with each to make sure they all produced the same levels in recordings. Reference tones and noise (200–10,000 Hz) were played back in a test pool and in the air, while recording the frequency response for each of the hydrophones. Sonobuoy recordings were compared with recordings made simultaneously using a reference hydrophone: Gunnar Rasmussen Hydrophone Model 10CS (−211.7 dB re 1 V/μPa sensitivity, frequency response 0.1–25,000 Hz). The reference hydrophone output voltage was simultaneously recorded to a digital recorder (SONY DAT tape or Zoom Recorder). Sine waves produced by a signal generator with input voltages measured on the oscilloscope were also recorded digitally. The amplitude of the reference hydrophone associated with the input voltages from the signal generator was also recorded for each sine wave test tone. The audiocassette tape in the sonobuoy and the reference hydrophone output were digitized on a Zoom F8 Recorder at 44.1 kHz with a +25 dB gain. The Gulton sonobuoy hydrophone was compared against the reference hydrophone using the known input voltages and digitized audio amplitudes as received at the two hydrophones to develop a calibration relationship. Digitized field tape recordings from the ECU Sonobuoys were recorded on the Zoom F8 multitrack recorder using the same settings.

An inter-hydrophone and recording system comparison test was conducted for the three systems used (ECU sonobuoy, LARS, and icListen) in a freshwater pool and in air to compare the sound pressure levels recorded and the frequency response of each passive acoustic recording system. Such inter-recorder calibration is essential to make comparisons of field recordings by each of the systems over time. To accomplish this inter-hydrophone calibration, comparisons were made of sound recordings from the three recording systems in the pool at distances of 11 m while playing a series of tones and white or pink noise signals through an underwater speaker (Clark Synthesis AQ-339) with a power amplifier (Pyle PMLRA200). For air intercalibration measurements, an amplified JBL public address system (JBL model EON208P) was used to play the same sounds at a distance of 1 m from the three hydrophone and recording systems.

Power Spectral Analysis

The procedure in this section was previously published (Luczkovich and Sprague 2022). Power spectral band sums (PSB sums) were computed for specific frequency bands associated with known fish sounds. Table 2 shows the frequency range associated with different fish species. These frequency bands were chosen as indicators of calls by the various species. The bands do not contain all frequencies in the calls. The PSB sum S_{PSB} is the sum of all power spectrum components P_n for frequencies in the band $f_{min} \le f_n \le f_{max}$

$$S_{PSB}(f_{min}, f_{max}) = \sum_{n_{min}}^{n_{max}} P_n \Delta f$$

where n_{min} is the index of the smallest frequency component in the band, n_{max} is the index of the largest frequency component in the band, and Δf the frequency interval in the power spectrum.

The average PSB sum was computed for each band in Table 2 using 10 s of the recording. The PSB sums were plotted versus time to identify times in the recordings likely to contain fish sounds. One indication of fish activity is when the PSB sum for a frequency band increased with a different pattern than the other bands.

Table 2 The bands used in the power spectra analysis (power spectral band sums, with frequency max and min) and the fish species that are dominant within each frequency band. A similar table with different band numbers was previously published (Luczkovich and Sprague 2022). Atlantic croaker is assigned to Band IV in this table with a wider frequency range than what was used in the previous study

Frequency band (Hz)	Common name, species (family)
Band I: 100–200	Red drum, *Sciaenops ocellatus* (Sciaenidae)
Band II: 200–300	Oyster toadfish, *Opsanus tau* (Batrachoididae)
Band III: 300–600	Spotted seatrout, *Cynoscion nebulosus* (Sciaenidae) Weakfish, *Cynoscion regalis* (Sciaenidae)
Band IV: 300–1000	Atlantic croaker, *Micropogonias undulatus* (Sciaenidae)
Band V: 600–1500	Silver perch, *Bairdiella chrysoura* (Sciaenidae)
Band VI: 1500–2000	Striped cusk eel, *Ophidion marginatum* (Ophidiidae)

Study Design

The 1998 ECU sonobuoy survey was used to develop maps of sounds heard at different locations using the Summed Nightly Drumming Index (SNDI), which was scored on 0 (no fish sounds) to 3 (loud chorusing) scale by a human listener for red drum *Sciaenops ocellatus*, spotted seatrout *Cynoscion nebulosus*, weakfish *C. regalis*, and silver perch *Bairdiella chrysoura* (Luczkovich et al. 2008). These sonobuoys were deployed and recovered at random locations (located with GPS coordinates) chosen within two grids (Ocracoke Inlet and Bay River) every month from May through October 1998 (Fig. 1; see the detailed description of the sampling design in the original study Luczkovich et al. 2008). These geolocated passive acoustic recordings were used to produce spatial soundscape analysis via geostatistical kriging interpolation (ArcMap 10.6.1) of the nightly PSB sums for each of the power spectra bands associated with the fish species heard (Table 2) from the digitalized sonobuoy tapes.

The Bay River location was used thereafter for temporal comparisons with the LARS and icListen recording systems in focal years 2006 through 2018 (Fig. 2). Spotted seatrout and red drum are known to spawn in this Bay River grid location. Also, the Bay River grid location is affected by periodic hypoxic conditions and salinity variation, thus temporal changes in the soundscape were associated with these changing environmental conditions. Long-term continuous recordings were made at the Bay River grid fish and at known fish spawning hotspots (Fig. 2). The LARS recorders were used to record the soundscape from May through October 2006 (with a programmed recording duty cycle of 10 s recordings every 15 min). In addition, a water quality sonde (YSI model 6600) was deployed alongside the LARS to monitor temperature (Luczkovich et al. 2013a). The icListen recording system was deployed within the Bay River grid and at a nearby location from August through October in both 2017 and 2018. The icListen duty cycle was programmed to log 5-min recordings at 15 min intervals during this time.

Spatial Variation in Soundscape

There are differences in the soundscape within the eastern (Ocracoke Inlet) and western (Bay River) sonobuoy grids, with red drum “knocking” sounds and spotted seatrout “grunting” sounds heard and scored using the SNDI index and then interpolated to create soundscape maps (Fig. 3 is the soundscape map for red drum; Fig. 4 is the soundscape map for spotted seatrout). Red drum were highly aggregated and localized in these two grids, occurring more often in deep water (>3 m), whereas spotted seatrout were widespread and occurred over much of the area of both grids; they were heard more often in shallow water (<3 m). The weakfish and silver perch were more dominant in the eastern grid (Ocracoke Inlet) in higher salinity waters (Fig. 5 is the map for weakfish, and Fig. 6 is the map for silver perch).

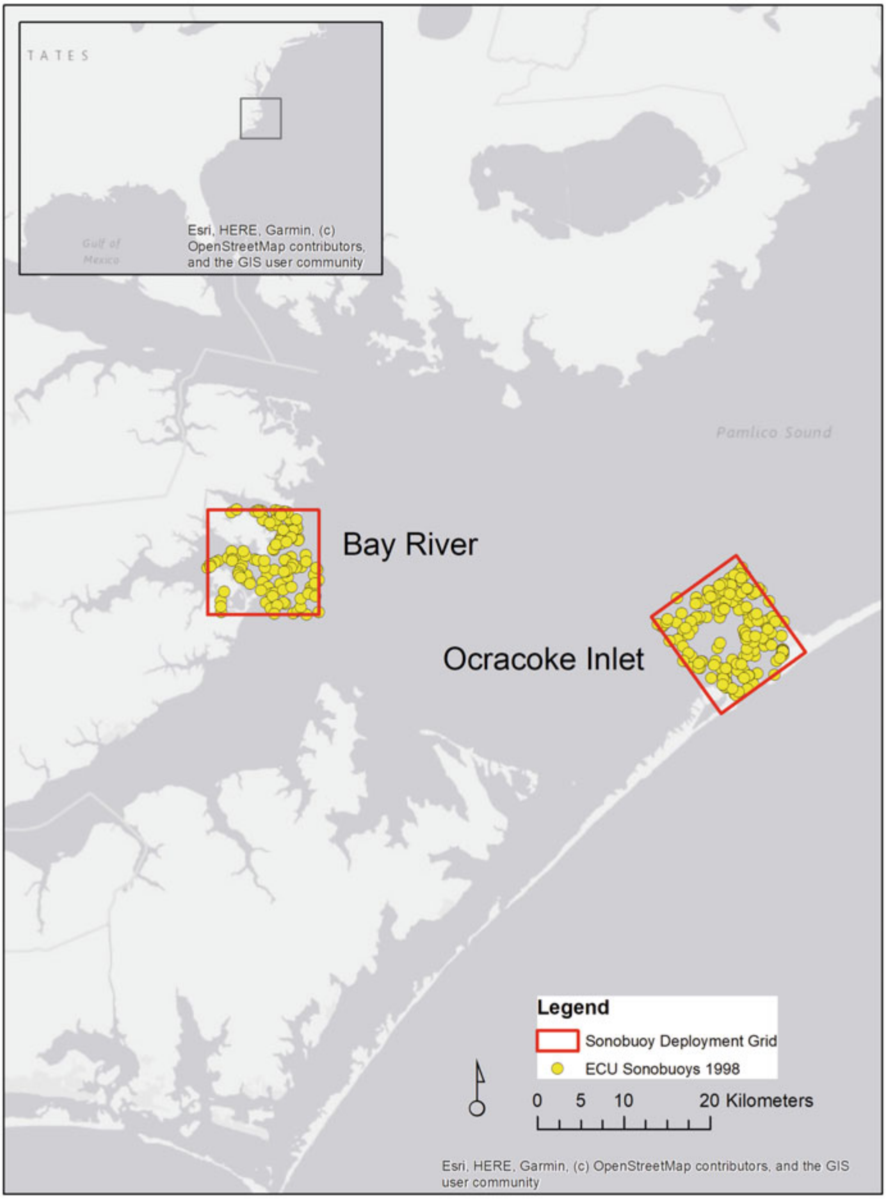


Fig. 1 Overview map of the Bay River and Ocracoke Inlet study sites in Pamlico Sound North Carolina, USA. ECU Sonobuoys were deployed (yellow circles) May–Oct 1998. Also placed in the Bay River: the LARS recording system was deployed in May–Oct 2006; the icListen hydrophone recording systems was deployed in Aug–Oct 2017 and 2018 (Base map reprinted with permission from Esri, Inc.)

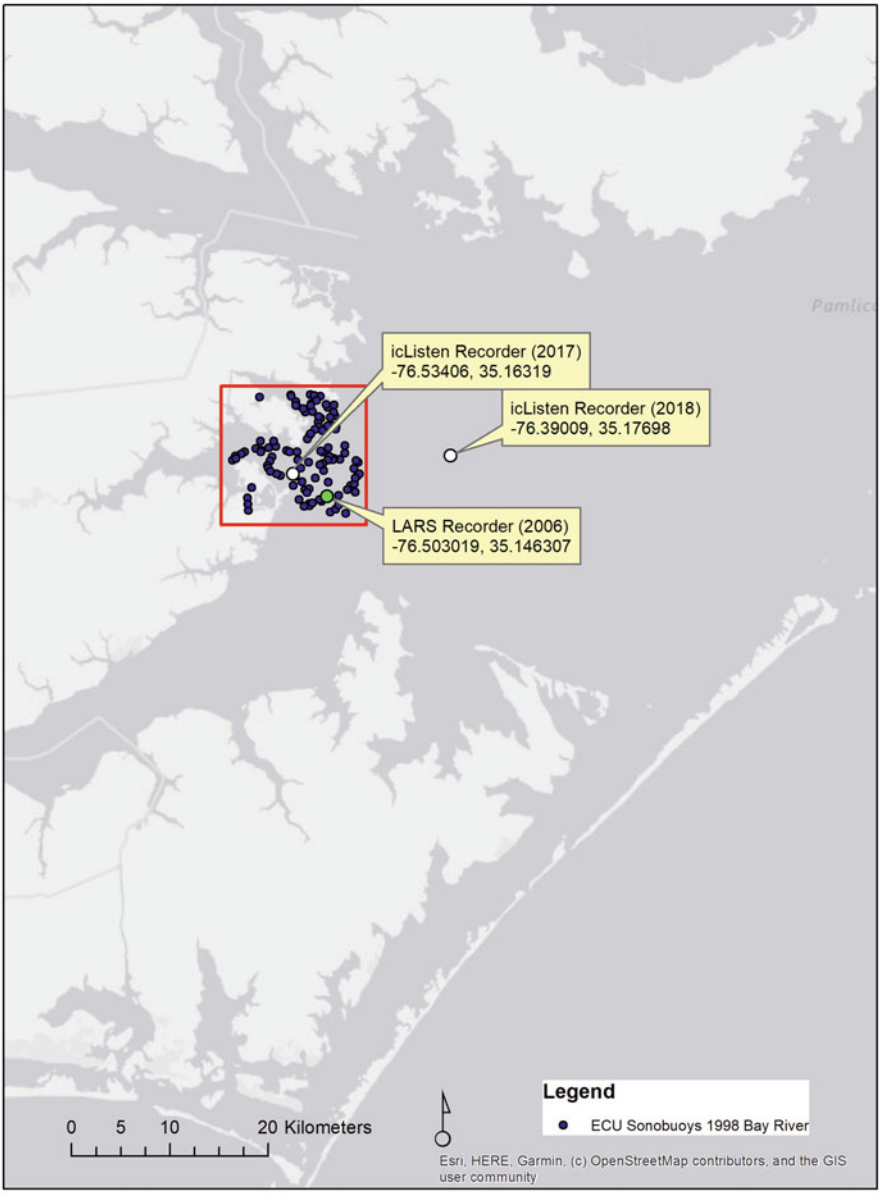
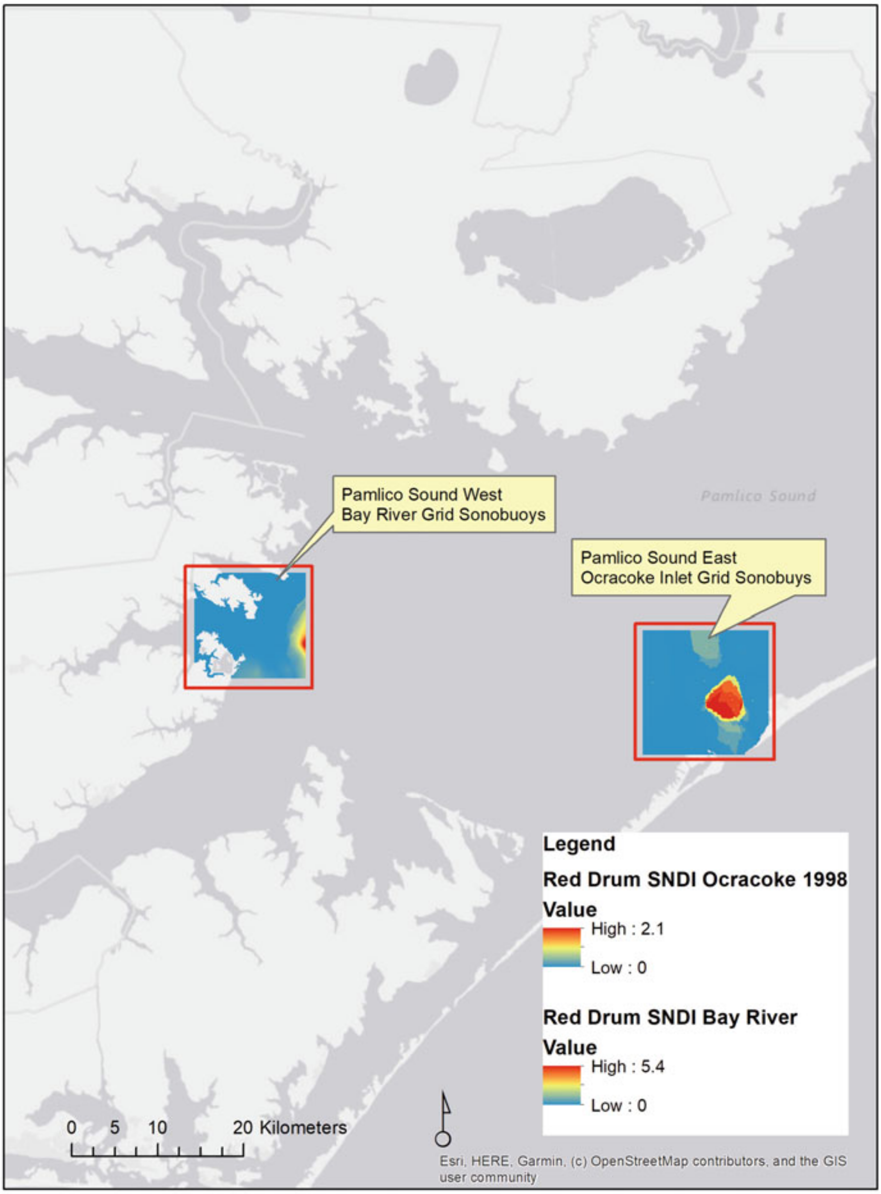


Fig. 2 Overview map of the Bay River study sites in Pamlico Sound North Carolina, USA. ECU Sonobuoys were deployed at the points indicated during May–Oct 1998. The LARS recording system was deployed in May–Oct 2006 at the position indicated. The icListen hydrophone recording systems was deployed at two locations indicated during Aug–Oct 2017 and again in 2018 (Base map reprinted with permission from Esri, Inc.)



Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

Fig. 3 The soundscape map for red drum *Sciaenops ocellatus* based on kriging interpolation of Summed Nightly Drumming Index SNDI values from sonobuoy recordings made in 1998 at Bay River and Ocracoke Inlet grids in Pamlico Sound, North Carolina, USA (Base map reprinted with permission from Esri, Inc.)

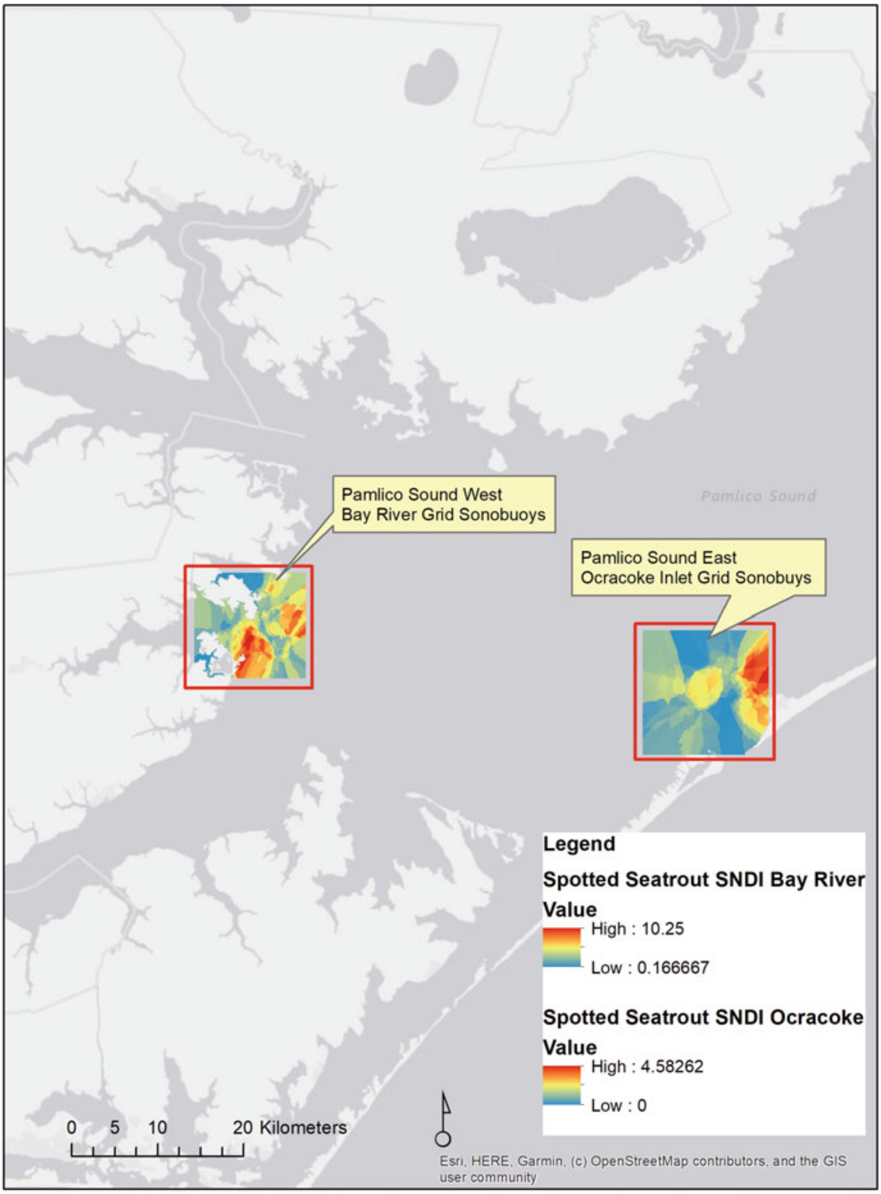


Fig. 4 The soundscape map for spotted seatrout *Cynoscion nebulosus* based on kriging interpolation of Summed Nightly Drumming Index SNDI values from sonobuoy recordings made in 1998 at Bay River and Ocracoke Inlet grids in Pamlico Sound, North Carolina, USA (Base map reprinted with permission from Esri, Inc.)

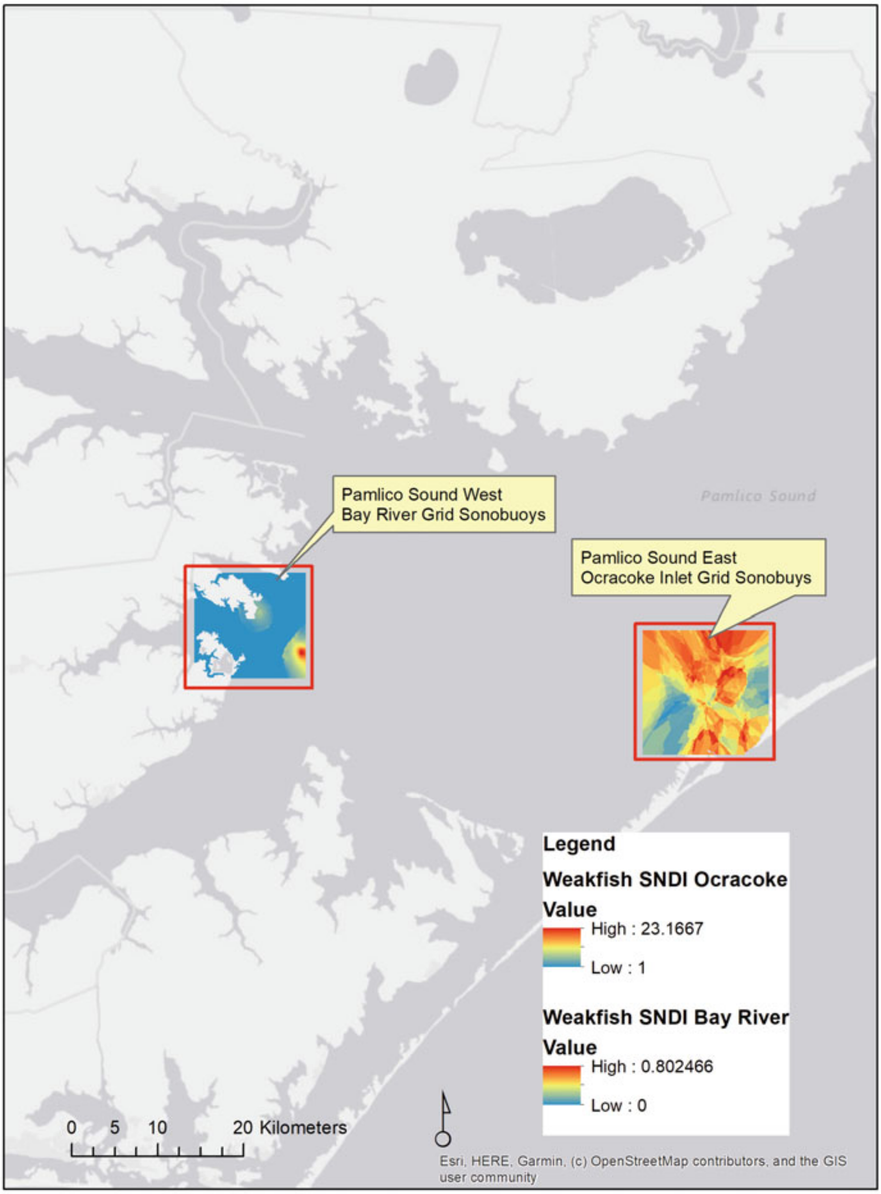


Fig. 5 The soundscape map for weakfish *Cynoscion regalis* based on kriging interpolation of Summed Nightly Drumming Index SNDI values from sonobuoy recordings made in 1998 at Bay River and Ocracoke Inlet grids in Pamlico Sound, North Carolina, USA (Base map reprinted with permission from Esri, Inc.)

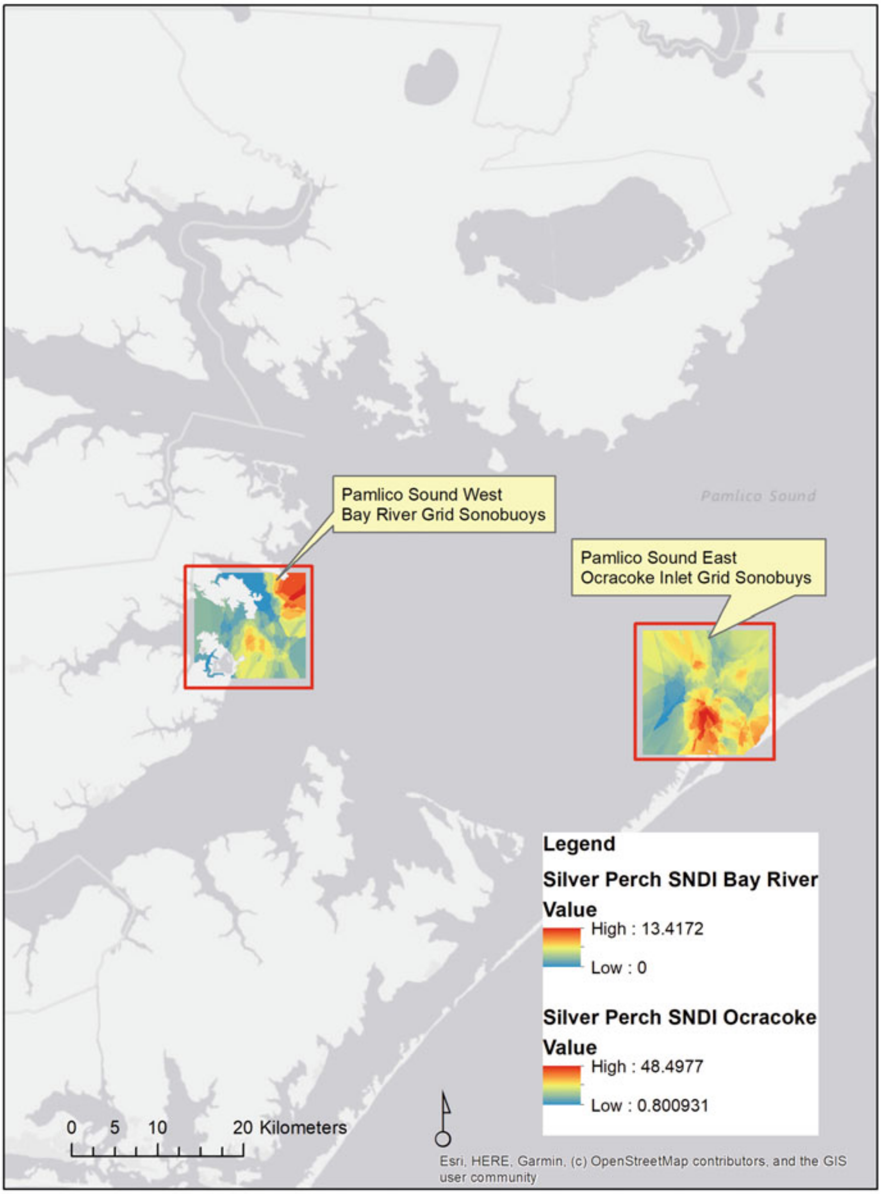


Fig. 6 The soundscape map for silver perch *Bairdiella chrysoura* based on kriging interpolation of Summed Nightly Drumming Index SNDI values from sonobuoy recordings made in 1998 at Bay River and Ocracoke Inlet grids in Pamlico Sound, North Carolina, USA (Base map reprinted with permission from Esri, Inc.)

Temporal Variation in Soundscape

Diurnal Variation in the Soundscape

There was a regular nocturnal chorusing of fish on these passive acoustic recordings. Fish made sounds before sunset but PSD band sums peaked after sunset. As an illustrative example, a typical Sciaenidae fish chorus can be observed on 18 Aug 2018 in the Bay River grid area (Fig. 7). The PSB sums (Fig. 7a) indicated that the primary contributors early after sunset were red drum and spotted seatrout (Band I 100–200 Hz and Band III 300–600 Hz show peaks on 18 Aug 2018 at approximately 21:00 local time UTC −5 h; the calls of these species were confirmed by listening to these recordings). This mixed species sciaenid chorus ended by midnight on 18 Aug (0000 local time UTC −5 h, Fig. 7b). Later in this same set of recordings on 19 Aug between 0400 and 0600 local times (UTC −5 h), a rise was detected in Band VI associated with striped cusk eels *Ophidion marginatum* (Fig. 7a). These are higher frequency (1.5–2.0 kHz) “chattering” calls (Fig. 7b). These sciaenid choruses and individual striped cusk eel chatter sounds became less dominant by daybreak (after 0600 local time) and remained low during each diurnal period, increasing again at sunset the next night. This pattern repeated every night throughout the summer.

Seasonal Variation in the Soundscape

The soundscape was recorded at a single location (Fig. 2, Latitude 35.146307N and Longitude 76.503019W) in the Bay River grid 2006 from 30 April through 04 October using the LARS passive acoustic recording system. In this long sequence of recordings, using a 10-s recording period with a duty cycle repeating at 600 s intervals (every 10 min), taken over 157 days or more than 5 months, the changing phenology of the soundscape was visualized in a composite spectrogram. The seasonal change in the soundscape reflected different species participating in the chorusing, changing environmental conditions that affected the calling behavior, including warming and cooling water temperatures, lengthening and shortening photoperiods, salinity fluctuations, hypoxic events, multiple species of Sciaenidae (silver perch, weakfish, spotted seatrout, Atlantic croaker *Micropogonias undulatus*, and red drum), Batrachoididae (oyster toadfish *Opsanus tau*), and striped cusk eels performing their nightly choruses with quiet daytime periods intervening were recorded. These increases and decreases in sound amplitude in each of the frequency bands associated with these different fish species (Table 2) are visible as nightly pulsing variations in the PSB sums plots (Fig. 8a 30 April–7 Jun; Fig. 9a 30 June–15 Aug; Fig. 10a, 20 Aug–25 Sep; Fig. 11a, 03 Oct–10 Oct; and Fig. 12a, 28 Sep–04 Nov). Each night, as the fish in the area reached a crescendo of calling activity in a chorus, the PSD sum increased, and in the daytime, as the fish chorusing activity ceased, the PSB sums fell back to a baseline. This pattern was repeated each night for the entire summer, but the choruses’ dominant frequency shifted upwards as the environment changed. The water became warmer in May and June, rising from

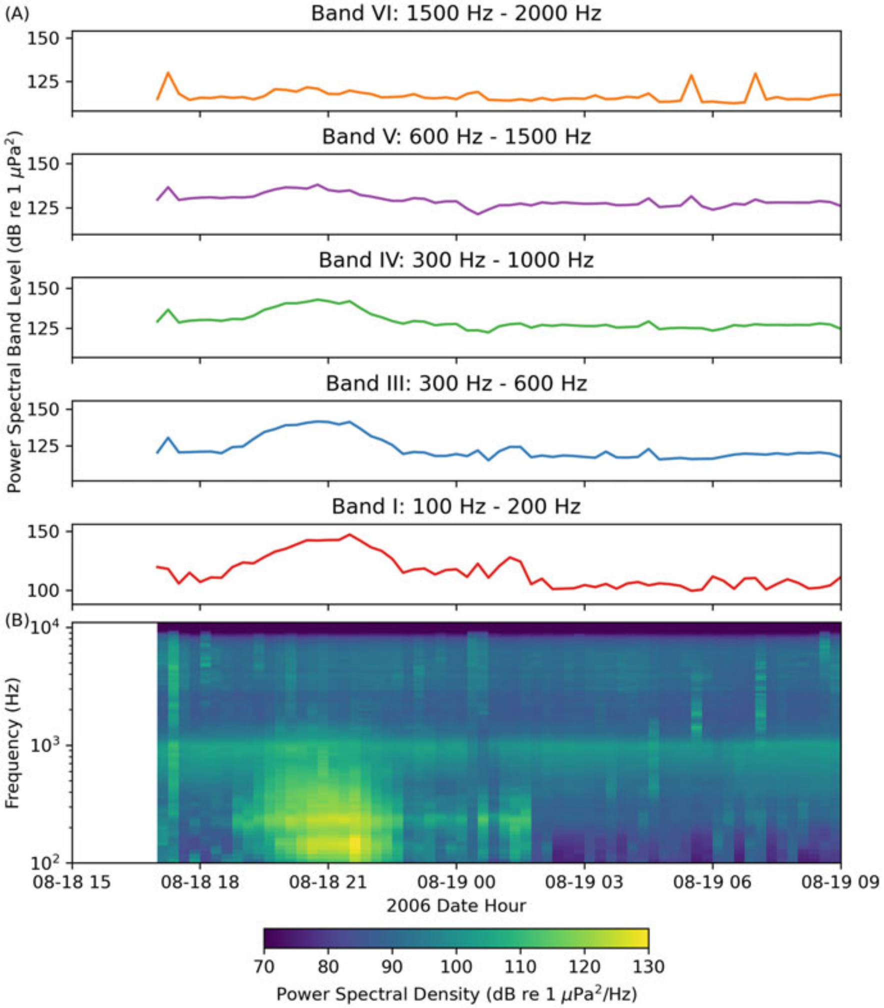


Fig. 7 The nocturnal choruses of fish the Bay River grid on 18 Aug 2006 1700 through 9 Aug 2006 0900 (local time UTC −5. (**a**) The power spectral band sums (dB re 1 μPa^2/Hz) for the frequency bands indicated and associated with fish species are given in Table 2. (**b**) The composite spectrogram of recordings made that night using the LARS recorder system

13 °C on 3 May to 23 °C by 30 May on the water quality sonde deployed along with the LARS (Luczkovich et al. 2013b). As water temperature warmed, the dominant frequency of the fish choruses increased (Fig. 8b) from <200 Hz to 200–250 Hz by 30 May. Water temperatures stabilized in the summer months of July and August (26–28 °C), leading to a regular pattern of seatrout grunting choruses (Fig. 9), and then fell back to lower frequencies in the cooler water in Sep and Oct (Fig. 10, Fig. 11). In Fig. 8b, a frequency band around 200 Hz (Band I, 100–200 Hz) can be

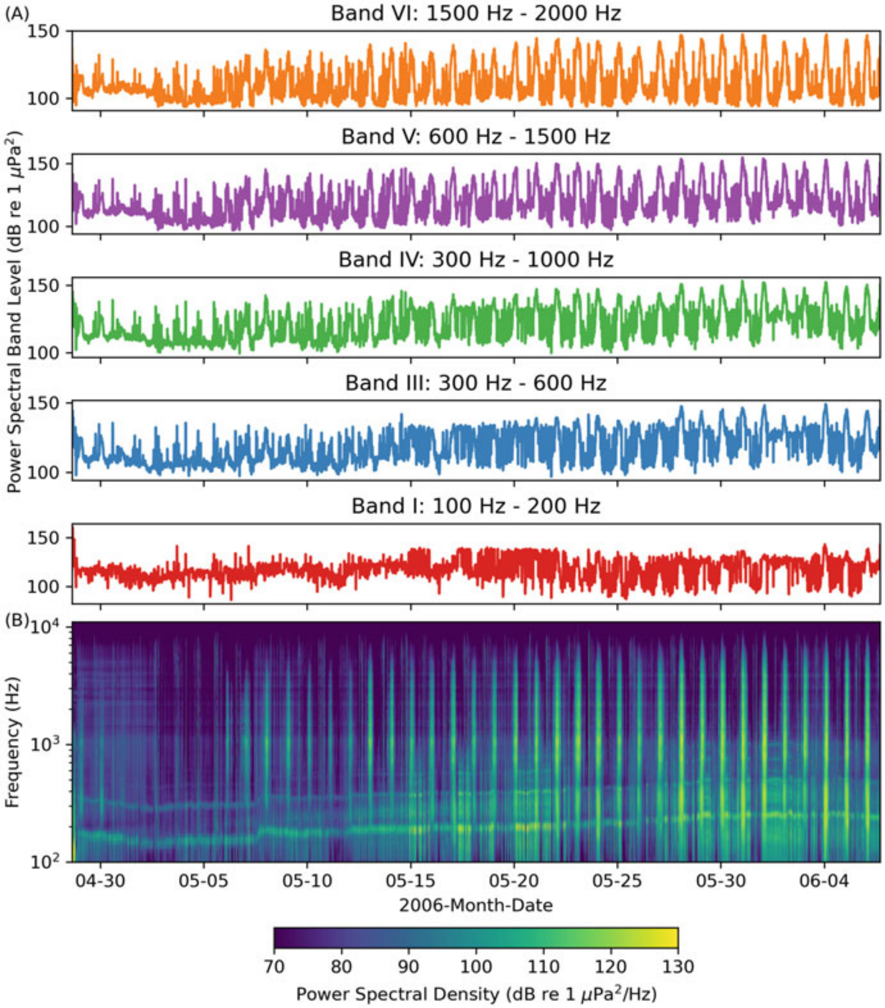


Fig. 8 The PSB sums and composite spectrograms plotted over time from LARS recordings made between 29 April and 6 June 2006 in the Bay River grid. (**a**) PSB sums for frequency Bands I, III, IV, V, and VI associated with fish species in Table 2. (**b**) The composite spectrogram of the soundscape for this same period with frequency on a log scale (100 Hz–10 kHz) and color ramp scale. All PSD sums and color ramp units are given in dB re 1 μPa^2/Hz

observed increasing in frequency each day through the month of May; this activity persisted during the daytime. This frequency band increase was due to an increase in oyster toadfish *Opsanus tau* calling (human listeners could discern individual toadfish calling during daytime on these recordings) and was associated with the warming of the water temperature at the site. Silver perch (PSB Band V 600–1500 Hz) frequency band also showed this increase in temperature-associated

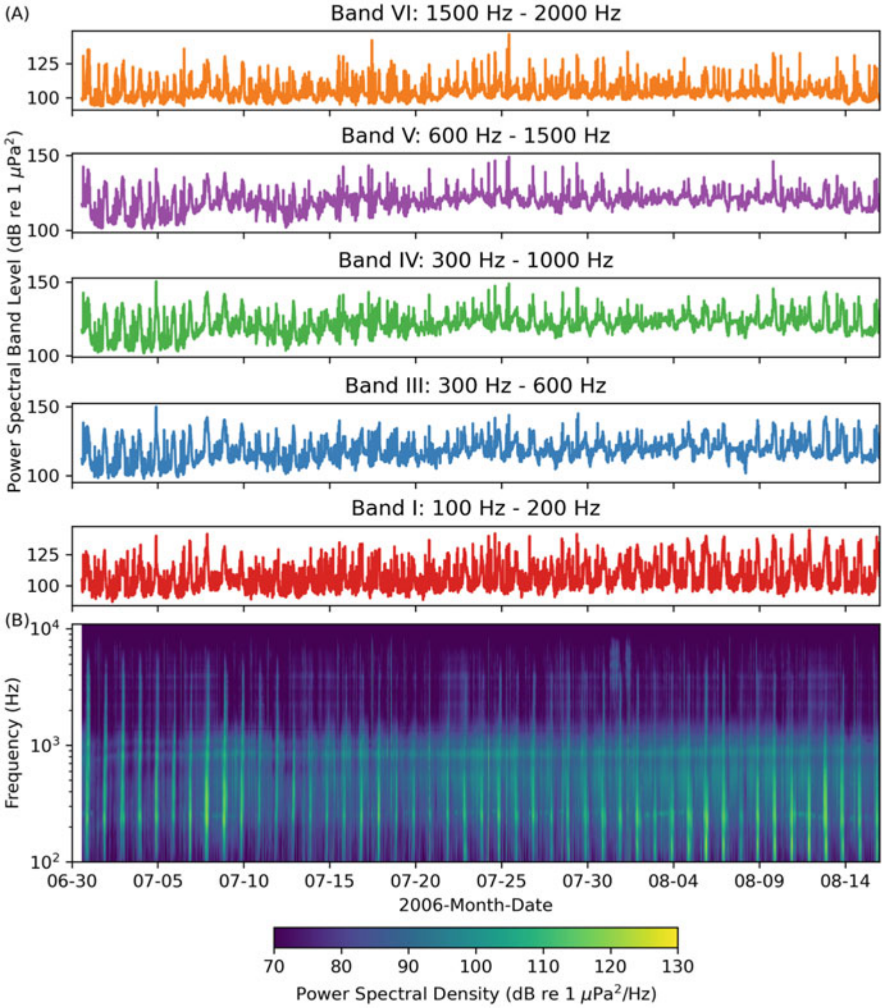


Fig. 9 The PSB sums and composite spectrograms plotted over time from LARS recordings made between 30 June and 16 Aug 2006 in the Bay River grid. (**a**) PSB sums for frequency Bands I, III, IV, V, and VI associated with fish species in Table 2. (**b**) The composite spectrogram of the soundscape for this same period with frequency on a log scale (100 Hz–10 kHz) and color ramp scale. All PSD sums and color ramp units are given in dB re 1 μPa^2/Hz

calling activity, although this species was largely nocturnal in its calling activity. Increased PSB sum with increased water temperature can be seen as increased peaks in the Bands III, IV, and V and as broad spectral pulses (300–1500 Hz) in the composite spectrogram occurring each night (Fig. 8b); these nocturnal choruses became more intense at the end of May and the start of June. During July and August (Fig. 9), the nightly spotted seatrout chorus became less intense and no

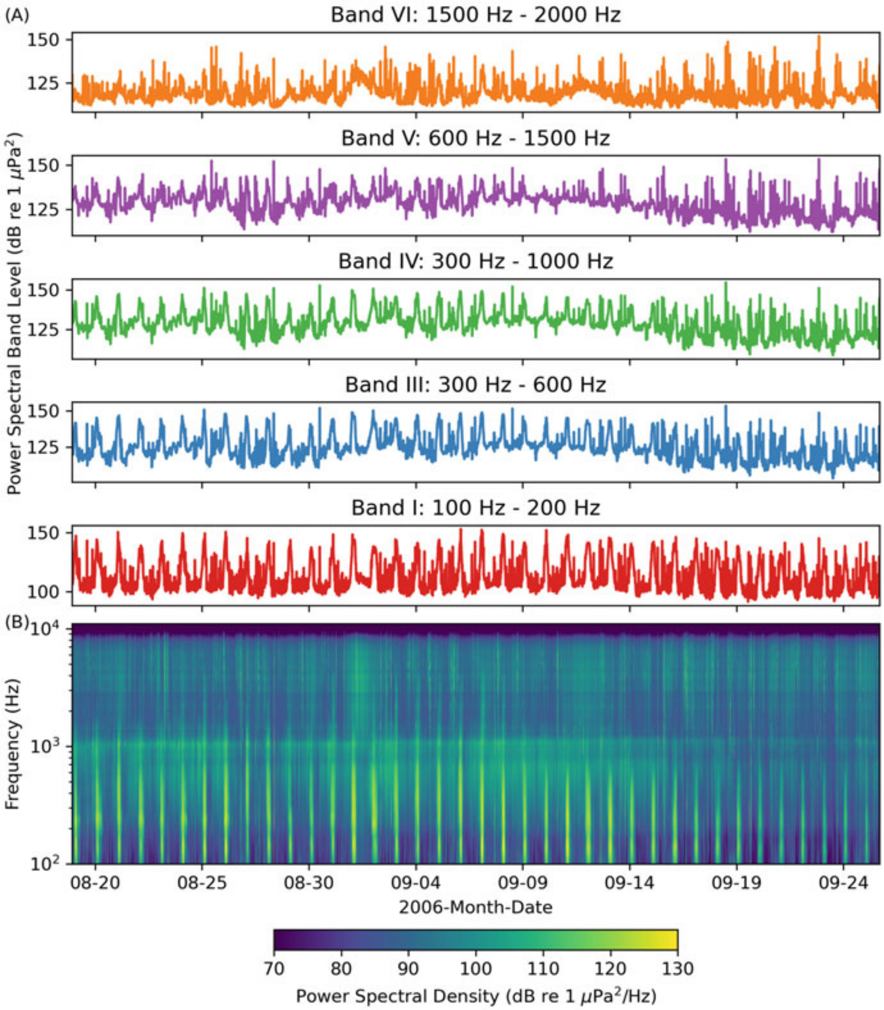


Fig. 10 The PSB sums and composite spectrograms plotted over time from LARS recordings made between 20 Aug and 25 Sep 2006 in the Bay River grid. (**a**) PSB sums for frequency Bands I, III, IV, V, and VI associated with fish species in Table 2. (**b**) The composite spectrogram of the soundscape for this same period with frequency on a log scale (100 Hz–10 kHz) and color ramp scale. All PSD sums and color ramp units are given in dB re 1 μPa^2/Hz

longer had the dominant frequency of 200 Hz during the daytime, as the oyster toadfish had ceased calling as much during the day. Instead, during this summer period, spotted seatrout grunts (Band III 300–600 Hz) and red drum knocking (Band I 100–200 Hz) can be heard in late August and September 2006 as part of the nightly mixed sciaenid chorus (Fig. 10). In addition, the nightly chorus at this time was dominated by the grunting of spotted seatrout (Fig. 10a, Band III, 300–600 Hz), which then dominated the soundscape nocturnally. By the end of September (24 Sep

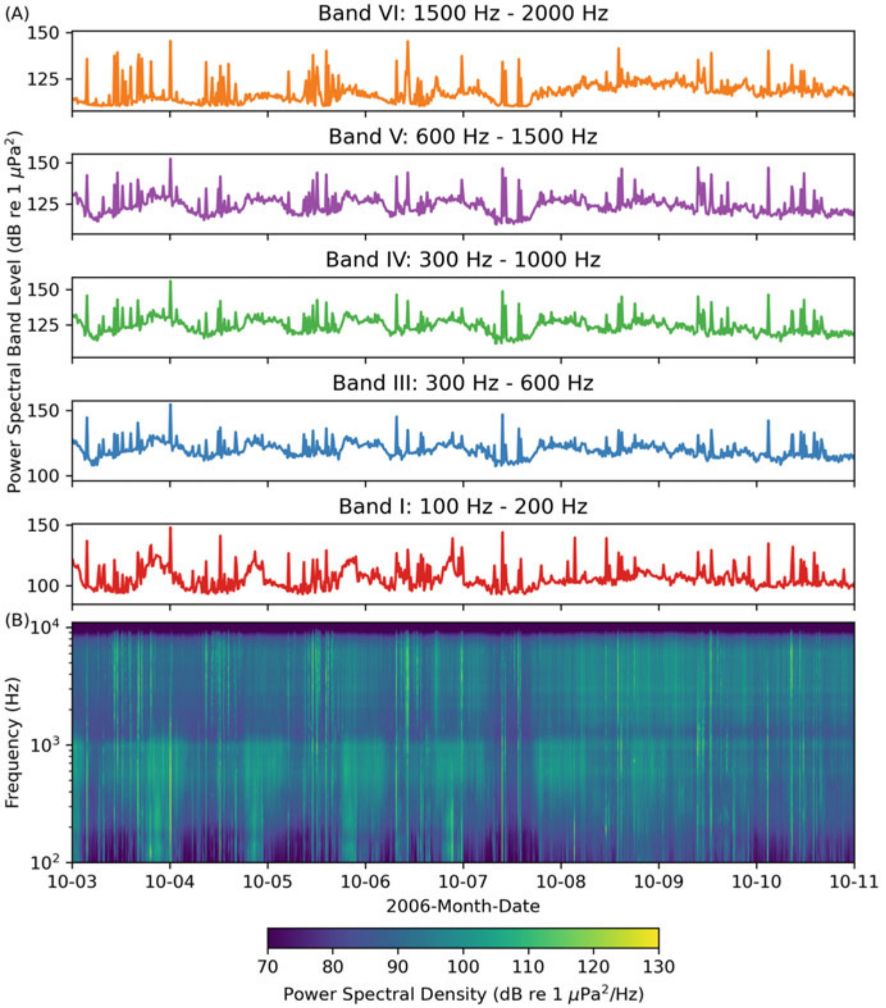


Fig. 11 The PSB sums and composite spectrograms plotted over a short time window so the diminishing Sciaenidae chorusing can be observed from LARS recordings made between 3 Oct and 11 Oct 2006 in the Bay River grid. (**a**) PSB sums for frequency Bands I, III, IV, V, and VI associated with fish species in Table 2. (**b**) The composite spectrogram of the soundscape for this same period with frequency on a log scale (100 Hz–10 kHz) and color ramp scale. All PSD sums and color ramp units are given in dB re 1 μPa^2/Hz

2006), this seatrout chorus had become less dominant in the soundscape (Fig. 10b). A listener could also hear Atlantic croaker “popping” sounds in this period in Band IV (Fig. 10a), the sound of which overlaps with the *Cynoscion* grunts in Band III but has higher frequency components. In Fig. 11a, b, at the beginning of October, a shorter time window period (03 October through 11 October) was visualized in order to observe the diminished Sciaenidae chorus. (It is still dominated by the species

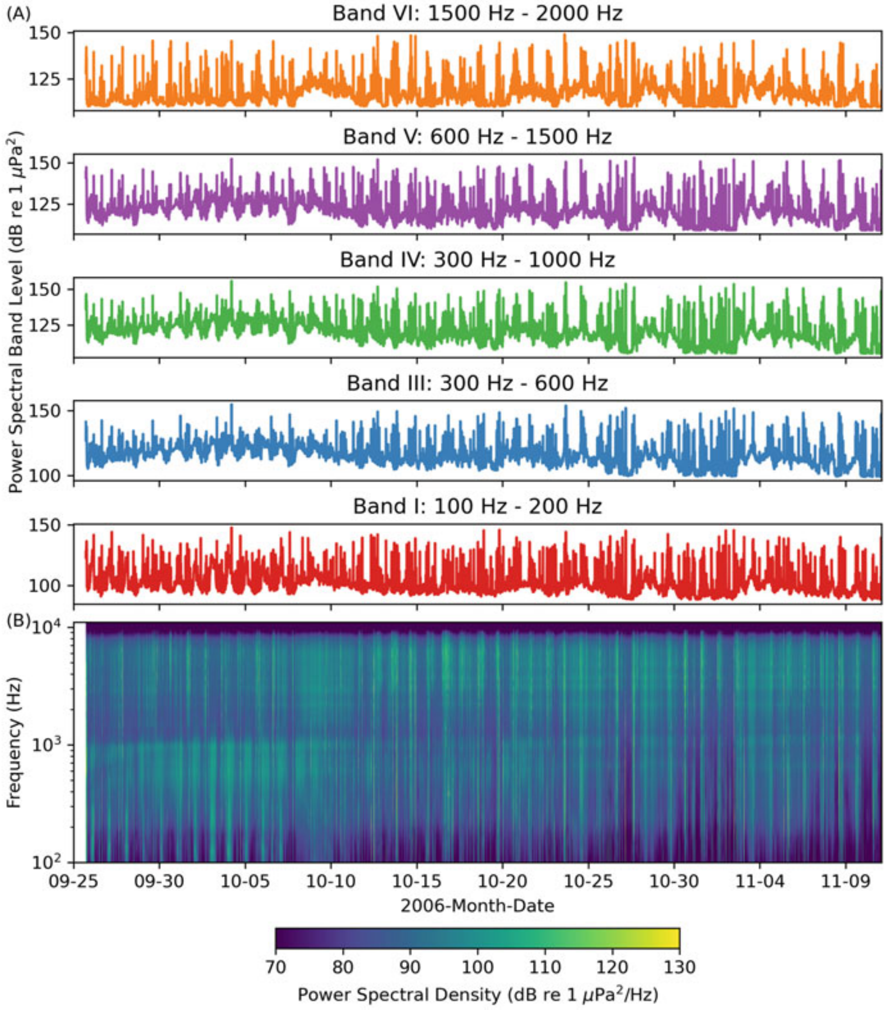


Fig. 12 The PSB sums and composite spectrograms plotted over time from LARS recordings made between 25 Sep and 11 Nov 2006 in the Bay River grid. (**a**) PSB sums for frequency Bands I, III, IV, V, and VI associated with fish species in Table 2. (**b**) The composite spectrogram of the soundscape for this same period with frequency on a log scale (100 Hz–10 kHz) and color ramp scale. All PSD sums and color ramp units are given in dB re 1 μPa^2/Hz

above, spotted seatrout, red drum, and Atlantic croaker, but the chorus is greatly reduced in calling activity at the end of this period.) These nightly Sciaenidae choruses persisted throughout October (PSB sums in Fig. 12a and in the spectrogram in Fig. 12b), but at a lower intensity of calling. This is due most likely to the shortening photoperiods, and colder water temperatures (water temperature dropped from 26 °C to 20 °C) at this time of year. By 9 November, the calling activity and fish chorusing is at a minimum, although it still occurs nocturnally, and most spawning activity has ceased (Fig. 12).

Interannual Variation in Soundscape

The Band I (red drum 100–200 Hz) PSB sum intensity over the years 2006–2018 at sites in the Bay River grid and on Brant Island Shoal was visualized in a composite spectrogram (Fig. 2). There was no reliable intercalibration possible for the ECU Sonobuoys used in 1998 due to reliability issues with old cassette decks, so these recordings were omitted in the interannual comparisons, limiting this to a 12-year comparison (2006–2018). These measurements were restricted to the months of Aug–Oct, when red drum are actively calling and reproduction is occurring, effectively excluding any other species besides the red drum when examining Band 1. The icListen recording system was used as the comparative standard and transformed the LARS PSB sums to an equivalent level. Generally, these two recording systems responded similarly when tested in the pool and in air calibration tests to changes in the sound source frequencies and levels. This was especially true in Band 1, but a conversion factor (−0.7 dB LARS to icListen, with the LARS measuring slightly lower than the icListen in this frequency range based on the air and pool calibration tests) needed to be applied to standardize these systems' responses.

The result of the interannual comparison is shown in Fig. 13. There was a significant decline of 27.5 dB in PSB sum values associated with this Band 1 across the years (Table 3; ANOVA $F_{2,24} = 58.7, 5.72 \times 10^{-10}$). The year with the greatest PSB sum for red drum was 2006, and this has declined over time so 2018 was the lowest year. The difference between 2006 and 2018 was the most significant (Table 3, Tukey's HSD $P = 0.000001$), although there was a significant decline of 19.4 dB between 2006 and 2017 as well. This suggests that a decline in the calling activity of red drum in the area around the Bay River has occurred over the period 2006–2018. This is a region well known to local fishermen that target the large spawning red drum aggregations for sport fishing. This soundscape measure of fish calling activity could be due to lower red drum population size perhaps due to increased sportfish harvest (prior to this observation period, between 2000 and 2006,

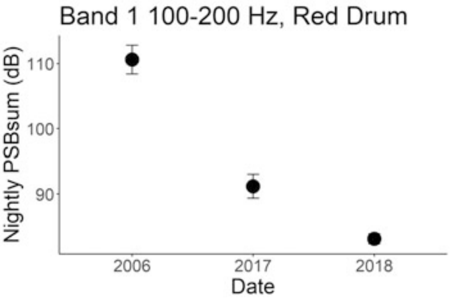


Fig. 13 A plot of the mean nightly PSB sum during the months of Aug, Sep, and Oct over the years 2006 through 2018 for Band 1 (100–200 Hz), which is associated with red drum Sciaenops ocellatus calling activity. The means are dB ± 1SE (re 1 $\mu Pa^2/Hz$)

Table 3 Tukey's HSD multiple comparison tests of mean PSB sum means for Band 1 (100–200 Hz), the red drum spectral band

Comparison years	The difference in PSB means (dB)	Lower bound The difference in means (dB)	Upper bound The difference in means (dB)	P adjusted
2017–2006	−19.39	−27.34	−11.45	0.0000079
2018–2006	−27.49	−34.04	−20.95	0.0000000
2018–2017	−8.1	−16.52	−0.31	0.0607722

red drum sport fish harvest averaged 823,991 fish per year ±18.17 Proportional Standard Error (PSE) in North Carolina, whereas in 2017 and 2018, the sportfishing harvest had increased to 2,156,815 ± 18.62 PSE fish per year between 2014 and 2018; NOAA Marine Recreational Information program MRIP statistics, https://www.fisheries.noaa.gov/data-tools/recreational-fisheries-statistics-queries). Another possible cause in the soundscape associated with adult red drum might be due to migration away from this part of the ecosystem to avoid hypoxic stress in the low salinity regions from river runoff and nutrients input causing algal blooms at the river mouth, or some other factors as yet unknown. Water temperature alone is not likely to be responsible for this decline, because if anything, water temperatures have increased over this period.

Summary

The soundscape in Pamlico Sound has become noticeably quieter in the frequency bands (<1 kHz) used by fishes after accounting for variation in the three recording systems used. There were significant changes in PSB Band I (red drum adults in the Sciaenidae), with a 27.5 dB decrease in PSB sum values. This acoustic soundscape metric (PSB sum) can be used to assess changes in the calling behavior of these fishes, which is closely tied to their spawning and reproductive activity and should be used as a proxy for the health of this Pamlico Sound red drum population. The observed decline in PSB Band I is an indication that the red drum spawning behavior is declining. The methods of soundscape measurements proposed here can be used as a long-term fishery assessment tool.

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