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Sablefish (*Anoplopoma fimbria*) produce high frequency rasp sounds with frequency modulation[a)]

Amalis Riera,[b)] Rodney A. Rountree, Lucas Agagnier, and Francis Juanes
Department of Biology, University of Victoria, 3800 Finnerty Road, Victoria, BC V8P 5C2, Canada

ABSTRACT:
Sablefish sounds, named rasps, were recorded at two captive facilities in British Columbia and Washington State. Rasps consisted of highly variable broadband trains of 2 to 336 ticks that lasted between 74 and 10 500 ms. The 260 rasps that were measured contained frequencies between 344 and 34 000 Hz with an average peak frequency of 3409 Hz. The frequency structure of ticks within rasps was highly variable and included both positive and negative trends. This finding makes sablefish one of the few deep-sea fish for which sounds have been validated and described. The documentation of sablefish sounds will enable the use of passive acoustic monitoring methods in fisheries and ecological studies of this commercially important deep-sea fish. © *2020 Acoustical Society of America*.
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I. INTRODUCTION

Fish sounds have been studied since at least the late 1800 s (Dufossé, 1874) and since then there have been numerous accounts of the variability that exists in fish sound production (Fish, 1948; Fish *et al.*, 1952; Moulton, 1963; Schneider, 1966; Tavolga, 1971; Hawkins, 1993; Kaatz, 2002; Ladich, 2004; Fine and Parmentier, 2015; Zeyl *et al.*, 2016). The ability to recognize fish sounds is becoming increasingly useful for passive acoustic monitoring (PAM) studies on population and ecosystem health (Rountree *et al.*, 2006; Slabbekoorn *et al.*, 2010; Riera *et al.*, 2016; Archer *et al.*, 2018; Lindseth and Lobel, 2018). In order to use PAM, examples of sounds from each species of fish need to be validated and available for comparison to the sounds recorded through PAM (Rountree *et al.*, 2002). There are currently ∼34 300 known fish species (Froese and Pauly, 2019) and sound production has been reported for fewer than 1000 species (Lobel *et al.*, 2010), although an updated number remains to be confirmed. This number is growing as new fish sounds are being described (Wilson *et al.*, 2004; Riera *et al.*, 2018; Rountree *et al.*, 2018). Despite these efforts, the capacity for sound production remains to be investigated for the majority of fish species (Rountree *et al.*, 2002, 2019).

There is increasing interest in understanding the dynamics and health of deep-sea ecosystems such as sponge reefs (Archer *et al.*, 2018), seamounts (Department of Fisheries and Oceans Canada, 2011), and banks, as these systems are fragile and vulnerable to overfishing (Koslow *et al.*, 2000). The soundscape of the deep sea is poorly known and the use of PAM methods to study these ecosystems is becoming more common (Rountree *et al.*, 2012; Wall *et al.*, 2014). The deep-sea sablefish (*Anoplopoma fimbria*, order Scorpaeniformes, family Anoplopomatidae), also known as black cod, is an economically important ground fish native to the North Pacific Ocean ranging from Baja California to the Bering Sea and throughout the Aleutian Islands into waters off the Kamchatka Peninsula, Russia, and northern Japan (Wilkins and Saunders, 1997; Jacobson *et al.*, 2001). Adult sablefish inhabit the upper continental slope and deep continental shelf at depths of 200–1280 m (Wilkins and Saunders, 1997; Jacobson *et al.*, 2001). Sablefish support valuable commercial and recreational fisheries in Alaska (Warpinski *et al.*, 2016), Japan, Russia, and along the U.S. West Coast (Koslow *et al.*, 2000). In addition, thanks to its high growth rate and market value, sablefish aquaculture is developing in several countries, including the U.S. and Canada (Sumaila *et al.*, 2007; Sanchez-Serrano *et al.*, 2014; National Marine Fisheries Service, 2017). The sablefish was first suggested to produce sounds in an unpublished study of captive fish by Meldrim (1965) and later based on deep-sea recordings associated with sablefish presence at deep-sea observatories (Sirovic *et al.*, 2012), but these observations have not been substantiated. Confirmation of sablefish sound production, together with a validated description of sablefish sound characteristics, would provide researchers with a new tool to monitor the species using passive acoustics.

The goal of this study was to determine if sablefish produce sounds, and if so, to provide validated sound descriptions to enable future PAM studies of the species. Captive sablefish were observed and recorded both in an open-water aquaculture facility and in a sablefish research station.

II. MATERIALS AND METHODS

A. Data collection

Acoustic recordings were obtained at two facilities: Golden Eagle Sablefish Farm (GESF) (BC, Canada), where

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[b)]Electronic mail: ariera@uvic.ca

a few hundred sablefish were held in 30 m^2 net pens, and the NOAA Northwest Fisheries Science Center at Manchester Research Station (NWFSC-MRS) (WA, USA), where 20–30 sablefish were held in 3.66 m diameter tanks. There were only mature adult sablefish at GESF [size range: 46–85 cm total length (TL)]. At the NWFSC-MRS adult sablefish (size range: 35–75 cm TL) were monitored from seven tanks, and juveniles (size range: 3–5 cm TL) from a single tank. The adult sablefish at NWFSC-MRS were distributed in four tanks with mixed sexes, one tank with only males, and two tanks with unknown sexes.

At both facilities, sablefish were monitored for sound production in real time. Recordings were made at 96 kHz (24 bit), to a Zoom-H1 recorder (Zoom North America, Hauppauge, NY) with an uncalibrated SQ26-01 hydrophone (sensitivity = −193.5 dB re: 1 V/μPa, Cetacean Research Technology, Seattle, WA). At the NWFSC-MRS, water pumps were turned off in order to reduce noise.

A Song Meter SM4 recorder (Wildlife Acoustics, Maynard, MA) with an HTI hydrophone (sensitivity = −165 dB re: 1 V/μPa, High Tech Inc., Long Beach, MS) was also deployed in a tank containing juvenile sablefish at NWFSC-MRS to collect data on a continuous duty cycle at 96 kHz (16 bit) for up to 4 days. No alterations were made to the regular schedules of pumps and filters for SM4 recordings.

B. Data post-processing

Acoustic measurements of selected parameters of all sablefish sounds were made in Raven Pro 1.5 acoustic software (Center for Conservation Bioacoustics, 2014) following Charif *et al.* (2010). Recordings were visually inspected in their entirety to identify sablefish sounds. Spectrograms were displayed 15 s at a time with frequencies between 0 and 11 kHz [2825 fast Fourier transform (FFT), Hann window, 85% overlap]. Selection boxes were drawn around each sound to measure the sound duration, the lowest peak, and highest frequency, the 5th and 95th percentile frequencies (F. 5% and F. 95%, respectively), and bandwidth 90% (BW 90%) (Charif *et al.*, 2010). Raven Pro automatically computed these values based on the selection boundaries. F. 5% is the frequency that divides the selection into two frequency intervals containing 5% of the energy at the bottom and 95% of the energy at the top, while F. 95% is the frequency separating 95% of the energy at the bottom and 5% at the top. BW 90% is the difference between F. 5% and F. 95% frequencies. The peak frequency is the frequency at which maximum power occurs within the signal. For each variable, the measurements reported include minimum, maximum, and mean ±SE (standard error).

Sablefish sounds are comprised of a number of broadband ticks that are separated from each other by variable durations. To differentiate between one sound and the next, an arbitrary cutoff of 1 s was used.

A subset of 72 sablefish sounds from the NWFSC-MRS was used to count the number of ticks per sound and measure tick-specific duration and frequency parameters (724 FFT, Hann window, 85% overlap). The duration between ticks, or period, was calculated as the time between the beginning of one tick and the beginning of the next tick (Fig. 1). The inter-tick interval was calculated as the time between the end of one tick and the beginning of the next tick. The tick repetition rate was calculated by dividing the number of ticks in a given sound by the duration of that sound. Within-sound variation in tick frequency structure (F. 5%, peak, F. 95%, and BW 90%) was tested for correlation with elapsed time for 57 unique sounds having 8 or more ticks. Spearman Rank correlation on log transformed frequencies was performed due to non-linear data trends using SAS/STAT software (SAS Institute Inc., 2012).

Mm. 1. Audio clip of short sablefish rasp (with fewer than eight ticks) corresponding to the spectrogram displayed in Fig. 1. This is a file of type "WAV" (561 KB).

III. RESULTS

Sounds attributed to adult sablefish were produced by highly agitated fish that displayed aggressive behavior (charging and nipping the hydrophone) during net pen transfer at GESF. Similar sounds were recorded from captive specimens at the NWFSC-MRS but were not associated with any specific behavior.

Sounds were recorded at GESF between 2:00 pm and 6:00 pm. Sounds were recorded at the NWFSC-MRS in 5 °C water between 7:00 am and 4:30 pm. At NWFSC-MRS, two or more rasps were heard in each of the four tanks that contained mixed genders, and the tank that had only males. No rasps were positively identified in the recordings from the two tanks with unknown genders nor in the tank that contained juveniles.

The duration of sablefish sounds ranged between 74 and 10 493 ms (average of 1342 ± 96 SE; Table I) and they

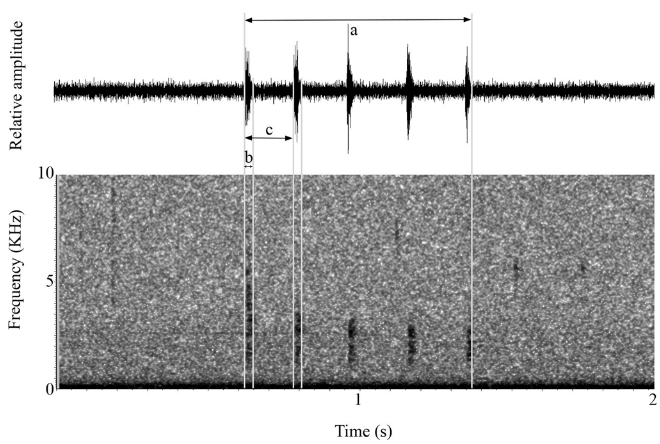

FIG. 1. Waveform (top) and spectrogram (bottom) of a short rasp (with fewer than eight ticks) produced by sablefish (*Anoplopoma fimbria*) at the Northwest Fisheries Science Center in Manchester (1800 FFT Hann window with 85% overlap). The temporal measurements are illustrated: rasp duration (a), tick duration (b), and period (c). A clip of the sound is available as a multimedia file (Mm. 1).

TABLE I. Acoustic variables for sablefish (*Anoplopoma fimbria*) rasps recorded at two facilities, showing stats for each of them and both pooled together. SE = standard error of the mean. Min = minimum. Max = maximum. F. = Frequency. BW = Bandwidth. F. 5% is the frequency that divides the signal into two frequency intervals containing 5% and 95% of the energy in the signal. F. 95% is the frequency that divides the signal into two frequency intervals containing 95% and 5% of the energy in the signal. BW 90% is the difference between the 5% and 95% frequencies.

	GESF (N = 152)			Manchester Research Station (N = 108)			Pooled (N = 260)		
Acoustic variables	Min	Max	Mean (±SE)	Min	Max	Mean (±SE)	Min	Max	Mean (±SE)
Low F. (Hz)	535	11 668	2446 ± 111	344	4817	1826 ± 99	344	11 668	2188 ± 79
F. 5% (Hz)	551	11 766	2552 ± 113	773	5859	2358 ± 109	551	11 766	2471 ± 80
Peak F. (Hz)	574	12 258	3086 ± 144	434	9234	3863 ± 192	434	12 258	3409 ± 118
F. 95% (Hz)	1816	13 090	5418 ± 182	2203	30 305	9493 ± 581	1816	30 305	7111 ± 291
High F. (Hz)	2053	13 154	6549 ± 209	2395	33 968	11 362 ± 716	2053	33 968	8548 ± 353
BW 90% (Hz)	375	8988	2866 ± 150	891	25 711	7136 ± 528	375	25 711	4640 ± 269
Duration (ms)	74	4323	732 ± 52	98	10 493	2201 ± 192	74	10 493	1342 ± 96

consisted of highly variable trains of 3 to 336 ticks (average 30 ± 5, Table II).

Due to the similarity of these sounds with cetacean rasps (Marrero Pérez *et al.*, 2017), they were subsequently referred to as "rasps." Rasps were highly variable in duration, number of ticks, and frequency structure (Figs. 1 and 2). Rasp frequency ranged from 344 to 33 968 Hz, with an average peak frequency of 3409 Hz ± 118 (Table I). Additional frequency- and time-based measurements of sablefish rasps are presented in Table I.

Mm. 2. Audio clip of long sablefish rasp (with more than eight ticks) corresponding to the spectrogram displayed in Fig. 2(A). This is a file of type "WAV" (843 KB).

Mm. 3. Audio clip of long sablefish rasp (with more than eight ticks) corresponding to the spectrogram displayed in Fig. 2(B). This is a file of type "WAV" (840 KB).

TABLE II. Acoustic variables for the sablefish (*Anoplopoma fimbria*) ticks recorded at the Manchester Research Station (N = 2136 except for the period and inter-tick interval where N = 2064, and the tick repetition rate where N = 72). Ticks are the broadband pulses that make up the rasps. These ticks were measured from a sub-sample of 72 rasps. SE = standard error of the mean. Min = minimum. Max = maximum. F. = Frequency. BW = Bandwidth. F. 5% is the frequency that divides the signal into two frequency intervals containing 5% and 95% of the energy in the signal. F. 95% is the frequency that divides the signal into two frequency intervals containing 95% and 5% of the energy in the signal. BW 90% is the difference between the 5% and 95% frequencies.

Acoustic variables	Min	Max	Mean (±SE)
Low F. (Hz)	401	22 140	2570 ± 39
F. 5% (Hz)	797	22 406	3178 ± 39
Peak F. (Hz)	1066	23 801	5398 ± 62
F. 95% (Hz)	2133	32 180	10 540 ± 102
High F. (Hz)	2481	41 463	12 225 ± 114
BW 90% (Hz)	363	28 852	7362 ± 96
Duration (ms)	1	53	11 ± 0.1
Number of ticks/rasp	3	336	30 ± 5
Period (ms)	0.2	64.3	6 ± 0.1
Inter-tick interval (ms)	0	63	5 ± 0.1
Tick repetition rate (number of ticks/s)	5	63	18 ± 1

Mm. 4. Audio clip of long sablefish rasp (with more than eight ticks) corresponding to the spectrogram displayed in Fig. 2(C). This is a file of type "WAV" (1543 KB).

In addition to inter-rasp frequency variation, the inspection of individual ticks uncovered wide intra-rasp frequency variation (Table II). Some rasps were made of ticks whose bandwidth remained relatively constant throughout the entire call (e.g., the tick with the greatest bandwidth was only about 400 Hz higher than the tick with the smallest bandwidth). Other rasps presented bandwidth variability among their ticks as great as 27.5 kHz. For some rasps, the bandwidth was greater for the first few ticks, and then became narrower as the call progressed [e.g., Figs. 1 and 2(A)]. Most rasps exhibited significant positive correlations between one or more tick frequency measures and elapsed time within the rasp (see supplementary Table I in the supplemental material[1]). Examples of both significant positive and negative trends in tick frequency within a rasp are shown in Fig. 3.

The duration of ticks ranged between 1 and 53 ms, with an average of 11 ms ± 0.1 (Table II). The period ranged between 0.2 and 64.3 ms, with an average of 6 ms ± 0.1 (Table II). Within the same rasp, the period varied as little as 0.2 ms (in a rasp with 3 ticks) and as much as 62.7 ms (in a rasp with 23 ticks).

IV. DISCUSSION

The analysis of the recordings collected at both locations revealed a total of 260 broadband high-frequency sounds (average ~3 KHz peak) referred to as rasps. These sounds were composed of a series of short (average 11 ms), broadband tick sounds that varied in frequency content and time-interval between successive ticks (period). These characteristics match the description of the sounds reported by Meldrim (1965) from his unpublished study on captive sablefish, and also support the hypothesis that sablefish could have been the source of the broadband pulses recorded by Sirovic *et al.* (2012) in Barkley Canyon. The attribution of the rasp sounds to sablefish was supported by independent observations in two different facilities. Real-time

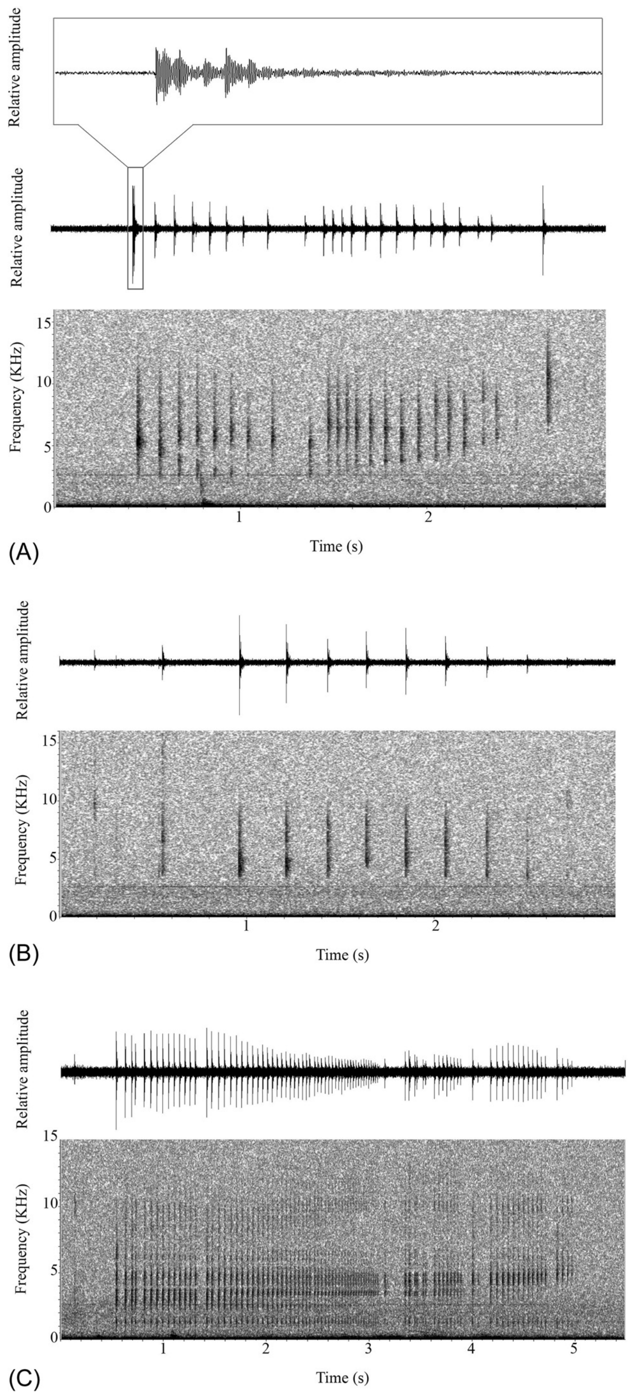

FIG. 2. Three examples of sablefish rasps illustrating the high variation in rasp structures and variation in tick frequency structure produced by sablefish (*Anoplopoma fimbria*) at the Northwest Fisheries Science Center in Manchester. Each example includes waveform (top) and spectrogram (bottom) (1800 FFT Hann window with 85% overlap). A clip of each sound is available as multimedia files (Mm. 2–Mm. 4). (A) Rasp with a trend for increasing F.5. (Mm. 2). The top panel is an expansion of the first tick in the middle panel, delineated with a box. (B) Rasp with relatively constant tick frequency structure (Mm. 3). (C) Long rasp with high variation in tick frequency structure (Mm. 4).

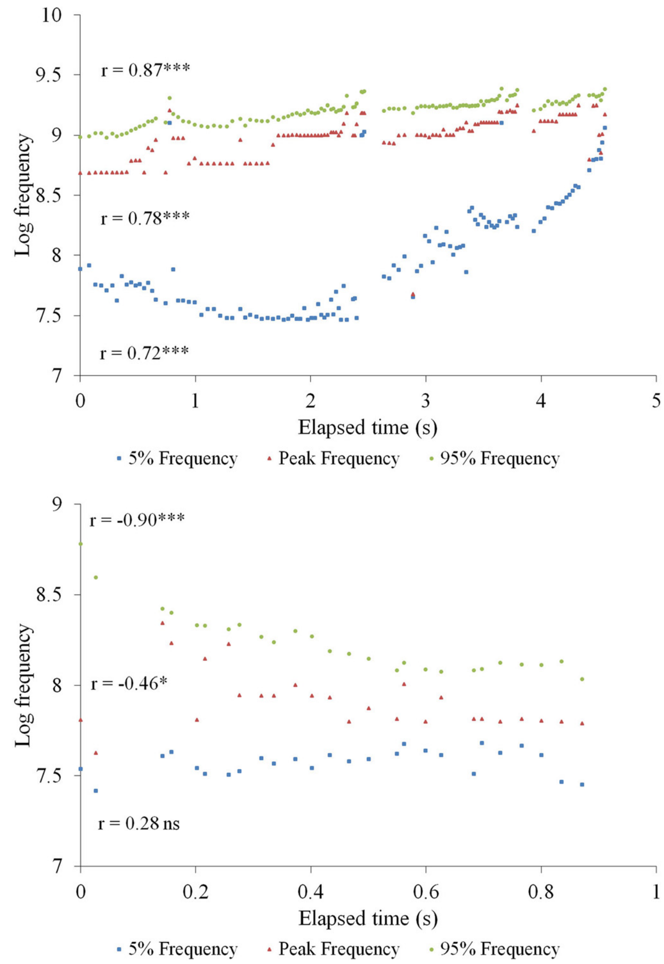

FIG. 3. (Color online) Examples of two rasps exhibiting significant correlations of tick frequency parameters (5% frequency: square, peak frequency: triangle, 95% frequency: circle) with the elapsed time from the beginning of the rasp. The Spearman Rank Correlation (r) is indicated for 95% frequency (top), peak frequency (middle), and 5% frequency (bottom) with asterisks representing its significance level (* = 0.05, ** = 0.01, *** = 0.001, ns = not significant). (Top) Positive correlation (rasp ID 39 in the supplementary table in the supplemental material[1]). (Bottom) Negative correlation (rasp ID 48 in the supplementary table in the supplemental table[1]).

observations at GESF indicated that an artificial source of the sounds was highly unlikely, though the possibility of other biological sources could not be ruled out in the open water pens. However, recordings of the same type of sounds in tanks of adult sablefish at the NWFSC-MRS facility confirmed sablefish as the only possible source. The fact that rasps were recorded in multiple tanks with adults but were absent from other tanks further reduces the likelihood that they were artifacts.

This newly validated description of sablefish sounds suggests that PAM surveys for sablefish can be used both in fisheries applications and in studies of deep-sea ecology in areas within the species' geographic range.

Sablefish is one of the top 10 key commercial species in the U.S., with an important fishery in the North Pacific Region (Alaska) and Pacific Region (California, Oregon, Washington), where the total annual landings revenue was between 102 and 185 $\times 10^6$ U.S. dollars between 2006 and 2015 (National Marine Fisheries Service, 2017). In British Columbia, there have been concerns about the sablefish stock declining below a sustainable yield, and management strategies have been designed to promote stock growth while attempting to maintain the economic performance (Cox *et al.*, 2011). Stock biomass is currently assessed via trawling surveys and fishery catch data (Wilkins and Saunders, 1997; Koslow *et al.*, 2000; Warpinski *et al.*, 2016). The use of PAM has the potential to enhance current sablefish management by providing another independent monitoring tool.

The sablefish fishery in the Gulf of Alaska suffers great reductions in catches due to sperm whale (*Physeter macrocephalus*) and killer whale (*Orcinus orca*) depredation on longline fishing gear (Peterson and Hanselman, 2017; Wild *et al.*, 2017). An acoustic decoy has been used to broadcast vessel-hauling noises known to attract whales at a distance away from the vessel performing true hauls, thus reducing the number of interactions between whales and fishing vessels (Wild *et al.*, 2017). It would be interesting to investigate the response of whales to sablefish sounds. If whales are attracted to rasps, perhaps adding recordings of sablefish rasps to the vessel-hauling sounds could increase the efficacy of the decoy as an attractant.

The soundscape of the deep-sea is poorly known, and fish sounds have been described for very few deep-sea species (see reviews in Rountree *et al.*, 2012; Wall *et al.*, 2014; Parmentier *et al.*, 2018). This limited knowledge could be due to a series of factors including the need for specialized equipment, inaccessibility, the non-continuous nature of fish sound production (they might not be vocal at the moment of recording), and the low amplitude of fish sounds that makes them susceptible to masking and reduces their detection range (Rountree *et al.*, 2012; Wall *et al.*, 2014). The results presented here add sablefish as one of the few demonstrated cases of sound production in deep-sea fishes. Knowing what sablefish sound like will also facilitate a more complete understanding of events that are already being monitored with video at underwater cabled observatories (Doya *et al.*, 2014) where concurrent acoustic recordings are available.

This study demonstrates that sablefish produce sounds, and therefore this knowledge is useful for PAM studies. How and why the fish make the sound (if there is a specific function) is unknown, and what follows is a discussion of some options.

The mechanism by which sablefish produce sounds is currently unknown. The phylogenetic relationships of sablefish to other scorpaeniform fishes is uncertain, but the family Anoplopomatidae is currently thought to be most closely related to the greenlings (Hexagrammidae) and sculpins (Cottidae) (Imamura and Yabe, 2002; Shinohara and Imamura, 2007; Nelson *et al.*, 2016). Unfortunately, despite the high diversity of sculpins, sounds have only been described in two genera (see reviews in Zeyl *et al.*, 2016; Bolgan *et al.*, 2019) and it is unknown in greenlings.

The broadband high-frequency rasps produced by sablefish are highly unusual among fish, and previously unknown for any scorpaeniform fish (Bolgan *et al.*, 2019). High frequency fish sounds have been reported for Clupeiformes (Wilson *et al.*, 2004; Rountree *et al.*, 2018), Cypriniformes and Salmoniformes (Rountree *et al.*, 2018), Perciformes such as grunts (Bertucci *et al.*, 2014) and cichlids (Lanzing, 1974; Nelissen, 1978; Kottege *et al.*, 2015; Spinks *et al.*, 2017), Siluriformes (Ghahramani *et al.*, 2014; Mohajer *et al.*, 2015), and Gadiformes (Vester *et al.*, 2004). An important distinction between the high frequency sounds produced by sablefish and those produced by other fishes, is that in most other known cases, the sound production mechanism involves the gas bladder (Tavolga, 1971; Ladich, 2004) which is absent in sablefish (Nelson *et al.*, 2016). In fish that lack a swim bladder, the most common sound-producing mechanism is stridulation, which consists of rubbing hard body parts together, such as bones, teeth, or fin spines (Tavolga, 1971; Ladich, 2004). The high variation in sablefish rasp frequency is consistent with a stridulatory mechanism (Fine and Parmentier, 2015). For the sculpin species whose sound production has been described, average peak frequency was between 50 and 500 Hz (Zeyl *et al.*, 2016), which is much lower than that of sablefish ticks (5398 ± 62 Hz; Table II). The tick duration for cottid fishes was also shorter than that of sablefish; an average of 30 ± 4 ms to 68 ± 12 ms (Zeyl *et al.*, 2016) compared to 11 ± 0.1 ms (Table II).

High frequency stridulatory sounds can also be found in some catfish (Ghahramani *et al.*, 2014; Mohajer *et al.*, 2015), grunt (Bertucci *et al.*, 2014), and cichlid (Lanzing, 1974; Nelissen, 1978; Kottege *et al.*, 2015; Spinks *et al.*, 2017) species. The average peak frequency for catfish has been reported to be between 521 ± 240 Hz and 2895 ± 276 Hz (Parmentier *et al.*, 2010), while the average peak frequency for grunts was 718 ± 180 Hz (Bertucci *et al.*, 2014). Sounds produced by grunts also consisted of a series of units that were themselves composed of a variable number of pulses (Bertucci *et al.*, 2014). In sablefish, frequency parameters vary greatly between ticks within the same rasp (Fig. 3), but how the frequency of each unit varies within the series is not described for grunts, making comparisons difficult. One of the biggest differences between sablefish rasps and the cichlid high-frequency sounds is the number of components; cichlids have calls composed of an average of two pulses (Spinks *et al.*, 2017), whereas sablefish rasps have an average of 30 and up to 300 ticks per rasp. This difference translates into an overall longer duration for rasps.

Another less well-known sound production mechanism found in some scorpaeniform species uses a novel "chordophone" mechanism involving vibrations of tendons to achieve higher frequencies than possible through muscle contraction alone (see review in Bolgan *et al.*, 2019). Future research is needed to determine if sablefish sounds are produced by a stridulatory, chordophone, or other mechanism.

Although the lack of a swim bladder precludes an air movement sound production mechanism (see review in Rountree *et al.*, 2018) in sablefish, a superficial similarity to Pacific herring (*Clupea pallasii*) "fast repetitive tick" (FRT) sounds has implications for PAM applications. Pacific herring sounds are also composed of long trains of up to 65 ticks (Wilson *et al.*, 2004). The durations of rasps and FRTs are also comparable, ranging between 0.7 and 10.5 s (average 1.3 s) for rasps and 0.6 and 7.6 s (average 2.6 s) for FRTs (Wilson *et al.*, 2004). However, the period for rasps was highly variable (presenting no clear pattern), whereas the period for herring FRTs usually increases or decreases at a steady rate (Wahlberg and Westerberg, 2003; Wilson *et al.*, 2004; Kuznetsov, 2009).

Most fishes where hearing has been examined hear best around 200 Hz (Mann *et al.*, 2007) and have audibility thresholds up to 3 kHz (Ladich and Fay, 2013) but sablefish rasps can get up to 30 kHz and whether they can hear their own sounds remains unknown. The ability to produce sounds is not necessarily associated with a matching sensitivity to hear them (Ladich, 2000), so an inability to hear the rasps does not preclude the possibility of other functions such as predator avoidance. However, high frequency hearing exists for some fishes in the subfamily Alosinae, which have been reported to hear ultrasounds from 40 to 80 kHz (Mann *et al.*, 2001). Those Alosinae species can also hear the lower frequency components of sounds, down to 200 Hz (Mann *et al.*, 2001), which indicates that the ability to hear ultrasounds does not rule out the ability to hear low frequencies. All fishes can detect particle motion through the otolith organs, but their ability to perceive sound pressure could be limited to the presence of gas-filled structures (Hawkins and Popper, 2018), which are absent in sablefish (Nelson *et al.*, 2016). Sablefish rasps have a mean peak of 3409 ± 118 Hz (Table I), which falls within the range of hearing thresholds of hearing specialists (Ladich, 2000), so it is possible they have evolved a similar hearing specialist ability through an unknown mechanism not involving the gas bladder. The hearing abilities of sablefish need to be investigated, and if possible, such studies should design methodologies that produce data that are comparable between species and laboratories (Popper *et al.*, 2019).

The skilfish, *Erilepis zonifer*, is the only other species in the family Anoplopomatidae (Froese and Pauly, 2019). A few studies have been conducted on the distribution and biology of the skilfish (Zolotov *et al.*, 2014), but no data is available regarding their possible sound production. The capacity for sound production is often shared by species of the same family (Wall *et al.*, 2014; Spinks *et al.*, 2017; Parmentier *et al.*, 2018), which makes the skilfish a good candidate for further studies to verify the hypothesis.

Although sound production in sablefish has been demonstrated, it remains unclear if the sounds are produced for an acoustic function such as intra-species communication which requires an unexpected ability to hear high frequency sounds, an inter-species signal that aids in predator avoidance which does not require hearing sensitivity, or is entirely incidental to some unknown physiological function. Regardless, the description of sablefish sounds provides scientists with the opportunity to use PAM methodologies in the study and management of the species. In addition, even if entirely incidental, determination of the physiological mechanism that produces such unusual sounds would be informative in and of itself, and suggests that PAM could be used to monitor spatial and temporal patterns in that physiological process. Future work could include studies on hearing, sound production mechanism, and behaviours associated with vocal activity.

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[1]See supplementary material at https://doi.org/10.1121/10.0001071 for details on the Spearman Rank Correlation of acoustic log transformed frequency measures of ticks against time for rasps with eight or more ticks.

Archer, S. K., Halliday, W. D., Riera, A., Mouy, X., Pine, M. K., Chu, J. W. F., Dunham, A., and Juanes, F. (**2018**). "First description of a glass sponge reef soundscape reveals fish calls and elevated sound pressure levels," Mar. Ecol. Prog. Ser. **595**, 245–252.

Bertucci, F., Ruppe, L., Van Wassenbergh, S., Compere, P., and Parmentier, E. (**2014**). "New insights into the role of the pharyngeal jaw apparatus in the sound-producing mechanism of *Haemulon flavolineatum* (Haemulidae)," J. Exp. Biol. **217**, 3862–3869.

Bolgan, M., Soulard, J., Iorio, L. D., Gervaise, C., Lejeune, P., Gobert, S., and Parmentier, E. (**2019**). "Sea chordophones make the mysterious /Kwa/ sound: Identification of the emitter of the dominant fish sound in Mediterranean seagrass meadows," J. Exp. Biol. **222**, 1–11.

Center for Conservation Bioacoustics (**2014**). "Raven Pro: Interactive Sound Analysis Software," Version 1.5 [Computer software]. Ithaca, NY: The Cornell Lab of Ornithology. Available from http://ravensoundsoftware.com/.

Charif, R., Strickman, L., and Waack, A. (**2010**). "Raven Pro 1.4 User's Manual" (Ithaca, NY), 379 p.

Cox, S. P., Kronlund, A. R., and Lacko, L. (**2011**). "Management procedures for the multi-gear sablefish (Anoplopoma fimbria) fishery in British Columbia, Canada," *DFO Can. Sci. Advis. Sec.*, Res. Doc. 2011/063 (Fisheries and Oceans Canada, Nanaimo, BC), viii + 45 p.

Department of Fisheries and Oceans Canada (**2011**). "Sgaan Kinghlas Bowie Seamount Marine Protected Area Monitoring Indicators, Protocols and Strategies," *DFO Can. Sci. Advis. Sec.*, Advis. Rep. 2011/036 (Fisheries and Oceans Canada, Nanaimo, BC), 13 p.

Doya, C., Aguzzi, J., Pardo, M., Matabos, M., Company, J. B., Costa, C., Mihaly, S., and Canals, M. (**2014**). "Diel behavioral rhythms in sablefish (*Anoplopoma fimbria*) and other benthic species, as recorded by the Deep-sea cabled observatories in Barkley Canyon (NEPTUNE-Canada)," J. Mar. Syst. **130**, 69–78.

Dufossé, L. (**1874**). *Recherches sur les bruits et les sons expressifs que font entendre les poissons d'Europe et sur les organes producteurs de ces phénomènes acoustisques* [*Research on the Expressive Noises and Sounds Heard from Fishes from Europe, and on the Organs that Produce These Acoustic Phenomena*] (E. Martinet Printing House, Paris).

Fine, M. L., and Parmentier, E. (**2015**). "Mechanisms of fish sound production," in *Sound Communication in Fishes. Animal Signals and Communication*, Vol 4., edited by F. Ladich (Springer, Vienna), pp. 77–126.

Fish, M. P. (**1948**). "Sonic fishes of the Pacific," *Office of Naval Research*, Technical Report No. 2 (Woods Hole Oceanographic Institution, Woods Hole, MA), 144 p.

Fish, M. P., Kelsey, A. S. J., and Mowbray, W. H. (**1952**). "Studies on the production of underwater sound by North Atlantic coastal fishes," J. Mar. Res. **11**, 180–193.

Froese, R., and Pauly, D. (**2019**). "FishBase," World Wide Web Electronic Publication, available from www.fishbase.org (Last viewed October 25, 2019).

Ghahramani, Z. N., Mohajer, Y., and Fine, M. L. (**2014**). "Developmental variation in sound production in water and air in the blue catfish *Ictalurus furcatus*," J. Exp. Biol. **217**, 4244–4251.

Hawkins, A. D. (**1993**). "Underwater sound and fish behaviour," in *Behaviour of Teleost Fishes*, edited by T. J. Pitcher (Chapman and Hall, London), pp. 129–169.

Hawkins, A. D., and Popper, A. N. (**2018**). "Directional hearing and sound source localization by fishes," J. Acoust. Soc. Am. **144**, 3329–3350.

Imamura, H., and Yabe, M. (**2002**). "Demise of the Scorpaeniformes (Actinopterygii: Percomorpha): An alternative phylogenetic hypothesis," Bull. Fish. Sci. Hokkaido Univ. **53**, 107–128.

Jacobson, L. D., Brodziak, J., and Rogers, J. (**2001**). "Depth distributions and time-varying bottom trawl selectivities for Dover sole (*Microstomus pacificus*), sablefish (*Anoplopoma fimbria*), and thornyheads (*Sebastolobus alascanus* and *S. altivelis*) in a commercial fishery," Fish. Bull. **99**, 309–327.
Kaatz, I. M. (**2002**). "Multiple sound-producing mechanisms in teleost fishes and hypotheses regarding their behavioural significance," Bioacoust. **12**, 230–233.
Koslow, J. A., Boehlert, G. W., Gordon, J. D. M., Haedrich, R. L., Lorance, P., and Parin, N. (**2000**). "Continental slope and deep-sea fisheries: Implications for a fragile ecosystem," ICES J. Mar. Sci. **57**, 548–557.
Kottege, N., Jurdak, R., Kroon, F., and Jones, D. (**2015**). "Automated detection of broadband clicks of freshwater fish using spectro-temporal features," J. Acoust. Soc. Am. **137**, 2502–2511.
Kuznetsov, M. Y. (**2009**). "Traits of acoustic signalization and generation of sounds by some schooling physostomous fish," Acoust. Phys. **55**, 866–875.
Ladich, F. (**2000**). "Acoustic communication and the evolution of hearing in fishes," Philos. Trans. Royal Soc. B **355**, 1285–1288.
Ladich, F. (**2004**). "Sound production and acoustic communication," in *The Senses of Fish*, edited by G. von der Emde, J. Mogdans, and B. G. Kapoor (Springer, Dordrecht), pp. 210–230.
Ladich, F., and Fay, R. R. (**2013**). "Auditory evoked potential audiometry in fish," Rev. Fish Biol. Fish. **23**, 317–364.
Lanzing, W. J. R. (**1974**). "Sound production in the cichlid *Tilapia mossambica* Peters," J. Fish Biol. **6**, 341–347.
Lindseth, A., and Lobel, P. (**2018**). "Underwater soundscape monitoring and fish bioacoustics: A review," Fishes **3**, 36.
Lobel, P. S., Kaatz, I., and Rice, A. N. (**2010**). "Acoustical behavior in coral reef fishes," in *Reproduction and Sexuality in Marine Fishes: Patterns and Processes*, edited by K. S. Cole (University of California Press, Berkeley, CA), pp. 307–387.
Mann, D. A., Cott, P. A., Hanna, B. W., and Popper, A. N. (**2007**). "Hearing in eight species of northern Canadian freshwater fishes," J. Fish Biol. **70**, 109–120.
Mann, D. A., Higgs, D. M., Tavolga, W. N., Souza, M. J., and Popper, A. N. (**2001**). "Ultrasound detection by clupeiform fishes," J. Acoust. Soc. Am. **109**, 3048–3054.
Marrero Pérez, J., Jensen, F. H., Rojano-Doñate, L., and Aguilar de Soto, N. (**2017**). "Different modes of acoustic communication in deep-diving short-finned pilot whales (*Globicephala macrorhynchus*)," Mar. Mamm. Sci. **33**, 59–79.
Meldrim, J. W. (**1965**). (personal communication).
Mohajer, Y., Ghahramani, Z., and Fine, M. L. (**2015**). "Pectoral sound generation in the blue catfish *Ictalurus furcatus*," J. Comp. Physiol. A **201**, 305–315.
Moulton, J. M. (**1963**). "Acoustic behaviour of fishes," in *Acoustic Behaviour of Animals*, edited by R. G. Busnel (Elsevier, New York), pp. 210–223.
National Marine Fisheries Service (**2017**). "Fisheries economics of the United States, 2015," U.S. Department of Commerce, NOAA Technical Memorandum NMFS-F/SPO-170 (National Marine Fisheries Service, Silver Spring, MD), 247 p.
Nelissen, M. H. (**1978**). "Sound production by some Tanganyikan cichlid fishes and a hypothesis for the evolution of their communication mechanisms," Behaviour **64**, 137–147.
Nelson, J. S., Grande, T., and Wilson, M. V. H. (**2016**). *Fishes of the World* (John Wiley & Sons, Inc., New York), 752 p.
Parmentier, E., Bahri, M. A., Plenevaux, A., Fine, M. L., and Estrada, J. M. (**2018**). "Sound production and sonic apparatus in deep-living cusk-eels (*Genypterus chilensis* and *Genypterus maculatus*)," Deep Sea Res. Pt. I **141**, 83–92.
Parmentier, E., Fabri, G., Kaatz, I., Decloux, N., Planes, S., and Vandewalle, P. (**2010**). "Functional study of the pectoral spine stridulation mechanism in different mochokid catfishes," J. Exp. Biol. **213**, 1107–1114.
Peterson, M. J., and Hanselman, D. (**2017**). "Sablefish mortality associated with whale depredation in Alaska," ICES J. Mar. Sci. **74**, 1382–1394.
Popper, A. N., Hawkins, A. D., Sand, O., and Sisneros, J. A. (**2019**). "Examining the hearing abilities of fishes," J. Acoust. Soc. Am. **146**, 948–955.
Riera, A., Rountree, R. A., Mouy, X., Ford, J. K., and Juanes, F. (**2016**). "Effects of anthropogenic noise on fishes at the SGaan Kinghlas-Bowie Seamount Marine Protected Area," Proc. Meet. Acoust. **27**, 010005.
Riera, A., Rountree, R. A., Pine, M. K., and Juanes, F. (**2018**). "Sounds of Arctic cod (*Boreogadus saida*) in captivity: A preliminary description," J. Acoust. Soc. Am. **143**, EL217–EL321.
Rountree, R. A., Bolgan, M., and Juanes, F. (**2019**). "How can we understand freshwater soundscapes without fish sound descriptions?," Fisheries **44**, 137–143.
Rountree, R. A., Gilmore, R. G., Goudey, C. A., Hawkins, A. D., Luczkovich, J. J., and Mann, D. A. (**2006**). "Listening to fish: Applications of passive acoustics to fisheries science," Fisheries **31**, 433–446.
Rountree, R. A., Juanes, F., and Bolgan, M. (**2018**). "Air movement sound production by alewife, white sucker, and four salmonid fishes suggests the phenomenon is widespread among freshwater fishes," PLoS One **13**, 1–32.
Rountree, R. A., Juanes, F., Goudey, C. A., and Ekstrom, K. E. (**2012**). "Is biological sound production important in the deep sea?," in *The Effects of Noise on Aquatic Life*, edited by A. N. Popper, and A. D. Hawkins (Springer, New York), pp. 181–183.
Rountree, R. A., Perkins, P. J., Kenney, R. D., and Hinga, K. R. (**2002**). "Sounds of Western North Atlantic fishes: Data rescue," Bioacoustics **12**, 242–244.
Sanchez-Serrano, S., Paniagua-Chavez, C. G., Segovia, M., and Weirich, C. R. (**2014**). "Short and long-term preservation of sablefish sperm from Baja California, Mexico," N. Am. J. Aquacult. **76**, 245–254.
SAS Institute Inc. (**2012**). "SAS/STAT 12.1 user's guide," Version 12.1, [Computer software]. Cary, NC: SAS Institute Inc. Available from https://www.sas.com.
Schneider, H. (**1966**). "Morphology and physiology of sound-producing mechanisms in teleost fishes," in *Marine Bio-Acoustics*, edited by W. N. Tavolga (Pergamon Press, New York), pp. 135–158.
Shinohara, G., and Imamura, H. (**2007**). "Revisiting recent phylogenetic studies of 'Scorpaeniformes'," Ichthyol. Res. **54**, 92–99.
Sirovic, A., Brandstatter, S., and Hildebrand, J. A. (**2012**). "Fish recordings from NEPTUNE Canada," J. Acoust. Soc. Am. **132**, 1916–1916.
Slabbekoorn, H., Bouton, N., van Opzeeland, I., Coers, A., ten Cate, C., and Popper, A. N. (**2010**). "A noisy spring: The impact of globally rising underwater sound levels on fish," Trends Ecol. Evol. **25**, 419–427.
Spinks, R. K., Muschick, M., Salzburger, W., and Gante, H. F. (**2017**). "Singing above the chorus: Cooperative princess cichlid fish (*Neolamprologus pulcher*) has high pitch," Hydrobiologia **791**, 115–125.
Sumaila, U. R., Volpe, J., and Liu, Y. (**2007**). "Potential economic benefits from sablefish farming in British Columbia," Mar. Policy **31**, 81–84.
Tavolga, W. N. (**1971**). "Sound production and detection," in *Fish Physiology*, edited by W. S. Hoar and D. J. Randall (Academic Press, New York), pp. 135–205.
Vester, H. I., Folkow, L. P., and Blix, A. S. (**2004**). "Click sounds produced by cod (*Gadus morhua*)," J. Acoust. Soc. Am. **115**, 914–919.
Wahlberg, M., and Westerberg, H. (**2003**). "Sounds produced by herring (*Clupea harengus*) bubble release," Aquat. Living Resour. **16**, 271–275.
Wall, C. C., Rountree, R. A., Pomerleau, C., and Juanes, F. (**2014**). "An exploration for deep-sea fish sounds off Vancouver Island from the NEPTUNE Canada ocean observing system," Deep Sea Res. Pt. I **83**, 57–64.
Warpinski, S., Herrmann, M., Greenberg, J. A., and Criddle, K. R. (**2016**). "Alaska's sablefish fishery after Individual Fishing Quota (IFQ) program implementation: An international economic market model," N. Am. J. Fish. Manage. **36**, 864–875.
Wild, L., Thode, A., Straley, J., Rhoads, S., Falvey, D., and Liddle, J. (**2017**). "Field trials of an acoustic decoy to attract sperm whales away from commercial longline fishing vessels in western Gulf of Alaska," Fish. Res. **196**, 141–150.
Wilkins, M. E., and Saunders, M. W. (**1997**). "Biology and management of sablefish, *Anoplopoma fimbria*," in *International Symposium on the Biology and Management of Sablefish* (April 13–15, 1993), edited by U.S. Department of Commerce (NOAA Technical Report NMFS 130, Seattle, Washington), p. 267.
Wilson, B., Batty, R. S., and Dill, L. M. (**2004**). "Pacific and Atlantic herring produce burst pulse sounds," Proc. Royal Soc. B **271 Suppl.**, S95–S97.
Zeyl, J. N., Malavasi, S., Holt, D. E., Noel, P., Lugli, M., and Johnston, C. E. (**2016**). "Convergent aspects of acoustic communication in darters, sculpins, and gobies," in *Fish Hearing and Bioacoustics: An Anthology in Honor of Arthur N. Popper and Richard R. Fay*, edited by J. A. Sisneros (Springer, Cham), pp. 93–120.
Zolotov, O. G., Spirin, I. Y., and Zudina, S. M. (**2014**). "New data on the range, biology, and abundance of skilfish *Erilepis zonifer* (Anoplopomatidae)," J. Appl. Ichthyol. **54**, 251–265.