The Journal of the Elisha Mitchell Scientific Society, 116(2), 2000, pp. 124–145

USING SPECTRAL ANALYSIS TO IDENTIFY DRUMMING SOUNDS OF SOME NORTH CAROLINA FISHES IN THE FAMILY SCIAENIDAE

MARK W. SPRAGUE,[a] JOSEPH J. LUCZKOVICH,[b,c]
R. CHRISTOPHER PULLINGER,[b] STEPHEN E. JOHNSON,[b]
TODD JENKINS,[a] and HAL J. DANIEL, III[b]

[a]*Department of Physics,* [b]*Department of Biology*
[c]*Institute for Coastal and Marine Resources*
East Carolina University, Greenville, NC 27858

Abstract: Many of the commercially and recreationally important fishes in the family Sciaenidae are soniferous. Knowledge of their species-specific "drumming" sounds may indicate the presence of species at a given location and time. Activities such as spawning can now be mapped, as sound production is associated with courtship and egg production in some species. This paper presents sonagrams and plots of average power spectra of captive and field-recorded sounds produced by four of the acoustically dominant Sciaenid species in North Carolina estuarine waters: weakfish, *Cynoscion regalis*; spotted seatrout, *Cynoscion nebulosus*; silver perch, *Bairdiella chrysoura*; and red drum, *Sciaenops ocellatus.* Oscillograms of sounds produced by captive fish are given to show the envelope and higher frequency oscillations in each sound. Spectral analysis, using both sonagrams and average power spectra, is advantageous for identification of these fish sounds. Sonograms, which contain information about how the frequency components in a sound change in time, are useful for examining changing sounds such as calls produced by individual fish. Average power spectra contain no time information, but they are useful for determining the dominant frequencies in a segment of a recording. Average power spectra are useful for analyzing the almost constant sounds produced by fish aggregations.

Key Words: Fish sound production; spectral analysis; spawning; Sciaenidae; *Cynoscion regalis*; *Cynoscion nebulosus*; *Sciaenops ocellatus*; *Bairdiella chrysoura*; North Carolina.

INTRODUCTION

It has been known for some time that many fishes make sounds to communicate with one another (Myrberg et al., 1965; Fish and Mowbray, 1970; Fine et al., 1977; Myrberg, 1981; Mann et al., 1997). Furthermore, males of the family Sciaenidae make species-specific drumming sounds during courtship of the females at locations where spawning occurs (Fish and Mowbray, 1970; Mok and Gilmore, 1983; Connaughton and Taylor, 1995; Connaughton and Taylor, 1996; Luczkovich et al., 1999a; Luczkovich et al., 1999b). Soniferous fishes of North Carolina include weakfish, *Cynoscion regalis*; silver perch, *Bairdiella chrysoura*; spotted seatrout, *Cynoscion nebulosus*; and red drum, *Sciaenops ocellatus* (Fish and Mowbray, 1970; Luczkovich et al., 1999b). Calls of these fishes, known as "drumming" for Sciaenidae, are associated with spawning activity in the laboratory (Guest and Lasswell, 1978 for red drum; Connaughton and Taylor, 1996 for weakfish) or are detected in association with recently released sciaenid eggs (Luczkovich et al., 1999a for weakfish; Mok and Gillmore, 1983 and Luczkovich et al., 1999b for spotted seatrout; Mok and Gillmore, 1983 and Luczkovich et al., 1999a for silver perch). During the past four years we have been recording the soniferous fishes of the Pamlico Sound of North Carolina, USA as part of a survey to characterize spawning habitats of weakfish, spotted seatrout, red drum, and silver perch (Luczkovich et al., 1999b). We present sonagrams and average power spectra of both laboratory and field recordings of these four fishes. By performing spectral analyses of recordings from captive fish, we were able to identify unique patterns of drumming for each species. Such spectral analysis may be useful for identifying the sound-producing fishes present in a given location at a given time. The use of spectral analysis, if done as described below, could significantly improve the characterization of spawning habitats of soniferous fishes, potentially over large areas. The objective of this study is to present examples of spectral analysis for use in identifying fish sounds in field recordings.

METHODS

Acoustical Recording Equipment: We recorded fish sounds using an InterOcean Model 902 Acoustic Listening and Calibration System (frequency range: 20 Hz to 10,000 Hz; sensitivity: 100 dB re 1 μPa RMS pressure) consisting of an InterOcean Model T-902 hydrophone (omnidirectional with sensitivity −195 dB re 1 V/μPa) connected to an amplifier (gain adjustable from 15 to 95 dB in 10 dB increments plus vernier adjustment). The amplifier has a rectifier-type AC meter (peak deflection within 3 dB of continuous signal for 100 ms pulse), calibrated in dB, connected to the amplifier output. We recorded the amplifier output with a portable battery-operated digital audio tape (DAT) cassette recorder (Sony TCD-D8 recorder, frequency range: 20 Hz–22,000 Hz ±1 dB) with 16 bits of resolution and a sampling rate of 48 kHz.

Captive Fish Collection and Recording: Fish were caught during the spawning season by hook and line and placed in aerated seawater transport tanks. Most fish called upon first capture, and recordings were made immediately after capture in air or in water. Recordings of a captive male weakfish (340 mm SL) caught at Teache's Hole, Ocracoke Inlet (Fig. 1, station 11) in June 1998 were made immediately after capture in a 89-L cooler filled with sea water. Sounds made by a male silver perch (150 mm SL) caught in Bogue Sound in May 1998 were recorded in air one hour after capture. Sounds made by a male spotted seatrout (200 mm SL) caught in Roanoke Sound in August 1998 were recorded in air 3 hr after capture. Red drum (24 fish; $\bar{x}$ = 660 mm SL; range: 500–780 mm SL) were held during 1997 and 1998 in 37,854-L tanks with flow-through water at the Pamlico Aquaculture Field Laboratory. They produced sound in captivity only during August and September of both years.

Field Recordings: We made acoustical recordings at 16 locations throughout Pamlico Sound and three locations in Bogue Sound from a small boat stationed over the study sites or from a dock (Fig. 1). The boat motor was not running during the collection of acoustical data. Recordings (a minimum of 2 min duration) were made at each site, with the hydrophone placed at 1–2 m depths below the water surface, from one hour before sunset and continuing at intervals of ¼–

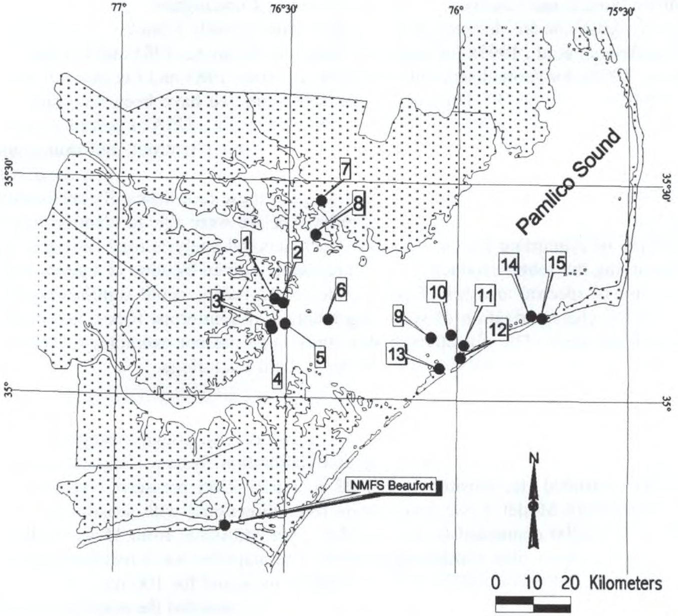

FIG. 1. Map of the study sites. Hydrophone listening stations: 1. Jones Bay East; 2. Jones Bay West; 3. Fisherman's Bay West; 4. Fisherman's Bay East; 5. Bay River Mouth; 6. Brant Island Shoal; 7. Rose Bay Creek; 8. Rose Bay Mouth; 9. Royal Shoal; 10. Lehigh Dredge; 11. Teach's Hole. 12. Teach's Hole Channel Marker 29; 13. Wallace Channel; 14. Hatteras Hole; 15. North Hatteras Inlet.

1 hr until two hours after sunset. Previous studies, based on pelagic egg surveys, have suggested that sciaenids spawn in the evening just after sunset (Holt et al., 1985).

Spectral Analysis: We analyzed the recorded sounds using sonagrams and average power spectra, both of which we calculated from sampled data using the Fast Fourier Transform (FFT). Before computing FFTs of recorded sounds, we first reduced the sampling rate from 48 to 24 kHz to save on computational resources required. We re-sampled the data using a National Instruments NB-2150F analog-to-digital board with anti-aliasing filters in a Power Macintosh computer. All power spectra were calculated from 24 kHz-sampled data using a 1,024-point FFT with a Hanning window (Walker, 1991). The frequency resolution, determined by the sampling frequency and the number of samples in the FFTs used to compute each power spectrum, is 23.4 Hz. The power spectrum consists of 23.4 Hz wide bands containing all signal elements having frequencies within that bandwidth. For example, the frequency band at 304.7 Hz contains all signal elements whose frequency f is in the range $304.7 \text{ Hz} \geq f > 328.1 \text{ Hz}$.

We calculated sonagrams and power spectra with the parameters described above using programs known as "Virtual Instruments" (VIs) that we wrote using the *Labview* (National Instruments, Austin, TX) platform. Our VIs had graphical interfaces that allowed the user to select segments of the recording for analysis. The VIs featured movable cursors that allowed a user to determine the components of a point on a graph (such as time, frequency, or power spectral density) with a high precision.

A sonagram (often called a spectrogram) is traditionally used to graphically represent an animal's call. A sonagram shows the time variation of the frequency content of the signal with a three dimensional plot of consecutive windowed power spectra. The horizontal (x) axis in most sonagrams is time, the vertical (y) axis frequency, and the color (z) axis power spectral density. Thus, a vertical slice of a sonagram is a power spectrum. We programmed our VI to display a sonogram on the screen for detailed analysis and to produce graphics files for printing.

One technique for smoothing the sonagrams over time is to introduce an overlap in the segments used to compute consecutive power spectra in the sonagram. This overlap Ω is determined by the slide factor s_f or the number of samples between the beginning samples of the segments used for consecutive power spectra, by $\Omega = 1 - s_f/N$, where N is the number of samples in the FFT. For example, a sonagram computed with a 1,024-point-FFT with a slide factor of 256 points would have an overlap of ¾ because each power spectrum contains ¾ of the points from the previous power spectrum. Regardless of the slide factor, each power spectrum in the sonagram represents a time window used for the FFT. The 1,024-point window sampled at 24 kHz in our example is a 4.27×10^{-2}-s segment of the recording. Although an overlap does not decrease the time window required for each power spectrum, it does increase the number of power spectra in the sonagram. Smoothing occurs because the similarity of each power spectrum to the previous power spectrum causes the sonagram to appear less "grainy" in the time direction. One advantage of using an overlap is that short-duration sounds are more likely to be captured in an entire time window for a power spectrum. Without the overlap, the short-duration sound may be split into consecutive windows and its contribution the each of the power spectra will be diminished. Using a slide factor that is a power of two, such as 128, 256, 512, or 1,024, insures that the sonagram computed with the overlap contains power spectra that begin at the same samples as the power spectra in a sonagram computed without an overlap. Higher overlaps require more computation time because they require more power spectra to be calculated and more computer memory to store the results. Our VIs are capable of storing a sonagram containing 660 power spectra computed with 1,024-point FFTs. The maximum overlap used was ⅞ (slide factor of 128) because this value was sufficient to include all the important details that could be resolved using our 1,024-point FFT. Thus, we chose the power-of-two slide factor 1,024, 512, 256, or 128 that maximized the overlap within the constraints of our program.

We plotted each sonagram using relative power spectral densities adjusted so that the background level in each sonagram (the lightest region) was 0 dB. The maximum frequency calculated by an FFT is the Nyquist frequency or ½ the sampling frequency (Walker, 1991). This was 12,000 Hz (½ × 24,000 Hz) in our calculations. In most cases, the figures show only frequencies 0 Hz to 2,000 Hz because there were no significant contributions from higher frequencies.

Average power spectra emphasize the frequency components that occur continually in a recording segment and are useful for analyzing sounds that do not change rapidly. We programmed our VIs to compute the average power spectrum by averaging the spectral components of power spectra computed from successive 1,024-sample windows in the signal. The spectral components used to compute the average power spectrum were expressed in linear power spectral units, V^2/Hz—not in logarithmic units like decibels. The resulting average power spectrum was converted to decibels for display.

Three spectral characteristics useful for identifying fish sounds are the fundamental frequency, harmonic frequencies, and the dominant frequency. The fundamental frequency is the lowest frequency component in the sound, and harmonic frequencies are integer multiples of the fundamental frequency (Beranek, 1988). The fundamental frequency was calculated by subtracting the frequencies of consecutive harmonics. The dominant frequency had the largest spectral component (i.e., largest power spectral density) in the sound. We estimated peak frequencies (f_{peak}) associated with dominant frequencies and harmonics by calculating the expectation value of the frequency using the points along the peak surrounding the maximum in the sampled power spectrum. If a maximum value of the sampled power spectrum occurred at the sample index M with frequency f_M and power spectral density PS_M, the expectation value of the peak frequency was the sum $\Sigma_n (f_n \times PS_n)$ divided by the sum $\Sigma_n PS_n$, where the sums were calculated using only points along the peak. The power spectrum for this calculation was in linear units for the power spectrum, V^2/Hz. Where possible, we used the maximum point at index M and three points in either direction. If a peak was close to a neighboring peak, we used the largest number of points (two or one in each direction of the maximum) for which all sample points in both directions were part of the same peak.

An oscillogram is a graph of signal pressure (or the voltage output from the amplifier) vs. time. In general, these plots are useful for examining the envelope and higher frequency oscillations in a sound. In the context of our work here, oscillograms were useful for identifying the harmonic content in a sound and patterns of swimbladder vibrations for different species recorded under captive conditions. We programmed VIs to display oscillograms of each captive fish recording and used them to identify the envelope and higher-frequency oscillations. We normalized each oscillogram so that the oscillations had approximately unit amplitude. We did not use these plots for species identification in field recordings because oscillograms can be extremely complicated when sounds from several sources are present in a recording.

RESULTS

We present spectral analyses of both captive and field recordings of weakfish, silver perch, spotted seatrout, and red drum. We present the sonogram and average power spectrum used to characterize the sound frequency. We also present oscillograms from captive fish recordings to allow analysis of envelopes.

Weakfish: Spawning male weakfish, *Cynoscion regalis,* produce sounds by causing oscillations of their swimbladders (Tower, 1908). This sound has been termed "drumming" by Connaughton and Taylor (1995), but we prefer the name "purring" (Luczkovich et al., 1999a, Luczkovich et al., 1999b) so that the sound is not confused with the "drumming" of the red drum. The "purr" produced by a captive male weakfish (340 mm SL) consisted of 15 pulses within a 0.5-sec interval (Fig. 2A). Each pulse had a broad frequency peak with most sound energy between 175 and 400 Hz. The average power spectrum for the entire "purr" (Fig. 2B) had the same broad peak with a maximum at 282 Hz. Individual pulses in the sonagram were not artifacts. They were visible because the ⅞ overlap (slide factor 128) in the sonagram insured that there were individual power spectra within the sonagram containing each pulse and power spectra containing the space between each pulse. An oscillogram of the "purr" (Fig. 2C) revealed that it consisted of higher frequency oscillations modulated by a low frequency envelope. Each pulse consisted of 1.5 oscillations (three half-cycles). The convolution of this envelope with the high frequency oscillations caused the power spectrum to spread in frequency rather than have sharp frequency peaks.

Individual weakfish producing "purrs" were recorded in the field 15 July 1997 in Hatteras Hole, near the Hatteras Inlet (station 14). A sonagram of that recording (Fig. 3A) revealed nine distinct "purrs" with some background noise from other "purring" weakfish in the vicinity. As in captive weakfish recordings, each "purr" consisted of many short pulses of sound energy between 250 Hz and 515 Hz. The dominant frequency in the average power spectrum (Fig. 3B) occurred at 330 Hz.

We recorded a chorus of "purring" weakfish in a large aggregation 6 August 1998 near Ocracoke Inlet in Teach's Hole. The large aggregation produced a "rumble" in which individual "purrs" could not be distinguished in the sonagram (Fig. 3C), but the power-spectral density in the sonagram fluctuated in a pattern that is similar to power-spectral density fluctuations in sonagrams of individual weakfish "purrs." The average power spectrum had the same broad peak as an individual "purr." The dominant frequency of this aggregation was 305 Hz (Fig. 3D). The average dominant frequency of weakfish purrs in our field recordings (n = 26) was 347 Hz, ranging from a minimum of 283 Hz to a maximum of 451 Hz with a standard deviation of 38 Hz (see Table 1).

Silver Perch: Male silver perch, *Bairdiella chrysoura,* produce a train of "knocks" associated with spawning behavior (Mok and Gilmore, 1983). This is the same sound that has been called the "cluck" (Luczkovich et al., 1999a,b, in press). The sonogram of the captive silver perch (150 mm SL) consisted of five "knocks" produced within a one second interval (Fig. 4A). Each "knock" in Figure 4A was followed by a lower intensity echo that was not part of the original sound. The average power spectrum (Fig. 4B) of the "knocks" had many peaks between 650 and 3,000 Hz with dominant frequency 667 Hz. The peak at 2,514 Hz was almost as large as the dominant peak. An oscillogram of the "knock" (Fig. 4C) revealed that it consisted of several pulses of high frequency oscillations. Each pulse consisted of a spike followed by decaying high-amplitude oscillations. The "knock" in the oscillogram consisted of a train of eight pulses.

We recorded an individual silver perch producing "knocks" 23 June 1999 at the National Marine Fisheries Service, Beaufort Laboratory, Beaufort, NC dock. Each "knock" was a pulse of sound energy extending from 650 Hz to 4,000 Hz in the sonagram (Fig. 5A). Oyster toadfish (*Opsanus tau*) were also present in this recording producing their characteristic "boatwhistle" sound (Fish and Mowbray, 1970) with harmonics near 230 and 460 Hz lasting as long as 0.3 sec. The average power spectrum (Fig. 5B) had peaks at 753, 931, 1031, and 1148 Hz

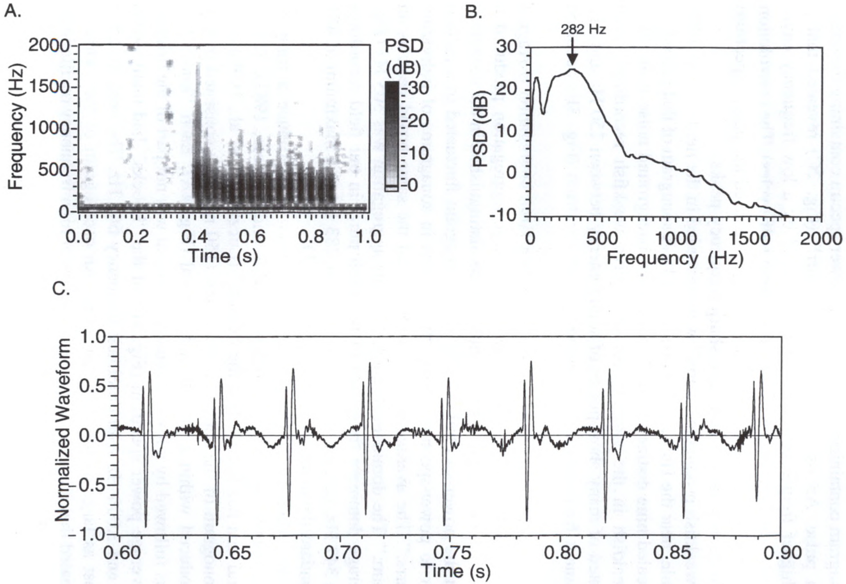

FIG. 2. Sound produced by a captive male weakfish (340 mm SL) in a 89-1 cooler. A) Sonagram of a "purr". Slide factor: 128 samples. B) Average power spectrum from the captive weakfish "purr" taken from 0.395 to 0.885 sec in the recording (11 consecutive power spectra). The dominant frequency of this "purr" was 282 Hz with most of the sound energy occurring between 175 and 400 Hz. The low-frequency peaks in both the sonogram and power spectrum are a result of 60-Hz noise. These peaks are not part of the fish sound. C) An oscillogram of a 0.3-sec segment of the weakfish "purr." Each individual pulse consisted of a high frequency oscillation within a lower frequency envelope.

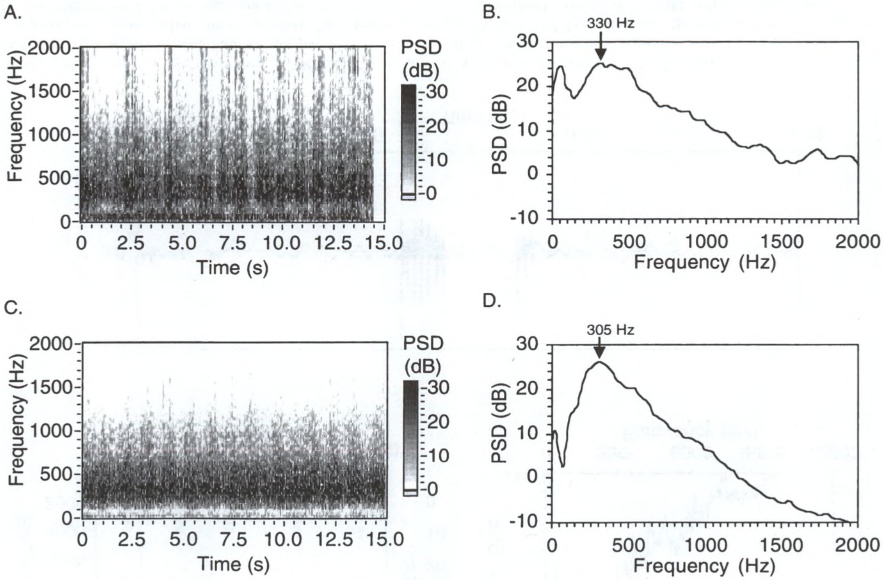

FIG. 3. A) Sonogram of weakfish "purring" recorded 14 July 1997 at station 15. Slide factor: 1024 samples. B) Average power spectrum of weakfish "purring" taken from 0.000 to 14.000 sec in the same recording used for Figure 3A (351 consecutive power spectra). The dominant frequency is at 330 Hz, and most of the sound energy occurs in the broad peak between 230 and 540 Hz. C) Sonogram of weakfish large aggregation "purring". Slide factor: 1024 samples recorded 6 August 1998 at station 12. D) Average power spectrum taken from 0.000 to 15.000 sec in the recording used for Figure 3C. (351 consecutive power spectra). The dominant frequency is at 305 Hz. The low-frequency peaks in the sonograms and power spectra are from 60-Hz noise. These peaks are not part of the fish sound.

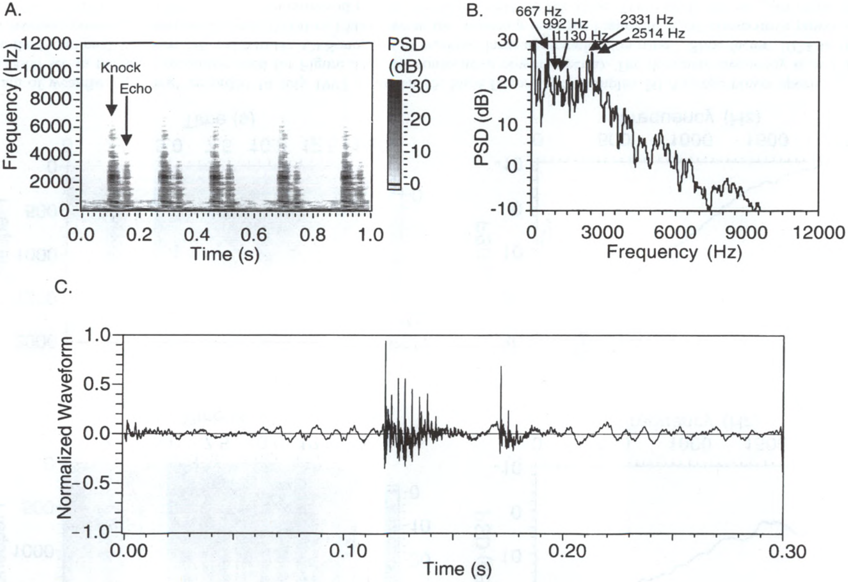

FIG. 4. Sound produced by a captive male silver perch (150 mm SL) in air. A) Sonogram of "knocks." Slide factor: 128 samples. The smaller pulses, which occurred following each larger pulse, are echoes and are not part of the "knock." B) Average power spectrum from the silver perch "knocks" taken from 0.091 to 0.976 sec in the recording (20 consecutive power spectra). The dominant frequency was 667 Hz, although the peak at 2514 Hz was almost as high as the dominant peak. C) An oscillogram of a 0.3-sec segment of the silver perch "knock." The knock consisted of eight pulses of high frequency oscillations between 0.119 and 0.145 sec. The smaller train of pulses beginning at 0.571 sec is an echo of the "knock." The echo is not part of the "knock."

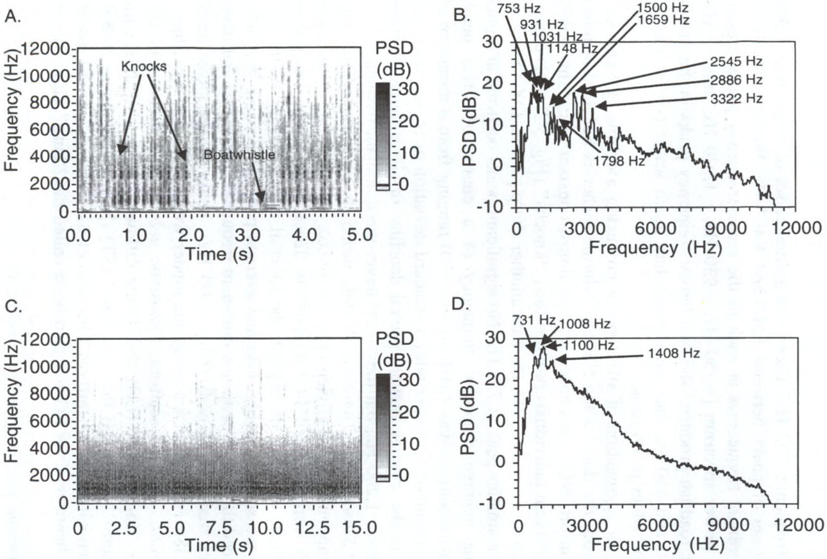

FIG. 5. A) Sonagram of silver perch "knocks" recorded 23 June 1999 from the dock at the National Marine Fisheries Service, Beaufort Laboratory. Slide factor: 256 samples. The sound with harmonics near 230 and 460 Hz at 0.7, 1.4, 2.3, 2.8, 3.3, and 4.2 sec was a distant oyster toadfish (*Opsanus tau*) producing its characteristic "boatwhistle" sound. The oyster toadfish sounds were not pictured in greater detail because this sonogram was optimized to show the silver perch "knocks." B) Average power spectrum taken from 0.618 to 1.930 sec in the same recording used for Fig. 5A (30 consecutive power spectra). The dominant frequency was 753 Hz. C) Sonogram of silver perch chorusing, slide factor: 1024 samples, was recorded 20 May 1999 from the dock at the National Marine Fisheries Service, Beaufort Laboratory. D) Average power spectrum taken from 0.000 to 15.000 sec in the same recording used for Fig. 5C (351 consecutive power spectra). The dominant frequency was 1,102 Hz.

Table 1. Characteristic Frequency (Hz) by Species.

Species	Average	Standard Deviation	n
Weakfish	347	38	26
Silver perch	1,046	66	30
Spotted seatrout	300	85	16
Red drum	139	5	6

with dominant frequency 753 Hz. There was a smaller set of peaks near 1,500 Hz and a larger set of peaks between 2,500 and 3,400 Hz. We have measured silver perch dominant frequencies at each of the lower-frequency peaks present in this average power spectrum (~750 Hz, ~930 Hz, ~1,020 Hz, and ~1,100 Hz). The oyster toadfish produced the two lowest-frequency peaks in the power spectrum at 230 and 460 Hz, but these peaks had much lower power spectral densities than the silver perch peaks.

We recorded an aggregation of silver perch producing a chorus of "knocks" 20 May 1999 from the dock at the National Marine Fisheries Service, Beaufort Laboratory, Beaufort, NC. The chorus was an almost constant sound that varies in intensity as different individuals produce their "knocks" (Fig. 5C). This chorus had a dominant frequency of 1,100. Hz with another sharp peak at 1,008 Hz (Fig. 5D). There was a smaller peak at 731 Hz. No significant peaks occurred at higher frequencies. The average dominant frequency of a chorus of silver perch "knocks" in our recordings was 1,046 Hz (n = 30) ranging from a minimum of 921 Hz to a maximum of 1,195 Hz with a standard deviation of 66 Hz (Table 1). Peaks occurred in the average power spectral densities of silver perch choruses near 750 and above 1,200 Hz, but they were never the dominant frequencies.

Weakfish and Silver Perch Together: Often, weakfish and silver perch could be heard simultaneously (Luczkovich et al., 1999a,b). Aggregations of weakfish and silver perch were recorded 14 July 1997 in Teach's Hole Channel (station 11) Ocracoke Inlet. One can distinguish the spectral characteristics of the two species in both the sonagram (Fig. 6A) and average power spectrum (Fig. 6B). Weakfish produced the sounds with low dominant frequencies (328 Hz) and silver perch the higher frequency sounds (650–4,000 Hz). Peaks in the silver perch chorus below 1385 Hz were obscured by the louder weakfish in this recording.

Spotted Seatrout: Spotted seatrout, *Cynoscion nebulosus,* produce four distinct sounds, the "long grunt" (LG), the "grunt followed by knocks" (GK), the "aggregated grunts" (AG), and the "staccato" (ST) (Mok and Gilmore, 1983). The GK has been called the "heartbeat" because of its "lub-dub" sound resembling a beating heart, and the LG has also been called the "burp" (Luczkovich et al., 1999b). These sounds are often heard in succession in the field recordings. A sonagram, average power spectrum, and oscillograms of LGs produced by a captive male spotted seatrout (200 mm SL) is depleted in Figure 7. The fish produced three LGs: the first lasts 0.19 sec, the second 0.13 sec, and the third 0.11 sec (Fig. 7A). The dominant frequency of each of LG began at a higher frequency and moved downward in time. The fundamental frequency was near 140 Hz and dominant frequency at 280 Hz at the beginning of the first LG. The fundamental frequency shifted down to near 90 Hz and the dominant frequency to 263 Hz at the end of the LG. The average power spectrum (Fig. 7B) of the

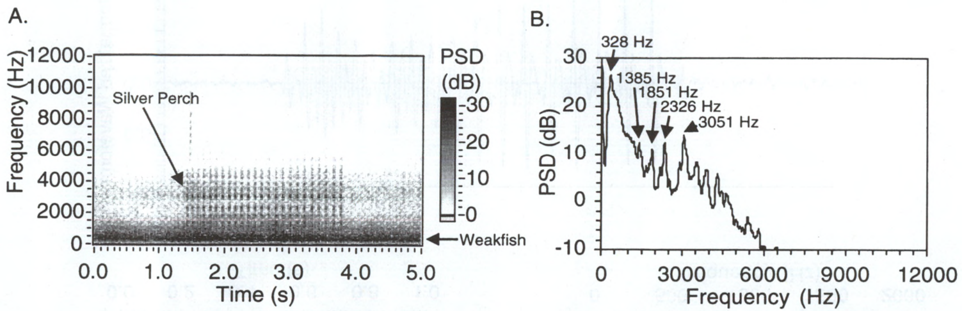

FIG. 6. A) Sonagram of weakfish and silver perch together recorded 14 July 1997 at station 11. B) Average power spectrum taken from 0.000 to 5.000 sec in the recording (117 consecutive power spectra). The weakfish produce the nearly constant sound with dominant frequency 328 Hz, and the silver perch produce the higher frequency pulses between 650–4,000 Hz.

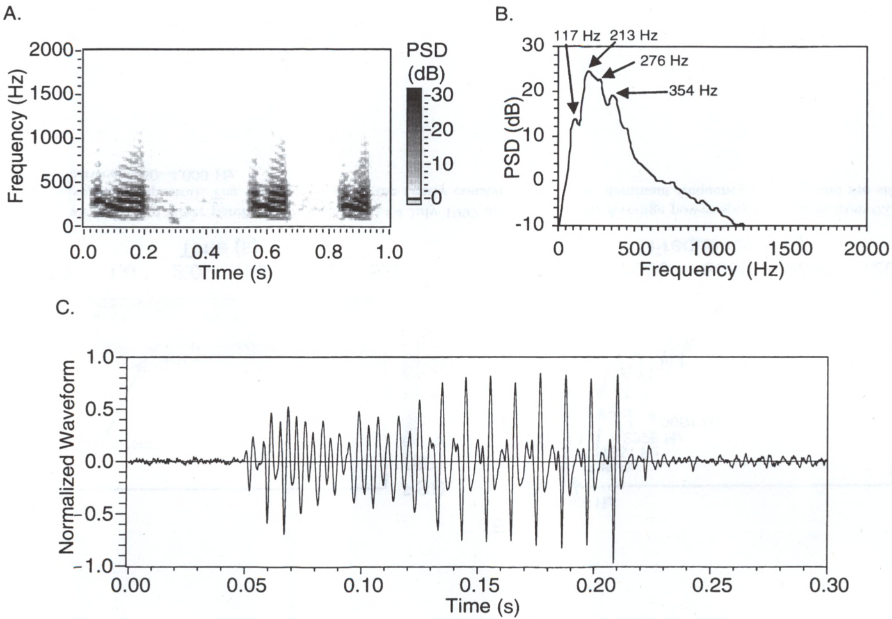

FIG. 7. Sound produced by a captive male spotted seatrout (200 mm SL) in air. A) Sonogram of a captive spotted seatrout "long grunt" (LG). Slide factor: 128 samples. B) Average power spectrum taken from 0.027 to 0.939 sec in the recording (21 consecutive power spectra). The dominant frequency was 223 Hz. C) An oscillogram of a 0.3-sec segment of the LG.

segment had a dominant frequency at 213 Hz, but it did not contain the sharp peaks in the sonagram because the power spectral densities were averaged as the frequencies shifted in the LG. The oscillogram (Fig. 7C) demonstrated the harmonic nature of this sound due to the oscillations which occurred at different frequencies. These oscillations were multiples of the fundamental frequency and changed in intensity during the downward shift in dominant frequency. We have not recorded the other spotted seatrout sounds in captivity.

We recorded spotted seatrout at the Lehigh Dredge (station 10) near Ocracoke Island producing three of the four spotted seatrout sounds, the LG, the GK and the AG 12 August 1997. The two LGs occurred from 0.0–0.3 sec and from 3.6–3.8 sec in the recording (Fig. 8A). The average power spectrum (Fig. 8B) had a dominant frequency of 241 Hz and a broad peak at 359 Hz. An average power spectrum of the second LG (Fig. 8C) exhibited two distinct peaks at 239 Hz (the dominant frequency) and 351 Hz. The difference in these two peak frequencies indicated that the fundamental frequency was near 112 Hz. The GK in Figure 8A consisted of a short "grunt" near 1.0 sec followed by two rapid pulses near 1.1 and 1.2 sec. An AG occurred in the sonogram as a series of four rapid pulses from 2.7–3.0 sec. The average power spectrum of the AG (Fig. 8D) had a dominant frequency of 405 Hz with lower peaks at 139, 259, and 555 Hz.

A spotted seatrout producing two of the four spotted seatrout sounds, the ST and the LG, was recorded in the field at Wallace Channel (station 13) 14 July 1997 (Fig. 9). The ST in this recording consisted of 35 clicks in a 1.72-sec interval from 0.0–1.7 sec in the sonagram, and the LG occurred from 3.9–4.2 sec (Fig. 9A). Figure 9B shows an average power spectrum of the entire 5-sec segment shown in Figure 9A. The dominant frequency for this segment was 262 Hz. Some of the low frequency content in the average power spectrum was caused by the loud low-frequency background noise near 2.2 sec. The average power spectrum of the ST (Fig. 9C) had a dominant fundamental frequency of 263 Hz. There were other peaks at 417, 522, and 728 Hz, in addition to a large peak at 1,160 Hz.

An aggregation of spotted seatrout was recorded at Teach's Hole (station 12) 11 June 1998. Individual LG, AG, GK, and ST were difficult to resolve in the sonagram (Fig. 10A). The average power spectrum had a broad peak with dominant frequency 310 Hz (Fig. 10B). A LG did occur in this sonagram between 6.0 and 6.2 sec, and its distinct pattern of frequency peaks could be seen in a magnified sonogram (Fig. 10C). The average dominant frequency of spotted seatrout aggregations in our recordings was 300. Hz (n = 16), ranging from a minimum of 234 Hz to a maximum of 493 Hz with a standard deviation of 85 Hz (Table 1).

Red Drum: A male red drum, *Sciaenops ocellatus,* was recorded in a tank at the Pamlico Aquaculture Field Laboratory (PAFL), Aurora, NC (one of a group of 24 fish; $\bar{x}$ = 660 mm SL; range: 500–780 mm SL). The sonagram (Fig. 11A) contained three "drums," each lasting 0.03 sec. Each "drum" had a dominant frequency of 109 Hz and another peak at 226 Hz in the average power spectrum (Fig. 11B). The average power spectrum revealed smaller peaks at 422 Hz and 589 Hz. An oscillograms of the red drum "drums" (Fig. 11C) showed the oscillations of the swim bladders and the envelope.

We recorded red drum making their characteristic "drums" at the mouth of the

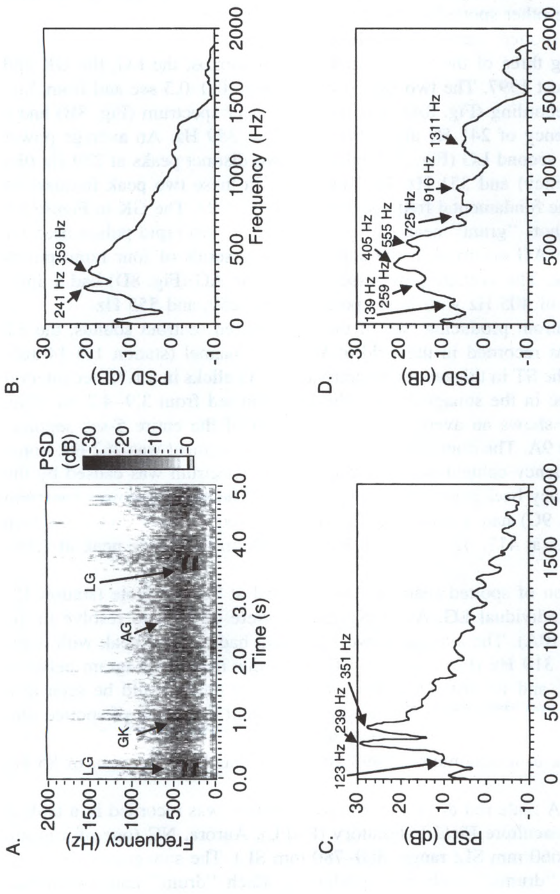

FIG. 8. A) Sonagram of a spotted seatrout sonogram showing the "long grunt" (LG) and "grunt followed by knocks" (GK) and "aggregated grunt" (AG) calls. Slide factor: 256 samples. This sound was recorded 12 August 1997 at station 10. B) Average power spectrum taken from 0.000 to 5.000 sec in the recording (117 consecutive power spectra). The dominant frequency in this segment was 241 Hz. C) Average power spectrum of the LG taken from 3.565 to 3.832 sec in the recording (6 consecutive power spectra). The dominant frequency was 239 Hz. D) Average power spectrum of the AG taken from 2.731 to 2.981 sec in the recording (5 consecutive power spectra). The dominant frequency was 405 Hz.

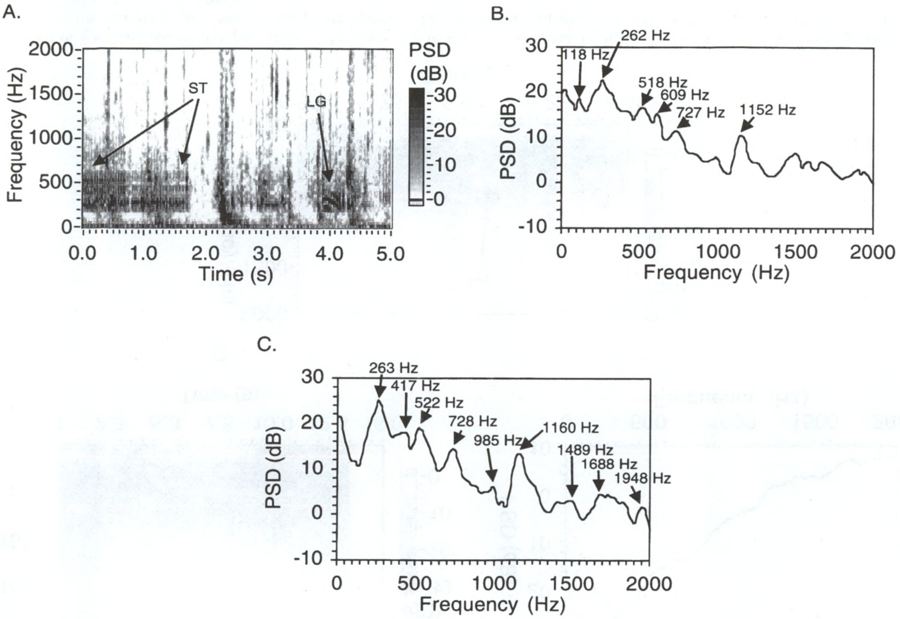

FIG. 9. A) Sonagram showing spotted seatrout "staccato" (ST) and "long grunt" (LG) calls, slide factor: 256 samples, recorded 14 July 1997 at station 13. B) Average power spectrum of the entire segment of the recording (316 consecutive power spectra). The dominant frequency was 262 Hz. C) Average power spectrum of the ST taken from 0.000 to 1.728 sec in the recording (40 consecutive power spectra). The dominant frequency was 263 Hz.

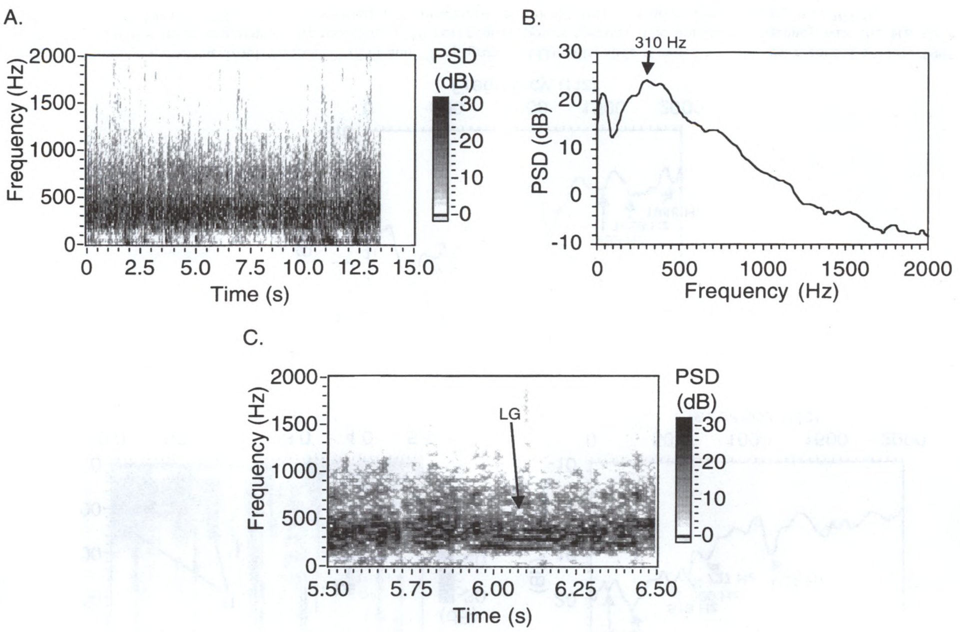

FIG. 10. A) Sonagram of a spotted sea trout aggregation, slide factor: 1,024 samples, recorded 11 June 1998 at station 11. B) Average power spectrum taken from 0.000 to 15.000 sec in the recording (351 consecutive power spectra). The dominant frequency was 310 Hz. C) Sonagram of a one second segment which containing a "long grunt". Slide factor: 128 samples.

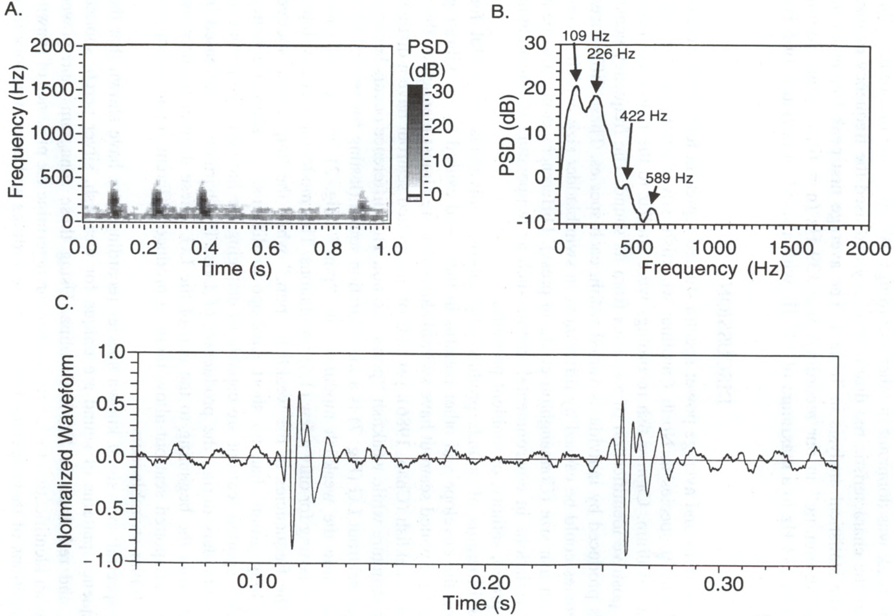

FIG. 11. Sound was produced by a captive male red drum (one of a group of 24 fish; $\bar{x}$ = 660 mm SL; range: 500–780 mm SL) in a 37,854-L tank. A) Sonagram of a "drum". Slide factor: 128 samples. B) Average power spectrum taken from 0.080 to 0.416 sec in the recording (7 consecutive power spectra). The dominant frequency was 109 Hz. C) An oscillogram of a 0.3-sec segment containing the first two "drums."

Bay River 17 September 1997. Four successive "drums" occurred in a 0.74-sec interval (Fig. 12A). The average power spectrum (Fig. 12B) showed four distinct frequency peaks at 133, 287, 434, and 537 Hz. The dominant frequency of this short interval is 287 Hz, although the peak at 133 Hz was almost as large as the 287-Hz peak. The first peak was dominant in some recordings of red drum while the second peak was dominant in other recordings. We chose the first peak of the "drum" as the characteristic red drum frequency and used the frequency of that peak for the statistical analysis in Table 1. The average first peak frequency of red drum "drumming" in our recordings was 139 Hz (n = 6), ranging from a minimum of 133 Hz to a maximum of 147 Hz with a standard deviation of 5 Hz (Table 1).

DISCUSSION

The sonagrams and average power spectra studied represent four of the acoustically dominant species in North Carolina: weakfish, silver perch, spotted seatrout, and red drum. Captive fish recordings were similar to the field recordings allowing positive identification of a species from its sound. The frequency peaks in sounds produced by individuals varied within each species. These differences in frequencies could be caused by differences in swimbladder size, which is correlated with fish size (Connaughton et al., in press). Differences could also be a result of variations in environmental factors such as temperature (Connaughton et al., in press), salinity, or ambient pressure.

The oscillograms of sounds produced by captive individuals are useful for identifying the envelope and other patterns in the sound caused by the vibrating swimbladder. Spotted seatrout have swimbladders that are almost identical to their congeners, weakfish (Chao, 1986), yet LGs of the spotted seatrout have a distinct harmonic structure while weakfish "purrs" do not. This difference occurs because the spotted seatrout LG (Fig. 7) is a long duration sound (lasting for several FFT windows) while the weakfish modulates its "purr" (Fig. 2) into several short pulses, each lasting for only a few (1.5) oscillations. This modulation, or envelope, smeared the frequencies in the weakfish "purr," while the long-lasting spotted seatrout "long grunt" had no short envelope to diminish its sharp frequency peaks. Also, spotted seatrout are capable of changing the harmonic properties of their swimbladders during the production of LGs. The harmonics decreased in frequency from the beginning to the end of the LG. These differences between weakfish and spotted seatrout allow them to produce different sounds using essentially similar swimbladders.

Using spectral analysis of known species recordings, we have shown that the time-frequency patterns of sound are unique for weakfish, silver perch, spotted seatrout, and red drum in North Carolina. Using these sonagrams and power spectra as an identification tool, a researcher can determine the presence of spawning aggregations of these species from sound recordings and determine locations of spawning areas.

Although sonograms have been used in the past to identify fish sounds, average power spectra are useful for fish identification especially where aggregations occur. Traditionally, sonagrams are used to analyze and identify fish sounds as they contain information about how the frequency components change in time (Fish and Mowbray, 1970; Mok and Gilmore, 1983; Mann et al., 1996). However, when

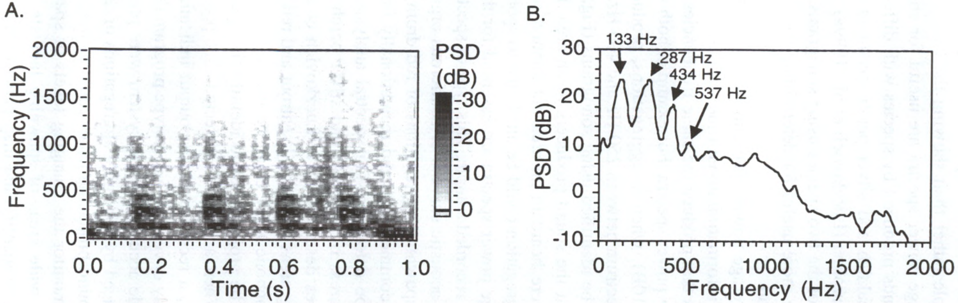

FIG. 12. A) Sonagram of red drum "drum", slide factor: 128 samples, recorded 17 September 1997 at station 5. B) Average power spectrum taken from 0.133 to 0.848 sec in the recording (16 consecutive power spectra). Peaks in the power spectrum occurred at 133, 287 and 434 Hz. The dominant frequency was 287 Hz, although the peak at 133 Hz was almost as large. A very small maximum occurred at 537 Hz.

large aggregations produce an almost constant sound, as do spawning male weakfish (Fig. 3C), the patterns of individual calls are no longer visible in the sonogram, and an average power spectrum (Fig. 3D) is more useful for sound identification. The average power spectrum emphasizes the dominant frequency components for the entire sample rather than showing the change of the frequency components in time. Average power spectra are useful for characterizing, separating, and quantifying sounds produced by species with different dominant frequencies. For example, weakfish and silver perch spawn in the inlets in May through August in North Carolina (Luczkovich et al., 1999a). Although one can distinguish individual calls of the two species using sonagrams (Fig. 6A), average power spectra (Fig. 6B) are more useful for determining each aggregation's contribution to the overall sound.

A shortcoming of the average power spectrum method is that it contains frequency information but no information about time variation in the signals. Thus, aggregations of two species that produce the same frequencies would be difficult to distinguish using average power spectra. For example, both weakfish (Fig. 3D) and spotted seatrout (Fig. 10B), when in aggregations, produce a sound with a broad peak in the power spectrum between 250 Hz and 400 Hz. Often individuals within the aggregation can be identified using sonograms (Fig. 10C) allowing an inference to be drawn about the sound producers in an area. If, over the course of evening, no weakfish were heard in an area but spotted seatrout individuals were identified, then an aggregation could be attributed to spotted seatrout. Thus, both sonagrams and average power spectra are essential for the identification of species-specific sounds in a recorded sample. This type of spectral analysis should be employed in all passive acoustic surveys of soniferous organisms.

Sounds associated with spawning aggregations of red drum, weakfish, spotted seatrout, and silver perch, commercially and recreationally important species in North Carolina, can now be detected using spectral analysis. We have already delimited some spawning areas of weakfish and silver perch in Pamlico Sound using the spectral techniques described here (Luczkovich et al. 1999a), and we will be describing spawning areas for spotted seatrout and red drum in forthcoming papers. Hence, a hydrophone array could be placed in or towed through an area and a computer could be programmed to identify the spectral characteristics described in this paper. When a sound is detected that possesses the spectral characteristics of a species, a record could be output indicating the presence of that species. We have already developed a prototype program that identifies weakfish "purrs" with reasonable accuracy. If the system were properly calibrated to variable sound levels produced by spawning aggregations of different species, an estimate of abundance of sound-producing fishes could be made. These automated records could be used to monitor the changing levels of spawning stocks temporally and spatially over wide areas of spawning habitats. Fishery biologists would use this information to identify and map patterns of habitat used by soniferous fishes. However, much more research is needed before such a system can be deployed to properly account for the variations in spectral parameters as they are influenced by depth, bottom type, distance from the hydrophone to the sound source, currents, and background noise.

Acknowledgments: We would like to acknowledge the following people for help at various times during this study: Gary Burr, Garcy Ward, Kay Evans, Cindy Harper, Trip Lamb, Theresa Sprague, Jill Greene Luczkovich, Todd Launt, Roger Rulifson, Phil Evans, Al Sprague, Ray Mills, Carl Hartsfield, Dan Kleinert, Jim Gilbert, and Jim Watson (ECU Geology Department). Andy McGinty and Ron Hodson (NC State University Pamlico Aquaculture Field Laboratory) provided us tank space and maintenance of the captive red drum. We thank the United States Coast Guard (USCG) group Hatteras, station Ocracoke, and USCG Group Fort Macon, station Hobucken for allotting dock space. This study was supported with funding from the Wallop-Breaux Sportfish Restoration Program, F-62, NC Division of Marine Fisheries and the US Fish and Wildlife Service.

REFERENCES CITED

BERANEK, L. L. 1988. Acoustical Measurements. Am. Inst. Physics, College Park, MD. p. 23.

CHAO, N. L. 1986. A synopsis on zoogeography of the Sciaenidae. Pp. 570–589 in T. Uyeno, R. Arai, T. Taniuchi, and K. Matsuura (eds.), Indo-Pacific Fish Biology. Proc. Second Internat. Conf. Indo-Pacific Fishes. Ichthyological Soc. Japan, Tokyo, Japan.

CONNAUGHTON, M. A., AND M. H. TAYLOR. 1995. Seasonal and daily cycles in sound production associated with spawning in weakfish, *Cynoscion regalis*. Env. Biol. Fish. 42:233–240.

———, ———. 1996. Drumming, courtship, and spawning behavior in captive weakfish, *Cynoscion regalis*. Copeia 1996(1):195–199.

———, ———, AND M. L. FINE. In press. Effects of fish size and temperature on weakfish disturbance calls: implications for the mechanism of sound generation. J. Exp. Biol.

FINE, M. L., H. E. WINN, AND B. L. OLLA. 1977. Communication in fishes. Pp. 472–518 in T. A. Sebeok (ed.), How Animals Communicate. Indiana Univ. Press, Bloomington, IN.

FISH, M. P., AND W. H. MOWBRAY. 1970. Sounds of the Western North Atlantic Fishes. Johns Hopkins Press, Baltimore, MD. 207 p.

GUEST, W. C., AND J. L. LASSWELL. 1978. A note on courtship behavior and sound production of red drum. Copeia 1978:337–338.

HOLT, G. J., S. A. HOLT, AND C. R. ARNOLD. 1985. Diel periodicity of spawning in sciaenids. Marine Ecol. Prog. Ser. 27:1–7.

LUCZKOVICH, J. J., M. W. SPRAGUE, S. E. JOHNSON, AND R. C. PULLINGER. 1999a. Delimiting spawning areas of weakfish, *Cynoscion regalis* (family Sciaenidae), in Pamlico Sound, North Carolina using passive hydroacoustic surveys. Bioacoustics 10:143–160.

———, H. J. DANIEL III, M. HUTCHINSON, T. JENKINS, S. E. JOHNSON, R. C. PULLINGER, AND M. W. SPRAGUE. In press. Sounds of sex and death in the sea: bottlenose dolphin whistles suppress mating choruses of silver perch. Bioacoustics.

———, ———, M. W. SPRAGUE, S. E. JOHNSON, R. C. PULLINGER, T. JENKINS, AND M. HUTCHINSON. 1999b. Characterization of critical spawning habitats of weakfish, spotted seatrout and red drum in Pamlico Sound using hydrophone surveys. No. Car. Dept. Env. Nat. Resour., Div. Mar. Fish., Morehead City, NC. 128 p.

MANN, D. A., J. BOWERS-ALTMAN, AND R. A. ROUNTREE. 1997. Sounds produced by the Striped Cusk-eel *Ophidion marginatum* (Ophidiidae). Copeia 3:610–612.

MOK, H. K., AND R. G. GILMORE. 1983. Analysis of sound production in estuarine fish aggregations of *Pogonias cromis, Bairdiella chrysoura,* and *Cynoscion nebulosus* (Sciaenidae). Bull. Inst. Zool. Acad. Sinica 22:157–186.

MYRBERG, A. A. 1981. Sound communication and interception in fishes. Pp. 395–425 in W. N. Tavolga, A. N. Popper, and R. R. Fay (eds.), Hearing and sound communication in fishes. Springer-Verlag, New York, NY.

———, E. KRAMER, AND P. HEINECKE. 1965. Sound production by cichlid fishes. Science 149:555–558.

TOWER, R. W. 1908. The production of sound in the drumfishes, the sea-robin and the toadfish. Annal. N. Y. Acad. Sci. 18:149–180.

WALKER, J. S. 1991. Fast Fourier Transforms. CRC Press, Boca Raton, FL. Pp. 135–194.

Received 18 December 1999