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DELIMITING SPAWNING AREAS OF WEAKFISH *CYNOSCION REGALIS* (FAMILY SCIAENIDAE) IN PAMLICO SOUND, NORTH CAROLINA USING PASSIVE HYDROACOUSTIC SURVEYS

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ABSTRACT

Exact locations of spawning areas used by marine fishes are needed to design marine reserves and estimate spawning stocks. The location of spawning areas of soniferous fishes such as weakfish *Cynoscion regalis* can be determined by means of passive hydroacoustic surveys. We conducted nocturnal hydrophone surveys at 12 locations in Pamlico Sound in May of 1996 and 1997. Digital audio tapes were made of weakfish "purring" sounds, the tapes were analyzed spectrographically and compared with ichthyoplankton surveys taken at the same stations and times. All weakfish "purring" sounds were recorded at stations near inlets. Maximum sound pressure levels recorded after sunset were 127 dB (re 1 μPa) for individual weakfish, but reached a maximum of 147 dB when weakfish and other fish were producing sounds simultaneously. The maximum distance that an individual weakfish "purr" can be detected above the background sound, assuming a cylindrical spreading model, is approximately 50 m. There was a strong association (r = 0.78) between the $\log_{10}$-transformed abundance of early-stage sciaenid-type eggs and maximum sound pressure levels, with the greatest numbers occurring at the inlet stations. These results suggest that passive hydroacoustic surveys can be used to delimit spawning areas for conservation and management purposes.

Keywords: Fisheries, underwater acoustics, hydrophone surveys, ichthyoplankton, sound attenuation

INTRODUCTION

Knowledge of spawning habitats is essential for the conservation of exploited fish stocks. Marine reserves and closure of fishing areas have been proposed for conservation of exploited fish stocks (Clark 1996,

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Ogden 1997, Roberts 1997, Allison et al. 1998, Lauck et al. 1998). The establishment of marine reserves will require precise spatial data on the spawning areas for exploited fishes.

Most traditional methods of establishing spawning locations for marine fishes are labor-intensive net-harvest methods directed at the larvae or the adults. One approach involves collection of eggs, larvae, or pelagic juvenile fishes. The spawning areas and times are estimated from age-specific growth data and current patterns, which are projected backwards in time using estimates of fish age, growth and estuarine hydrography (Holt et al. 1985, Peters and McMichael 1987, Johnson and Funicelli 1991). This method is not efficient because of the great amount of work involved in conducting net surveys, the uncertainty over the identity of species collected at early life stages (Daniel and Graves 1994), the extensive knowledge of estuarine hydrography required, and the spatial extrapolation involved. Another method that has been used extensively to locate spawning adults of many species, including weakfish *Cynoscion regalis* and spotted seatrout *C. nebulosus*, is to capture fishes with nets and determine the gonadal condition in a variety of areas (Merriner 1976, Brown-Peterson et al. 1988, Murphy and Taylor 1990, Lowe-Barbieri et al. 1996). Determining the stage of gonadal development is a time-consuming and subjective technique that can only be made by an experienced observer. It requires that the spawning fishes be captured and dissected for histological samples of the gonad. This method depends on the previous knowledge of spawning locations so that nets can be deployed and spawners captured. Furthermore, the spawning location may not be the same as the location where the gonadally ripe adults occur because fish often migrate prior to spawning, thus introducing error in the position of spawning habitat. The adults examined for gonadal condition are often collected by fishers themselves (e.g. data are obtained from the recreational or commercial catch), so that areas are not sampled randomly, the data may be subject to under-reporting, and the data may contain misleading information on area of capture. Although both methods eventually may provide data on spawning locations and seasons, they are very slow and do not lend themselves to easy use by fishery managers, who must often assess population status quickly and make area and season closure decisions rapidly.

One alternative to the above methods may be available for fishes that produce sounds (soniferous fishes). It has been known for some time that many fishes, including most members of the Sciaenidae (drums and croakers), make sounds and communicate with one another using these signals (Myrberg et al. 1965, Fish and Mowbray 1970, Fine et al. 1977, Myrberg 1981). Furthermore, it is apparent that males of the Sciaenidae, especially the weakfish *Cynoscion regalis*, make species-specific calls during courtship of the females at locations where spawning occurs (Fish and Mowbray 1970, Connaughton and Taylor 1995, Connaughton and Taylor 1996). Hydroacoustic monitoring of "drumming" or calling by male sciaenids, including weakfish, has been undertaken recently in the field and laboratory (Mok and Gilmore 1983, Johnson and Funicelli 1991, Saucier et al. 1992, Saucier and Baltz 1993, Connaughton and Taylor 1995). Weakfish drumming has been observed immediately prior to spawning in the laboratory (Connaughton and Taylor 1996). Only male weakfish make drumming sounds (Tower 1908, Fish and Mowbray 1970, Connaughton and Taylor 1996), which we describe here as "purring" sounds. By monitoring the spatial distribution of calling male weakfish using hydrophones and the Global Positioning System (GPS) of navigation satellites, it is now possible to establish the probable spawning locations and seasons using an unequivocal, rapid, and cost-effective technique.

It was our purpose to ascertain if male weakfish calling sites can be identified and accurately mapped. In order to do this, the weakfish calls heard at a location must be differentiated from other species of soniferous fishes that may also be present. There may be as many as 15 species of sound-producing fishes co-occurring in the estuaries of the Southeastern United States in the families Ariidae, Batrachoididae, Blenniidae, Carangidae, Gobiidae, Haemulidae, Lutjanidae, Sparidae, and Sciaenidae (Fish and Mowbray 1970, Myrberg 1981, Mok and Gilmore 1983). We have been able to separate our species of interest from these other species by ear and on the basis of spectrographs made from calls recorded on captive fishes. We also estimated the acoustical background noise during daylight at the site to establish a threshold for background noise. Using a cylindrical spreading model, we estimated the greatest distance over which the dominant sound frequency produced by a "purring" male weakfish could be heard under those conditions. This allowed us to plot the area of maximum likelihood in which the male weakfish could be producing sounds. Finally, to determine if variation in fish sound production was associated with variation in spawning behavior, we compared sound pressure levels associated with acoustic recordings of fish sounds for each location with an ichthyoplankton net survey, which is a traditional method of assessing spawning.

MATERIALS AND METHODS

In May 1997, we sampled weakfish spawning populations with hydrophone surveys and plankton nets at twelve stations off the North Carolina coast, USA: on the eastern side of Pamlico Sound near Ocracoke Inlet (Teaches Hole stations 1, 2, 3, and 4; Wallace Channel; Lehigh Dredge; and Royal Shoal) and near Hatteras Inlet (Hatteras

Hole and Hatteras North); and on the western side of the sound near Rose Bay (Rose Bay 1 and 2) and Fishermans Bay. In 1996, a limited series of stations were visited at the southwestern end of Ocracoke Island in the Ocracoke Inlet channels; Hatteras Inlet was not sampled in 1996. At all hydrophone sampling locations, precise geographical positions (latitude and longitude) were determined using either a Trimble Pathfinder Basic Plus Global Positioning System (GPS) satellite receiver or a Trimble NT200 GPS chartplotter receiver with a ProBeacon MSK receiver operating in real-time differential mode (± 10 m Circular Error Probable accuracy; see Pietraszewski et al. 1993). At each station, we measured the salinity and temperature profile at 1.0-m intervals of depth using a Hydrolab Surveyor II probe or a YSI Model 85 probe; vertical sound speed-profiles were calculated from temperature, salinity, and depth using the formula in Medwin (1975). We examined vertical sound-speed profiles for sharp changes, which may cause refraction in sound waves and could increase the propagation distance of sound waves. Recordings (a minimum of 2 min in duration) were made at each site from May 12 through May 18 commencing at one hour before sunset and continuing at intervals of 15 min–60 min until two hours after sunset during 1996. In 1997, acoustic samples were from 1 h before sundown until 2 h after sundown at hydrophone stations beginning on May 13 and lasting until May 22, 1997.

Collection of Acoustical Data

Acoustical recordings were made from a small boat stationed over the study sites. The motor was not running during the collection of acoustical data. Recordings were made 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), which consisted of an InterOcean Model T-902 hydrophone (omnidirectional with sensitivity −195 dB Nominal re 1 V/μPa) connected to an amplifier (gain adjustable from 15 dB to 95 dB in 10 dB increments plus vernier adjustment) with 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. The hydrophone was placed at 1–2 m depth below the water surface. The sound pressure levels, both during background sound measurements during the day and during periods of fish sound production at night, were measured over the entire frequency range. The acoustical data were recorded with a portable battery-operated digital audio tape (DAT) cassette recorder (Sony TCD-D8 recorder, frequency range: 20 Hz–22,000 Hz ± 1 dB).

Statistical Analysis of Acoustical Data

The measured sound pressure levels (*SPL*) in decibels were converted to pressures (p) in µPa before statistical analysis. Averages and standard deviations were calculated using the pressures, and the results were transformed back to decibels.

Signal Analysis of Acoustical Data

The samples of weakfish "purring" calls and other sounds produced by other soniferous organisms at each site were recorded on a DAT with 16 bits of resolution. The sampling rate was 48 kHz when sounds were recorded on the DAT. We reduced the sampling rate to 24 kHz for our spectrographic analysis by resampling using a National Instruments NB-2150F analog-to-digital board with anti-aliasing filters in a Power Macintosh computer. Power spectra were calculated using a 1024-point Fast Fourier Transform (FFT) with a Hanning window. The frequency resolution, determined by the sampling frequency and the number of points in the FFTs in each power spectrum, is 23.4 Hz. Spectrographs were plotted using the power spectrum and time information in the sampled sounds. The relative power spectral density in each spectrograph is given such that the background level in each spectrograph (the lightest region) is 0 dB. In each of our spectrographs, there is no significant contribution (within 30 dB of the peak value) above 6000 Hz; therefore, only the frequencies from 0 Hz to 6000 Hz are shown.

We were able to compare the spectrographs of weakfish "purring" sounds with the spectrographs of silver perch *Bairdiella chrysoura* courtship calls. Using our spectrographic analyses, published spectrographs (Fish and Mowbray 1970), and spectrographs produced from our own and other's audio tape recordings of captive specimens (recordings from Martin Connaughton, Washington College, Chestertown, MD and R. G. Gilmore, Harbor Branch Oceanographic Institution, Ft. Pierce, FL), we were able to easily discriminate between the two species' calls.

Estimated Sound Attenuation

The sound produced by the fish must propagate through the water to the hydrophone. In the process, the sound wave will attenuate as it spreads out and will be affected by absorption, reflection (from the bottom and surface), refraction (by temperature, current, and salinity gradients), and scattering (from bubbles, turbulence and surface roughness or waves). The energy in the sound wave spreads spherically ($1/r^2$) in deep water and cylindrically ($1/r$) in shallow water (Urick 1983). Mann and Lobel (1997) have measured the propagation of damselfish *Dascyllus albisella* (Pomacentridae) courtship sounds in shallow water (< 7 m) and suggested that the spreading of the sounds is nearly cylindrical. Because weakfish spawn in water depths of less than 10 m, we model the sounds here as spreading cylindrically.

The sound pressure level of an acoustic signal can be accurately measured when it is above the background sound pressure level at the signal frequency (Pierce 1988). Using Pierce's (1988) criterion for the detectability of a signal above the background and assuming cylindrical spreading, the distance $r_{\max}$ that the signal will travel before being undetectable is given by

$$r_{\max} = 10^{(L_s - L_{bg})/10} \tag{1}$$

where L_s is the sound pressure level of the source at a distance of 1 m; and L_{bg} is the background sound pressure level. We used $r_{\max}$ to estimate the theoretical maximum distance over which we could detect the "purring" sounds of individual male weakfish.

Plankton Net Surveys

Sciaenid egg collections were taken with 25-cm diameter "bongo" plankton net frame fitted with two 1.5-m long 500μm mesh plankton nets. The nets were pulled behind a small boat at the surface at speeds of 4–6 km/h for 5 min. A General Oceanics flow meter (Model 2030R or 2030R2) was attached to the frame inside the mouth of one of the nets and used to calculate volumes of water filtered for each sample. Using the egg counts and the estimated volume of water filtered, egg densities per m^3 were obtained. Plankton samples were passed through a 2000 μm sieve immediately after collection in order to remove seagrasses and ctenophores that could affect egg counts. Samples were then preserved in 5% formalin and examined for early-stage fish eggs (< 1 day old) with characteristics of the Sciaenidae (750–1000 μm egg diameter, 1–3 internal oil globules) later in the laboratory (Holt et al. 1988).

RESULTS

We recorded weakfish "purring" after sunset on the eastern side of Pamlico Sound in May of 1996 in Ocracoke Inlet and again in May of 1997 in Ocracoke and Hatteras Inlets. We analyzed the "purring" sound to obtain its spectrographic characteristics for use in identification of weakfish in a location. A spectrograph of a typical individual male weakfish "purring" sound shows that the peak intensity of pulses occurs in three "purrs" or sequences of pulses (Figure 1): the first is 1.68 s in length; after a 1.59-s delay, the second "purr" lasts 1.48 s; and then after a 1.55-s delay, there is a third burst that lasts 0.98 sec. The highest power spectral densities occurred between 300 Hz and 400 Hz during the recording.

Sound recordings made after sunset indicated that both individuals and groups of weakfish produced "purring" sounds at most stations close to the inlets. We made 37 digital audio tape recordings with fish sounds after sunset near the inlets in May 1996 and May 1997; 26 of these contained "purring". For a subset of these recordings with "purring" sounds (n = 7), in which we were able to clearly distinguish individual weakfish males, we measured the average pulse repetition rate as 15.4 pulses/s and the average dominant frequency was 360 Hz. Individual weakfish had a maximum sound pressure level of 127 dB (re 1 μPa), based on these field recordings. On all of the recordings in which "purring" was heard, there were portions in which individual weakfish could not be distinguished; we believe that such recordings are of aggregations of "purring" weakfish. There are no distinct "purrs" in a spectrograph of such a recording, because the spaces between each individual's "purrs" are filled with the "purrs" of the other individuals of the aggregation, so that there is an almost

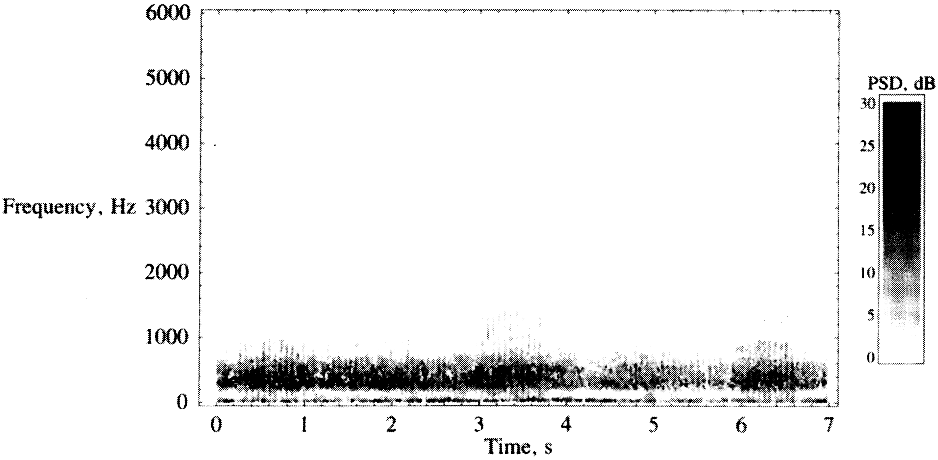

Figure 1. A spectrograph of an individual male weakfish "purring", recorded at Hatteras Inlet 22 May 1997 at 18:33 Eastern Standard Time. Power spectra were calculated using a 1024-point Fast Fourier Transform (FFT) with a Hanning window. The frequency resolution is 23.4 Hz. The relative power spectral density in each spectrograph is given such that the background level in each spectrograph (the lightest region) is 0 dB. In each of our spectrographs, there is no significant contribution (within 30 dB of the peak value) above 6000 Hz; therefore, only the frequencies from 0 Hz to 6000 Hz are shown.

continuous sound at the dominant frequency (x = 350 Hz, n = 26) of an individual "purr" (Figure 2). For all individual and aggregation recordings, the overall sound pressure levels ranged from 110 to 147 dB (re 1 µPa) and averaged 134 dB. In these recordings, one standard deviation in sound pressure above the mean sound pressure corresponds to a sound pressure level of 139 dB, and one standard deviation below the mean sound pressure is 124 dB.

Other biological sources of sound contributed to the sound pressure level in some of these recordings. The soniferous silver perch *Bairdiella chrysoura* (Sciaenidae) were recorded "clucking" on the inlet recordings, but were also recorded away from the inlets at 2 sites (5 recordings out of 12 made after sunset in Rose Bay and Fishermans Bay). On many inlet recordings, weakfish could be heard "purring" simultaneously with silver perch "clucking". Because these two species co-occurred at most inlet locations, we performed spectrographic analyses to identify the presence of silver perch "clucking" in recordings where weakfish were also recorded "purring". The peak intensity of silver perch sounds occurred in pulses or "clucks"; twelve distinct "clucks" can be seen in the spectrograph of an individual male silver perch recorded in Fisherman's Bay on the western side of Pamlico Sound (Figure 3). For a subset (n = 13) of all inlet recordings with fishes, in which individual male silver perch were clearly distinguished from background sounds, the average "cluck" or pulse repetition rate was 6.5 pulses/s, with each of the "clucks" having an average peak frequency of 1080 Hz. The maximum overall sound pressure level of these recordings was 136 dB (re 1 µPa). Silver perch were also heard "clucking" in groups; a typical spectrograph of a group

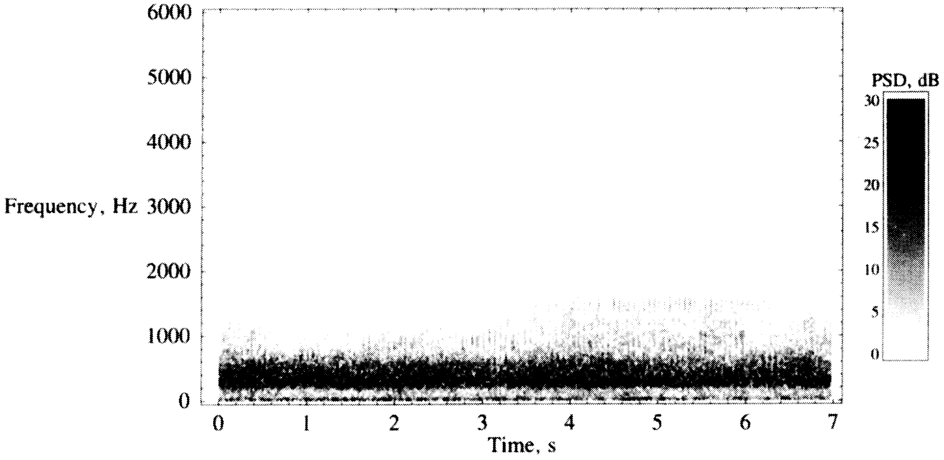

Figure 2. A spectrograph of an aggregation male weakfish "purring", recorded at Hatteras Inlet 22 May 1997 at 19:02 Eastern Standard Time. Spectrographs calculated and formatted as described in Figure 1.

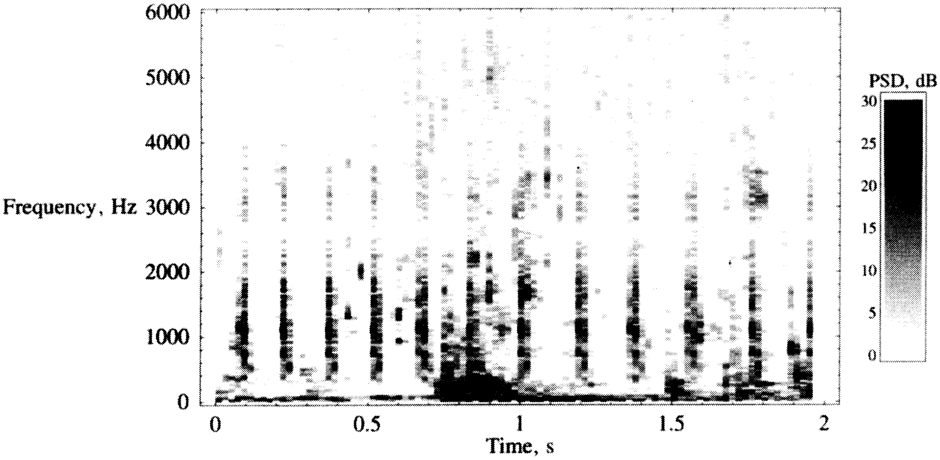

Figure 3. A spectrograph of an individual silver perch, recorded in Fisherman's Bay near Hobucken, NC on 13 May 1997 at 19:36 Eastern Standard Time. The low-frequency spectral energy between 0.75 and 1.00 s is wave noise. Spectrographs calculated and formatted as described in Figure 1.

of silver perch had an average dominant frequency of 1025 Hz (Figure 4). The average sound pressure levels were 135 dB for groups of silver perch calling without weakfish present, with one standard deviation in sound pressure above the mean sound pressure corresponds to a sound pressure level of 138 dB, and one standard deviation below the mean sound pressure is 130 dB. When both species were calling together, a spectrographic analysis shows two dominant frequencies, one at 300–400 Hz and another at 1000 Hz (Figure 5). After spectrographic analysis, we determined that of the 37 recordings made at the inlet sites after sunset with fish sounds, 11 recordings had silver perch "clucking" individually or in groups, 1 recording had "purring" weakfish in a group, and 25 recordings had silver perch and weakfish calling simultaneously in groups. Thus, although silver perch and weakfish both produce sounds at the same time of year and in some of the same locations, the presence of either species can be determined from their distinctive spectrographic signatures. A map of the sites where we recorded "purring" by male weakfish (Figure 6) shows that weakfish spawning was restricted to the eastern side of Pamlico Sound. In contrast, silver perch "clucking" was recorded on both the western side of the sound and at the inlet stations (Figure 7).

The "purring" sounds were associated with weakfish spawning behavior, because sciaenid-type eggs were collected in plankton samples made at many of those sites, including the recordings characterized above. Sciaenid-type eggs were collected in May 1996 in Ocracoke Inlet, but quantitative estimates of egg density were not

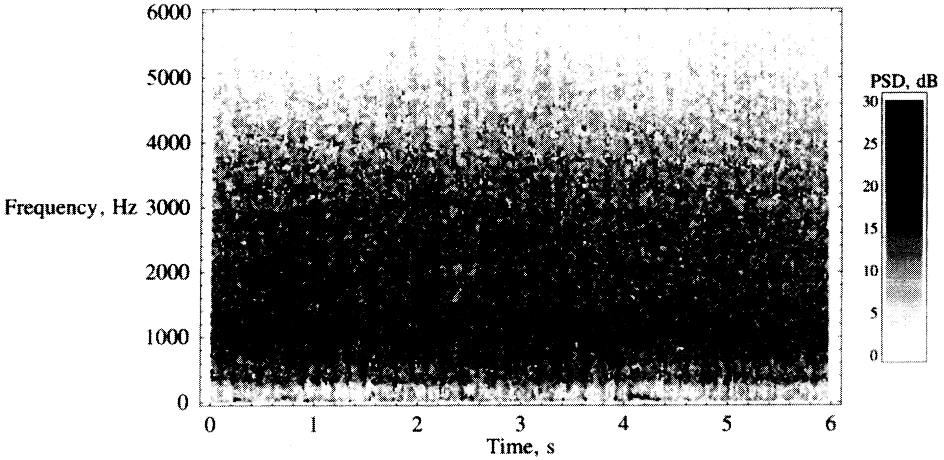

Figure 4. A spectrograph of an aggregation silver perch, recorded in Teaches Hole on 19 May 1997 at 20:31 Eastern Standard Time. Spectrographs calculated and formatted as described in Figure 1.

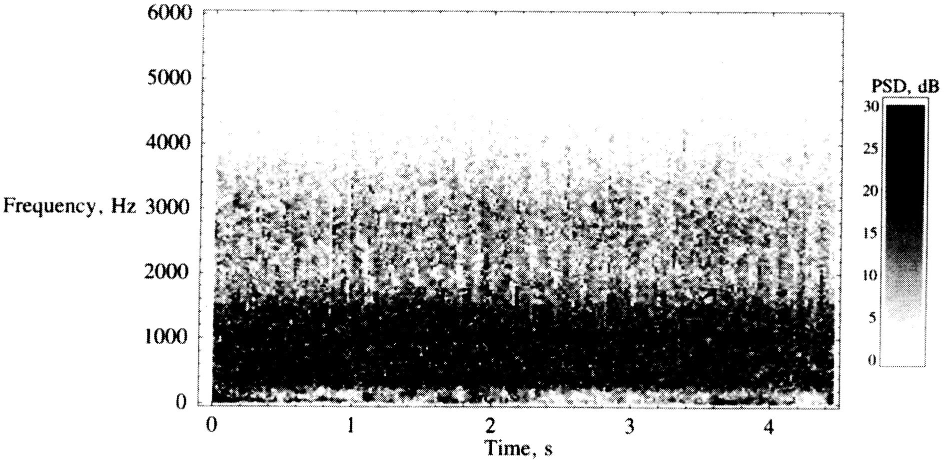

Figure 5. A spectrograph of an aggregation silver perch and weakfish recorded on 18 May 1997 at the Lehigh Dredge at 19:38 Eastern Standard Time. Spectrographs calculated and formatted as described in Figure 1.

made that year. Nonetheless, sciaenid-type eggs appeared to be most abundant at stations where weakfish "purring" and silver perch "clucking" were recorded in May 1996. Sciaenid-type eggs co-occurred with areas of maximum weakfish "purring" in May 1997 (Figure 8). Maximum sound pressure levels at stations where weakfish "purring" and silver perch "clucking" were recorded after sunset was positively correlated with $\log_{10}$- transformed sciaenid-type egg densities at those

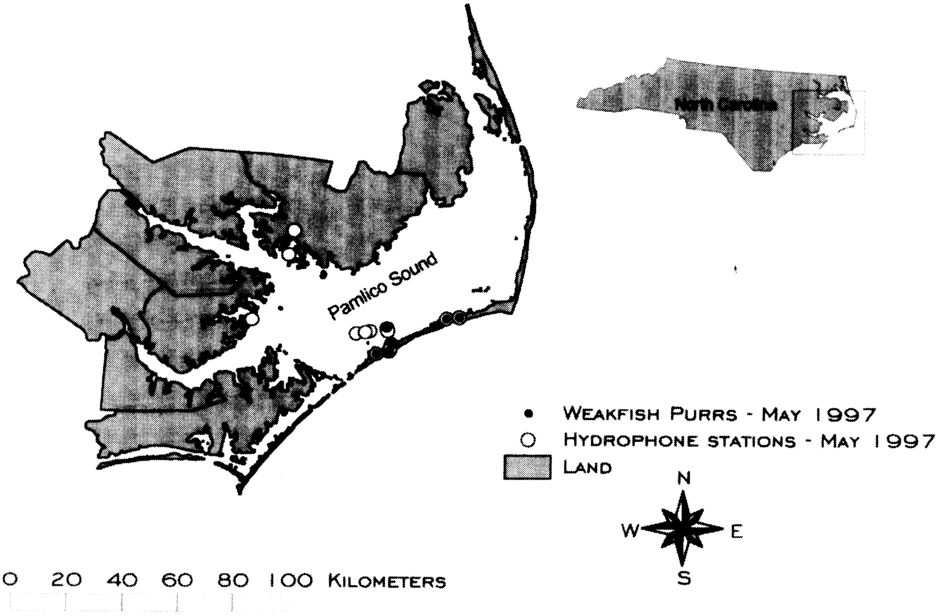

Figure 6. A map of Pamlico Sound showing sampling locations and locations where weakfish "purring" was recorded. Open symbols indicate locations of hydrophone listening stations and plankton tow samples. The closed symbols indicate stations where weakfish *Cynoscion regalis* males were heard "purring".

same stations (Pearson correlation coefficient, $r = 0.78$; $p = 0.002$; $n = 13$). No sciaenid-type eggs were collected on the western side of Pamlico Sound during May in 1997, but high densities of sciaenid-type eggs were collected in Ocracoke and Hatteras Inlets in May of 1996 and 1997.

We do not know the distance between the fish and the hydrophone in our measurements made in nature, but undoubtedly some fish were close by and others more distant. We will assume, for the purpose of estimation of a region within which the fish we heard were mostly likely to occur, that the loudest recorded sound was produced by a nearby fish or group of fishes. Using 127 dB as the sound pressure level generated by an individual weakfish, equation (1), and assuming a background sound level of 110 dB (the average of sound pressure levels recorded at the inlet stations in the morning), we estimate $r_{\max} = 50$ m for an individual weakfish. Thus, we assumed that an individual fish may be heard above the background no more than about 50 m away. Beyond this distance, the cylindrical spreading model would be inappropriate as the propagating sound wave would encounter shallow sand bars and other obstacles, which would attenuate it even more.

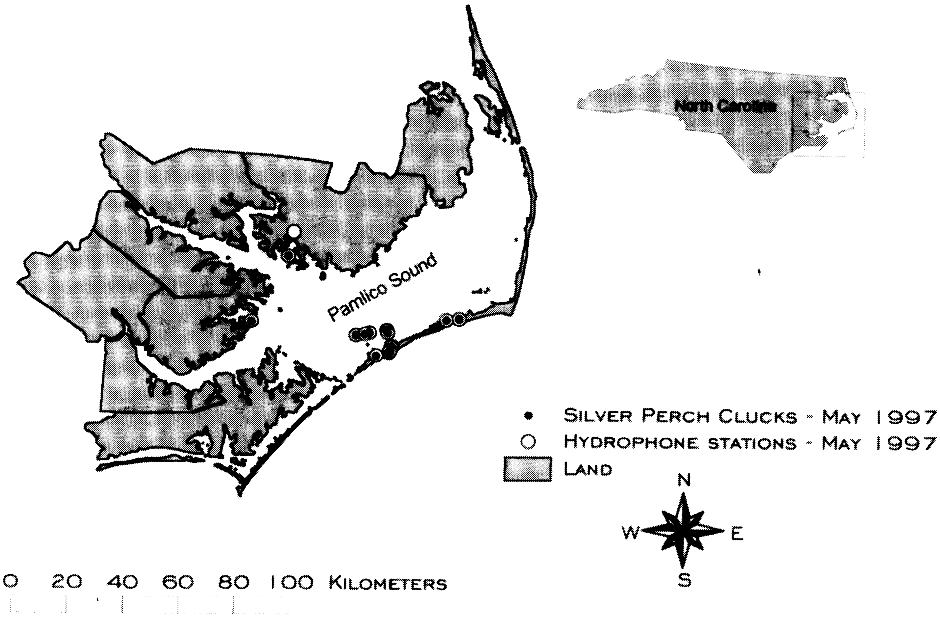

Figure 7. A map of Pamlico Sound showing sampling locations and locations where silver perch "clucking" was recorded. Open symbols indicate locations of hydrophone listening stations and plankton tow samples. The closed symbols indicate stations where silver perch *Bairdiella chrysoura* males were heard "clucking".

Water quality conditions were different in the eastern and western side of Pamlico Sound during our study, with the western side having lower salinity than the eastern side of the sound (Table 1). There were no acoustically significant vertical water density or sound speed-gradients at any location in 1997 (Figure 9), so refraction of sound waves due to such gradients was unlikely. It appears that habitat characteristics that are important for weakfish spawning are proximity to inlets and high but variable salinity conditions (~25 ‰).

DISCUSSION

We have recorded and spectrographically analyzed the sounds produced by individual male weakfish *Cynoscion regalis* and silver perch *Bairdiella chrysoura*. The sounds were as loud as 127 dB (re 1 µPa) for individual weakfish, 136 dB for individual silver perch, and 147 dB for groups of these two fishes. It was apparent that some of the recordings contained the "purring" sounds of many individual male weakfish along with "clucking" sounds of many individual silver perch calling simultaneously. At those times, the sound pressure levels were near

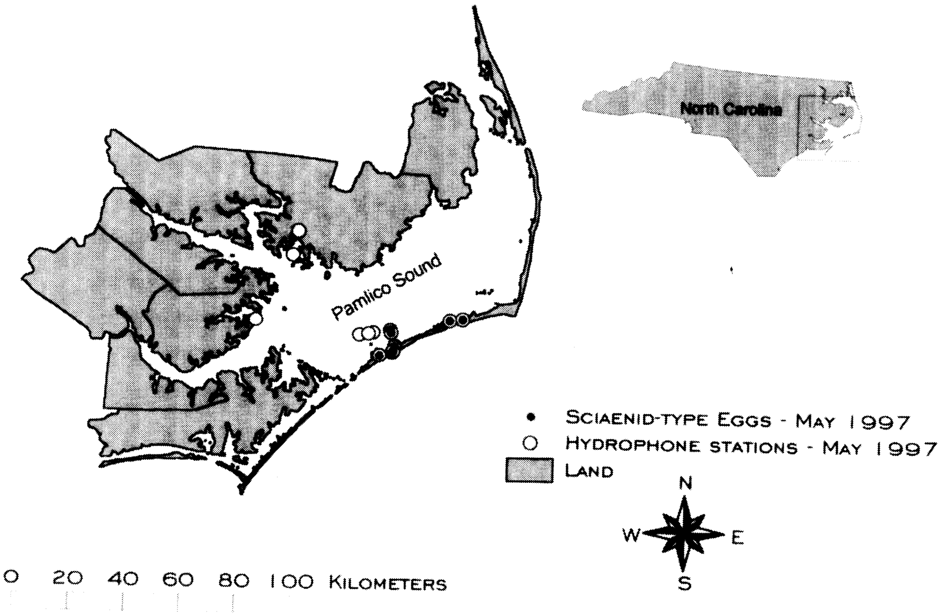

Figure 8. A map of Pamlico Sound showing sampling locations and locations where sciaenid-type eggs were collected. Open symbols indicate locations of hydrophone listening stations and plankton tow samples. The closed symbols indicate stations where sciaenid-type eggs were collected in the plankton tows.

the maximum recorded. Thus, both weakfish males and silver perch may “purr” and “cluck” in groups, but we do not have enough information about spatial distribution or abundance of these fishes to adequately model the sound propagation produced by these aggregations. We expect that the group calling of weakfish and silver perch would be louder than an individual fish “purring” or “clucking”, and thus would explain the maximal sound pressure levels that we recorded at those sites.

Significantly, there is a correlation between overall sound pressure levels of the two common sciaenid fish sounds and sciaenid-type egg densities in the surface waters at the hydrophone stations. This correlation was most likely due to either one or both of the following factors: 1) differences in the number of weakfish and silver perch in the spawning aggregations at some stations, which would influence both the recorded sound pressure levels and the sciaenid egg density measured at any site; or 2) variations in the distance between our hydrophone and the spawning aggregation, which would cause low sound pressure levels due to sound attenuation and a corresponding plume of eggs that was dispersed in the water column, thus appearing as a low density in our samples. At stations where no weakfish

TABLE 1

The habitat characteristics associated with locations where weakfish, *Cynoscion regalis*, “purring” was recorded in Pamlico Sound, NC in May of 1997. The temperature and salinity conditions reported are for the bottom sample in a vertical profile.

Station name	Date	Location in Pamlico Sound	Latitude (N)	Longitude (W)	Temperature (°C)	Salinity (‰)	Depth (m)
Teaches Hole 1	16 May 1997	Eastern	35° 04′57.1″	75° 59′58.9″	19.1	33.0	3.7
Teaches Hole 2	19 May 1997	Eastern	35° 05′16.0″	75° 59′46.6″	20.8	33.5	3.0
Teaches Hole 3	19 May 1997	Eastern	35° 06′10.4″	75° 59′26.4″	22.6	25.2	4.0
Teaches Hole 4	21 May 1997	Eastern	35° 05′16.5″	75° 59′46.0″	20.4	34.7	5.4
Wallace Channel	16 May 1997	Eastern	35° 04′14.3″	76° 02′54.2″	19.7	32.0	7.6
Lehigh Dredge	18 May 1997	Eastern	35° 09′18.7″	76° 00′48.1″	21.9	17.6	2.7
Royal Shoal	18 May 1997	Eastern	35° 08′17.5″	76° 05′52.4″	21.3	15.1	2.1
Hatteras Hole	22 May 1997	Eastern	35° 11′50.7″	75° 46′49.3″	20.3	33.9	4.6
Hatteras North	22 May 1997	Eastern	35° 12′14.3″	75° 43′51.7″	20.3	34.2	2.4
Average Eastern sites					20.71	28.8	2.61
Standard Deviation					1.08	7.63	1.43
Fisherman’s Bay	13 May 1997	Western	35° 09′31.6″	76° 32′43.1″	21.1	10.6	1.2
Rose Bay 1	15 May 1997	Western	35° 22′39.0″	76° 25'07.8″	21.4	8.2	2.4
Rose Bay 2	15 May 1997	Western	35° 27′24.9″	76° 24′13.9″	22.5	3.6	0.9
Average Western sites					21.67	7.4	1.5
Standard Deviation					0.73	3.56	0.79

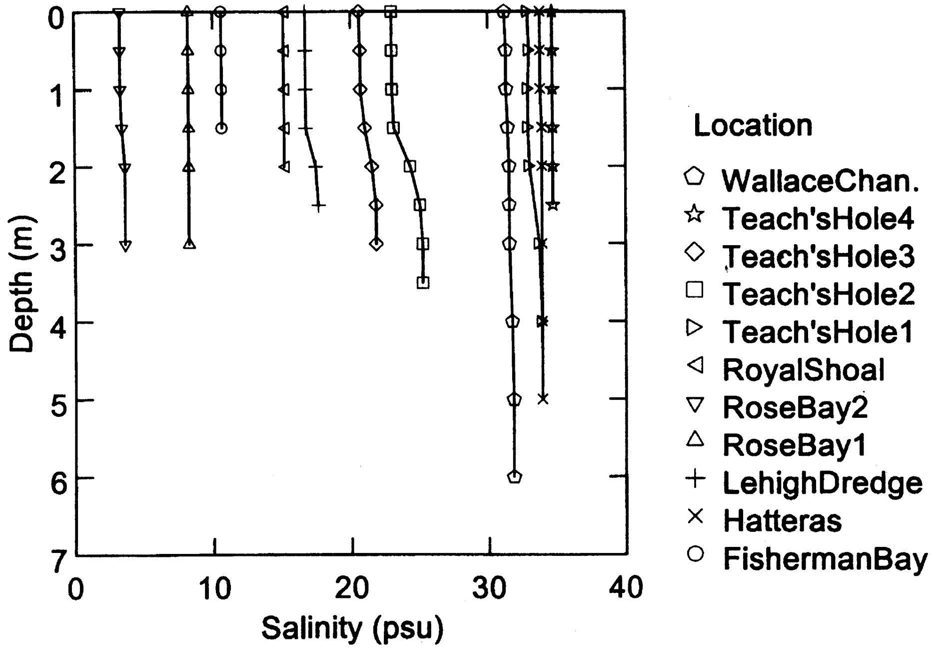

Figure 9. The vertical profile of sound speed calculated from salinity, temperature, and depth measured at selected hydrophone stations in May 1997.

"purring" was detected, we can assume that they were absent from those areas, or perhaps that weakfish males were present, but not drumming, because enviromnental factors (e.g., photoperiod or temperature) were poor for spawning. During some nights at some locations, we recorded "purring" sounds but did not collect developing eggs, which contributed to the imperfect correlation between sound pressure level and egg density. Most of these instances occurred early in the evening just prior to or at sunset. Connaughton and Taylor (1996) reported that the "purring" or drumming sound made by male weakfish under laboratory conditions began before spawning, ceased during the actual spawning activity, then began again immediately after spawning. In our samples, the detection of weakfish "purring" and the absence of eggs may indicate that male weakfish were present and signaling their readiness to spawn, but that spawning had not yet occurred (perhaps because females were not yet present or ready to spawn at that time). Other alternative explanations are that the weakfish could be heard over a large area (7891 m^2), but the pelagic eggs were present in a smaller area and we missed them with the plankton net. In either case, our plankton net did not intercept a plume of eggs released during spawning at these stations. We favor the idea that weakfish make their presence known just prior to spawning, but do not necessarily spawn when calling. Thus, stations where weakfish produced "purring" early in the evening may be best referred to as potential spawning sites that indicate where eggs will produced at some later time.

Although the eggs we collected appear externally similar to descriptions of eggs produced by weakfish, we cannot conclusively identify the sciaenid-type eggs collected in this study as weakfish eggs based on morphological characteristics alone. Because early-stage eggs of silver perch and weakfish are very close in appearance, a molecular identification approach has been used to distinguish them (Daniel and Graves 1994). Although the molecular approach is precise with regard to species identification, it is labor-intensive and it is impossible to perform on the numerous eggs that are typically collected in a plankton sample. Currently, we are attempting to verify the presence of weakfish eggs in a sub-sample of all sciaenid-type eggs at these "purring" sites by examining the mitochondrial-DNA restriction fragment length polymorphisms of adult fish and individual eggs. In the absence of such independent molecular data to identify the eggs, we may conclude that the strong correlation between weakfish "purring" and sciaenid-type eggs suggests that weakfish were spawning near the inlets of Pamlico Sound in May 1997. As we obtained similar qualitative results for both 1996 and 1997, this is good evidence that the inlet areas are being used as spawning areas by this species in May each year.

We cannot rule out several alternative interpretations of our results. Weakfish may spawn in areas not adequately sampled in this study (center of the Pamlico Sound, offshore in the Atlantic Ocean, etc.), but we could not detect them because of their great distance from our listening stations. In addition, morphologically similar sciaenid eggs may be produced by other species of sciaenid fish, including the silver perch *Bairdiella chrysoura*, which are also soniferous and spawn in these areas at the same time. Indeed, silver perch "clucking" was recorded at the most hydrophone stations. The spectrographic analysis presented here allows good discrimination between weakfish and silver perch. We have mapped both species spawning areas based on the sound production alone. Although the areas overlap, the silver perch "clucking" was heard on both sides of the sound, but weakfish "purring" was recorded only at the inlets. Thus, the sciaenid-type eggs that we collected appear to be more closely associated with weakfish "purring", although we cannot rule out the possibility of silver perch eggs contributing to the sciaenid-type egg abundance.

Passive hydroacoustic surveys will greatly reduce the effort required in planning marine reserves for weakfish, because spawning areas of fishes can be easily delimited using hydrophones. Although this method cannot totally replace the careful estimation of fish egg production by traditional means, it is a reliable, rapid, and nondisruptive method of determining the location of spawning grounds of soniferous fishes in the family Sciaenidae, and may be applicable to other commercial species as well.

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