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Characterizing Sound Production in Nearshore Rockfishes (*Sebastes spp.*)

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by

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Characterizing Sound Production In Nearshore Rockfishes (*Sebastes spp*.)

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Abstract

Rockfishes of the genus *Sebastes* are trophically important in most nearshore environments of the west coast of North America, and support important commercial and recreational fisheries. Though the 72 northeast Pacific species have drumming muscles along their swim bladders, little is known about sound production in the genus. Sounds produced by nearshore rockfish were recorded using fixed hydrophones and underwater video in aquaria, and acoustical dataloggers in the field. Sounds were analyzed from six species: *Sebastes nebulosus, S. atrovirens, S.carnatus, S. chrysomelas, S. caurinus*, *and S. maliger*. These six species are closely related, mostly bottom dwelling species with similar drumming musculature. No sounds were recorded from twelve other species in response to diver harassment or agonistic interactions. All the sound production observed was close range, agonistic and relatively quiet (estimated source level 122 dB re 1μPa). Sounds were recorded at all times of the day in the field, presumably from *S. nebulosus*. While courtship type behavior was observed and video-recorded for only two species, no sounds were produced during courtship. Analysis of the sounds (duration, number of pulses, pulse rate, peak frequency, interpulse interval) from the six species showed considerable overlap between call characteristics, although *S. carnatus* and *S. chrysomelas* produced some longer calls with more pulses than the other species. It appears that these agonistic sounds are designed for short-range communication and that they are not species-specific.

INTRODUCTION

West coast rockfishes (*Sebastes spp*.) are important predators over many nearshore habitats from California to Alaska. Smaller species as well as juveniles are prey for a variety of other fishes, birds and mammals. Rockfishes, members of the family Scorpaenidae, are long-lived (*S. aleutianus* Jordan & Evermann has been aged to 205 years) and many species do not reach sexual maturity for over a decade. There are approximately 102 species in the genus, a remarkable diversification. From a human perspective, they are also the target of large commercial and recreational fisheries, though their numbers have dropped catastrophically over much of their range (Love et al. 2002).

Unlike most fishes, rockfishes have internal fertilization – they mate and the embryo develops inside of the female. At least some and probably all are matrotrophically viviparous – that is, the embryos receive energy directly from their mother as well as a yolk sac. Rockfishes are long lived and fecund – successful larval settlement years may be a decade apart. All species have at least basic venom glands at the base of some fin spines. There are at least 65 species along the west coast of North America, with the greatest diversity (56 species) off Southern California. Rockfishes can be found from the intertidal zone to depths of over 2800 meters (Love et al. 2002).

Many fishes produce sound and Hallacher (1974) showed that numerous rockfish species have sonic muscles alongside their swim bladders. At least three Northwest species are capable of growling loud enough for a diver to hear (personal observation): China (*S. nebulosus* Ayers), copper (*S. caurinus* Richardson) and quillback rockfish (*S. maliger* Jordan & Gilbert). One unpublished study (Fletcher 1983) recorded agonistic sounds produced by two species: *S. nebulosus* and black rockfish (*S. melanops* Girard).

Considering the economic importance of the various rockfish fisheries and the threatened status of many populations, there is a surprising lack of information on sound production in this genus. Very little has been published on the topic and it is largely unknown which species actually do produce sounds, what sort of sounds they are, and why they might do it. Reasons for this may include the facts that:

- many people that are familiar with rockfishes have no idea they produce sound as they typically don't when feeding, caught or handled
- rockfishes do not appear to chorus loudly like some soniferous fishes
- most species do not produce sound even when harassed, so scuba divers do not hear them
- fish sound researchers are concentrated on the East Coast

Drumming Muscle Anatomy

Sound is important to fish, and indeed to nearly all vertebrates (Popper et al. 2003). Communication is not the only reason - underwater, where sound travels much farther than light, sound provides sensory information from much greater distances. Tavolga (1964) discusses the anatomy, physiology and sound production characteristics of extrinsic swimbladder musculature in a variety of fish families. Though the exact anatomy differs between and within families, sounds are produced by contraction of muscles near the swimbladder, causing it to either expand or contract. The resulting pressure and volume changes cause the bladder to pulsate, producing displacement which passes through the fish into the surrounding water. He reported no cases where there was a muscular antagonist to the swimbladder muscles, observing instead that the elasticity of associated skeletal and connective tissue caused the muscles to return to their initial state. Tavolga called this a "highly efficient system" functioning as a low frequency underwater loudspeaker.

The large number of species in the *Sebastes* genus makes it an interesting topic for taxonomists, and there has been considerable shuffling at the genus and species level over the years. Matsubara (1943) considered the swimbladder muscles of Japanese scorpaenids to be excellent taxonomic characteristics. Hallacher (1974) examined the "gasbladder" muscles of North American rockfishes, separating them into two major categories with three or four subdivisions each. He concluded that most species were capable of producing sounds. In cases where both sexes of a species were examined, he found no sexual dimorphism in the swimbladder musculature. Figure 1 illustrates the basic anatomy of Hallacher's type I a-z rockfish muscles, the most common type in the genus. Every species found to produce sound in this study had the rarer type II a-v musculature, also illustrated in Figure 1. Hallacher found this muscle group to be the largest in the genus.

Ocean Sound

Popper et al. (2003) reviewed studies showing that anthropogenic ocean sound is increasing and may be affecting fish populations. The increasing sound comes from a variety of sources, especially shipping, pleasure craft, seismic surveys, pile driving, sonar, and scientific exploration, all of which occur in the continental shelf and nearshore habitats occupied by rockfish species. Though no work has been done on hearing in rockfishes, Hallacher's (1974) anatomical studies showed that rockfishes have large otoliths, and that the swimbladder muscles originate in the cranium "in the general proximity" of the otoliths. Until sufficient hearing studies are conducted, it can be assumed that fish are unlikely to produce sounds they cannot hear themselves.

A growing body of knowledge indicates that noise in the oceans can affect fish adversely. Increasing background noise may "mask" sounds that are biologically important to fish (Fay and Megela Simmons 1999). As the inner ear sensory hair cells of fishes are remarkably similar to our own, louder noises, such as those from seismic testing, may cause permanent or short term hearing loss (Popper et al. 2005). Finally, loud noises may induce physiological stress responses in fish (Smith et al. 2004).

All of these factors could be highly disruptive to fish behavior and ecology. In order to make the best decisions regarding the effect of increasing ocean sound on rockfish populations, it will be necessary to have a much better understanding of how, why and when they use sound.

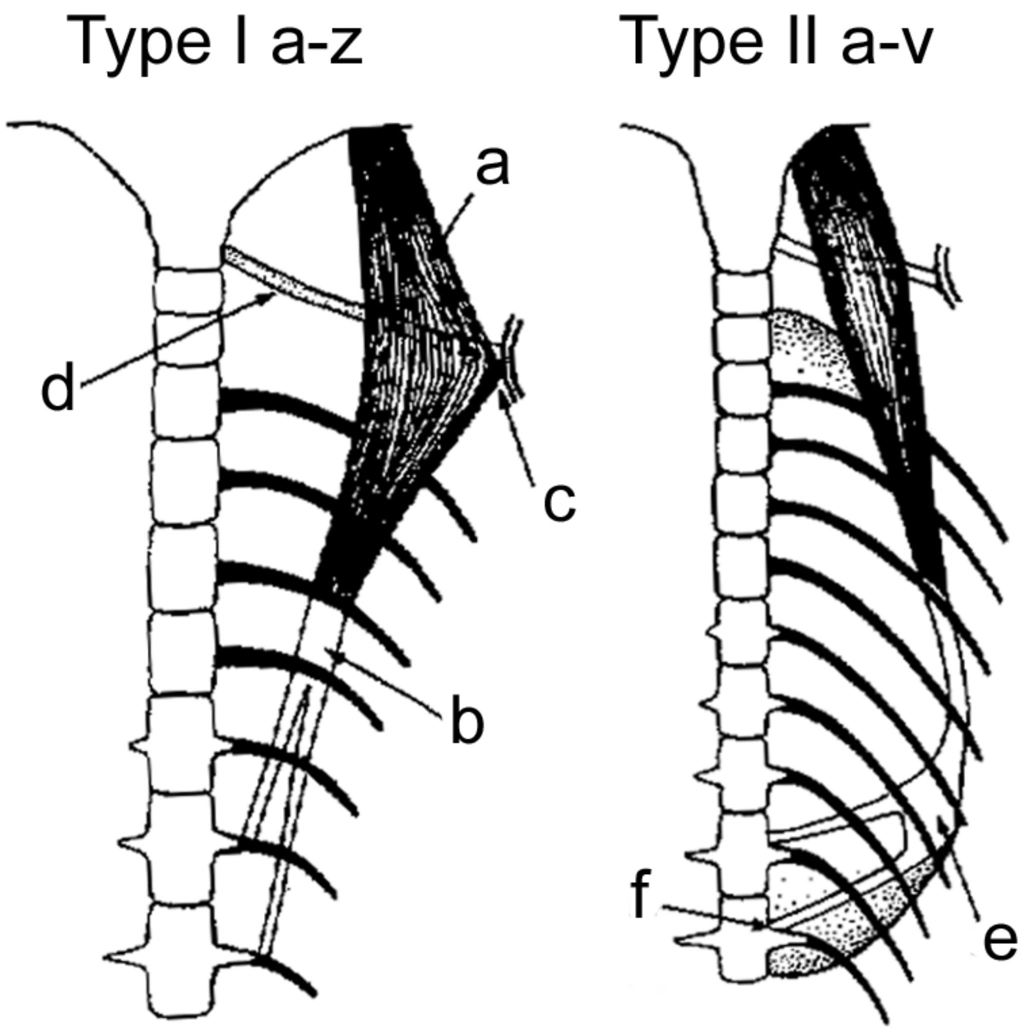


Figure 1 Two types of Sebastes swimbladder muscles, showing right side only. Type I a-z is the most common type in the genus; the diagram shows a) striated muscle, b) tendon, c) attachment to the pectoral girdle, and d) Baudelot's ligament. The muscles originate on the occipital cranium and insert on the ribs. Type II a-v is less common, but contains all the species investigated in this study. Type II a-v muscles are relatively larger and bypass the pectoral girdle. The tendon attaches to the swimbladder (e) and inserts onto the vertebral parapophyses (f). Adapted from Hallacher (1974).

Passive Hydroacoustics

Passive hydroacoustic techniques, where fixed or drifting hydrophones are used to listen for fish, are becoming more common. Luczkovich et al. (1999) showed that passive hydroacoustic surveys could delineate weakfish (*Cynoscion regalis*) spawning areas, and argued that that passive acoustic techniques could be a valuable tool for management, including the designation of marine reserves. Locascio & Mann (2005) developed a technique using hydrophones attached to housings with dataloggers to show diel periodicity in fish sound production off Florida. If rockfish sound production was better understood, the rapidly advancing field of passive acoustics could help supplement fisheries independent data, which is limited or nonexistent for most rockfish species.

Rediscovering Lost Data

An extensive literature search turned up very little on the topic of sound production in rockfishes, although three unpublished studies proved useful. One, a Master's thesis (Fletcher 1983), is available as microfiche from the Library of Canada but was not otherwise published. Another (Yearsley 1970) existed as a version that was cited as "in press" by a number of papers, but apparently never made it to publication. An early version was read by this author after tracking down the original supervising professor and requesting a copy. This study was undertaken based on personal observations and the evidence of these papers, which cumulatively stated that at least five species of nearshore rockfishes had produced sounds in either the lab or field.

Another important piece of the puzzle came from Greg Caillet, an ichthyologist at Moss Landing who remembered a graduate student who had recorded rockfish sounds sixteen years previous. That student, Lucy Wold (now Lucy Littlejohn), was tracked to a ranch in Idaho, and the tapes and observations she made (Wold 1991) were incorporated into this study.

METHODS

Moss Landing 1988

VHS tapes originally recorded in 1988 at the Moss Landing Marine Lab were retrieved and digitized (44.1 kHz) as AVI files using a Sony camcorder (DCR-PC110) to record them directly to a computer hard drive. Fish sounds were then saved as individual files by watching the recordings in Adobe Premiere Pro and cutting the footage into individual events, typically chases. Sound was extracted from these events as a WAV file for analysis.

Audio tapes recorded in the 1988 study were also digitized directly into Syntrillium Software Corporation's Cool Edit 2000 (6 kHz sample rate), and individual fish calls were separated for analysis. Both video and audio tapes were originally recorded as part of a Masters Thesis (Wold 1991) and contain footage and hydrophone audio of three closely related species of California rockfishes: kelp (*S. atrovirens* Jordan & Gilbert), gopher (*S. carnatus* Jordan & Gilbert) and black & yellow (*S. chrysomelas* Jordan & Gilbert). Sound analysis was not published at the time as the focus of the study was on larval development. Because of difficulties involving calibration of both the hydrophone and original video system, absolute sound levels were not calculated for these species in this study.

Bamfield 2004

Since so little was known about rockfish sound production in the field, a wide variety of data collection techniques were attempted at the Bamfield Marine Sciences Centre on the west coast of Vancouver Island, British Columbia, Canada. Data were collected in June and July, 2004. Fishes were captured under a permit from the Department of Fisheries and Oceans, Canada and all research was approved by the Institutional Animal Care and Use Committee of the University of South Florida.

Hydrophone Recordings

A series of hydrophone recordings were made by hanging a hydrophone (HTI 96min; -164 dBV/μPa) from a dock, small boat or kayak. The recordings were originally made to a micro cassette recorder, then digitized. These were done at nearshore locations, including sites in 100 meter deep Trevor Channel, in order to establish typical background noises and ascertain if fish sounds could be heard.

Datalogger

A datalogger system including a hydrophone (HTI 96min; -164 dBV/μPa) and battery pack attached to a Toshiba E755 PocketPC in an underwater housing was deployed in several locations near the field station. Sound was recorded for 30 second intervals every five minutes with a sampling rate of 8820 Hz. The datalogger was primarily deployed just north of Ohiat Islet, where it was placed by divers next to a *S. nebulosus* "den" (at least one individual was seen in close proximity on every dive and it is likely that it was the same fish each time). In some of the recordings the internal microphone of the PocketPC overrode the hydrophone input. Fish sounds were nonetheless clearly audible in these recordings, and while they were not used for individual call analysis, the data were useful to show temporal patterns of sound production. Table 1 summarizes the datalogger deployments.

The Reef Environmental Education Foundation (REEF) roving diver fish survey technique (Schmitt et. al 1998) was used at each location where the datalogger was deployed to help characterize the fish assemblage. At least four such surveys were done at each site.

A video camera (Sony PC110) was set up in an underwater housing with a hydrophone attached (HTI 96min; -164 dBV/μPa). The camera was used by divers, mostly at the Ohiat Islet site, to attempt to record rockfish sounds in the field. Various species were approached underwater, especially: *S. nebulosus*, *S. melanops*, *S. caurinus*, and *S. maliger*. Due to the apparently imperturbable, even curious nature of most rockfishes at the site, it was difficult to provoke sounds.

Table 1 Summary of field datalogger deployments on the west coast of Vancouver Island. Dp is deployment number, Min is the total minutes recorded (30 seconds at a time). Depths are in meters. * For deployments 1 and 2, the system worked properly – for deployments 4 through 8, the internal microphone overrode the hydrophone input.

Dp	Date In	Date Out	Min	Location	Lat N	Long W	Depth
D1	2004-06-23 13:24	2004-06-24 16:15	180	Ohiat	48 51.356	125 10.973	12
D2	2004-06-28 12:00	2004-06-29 14:51	180	Ohiat	48 51.356	125 10.973	12
D4	2004-07-05 12:00	2004-07-07 04:02	481	Ohiat*	48 51.356	125 10.973	15
D5	2004-07-08 17:00	2004-07-10 09:02	481	Ohiat*	48 51.356	125 10.973	15
D6	2004-07-10 14:00	2004-07-12 16:28	433	Blackfish*	48 50.80	125 09.65	13
D7	2004-07-13 14:00	2004-07-14 17:01	481	Gobytown*	48 50.59	125 07.87	8
D8	2004-07-15 16:00	2004-07-16 20:35	291	Ohiat*	48 51.356	125 10.973	15

Captive Rockfishes

Two copper (*S. caurinus*) and two China (*S. nebulosus*) rockfish were captured and brought back to the lab. The copper rockfish were collected by hook and line from shallow water at the edge of a kelp bed near the marine station; the China rockfish were collected by divers between 10 and 15 meters deep near the Ohiat site, using a one meter jig.

After allowing sufficient time (up to 48 hrs for *S. nebulosus*) for their swim bladders to adjust, the fish were put in shallow outdoor tanks (approximately 1.5 meters square) in an area open on three sides but protected from the rain. After more time to acclimate to their surroundings, various attempts to elicit sounds were made. These included manually harassing the fish, placing a mirror into the tank, placing a small decorator crab (*Scyra sp.*) and larger red rock crab (*Cancer productus*) nearby, and placing one fish in with another. The *S. caurinus* individuals, both relatively small, never acclimated to captive conditions well enough to take food. The *S. nebulosus* individuals only began to take food in the days before the study ended.

Seattle Aquarium 2005

The Seattle Aquarium was visited in February 2005, when a number of species of rockfishes were reported to be breeding. Research was conducted in the aquarium's large, walk through tank, which holds approximately fifteen rockfish species, as well as numerous other Northwest fishes. A hydrophone (HTI 96min; -164 dBV/µPa) on a long cable was connected to a computer and/or video camera inside the viewing room, so visual observations could be made at the same time as audio recordings. Rockfishes of various species were watched at all daylight hours over the course of four days, while near continuous sound and occasional video/sound recordings were made. The computer was calibrated with a test tone of a known voltage so that received sound levels could be calculated. Sound data were analyzed in Cool Edit and separated into individual calls, especially the ones that were captured on video and could be associated with a certain species.

Table 2 Rockfish species known to be present in the Seattle Aquarium's large tank at the time of this study, including their observed relationship to the hydrophone. The last column shows which species were known to be breeding around the time of the study.

common	species	near most of the time	often near	often passing	breeding
china	*nebulosus*	Y			Y
canary	*pinniger*	Y			1 mo prev.
tiger	*nigrocinctus*	Y			?
widow	*entomelas*	Y			?
brown	*auriculatus*	Y			Y
black	*melanops*		Y		?
yelloweye	*ruberrimus*		Y		Y
quillback	*maliger*		Y		Y
copper	*caurinus*		Y		Y
yellowtail	*flavidus*		Y		N
rosy	*rosaceus*		Y		Y
redbanded	*babcocki*		Y		?
Puget Sound	*emphaeus*		Y		?
vermillion	*miniatus*			Y	?
blue	*mystinus*			Y	N

A diver also entered the tank with a hydrophone (HTI 96min; -164 dBV/µPa) attached to a housed video camera, and attempted to elicit sounds from various species of rockfishes, mainly by harassment but on a couple occasions by "herding" one territorial species into another's territory.

Due to logistics as well as ambient noise levels, the fixed hydrophone stayed in one particular section of the tank, mainly in between four pilings above a rocky bottom. Table 2 describes the approximately 15 rockfish species in the tank, and their relationship to the hydrophone. According to aquarium biologist Jeff Christiansen, it was possible (but "not likely") there may have been chilipepper (*S. goodie* Eigenmann) and/or dusky (*S. ciliatus* Tilesius) rockfish mixed with the widow rockfish (*S. entomelas* Jordan & Gilbert). Table 2 also shows which species were known to be breeding near the time of the study, also according to the aquarium biologist.

Analysis

Temporal Data

Data from the datalogger deployments in Bamfield were grouped by time of day into hour-long blocks. Each thirty-second recording that contained recognizable fish sounds (defined as at least one growl of three beats or more) was tallied in the hour long block in which it occurred. The sums were then divided into the total number of blocks in that hour to come up with a percentage. Time intervals which contained only pop type vocalizations (presumably a single hit on the bladder) were not included, in order not to mistake pops for sounds that were not produced by rockfishes. Boat noise was tallied from the first two Ohiat deployments by summing the number of 30 second intervals in which boat noise (including engines, nets and anchors) significantly masked other sounds. These were then averaged and expressed as a percentage of the total number of 30 second intervals per hour.

Due to technical difficulties, only the first two deployments (six hours recorded over approximately two days) contain valid recordings from the hydrophone – calls on these deployments were included in subsequent call analysis. During the remaining five deployments, which included 36 hours of recordings taken over approximately seven days, the internal microphone of the PDA overrode the hydrophone input. Despite this, there were recognizable fish calls in the data - while these were not considered as part of the call analysis, the 30 second blocks in which they occurred were tallied as simple sums in the hour in which they occurred, to add to the temporal data.

Individual Calls

Individual rockfish calls (saved as WAV sound files) were analyzed using Cool Edit 2000 as well as HotWav, a custom designed MATLAB (The Math Works, Inc.) program. Background noise can be considerable and variable in aquaria (see Figure 2), so some calls with a poor signal to noise ratio could not be used. Also, sounds that appeared to be one call superimposed on another were left out of the analyses, though this raises important questions that can only be answered by further studies that include close observation, video and more than one hydrophone in order to isolate which fish is making which call.

For the purposes of this study, a "call" was defined as a series of closely spaced pulses. Calls containing less than three pulses were not considered in the analysis. Rockfish calls were categorized for analysis in a number of ways (see Table 3). The species with enough recorded calls to be compared were *S. nebulosus* (n=207), *S. atrovirens* (n=64), *S. carnatus* (n=34) and *S. chrysomelas* (n=53). At the Seattle Aquarium, calls were elicited by harassment from *S. caurinus* (n=3) and *S. maliger* (n=2), and observed agonistically in *S. caurinus* (n=1), but not enough times for statistical analysis. Furthermore, there were reasonably clear calls on one of the datalogger sets in an area where the region's primary sound producer, *S. nebulosus*, was not observed, but where several mature brown rockfish (*S. auriculatus* Girard) were seen upon deployment and retrieval of the datalogger.

In addition to comparing calls between species, a distinction was made between the "harassed" calls of *S. nebulosus*, where a diver elicited a call from a single fish, and agonistic calls by the same species, where two individuals interacted and aggression was observed. Calls by *S. nebulosus* captured recently from the wild in Bamfield, British

Columbia, were compared with those of aquarium residents in Seattle. Finally, captive calls of known species were compared to sounds recorded from a datalogger set on a *S. nebulosus* den in the wild off British Columbia.

Background noise levels were particularly high in the frequency bands that rockfishes call at during studies at the Seattle Aquarium (Figure 2) and for the Bamfield captives. This decreases the signal to noise ration and makes analysis more difficult.

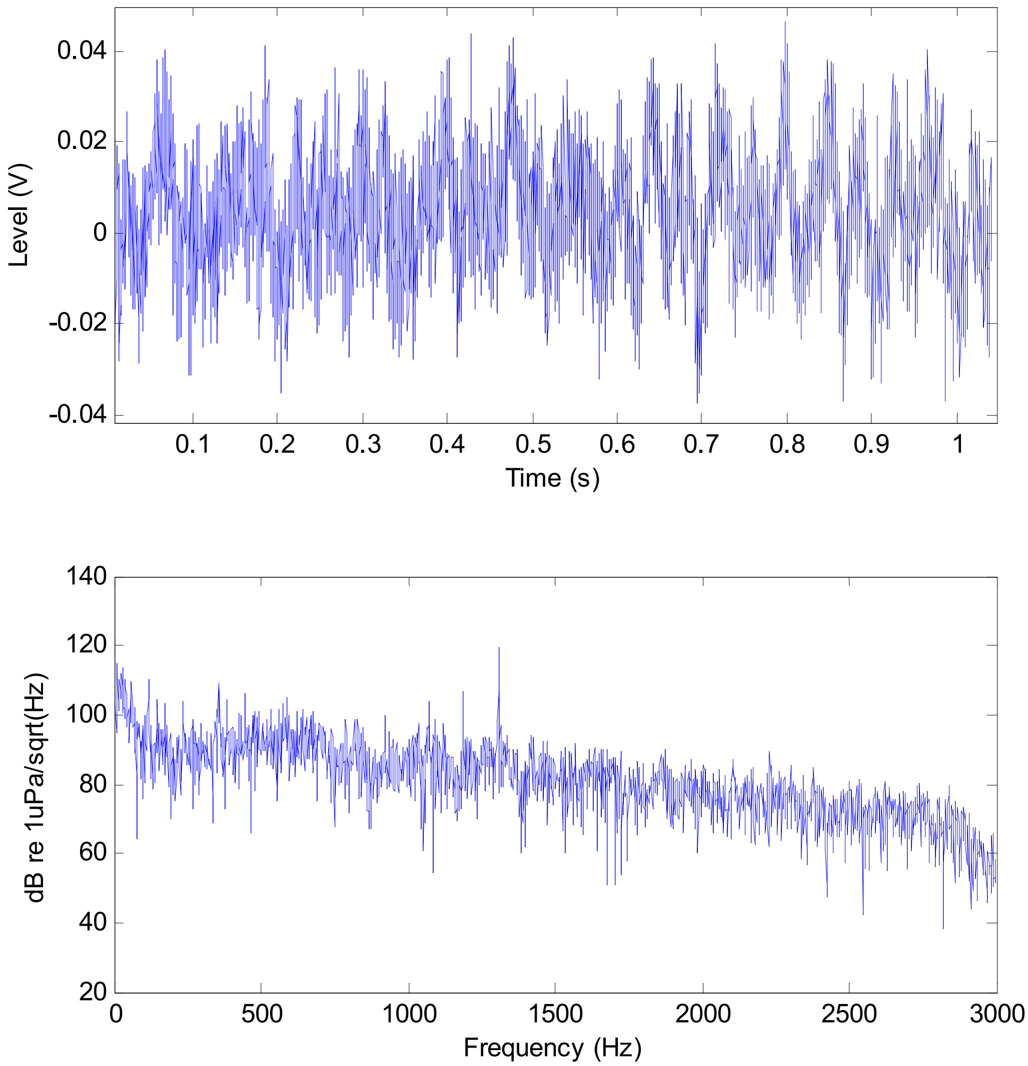


Figure 2 Oscillogram and power spectrum showing background noise in the Seattle Aquarium, taken from just after an *S. nebulosus* chase and call from which absolute sound levels were calculated.

Table 3 Rockfish calls were placed into the following groups (labeled by three letter codes) for comparative analysis. To focus on species differences, the five *S. nebulosus* groups were considered together for some analyses.

Code	Species	Description	# of calls
nSa	China *nebulosus*	Seattle agonistic: fish interactions observed on video	21
nSh	*nebulosus*	Seattle harassed: sounds provoked by a diver	27
nBa	*nebulosus*	Bamfield agonistic: sounds recorded between captive fish	31
nSm	*nebulosus?*	Seattle miscellaneous: sounds recorded with no accompanying video but presumed to be *S. nebulosus* due to hydrophone location and fish activity	49
nBw	*nebulosus?*	Bamfield wild: sounds recorded from a datalogger deployed next to a *S. nebulosus* den	79
aMa	kelp *atrovirens*	Moss agonistic: sounds recorded from captive fish	64
cMa	gopher *carnatus*	Moss agonistic: sounds recorded from captive fish	34
yMa	black & yellow *chrysomelas*	Moss agonistic: sounds recorded from captive fish	53

In order to compare calls between the different categories, a number of characteristics of each call were measured. These included:

1. call duration – the amount of time between the beginning and end of the call, estimated from the peak of the first pulse until the peak of the last recognizable pulse
2. number of pulses – the number of pulses contained within a call, inferred to correspond with the number of strikes on the swimbladder
3. peak frequency – the frequency that contained the highest energy levels, calculated in a custom MATLAB program
4. the coefficient of variation (SD/mean) of the interpulse intervals, measured from pulse peak to pulse peak

Amplitude was not considered in this analysis because of the potential differences in hydrophone sensitivity, as well as variable and/or unknown distances between the calling fish and the hydrophone. Rockfishes typically call during a chase, so the distance of the calling fish to the hydrophone often changed throughout the duration of the call.

Means and standard deviations were calculated for each of the call characteristics in order to show differences between categories and species. However, small differences in the means of any of the call characteristics are not likely to be biologically relevant, so more complex statistical comparisons were not attempted.

Source level (sound pressure level at 1 m from the hydrophone) was calculated from one call of *S. nebulosus* recorded at the Seattle Aquarium. This call was made in an aggressive chase approximately 1 m from the recording hydrophone. Source level was calculated as the route mean square level of the entire call and the peak-peak level of the loudest pulse.

RESULTS

Hydrophone Recordings

Thirty-seven different hydrophone recordings (duration 30 to 60 seconds) were made at a variety of locations, including the dock at the Bamfield Marine Research Station and the dive site where rockfishes of a variety of species were known to live. Numerous snaps and clicks of a likely biological origin were recorded, possibly generated by crustaceans or the jaws of surfperch (Family Embiotocidae). However, no sounds positively recognizable as rockfishes were detected on any of these recordings. During the day, boat noise, even from distant vessels, was probably loud enough to often mask rockfish calls that were not relatively close to the hydrophone.

Call Analysis

Peak sound pressure level was calculated from a chase (*S. nebulosus*) at the Seattle Aquarium where the fish were observed at a distance of approximately one meter from the hydrophone, and came to 139 dB re 1 μPa (peak). The root mean square sound pressure level was calculated as 111 dB re 1 μPa (RMS) after the signal was low pass filtered at 450 Hz to remove background noise.

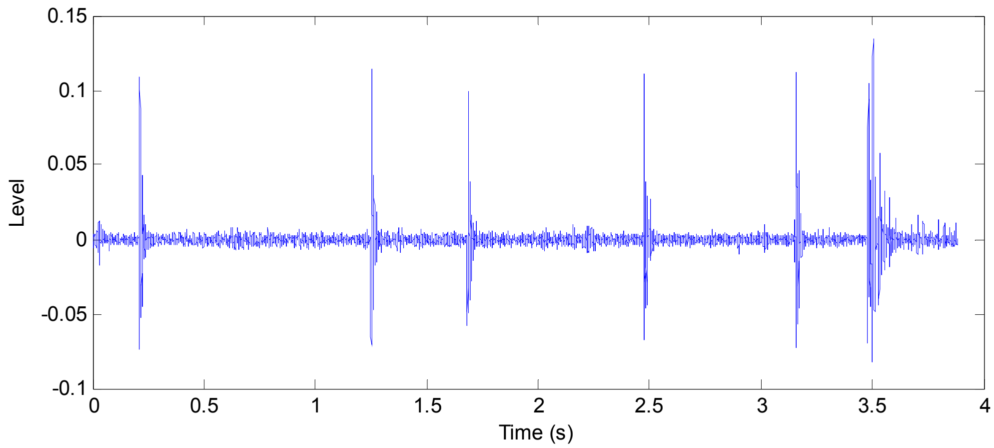
To assist with descriptions, the following terms will be used when discussing rockfish calls:

1. POP (Figure 3): a single, discrete hit on the swim bladder. Pops were observed on their own as well as before and after longer calls, but were not included in call analysis in order to avoid confusion with sounds from other sources.
2. GROWL (Figure 4): a short call consisting of a series of rapid beats (at least three), often with descending fundamental frequencies and amplitudes.
3. RUMBLE (Figure 5): calls longer than two seconds (and typically containing more than 75 pulses).

Yearsley (1970) and Fletcher (1983) both referred to call type two as a burp; both studies as well as this one noted such calls were usually associated with body movement.

Neither Yearsley nor Fletcher reported rumble type calls, which this study found to be exclusive to *S. carnatus*, *S. chrysomelas* and *S. atrovirens*, closely related California species not found in the Northwest.

Though twitching behavior that produced mechanical sounds was occasionally recorded, the following species were repeatedly harassed in the Seattle Aquarium without producing detectable growls or pops: *S. pinniger*, *S. rocaceous*, *S. entomelas*, *S. mystinus*, *S. melanops* and *S. miniatus*. In the Seattle Aquarium, *S. nigrocinctus* and *S. ruberrimus* were not only harassed but also recorded while displaying agonistic and/or courtship type behavior, with no associated detectable sounds. See Table 4 for a summary.



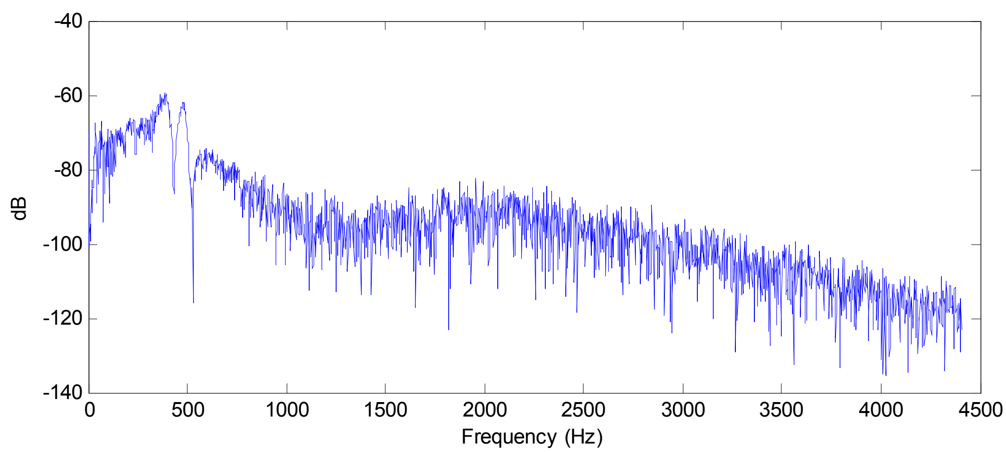


Figure 3 Oscillogram (top) showing a series of pop sounds followed by a short growl. Taken from a datalogger set on a *S. nebulosus* den off Vancouver Island. The power spectrum below is taken from an individual pop. The dB scale is a relative scale since these recordings were not from a calibrated system.

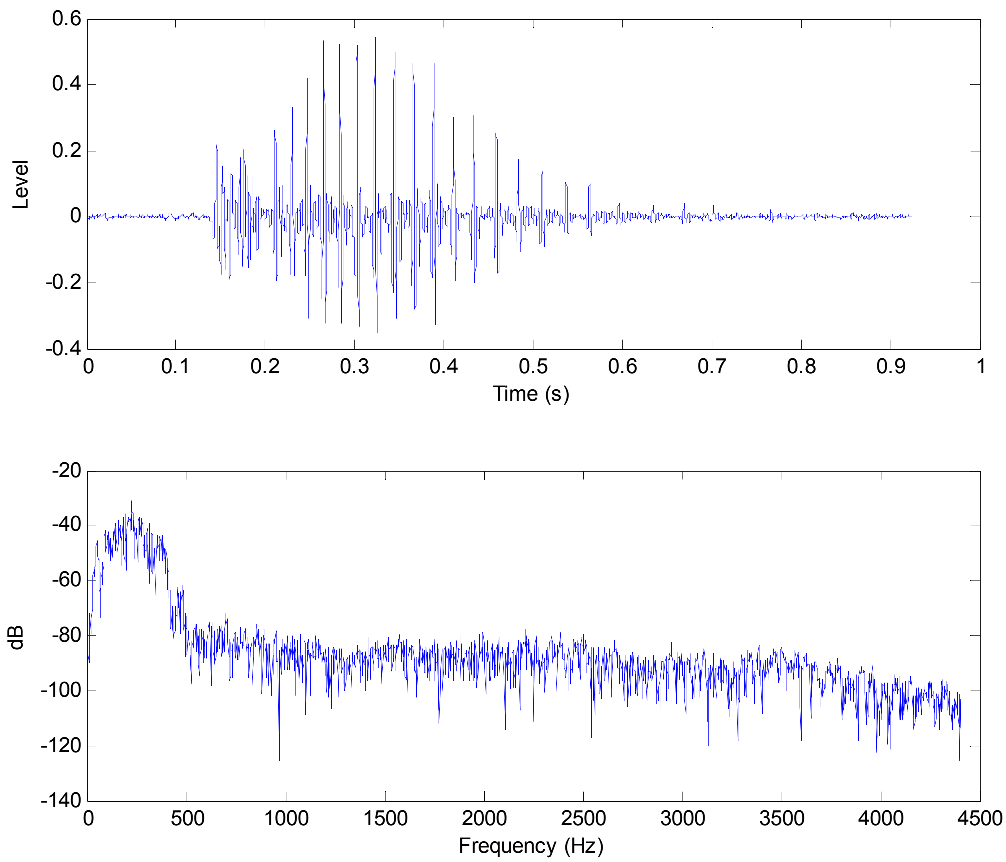


Figure 4 Oscillogram and power spectrum of a growl type call. Taken from a datalogger set on a *S. nebulosus* den off Vancouver Island.

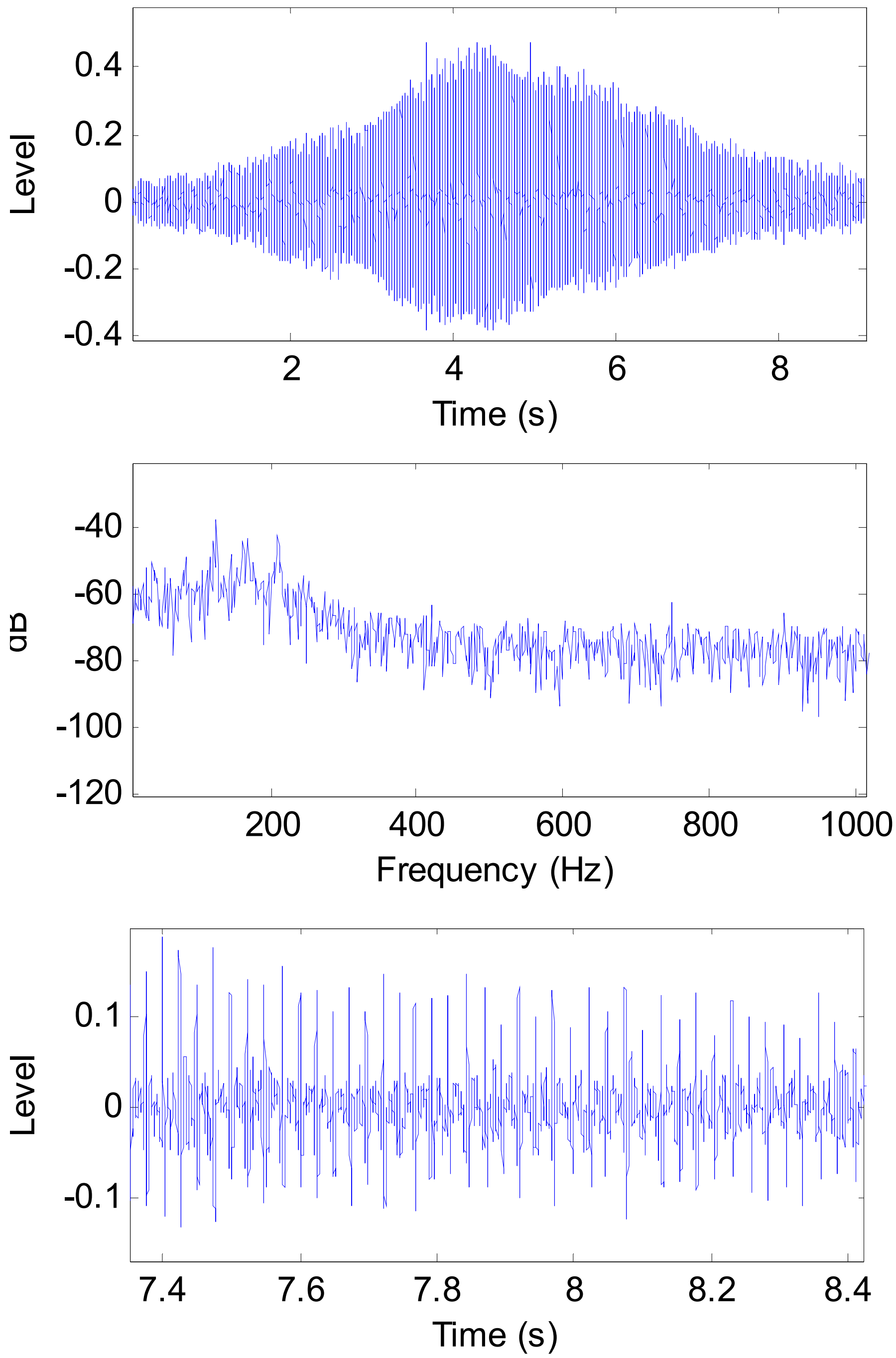


Figure 5 Oscillogram (top) and power spectrum (middle) of a rumble type call. The bottom oscillogram is a zoomed in view showing the distinct pulses.

Table 4 List of rockfish species at the Seattle Aquarium showing swimbladder muscle type (Hallacher 1974) as well as success at recording sounds produced in association with three different types of behavior. A "Y" means the sound was recorded in association with the behavior for the respective species. A "N" means the behavior was observed near a hydrophone but no sound was detected. Mechanical or muscle twitch sounds were not included. A "-" means the behavior was not observed, or not observed near a hydrophone.

Common	Species	Musculature	Harassed	Agonistic	Courtship
China	*nebulosus*	II a-v	Y	Y	N
copper	*caurinus*	II a-v	Y	Y	-
quillback	*maliger*	II a-v	Y	-	-
canary	*pinniger*	I a-z	N	N	-
tiger	*nigrocinctus*	I a-z	N	N	-
widow	*entomelas*	I a-z	N	-	-
brown	*auriculatus*	I a-z	-	-	-
black	*melanops*	I a-z	N	-	-
yelloweye	*ruberrimus*	I a-z	N	N	-
yellowtail	*flavidus*	I a-z	-	-	-
rosy	*rosaceus*	I a-z	N	-	-
redbanded	*babcocki*	I a-z	-	-	-
Puget Sound	*emphaeus*	I a-z	-	-	N
vermillion	*miniatus*	I a-z	N	-	-
blue	*mystinus*	I a-z	N	-	-

The individual pulses were very short, and likely produced by a single muscle twitch on the swimbladder (Figure 5). Figures 6 through 12 show the results of analyzing 359 calls from at least four different species. The graphs make it clear there is considerable overlap in every parameter – peak frequency, call duration, number of pulses, pulse rate and the coefficient of variation of the interpulse interval. All rockfish calling is low frequency, similar to other species that utilize extrinsic swimbladder musculature. The only discernible characteristics appear to be the duration and number of pulses, which are directly related (Figure 13). Though any given growl could have come from each of the four species, rumbles appear to be restricted to the California species, especially the *S. carnatus/chrysomelas* species complex.

As it was impossible to discern which individual fish were making the calls in the bulk of this study, it would be impossible to differentiate variance between individuals and variance between species. For this reason, means and standard deviations were graphed to display the data, but more complex statistical comparisons were not used. Furthermore, minor differences in the means of any of these characteristics would be unlikely to be biologically relevant, even if they were statistically significant.

Figure 6 shows the means each of the call characteristics, plus or minus one standard deviation. While call duration and number of pulses stand out, *S. nebulosus* appears to make short calls whether behaving agonistically or being harassed by a diver. Calls were also short for this species whether in the Seattle Aquarium, small tanks in Bamfield or in the wild, therefore subsequent graphs group all the *S. nebulosus* categories together. Note that higher peak frequency values are strictly a result of the wild recordings – the considerable background noise associated with aquaria and laboratory tanks may be partly or solely responsible for this.

Qualitative Observations

In addition to quantifying sounds, some observations made in the field and lab are worth noting:

1) most nearshore rockfishes rarely, if ever, make sound when harassed or handled; of the 15 species present at the Seattle Aquarium, considerable

harassment by a diver only elicited calls from three species (*S. caurinus*, *S. maliger* and *S. nebulosus*) and of those, only one species (*S. nebulosus*) would produce noise regularly

2) certain agonistic behaviors will sometimes be accompanied by sound production; sometimes not

3) sound production usually peaks when the agonistic fish are closest together in a charge/chase

4) though courtship behavior was observed near a hydrophone for at least two species in Seattle (*S. nebulosus*, *S. emphaeus*) and one in California (*S. atrovirens*), it appears to be visual - sounds were not associated with it

5) captive rockfishes from most sources are unlikely to be immediately suitable for sound or hearing studies due to swim bladder damage. It is unknown how long such injuries would take to recover, or if permanent damage is possible. Exceptions may include some of the more pelagic species (e.g. *S. melanops*, *S. flavidus*) which are more likely to be caught near the surface, and/or better able to off gas.

6) the noise level in aquaria may be sufficient to cause significant masking and even hearing damage in rockfishes, making acoustical studies more challenging

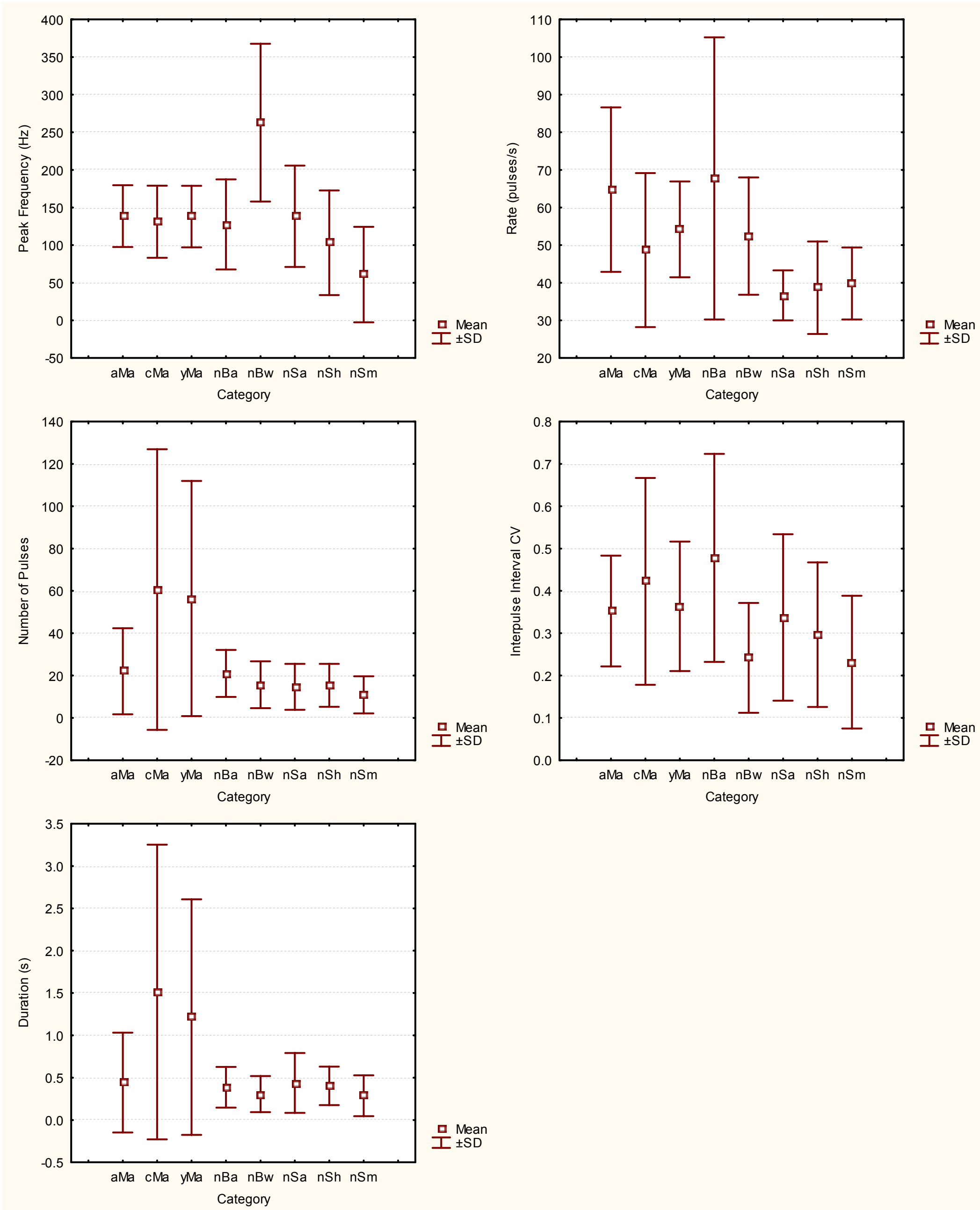


Figure 6 Means plus or minus one standard deviation for each of the call characteristics measured. Graphs are grouped by categories on the X axis - the first three represent California species recorded at the Moss Landing Marine Lab – the latter five are *S. nebulosus*. Categories are aMa – *S. atrovirens*; cMa – *S.carnatus*; yMa – *S.chrysomelas*; nBa – *S. nebulosus* Bamfield agonistic; nBw – *S. nebulosus in situ* datalogger; nSa – *S. nebulosus* Seattle agonistic; nSh – *S. nebulosus* Seattle harassed; nSm – *S. nebulosus* Seattle without video. Also see Table 3

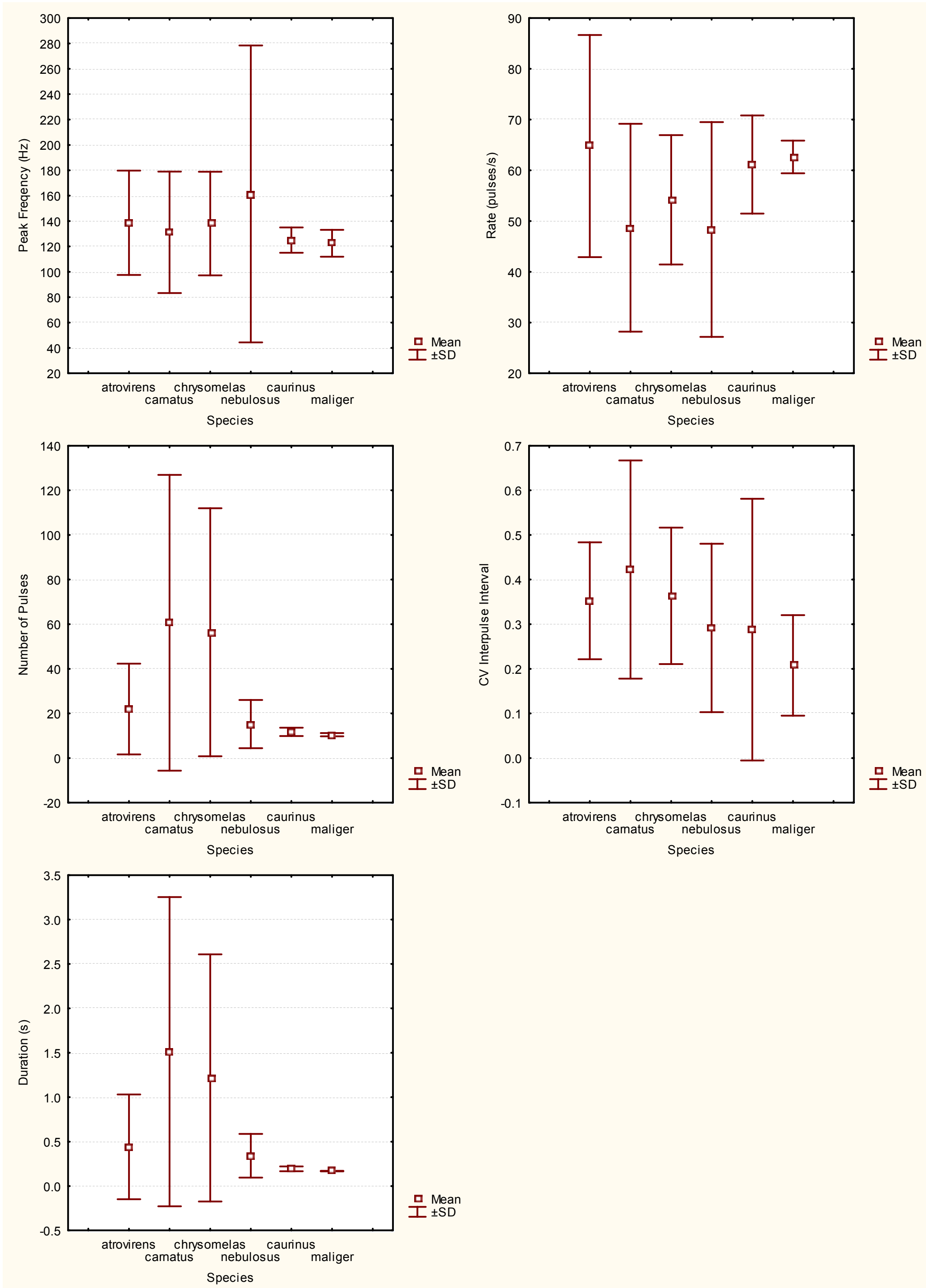


Figure 7 Means plus or minus one standard deviation for each of the call characteristics measured. Data are grouped by species along the X axis, including the two species where n<20 (*S. caurinus* n=4, *S. maliger* n=2). Note the considerable overlap in every characteristic apart from longer, rumble-type calls.

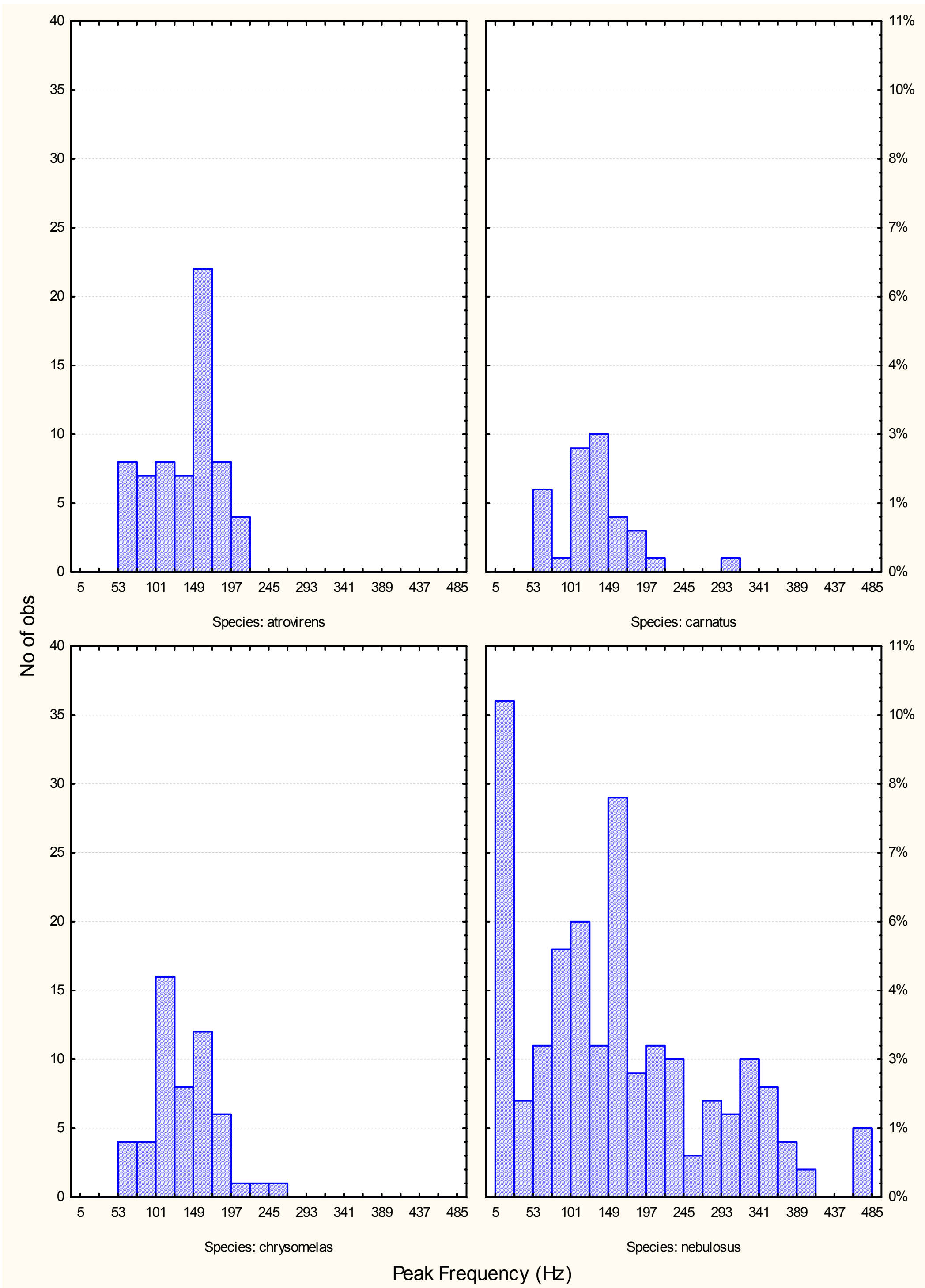


Figure 8 Histograms of peak frequencies (Hz) for the four rockfish species studied.

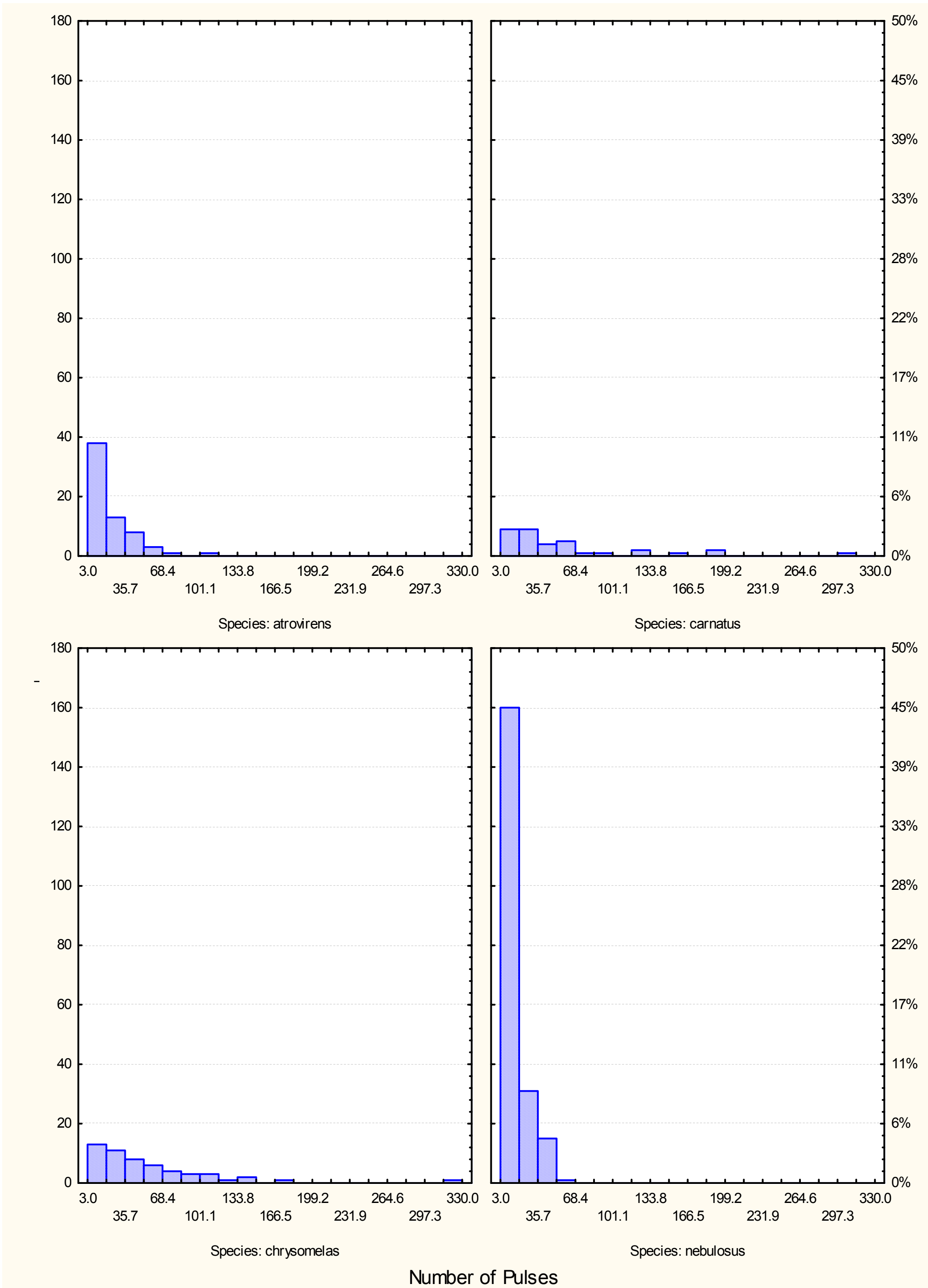


Figure 9 Histograms showing the number of pulses per call in each of the four species studied.

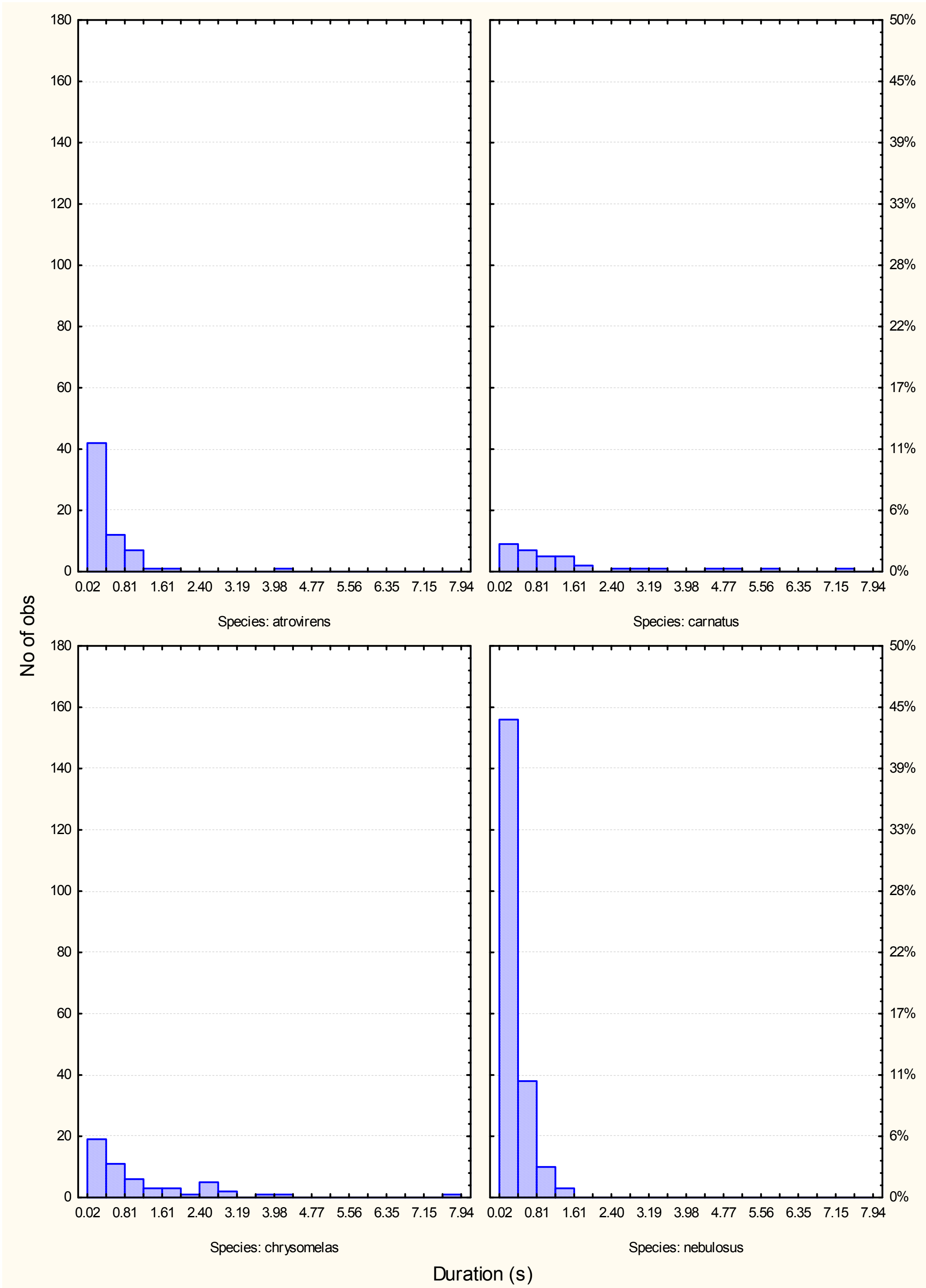


Figure 10 Histograms showing the call duration (in seconds) for each species.

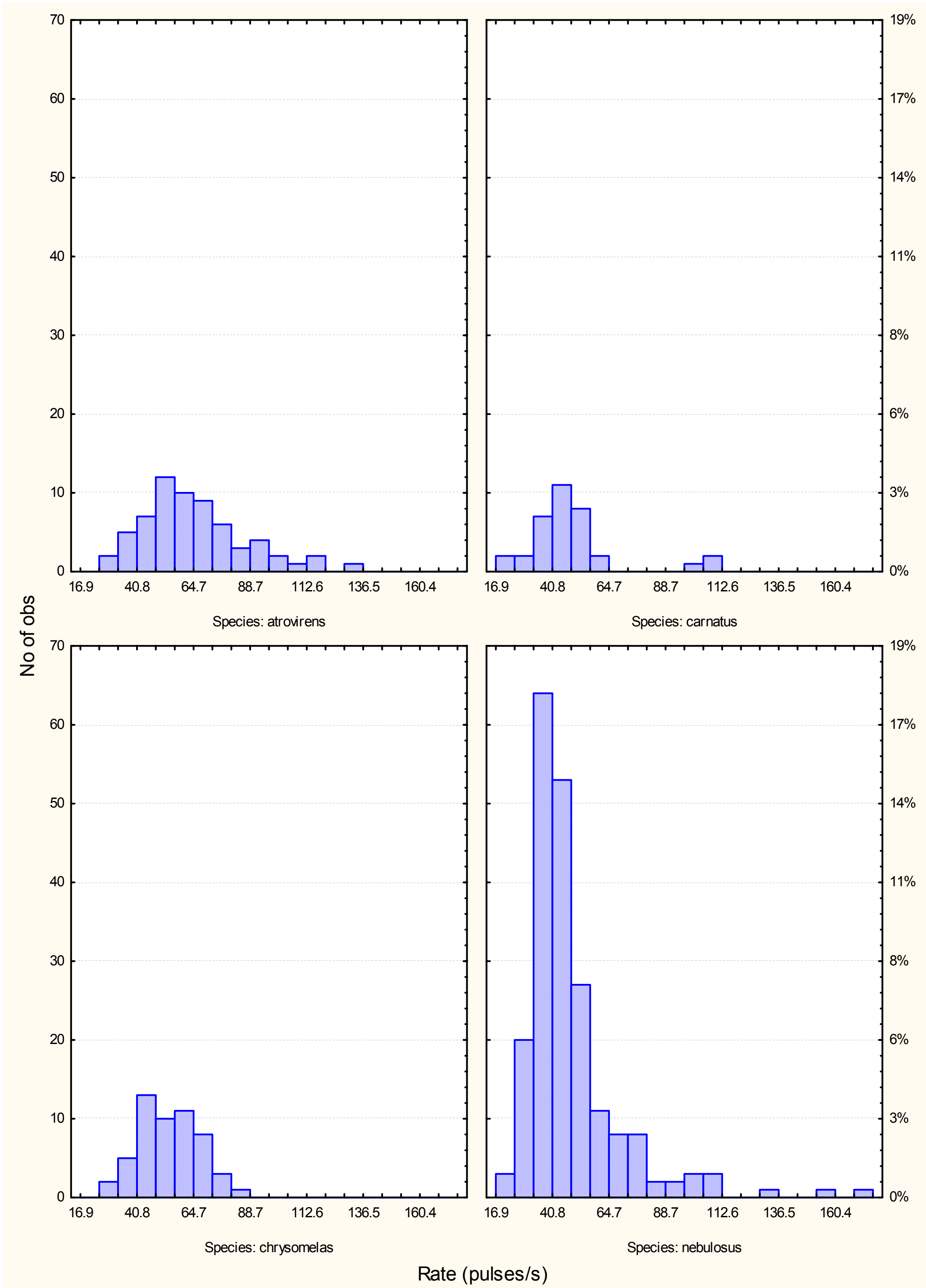


Figure 11 Pulse rate (pulses/s) histograms for the four species studied.

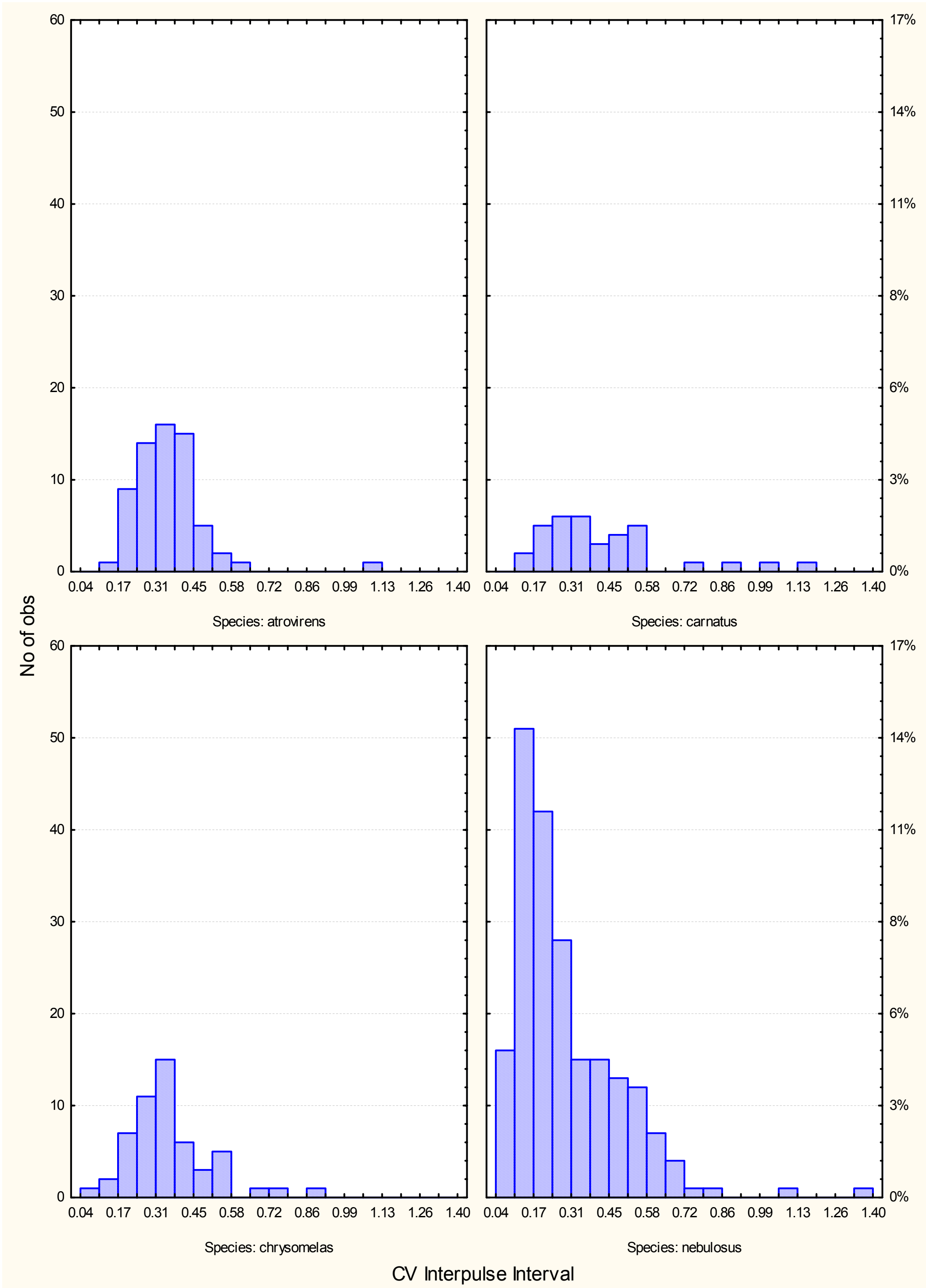


Figure 12 Histograms for each of the species studied showing coefficient of variation for the interpulse interval.

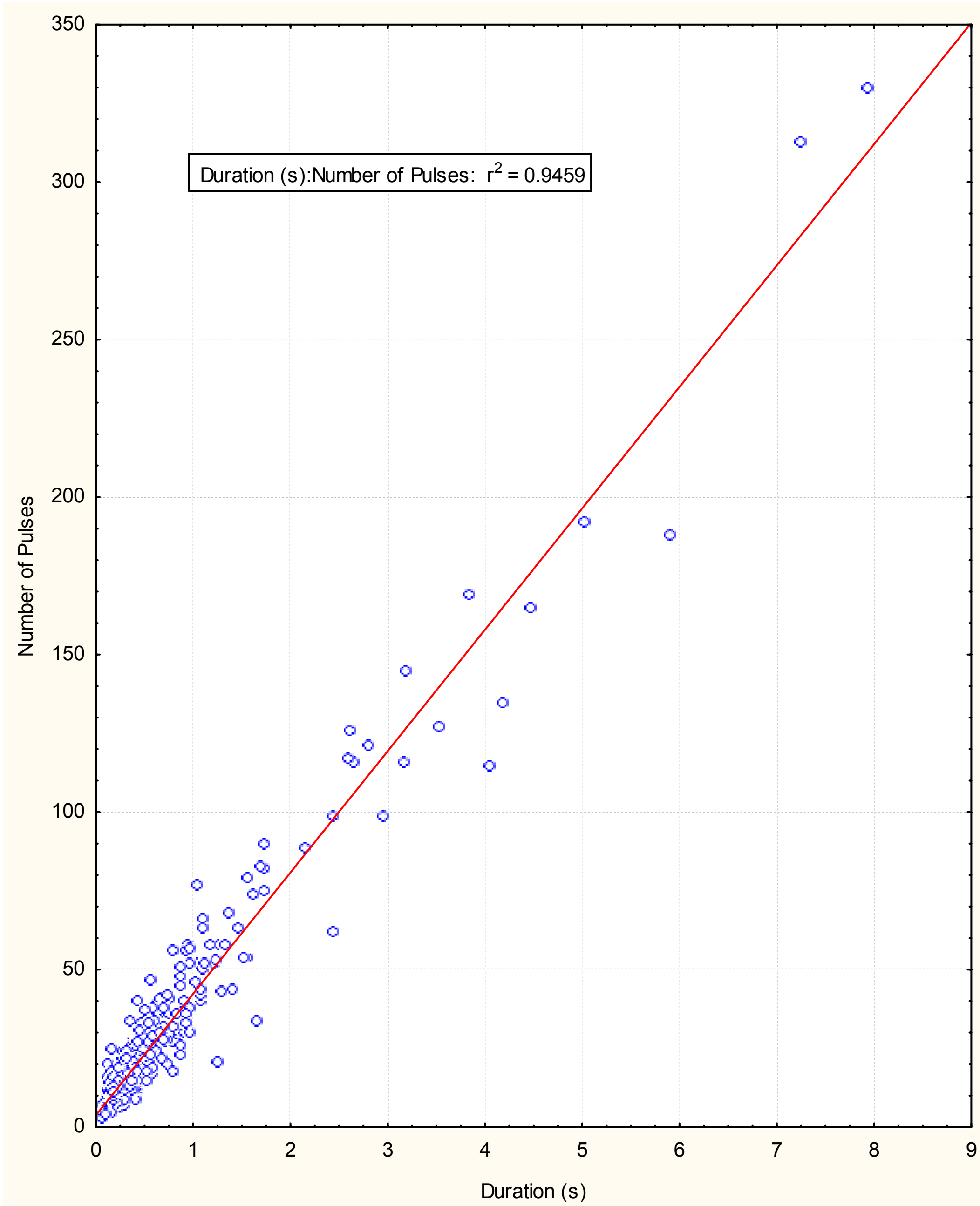


Figure 13 Number of pulses per call plotted against duration. All six species recorded (n=365) were included.

Datalogger

Table 5 shows the fish assemblages at each of the datalogger deployment sites, taken from dive surveys done by the primary author and stored in the Reef Environmental Education Foundation database. Note that rockfish species make up 29 percent of the total fish species observed. Also note that China rockfish (*S. nebulosus*), which were observed to be by far the most vocal species in the Seattle Aquarium, were seen on every dive at Ohiat but rarely or not at all at the other two sites.

Data from the first two datalogger deployments where the hydrophone was fully functional, both conducted at Ohiat Islet, are shown in Figure 14. The lighter area in the center of the graph represents daylight hours, taken from U.S. Naval Observatory's Astronomical Applications Department (http://aa.usno.navy.mil/data/docs/RS_OneYear.html). The approximate beginning and end of civil twilight were used. The datalogger was deployed right above a *S. nebulosus* "den" at a depth of 12 meters. The data show that sound appears to play an important role in the life of that species – 23.6 percent of the 30-second recordings had recognizable fish growls in them. Interestingly, rockfish growls were recorded throughout the day and night, with the most notable lull around 0800.

Figure 15 shows boat noise taken from the same two datalogger deployments at Ohiat. Both recreational and commercial fishing for salmon were occurring around the time of the study and are probably responsible for the majority of the boat noise. Masking of calls by boat noise does not appear to be directly responsible for the lows in calling activity that are shown in Figure 14.

Figure 16 shows the results of the remaining five deployments, which included 36 hours of recordings taken over approximately seven days, when the internal microphone of the PDA overrode the hydrophone input. The results, though limited to only the loudest and/or closest calls, also show calling throughout the night and a similar lull in activity around 0800.

Table 5 Species assemblage observed at the three datalogger deployment sites. The number of REEF surveys at each site is noted, and the sighting frequency (SF) and density index (DI) taken from the REEF database are provided for each species. REEF surveys record the species seen and an abundance category for each species. The DI is a measure of how many individuals of a species are observed based on a scale of 1-4. It is representative of the abundance category (1-4) which was most frequently recorded for the species when it was observed. Abundance categories are Single=1, Few=2, Many=3, and Abundant=4.

	Site	Ohiat It		Gobytown		Blackfish	
	# of surveys	9		8		4	
common	species	SF %	DI	SF %	DI	SF %	DI
Yellowtail Rockfish	*Sebastes flavidus*	100	3	100	2.8	100	3
Black Rockfish	*Sebastes melanops*	100	3	75	2.1	75	2.6
Blackeye Goby	*Coryphopterus nicholsi*	100	2.4	100	3.1	100	3
Longfin Sculpin	*Jordania zonope*	100	2	63	1.8	100	2
Copper Rockfish	*Sebastes caurinus*	100	2	100	2.1	100	2.2
China Rockfish	*Sebastes nebulosus*	100	2			25	1
Kelp Greenling	*Hexagrammos decagrammus*	89	2.6	100	2	100	2.2
Quillback Rockfish	*Sebastes maliger*	89	2.3	100	1.7	75	2
Unidentified Sculpin		78	2	100	2	50	1.5
Painted Greenling	*Oxylebius pictus*	78	1.8	100	1.7	50	1.5
Vermilion Rockfish	*Sebastes miniatus*	78	1.7	75	2	100	2.7
Pile Perch	*Rhacochilus vacca*	78	1.5	25	1.5	50	1.5
Striped Seaperch	*Embiotoca lateralis*	67	1.8	88	1.7	75	1.6
Shiner Surfperch	*Cymatogaster aggregata*	56	2.2	88	2.4	50	2.5
Lingcod	*Ophiodon elongates*	44	1.5			50	1
Wolf-Eel	*Anarrhichthys ocellatus*	33	1	25	1		
Grunt Sculpin	*Rhamphocottus richardsoni*	33	1	13	1		
Kelp Surfperch	*Brachyistius frenatus*	22	1.5	50	1.5	25	1
Spotted Ratfish	*Hydrolagus colliei*	22	1	38	1.3	75	1.6
Red Irish Lord	*Hemilepidotus hemilepidotus*	22	1				
Juv. Rockfish	*Sebastes sp.*	11	2	25	2	75	2
Rock Sole	*Pleuronectes bilineatus*			75	2.1		
Brown Rockfish	*Sebastes auriculatus*			50	1		
Tube-Snout	*Aulorhynchus flavidus*			25	2		
Unidentified Flatfish				13	2		
C-O Sole	*Pleuronichthys coenosus*			13	1		
Longfin Gunnel	*Pholis clemensi*			13	1		
Buffalo Sculpin	*Enophrys bison*			13	1		
Canary Rockfish	*Sebastes pinniger*					75	2
Unidentified Rockfish	*Sebastes sp.*					50	2
Pacific Sandlance	*Ammodytes hexapterus*					25	3
Spiny Dogfish	*Squalus acanthias*					25	1

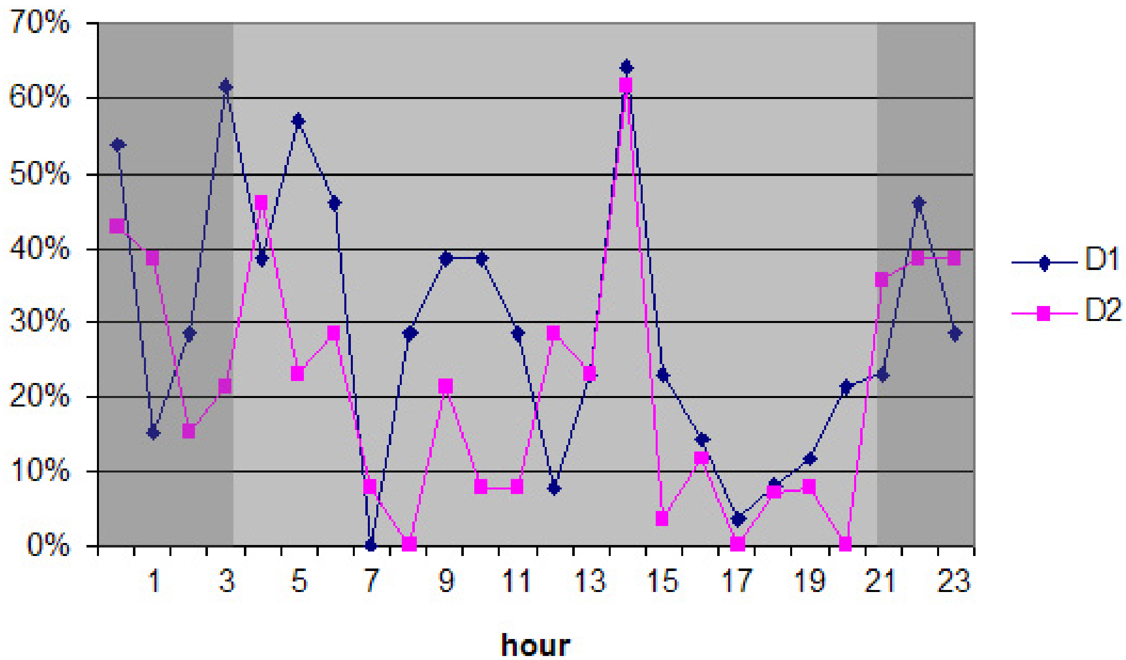


Figure 14 Calling behavior from two deployments of a datalogger next to the apparent den site of a China rockfish (*S. nebulosus*) at a field site near Ohiat Islet, British Columbia. The X axis is hour of the day from midnight to 23:59 – the lighter area in the center represents civil twilight and daylight. The Y axis is the percentage per hour of 30s recordings that contained at least one recognizable fish growl.

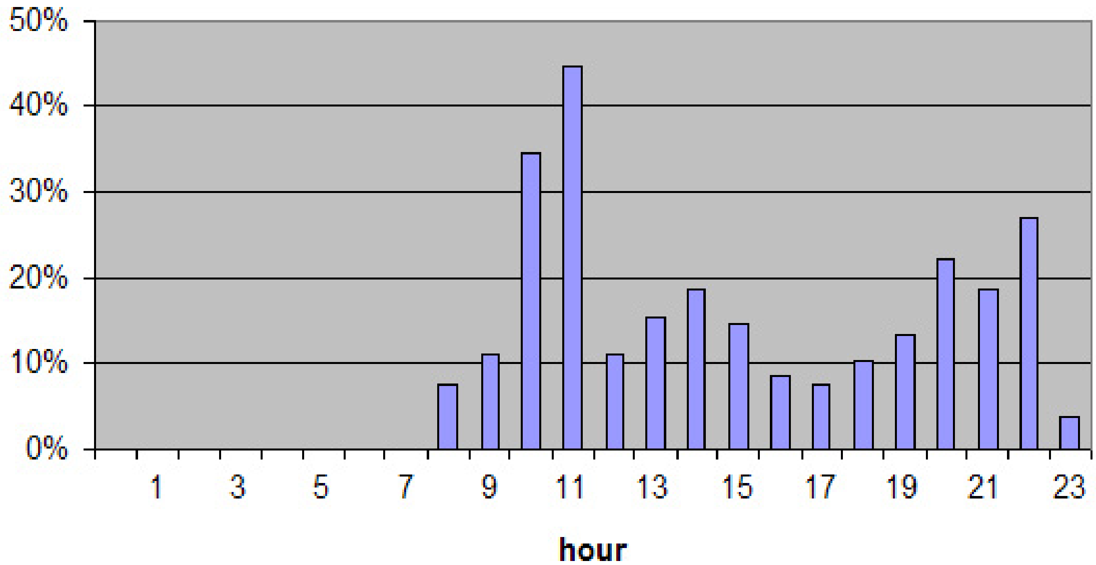


Figure 15 Percentage of 30 second recordings per hour in which boat noise significantly masked other sounds, averaged over deployments D1 and D2 at Ohiat Islet.

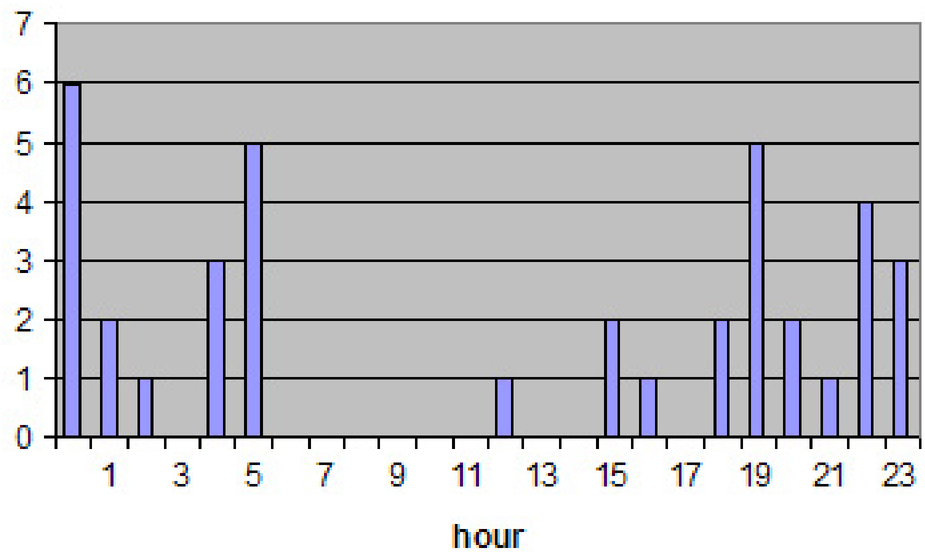


Figure 16 Sums of the 30 second blocks containing fish growls in each hour of the day, taken from the four datalogger deployments where the internal microphone overrode the hydrophone. The graph represents a total of 36 hours worth of 30s recordings, taken from five deployments at three different locales.

DISCUSSION

Swimbladder muscle type

Though it contains only seven of the eighty two Sebastes species (8.5 percent) examined by Hallacher (1974), his type II a-v musculature classification is obviously important to sound production. Of the fifteen species of rockfishes housed at the Seattle Aquarium, this study was only able to confirm sounds from three species, each of which had type II a-v musculature (Table 4). Furthermore, no other members of the group were present in the aquarium, but the other half of them, three species with ranges that end south of Washington State, make up the total of Wold's (1991) study. Not surprisingly then, the rockfish species with the largest drumming musculature appear to be the ones that make the most sound. At the time of the Seattle Aquarium study, it was estimated that well over ninety percent of the rockfish calls overheard spontaneously were associated with just one species, *S. nebulosus*, though that could be subject to seasonal changes or crowding.

Hallacher's seventh type II a-v species, *S. vexillaris*, has been subsequently grouped with the wide ranging and diversely patterned copper rockfish, *S. caurinus*. All six (or seven) of Hallacher's type II a-v species belong to the Sebastes subgenus Pteropodus (Kendall 2000). Molecular studies have shown *S. caurinus* is closely related to *S. maliger* (Gharret et al. 2001), while *S. atrovirens* is closest to *S. chrysomelas* and *S. carnatus,* and many authorities do not agree on whether the latter two are even separate species (Love et al. 2002). These six species are closely related even for Sebastes, a genus known for rapid speciation and controversial taxonomy.

There are ecological similarities as well - all six type II a-v species are considered benthic (seasonally in the case of *S. atrovirens)*, shallow dwelling species with small home ranges (Love et al. 2002). *S. nebulosus*, *S. chrysomelas* and *S. carnatus* are all considered territorial. Though *S. atrovirens* presently isn't, Littlejohn (personal communication) observed a seasonal shift to territorial behavior in captive specimens. This may correspond to a migration from kelp to benthic habitats observed in the wild (Van Dykhuizen 1983).

The other muscle group with sound related references was type I a-z, which Hallacher (1974) describes as the basic muscle structure found in the genus. It characterizes 62 of the 82 species examined (75.6 percent). Based on his dissections he concludes that most rockfish species are capable of sound production. To support this, both Yearsley (1970) and Fletcher (1983) reported recording sounds from black rockfish (*S. melanops*), a schooling mid water fish with type I a-z musculature, while Yearsley also recorded pops (only) from tiger rockfish (*S. nigrocinctus*), a territorial bottom dweller.

Combining Hallacher's work with this study, as well as the results of the unpublished acoustical studies, it would seem likely that most, if not all rockfish species are at least capable of producing pop sounds, though they may only rarely do so. At the Seattle Aquarium, repeated and varied attempts to record or illicit sounds from a number of *S. nigrocinctus* individuals were unsuccessful.

Speciation

There has been considerable interest in evolution and speciation within *Sebastes*, and sound production may be a new way to examine relationships. Are members of the genus diverging because they can produce and discern different sounds? Internal fertilization allows for courtship rituals that may include specific sounds or sound patterns. Parmentier *et al.* (2005) recently described regional differences in sound production characteristics of anemonefish (*Amphiprion akallopisos*).

Based on the results of this study, sound production is unlikely to be contributing to rockfish speciation. This is primarily because all the sound production appeared to be associated with agonistic rather than courtship behavior. This is in keeping with Hallacher's (1974) findings that both male and female rockfish have sonic muscles – species such as weakfish (*Cynoscion regalis*) that have been shown to produce sounds related to courtship and spawning, show sexual dimorphism in their sound producing musculature (Connaughton et al. 2002). In other Sciaenidae (drumfish and croakers), a family well known for sound production and mating choruses, sonic muscles are generally present in mature males only (Tavolga 1964).

In addition to the lack of sexual dimorphism in musculature and our failure to observe sound production directly related to courtship or mating, the overlapping nature of the calls we observed also indicates sound does not play a role in rockfish speciation. As it was not possible to discern the species of a call through our analysis, it is unlikely (though still possible) that individual fish can do so. The calls may overlap simply because of the close phylogenetic relationships and similar anatomy of the species examined. Closely related rockfish species with overlapping ranges appear to be courting each other with visual cues, not sonic ones, though considerably more research needs to be done to verify this. The paucity of observations of rockfish courting and mating, with or without hydrophones present, makes this question difficult to resolve.

Growls and Rumbles

The only major difference between calls that showed up in the analysis was the fact that *S. carnatus* and *S. chrysomelas*, two very closely related species, appeared to be the only ones to regularly make long duration rumbles as well as shorter growls. Three possible reasons for this are:

1. all six *Sebastes* species studied can rumble but the two observed do it much more often

2. all six *Sebastes* species studied can rumble and the observed difference was related to external variables such as season, environment or crowding. This is supported by evidence from video clips that appear to show *S. atrovirens* rumbling in their territorial phase.

3. anatomical or physiological differences prevent some species from rumbling.

Fish sonic muscles are capable of contracting and recovering at unusually quick rates (Tavolga 1964). It is possible that due to differences in anatomy and/or muscle physiology, only certain species are capable of sustaining a longer call. In this study, pulse rate and number of pulses showed a significant but slight negative correlation (r =

-0.11, n=365). This can be seen in Figure 17, which shows a minor negative trend towards slower pulse rates as calls get longer. *S. atrovirens* appeared to rumble in captivity, but not as often as *S. carnatus* or *S. chrysomelas*. *S. nebulosus* didn't seem to rumble, either in captivity or in situ. Thus, the production of rumbling sounds coincides with molecular evidence of how closely related these four species are. Further acoustical study on a wider range of rockfish species would help resolve this interesting question.

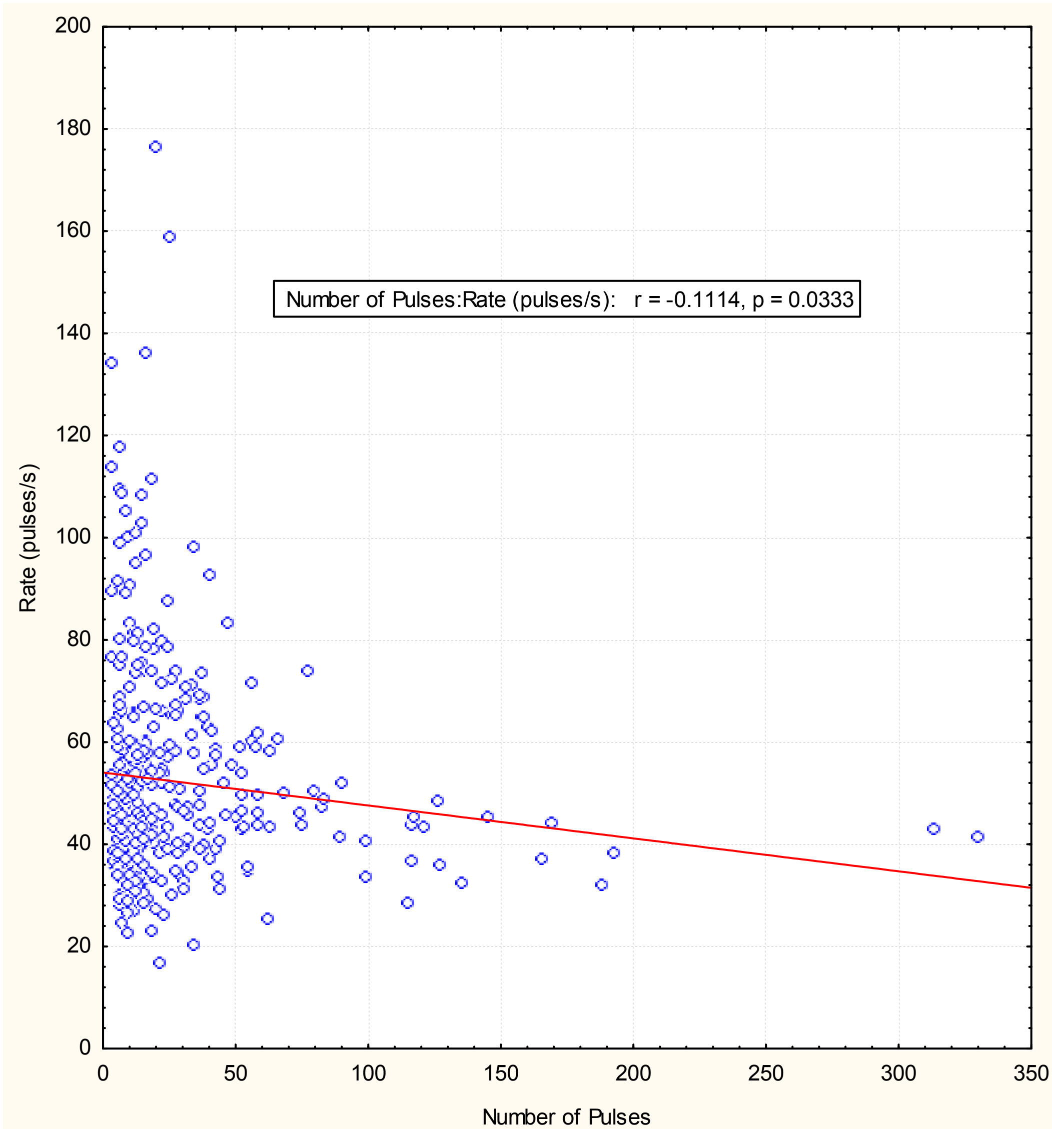


Figure 17 Pulse rate plotted against number of pulses for all *Sebastes* recorded (n=365). There was a slight negative correlation between the two (r=-0.11); note that none of the calls with more than 80 pulses had rates higher than approximately 50 beats per second.

Reasons for Calling

The calculated root mean square amplitude of the calls confirms anecdotal evidence – though at least some rockfishes do call, they do not make loud calls. Given typical hearing thresholds in fishes, it must be concluded that rockfishes do not use sound for long distance communication (Fay 1988). This is supported by observational data – any behavior associated with calling was agonistic and took place between fish less than four meters apart.

Based on a number of factors observed in the lab (loudness of sounds versus distance to hydrophone; single fish with mirror; tests with different species and harassment with a net) Yearsley (1970) concluded that only dominant fish produced "pops". This study supports the dominant pop idea – when observed, pops appear to be issued as a challenge.

Could the pops be an indicator of how big the fish is? Myrberg et al. (1993) reported a direct relationship between the length of damselfish and the peak frequency of their calls. If rockfishes could produce and detect aggressive sounds that indicated their swimbladder size, it might be useful in reducing the energy expenditure of chases and potential harm of direct physical challenges – *S. nebulosus* can be very aggressive towards conspecific intruders.

Pops may occur when an individual fish feels another is approaching too closely. As the intruder gets closer, the popping sounds of the aggravated fish become faster and perhaps louder, until the growl of a chase follows. This strategy would let an intruder know if it was getting too close. Conversely, an approaching fish may pop to intimidate a territory holder.

Growls are more difficult to explain. Yearsley (1970) believed that some species never produced sound when submissive but others did, and two species produced growls whether dominant or submissive but usually associated with sudden locomotory movement. Because of the dynamic nature of chases and their accompanying growls, it is difficult to ascertain which fish is making the sound, or even if it is just one. As the sounds made by *S. nebulosus* individuals harassed by a diver were indistinguishable from those made during agonistic behavior, it may often be the submissive fish growling, not the aggressor. This is supported by at least two observations when growls were recorded from *S. nebulosus* individuals that were chased by fish (kelp greenling, *Hexagrammos decagrammus*) other than rockfishes.

Temporal Data

Though other studies (see Love et al. 2002, p. 55-56) have indicated that most species of rockfishes are primarily diurnal, there appear to be calls on the field datalogger throughout the night (Figures 14 and 16). While sounds recorded on the datalogger cannot be positively identified to species, the location of the deployment, on the den site of at least one *S. nebulosus*, the most vocal Northwest species, makes it likely that the vast majority of the calls recorded were made by that species, perhaps even by one or two individuals.

Diel periodicity in mating choruses has been shown for sand sea trout (*Cynoscion arenarius*), a broadcast spawner, using dataloggers (Locascio and Mann 2005). In this study no choruses were detected, but there were more calls per hour after midnight and around 0500 and 1500. There were also lulls around 0800 and 1800 – these patterns might be coincidence, but could also represent changes in activity levels for the resident fish at the den site. The datalogger would appear to indicate that *S. nebulosus* is active throughout the night and perhaps more sedentary in the morning, though it could also be that the individual left the area during the morning. More deployments and visual observations would help resolve this issue and provide important information about the ecology of this species.

Further Research

One of the main purposes of this study was to direct further research. Considerable effort was involved in gathering the results of unpublished work, all at least sixteen years old but relevant and helpful. Some of the research methods attempted during this study (eg. hydrophone trawls) proved to be unproductive, given the nature of rockfish sound production. It would appear that one of the main reasons why rockfish sound production is so poorly known is that most species of nearshore rockfishes don't make sounds very often, and few (if any) make sounds that are relatively loud.

Rockfishes apparently use sound for agonistic purposes, but only up close – unlike other territorial soniferous fish, they do not appear to "call out" their territories. However, due to the lack of mating data from either wild or captive fish, it is difficult to rule out reproductively related sounds. Certainly, the Moss Landing captive studies showed at least one species (*S. atrovirens)* changes its behavior dramatically during mating season, resulting in more territorial and agonistic behavior, with an associated increase in agonistic sound production.

What should the next studies focus on? Passive acoustical techniques will be unlikely to reveal mating activity as they do with other species, though they may help identify areas where rockfishes are and could possibly be helpful with monitoring size and/or abundance. Further study will benefit from more extensive use of *in situ* dataloggers, as the acoustic conditions in aquaria or laboratories are rarely conducive to studying the relatively low amplitude sounds that most rockfishes produce. It is also likely that rockfish species that live beyond safe diving depths are sound producers, and placement of hydrophones on deep reefs will help address this.

Perhaps the most interesting line of research would be to see if there is a correlation between the pop sounds that rockfishes make and the size of the individual, and whether rockfishes are capable of detecting it. If so, acoustical dataloggers may be helpful in passively monitoring size changes over time, something especially helpful in studies involving marine reserves.

Because of the logistics of catching and acclimating rockfishes to tanks, which can take weeks or even months, captive sound work would be best suited to a longer term project. Very few aquaria, even those with large tanks, have had much success breeding rockfishes, so mating studies would be difficult. However, using captive studies to examine relationships between sound production, species, size, gender, and season would be most interesting. As acoustical background noise in many existing aquaria is difficult to work with, it is worth outlining an ideal setup. A relatively large tank, lit by ambient light, containing den sites, an array of fixed hydrophones, with viewing possibilities for video, dampened or isolated mechanical noise, and sound absorbing walls would be an excellent start.

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