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[Article]

Soniferous Fishes in the Hudson River

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Abstract.—Although soniferous fishes have been studied in many different parts of the world, very few studies have been conducted in North American freshwater systems. The purpose of this study was to catalog and identify types of underwater sounds in the Hudson River, New York. We recorded underwater sounds with an autonomous underwater listening system consisting of a hydrophone, digital sound recorder, and weatherproof housing. Approximately 164 h of recordings were made from two sites located along the Hudson River during 2003. One site was located near the mouth of the river on Manhattan Island. The second site was located 153 km upriver within Tivoli Bays at the Hudson River National Estuarine Research Reserve. Additional manned recordings and sound auditioning of captured fishes were conducted in 2004 to identify biological and unknown sounds from Tivoli Bays. In all, we recorded 62 different sounds. Only four sounds could be identified to fish species: oyster toadfish *Opsanus tau*, striped cusk-eel *Ophidion marginatum*, brown bullhead *Ameiurus nebulosus*, and channel catfish *Ictalurus punctatus*. An additional 21 sounds were categorized as biological, 5 as nonbiological, and 32 as unknown. We believe that many of the sounds classified as biological and unknown are in fact produced by fishes but could not be identified due to the scarcity of studies on the sound production of freshwater and estuarine fishes of the Hudson River. Future research focused on the identification of these unknown underwater sounds will provide new insights into the ecology of the Hudson River. The diversity of underwater sounds we recorded in the Hudson River strongly suggests that sound production is an important behavior in aquatic systems and that passive acoustics can be an important new tool for the study of the river's ecology.

Though there are over 700 known soniferous species worldwide (Myrberg 1981; Kaatz 2002), there are many fishes yet to be sampled for sound production, leading us to believe that this number is underestimated. Fish are known to make sound associated with specific behaviors (Tavolga 1960), including disturbance, competition for food, territory defense (e.g., Myrberg 1997), and courtship or spawning (e.g., Mann and Lobel 1995; Rountree et al. 2003a). Fish produce sound mainly by using modified muscles attached to their swim bladders (drumming) or rubbing body parts together (stridulating; Fine et al. 1977). Passive acoustics is a technique that enables scientists to listen to and record underwater sounds of aquatic and marine fishes and invertebrates (Hawkins 1993). Using this technique, scientists can gain useful information about the temporal and spatial distribution patterns of soniferous fishes and the locations of spawning and feeding grounds (e.g., Luczkovich et al. 1999).

The purpose of this study was to conduct the first passive acoustic survey in the Hudson River, New York, to identify and catalog the occurrence of underwater sounds. Specific objectives were to (1) determine what underwater sounds occur at the two different locations along the Hudson River; (2) categorize recorded sounds by type (fish, biological, nonbiological, and unknown); (3) audition fishes captured at the sample sites to document the identity of unknown sound sources; and (4) determine the daily pattern of sound occurrence.

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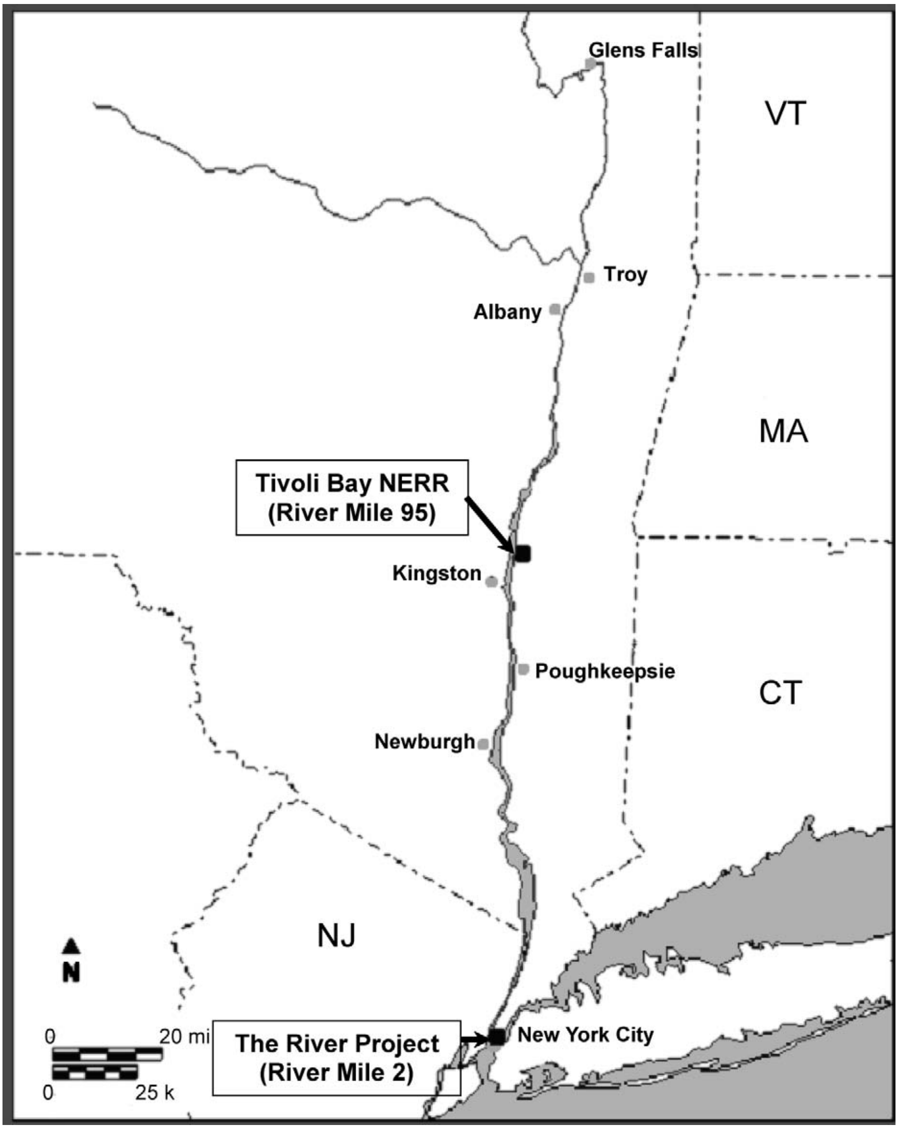

FIGURE 1.—Map of the study area in the Hudson River, New York, showing the two main sampling locations at the River Project and Tivoli Bays, where underwater sounds were cataloged.

Study Area

Passive acoustic sampling was conducted at two sites on the Hudson River (Figure 1). One site was Tivoli Bays in Red Hook, New York (40°43′28″N, 74°00′78″W), located at river kilometer (rkm) 153 (rkm 0 = Hudson River mouth), a tidal freshwater system (salinity < 0.5 ‰) with an average water depth of 0.5–3.0 m. The Tivoli Bays site is one component within the 20-km^2 Hudson River National Estuarine Research Reserve (NERR). Habitats at Tivoli Bays include freshwater intertidal marsh, open waters, riparian areas, subtidal shallows, mudflats, tidal swamp, and mixed-forest uplands (National Estuarine Research Reserve System 2005). The second site was located on Pier 26, Manhattan Island, at the River Project facility (rkm 3.2; 40°43′83″N, 73°59′822″W); this site is a mesohaline area (salinity range = 5–18‰) with an average water depth of 10–16 m (C. Drew, River Project, personal communication).

Methods

A modified autonomous underwater listening system (AULS) created by C. Goudey (Center for Fisheries

Research Engineering, Sea Grant College Program, Massachusetts Institute of Technology, Cambridge) was used to record underwater sounds. The AULS was designed to be deployed from shore and left to record continuously for up to 60 h. It consisted of a hydrophone, 33 m of cable, and a digital recording device housed in a weather-proof case. The hydrophone (High Tech Industries, Gulfport, Mississippi; Model HTI-96-MIN) had a frequency response of 2–30 kHz and nominal sensitivity of -165 dB referenced to 1 V/μPa at 1 m and was powered by two 9-V batteries. The digital recorder (Creative Laboratories; Nomad Jukebox) was set to record with an 11-kHz sample rate and a 15-dB gain and was powered by one rechargeable 6-V battery. Files were stored sequentially every 15 min in standard audio .wav format.

Underwater sounds were recorded from approximately 1600 to 0400 hours several times each week during July–September 2003. The AULS was deployed from a pier at the River Project site and from a train bridge at the Tivoli Bays site in the late afternoon and retrieved the next morning. Recording times ranged from 7 to 12 h. Hydrophones were placed so as to maintain a minimum depth of 1 m at low tide. Sampling was focused around sunset because (1) our previous experience indicated that sunset was the optimal onset time for sound activity and (2) we wanted to avoid the boating noise that was common during daylight hours at the River Project site.

In 2004, we returned to the Tivoli Bays NERR site to catch and audition fish with the objective of identifying the source of the unknown sounds recorded during the previous year. Sampling was conducted at various times during 28 June–2 July and 7–8 August. Fish were caught variously by hook and line, 23-m seine, and 38-m experimental gill net (panel mesh size = 1–11 cm). All captured fish were identified to species, measured, and auditioned. Auditioning consisted of recording sounds during a 10–30-min period as specimens were held in either a 19-L bucket or in a bait basket suspended within the river. Another method of auditioning was to record the sounds made by fishes as they were captured with hook and line. Specimens were periodically handled during auditioning to induce disturbance sounds.

All field recordings were later downloaded for storage in external hard drives. All recordings from the Tivoli Bays NERR were monitored in their entirety for the occurrence of sounds using Cool Edit acoustic software (Syntrillium Software Corporation). The more extensive recordings made at the River Project were subsampled by monitoring the first 15 min of each hour. Characteristics such as duration, number of pulses, pulse period, and frequency of selected sounds were measured with Signal (Engineering Design) or Raven (Cornell University, Ithaca, New York). Sounds of interest were selected by ear and simultaneous visual monitoring of waveforms and spectrograms. Some sounds were filtered to remove background noise or sound frequencies from known sources (e.g., boats) to improve the measurement of sound characteristics. Sound filtering details are given in figure captions.

All sounds were categorized as originating from fish or from biological, nonbiological, or unknown sources (Figure 2). Fish sounds were those we recorded during auditions or those with characteristics (duration, number of pulses, pulse period, and frequency) that matched previously published recordings of known fish sounds (Fish and Mowbray 1970). Sounds that exhibited characteristics similar to known fish sounds but that could not be matched to a particular species were categorized as biological sounds. Nonbiological sounds were those validated through a manned recording to have come from an anthropogenic (e.g., boat motor) or natural (e.g., wave action) source. Unknown sounds were those that could not be classified into any of the other categories. Biological and unknown sounds were given labels that described the sound (e.g., honk, groan, bark, etc.). In some cases, similar sounds with different characteristics were assigned letters (e.g., honk A, honk B, etc.). Sounds that were difficult to describe were given an arbitrary label (e.g., unknown 1, unknown 2, etc.).

Results

Approximately 104 h of sounds were recorded at the River Project site, yielding 44 different types of sound; 60 h were recorded at the Tivoli Bays site, yielding 18 different types of sound (selected sounds are represented in Figures 3, 4). Spectrograms and waveforms of representative fish, biological, nonbiological, and unknown sounds recorded during this study are shown in Figure 2. Two common sounds at the River Project site were categorized as fish sounds and were identified as originating from striped cusk-eels *Ophidion marginatum* and oyster toadfish *Opsanus tau* based on our previous experience working with these species (Mann et al. 1997; Rountree and Bowers-Altman 2002; Rountree et al. 2003b). The sounds of two species, the brown bullhead *Ameiurus nebulosus* and channel catfish, *Ictalurus punctatus*, were identified at the Tivoli Bays site through auditions of captured specimens (see below). At the River Project, 15 other sounds were categorized as biological, 3 sounds were nonbiological, and 24 sounds were unknown. At the Tivoli Bays site, six other sounds were classified as biological, two were nonbiological, and eight were unknown. Representative biological and unknown sounds from each site are shown in Figures 3 and 4.

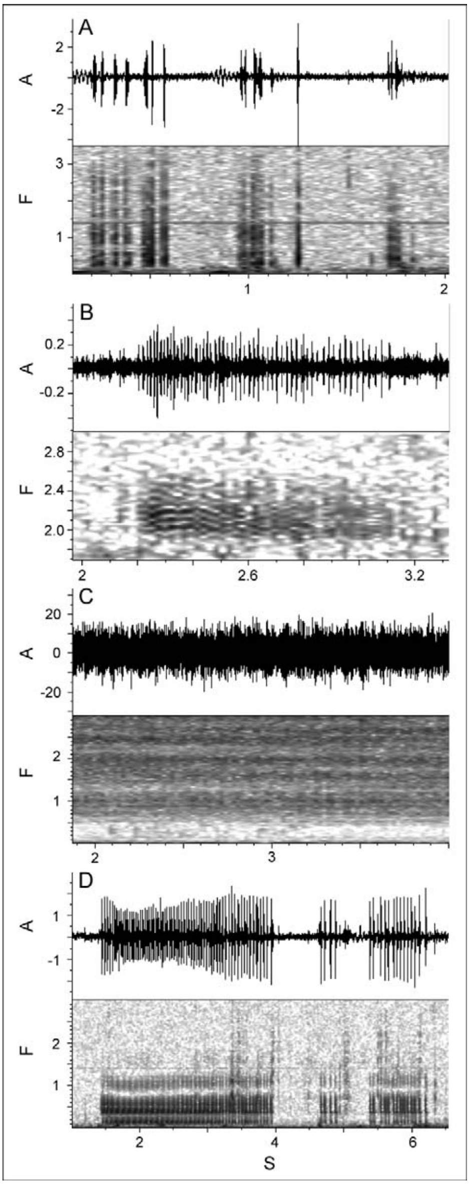

FIGURE 2.—Representative samples of Hudson River, New York, underwater sounds assigned to four categories: **(A)** fish sound recorded from a channel catfish as it was captured with hook and line at Tivoli Bays (7 August 2004 at 1917 hours); **(B)** unknown sound recorded at the River Project at 2347 hours in July 2003 and 1132 hours in September 2003; **(C)** nonbiological sound from boat noise, which was often recorded at both study sites; and **(D)** purring, staccato-like biological sound recorded at the River Project on three different nights (between 1900 and 2400 hours) in August and September 2003. Each panel shows the sound waveform (top; A = amplitude, normalized to the loudest part of the sound) and spectrogram (bottom; F = frequency [kHz]; S = time [s]). Spectrograms were produced using the Hanning window function (discrete Fourier transform = 512).

The dominant frequency (DF) and duration of each call are given in Table 1. We recorded several different honk types at the River Project (Figure 5).

Nonbiological sounds that were positively identified were wave action and floating dock movements (River Project), a train passing over a bridge (Tivoli Bays), and boat sounds (both sites). Sounds thought to be made by fishes during feeding (e.g., Figure 4D) were recorded at both sites.

Fish of eight taxa were auditioned at Tivoli Bays in 2004: brown bullheads, channel catfish, largemouth bass *Micropterus salmoides*, smallmouth bass *Micropterus dolomieu*, white perch *Morone americanus*, various sunfishes *Lepomis* spp., white suckers *Catostomus commersonii*, and American eels *Anguilla rostrata*. We successfully recorded vocalization from a channel catfish (25 cm total length [TL]) as it was caught on hook and line (Figure 2A) and from three brown bullheads (24, 26, and 27 cm TL) while they were contained in a 19-L bucket (Figure 6, top). Both successful auditions were recorded at night. No sounds were heard from other species during auditions.

The audition recording of the brown bullheads (Figure 6, top) exhibited characteristics similar to those of an unidentified barking sound recorded in 2003 at Tivoli Bays (Figure 6, bottom). The DF of the brown bullhead audition was 0.210 kHz (Figure 6D, top), whereas the DF of the unidentified barking sound was 0.175 kHz (Figure 6D, bottom). We note that the brown bullheads were captured and auditioned between 2030 and 2200 hours, whereas the barking sounds were recorded at 1915, 2030, and 2300 hours. Based on the similarity of these sounds recorded in captivity in 2004 and in the wild in 2003, we concluded that brown bullheads were the source of the unidentified barking sound.

Biological sound production (all categories except nonbiological) exhibited a strong daily pattern at both river sites; activity was greatest after sunset and decreased at dawn (Figure 7). This is a pattern also observed in other soniferous fish studies (Breder 1968; Mok and Gilmore 1983). Ninety percent of the sounds (excluding nonbiological sounds) from both sites were recorded between 1500 and 0600 hours. At the River Project, sounds were most frequent between 2100 and 0600 hours, although a majority of recordings made at other times were dominated by boat noise, which may have masked other sounds. At the Tivoli Bays site, sounds were most frequently heard between 1800 and 2400 hours, and boat sounds occurred only periodically during daylight hours.

Discussion

This study demonstrates the potential importance of passive acoustic applications for studies of freshwater

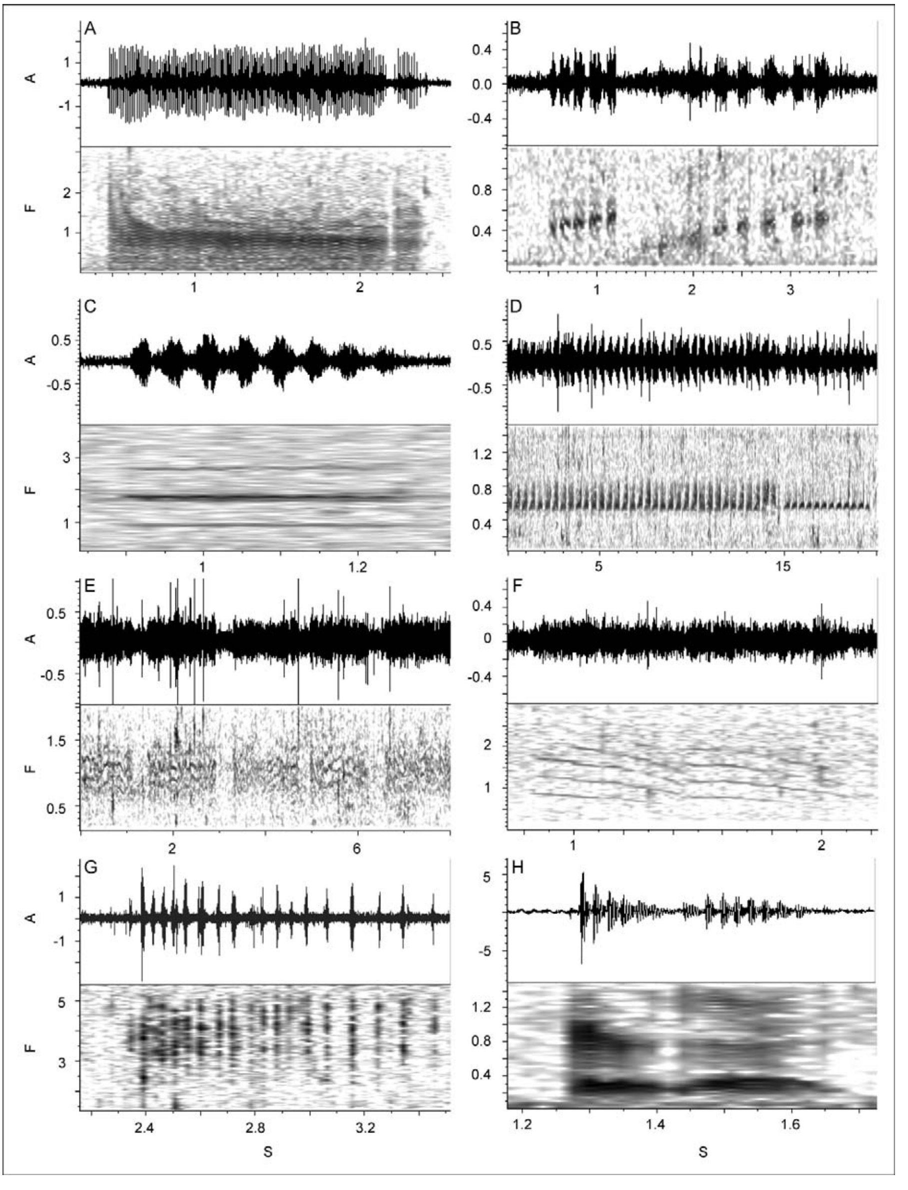

FIGURE 3.—Selected underwater sounds recorded at the River Project, Hudson River, New York, in 2003: **(A)** unknown sound recorded at 0434 hours during August (filters: <0.05 and >3.00 kHz); **(B)** unknown sound recorded at 0219 hours in August (<0.05 and >1.20 kHz); **(C)** unknown sound recorded at 0343 hours in August (<0.14 and >4.00 kHz); **(D)** unknown, sonarlike sound recorded at 0308 hours in July (<0.065 and >1.500 kHz); **(E)** unknown, whining-like sound recorded at 0212 hours in July (<0.150 and >2.000 kHz); **(F)** unknown, cawlike sound recorded at 0532 hours in August (<0.2 and >3.0 kHz); **(G)** rattlelike sound categorized as biological in origin and recorded at 0154 hours in July (<1.4 kHz); and **(H)** burplike sound of possibly biological origin recorded at 0113 hours in July (<0.030 and >1.500 kHz). Each panel shows the sound waveform (top; A = amplitude, normalized to the loudest part of the sound) and spectrogram (bottom; F = frequency [kHz]; S = time [s]). Spectrograms were produced using the Hanning window function (discrete Fourier transform = 512). Durations and dominant frequencies of the sounds are listed in Table 1.

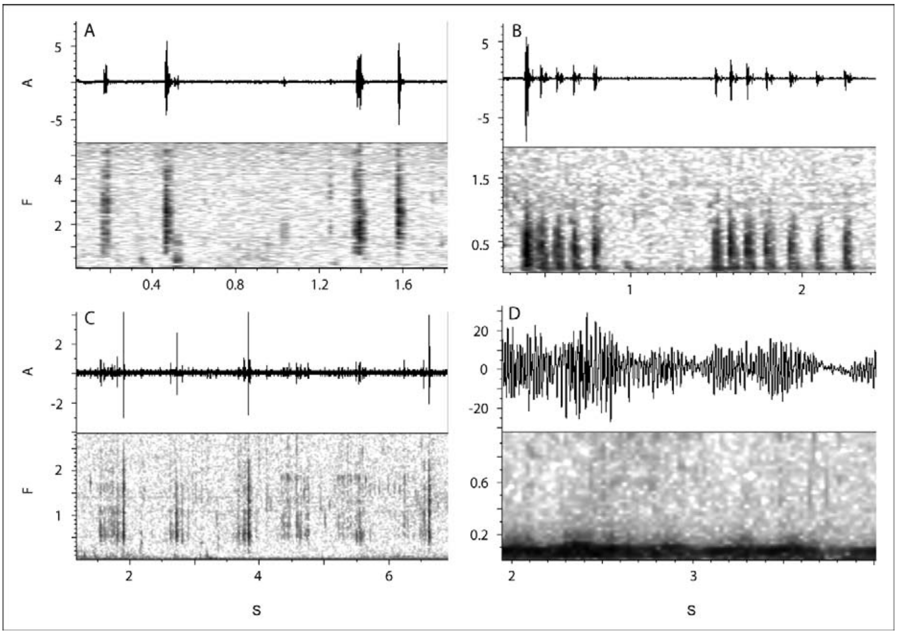

FIGURE 4.—Selected underwater sounds recorded at the Tivoli Bays National Estuarine Research Reserve, Hudson River, New York, during September 2003: **(A)** clapping-like sound categorized as biological in origin and recorded at 1203 hours; **(B)** drumming-like sound of possibly biological origin recorded at 1147 hours; **(C)** presumed fish feeding sound recorded at 1202 hours; and **(D)** continuous base sound of unknown origin, recorded at 1432 hours. Each panel shows the sound waveform (top; A = amplitude, normalized to the loudest part of the sound) and spectrogram (bottom; F = frequency [kHz]; S = time [s]). Spectrograms were produced using the Hanning window function (discrete Fourier transform = 512). Durations and dominant frequencies of the sounds are listed in Table 1.

ecosystems in North America. In the Hudson River, we recorded a wide variety of unknown underwater sounds that we feel originated primarily from the common fish fauna, but the sources of these sounds could not be identified because of the lack of basic data on sound production in North American freshwater fishes. Future studies aimed at cataloging sound production in Hudson River fishes as well as in other systems are greatly needed. All sound samples reported herein are available on the Internet (Rountree 1999). The methodology can be applied and expanded upon in further studies in North American aquatic systems.

TABLE 1.—Dominant frequency (DF) and duration of selected sounds recorded at the River Project and Tivoli Bays on the Hudson River, New York, during 2003. Spectrograms and waveforms are shown in Figures 3 and 4.

Sound	Category	Time of recording (hours)	DF (Hz)	Duration (ms)
		River Project		
Air release	Unknown	0434	775	1,889
Burp	Biological	0113	258	352
Whining	Unknown	0212	969	8,030
Sonarlike	Unknown	0308	151	19,604
High-pitched echo	Unknown	0348	1,765	0.36
Cawlike	Unknown	0532	1,528	1,307
Rattlelike	Biological	0154	2,433	1,122
Unknown 1	Unknown	0219	516	2,897
		Tivoli Bays		
Clapping	Biological	2402	2,019	41
Drumming	Biological	2347	26	392
Continuous base	Unknown	1432	59	75,600
Feeding	Biological	2402	476	646

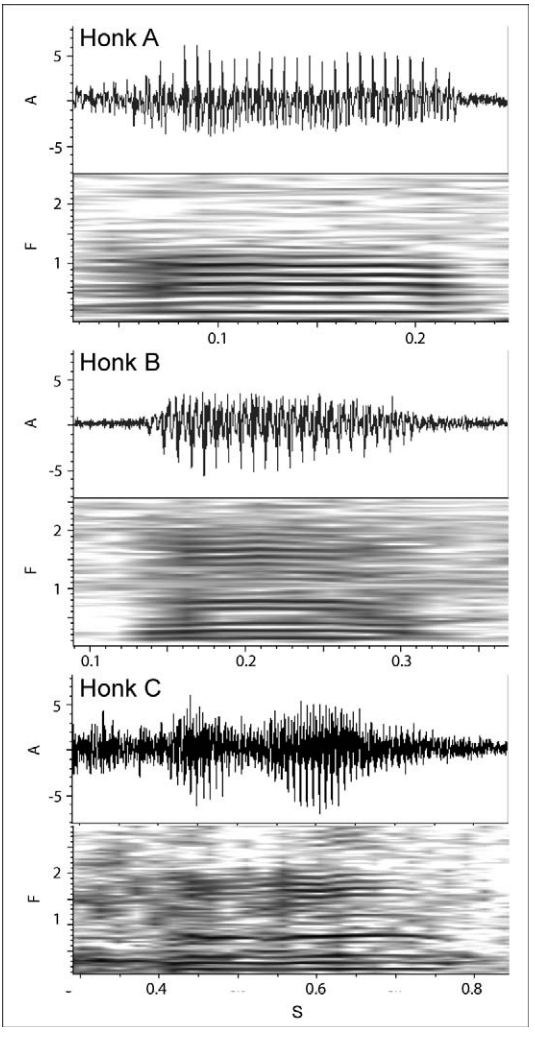

FIGURE 5.—Three examples of honk sounds that differed in acoustic characteristics, suggesting different possible sources; all were recorded at the River Project, Hudson River, New York: **(A)** honk with a dominant frequency (DF) of 0.987 kHz and duration of 186 ms; **(B)** honk with a DF of 0.236 kHz and duration of 160 ms; and **(C)** double honk with a DF of 0.754 kHz and duration of 333 ms (almost twice the duration of honks A and B). Each honk sound consisted of four or more distinct, powerful harmonics. Each panel shows the sound waveform (top; A = amplitude [kU], normalized to the loudest part of the sound) and spectrogram (bottom; F = frequency [kHz]; S = time [s]). Spectrograms were produced using the Hanning window function (discrete Fourier transform = 512).

One difficulty with passive acoustic techniques is the lack of standardized terminology for naming sounds. Distinguishing fish sounds from other sounds poses many questions that are yet unanswered. Can physical sound attributes, such as DF and pulse pattern, provide sufficient information to distinguish fish sounds from other sound sources? How much variability exists in the characteristics of one species' call? We were challenged with these questions in recording a series of unique biological honk sounds at the River Project (Figure 5). We recorded three honklike sounds that shared similar characteristics, including duration and pulse pattern, but that varied drastically in DF. Could all three honks be a different variation of a call produced by one species, or is each honk unique to three different species?

We were able to positively identify the source species of two fish sounds from the River Project by comparing call characteristics with published data on the courtship boatwhistle call of oyster toadfish (Fine 1978) and the courtship call of striped cusk-eels (Rountree and Bowers-Altman. 2002). Our recording of the courtship sounds of striped cusk-eels at the low-salinity River Project site provides new data on the distribution and spawning habits of the species (Collette and Klein-MacPhee 2002). This finding is noteworthy, because striped cusk-eels have never been collected at the River Project site despite regular sampling with killi-traps and eel-pots over the last 10 years (C. Drew, personal communication).

The importance of auditioning organisms in the field at the time and location of sound recording is illustrated by our successful identification of an unknown sound from Tivoli Bays as that of a brown bullhead. However, auditioning also revealed sound production of channel catfish, despite our failure to record the species during unmanned sampling in 2003. To our knowledge, our recordings of brown bullheads are the first to be accomplished in the field, although this species has previously been recorded in the laboratory (Rigley and Muir 1979).

Rigley and Muir (1979) performed experiments to determine whether brown bullheads used sound for conspecific communication. They found that brown bullheads produce sound during aggressive conspecific encounters. Rigley and Muir (1979) described a ratchetlike sound produced by the abduction and adduction of the pectoral fins in the pectoral girdle. The sounds were composed of short-duration pulses (mean duration = 5 ms) and short interpulse intervals (mean duration = 4 ms). The frequency of the sound was mainly under 0.2 kHz, but occasionally there was a second energy band between 0.4 and 0.6 kHz. These frequencies are similar to those we observed in our field audition and field recording of the species. We measured a mean DF of 0.210 kHz and a second energy band at 0.410 kHz for the auditioned sound (Figure 6D, top); a mean DF of 0.175 kHz and a second energy band at 0.400 kHz were measured in the field recording (Figure 6D, bottom). Unfortunately, we

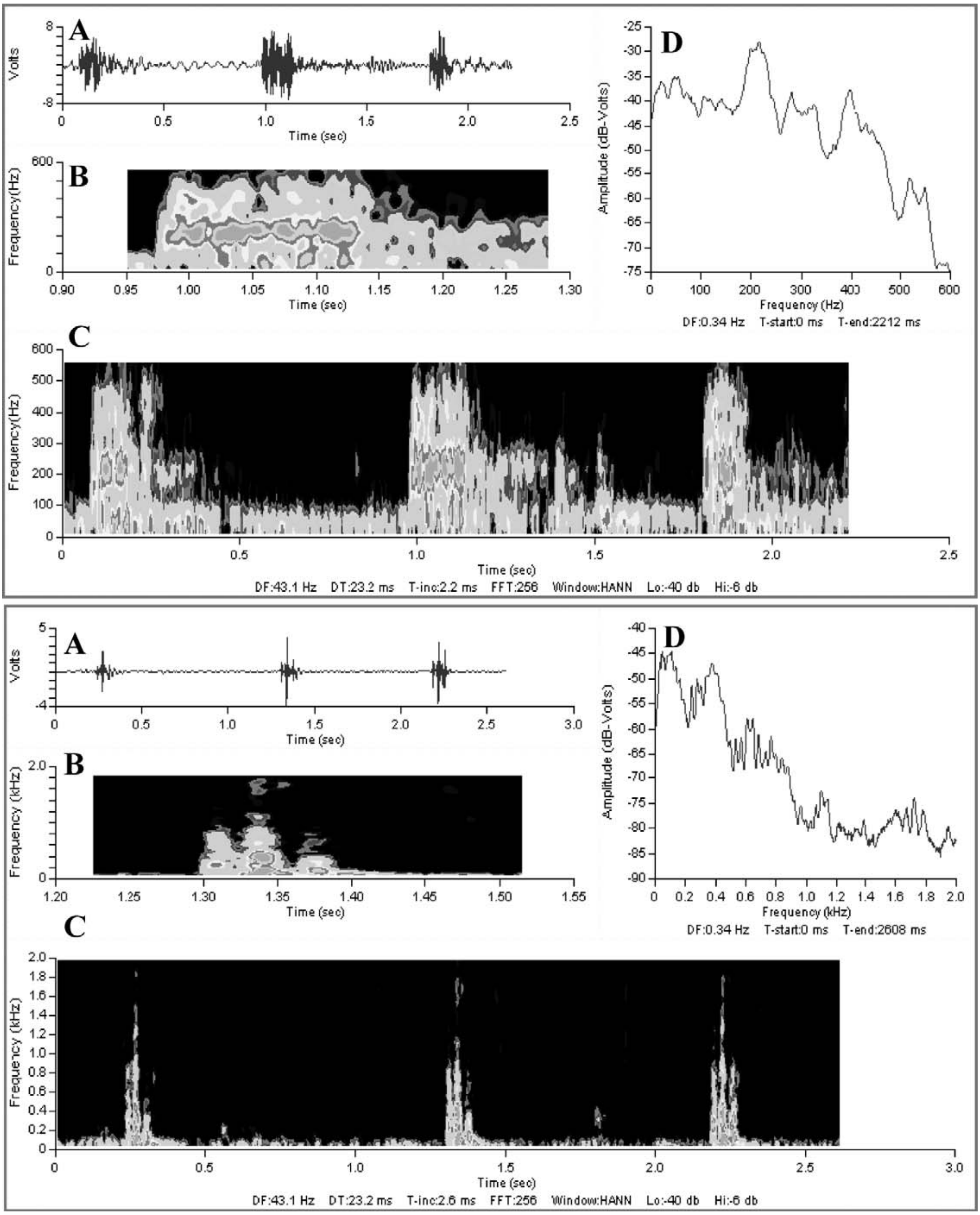

FIGURE 6.—Top: brown bullhead sounds recorded during an audition at Tivoli Bays, Hudson River, New York (30 June 2004 at 2149 hours): **(A)** waveform of three calls measured (V) over time (s); **(B)** sound spectrogram of one of the calls; **(C)** spectrogram of the three calls averaged over 2.608 s in the entire sound sequence from (A); and **(D)** average power spectrum of the three calls. Bottom: analyses of three unknown barking sounds recorded at Tivoli Bays (9 September 2003 at 2030 hours) are presented: **(A)** waveform of the three sounds; **(B)** spectrogram of one of the sounds; **(C)** spectrogram of all three sounds; and **(D)** average power spectrum of the sounds.

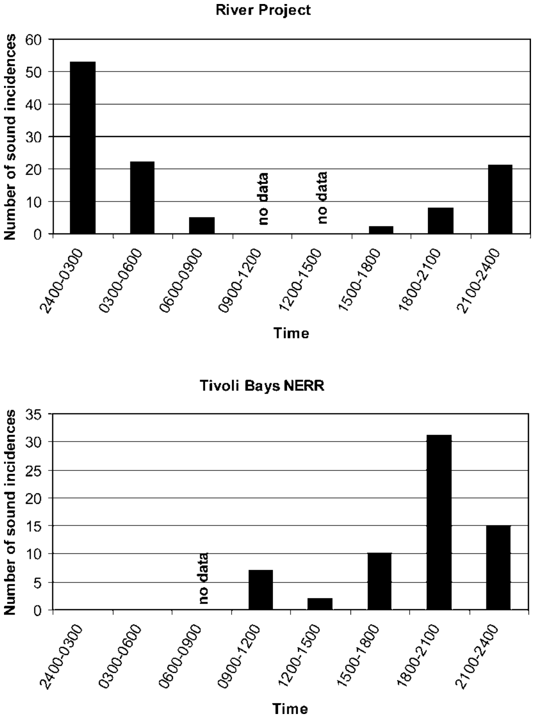

FIGURE 7.—Number of sounds recorded during 2003 at the River Project (top) and Tivoli Bays (bottom), Hudson River, New York, categorized by time of day. Eighty percent of the sounds at the River Project were recorded between 2100 and 0600 hours (just before and after sunset), and 70% of the sounds at Tivoli Bays were recorded between 1800 and 2400 hours.

could not accurately measure other characteristics (e.g., pulse duration) from the auditioned sounds because an echoing effect distorted the spectrograms. This effect can be lessened in the future by auditioning the fish in larger containers or enclosures (Okumura et al. 2002). However, in the field recording of the barking sound, we were able to determine a mean pulse duration of 1.7 ms and an interpulse interval of 1.2 ms. Thus, our recorded calls were considerably shorter in both pulse duration and interpulse interval than those recorded by Rigley and Muir (1979). We believe that the sounds produced during our audition of the brown bullheads were made because the fish were disturbed by confinement in the bucket. Therefore, sound characteristics reported by Rigley and Muir (1979) and ourselves are probably different because they are based on different behaviors, although we cannot rule out the possibility of container artifacts. We hypothesize that brown bullheads produce different aggression and disturbance calls as measured by the different studies. Further research is needed to test this hypothesis.

Fine et al. (1996, 1997) state that the sounds produced by channel catfish contain groups of pulses that vary in frequency, amplitude, duration, and pulse pattern. This description closely matches the pattern we noted in the sound characteristics from our audition of channel catfish. Fine et al. (1996, 1997) recorded sound from 52 pond-raised specimens to determine the sound production mechanism. Fish were removed from holding pens or tanks, and their disturbance sounds were immediately recorded in air. The study showed that channel catfish produce sounds by stridulation, caused by a continuous fin sweep in which the dorsal process firmly rubs against a channel in the pectoral girdle. This is similar to the mechanism proposed by Rigley and Muir (1979) for sound production in brown bullheads. Whether channel catfish produce nondisturbance sounds is currently unknown.

Anthropogenic sounds generated from the highly industrial urban environment of New York City made the identification of sounds problematic at the River Project. However, much of this noise subsided enough during the evening to allow for the recording of some underwater sounds. These observations suggest the need for a study of the impacts of noise on Hudson River fish communities. The effect of intense, chronic noise on local fishes in the Hudson River is unknown and deserves the attention of the scientific community.

At both sites, one commonly recorded sound, categorized as biological, was presumed feeding noise. When the source species of a feeding sound is identified, the sound can then be used in determining distribution, feeding locations, and consumption rates. We therefore propose the use of passive acoustics as a tool for the study of feeding behavior of fishes in the Hudson River and elsewhere. Studies of the detection range for these feeding sounds and identification of the species producing them would allow for studies of daily feeding cycles and cropping rates (e.g., Sartori and Bright 1973). Lagardere and Mallekh (2000) and Mallekh et al. (2003) were able to detect feeding activity through acoustic monitoring in an aquaculture facility and used that information to control food supply. Kaparang et al. (1998) found a relation between the frequency of feeding sounds and body size in yellowtail *Seriola quinqueradiata* and greater amberjacks *Seriola dumerili*. Large silver carp *Hypophthalmichthys molitrix* were abundant at the Tivoli Bays NERR site during our sampling, and we suspect that they produced many of the long sequences of feeding sounds recorded at that location.

We have shown that there is great potential for expanding our knowledge of the ecology of fishes in the Hudson River through passive acoustics. Passive acoustic techniques enable one to study fish from a new standpoint with little encroachment upon the fish or its habitat. By conducting advanced passive acoustic surveys, scientists can increase their understanding of fish temporal and spatial distribution patterns, spawning and feeding behavior, and habitat requirements. Future research focused on the identification of unknown underwater sounds in the Hudson River promises to provide scientists with new insights into the river's ecology.

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