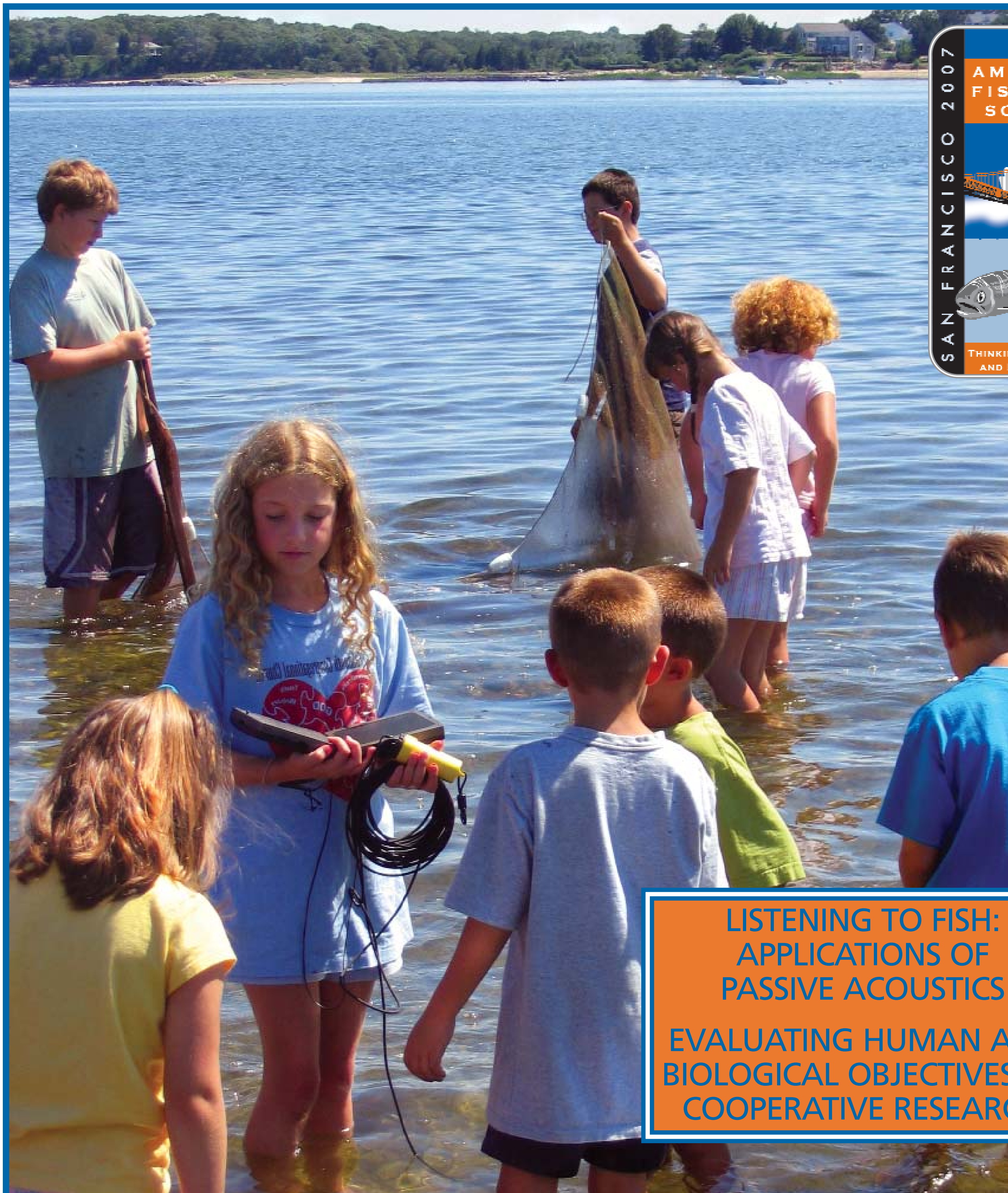
Fisheries

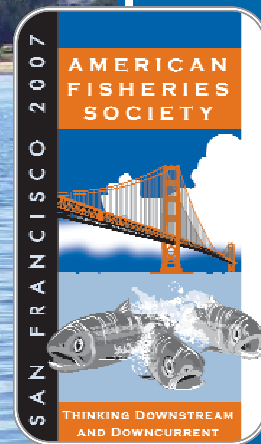
SEPTEMBER 2006
VOL 31 NO 9

AFS

American Fisheries Society • www.fisheries.org

Fish News
Legislative Update
Journal Highlights
Calendar
Job Center





LISTENING TO FISH: APPLICATIONS OF PASSIVE ACOUSTICS

EVALUATING HUMAN AND BIOLOGICAL OBJECTIVES OF COOPERATIVE RESEARCH

Cover: Passive acoustics can be an excellent tool for public education. Here children listen to underwater sounds as they learn about the estuarine environment.

Credit: North Falmouth Congregational Church

SCOTT HOLT, UNIVERSITY OF TEXAS AT AUSTIN

Scott Holt listens to red drum sounds from a fish pier in Texas.

Listening to Fish: Applications of Passive Acoustics to Fisheries Science

Rodney A. Rountree
R. Grant Gilmore
Clifford A. Goudey
Anthony D. Hawkins
Joseph J. Luczkovich
David A. Mann

Rountree is a senior scientist at Marine Ecology and Technology Applications, Inc., Waquoit, MA. He can be reached at rrountree@fishecology.org. Gilmore is a senior scientist, Estuarine, Coastal, and Ocean Science, Inc., Vero Beach, FL. Goudey is director, Center for Fisheries Engineering Research, MIT Sea Grant College Program, Cambridge, MA. Hawkins is director, Loughine Ltd Aberdeen, Scotland. Luczkovich is an associate professor at the Institute for Coastal and Marine Resources, Department of Biology, East Carolina University, Greenville, NC. Mann is an assistant professor, University of South Florida, College of Marine Science, St. Petersburg.

Passive acoustics is a rapidly emerging field of marine biology that until recently has received little attention from fisheries scientists and managers. In its simplest form, it is the act of listening to the sounds made by fishes and using that information as an aid in locating fish so that their habitat requirements and behaviors can be studied. We believe that with the advent of new acoustic technologies, passive acoustics will become one of the most important and exciting areas of fisheries research in the next decade. However, a widespread lack of familiarity with the technology, methodologies, and potential of passive acoustics has hampered the growth of the field and limited funding opportunities. Herein, we provide an overview of important new developments in passive acoustics together with a summary of research, hardware, and software needs to advance the field.

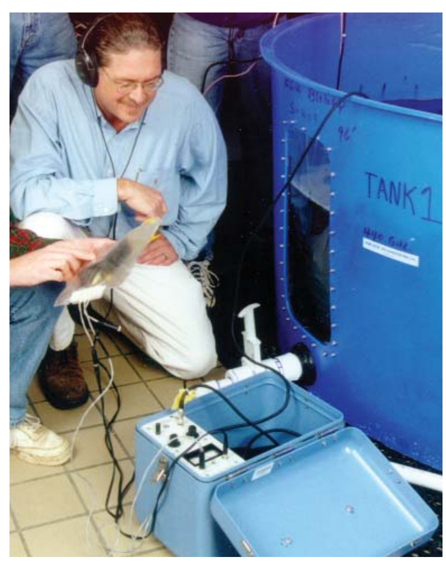
INTRODUCTION

Listen to fish? Although most fisheries biologists are generally aware that some fishes are soniferous (sound producing), relatively few have stopped to consider the potential importance of listening to fish sounds to their fields of study. In fact, few realize that many important recreational and commercial fishery species are highly soniferous, including many in the cod and drum families. Fishes produce sounds to communicate with one another while they are feeding, mating, or being aggressive and also make incidental noises associated with feeding, swimming, and other behaviors (Fine et al. 1977b). Far from Jacques Cousteau's *The Silent World* (Cousteau and Dumas 1953), our estuaries, seas, and oceans are teaming with the sounds of marine life.

Fish are difficult to see and study in the ocean. Scuba techniques can help in shallow waters and a range of active acoustic and optical techniques can assist in deep water, but we are still largely ignorant of the distribution and behavior of the great majority of marine fish. Possibly one of the greatest challenges to researchers attempting to study the behavioral ecology of fishes is that of finding the fish in the first place. Often a scientist must go to great lengths conducting expensive and time-consuming biological surveys simply to determine the locations or habitats where a fish can be found, before any attempt to study its biotic and abiotic interactions can be made. After all, you can't study something you can't find. Any tool that can help scientists to locate fish is therefore valuable.

A new field of passive acoustics is rapidly emerging in fisheries science and marine biology, in which scientists use underwater technology to listen in on the noisy aquatic realm. Passive acoustics is distinguished from other types of bioacoustics, because it uses naturally occurring sounds to gather information on fishes and other marine organisms, rather than using artificially generated sounds. Passive acoustics provides a number of important benefits for fisheries research. First, it provides a method of non-optically observing fish activity and distribution. That is, it can be used to find and monitor fishes (and other animals) that produce sound. Second, passive acoustics is a non-invasive and non-destructive observational tool. Third, it provides the capability of

Joe Luczkovich monitors fish sounds in the laboratory at East Carolina University.



JOE LUCZKOVICH, EAST CAROLINA UNIVERSITY

Figure 1. Representative calls of sciaenid fishes. Energy distribution patterns associated with harmonic frequency bands and fundamental frequencies are species specific and can be used to identify species presence based on the call characteristics.

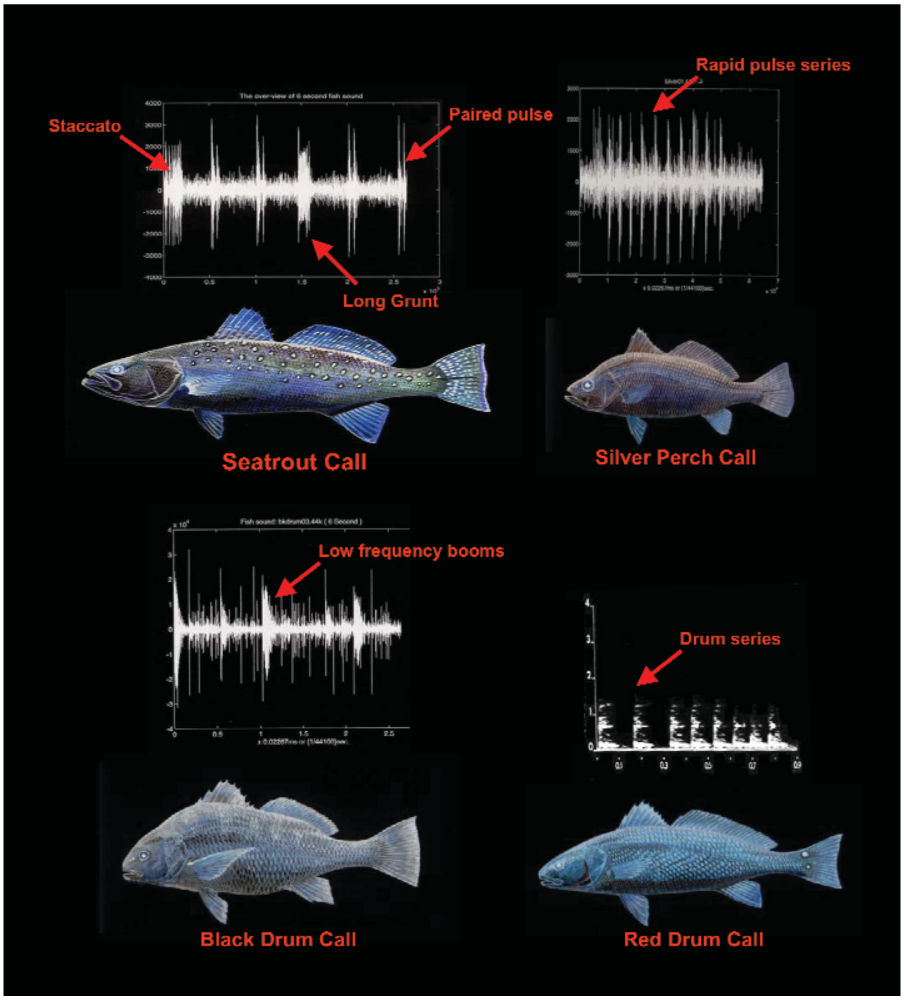


Figure 2. Representative sciaenid internal anatomy revealing the gas bladder and sonic muscles of a male weakfish, *Cynoscion regalis.*

GRANT GILMORE, ECOUS

Figure 3. Temporal overlap pattern of soniferous activity among sciaenid fishes in a Florida estuary.

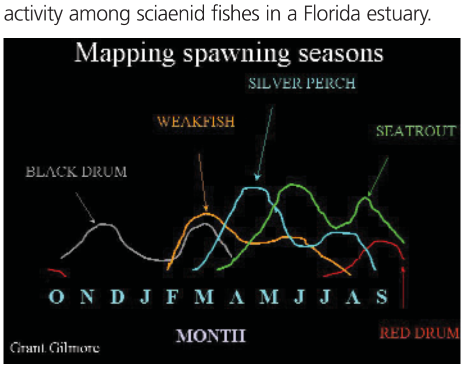


Figure 4. Spatial distribution of spawning aggregations of sciaenid fishes as determined by soniferous activity in a Florida estuary. Spawning locations of different species are represented by ellipses with different shading patterns.

continuous or long-term monitoring as well as remote monitoring. Such long-term monitoring can provide important information on daily and seasonal activity patterns of fishes and other marine organisms. In addition, passive acoustics can also be used to simultaneously monitor sources of noise pollution, and to study the impact of man's activities on marine communities. Anthropogenic sources include noise generated by boating activity, seismic surveys, sonars, fish finders, depth finders, drilling for oil and gas, and military activities. As recently reviewed by Popper (2003) these anthropogenic noise sources all have potentially important impacts on marine fauna.

The ability to listen to fish and other marine life allows scientists to identify, record, and study underwater animals even in the absence of visual information. Coupling passive acoustics with conventional fishery sampling techniques provides a powerful new approach to fisheries research. We seek to promote a better understanding of passive acoustics applications to fisheries among fisheries professionals, and feel that passive acoustics will become a major area of fisheries research in the next decade. Towards this purpose, we provide, herein, an overview of some important developments in passive acoustics applications to fisheries and summarize areas of research and development that we believe are needed to catalyze advancement in the field.

BACKGROUND

Over 800 species of fishes from 109 families worldwide are known to be soniferous (Kaatz 2002), though this is likely to be a great underestimate. Of these, over 150 species are found in the northwest Atlantic (Fish and Mowbray 1970). Amongst the soniferous fishes are some of the most abundant and important commercial fish species, including many codfishes, drum fishes, grunts, groupers, snappers, jacks, and catfishes. Some invertebrates with important fisheries also produce sounds, including mussels (*Mytilus edulis*), sea urchins (Fish 1964), white shrimp (*Penaeus setiferus*, Berk 1998), spiny lobsters (Moulton 1957; Fish 1964; Patek 2002), American lobster (*Homarus americanus*, Fish 1966; Henninger and Watson

2005), and perhaps squid (Iversen et al. 1963).

Passive acoustics has been used for over 50 years in fish biology and fisheries surveys (see Fish et al. 1952 and Fish and Mowbray 1970 for a summary of early work) and is being used routinely today to determine habitat use, delineate and monitor spawning areas, and study the behavior of fishes (Hawkins 1986; Rountree et al. 2003a, 2003b). Using hydrophones, marine ecologists and fishery biologists have been able to listen to the sounds fishes produce and identify species specific (Hawkins and Rasmussen 1978; Myrberg and Riggio 1985; Lobel 1998), and even individual specific (Wood et al. 2002), signatures using signal processing and spectral analysis computer algorithms. Often these sounds dominate the acoustic environment where they occur, as in the drum family (Sciaenidae), so much so that they interfere with military and petroleum prospecting operations that involve acoustic monitoring (e.g., Fish and Mowbray 1970). In other situations, such as damselfishes on coral reefs, the sounds are not loud and require specialized techniques to detect them (Mann and Lobel 1995a,b).

To identify the species of fish producing a sound, one first must do "sound truthing." There are two main ways this has been accomplished: (1) captive fish recordings and (2) in situ (i.e., in the field under natural conditions) recordings. Although acoustic complications in a tank or aquarium, combined with unnatural behavior and sound production, make captive fish recordings problematic, especially for larger fishes, such problems can be overcome (Okumura et al. 2002). Field recordings, on the other hand, sometimes suffer from the difficulty of matching sounds to species and behaviors. Field methods have been particularly successful in tropical waters where environmental conditions allow the use of advanced scuba and underwater video technologies (Lobel 2001, 2002). Knowledge of sound source levels is important for calculating the detection limits of hydrophones (e.g., Sprague and Luczkovich 2004). Precise measurement of sound source requires knowledge of the location of the fish and of the hydrophones' characteristics. Despite these difficulties, biologists have been able to link the aggressive and spawning behaviors of some fisheries species to their sound production using a combination of in situ and tank studies. For example sounds produced by haddock (*Melanogrammus aeglefinus*) during courtship and mating have been recorded and analyzed in this manner (e.g., Hawkins 1986). Once the association of sounds to specific species and behaviors has been established, passive acoustics provides a rapid way of establishing the spawning component of essential fish habitat (EFH).

EXAMPLES OF FISHERIES APPLICATIONS

Passive acoustics studies using relatively simple techniques have been successful in locating concentrations of important fish species, opening the way for further, more detailed studies of their behavior, distribution, and habitat use. Below we provide a brief review of past and current research on two groups of soniferous fishes that support large fisheries, the drumfishes (sciaenids) and codfishes (gadids).

Drum fishes (Sciaenids)

History—Sciaenid fishes have been known to produce sound for centuries (Aristotle 1910; Dufossé 1874a, 1874b) and the association of sciaenid sounds with spawning has been known nearly as long (Darwin 1874; Goode 1887). For hundreds of years the Chinese have located sciaenid spawning sites from their water craft by listening to drumming sounds emanating from the water through the hull of their boats (Han Ling Wu, Shanghai Fisheries Institute, pers. comm.). The location of sciaenid spawning sites using underwater technology is recent and dependent on the availability of underwater transducers, hydrophones, and acoustic recorders used to access and study underwater sounds (Fish and Mowbray 1970). Hydrophone tape recordings of sounds produced by large sciaenid aggregations during spawning were pioneered by Dobrin (1947), Dijkgraaf (1947, 1949), Knudsen et al. (1948), Protasov and Aronov (1960), Tavolga (1960, 1980), and Fish and Mowbray (1970).

The location and description of soniferous sciaenid aggregations using mobile hydrophones moving along a sound transect at spawning sites was conducted by Takemura et al. (1978), Mok and Gilmore (1983) and Qi et al. (1984). A portable hydrophone and recording system was carried via a boat from one site to another along a measured transect with recordings made along a preset grid or in a linear series (Mok and Gilmore 1983; Gilmore 2002). Recordings were made for 30–300 seconds at each site depending on transect length. Recorded sounds were verified by auditioning of captured specimens. This technique allowed spatial and temporal isolation and identification of species-specific sounds produced by sciaenid fishes, particularly under conditions of high sound attenuation for large group sounds (low frequency, high intensity sounds). Using detailed sonographic analyses of field recordings made on transects, Mok and Gilmore (1983) described the characteristic sounds of black drum (*Pogonias cromis*), spotted sea trout (*Cynoscion nebulosus*), and silver perch (*Bairdiella chrysoura*, Figure 1). Subsequent to these observations, considerable additional work has been done on sound characterization in these species, as well as the weakfish (*C. regalis*) and the red drum (*Sciaenops ocellata*). Passive acoustic transect techniques have been used by several investigators to locate spawning sciaenid groups in the field (Saucier and Baltz 1992, 1993; Connaughton and Taylor 1994, 1995; Luczkovich et al. 1999, 2000).

Function of Sound Production in Sciaenids—The most predictable and robust sounds produced by many fishes are those associated with reproduction. As in many soniferous animals, it is the male that must attract a mate and induce her to donate eggs for fertilization, and, therefore, it is often only the male that produces sound. Large choral aggregations of male sciaenid species are formed by spotted seatrout, weakfish, red drum, and silver perch specifically to attract females with which to spawn.

Sciaenid Sound Production Mechanisms—The most robust and energetic sciaenid sounds are produced by sonic muscles indirectly or directly vibrating the membrane of the gas bladder. When a freshly captured, recently calling, male seatrout is dissected, the bright red sonic muscles surrounding the gas bladder can be easily differentiated from the exterior lateral body muscles

(Figure 2). The muscle vibratory rate is directly associated with the fundamental frequency of the characteristic seatrout call produced by the gas bladder.

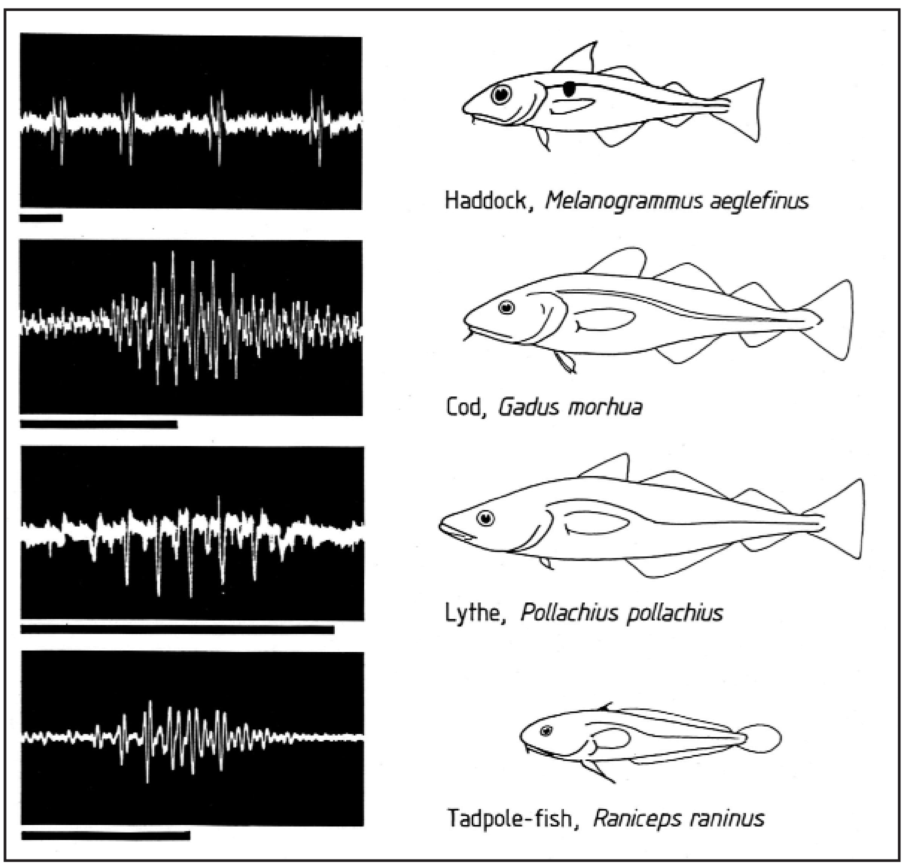
Most of the 270 species in this family probably produce sound using sonic muscles associated with the gas bladder. Using the species specific muscle contraction rates and the gas bladder shape, sciaenids produce sounds that can be used to identify species within the family (Mok and Gilmore 1983), as has been demonstrated in amphibians and birds. The characteristic shape of the sciaenid gas bladder is so conservative that it has been used as one of the primary morphological characters to classify sciaenids and to determine their phyletic relationships (Chu 1963; Chao 1978).

When and Where Do Sciaenids Produce Sound?—Mok and Gilmore (1983) demonstrated that sciaenid sound production was specifically associated with crepuscular and nocturnal courtship and spawning activities. Pelagic eggs and larvae of the spotted seatrout were collected with plankton nets at spawning sites during periods of sound production (Mok and Gilmore 1983; Alshuth and Gilmore 1993, 1994, 1995). The seasonal mating calls were directly associated with primary spawning activity in east-central Florida sciaenids. Soniferous activity of various sciaenid species exhibited distinct seasonal patterns, based on an analysis of over 300 acoustic transects collected between 1978–2002 (Figure 3). These same studies of soniferous spawning aggregations have demonstrated long term stability of spawning site locations (Figure 4), with the principal spawning sites identified by Mok and Gilmore (1983) being used for over 20 years (Gilmore 2002).

Codfishes (gadids)

A number of gadid species are soniferous and the trait is likely widespread within the family (Figure 5; Hawkins and Rasmussen 1978; Almada et al. 1996). A strong correlation between soniferous activity and the spawning cycle has been observed in most species studied to date (Hawkins and Rasmussen 1978). Although Atlantic cod (*Gadus morhua*) have a limited sound production repertoire, haddock have been shown to exhibit different calls at different stages of courtship (Figure 6; Hawkins et al. 1967; Hawkins and Rasmussen 1978; Hawkins 1986). Both species have specialized sonic muscles that vibrate the swim bladder to produce sounds for communication (Hawkins 1986). The sonic muscle is sexually dimorphic in haddock and Atlantic cod, with males having significantly larger muscles than females (Templeman and Hodder 1958; Templeman et al. 1978; Rowe and Hutchings 2004). In addition, the sonic muscle undergoes seasonal maturation in concert with the gonad maturation cycle. Evidence for sexual selection of sonic muscle size has been reported (Engen and Folstad 1999; Nordeide and Folstad 2000; Rowe and Hutchings 2004).

Figure 5. Representative calls of gadid fishes. Each species can be identified by its unique pulse pattern. For scale, the horizontal bar under each graph represents 100 ms. (Redrawn from Hawkins 1986).

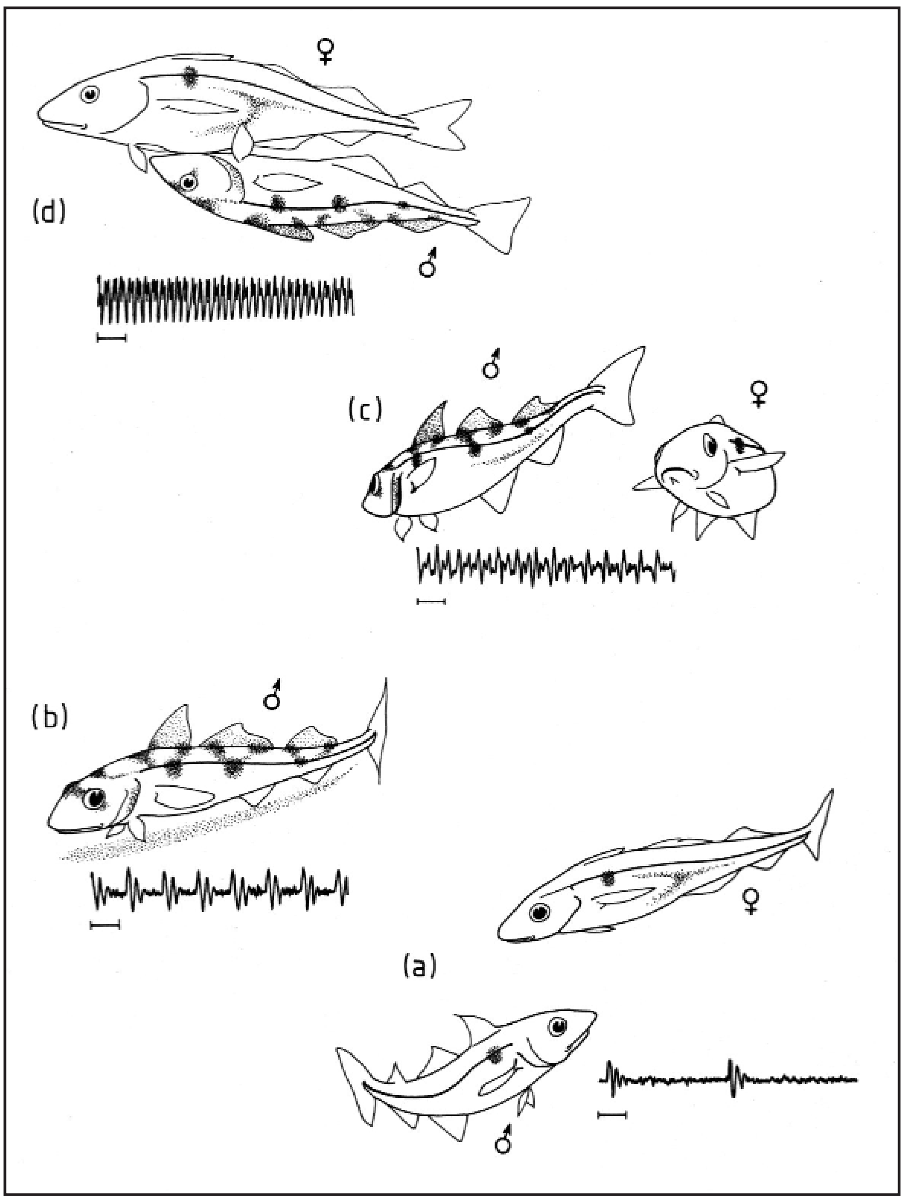


Brawn (1961a, b, c) provided the best description to date of the role of sound communication in courtship and spawning behavior in Atlantic cod based on laboratory studies. She found that soniferous activity is most common during the spawning season, being rare at other times, except for a fall "aggression period." She hypothesized that the fall soniferous period was related to increased aggressive interactions prior to dispersal to the foraging grounds. In the spawning season soniferous behavior is strongly associated with spawning and both spawning activity and call frequency peaked during the early evening hours. Interestingly, soniferous activity is most frequent at night during the spawning season, but most frequent during the day during the fall "aggression period." Brawn (1961a, b, c) attributed this to nocturnal spawning in the winter, and diurnal feeding interactions during the fall. Unfortunately, Brawn did not provide us with a detailed statistical description of Atlantic cod sound characteristics. However, later studies indicate that Atlantic cod produce sounds predominantly in the frequency range of 80–500 Hz (Fish and Mowbray 1970; Hawkins and Rasmussen 1978; Finstad and Nordeide 2004). Nordeide and Kjellsby (1999) recently recorded sounds of Atlantic cod from the spawning grounds off of Norway, and suggested that passive acoustics could be used to study spawning in the field.

The soniferous behavior of haddock is somewhat better described than that of Atlantic cod (Figure 6; Hawkins et al. 1967; Hawkins and Rasmussen 1978; Hawkins 1986). They have a similar frequency range, but can be distinguished by differences in pulse characteristics (Figure 5; Hawkins and Rasmussen 1978). Hawkins and his colleagues are currently conducting studies aimed at using passive acoustics as a tool to identify spawning habitat of haddock in European waters (Hawkins et al. 2002; Hawkins 2003). In an Arctic fjord in northern Norway, workers from the FRS Marine Laboratory, Aberdeen and the University of Tromsø have located a spawning ground of haddock. Passive listening has revealed that this species, previously thought to spawn offshore in deep water, can also form large spawning concentrations close to shore (Hawkins et al. 2002; Hawkins 2003).

Norwegian researchers at the Institute of Marine Research have pioneered the use of remote controlled platforms to obtain video and audio data on the spawning behavior of Atlantic cod and other gadids important in European fisheries (Svellingen et al. 2002).

Figure 6. Different stages of the courtship behavior of haddock, *Melanogrammus aeglefinus*, can be distinguished by differences in the pulse repetition rate of the call. The time-base, scale bar, for the calls is 50 ms. (Redrawn from Hawkins 1986).



A PRIMER ON TECHNIQUES

The success and development of passive acoustics applications to fisheries depends on high quality recording systems and analysis software. The technology should be matched to the questions being asked. For most questions, the needed technology exists for advancing the field and the main impediment is insufficient knowledge on the use of technology.

Hydrophones

Hydrophones are the most basic element of any recording system. They are underwater microphones that typically convert sound pressure into an electrical signal that can be recorded by a data acquisition system. Many commercially available hydrophones can be used for fish bioacoustics studies. When choosing a hydrophone, researchers must consider its sensitivity and frequency response characteristics to ensure it is well suited to their needs. Since most fish sounds range in frequency from 20 Hz for the largest fishes to 4 kHz for the smallest fishes, the hydrophone should cover this frequency range. The hydrophone sensitivity should be such that a loud fish sound produces a signal of about 1 V, and thus, a sensitivity range of around -160 to -170 dBV/μPa at 1 m (decibel volts/micro pascal) is good for most fisheries applications.

Data storage

Data storage devices include analog and digital tape recorders, audio video recorders (Lobel 2003), and computers with sound cards. Digital systems provide obvious advantages over analog systems in terms of greater frequency bandwidth and dynamic range, and will be the most commonly used systems in the future. Which system is chosen will depend on the recording situation. Computer systems that may be practical for recordings made in the laboratory may not be practical in a field situation, because of power, portability, and environmental issues. One important development is the use of remotely operated vehicles (ROVs), telemetry, and underwater listening stations for monitoring sound producing fishes (Mann and Lobel 1995b; Sprague and

Luczkovich 2004; Locascio and Mann 2005). These systems will be important in characterizing which species produce which sounds, especially for species that are difficult to maintain in a laboratory tank. They will also prove useful for documenting behavior of fish aggregations when multiple individuals call simultaneously.

One needs to be aware of several caveats of recording systems.

1. **Data compression:** Some recorders (such as mini disc and MP3) use data compression techniques that alter the recorded sound frequency and level. These would not be appropriate when detailed descriptions of sound characteristics are required, but could be useful for ecological monitoring of temporal and spatial patterns of well known sounds.
2. **Automatic Gain Control (AGC):** Many systems (especially many analog and digital tape recorders and video cameras) use AGC to keep the recorded volume within the same range. If a system uses AGC, it will not be possible to determine the received sound level.
3. **Bit resolution:** Systems that record with a higher bit resolution will have a larger dynamic range (the range of the quietest and loudest sounds that can be recorded).

One problem that many researchers have encountered is boat induced noise on recording systems, either through electrical noise on the boat, or the physical movement of the boat causing the hydrophone to move. Bungee cords have been successfully used to decouple boat movement and hydrophone movement, and acceleration canceling hydrophones are commercially available.

Data loggers

Acoustic data loggers are useful for recording over long periods of time in many locations simultaneously. Data loggers provide a way to gather information on the temporal distributions of sound producing fish that would not be possible otherwise without considerable investment of human resources. A good example of this are the pop-up recorders (Calupca et al. 2000). Computers are the best option for recording where continuous power is available, such as from shore or on a large boat. Commercial software (see below) exists for recording on a given duty cycle. However, continuous power is rarely available in field situations where one would like to make recordings. In these situations, low power battery operated acoustic data loggers are required.

Examples of data logger use in passive acoustics.

TOP: Autonomous underwater listening system (AULS) designed by Cliff Goudey.

MIDDLE: Commercial fishermen John and Moe Montgomery of the F/V *Chandelle* deploying an AULS on Jefferies Ledge in the Gulf of Maine as part of a cooperative study of haddock spawning.

BOTTOM: AULS deployed in the MacGregor Point coral reef in Maui as part of the Sanctuary Sounds project.

CENTER FOR FISHERIES ENGINEERING RESEARCH, MIT SEA GRANT

KATIE ANDERSON, UNIVERSITY OF MASSACHUSETTS AT AMHERST

NORM GARON, HAWAII ISLAND HUMPBACK WHALE NATIONAL MARINE SANCTUARY

To date all acoustic data loggers that have been used for passive acoustics have been engineered by individual laboratories to perform this task. These include analog tape recorders that have been modified to record on a particular duty cycle (Luczkovich et al. 2000), and digital dataloggers that have been programmed to record as desired (Mann and Lobel 1995b; Calupca et al. 2000; Sakas et al. 2005). No data loggers can be purchased and used directly without either engineering or software programming (usually both). This lack of an off -the-shelf product has greatly limited their use in passive acoustic applications to fisheries.

Telemetry

Telemetry systems broadcast a hydrophone signal to a boat or shore based receiver. They perform the same function as data loggers in allowing recordings over a large area for long periods of time. Several types of telemetry systems are available including sonobuoys (VHF), cell phone systems, and short range microwave systems. All of these systems require line of sight between the transmitter and receiver, and a relatively high level of engineering to set up and maintain. Telemetry is also capable of delivering video to document behavior during sound production (Svellingen et al. 2002). Satellite systems generally do not support the bandwidth needed for transmitting acoustic data. At this point, some amount of preprocessing would be required, so that limited data on sound characteristics (e.g., root-mean-square amplitude, frequency spectra) could be transmitted.

Hydrophone Arrays

Fixed and towed hydrophone arrays have been used for determining the locations of vocalizing whales in many different situations (e.g., Watkins and Schevill 1972; Clark 1980), but have only recently been applied to fishes (Barimo and Fine 1998; Mann and Jarvis 2004). Hydrophone arrays hold promise in answering questions about fish distributions that could not be otherwise obtained with single hydrophone recordings (D'Spain et al. 1996), but require a high level of sophistication for setting up, operating, and analyzing the data. The minimum spacing between hydrophones in an array needed for localization is calculated as the speed of sound in water (approximately 1,500 m/s) divided by the sound frequency. For example, to locate a fish calling at 1,000 Hz (e.g., silver perch), a minimum spacing of 1.5 m is required, while a spacing of 12 m is required to locate a fish calling at 125 Hz (e.g., red drum).

Signal Processing Software

Many packages are available for data acquisition and signal processing. Some such as MATLAB (Mathworks, Inc.) have a great deal of flexibility and power, but require a high level of programing knowledge. Others are targeted specifically at bioacousticians including Signal (Engineering Design), Raven (and its precursor Canary; Cornell University), SASLab Pro (Avisoft Bioacoustics), and Adobe Audition (formerly Cool Edit). The manuals to these software programs are often the clearest source of information for learning signal processing techniques and their application.

FUNDING PRIORITIES AND RESEARCH NEEDS

Research presented at an international workshop on the "Applications of Passive Acoustics to Fisheries" in April 2002 underscored the great strides that have been made in the application of passive acoustics to fisheries and related issues over the last two decades (Rountree et al. 2003a, b). The workshop was followed by a special symposium on passive acoustics applications to fisheries held at the American Fisheries Society Annual Meeting in Quebec in August 2003 and organized by Luczkovich, Mann, and Rountree that again highlighted the rapid advances in the field (Luczkovich et al. unpublished). And most significantly, important new initiatives in passive acoustics have begun in many areas of the United States. Although passive acoustics is currently underutilized as a research tool, the success of the workshop and symposium demonstrates how rapidly the field is emerging and suggests great promise for future research.

As a result of discussions and correspondences initiated at the workshop and symposium, we have prepared a comprehensive description of areas that participating scientists felt needed to be addressed to advance the field of passive acoustics in fisheries. These areas can be categorized as research, software, hardware, and education/outreach needs.

Data loggers have been used to study deep sea fishes in cooperation with commercial red crab fishermen.

TOP: Cliff Goudey demonstrates data logger to Daher Jorge of the F/V *Krystal James.*

BOTTOM: Juan Espana aboard the F/V *Hanna Boden* prepares to deploy a data logger attached to the inside of a red crab pot.

RODNEY ROUNTREE

Research Needs

Research needs can be simplistically summarized as the questions: what, when, where, and how many?

What?—What fishes and invertebrates are making sounds? To date we know of approximately 800 species of fishes worldwide that produce sounds. More soniferous species are reported on a frequent basis, but there are no current systematic efforts to catalogue soniferous fishes. The landmark studies by Marie Fish and William Mowbray (1970) ended over 30 years ago. No one has taken up the gauntlet since then. Knowledge of what produces underwater sounds is critical to the success of higher level studies. Currently the number of unidentified underwater sounds attributed to fishes is far greater than those that can be positively identified. Rountree and Goudey (unpublished) recently recorded unknown sounds on the commercial fishing grounds off the coast of Massachusetts. Even more remarkably, Rountree and Juanes (unpublished) and their students recorded many unknown sounds in areas that have been extensively studied by conventional means (e.g., Woods Hole, Massachusetts), or that are in the very heart of the industrial world (the docks on Manhattan Island, New York; Anderson et al. unpublished). How can it be that we know so little about fishes in these areas that we can not even identify some of the most frequent and widespread fish sounds? As biologists, we find the lure of the unknown so close to the doorstep to be a powerful motivator. Although some progress is being made in this area, the most pressing needs are:

1. an effort to catalogue historic records of known and unknown sounds;
2. systematic efforts to identify and validate sound sources;
3. studies to determine the correlation between sound production and specific behaviors; and
4. studies to determine under what behavioral conditions fish/invertebrates make sounds.

Efforts are now underway to digitize and catalogue sound archives from laboratories across North America and in Europe (Rountree et al. 2002; Bradbury and Bloomgarden 2003). The MaCaulay Library of the Cornell Lab of Ornithology has recently made a large collection of fish sounds from these archives available to the public online (www.birds.cornell.edu/MacaulayLibrary/). Unfortunately, many of these historic recordings are poorly documented and were made with long outdated technologies. More importantly, they are insufficient for the needs of fisheries researchers, as they are only partially complete. Many of our most important commercial fishes that are soniferous have yet to be recorded. Information on soniferous freshwater fisheries species is almost entirely lacking in North America.

To expand the catalogue of fish and invertebrate sounds, field and laboratory studies are needed to identify unknown sounds, and audition fishes and invertebrates for sound production. Systematic efforts to identify sounds in each geographic region, including estuaries and tidal fresh waters, are critical to the advancement of passive acoustics. Evidence that a particular sound is made by, and unique to, a given species is of critical importance. Lack of, or perceived lack of, such evidence is the most common criticism encountered in funding proposals.

There are two major ways to go about cataloguing fish sounds in a particular region. The first, is through the systematic auditioning of animals collected in the field, in aquaculture facilities, and in public aquaria. Fish and Mowbray (1970) used this method to study the sounds of over 200 species of fishes. One major problem with such efforts is that failure to record fish sounds during auditions does not indicate the species is not soniferous, because soniferous behavior is often controlled by sex, age, maturation stage, and behavior. Sometimes fish are not physiologically ready for sound production outside of the spawning season. Additionally, auditioning programs like that carried out by Fish and Mowbray (1970) are sometime criticized as producing artificial sounds through electrical stimulation; however, we note that at least 47 of 150 species regarded as soniferous by Fish and Mowbray (1970) produced sounds spontaneously.

The second major method of cataloguing fish sounds is to conduct field surveys to identify temporal and spatial patterns of sound production. Once unknown sounds are identified and their temporal and spatial patterns described, research can be conducted to determine the identity of the fish, including the auditioning of fish captured in the appropriate place and time. The advantage of this approach is that the field of potential sound producers is narrowed down, and the researcher knows that the target species is at least physically capable of sound production at the time of auditioning. However, efforts by researchers to catalogue underwater sounds in freshwater and marine habitats are hampered by the failure of funding agencies to recognize the importance of such studies. Data on unidentified fish sounds are especially difficult to publish, even when extensive observations are available. We suggest that such studies are valuable in their own right as they provide the basic information necessary to systematically survey soniferous fishes by providing data on when and where soniferous activity occurs. Armed with such data, scientists can devise studies to determine the identity of the sound producers. The only alternative is to simply blindly capture fishes and audition them for sound production. We liken the denial of the usefulness of catalogues of unidentified fish sounds to the absurd notion that collections of ichthyoplankton for which identifications are not currently available are not useful.

Incidental sounds made by fishes can be just as important as soniferous behavior. For example, feeding sounds can be used to determine foraging times, locations, and consumption rates (Sartori and Bright 1973; Mallekh et al. 2003; Anderson et al. unpublished).

Often investigators have used terms such as "grunts," "knocks," "snaps," "pops," "staccato," "drumming," "humming," "rumbles," "percolating," "purring," etc., to describe the sounds heard; the names often being onomatopoeic. Standardizing these sound descriptions would allow rapid communication between biologists and other observers (Anderson et al. unpublished).

When?—Temporal patterns in sound occurrence are needed for two main reasons. First, knowledge of when fishes and invertebrates make sounds leads to knowledge about their biology and ecology. Second, we need this information to effectively use passive acoustics as a tool to locate fish, to identify their habitat requirements, and to conduct presence/absence and abundance surveys (see below). Some of the most important needs here are:

1. *Studies to determine the relationship of sound production to fish size*. Early studies have shown that sound characteristics sometimes change with fish size (e.g., dominant frequency) and hence the relationship between fish size and sound characteristics may be used to determine length frequency data for soniferous fishes (Fish and Mowbray 1970; Lobel and Mann 1995; Connaughton et al. 2000).
2. *Studies to determine the relationship of sound production to sex and maturity stage* (e.g., Connaughton and Taylor 1995). Do both male and females in a population produce sounds? Are the sounds the same or different? Do immature fish make sounds? Are the sounds made by immature and mature individuals different? The answers to these questions can provide scientists with valuable information on the temporal and spatial distribution patterns of fishes by sex and maturity stages. They can also provide data useful in studies of reproductive ecology and studies specifically important for fisheries assessment, such as the quantification of fish fecundity.
3. *Quantification of daily and seasonal patterns in sound production* (Breder 1968; Fine et al. 1977a; Connaughton and Taylor 1994). If we know when a fish produces sounds then studies of the daily and seasonal patterns of that soniferous activity can be correlated with daily and seasonal patterns of that specific behavior. For example, if it is known that a particular sound is only produced when a fish is spawning, then the determination of the daily pattern in soniferous activity can be used to infer the daily pattern of spawning (i.e., to determine what time of day the fish spawns). Similarly, seasonal patterns in soniferous activity can provide an index of the spawning season period (Figure 3).

Where?—Identifying where a fish occurs is one of the most fundamentally important topics in fish ecology and fisheries management. It is the first step towards identifying essential fish habitat (EFH) as mandated of fisheries managers by the reauthorization of the Magnuson Stevens Fishery Conservation and Management Act (Oct. 1996). Essential Fish Habitats are defined as "those waters and substrate necessary for fish for spawning, feeding or growth to maturity." The lowest level criterion for identification of EFH is simply presence/absence. At the minimum, passive acoustics surveys can be used to identify the presence of soniferous fishes in habitats. If the behavior associated with a particular fish sound is known, then higher levels of identification, such as the identification of spawning habitat, can be achieved.

To accurately associate underwater sounds with habitats, it is necessary to know the range at which the sound can be detected by the survey instruments. A lack of quantification of sound source detection ranges is the second most commonly cited criticism encountered in funding proposals. To determine sound source detection ranges several types of studies are needed. (a) How loud is it?—Quantification of sound source levels for a given species/stage/environment is the first step. (b) Sound Propagation—how far does sound travel under a given set of environmental conditions. This is the study of tomography. Studies in shallow water are especially needed. (c) Fish Shoals-studies are needed to examine how the multiple sound production of many fish in a shoal combine. How do sound pressure levels vary with shoal size and distance from the source?

Passive acoustic mapping of the spatial distribution of sounds is one of the most important potential products of passive acoustics technology. Studies to map the distribution of fish sounds, and hence the distribution of soniferous fishes and their essential fish habitat are strongly needed. Passive acoustics offers many advantages over traditional methods of mapping fish distribution. It is non-destructive, non invasive, and relatively inexpensive over the long run compared to traditional methods such as trawl surveys. If the "what" and "when" are known, then passive acoustics can be used to map EFH based on presence/absence for soniferous species. The "when" is important because spatial surveys with passive acoustics are only valid if conducted during the window of time when fish are soniferous. In many cases, fishes restrict their soniferous activity predominately to narrow windows of time. For example, spotted seatrout (*Cynoscion nebulosus*) calls predominantly from just before sunset into the early evening (Mok and Gilmore 1983), so attempts to use passive acoustics to map their distribution would have to be conducted within that time frame.

How many?—Quantification of fish abundance at a location and time is an important objective of many fisheries studies and monitoring programs. Once the what, when, and where questions have been addressed, additional studies can quantify abundance through passive acoustics techniques. The two most important study areas are: (1) correlation between the "amount" of sound production and the abundance of fish, and (2) determination of the proportion of fish that are soniferous at a given place and time.

In the simplest situation, the number of fish calls can be counted and correlated to the true amount of fish present. This requires the ability to distinguish individual calls. More rigorously it would also require the ability to distinguish individuals that call repeatedly from those that don't. Often, however, fish and calls are so numerous that individual calls cannot be distinguished. In these cases, studies are needed to determine the relationship between sound pressure level and fish abundance. For example, Luczkovich et al. (1999) showed a relationship between sound pressure level and egg abundance, and indicated that a relationship should exist between sound production and spawning stock size.

As mentioned above, soniferous behavior in many fishes is sex dependent. Often, only the males call. In addition, in some cases soniferous activity may be related to size and maturation stage, so that at a given place and time, the number of fish calling is a function of the size and maturation stage distribution of the population. However, individual fishes fail to produce sounds in a given situation for many reasons. Studies are needed to allow researchers to estimate the proportion of soniferous and non soniferous fishes over a given time period.

SOFTWARE NEEDS

To carry out the research priorities listed above, software must be developed in several areas. Programs should be packaged to allow biologists to process sound data to the fullest extent possible.

Automatic processing of sound recordings—The passive acoustics studies described above can generate large amounts of acoustic data (often thousands of hours of recordings) that are laborious to process fully to obtain the basic biological data sought (e.g., temporal activity patterns, spatial distribution, etc.). We suggest that software designed to address the following processing needs would greatly enhance the utility of passive acoustics to fisheries.

1. Automatic signal detection software used to detect the call of a given fish species amid long time series of sound recordings (thousands of hours) with multiple sound sources and high levels of "noise" is essential.
2. Temporal pattern analysis software to track the temporal occurrence patterns of hundreds to thousands of detected calls within long time series is critical to the efficient determination of daily and seasonal patterns in sound production.
3. Call characterization software to speed up the process of measuring call characteristics such as duration, pulse rate, pulse repetition, fundamental frequency, pulse width, sound level, etc., in large numbers of calls would increase statistical power in studies of location, behavior, and environmental effects on call characteristics.
4. Call classification software to aid in the identification of a new unknown sound through comparison of its call characteristics with the characteristics of calls contained in standard reference libraries of known and unknown sounds.

Localization of sound sources—Software and hardware developments are needed to simplify the localization of sound sources received by multiple hydrophone arrays. Automatic signal detection and classification software are important prerequisites. Currently localization is a laborious process of determining the starting points of the same sound received among multiple hydrophones and then using various statistical techniques such as time delay differences to triangulate on the calls. To develop the ability to produce real time GIS plots of soniferous fishes overlain on environmental parameters, these steps must be automated. One important product of localization, other than habitat association mapping, is the determination of true sound source levels (see discussion "Where?") under varying environmental conditions (e.g., Sprague and Luczkovich 2004).

HARDWARE NEEDS

Acoustic hardware technology is rapidly evolving; however, there are several specific needs that would enhance the development of passive acoustics in fisheries.

Data storage—Low cost, high capacity digital recorders are needed to allow field sampling at the rates and intensities necessary to study temporal and spatial patterns of sound production. Devices that can be programmed to record at varying sampling rates and time settings, including continuous and time lapse would be particularly valuable. Existing low-cost recorders developed by the music industry are rapidly becoming scarce due to the industry shift from wave file storage formats to MP3 file format storage (MP3 is less desirable because it compresses and distorts the sounds).

Coupled "visualization" technologies—To validate the identification of sound sources in the field, devices that couple passive acoustics with other technologies that can be used to identify a fish are needed. Coupled acoustic optic systems include devices that are capable of recording both underwater video and acoustic data are among the simplest to use and are highly reliable for identification (Lobel 2001). Amazingly, most underwater video technology marketed to researchers lacks acoustic recording capabilities. In our opinion this is entirely due to a failure of the manufacturers to recognize the market potential of such devices, rather than to technical issues. Another difficulty of acoustic-optic systems is the need to use artificial light sources for the video recording, and resulting dramatic change in fish behavior and probability of detection. In addition, artificial light provides a limited range of visibility. Infrared lights are only effective for a few feet, and even state-of-the-art low light level cameras are ineffective at night even at moderate depths. Finally studies are needed to understand the effect of light of various wavelengths and intensities on fish behavior to develop the optimum optic system.

Coupling passive acoustics with other visualization technologies such as active acoustics and laser line-scanning is also promising. Active acoustic technology has the advantage of providing relatively long range observation capabilities compared with video, but requires the input of acoustic energy into the environment. Laser line-scanning can provide high resolution imaging at short ranges (<10 m; Carey et al. 2003), but is currently relatively expensive.

Portable passive acoustic survey devices—Small, self-contained packages of acoustic gear would allow mobile recording of acoustic and video during shore or small boat based studies. Currently investigators have to purchase separate components and assemble them into a package themselves. Because components were not manufactured to work together, numerous in-line adapters often must be used to transfer the acoustic signal among components. Researchers need to be able to drop a hydrophone over the side of a small boat or dock, together with a small underwater video camera, and be able to simultaneously record and monitor video and acoustic data. Ideally, the audio and video data would be automatically converted to digital form for storage. Availability of low cost devices of this type would facilitate the feasibility of small-scale research projects for a larger scientific community.

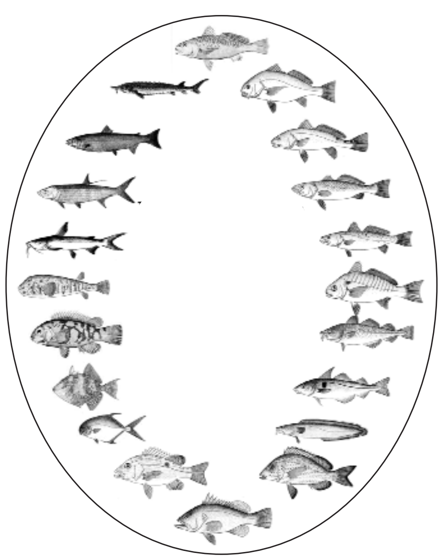
EDUCATION AND OUTREACH

Most fish bioacousticians are biologists first and engineers second. They have arrived at fish bioacoustics because it is a powerful tool for studying fishes. This means that engineering and signal processing principles must be learned on the job. Unfortunately, there is no one good source of information about recording and signal processing that is accessible and practical for the fish bioacoustician. This gap can be bridged both by producing these targeted materials, conducting training workshops, and by attracting engineers with a biological interest to the field. The workshop participants identified a strong need to educate scientists, managers, and the public on the uses of passive acoustics. Some specific needs include:

1. Manuals and other literature intended to introduce biologists to the field;
2. Workshops that bring biologists, acousticians, and engineers together are vital as they stimulate the transfer of knowledge and ideas among the disciplines;
3. Development of passive acoustic training centers for researchers and students; and
4. Incorporation of passive acoustics into fisheries curricula.

Passive acoustics technologies provide a unique public outreach potential. Scientists and laymen alike are often fascinated by the phenomenon of underwater sounds. Passive acoustics technologies are amenable to multimedia display via the Internet and have great potential as public education and outreach tools.

Selected examples of soniferous fishes that support important recreational or commercial fisheries (fish sketches courtesy of NOAA/NMFS Northeast Fisheries Science Center).



ACKNOWLEDGMENTS

We wish to acknowledge the contribution of numerous participants in the Passive Acoustics Workshop and AFS Symposium. Numerous discussions at these meetings, and in subsequent correspondences since, were invaluable to the authors in the development of this manuscript. The workshop and publication of the workshop proceedings received major funding from MIT Sea Grant, the Office of Naval Research, and from the Northeast Great Lakes Center of the National Undersea Research Program. Travel for some workshop participants was funded in whole, or in part by: Connecticut Sea Grant, Florida Sea Grant, Hawaii Sea Grant, Louisiana Sea Grant, North Carolina Sea Grant, the South Carolina Sea Grant Consortium, Texas Sea Grant, and the Woods Hole Sea Grant Programs. This is SMAST Contribution No. 06-0601.

REFERENCES

Almada, V. C., M. C. P. Amorin, E. Pereira, F. Almada, R. Matos and **R. Godinho.** 1996. Agonistic behaviour and sound production in *Gaidropsarus mediterraneus* (Gadidae). Journal of Fish Biology 49:363-366.

Alshuth, S., and **R. G. Gilmore.** 1993. Egg identification, early larval development and ecology of the spotted seatrout, *Cynoscion nebulosus* C. (Pisces: Sciaenidae). International Council for the Exploration of the Sea, Conference Manuscript 1993/G 28.

_____. 1994. Salinity and temperature tolerance limits for larval spotted seatrout, *Cynoscion nebulosus* C. (Pisces: Sciaenidae). International Council for the Exploration of the Sea, Conference Manuscript 1994/L:17.

_____. 1995. Egg and early larval characteristics of *Pogonias cromis*, *Bairdiella chrysoura*, *Cynoscion nebulosus* (Pisces: Sciaenidae), from the Indian River Lagoon, Florida. International Council for the Exploration of the Sea, Conference Manuscript 1995/L:17.

Aristotle. Historia Animalism, IV, 9. Trans. by D. D'A.Thompson. 1910. Clarendon Press, Oxford.

Barimo, J. F., and **M. L. Fine.** 1998. Relationship of swim-bladder shape to the directionality pattern of underwater sound in the oyster toadfish. Canadian Journal of Zoology 76:134-143.

Berk, I. M. 1998. Sound production by white shrimp (*Penaeus setiferus*), analysis of another crustacean-like sound from the Gulf of Mexico, and applications for passive sonar in the shrimp industry. Journal of Shellfish Research 17:1497-1500.

Bradbury, J. W., and **C. A. Bloomgarden.** 2003. Creating a web-based library of underwater biological sounds. Pages 103-106 *in* R. A. Rountree, C. Goudey, and T. Hawkins, eds. Listening to fish: proceedings of the international workshop on the applications of passive acoustics to fisheries. 8-10 April 2002. Dedham, MA. MIT Sea Grant Technical Report.

Brawn, V. M. 1961a. Aggressive behaviour in the cod (*Gadus callarias* L.). Behaviour 18:107-147.

_____. 1961b. Reproductive behaviour of the cod (*Gadus callarias* L). Behaviour 18:177-198.

_____. 1961c. Sound production by the cod (*Gadus callarias L.*). Behaviour 18:239-245.

Breder, C. M., Jr. 1968. Seasonal and diurnal occurrences of fish sounds in a small Florida Bay. Bulletin of the American Museum of Natural History 138:278-329.

Calupca, T. A., K. M. Fristrup and **C. W. Clark.** 2000. A compact digital recording system for autonomous bioacoustic monitoring. Journal of the Acoustic Society 108:2582.

Carey, D. A., D. C. Rhoads and **B. Hecker.** 2003. Use of laser line scan for assessment of response of benthic habitats and demersal fish to seafloor disturbance. Journal of Experimental Marine Biology and Ecology 285-286:435-452.

Chao, L. N. 1978. A basis for classifying western Atlantic sciaenidae (Teleostei: Perciformes). NOAA Technical Report NMFS Circular 415.

Chu, Y. T., Y. L. Lo, and **H. L. Wu.** 1963. A study on the classification of the sciaenoid fishes of China, with description of new genera and species. 1972 Reprint, Antiquariaat Junk, Netherlands.

Clark, C. W. 1980. A real-time direction finding device for determining the bearing to the underwater sounds of southern right whales, *Eubalaena australis*. Journal of the Acoustical Society of America 68(2):508-511.

Connaughton, M. A., and **M. H. Taylor.** 1994. Seasonal cycles in the sonic muscles of the weakfish, *Cynoscion regalis*. Fishery Bulletin 92:697-703.

_____. 1995. Seasonal and daily cycles in sound production associated with spawning in the weakfish, *Cynoscion regalis*. Environmental Biology of Fishes 42:233-240.

Connaughton, M. A., M. H. Taylor, and **M. L. Fine.** 2000. Effects of fish size and temperature on weakfish disturbance calls: implications for the mechanism of sound generation. Journal of Experimental Biology 203:1503-1512.

Cousteau, J. Y., and **F. Dumas.** 1953. The silent world. Perennial Library, Harper and Row, Publishers, New York.

Darwin, C. 1874. The descent of man. 2nd edition. H. H. Caldwell, New York.

Dijkgraaf, S. 1947. Ein tone erzeugender fisch in Neapler Aquarium. Experimenta 3:494.

_____. 1949. Untersuchungen uber die funktionen des ohrlabyrinths bei meeresfischen. Physiologia Comparata Oecoloia 2:81-106.

Dobrin, M. B. 1947. Measurements of underwater noise produced by marine life. Science 105:19-23.

D'Spain, G. L., W. A. Kuperman, L. P. Berger, and **W. S. Hodgkiss.** 1996. Geoacoustic inversion using fish sounds. The Journal of the Acoustical Society of America 100:2665.

Dufossé, A. 1874a. Rescherches sur les bruts et les sons expressifs que font entendre les poissons d'Europe et sur les organes producteurs de ces phenomenes acoustiques ainsi que sur les appareils de l'audition de plusieurs de ces animaux. Annales des Sciences Naturelles. Zoologie et Biologie Animale Series 5, Vol. 19.

_____. 1874b. Rescherches sur les bruts et les sons expressifs que font entendre les poissons d'Europe et sur les organes producteurs de ces phenomenes acoustiques ainsi que sur les appareils de l'audition de plusieurs de ces animaux. Annales des Sciences Naturelles. Zoologie et Biologie Animale Series 5, Vol. 20.

Engen, F., and **I. Folstad.** 1999. Cod courtship song: a song at the expense of dance? Canadian Journal of Zoology 77(4):542 550.

Fine, M. L., H. E. Winn, L. Joest and **P. J. Perkins.** 1977a. Temporal aspects of calling behavior in the oyster toadfish, *Opsanus tau*. Fishery Bulletin 75:871-874.

Fine, M. L., H. E. Winn and **B. Olla.** 1977b. Communication in fishes. Pages 472-518 *in* T. Sebok, ed. How animals communicate. Indiana University Press, Bloomington.

Finstad, J. L., and **J. T. Nordeide.** 2004. Acoustic repertoire of spawning cod, *Gadus morhua*. Environmental Biology of Fishes 70:427-433.

Fish, J. F. 1966. Sound production in the American lobster *Homarus americanus*. Crustaceana 11:105.

Fish, M. P. 1964. Biological sources of sustained ambient sea noise. Pages 175-194 *in* W. N. Tavolga, ed. Marine bio-acoustics. Pergamon Press, NY.

Fish, M. P., A. S. Kelsey, Jr., and **W. H. Mowbray.** 1952. Studies on the production of underwater sound by North Atlantic coastal fishes. Journal of Marine Research 11:180 193.

Fish, M. P., and **W. H. Mowbray.** 1970. Sounds of western North Atlantic fishes. Johns Hopkins Press, Baltimore, Maryland.

Gilmore, R. G, Jr. 2002. Sound production and communication in the spotted seatrout. Pages 177-195 *in* S. A. Bortone, ed. Biology of the spotted seatrout, CRC Press, Boca Raton, Florida.

Goode, G. B. 1887. American fishes: a popular treatise upon the game and food fishes of North America with special reference to habits and methods of capture. L. C. Page Co., Boston.

Hawkins, A. D. 1986. Underwater sound and fish behaviour. Pages 114-151 *in* T. J. Pitcher, ed. The behaviour of teleost fishes. Groom Hellm, London.

______. 2003. The use of passive acoustics to identify a haddock spawning area. Pages 49-53 *in* R. A. Rountree, C. Goudey, and T. Hawkins, eds. Listening to fish: proceedings of the international workshop on the applications of passive acoustics to fisheries. 8-10 April 2002. Dedham, MA. MIT Sea Grant Technical Report MITSG 03-2.

Hawkins, A. D., L. Casaretto, M. Picciulin, and **K. Olsen.** 2002. Locating spawning haddock by means of sound. Bioacoustics 12:284-286.

Hawkins, A. D., C. J. Chapman, and **D. J. Symonds.** 1967. Spawning of haddock in captivity. Nature 215:923 925.

Hawkins, A. D., and **K. J. Rasmussen.** 1978. The calls of gadoid fish. Journal of the Marine Biological Association of the United Kingdom 58:891 911.

Henninger, H. P., and **W. H. III., Watson.** 2005. Mechanisms underlying the production of carapace vibrations and associated waterborne sounds in the American lobster, *Homarus americanus*. The Journal of Experimental Biology 208:3421-3429.

Iversen, R. T. B., P. J. Perkins, and **R. D. Dionne.** 1963. An indication of underwater sound production by squid. Nature 199(4890):250-251.

Kaatz, I. M. 2002. Multiple sound producing mechanisms in teleost fishes and hypotheses regarding their behavioural significance. Bioacoustics 12:230-233.

Knudsen, V. O., R. S. Alfred, and **J. W. Emling.** 1948. Underwater ambient noise. Journal of Marine Research 7:410-429.

Lobel, P. S. 1998. Possible species specific courtship sounds by two sympatric cichlid fishes in Lake Malawi, Africa. Environmental Biology of Fishes 52:443-452.

______. 2001. Fish bioacoustics and behavior: passive acoustic detection and the application of a closed-circuit rebreather for field study. Marine Technology Journal 35(2):2-19.

______. 2002. Diversity of fish spawning sounds and the application of passive acoustic monitoring. Bioacoustics 12:286-289.

______. 2003. Synchronized underwater audio-video recording. Pages 136-139 *in* R. A. Rountree, C. Goudey, and T. Hawkins, eds. Listening to fish: proceedings of the international workshop on the applications of passive acoustics to fisheries. 8-10 April 2002. Dedham, MA. MIT Sea Grant Technical Report MITSG 03-2.

Lobel, P. S., and **D. A. Mann.** 1995. Spawning sounds of the damselfish, *Dascyllus albisella* (Pomacentridae), and relationship to male size. Bioacoustics 6(3):187-198.

Locascio, J. V., and D. A. Mann. 2005. Effects of Hurricane Charley on fish chorusing. Proceedings of the Royal Society of London Biological Letters 1:362 365.

Luczkovich, J. J., M. W. Sprague, S. E. Johnson, and R. C. Pullinger. 1999. Delimiting spawning areas of weakfish *Cynoscion regalis* (Family Sciaenidae) in Pamlico Sound, North Carolina using passive hydroacoustic surveys. Bioacoustics 10:143-160.

Luczkovich, J. J., J. D. Hall, III., M. Hutchinson, T. Jenkins, S. E. Johnson, R. C. Pullinger, and **M. W. Sprague.** 2000. Sounds of sex and death in the sea: bottlenose dolphin whistles suppress mating choruses of silver perch. Bioacoustics 10:323-334.

Mallekh, R., J. P. Lagardere, J. P. Eneau, and **C. Cloutour.** 2003. An acoustic detector of turbot feeding activity. Aquaculture 221:481-489.

Mann, D. A., and **S. M. Jarvis.** 2004. Potential sound production by a deep-sea fish. Journal of the Acoustical Society of America 115(5):2331-2333.

Mann, D. A., and **P. S. Lobel.** 1995a. Passive acoustic detection of fish sound production associated with courtship and spawning. Bulletin of Marine Science 57(3):705-706.

_____. 1995b. Passive acoustic detection of sounds produced by the damselfish, *Dascyllus albisella* (Pomacentridae). Bioacoustics 6:199-213.

Mok, H. K., and **R. G. Gilmore.** 1983. Analysis of sound production in estuarine aggregations of *Pogonias cromis*, *Bairdiella chrysoura*, and *Cynoscion nebulosus* (Sciaenidae). Bulletin of the Institute of Zoology, Academia Sinica 22:157-186.

Moulton, J. M. 1957. Sound production in the spiny lobster *Panulirus argus* (Latreille). Biological Bulletin 113:286-295.

Myrberg, A. A., and **R. J. Riggio.** 1985. Acoustically mediated individual recognition by a coral reef fish (*Pomacentrus partitus*). Animal Behavior 33:411-416.

Nordeide, J. T., and **I. Folstad.** 2000. Is cod lekking or a promiscuous group spawner? Fish and Fisheries 1:90-93.

Nordeide, J. T., and E. Kjellsby. 1999. Sound from spawning cod (*Gadus morhua* L.) at the spawning grounds. ICES Journal of Marine Science 56:326-332.

Okumura, T., T. Akamatsu, and **H. Y. Yan.** 2002. Analyses of small tank acoustics: empirical and theoretical approaches. Bioacoustics 12:330-332.

Patek, S. N. 2002. Squeaking with a sliding joint: mechanisms and motor control of sound production in palinurid lobsters. Journal of Experimental Biology 205:2375-2385.

Popper, A. N. 2003. Effects of anthropogenic sounds on fishes. Fisheries 28(10):24-31.

Protasov, V. R., and **M. I. Aronov.** 1960. On the biological significance of sounds of certain Black Sea fish. (In Russian). Biofizika 5:750 752.

Qi, M., S. Zhang, and **Z. Song.** 1984. Studies on the aggregate sound production of most species of croaker (sciaenoid fishes) in Bohai Sea, Yellow Sea and East China Sea. Studia Marina Sinica, Peking 21:253-264.

Rountree, R. A., P. J. Perkins, R. D. Kenney, and **K. R. Hinga.** 2002. Sounds of western North Atlantic fishes: data rescue. Bioacoustics 12(2/3):242 244.

Rountree, R. A., C. Goudey, T. Hawkins, J. Luczkovich and **D. Mann.** 2003a. Listening to fish: passive acoustic applications in marine fisheries. Sea Grant Digital Oceans. Massachusetts Institute of Technology Sea Grant College Program. MITSG 0301. Available at: http://web.mit.edu/seagrant/aqua/cfer/acoustics/PD9x9FINAL.pdf

Rountree, R. A., C. Goudey, and **T. Hawkins.** Editors. 2003b. Listening to fish: proceedings of the international workshop on the applications of passive acoustics to fisheries. 8-10 April 2002. Dedham, MA. MIT Sea Grant Technical Report MITSG 03-2. Available at: http://web.mit.edu/seagrant/aqua/cfer/acoustics/PAprocBrFINAL.pdf

Rowe, S., and **J. A. Hutchings.** 2004. The function of sound production by Atlantic cod as inferred from patterns of variation in drumming muscle mass. Canadian Journal of Zoology 82:1391-1398.

Sakas, C. J., C. Goudey and **R. A. Rountree.** 2005. Sanctuary sounds monitoring underwater sounds in the National Marine Sanctuaries. Oceans 2005 Marine Technology Society/Institute of Electrical and Electronics Engineers, Inc. Conference Proceedings. MTS.

Sartori, J. D., and **T. J. Bright.** 1973. Hydrophonic study of the feeding activities of certain Bahamian parrot fishes, family Scaridae. Hydro-Laboratory Journal 2:25-56.

Saucier, M. H., and **D. M. Baltz.** 1992. Hydrophone identification of spawning sites of spotted seatrout *Cynoscion nebulosus* (Ostichthys: Sciaenidae) near Charleston, South Carolina. Northeast Gulf Science 12(2):141-145.

_____. 1993. Spawning site selection by spotted seatrout, *Cynoscion nebulosus*, and black drum, Pogonias cromis, in Louisiana. Environmental Biology of Fishes 36:257-272.

Sprague, M. W., and **J. J. Luczkovich.** 2004. Measurement of an individual silver perch *Bairdiella chrysoura* sound pressure level in a field recording. Journal of the Acoustic Society of America 116(15):3186-3191.

Svellingen, I., B. Totland and **J. T. Oevredal.** 2002. A remote-controlled instrument platform for fish behaviour studies and sound monitoring. Bioacoustics 12:335-336.

Takemura, A., T. Takita, and **K. Mizue.** 1978. Studies on the underwater sound VII: Underwater calls of the Japanese marine drum fishes (Sciaenidae). Bulletin of the Japanese Society of Scientific Fisheries 44:121-125.

Tavolga, W. N. 1960. Sound production and underwater communication in fishes. Pages 93-136 *in* W. E. Lanyon and W. N. Tavolga, eds. Animal sounds and communication. American Institute of Biological Sciences, Washington, D.C.

________. 1980. Hearing and sound production in fishes in relation to fisheries management. Pages 102-123 *in* J. E. Bardach, J. J. Magnuson, R. C. May, and J. M. Reinhart, eds. Fish behavior and its use in the capture and culture of fishes. International Center for Living Aquatic Resources Management Conference Proceedings 5, Manila, Philippines.

Templeman,W., and **V. M. Hodder.** 1958. Variation with fish length, sex, stage of sexual maturity, and season in the appearance and volume of the drumming muscles of the swimbladder in the haddock, *Melanogrammus aeglefinus* L. Journal of the Fisheries Research Board of Canada 15:355-90.

Templeman, W., V. M. Hodder, and **R. Wells.** 1978. Sexual maturity and spawning in haddock, *Melanogrammus aeglefinus*, of the southern Grand Bank. The International Commission for the Northwest Atlantic Fisheries Research Bulletin 13:53-65.

Watkins, W. A., and **W. E. Schevill.** 1972. Sound source location by arrival-times on a non-ridid three-dimensional hydrophone array. Deep-Sea Research 19:691-706.

Wood, M., L. Casaretto, G. Horgan, and **A. D. Hawkins.** 2002. Discriminating between fish sounds a wavlet approach. Bioacoustics 12:337-339.