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

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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 3,409 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. https://doi.org/10.1121/10.0001071

I. INTRODUCTION

Fish sounds have been studied since at least the late 1800s (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 ~3,450 known fish species (Froese and Pauly, 2019) and sound production has been reported for fewer than 1,000 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...
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 $= -193.5 \text{ dB re: } 1 \text{ V/\mu Pa}$, 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 $= -165 \text{ dB re: } 1 \text{ V/\mu Pa}$, 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%, peak, F. 95%, and BW 90%, 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).](https://doi.org/10.1121/10.0001071)
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.

<table>
<thead>
<tr>
<th>Acoustic variables</th>
<th>GESF (N = 152)</th>
<th>Manchester Research Station (N = 108)</th>
<th>Pooled (N = 260)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Mean (±SE)</td>
</tr>
<tr>
<td>Low F. (Hz)</td>
<td>344</td>
<td>4817</td>
<td>1826 ± 99</td>
</tr>
<tr>
<td>F. 5% (Hz)</td>
<td>551</td>
<td>11766</td>
<td>7738 ± 109</td>
</tr>
<tr>
<td>Peak F. (Hz)</td>
<td>434</td>
<td>9234</td>
<td>3863 ± 192</td>
</tr>
<tr>
<td>F. 95% (Hz)</td>
<td>1916</td>
<td>13090</td>
<td>9493 ± 581</td>
</tr>
<tr>
<td>High F. (Hz)</td>
<td>2053</td>
<td>13154</td>
<td>33968 ± 209</td>
</tr>
<tr>
<td>BW 90% (Hz)</td>
<td>375</td>
<td>8988</td>
<td>7136 ± 528</td>
</tr>
<tr>
<td>Duration (ms)</td>
<td>74</td>
<td>4323</td>
<td>732 ± 52</td>
</tr>
</tbody>
</table>

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). 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). 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...
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 × 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 (Orcainus 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 pallasiis) “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 ultrasound 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 ultrasound 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 skiffish, 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 skiffish (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 skiffish 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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1See 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.