

UNIVERSITY OF GHENT
&
INSTITUTE OF MARINE RESEARCH

MASTER'S THESIS

**Recreational boating interferes with
the behaviour of Atlantic cod (*Gadus
morhua*)**

*A study about the effects of noise pollution from small, recreational vessels on
the movement patterns and vocalizations of cod in a fjord on the Norwegian
Skagerrak coast.*

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Executive Summary

Anthropogenic noise pollution puts growing pressure on the marine environment. Policies regarding noise pollution remain largely nonexistent due to a lack of standardized monitoring methods, fed by a general lack of knowledge about the problem. Monitoring of noise pollution is often based on vessel presence, which relies on Automatic Identification Systems (AIS). While AIS works to track large ships, small ships are not required to have this system on board, causing their impact to be underestimated. However, small recreational boats are the most abundant in vulnerable and important coastal habitats. This might affect the habitat of valuable species such as Atlantic cod (*Gadus morhua*).

This study considers the impact of cod in terms of vocalizations and movement patterns. A hydrophone is used to record vessel presence and vocalizations of cod. Acoustic telemetry is used to track the movement of cod in terms of home range size and depth. Noise is quantified with PAMGuide, while vocalizations are analyzed using Praat phonetics software. Temperature and day/night are included as covariates. Body length is included as an additional covariate for the telemetry data. Generalized Additive Mixed-effect Models are used to model the effect of noise on the response variables.

The results show that noise affects the depth use and home range size of cod, although the noise model only explains a minor portion of the variance. Length was excluded from the final telemetry models due to insignificance; this was likely due to measured length not being representative. Furthermore, the vocalization length and amount of pulses decrease during periods with high amounts of noise, while vocal fatigue increases. Temperature was excluded from the vocalization models. These impacts may negatively impact cod: The change in depth might negatively affect cod metabolism due to changes in temperature. The changing vocalizations may impact courtship success due to the role sound plays in courtship behavior.

Noise has been shown to negatively affect many other marine species as well. This research adds to the existing literature by showing the effect of noise on a species that is commercially important. Therefore, the cost of noise pollution might encompass more than environmental damages. Lack of regulation regarding noise pollution should therefore be urgently addressed.

Abstract

There is a growing concern about the impact of anthropogenic noise pollution on the marine environment. The problem is fed by a lack of knowledge, in which the effect of small recreational boats is especially underestimated. However, small recreational boats are the most abundant in vulnerable and important coastal habitats. This study addresses the issue by looking at the impact of noise on a coastal population of Atlantic cod (*Gadus morhua*).

The results of this study indicate that vocalizations and movement patterns of cod are affected by small boat noise. An increase in noise leads to a reduction of home range size and an increase in depth. Furthermore, the vocalization length and amount of pulses decrease during periods with high amounts of noise, while vocal fatigue increases.

This impact of boat noise on cod may negatively impact courtship success due to the importance of sound during courtship interactions. Additionally, the change in depth might negatively affect cod metabolism due to changes in temperature. This may have implications for the health of cod populations residing in areas with high amounts of ambient noise.

Negative impacts of noise have been previously described for other species. The negative impact on cod suggests that marine noise pollution may have economic consequences. Therefore, regulations regarding noise pollution should be urgently addressed.

1 Introduction

1.1 Relevance

Sound is of high importance for species living in the marine environment. Due to the weaker attenuation compared to other forms of energy, sound propagates through water with high efficiency. Therefore, acoustics play a large role in the sensory systems of marine animals (Au and Hastings, 2008). The term soundscape was first mentioned in “The Book of Noise” (Schafer, 1970) to describe the acoustic part of the human environment. Since then, its definition has evolved to describe the acoustic signature of an environment, as a composition of geophony, biophony, and anthrophony (Bertucci et al., 2015). Using this definition, the marine soundscape can be described by sounds from the physical environment (e.g. waves, wind), biotic sounds (e.g. animal vocalizations, particle motion due to movement), and human-generated sounds (e.g. boat noise, seismic surveying).

The latter has gotten substantially stronger over the centuries as more of the marine environment became exploited. This has become especially apparent during the last century due to the increase in overseas shipping and efforts to extract energy sources from the marine environment. Anthropogenic noise can generally be separated in two groups: impulsive noise (such as seismic surveying) and ambient (continuous) noise (Van der Graaf et al., 2012). This study will focus on the latter. One of the major anthropogenic contributions to ambient noise in marine environments is vessel traffic; Between the 1960s -1990s, ambient noise in the 20-80Hz frequency range have increased as much as 10dB in the North Pacific ocean, which can be attributed mostly to commercial shipping (Andrew et al., 2002). Increases in ambient noise have been found to affect different marine species in a variety of ways, such as masking of vocalizations (Putland et al., 2018), an increase in cortisol levels (Sierra-Flores et al., 2015), and reduced courtship behavior and spawning success (de Jong et al., 2018).

1.2 Problem statement

Vessel noise is often modeled through monitoring ship presence with AIS (Automatic Identification Systems) and estimating the produced noise level based on the characteristics of the tracked ship. AIS is only required on large vessels (IMO, 2009)), meaning smaller ships cannot be monitored through this method. However, small vessels are generally more abundant in coastal regions due to the suitability of the area for recreational boating. As such, their effect on coastal regions due to the noise they produce might be underestimated (Hermannsen et al., 2019).

The lack of knowledge about the impact of smaller vessels in coastal regions is concerning, as the health of coastal ecosystems may affect the entire marine biome, as coastal ecosystems offer crucial nursery habitats for many marine species (Post and Lundin, 1996). One of these species is Atlantic cod (*Gadus morhua*). Cod is an important marine resource for Norway: The export value of cod products was €527m in the first half of 2021 (Norwegian seafood council, 2021). Besides this, cod fishing is a century-old tradition that plays a role in many coastal villages. (Maurstad, 2000). This makes the species a valuable resource, both economically and culturally.

There have been several studies about the effect of vessel noise on cod. In a study on the stress response of cod to anthropogenic noise, exposure to noise was found to significantly decrease egg production and fertilization rate (Sierra-Flores et al., 2015). Stanley et al. (2017) proposed that the effective vocalization radius of Atlantic cod (i.e. the radius in the sound a cod produces is audible) was significantly reduced in presence of large vessels. A study on Arctic cod (*Boreogadus saida*) showed that shipping invokes anti-predator behavior, resulting in the cod moving away from the ships (both horizontally and vertically) and decreasing exploratory activities (Ivanova et al., 2020). However, it has not yet been observed whether cod adapt their vocalizations in order to compensate for the decreased vocalization radius, or whether Atlantic cod react to vessel noise in a similar manner as Arctic cod. Both of these effects are

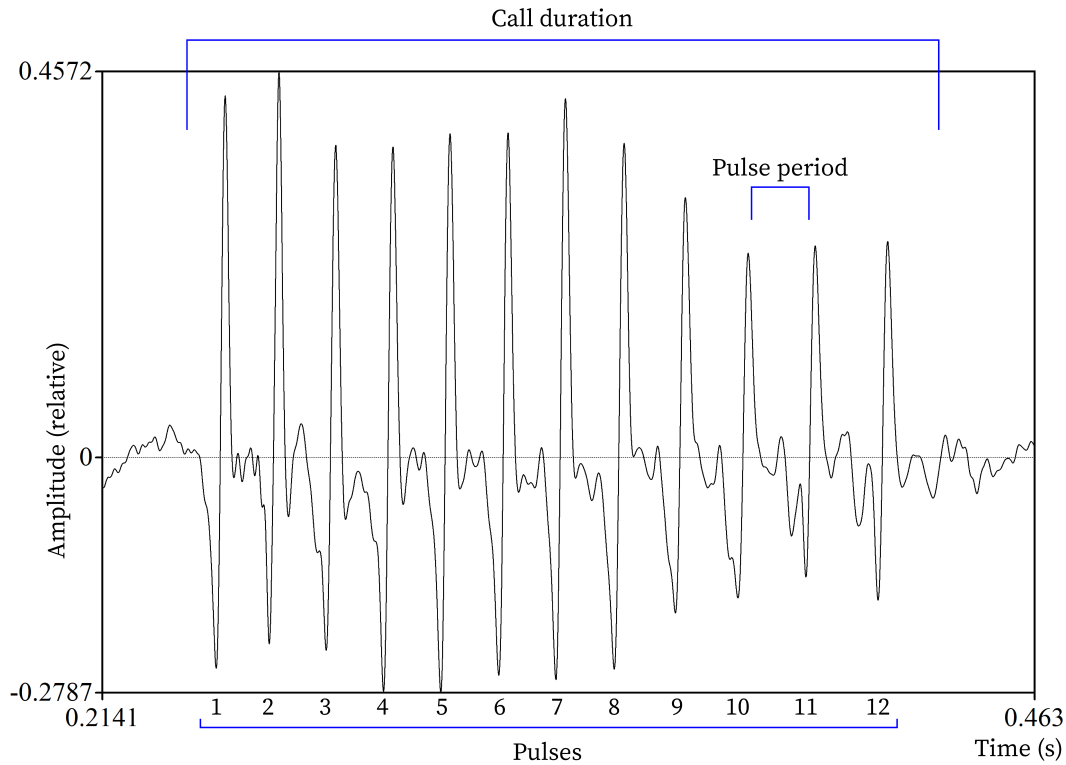


Figure 1: Waveform of a cod grunt.

important to infer whether the effects of noise pollution are harmful for cod, and are a first step in determining how harmful noise could be. Therefore, the two aspects of cod behavior were observed in the present study: Vocalizations and movement patterns.

1.2.1 Vocalizations

Cod produce sound by using a sonic muscle to rapidly pulse their swimbladder (Kasumyan, 2008). They do so during interaction with other individuals – such as antagonistic or courtship behavior – and when startled by an artificial stimulus (Hawkins and Rasmussen, 1978). They produce a multitude of sounds, such as thumps and knocks, which are short sounds that are difficult to distinguish from other species (Hawkins and Rasmussen, 1978). The most characteristic sound is called a grunt. Cod grunts can be described using a waveform (Fig. 1) that visualizes amplitude over time. The waveform can be used to describe several aspects of the vocalization:

- Number of pulses (N),
- Duration of the sound (s),
- Pulse repetition period: The time between pulses, measured from peak to peak.

In addition, the fundamental frequency (f_0) can be described as the lowest of the harmonics, and is what we perceive as the pitch of a sound.

The vocalizations of cod have been measured in various studies (Table 1). Peak frequencies range between 30 - 250 Hz, although mean frequencies are generally between 45-95 Hz. The mean duration of the calls is between 150-300 ms, and consist of an average of 9-11 pulses. The pulse period (i.e. length of a single pulse) is 17-22 ms.

Vocal species may involuntarily change their vocalizations due to increasing ambient noise. This is called the Lombard effect, and has been observed in both terrestrial and marine species. While this effect has not been observed in cod before, it has been observed for other marine species. Killer whales were found to increase the

Table 1: Table for comparing cod vocalizations found in different studies. In f0 column: 1 = Peak frequency, 2 = Fundamental frequency; Values between brackets are mean values, a ”*” signifies median is used instead.

Study	f0 (Hz)	Duration (ms)	Pulses (N)	PP (ms)	Notes
Midling et al. (2002)	50 – 120 ²	60-200	-	8-20	wild cod and net pens
Finstad and Nordeide (2004)	42 – 60 ² [49.7]	118-943 [215]	5-52 [9.6]	15-29 [19-22*]	Kept in outdoor tanks; Recorded during spawning
Wilson et al. (2014)	39 – 141 ¹ [95]	131-700 [230]	5-19 [9*]	5-61 [17*]	Permanently kept in indoor tanks
Fudge and Rose (2009)	30 – 250 ¹ [61.6]	242.3-407.2 [303.0]	9-16 [11.2]	-	Wild cod; Specifically spawning sounds
Fudge and Rose (2009)	30 – 210 ¹ [92.4]	117-1000 [294.4]	3-16 [8.6]	-	Holding tanks; Same study as above
Hernandez et al. (2013)	39.1 – 58.62 ² [49.7]	57-360 [167.6]	3-18 [9]	4.6-46.2 [19.6]	Wild
Hawkins and Rasmussen (1978)	95 ²	75-200	4-15	12	Old paper; Compares different species

call length by approximately 15% in presence of boats (Foote et al., 2004). Oyster toadfish (*Opsanus tau*) have been observed to increase their calling amplitude by up to 8.7 dB re 1 μPa^2 after being exposed to loud noise (Luczkovich et al., 2016). Painted- and Two spotted gobies were found to produce fewer calls after exposure to artificial boat noise (de Jong et al., 2018). Another study of gobies in different environments found that various populations adapted the frequency of their calls to the quiet window (i.e. frequency range with low amplitude) in the soundscape of their habitat (Lugli, 2010). This suggests that different species react differently to background noise. Therefore, all of the aforementioned vocalization characteristics should be measured to infer whether and in what way the vocalizations of cod are affected.

Additionally, since sound production requires contraction of a sonic muscle, sound production can result in muscle fatigue (Mitchell et al., 2008). Amorim et al. (2013) used the ratio between pulse periods at the beginning and mid-call to describe the vocal fatigue in painted gobies. Since cod and gobies produce sounds in a similar manner, this metric may also be applicable to cod vocalizations.

1.2.2 Movement patterns

Most organisms adapt their behavior when faced with potential danger. Juvenile cod have been observed to select habitat types associated with shelter during and after exposure to a predator (Gotceitas and Brown, 1993). Furthermore, results from a similar study suggest that the location of the predator is avoided, even if this predator is not actively foraging (Gotceitas et al., 1995). While boat noise might not be perceived as a direct threat, lab experiments have shown that noise can induce stress in cod: Plasma cortisol levels were significantly higher after exposure to background

noise in the frequency range of anthropogenic noise (Sierra-Flores et al., 2015).

In a study on the effect of trawling vessel presence Handegard et al. (2003), cod showed a significant vertical displacement in reaction to vessel passage, even before horizontal movement occurred. This suggests that vessel presence could also play a role in depth preference of cod. Because cod are ectotherms, the temperature of the surrounding water (which changes with depth) affects the body temperature. Internal body temperature affects bodily functions; unfavorable water temperatures can limit the ability of the circulatory and ventilatory system to meet the oxygen demand, ultimately restricting all higher functions (Pörtner and Knust (2007)). Because of this, the relationship between noise and depth preference is an important factor to include in the study.

1.3 Hypotheses

In this study, I hypothesized that cod 1) alter their vocalizations in response to anthropogenic noise, 2) decrease their exploratory activities in response to anthropogenic noise, resulting in a smaller home range, and 3) swim deeper when there is more anthropogenic noise to distance themselves from the source of the noise. The vocalization characteristics that were measured for this were fundamental frequency, call duration, number of pulses, pulse period, and fatigue.

2 Methodology

2.1 Study location

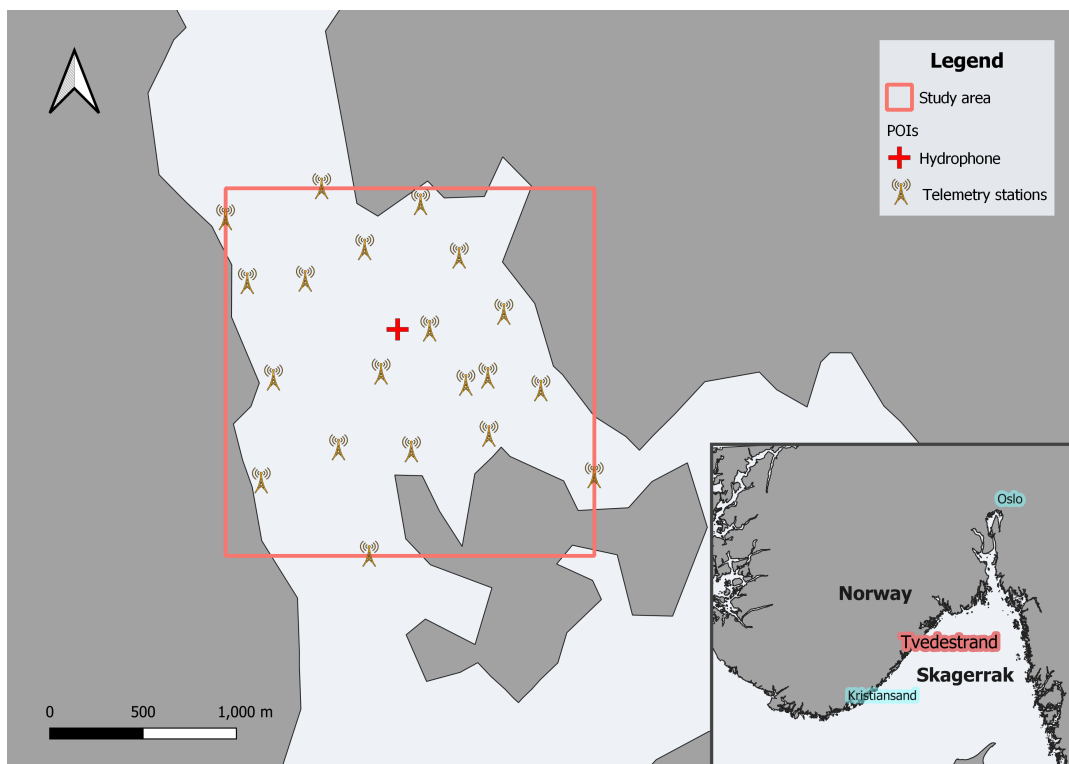


Figure 2: The study area within Tvedestrandfjorden, Norway.

The study area was located in a fjord in the Tvedestrand municipality on the Norwegian Skagerrak coast. Tvedestrandfjorden is a marine protected area with different sections, each of which have slightly different restrictions (Lovdata, 2012). The study area was entirely within the section comprising a no-take marine reserve. Furthermore, the fjord is not a general passage for larger (cargo) ships due to its location. Therefore, the study area is relatively undisturbed from anthropogenic activity outside of recreational boating. The seafloor is between 0-90 meters deep and houses different habitats, including eelgrass and boulders (Freitas et al., 2021), which are known to be used as shelter by juvenile cod.

Tvedestrandfjorden houses a telemetry grid with 56 receivers (Which was used in Freitas et al. (2015), Freitas et al. (2016), Freitas et al. (2021)), 20 of which are within the study area (Fig. 2). A single hydrophone was used to capture both anthropogenic and biogenic noise. The hydrophone was deployed in the middle of the study area. The central location was optimal for recording both ambient noise and cod vocalizations, because it was within several cod home ranges (Freitas et al., 2016). The hydrophone was kept in place at 5m above the seafloor by a concrete two-part deadweight mooring and a subsurface float (Fig. 3). This corresponded to a depth of 14.5m, which is around the average depth cod utilizes in the fjord (Freitas et al., 2021).

2.2 Study design

The hypotheses - that depth, home range and vocalizations of cod are affected by vessel noise - required several kinds of data. This included time-stamped data of ambient noise levels, recordings of cod vocalizations, cod movement data. Temperature and cod size were included as covariates. The acoustic data (ambient noise levels, cod vocalizations) were collected using a single hydrophone. Temperature was logged using an auxiliary sensor on the hydrophone. It is important to note that

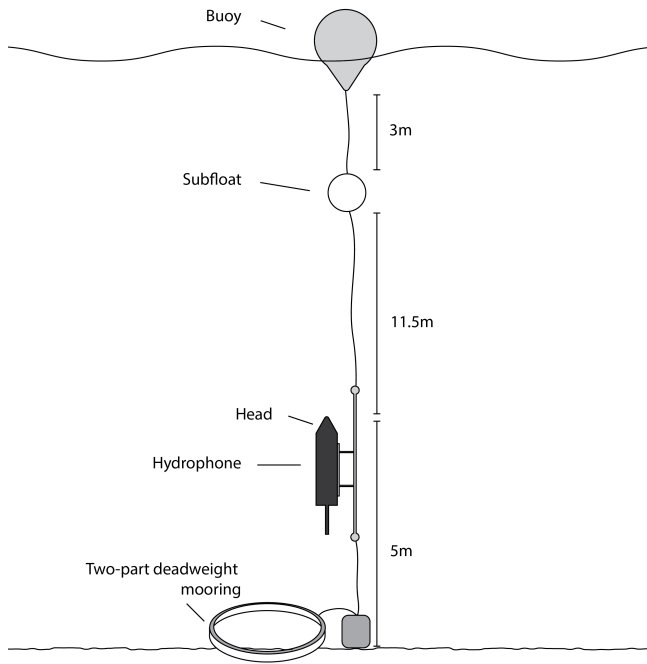


Figure 3: The setup of the hydrophone.

this hydrophone setup did not allow the collection of information on the individual producing the noise. Therefore, cod size could not be included as a covariate for the acoustic data.

The movement data was obtained using an acoustic telemetry system produced by VEMCO. Cod length was measured as part of the tagging process, which is part of an ongoing monitoring effort of the aforementioned Tvedestrand marine reserve. The body length was measured as the fork length rounded down to the nearest centimeter. To account for diel variations in cod behavior, sunrise and sunset were used to distinguish between day and night.

2.3 Acoustic data

2.3.1 Hydrophone configuration

The collection of acoustic data of the study area was done using a single hydrophone, similar to the setup used in Merchant et al. (2012). The hydrophone used was a Soundtrap 300HF from Ocean Instruments, with a frequency range of 20 Hz to 150 kHz. The hydrophone was set to record 10 minutes at an hourly interval at a sample rate of 48 kHz. This allowed for a theoretical battery life of 56 days without the use of an external battery (Ocean Instruments, 2020). Since the sounds produced by cod are often low intensity, the high gain setting on the hydrophone is used to pre-amplify the signal in the recording. The hydrophone was deployed on August 31st. The battery lasted until November 17th. This yielded complete data (i.e 24 recordings per day) from September 1st to November 16th, a total of 77 full days. The hydrophone was offloaded using the hydrophone specific software ‘SoundTrap Host’ (Ocean Instruments, 2021), and preprocessed in Python 3.9 (Van Rossum and Drake, 2009).

Table 2: Group boundaries for vocalization analysis

	<i>Quiet (<83.9dB)</i>	<i>Mid (83.9 - <92.7dB)</i>	<i>Loud (>92.7dB)</i>
Day	QD	MD	LD
Night	QN	MN	LN

2.3.2 Quantifying ambient noise

The recorded noise was calibrated and quantified using the R script "PAMGuide" (Merchant et al., 2014). PAMGuide is one of the suggested tools for obtaining calibrated noise levels by the hydrophone manufacturer (Ocean Instruments, 2020). The calibration values were provided by the hydrophone manufacturer.

The ambient noise produced by small boats particularly increase the sound intensity in the 100 – 1000 Hz range (Holmes et al., 2017; Kaplan and Mooney, 2015). Therefore, PAMGuide was set to analyze the average sound intensity of the 100 – 1000 Hz frequency range of each 10-minute recording. The window length was set equal to the sampling rate (i.e. 48kHz = 1s), with a 50% Hann window overlap. The median was used as the averaging method as it is more suitable for the study of noise on marine fauna, due to the mean being highly affected by outliers (McQuinn et al., 2011).

2.4 Cod vocalizations

2.4.1 Extracting vocalizations

The cod vocalizations and noise were recorded together. Therefore, the recordings of vocalizations had to be extracted from the files containing the noise recording. This has an inherent sampling bias; if we assume that noise masks the vocalizations of cod, these would be more difficult to find and therefore less abundant in the sample. To deal with this, an equal amount of samples was randomly selected from recordings with different amounts of noise for both day and night. This was done by grouping recordings using k-means clustering ($k = 3$) and dividing these further by day and night (Table 2). Then, samples were drawn until a total of 10 vocalizations per group was reached.

The vocalizations were then analyzed using the phonetics software "Praat" (Boersma and Weenink, 2021) in combination with Python (Van Rossum and Drake, 2009) using the Parselmouth library (Jadoul et al., 2018). This was done by first filtering the recordings to make it easier to find vocalizations. The vocalizations were timestamped in each filtered file. Then, the timestamps were used to perform the sound analysis on the corresponding unfiltered recording.

2.4.2 Vocalization analysis

The analyzed vocalization characteristics were call duration, number of pulses, fundamental frequency, mean pulse period, and fatigue. Call duration can be hard to distinguish in an environment with high background noise. As a tradeoff between accuracy and consistency, the start and end of a sound were defined by distance to-and-from the first and last peak, respectively.. The distance was calculated as half of the closest pulse repetition period, resulting in:

$$t_{start} = t_1 - 0.5(t_2 - t_1) \quad \text{and} \quad t_{end} = t_n - 0.5(t_n - t_{n-1})$$

The fundamental frequency was obtained by converting the call to a spectral slice and measuring the distance between the harmonics (Fig. 4). Pulse periods were calculated by noting the starting time of each pulse. This was then used to calculate

the mean pulse period. The calculation of fatigue was adapted from Amorim et al. (2013), and was calculated as the ratio between the three first and last pulse periods:

$$FAT = p_{start}/p_{end} = \frac{1}{3} \sum_{i=1}^3 p_i / \frac{1}{3} \sum_{i=n-2}^n p_i$$

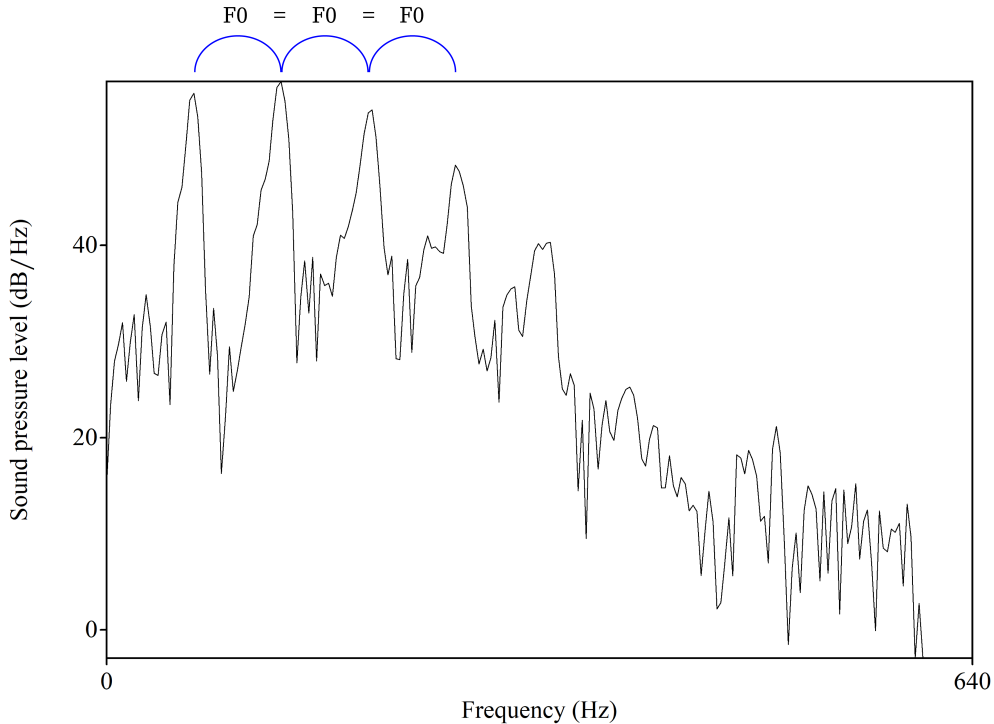


Figure 4: Spectral slice; The distance between the peaks is the harmonic/fundamental frequency

2.4.3 Distinguishing cod from other species

Tvedestrandfjorden is also home to other species besides cod such as pollock (*Pollachius pollachius*), haddock (*Melanogrammus aeglefinus*), as well as several species of the family Gobiidae (Freitas et al., 2021; Kovačić and Svensen, 2019). However, haddock is unlikely to be present in the study area, as it is generally too shallow (ICES, 2007).

The difference between the vocalizations of cod, pollock and gobies become apparent by putting the waveforms next to one another (Fig. 5). Cod and pollock produce grunts that are similar in shape and pulses, but cod can be distinguished by the vertical symmetry of the waveform. Painted gobies produce drums and grunts with a relatively short pulse period. Drums can sound similar to long cod grunts, but the waveforms show a nearly constant amplitude between pulses.. Thumps of the painted goby have a shape that is more similar to cod, but the length of the call is significantly shorter.

2.5 Telemetry data

Every station in the telemetry grid produces a receiver log, stating the time of arrival (ToA) of a transmission sent by an acoustic tag. This is the raw data obtained from the telemetry grid. Processing of this data begins in the VEMCO User Environment (VUE) software, which is complementary to the telemetry grid (Vemco, 2016). The software was necessary for decoding the data obtained from the receivers, and contains tools several tools to correct for clock drift, and account for code collisions and false detections (Smith, 2013). The threshold for defining false detections was set to two

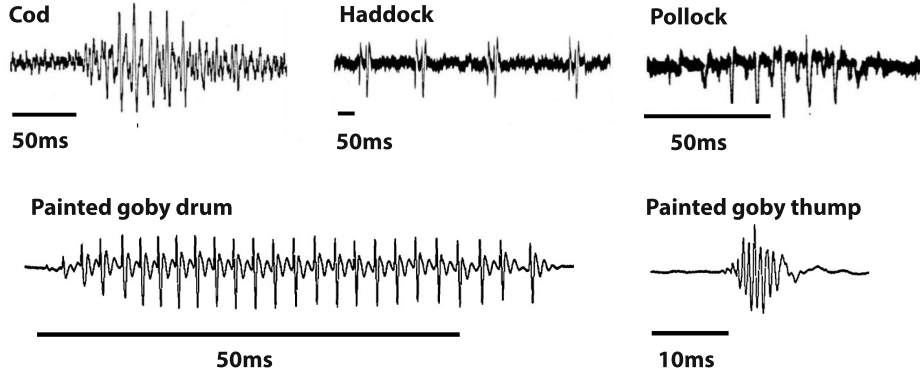


Figure 5: Calls of haddock, cod, pollack (Amorim, 2006), and painted goby (Amorim et al., 2013)

detections per 24 hours (Villegas-Ríos et al., 2017). After this, it was combined with other datasets containing information on the transmitting and receiving acoustic tags.

The resulting dataset contained the date and time an acoustic signal was received, the serial number of the acoustic tag, the horizontal position of the station that received the signal, and the depth as calculated from the pressure sensor in the acoustic tag (Table 3).

Table 3: Received transmissions per individual (serial_no), combined with position data.

Date	statnum	serial_no	Lat	Lon	Depth	Station name
2020-04-29T09:07:48Z	27	1253874	58.60413	8.9647	1.5159	Skibolidalen
2020-04-29T09:10:48Z	27	1253874	58.60413	8.9647	1.5159	Skibolidalen
2020-04-29T09:14:26Z	28	1253874	58.60292	8.96967	1.5159	Sagesund
2020-04-29T09:14:31Z	27	1253874	58.60413	8.9647	1.5159	Skibolidalen
2020-04-29T09:21:00Z	27	1253874	58.60413	8.9647	1.8191	Skibolidalen
2020-04-29T09:24:46Z	27	1253874	58.60413	8.9647	1.8191	Skibolidalen
2020-04-29T09:28:17Z	28	1253874	58.60292	8.96967	1.8191	Sagesund
2020-04-29T09:28:21Z	27	1253874	58.60413	8.9647	1.8191	Skibolidalen
2020-04-29T09:31:35Z	27	1253874	58.60413	8.9647	1.8191	Skibolidalen
2020-04-29T09:36:46Z	28	1253874	58.60292	8.96967	1.5159	Sagesund

From this, the position of the acoustic tags at a certain time was calculated as centers of activity (CoA): The average position of the receiver stations over a certain period of time, weighted by the amount of times they received a transmission (Villegas-Ríos et al., 2017). This was done according to the method of Simpfendorfer et al. (2002). The bin size (i.e. period of time over which to calculate the average) was 30 minutes, which was deemed the most appropriate after experimentation with different values. Then, the arithmetic mean was calculated for each bin as:

$$\bar{X}_{\Delta t} = \frac{\sum_{i=1}^n R_i X_i}{\sum_{i=1}^n R_i} \text{ and } \bar{Y}_{\Delta t} = \frac{\sum_{i=1}^n R_i Y_i}{\sum_{i=1}^n R_i}$$

where n is the number of receivers in the array; R_i is the number of receptions at the i^{th} receiver during Δt , X_i is the coordinate of the i^{th} receiver, and Y_i is the Y coordinate of the i^{th} receiver.

The 30 minute centers of activity were then used to calculate home ranges on a 3-hour resolution. Home ranges were calculated as a Kernel utilization distribution with a 95% likelihood. This was done in R using the package `adehabitatHR` (Calenge, 2015). Depth values were averaged using the arithmetic mean over the same three hour period for the sake of consistency.

Model selection was done based on the Bayesian Information Criterion (BIC). BIC was chosen because it penalizes the inclusion of extra variables more severely than the Akaike Information Criterion, thus preventing overcomplication of the model.

2.6 Statistical tests

Generalized additive mixed-effect models (GAMMs) were used to test whether the response variables (Vocalizations, home range, depth) were affected by the explanatory variables (Noise, temperature, length, day/night). The ‘`gamm`’ function of the package ‘`mgcv`’ (Wood, 2021) was used to achieve this. Smooth functions were applied using the `s()` function. Because the explanatory variables for both home range and depth were the same, the same model structure was used. This model had the form:

$$y_{i,j} = a + s(N_j) + s(T_j) + L_i + t + a_i$$

, where $y_{i,j}$ is the response (Home range or depth) of individual i at time j , a is the intercept, $s(N_j)$ is a smooth function for noise (dB *re* $1 \mu Pa$) at time j , $s(T_j)$ is the smooth function for temperature ($^{\circ}C$) at time j , L_i is the length (cm) of individual i , t is a factor variable to signify day or night, and a_i is a random effect for individual i . The random effect gives some room for individual differences. In addition, a first order autoregression was applied per individual to account for temporal autocorrelation.

The data for the vocalizations consisted of 60 observations, with 10 samples from each group representing different levels of noise and diel period (Table 2). Since no information on individuals could be collected for the vocalizations, cod length, random effects, and the correction for autocorrelation could not be applied. Therefore, the model had a slightly different form from the telemetry model:

$$y_j = a + s(N_j) + s(T_j) + t$$

, where y_j is the response (call duration, number of pulses, fundamental frequency, pulse period, or fatigue) at time j , a is the intercept, $s(N_j)$ is a smooth function for noise (dB *re* $1 \mu Pa$) at time j , $s(T_j)$ is the smooth function for temperature ($^{\circ}C$) at time j , and t is the factor for day or night.

3 Results

3.1 Collected data

1847 10-minute hydrophone recordings were made within the study duration. The average ambient noise level was $84.6dB(\pm 6.1)$, with higher levels during the day than during the night (Fig. 6). The median noise level was under $80dB$ (*ref* $1\mu Pa$) from 20:00-06:00, and generally reached over $90dB$ (*ref* $1\mu Pa$) from 11:00-16:00. The variance of the noise (excluding outliers) was generally higher during the day and was the greatest from 16:00-19:00, with lowest measurements being as much as 20dB lower than the highest measurements.

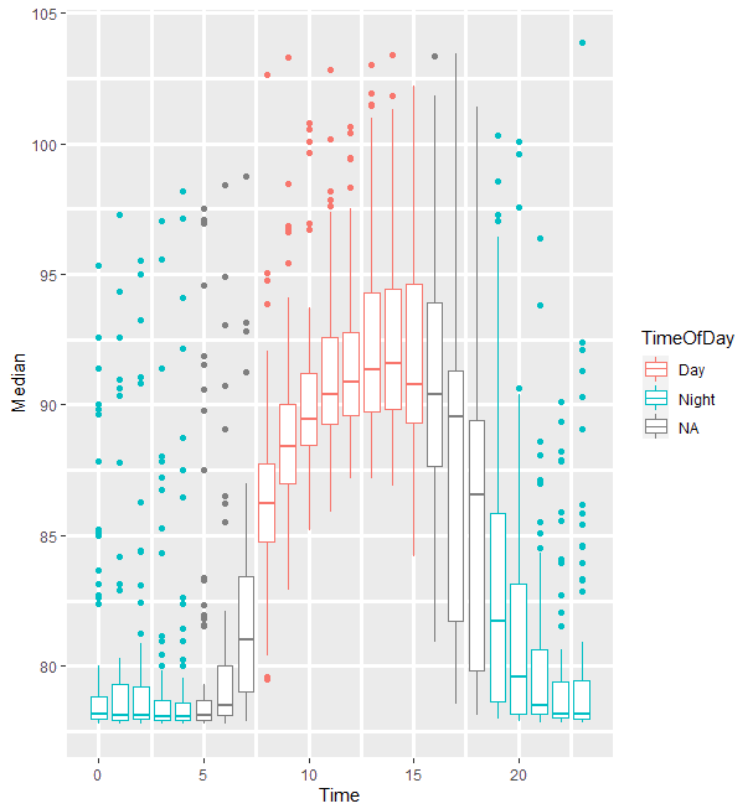


Figure 6: Median noise levels per time of day. Outliers signify values >1.5 times the interquartile range. Note that the hours around dusk and dawn are displayed as NA; This is because of the shift in sunrise and sunsets during the study.

3.1.1 Telemetry data

The raw telemetry data consisted of 17.5 million detections by the receivers in the grid. After filtering and processing, this corresponded to approximately 200,000 30-min COAs for 61 individuals. 31 of these individuals were consistently enough within the boundaries of the study area to calculate home ranges (>5 detections / 3 hours), which lead to a total of 12560 3-hour home ranges for these 31 individuals, with an average home range of $0.04km^2 (\pm 0.06)$. There were large differences between home ranges for different individuals; The median home ranges for 20 of the individuals was under $0.04km^2$, 10 individuals had home ranges between $0.05 - 0.09km^2$, while a single individual had a median home range of $0.36km^2$ (Fig. 7). One outlier was removed from the calculated home ranges, as it was significantly higher ($1.81km^2$) than the median home range ($0.027km^2$) for that individual.

The average depth that cod resided at was $17.1m (\pm 13.2m)$. The depth showed individual preferences as well, with most cod staying between the surface to 20m depth, while some clearly preferred deeper waters of up to 40m, with one individual staying mainly between 40 – 50m.

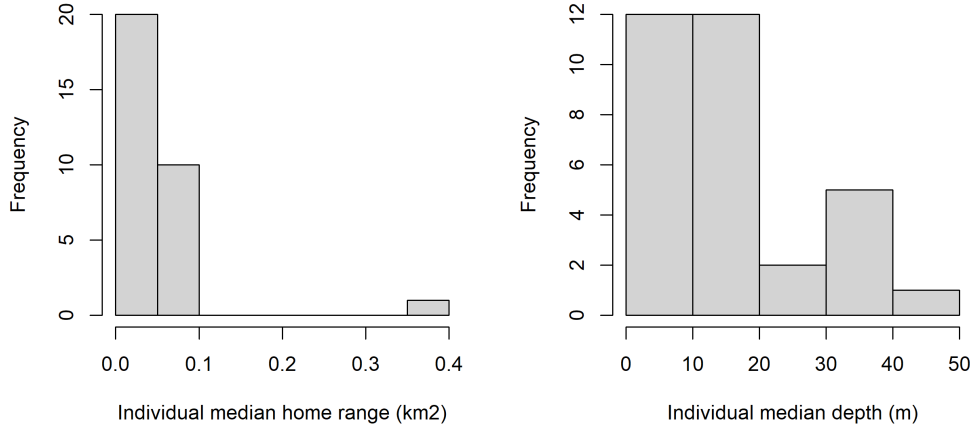


Figure 7: Bar plot of the median home range (left) and depth (right) per individual for the entire duration of the study.

3.1.2 Vocalizations

The 60 analyzed vocalizations had a mean length of $120ms$ ($\pm 36ms$) with a mean of 11.7 pulses (± 3.5). The average pulse period was $9.8ms$ ($\pm 0.8ms$). The mean fundamental frequency was $104Hz$ ($\pm 13Hz$).

3.1.3 Covariates

The average length of the cod in the study area was $49.76cm$ ($\pm 10.94cm$). The average temperature, measured at the depth of the hydrophone, was $12.4^{\circ}C$ (± 0.9) during the duration of the study, with a general decreasing trend from beginning to end (Fig. 8). There was little difference between the temperature during the night and day.

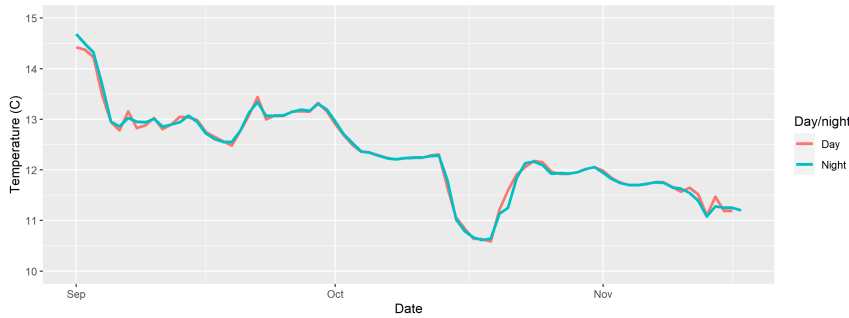


Figure 8: Plot of the average daily temperature over the course of the study area. Note that this is the temperature at 15m depth.

3.2 Telemetry GAMM

The final GAMM models for telemetry included the diel phase (day or night), noise level, and temperature (Table 4). Body length was excluded from all final models based on the BIC (Table 5). The partial plots for the telemetry models are shown in Fig. 9. The estimated values of the coefficients can be found in table 4. Home ranges were significantly smaller during the night ($p = 4.57E - 05$). Median noise was a significant predictor for home range size ($p = 1.06E - 06$). The standard error was much larger for noise louder than $95dB$. Although the response curves reveal no uniform direction, averaging the coefficients of the response curves' basis functions

revealed a slight decline in home range for both noise ($-0.00048km^2$) and temperature ($-0.00177km^2$).

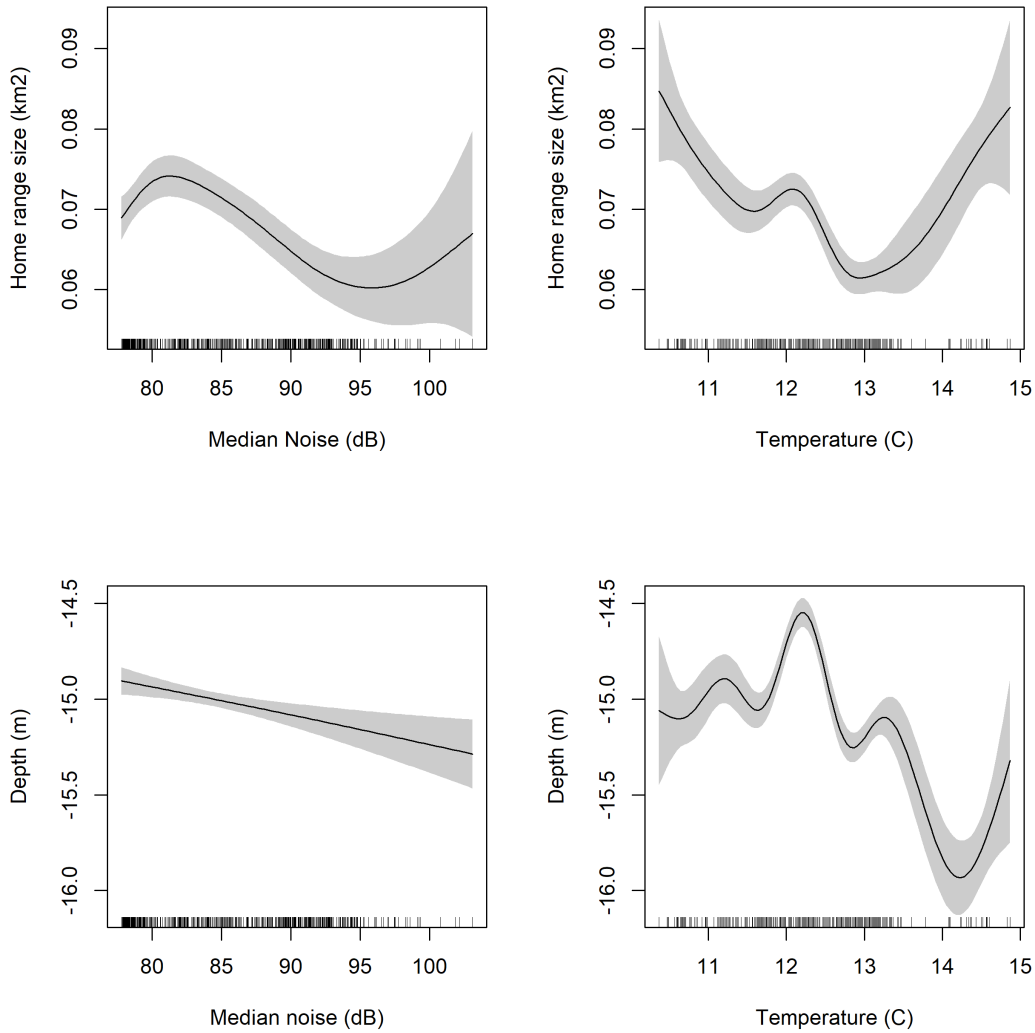


Figure 9: Partial effects plots of noise (left) and temperature (right) on the home range size (top) and depth (bottom). Note that the residuals are just plotted as a rug-plot on the x-axis. This is because the random effect is not included in the plot, resulting in a large variance of residuals, making the response curves unreadable.

Cod roamed approximately $0.2m$ deeper during the day than during the night ($p = 0.000187$). Furthermore, depth increased linearly with noise ($p = 0.00196$), with approximately $0.09cm$ per dB of noise. The average direction of the coefficient's smooth function was positive ($p = < 2e - 16$), indicating that cod were, on average, found in deeper waters when noise became louder.

3.3 Vocalization GAMM

Significant positive relationships were found between ambient noise and three of the analyzed vocal characteristics (Table 4): length ($p = 0.0455$), pulses ($p = 0.0111$), and fatigue ($p = 0.00897$). The relationship between noise and fatigue was linear (Fig. 10). While the relationship between noise and both pulses and length was not linear, the trend was always positive. Fundamental frequency and mean pulse period did not significantly correlate with any of the included model terms. Models including temperature and diel period were rejected on grounds of the BIC (Table 5).

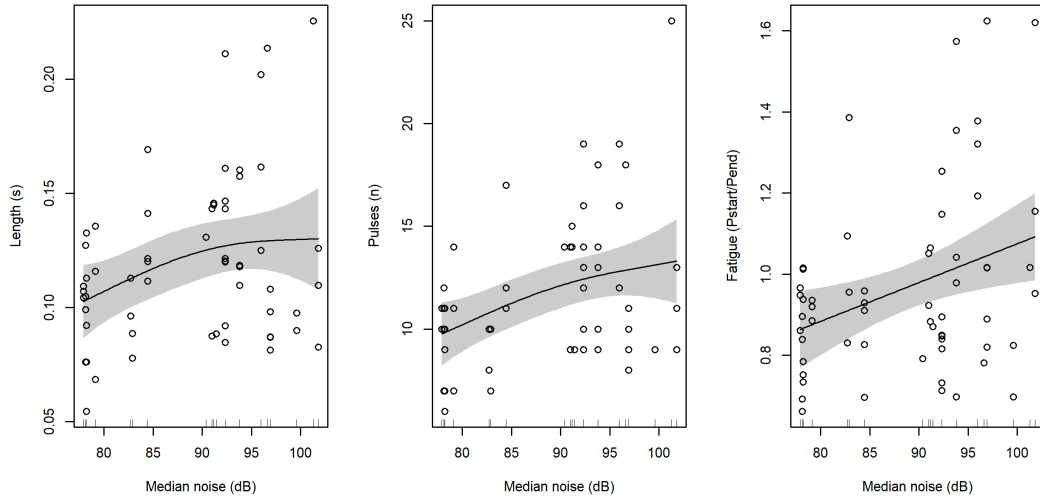


Figure 10: Partial effects plots of noise on the length (left), amount of pulses (middle), and fatigue (right) of cod vocalizations.

Table 4: GAMM output of the telemetry and vocalization data after model selection. Avg. noise is the arithmetic mean of the noise measurements taken during the 3-hour home range or depth average, while noise is the median noise measured in the recording that the analyzed vocalization occurred in. Note that the estimated coefficients for noise and temperature are averages of basis functions, and should be interpreted in combination with the figure of the smooths they represent (Fig. 9 & 10).

Telemetry

Response	Adj. R^2	Variable	Est. coef.	p-value
Home Range	0.279	Intercept	0.068397	$1.49E - 06$ **
		TimeNight	-0.00705	$4.57E - 05$ **
		Avg. noise	-0.00048	$1.06E - 06$ **
		T°	-0.00177	$< 2e - 16$ **
Depth	0.982	Intercept	-15.0039	$7.13E - 12$ **
		TimeNight	0.204115	0.000187 **
		Avg. noise	-0.00938	0.00196*
		T°	-0.19803	$< 2e - 16$ **

Vocalizations

Response	Adj. R^2	Variable	Est. coef.	p-value
Length	0.0853	Intercept	0.119551	$< 2e - 16$ **
		Noise	0.002264	0.0455*
N	0.123	Intercept	11.6667	$< 2e - 16$ **
		Noise	0.214718	0.0111*
Fatigue	0.0967	Intercept	0.96744	$< 2e - 16$ **
		Noise	0.008362	0.00897 **

Table 5: Model selection of the vocalization GAMM that were significant. Lower BIC means a better representation, which includes a penalty for extra added variables.

Telemetry

Model	BIC	Removed variable
$Length \sim Noise + Time + T^{\circ}C$	-175.866	
$Length \sim Noise + T^{\circ}C$	-186.674	Time
$Length \sim Noise$	-201.605	$T^{\circ}C$
$Pulses \sim Noise + Time + T^{\circ}C$	336.2293	
$Pulses \sim Noise + T^{\circ}C$	329.6353	Time
$Pulses \sim Noise$	328.4083	$T^{\circ}C$
$Fatigue \sim Noise + Time + T^{\circ}C$	28.45866	
$Fatigue \sim Noise + T^{\circ}C$	21.11972	Time
$Fatigue \sim Noise$	11.01943	$T^{\circ}C$

Vocalizations

Model	BIC	Removed variable
$Homerange \sim Noise + Time + T^{\circ}C +$ Body length	-33808.4	
$Homerange \sim Noise + Time + T^{\circ}C$	-33828.1	Body length
$Depth \sim Noise + Time + T^{\circ}C +$ Body length	47326.92	
$Depth \sim Noise + Time + T^{\circ}C$	47316.34	Body length

4 Discussion

4.1 Telemetry

The model for depth was able to explain a large portion of the variance with the diel component, noise, and temperature. The positive diel coefficient signifies that cod tend to swim shallower during the night, whereas the negative coefficient for temperature tells us that cod generally swim deeper when temperature increases. Both of these findings correspond with Freitas et al. (2021), who ascribed the depth preference of cod to their thermal sensitivity: When surface water gets colder, cod swim shallower; when surface water gets warmer, cod dive deeper.

Noise had similar effect on depth as temperature. While the effect was overall weaker, the relationship was found to be linear. The explanation of the relationship is therefore fairly straightforward; an increase in noise leads to an increase in depth. This is an important finding, as this suggests that cod take noise into consideration when selecting a thermal environment. Because of the importance of temperature on the bodily functions of cod, this could mean that noise might have indirect effects on the overall health of cod.

Furthermore, the GAMM for home range suggests that noise has an overall negative effect on the size of the area that cod uses. This corresponds with the work of Ivanova et al. (2020), who associated vessel presence with the decrease in exploratory activities in Arctic cod as their movement behavior becomes more cautious. However, the model in the present study had a low R-squared, meaning that a significant portion of the variance went unaccounted for in the model. This suggests that there could be other covariates that should have been incorporated in the model.

One such covariate could be habitat: Gotceitas et al. (1995) observed that juvenile cod have a clear preference for certain habitat types when confronted with the threat of predation. These habitats, such as kelp and cobble, could provide shelter should a predator approach. It is plausible that cod move to these types of habitats if noise is associated with predation threat. In addition, Freitas et al. (2021) found that temperature plays a large role in the habitat preference of cod. Cod were found to inhabit vegetated habitats under favorable temperatures ($< 16^{\circ}C$), such as eelgrass and macroalgae beds. Under increased temperatures, they inhabit deeper, colder habitats where there is a lack of vegetation. Since cod show clear habitat preferences under different environmental circumstances, habitat should be considered in future studies regarding the effect of noise on cod. In addition, horizontal and vertical position should be integrated in the same model due to the strong correspondence between habitat and depth.

4.2 Vocalizations

The GAMM for vocalizations show that cod vocalizations are likely affected by the input of noise. The length and amount of pulses showed an increase when ambient noise was louder. The length and number of pulses are related, as additional pulses add length to a call. Fatigue was also found to be significantly affected in cod. This corresponds with the hypothesis that cod adapt their calls to be heard despite an increase in environmental noise.

In other species, the adaptation of vocalizations was found to have had consequences that may influence fitness. In a laboratory experiment on gobies, anthropogenic noise reduced male courtship behavior and female spawning, which is suggested to be the cause of a reduction in male calling frequency and masking of the produced calls (de Jong et al., 2018). Acoustic courtship behavior plays an important role in cod as well: Rowe and Hutchings (2006) found that the occurrence of cod grunts is especially high during the peak of spawning, and that produced sounds visually correspond to courtship- and agonistic displays. This suggests that adaptation of vocalizations could negatively impact cod acoustic courtship behavior.

4.3 Considerations

One caveat of the study was the use of only a single hydrophone to record the noise. Due to the bathymetry of the study location, one hydrophone cannot capture sounds from the entire fjord. Because the telemetry stations cover a larger area, the size of the study area was limited by the availability of just one hydrophone. The amount of data for the telemetry part of the study could therefore be drastically increased with the addition of more hydrophones to make recordings of the noise.

In this study, centers of activity were used to estimate the location of cod due to the complexity of calculating the exact position. In addition to being less accurate, the temporal resolution of the data was reduced from 3-5 minutes to 30 minutes. As home ranges were calculated over 3-hour periods, this severely impacted the amount of datapoints used for every home range.

4.3.1 Telemetry data

Gotceitas and Brown (1993) found that larger juvenile cod are quicker than smaller individuals in leaving their shelter after exposure to a predator. Freitas et al. (2021) found a significant link between the depth response of cod to temperature and body size. These results indicate that body size plays a role in horizontal and vertical movements, and makes it questionable that body size was rejected in the models of the present study on grounds of not being significant. This can be explained by the time of measurement relative to the study. Freitas et al. (2021) used data from 2015-2018, which concerned cod tagged between 2015 and 2017. The present study used data solely collected between August - November 2020, while the cod were tagged in February 2020 or earlier.

Furthermore, the temperature was only measured at 15m depth for the present study, which might explain the wigglyness of the temperature response curves for the models of home range and depth. The suggestion for future studies is therefore that care should be taken in the measurement of body size, and that temperature at different depths should be taken into account.

4.3.2 Vocalization data

Amorim et al. (2013) used fatigue to describe the condition of male painted gobies under the premise that sound production costs energy, and the ability to sustain sound production therefore increases with the condition of the fish. While the mechanism of sound production is similar in gobies and cod, the produced sounds differ. The most obvious difference is in the average number of pulses in a call, which is an average of 8-12 in cod (Table 1) and 27 in gobies (Amorim et al., 2013). Therefore, it is not clear whether the method of calculating fatigue can be uniformly applied to cod as it was applied to gobies. Additionally, male condition is an important factor in fatigue; Amorim et al. (2013) found that fatigue depends largely on male size. Due to the in-situ nature of the present study, individual characteristics such as sex and body size could not be accounted for in the recorded vocalizations. Therefore, individual differences might be responsible for the low r-squared values for the vocalization models.

The uncertainty of individual characteristics of the cod that produced the calls is not just important for fatigue. As the physiology of cod's swim bladder and drumming muscles changes with the growth, it is likely that the produced sound changes as well. This is observed in for example Grey gurnards (*E. Gurnardus*), where duration of the call and pulses, and the number of pulses increased and peak frequency decreased as body size increased (Amorim et al., 2004).

Furthermore, individual depth preferences of cod have influenced the population size that could be recorded with the hydrophone. Since the hydrophone was fixed at 15m depth, only cod that were around that depth could have occurred in the recordings. Therefore, we can infer from the telemetry data that the recorded vocalization

were likely not representative for the entire population that resides in the study area.

Additionally, the analysis of vocalizations deals with an inherent bias. Vocalizations are masked when there is interference of background noise. Therefore, vocalizations are more difficult to distinguish, and it is more difficult to infer the basic vocal characteristics such as length, pulses, and fundamental frequency. The effect of masking on data collection is something to be considered, but which cannot be prevented in an in-situ experiment.

Most of the uncertainty of the results for the vocalizations therefore lies in the fact that there is no way to distinguish individuals. It is therefore highly suggested that these individual differences are accounted for in future studies. This can be done by for example placing a camera to identify individuals, and match recordings with accompanying visual cues to determine which individual made the sound in case there are multiple possible candidates. This recording of visual cues could also help with the recognition of vocalizations in general.

4.4 Management implications

The results of this research show that noise significantly impacts the movement and vocalizations of Atlantic cod. The research was conducted in a location that is not used as a shipping route, which implies that most of the noise was created by pleasure boating. This suggests that while recreational vessels may produce less disturbance than cargo vessels in terms of water displacement, they can still impact the marine habitat with the noise they produce. However, regulations for recreational vessels are scarce, which is concerning as the coastal environments in which these types of boats are most abundant are an essential part of the marine biome. Therefore, the research suggests that policies to reduce the amount of noise produced by boats should not only apply to large vessels such as cargo ships, but also to smaller, recreational vessels.

Despite the discovery of negative effects attributed to the increase of marine sound pollution, little effort is undertaken to reduce these. One reason for this is a general lack of understanding of how anthropogenic noise can be quantified. To illustrate this lack of understanding, I will refer to the Marine Strategy Framework Directive (MSFD). The directive was adopted in 2008 to tackle the pressures and impacts from human activities on the marine environment, the aim of which was to achieve a “Good environmental status” (GES) by 2020 (European commission, 2017). However, a report on the progress made until 2018 (Vighi et al., 2021) stated that “In almost no case MS provided target values or indicators, making the targets not measurable and thus not clear whether the defined targets would contribute to address the gap between current state and GES”, reportedly stemming from a lack of commonly agreed methodological standards, and lack of sufficient data for proper assessment.

5 Conclusion

This research has looked at the possible effects of anthropogenic noise on the behavior of Atlantic cod in a marine reserve in a Norwegian fjord. Two types of behavior were considered: Movement and vocalizations. Home range sizes were used to find patterns in horizontal movement, while average depth was used for vertical movements. Differences in vocalizations were analyzed using vocalization length, number of pulses, fundamental frequency, mean pulse period, and vocal fatigue. Movement data was collected using telemetry, while recordings of noise and cod vocalizations were collected using a single hydrophone. The response variables were tested for significance using GAMMs.

The results of the study indicate that anthropogenic noise significantly affects both the movement and vocalizations of cod. Cod were found to decrease the size of their home range during times where there was more noise. Cod also swam deeper, which is an important finding because this may impact their body temperature, and therefore their physiological functions. The length, number of pulses, and vocal fatigue were found to increase during periods with more noise. This suggests that the Lombard effect is also found in cod. Additionally, since vocalizations are important during courtship behavior, an increase in noise might negatively affect courtship success. In turn, this may adversely affect spawning performance. However, more research is needed to determine to which extent noise affects courtship success due to altered vocalizations.

This research adds on to the growing literature on the effects of noise pollution on the marine environment. However, while the evidence about the negative effects of noise pollution is growing, management remains absent. Despite the inclusion of noise pollution in the European Marine Strategy Framework Directive in 2012, hardly any of the member states have started to monitor noise pollution, let alone address policies for reducing the introduction of noise to the marine environment. The detrimental effects that noise has on an economically important marine resource such as cod suggest that management on noise pollution should be addressed urgently.

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