REMOTE SENSING OF FISH USING PASSIVE ACOUSTIC MONITORING

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Introduction

Lower a hydrophone into nearly any coastal area at dusk or night and you will be immersed in a world of clicks, knocks, and hums. After several seconds of listening and internally classifying sounds, you'll want to ask, "What made that sound?" While we are mostly familiar with the communication and echolocation sounds of marine mammals, thousands of other animals produce sound.

> *"Despite all of the research in fish bioacoustics, the answer to the question, 'What is making that sound?' is typically, 'We don't know'."*

Fishes are likely the largest source of biological sound in the coastal oceans. Partly this is due to some species being very loud, and partly this is due to their being so many fish producing sound. It seems that about every decade the public and press rediscover the fact that many fishes produce sounds. The town of Cape Coral, Florida was about to undertake an engineering study to discover source of mysterious late-night sounds, until it was determined that black drum were the source of the booms (Locascio and Mann, 2011). The black drum sounds were so loud, that they could be heard inside the houses adjacent to seawater canals. The midshipman toadfish in Sausalito, California has been the subject of many humorous news stories, as their incessant humming kept houseboat dwellers awake at night wondering whether there were nuclear submarines out back.

Fish bioacoustics

Some sound producing fishes have been known for millennia, and their common names reflect their sound producing nature. The fish family Sciaenidae is more commonly known as the croakers and drums. If you pick up a croaker, you will get sound.

Fish produce sounds by a variety of mechanisms. Many of the loudest species, such as the croakers and drums, have specialized muscles located on or next to the gas filled swimbladder. Other species, such as the catfishes, can also produce sounds by stridulating bones (Parmentier *et al.*, 2010). Clownfish, made popular by Disney's movie *Finding Nemo*, produce pulsed sounds by clapping their jaws together using a specialized sonic ligament (Parmentier *et al.*, 2007).

The acoustic characteristics of fish sounds are directly tied to the mechanisms of sound production. Toadfish twitch their sonic muscles to drive the swimbladder to produce sound. The swimbladder does not act as a resonator in these species; it is highly damped (Fine *et al.*, 2009). Thus, the fundamental frequency of the toadfish boatwhistle sound reflects the muscle contraction rate. In these species, the frequency of the sound can change seasonally as the water warms, allowing faster muscle contraction rates (Fine, 1978). Fish sounds are generally below 1 kHz, with some large fishes like the goliath grouper producing sounds as low as 60 Hz (Mann *et al.*, 2009). This frequency range generally matches the hearing range of fishes, which is best at low frequencies. In some cases, like the toadfish boatwhistle, harmonic frequency components of the sound may exceed their range of best hearing.

Fish sounds are stereotypical, like insect and frog sounds. While there is some inter-individual variation, it is small compared to variation between species. Still, different species in the same family often produce similar sounds. Many toadfish produce the distinctive boatwhistle call, but the contraction rate and number of elements varies between species (Tavolga, 1958; Amorim *et al.*, 2011). The stereotypical nature of fish sounds makes it relatively easy to identify which species made which sound, once the sound has been characterized. (See Figs. 1 and 2)

Sound production is by no means limited to marine fishes. Sound production by freshwater fishes is well described (e.g., sculpin: Kierl and Johnston, 2010; cichlids: Lobel, 1998;

Fig. 1. William Mowbray in an acoustic recording van used to record fish sounds. These studies were compiled into the only published compendium of fish sounds (Fish and Mowbray, 1970). Photo used with permission of T. Mowbray.

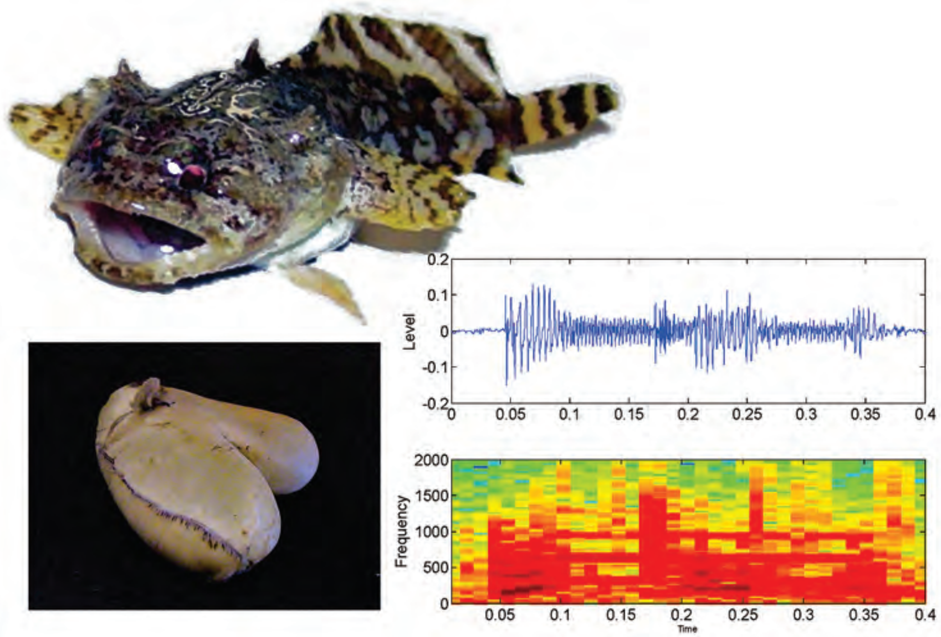


Fig. 2. The gulf toadfish swimbladder is lined with sonic muscles, which are the fastest known contracting vertebrate muscles. The oscillogram and spectrogram show field recordings from the Gulf of Mexico. Each pulse in the oscillogram corresponds to a sonic muscle contraction. (toadfish photo: USGS).

Amorim *et al.*, 2008; gobies: Lugli and Fine, 2003). Yet certain areas with high fish diversity, like tropical rivers, remain little studied. Interestingly, many invasive species, such as the walking catfish, likely produce sounds, and passive acoustics may provide a method to study their distribution.

Pioneering efforts by William Mowbray and Marie Poland Fish led to the publication of the only text devoted to characterizing fish sounds (Fish and Mowbray, 1970). They produced a compendium of fish sounds by collecting species and placing them in tanks to record the sounds they made. The original tape recordings from the University of Rhode Island have been recovered by Rodney Rountree and many are now available online at FishBase and the MacCauley Library at Cornell University.

For many species, early studies resorted to handling the fish to get them to produce sounds. While this technique identifies fishes that are capable of producing sounds, it may not reveal their full repertoire and will overlook species that don't produce sounds when handled. Underwater video cameras linked to hydrophones have been essential for documenting sound production associated with courtship and spawning in many species such as damselfish, hamletfish, and groupers. These tools have enabled us to unravel the full repertoire of fish sounds with recordings made in natural situations, where fish are more likely to engage in aggressive and courtship interactions. For example, the recordings of red hind grouper by Fish and Mowbray showed they would produce a single knock when handled. When recordings were made on a spawning aggregation site, red hind were found to produce longer distinctive sounds consisting of repetitive pulses that graded into hums (Mann *et al.*, 2010) (See Fig. 3).

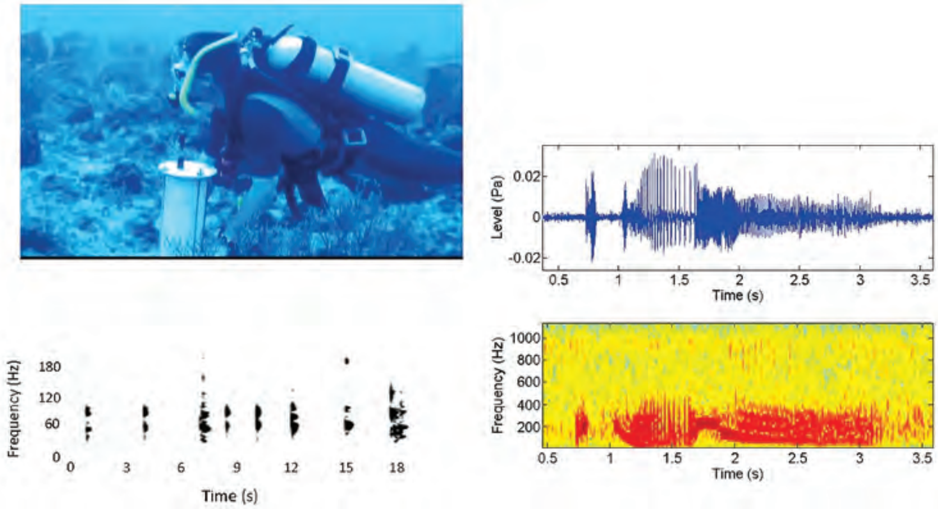


Fig. 3. Red hind grouper single pulse sound recorded when handling the fish (left) (Fish and Mowbray, 1970). A diver deploys a passive acoustic recorder at Mona Island, Puerto Rico to record red hind sounds. Sound recorded from a naturally behaving red hind showing a complex pulse structure (right).

Many commercially important fishes are from families that are prolific sound-producers. The cods and haddocks (Gadidae) are among the most important marine food fish species. Many of these species have been shown to produce sounds associated with courtship and spawning. The haddock produce relatively simple repeated pulsed sounds. The pulse rate increases as the reproductive sequence moves from courtship through reproduction (Hawkins and Amorim, 2000). Thus, passive acoustic eavesdropping on haddock would provide a means to locate spawning sites.

The great unknowns

Despite all of the research in fish bioacoustics, the answer to the question, "What is making that sound?" is typically, "We don't know." Walleye pollock, a member of the cod family, comprises the largest single-species finfish fishery in the United States with catches of nearly 1 million tons a year. Sound production by walleye pollock has yet to be investigated. Other families which are well known sound producers have only had the sounds of a few species identified. For instance, worldwide there are about 275 species of croaker and drums. The sounds of only about 10 species have been recorded and identified.

The deep-sea is the largest ecosystem by area in the world. Hundreds of deep-sea fish species have sonic musculature, including the grenadiers, cusk eels, deep-sea cods, and roughies (Marshall, 1967). Still, no deep-sea fish species sound has been identified. The only published report is of a fish-like sound recorded on the Navy Atlantic Undersea Test and Evaluation Center (AUTEC) hydrophone array in the Tongue of the Ocean, Bahamas (Mann and Jarvis, 2004). This sound was a pulsed, stereotyped sound produced at a depth of about 600 m, where the bottom depth was approximately 1,600 m. These species are not just of scientific interest. As coastal fisheries become depleted, fleets have begun exploiting species such as the hoki, a deep-sea hake species found off New Zealand. Have you had a fish sandwich at McDonald's? There is a good chance that you have eaten hoki.

Remote sensing of fish populations with passive acoustics

For species whose sounds have been documented, we can use passive acoustic recording to learn about the ecology of these species. Passive acoustics provides a near perfect ocean observatory sensor for biological activity in fishes. It is not susceptible to bio-fouling and is very low power. Since sound production is often linked to reproductive activities, passive acoustics provides an indirect way to determine spawning seasons and identify areas where fish may migrate to spawn. Development of passive acoustics as a tool in fisheries science has expanded greatly in the past 10 years. This is largely due to the availability of relatively inexpensive hydrophones and digital recording systems. Efforts have been made to bring the recent advances to the attention of fisheries biologists. Rountree *et al.* (2006) recently published an article in *Fishery* magazine to introduce fisheries scientists to passive acoustics as a tool. A special issue of the *Transactions of the American Fisheries Society* was recently devoted to new developments and research (Luczkovich *et al.*, 2008).

The beginning of the scientific use of eavesdropping on fish sounds to study behavioral patterns in fishes can be traced to Charles Breder's pioneering study listening to the sounds produced by fishes in Lemon Bay, off the Gulf of Mexico (Breder, 1968). Breder lowered a hydrophone off of a dock, and listened for fish sounds that had been previously identified, such as by the gulf toadfish and marine catfish (Tavolga, 1958). By listening for a period of five years he quantified patterns in sound production that likely reflect the seasonal patterns of reproductive activity of these species. One of the most interesting aspects of this paper was that he described other fish sounds, which were named the "galloper" and "repeater," but whose identities remain unknown.

Most studies in the 1960's–1970's were devoted to understanding mechanisms of fish sound production and behavioral analysis of sound production. Important work during this period showed that coexisting species of damselfish could distinguish each other's sounds, even though they were quite similar (Spanier, 1979). Foundational work identified sound production by three croaker and drum species and their patterns of sound production in the Indian River Lagoon on the Atlantic coast of Florida (Mok and Gilmore, 1983).

Up until this point, recording and analyzing fish sounds were creative endeavors. Scientists often had to create their own hydrophones, and used the Kay spectrograph machine to burn spectrograms into images. Breder used his brain's spectrograph to identify fish sounds. While still the best tool available, it is extremely time consuming to manually listen to fish sounds.

In the 1980's the development of personal computers made it possible to plot a spectrogram on a computer, and greatly increase the amount of data that could be analyzed. I began graduate school in 1990, and joined the laboratory of Phil Lobel, who impressed me with underwater video recordings showing sound production by the domino damselfish. This was exciting to me, because behavioral studies often seemed qualitative. With the ability to record behavior and sound production, we could become quantitative.

The domino damselfish is an ideal species with which to work because it lives on coral reefs and lays eggs in a nest, which makes it easy to determine spawning patterns just by looking for these nests. Furthermore, damselfish swim downward while producing a characteristic pulsed sound, so it is easy to identify the sound producer. Phil and engineers at Woods Hole Oceanographic Institution developed an automated detector system that automatically processed sounds received from a wireless hydrophone at Johnston Atoll. Using this system, we were able to show that patterns in sound production mirrored patterns in spawning (Mann and Lobel, 1995). This showed, at least for this species, that we could use passive acoustics to identify patterns in spawning.

Croakers and drums are more typical of marine species in that they spawn planktonic eggs, which float with the currents. Thus, it is a lot trickier to link sound production to

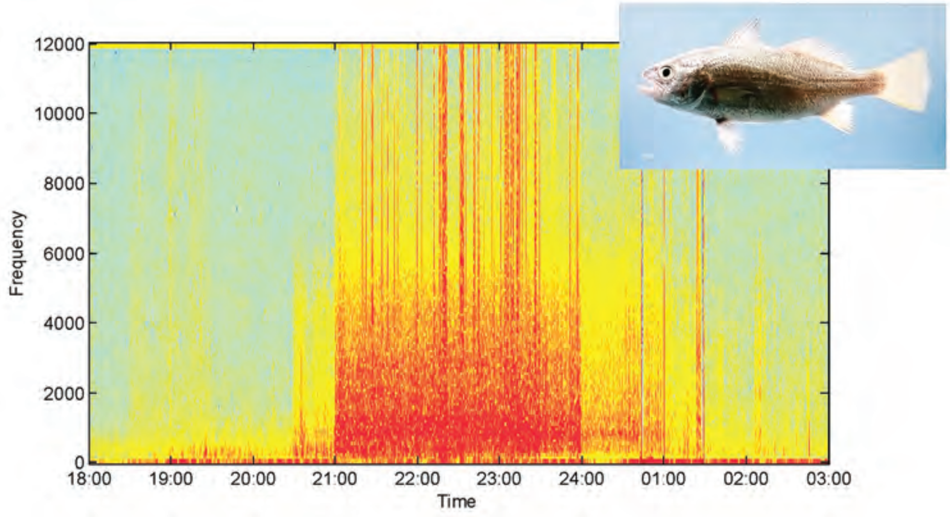


Fig. 4. Composite spectrogram showing the night time fish chorus in Charlotte Harbor, Florida. Each vertical band represents acoustic energy recorded in a 10 second file, with files recorded every 10 minutes. Early in the evening around 1900 hrs sound production begins with sand seatrout producing a purring sound. They are joined later with the higher frequency chatter sounds produced by silver perch. Ambient sound levels increase about 40 dB nightly due to fish sounds over a period of about 6 months. Photo of silver perch: National Oceanic and Atmospheric Administration (NOAA).

spawning in these species. Luczkovich *et al.* (1999) showed that they could locate areas and times of spawning of weakfish by combining mobile passive acoustic recordings with plankton tows to catch eggs. Aalbers (2008) showed that field-penned white seabass produced the greatest amounts of sound at the times of spawning (See Fig. 4).

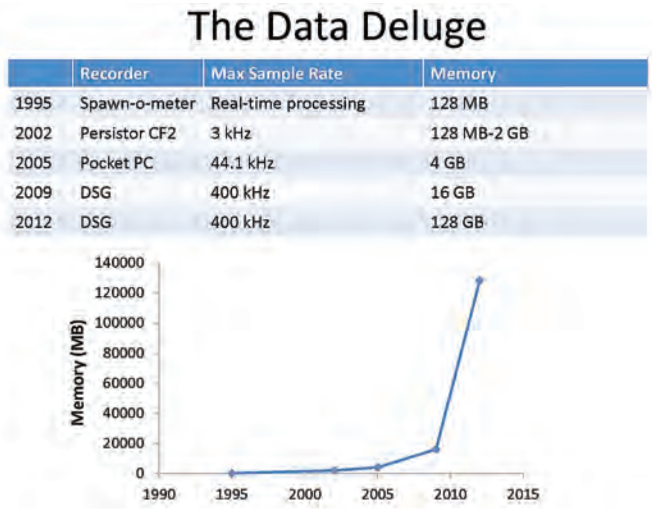
The mobile hydrophone mapping technique has been used to map sound-producing fish distributions across entire estuaries, such as Tampa Bay, the largest estuary in Florida (Walters *et al.*, 2009). More recently, effort has gone into the development and use of autonomous passive acoustic recorders. These recorders use flash memory to record sounds, usually at intervals. Since most fish sound production is frequent, recordings at intervals are sufficient to characterize daily and seasonal patterns in sound production (Locascio and Mann, 2008). The main advantage of autonomous recorders is that they enable recordings to be made over large spatial and temporal scales. Now you can be at more than one place at one time, in any kind of weather. Even in hurricanes, which don't put a damper on fish sound production (Locascio and Mann, 2005) (See Fig. 5).

Can we use sound levels to estimate the number of fish calling in an area? So far, not yet. To do this requires knowledge of source levels, calls rates, and propagation loss. This will require collaboration between biologists and acoustic modelers. The source levels of only a handful of species of fishes have been measured in the field. Some species, like the black drum have source levels up to 160 dB re: 1µPa (Locascio and Mann, 2011). Other fishes have source levels ranging from 125–135 dB re: 1µPa (oyster toadfish: Barimo and Fine, 1998, silver perch: Sprague and Luczkovich, 2004). Many fishes chorus, with so many individuals calling at once that it is not possible to separate sounds from different individuals.

Passive acoustics in ocean observatories

Long-term recorders are yielding insight into the timing of sound production and how it is affected by environmental factors. A good example of this is acoustic recordings from the LEO-15 ocean observatory off the coast of New Jersey. The continental shelf off New Jersey experiences high annual temperature variations and is highly dynamic. Sound production by chorusing croakers and weakfish varied in close concert with upwelling events, where sound production ceased as cold water invaded the observatory (Mann and Grothues, 2009). While it is not known whether the fish ceased producing sound or moved to another location, passive acoustics provided a means to study behavior on the same time scale as oceanographic events (See Fig. 6).

New buoyancy propelled electric gliders allow longer missions under a lower power budget than autonomous underwater vehicles (AUVs), and are potentially much quieter, since there is no mechanical propeller. Gliders are an important part of the development of ocean observatories


The Data Deluge

	Recorder	Max Sample Rate	Memory
1995	Spawn-o-meter	Real-time processing	128 MB
2002	Persistor CF2	3 kHz	128 MB-2 GB
2005	Pocket PC	44.1 kHz	4 GB
2009	DSG	400 kHz	16 GB
2012	DSG	400 kHz	128 GB

Fig. 5. History of capabilities of acoustic recorders used over the past 17 years. Recorders have evolved from intelligent real-time detection of specific sounds to high sample rate, large memory capacity recorders. The new challenge is now analyzing large acoustic datasets.

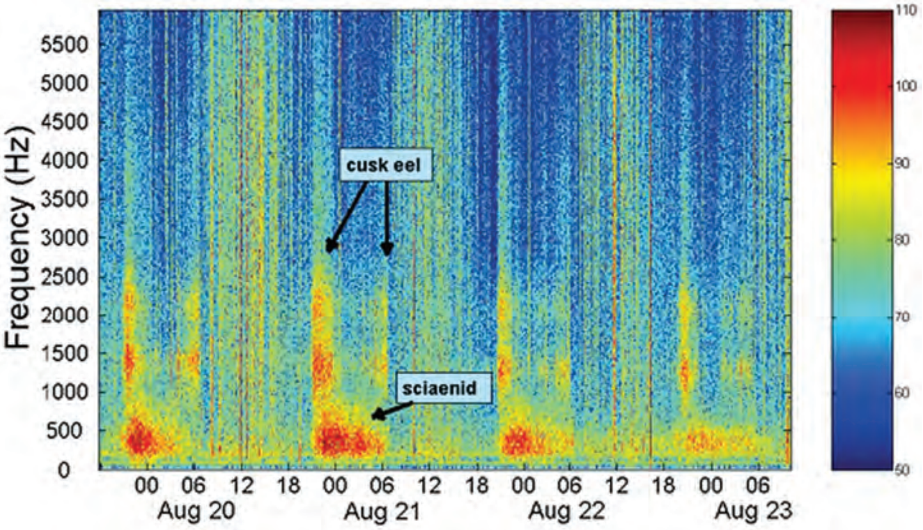


Fig. 6. Acoustic recordings from the LEO-15 ocean observatory off Tuckerton, New Jersey showing nightly chorusing by sciaenids (weakfish and croaker) and cusk eels. The composite spectrogram shows the cusk eel sounds are at a higher frequency than the croakers, and peak in sound production at dusk and dawn. Temperatures on August 23 decreased due to an upwelling event, which was correlated with reduced levels of sound production.

because they allow profiling of the water column along with the ability to extend the spatial range of observations. The first study using underwater gliders to study fish sound production was published just this year (Wall *et al.*, 2012). A Slocum glider was outfitted with a hydrophone and an internal acoustic recorder. The glider transited along a 135 km track in the Gulf of Mexico over the course of eight days. In this one short mission, suspected fish sounds from five species were mapped and their daily pattern of sound production was determined. Of these five sounds, four were previously unrecorded. One of the new sounds was a characteristic toadfish boatwhistle, from the offshore leopard toadfish. The only previously verified fish sound was from the red grouper, which had only been published in 2011 (Nelson *et al.*, 2011).

Gliders promise the ability to bring true shelf-scale ecosystem level mapping of the distribution of sound-producing fishes. One can envision gliders traveling entire continental coastlines giving us the first detailed maps of the locations of spawning groupers, cods, and drums. With repeated transects and large scale acoustic networks, we will be able to monitor the movement and reproductive activities of fishes as they respond to climate change (See Figs. 7 and 8).

A sea of opportunity

Passive acoustic recording using underwater gliders demonstrates the promise of large-scale mapping of fish

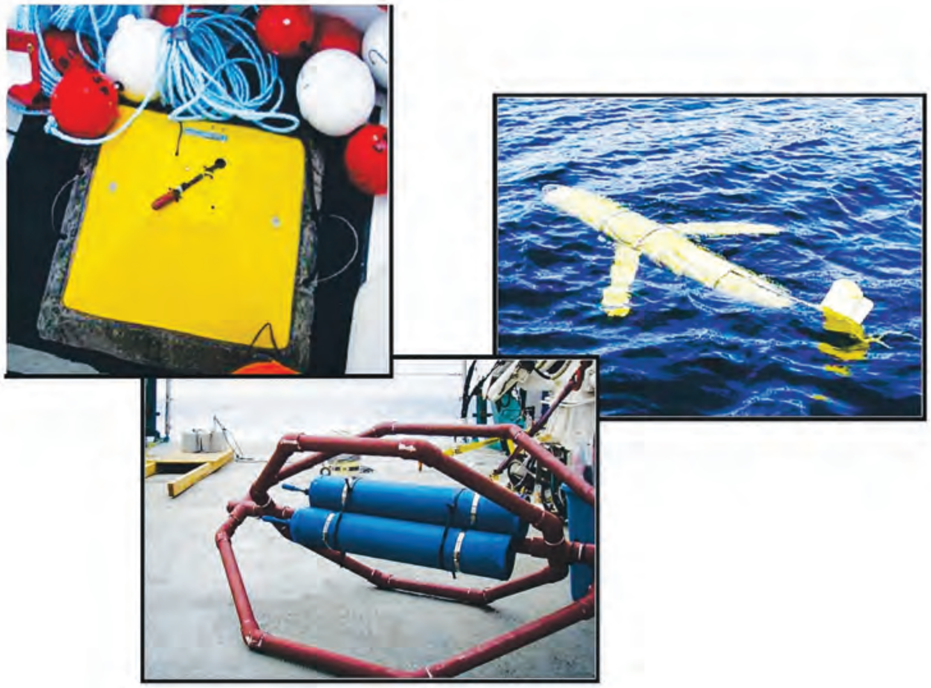


Fig. 7. Platforms used for passive acoustic recordings. From left, a bottom mounted recorder showing a hydrophone on the top, mid-water recorders located on a PVC float, and a Slocum glider containing an integrated hydrophone and digital recorder (photo by C. Lembke).

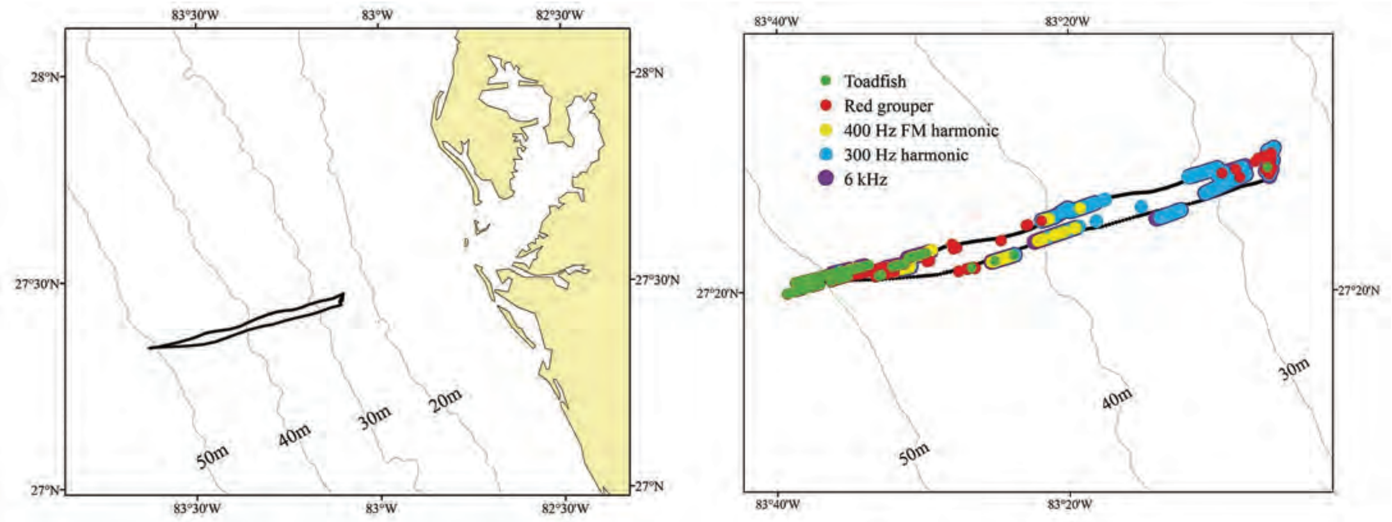


Fig. 8. Track of Slocum glider in the Gulf of Mexico and locations of detected fish sounds and suspected fish sounds. The toadfish found more offshore is likely the leopard toadfish, which had previously been unknown. Illustration by Carrie Wall.

Fig. 9. A deep-sea giant cusk eel on Davidson Seamount at 2,677 m depth. So far, no deep-sea fish sounds have been positively identified. Photo: National Oceanic and Atmospheric Administration (NOAA).

distributions. The glider recordings also demonstrate how little we know about the sound producers, literally in our backyards. New methods are needed to identify which species make which sounds. Video cameras only work where there is light, and often rely on intimate knowledge of the location and reproductive activity of a species to be able to capture these special moments. Marine mammal acoustic recording tags, like the Dtag and Acousonde, have yielded tremendous insights into the use of sound by dolphins and whales. But, they are too large for most fishes. One solution may be miniature, accelerometer recording tags to store the vibrations associated with sound production in fishes. Because most fish acoustic energy is below 1,000 Hz and relatively high level, an accelerometer should be capable of measuring the near-field particle acceleration component of sounds produced by a tagged fish. We need a renewed "Fish-and-Mowbray-like" effort to catalog sound production by marine animals in their natural habitats to realize the full potential of passive acoustic remote sensing of fish populations.

While it is has become easy to collect terabytes of acoustic recordings, analyzing those data is a critical challenge. It is impossible for a small laboratory to listen to all of the recordings they can make. Automated signal processing algorithms are a high priority to stem the data deluge. We have had success with automated routines for fixed locations where we had characterized all of the sounds from that site. These algorithms, however, have fallen apart when applied to glider recordings, or even to new locations where other sound producing species cause false alarms. We are at the dawn of a new age of both discovery and fisheries science with the integration of passive acoustics in ocean observatories. To fully develop this field requires the collaboration of engineers, experts in signal processing, and fisheries scientists. There is nothing like the thrill of being the first person to hear and identify a new sound, and there are plenty of fish in the sea waiting to be heard (See Fig. 9). **AT**

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