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Biomonitoring using tagged sentinel fish and acoustic telemetry in commercial salmon aquaculture: A feasibility study

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ABSTRACT

We tested if it is technically feasible to monitor fish in real-time in full-scale commercial fish farms using acoustic telemetry. 31 Atlantic salmon were equipped with acoustic transmitter tags containing depth sensors. Tagged fish were monitored for three months in two industrial scale sea-cages containing 180000 and 150000 fish, respectively. Each cage was fitted with two prototype acoustic receiver units designed to collect, interpret and store the information transmitted by the acoustic transmitter tags. Ten in each cage were also equipped with Data Storage Tags (DSTs) containing depth sensors to record individual-based datasets for comparison with the acoustically transmitted datasets. After compensation for sample loss caused by expected acoustic interference between the transmitter tags, the resulting dataset revealed that the receiver units collected 90–95% of the signals in both cages. Acoustic communication conditions in the sea-cages were not strongly impaired by factors such as fish density and local noise. Further, the dataset from the acoustic transmitters had comparable resolution and quality to that produced by the DSTs. However, acoustic tags provide data in real time and enable farmers to respond to the received information with farm management measures, whereas archival tags such as DSTs need to be retrieved and downloaded and hence have no real-time applications. We conclude that acoustic telemetry is feasible as a method to monitor the depth of fish in real-time commercial aquaculture.

1. Introduction

In terrestrial animal farming, there are numerous examples of farmers observing the individual behaviours of animals either directly or with remote monitoring techniques and adjusting farm practices with this information (e.g. Tebot et al., 2009; Darr and Epperson, 2009; Terrasson et al., 2016). In aquaculture settings, both the large number of small animals under production and the underwater environment make this approach more difficult. Atlantic salmon farming, which is the largest producer of fish in the sea worldwide, is a case in point. In modern farms, salmon are typically raised in an array of 10–15 sea-cages, each spanning a circumference of 157 m or more, with net depths from 10 to 50 m. Cages may contain hundreds of thousands of fish with stocking densities up to 25 kg m^{-3} (Norwegian Ministry of Fisheries and Coastal Affairs, 2008). The sheer number of fish at each farm makes it difficult for farmers to maintain an overview of production and integrate information from individuals into their farming strategies. This represents a challenge, as ethical considerations require farm operations to secure the welfare of the fish. Current animal husbandry legislation in many countries requires proper care and close observation of captive animals (Norwegian Ministry of Agriculture and Food, 2009). An ability to closely monitor fish throughout the production cycle would address these requirements, and could in turn lead to improved economic efficiency by helping to optimise operations.

Traditional methods used by farmers to observe farmed fish include the use of manual fish sampling, visual inspection from the surface, and submerged cameras. Although these methods provide farmers with an impression of the behaviours and responses of the fish, they are limited due to water visibility and the large volume and number of fish in production cages. Furthermore, such methods do not produce objective data describing the responses of individual animals. Individual-based sampling utilising electronic tags is a method that may supplement traditional observation techniques, and which gives the opportunity to monitor animals without having to directly interact with them or separate them from the rest of the population. In principle, two different types of electronic tags are used for individual animal monitoring; Data Storage Tags (DSTs) which store data in internal storage mediums (e.g. Kawabe et al., 2003; Tsuda et al., 2006; Gleiss et al., 2009; Johansson

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et al., 2009), and transmitter tags which convey data wirelessly to acoustic receiver units (Davidsen et al., 2009, e.g. Gargan et al., 2015) or radio antennae/satellites (e.g. Wanless et al., 1988; Eckert and Stewart, 2001). Both DSTs and transmitter tags may be equipped with different types of sensors to measure behavioural (e.g. Kawabe et al., 2003), physiological (e.g. Depasquale et al., 1994) or environmental variables inside or near the tagged animal. In addition, transmitter tags may be used to track the spatial positions of fish using triangulation (Begout Anras et al., 2000, e.g. Rillahan et al., 2009) or spatially distributed PIT antennae (e.g. Folkedal et al., 2012; Nilsson et al., 2013; Korsøen et al., 2012b). While DSTs need to be recollected after the observation period to obtain the data, transmitter tags enable online monitoring of the data simultaneously with data collection.

Whereas terrestrial telemetry is predominantly based on radio communication, hydroacoustic communication is usually preferred for seawater applications. This is because the high specific permittivity, magnetic permeability and electric conductivity of sea water increases signal attenuation and absorption, leading to shorter communication ranges for radio signals than in air (Wozniak and Dera, 2007). In contrast, hydroacoustic signals are transported further and with higher efficiency in water than in air. The resulting quality and effective data capture rate of a dataset collected through hydroacoustic communication depends on several factors, many of which are related to the physical properties and complexity of the underwater acoustic communication channels (Zhou and Wang, 2014). Underwater acoustic signals experience losses due to absorption, scattering and geometric spreading, and severe multipath interference may lead to inter-symbol interference which disrupts signal reception (Stojanovic, 1996). Furthermore, Doppler shifts may be present at the receiver, leading to frequency shifting and spreading, which makes the proper detection of acoustic signals more difficult (Stojanovic and Preisig, 2009). Another important physical factor is ambient and site-specific acoustic noise, which may be complex and spatially and temporally unpredictable (Hovem, 2004; Stojanovic and Preisig, 2009). In the fish farming environment, scattering and multipath effects could occur due to the large fish biomass, the short distance to the sea surface and bottom and the components of the farm (e.g. buoys, nets, chains). Furthermore, site specific and time dependent features such as weather and waves, farm machinery, moving structures and components, and the fish themselves will contribute to increasing the ambient noise levels. Collectively, these factors could make acoustic signal reception at a fish farm challenging and ultimately limit achievable communication bandwidth.

The transmitter tags in an acoustic telemetry system transmit digital information such as fish ID and sensor values by modulating the carrier wave emitted by an omnidirectional acoustic transducer at pre-programmed transmission intervals (see Føre et al., 2011 for more details on the construction of an acoustic transmitter tag). These modulated signals are detected and interpreted by receiver units in the system, which decode the acoustic signals back into digital information. Most current commercially available systems for acoustic telemetry employ a single carrier frequency for communication. This may increase the difficulties in achieving the desired data capture rates at a fish farming site, as the system is then more susceptible to acoustic interference or signal collision, which will occur when the acoustic signals from two or more transmitters using the same carrier frequency reach the receiver within overlapping time windows. The receiver will then have difficulties in decoding the convoluted acoustic signals into the digital values of the different tags, resulting in data loss. Such collision effects will be more severe when the number of tags transmitting acoustic signals on the same carrier frequency increases, or when the time interval between transmissions from each tag is reduced. An additional potentially negative effect of using a single carrier frequency is that the system will be more sensitive to frequency specific noise and distortion, which may impact narrow frequency bands.

Although acoustic telemetry has mainly been applied to wild fish research (e.g. Thorstad et al., 2008; Plantalech Manel-la et al., 2009; Jensen et al., 2014), the method has also been used to monitor farmed fish in small sea-cages (e.g. Begout Anras et al., 2000; Juell and Westerberg, 1993; Rillahan et al., 2009; Ward et al., 2012), primarily with the aim of collecting detailed datasets on the behaviours of individual fish. Earlier efforts within this area include 3D positioning of Atlantic salmon and Atlantic cod (Juell and Westerberg, 1993; Rillahan et al., 2011; Ward et al., 2012), depth movements and activity levels of salmon (Føre et al., 2011), and respiration and feed intake in salmon (Alfredsen et al., 2007). These predominantly small/medium scale studies demonstrate the potential for the scientific application of acoustic telemetry in fish farms, and illustrate some of the potential in using this technology as an operational tool in fish farming, particularly considering online monitoring possibilities. Using telemetry to observe fish behaviour during production could provide farmers with information to make pre-emptive decisions to alter production conditions for improving (or avoid impairing) fish welfare, health or growth. For example, real-time swimming depth data could be used as input to adjust the feeding regime.

Here, we evaluated whether acoustic telemetry is viable for real-time monitoring of fish in commercial fish farms with a typical industrial biomass (up to 1000 t per cage). We tested the extent of data loss due to factors such as acoustic noise or scattering based on biomass interaction impairing acoustic reception. Secondly, we investigated how acoustic reception success varied with time, number of receivers used and receiver placement within cages. We also compared system performance with respect to data capture against Data Storage Tags (DSTs).

2. Materials and methods

2.1. Acoustic transmitters and receivers

We used Thelma Biotel ADT-MP-13 (Thelma Biotel AS, Trondheim, Norway) acoustic transmitters, which were 13 mm in diameter and 42 mm in length, and weighed 6.9 g in water. This transmitter type has a power output of 153 dB re 1 μPa at 1 m, a typical battery life of 31 months when transmitting at intervals of 90 s, and contains a pressure sensor with an accuracy of between 0.5 and 1.0 m depending on temperature. The tags encode measured pressure values using an 8-bit code (0–255) which are used to derive the corresponding water depth. Our experiments were conducted in cages of 30 m depth and the transmitters were thus set up with a depth range of 0–50 m, leading to a depth resolution of approximately 0.2 m. All tags transmitted their data at an acoustic carrier frequency of 69 kHz, with each transmission encoding a unique tag identification number (ID) and the present depth value registered by the sensor. Coding of digital values to acoustic signals was conducted using a standard differential pulse position modulation scheme (DPPM) which uses about 4 s to convey each data/ID pair, including a checksum.

We collected the acoustic telemetry data using four units of a prototype acoustic online receiver type (AR) from Thelma Biotel AS. Each AR was equipped with an underwater interface providing external power and an RS-485 communication port, and a lithium battery securing stand-alone operation during potential loss of external power. Each of the ARs also contained an internal flash memory able to store up to 655280 registrations from acoustic transmitters. To keep track of received data, the ARs assigned each registration with a timestamp based on their internal clock circuits (20 ppm clock accuracy, drift of around 1.7 s per day) and a unique sequence number when storing them on the flash memory. The registrations were also associated with a set of values describing the quality of reception including an indicator of the background noise level. Noise indicator values were also registered regularly by the ARs at 1 min intervals to provide an impression of the general ambient noise level. When an AR interface was connected, all data written to its flash memory was also communicated through the RS-485 port.

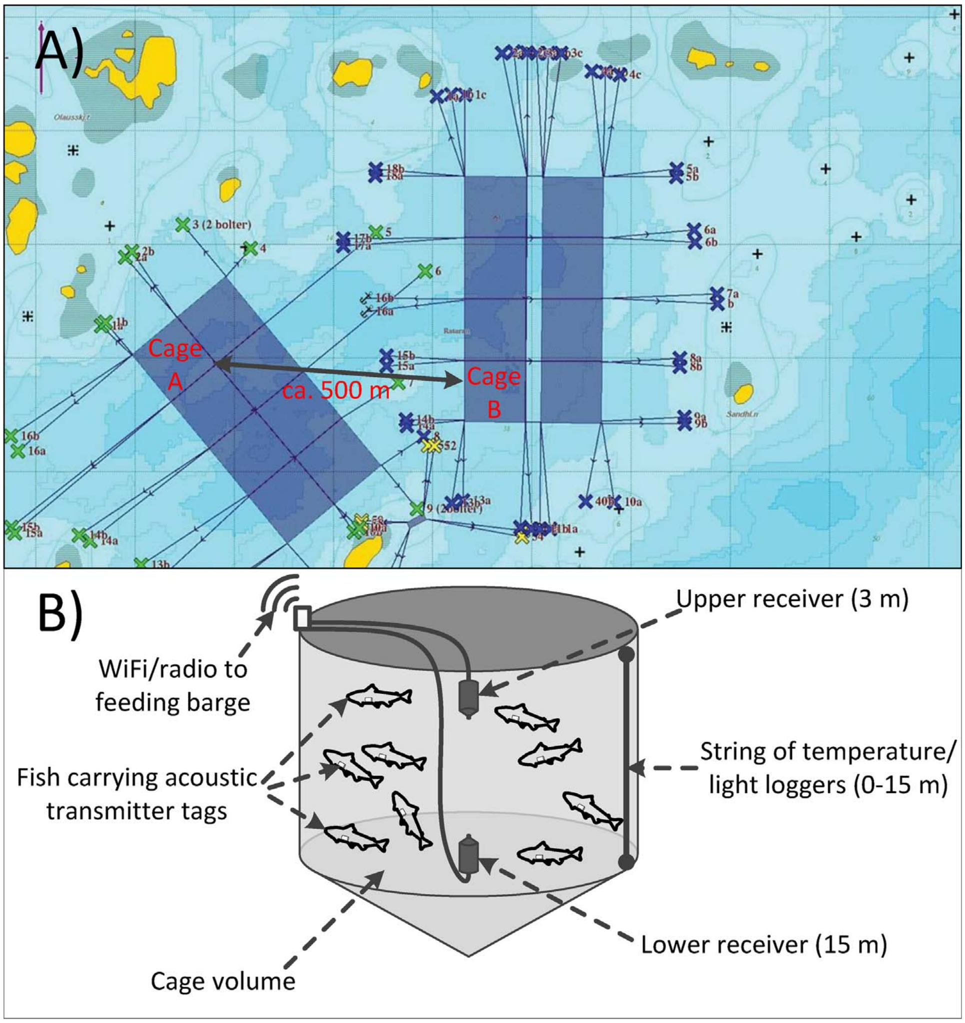

Fig. 1. Experimental setup at the SINTEF ACE location Rataren. A) physical layout of the farm site denoting the two cages A and B used in the experiments (map of farm: Christer Johansen SalMar Farming AS); B) schematic diagram (not to scale) of the experimental setup at a single cage illustrating placement of acoustic receivers and temperature/light loggers, and the presence of fish carrying acoustic transmitter tags.

Since the hydroacoustic system (tags and receivers) used in these experiments operated on a single frequency (69 kHz), the system was expected to experience transmission loss due to acoustic signal collisions. The transmitters used their internal clock circuits (20 ppm clock accuracy, drift of around 1.7 s per day) to keep track of the intervals between acoustic transmissions. These clocks could drift differently over time between different tags. With regular transmission intervals, differences in clock drift could therefore in time lead to two or more tags simultaneously sending signals, causing systematic data loss due to repeated signal collisions. To avoid this problem, we set up the transmitters with a time-division multiplexing transmission scheme, where the intermissions between consecutive acoustic messages emitted from a transmitter were randomly selected between 50 and 200 s (50/200 scheme, with a 125 s average transmitting interval).

2.2. Online monitoring system

Real-time monitoring of the system and hence the tagged fish, was facilitated through the RS-485 ports of the ARs. The RS-485 signal was converted to IEEE 802.3 standard (Ethernet) using industrial protocol converter units (Moxa Americas Inc., Brea, USA) mounted in a watertight cabinet on the floating collar of the cage. The converter unit was connected via radio link to a computer inside the feeding barge, which ran a Java based software program handling the communication with the receiver units. This software stored all data received through RS-485 from the receivers in a local database, essentially providing a backup of the internal storage in the receivers. To reduce the effects of clock drift on the datasets, the software was set to send RS-485 messages containing the present true time when receiver time was found to deviate with 5 s or more from true time. Further, to ensure that the dataset on the computer would be complete, the monitoring software issued requests for retrieval of data when gaps in the sequence numbers of data received over RS-485 were detected.

2.3. Data storage tags (DST)

Star Oddi DST micro TD (Star Oddi, Iceland) were used in the experiments, which feature temperature and pressure sensors and an internal memory with a capacity of 43234 data points. Since the tags were to be used in 30 m deep cages, we selected the smallest range available for this tag type (0–150 m), resulting in a resolution of 0.12 m and an accuracy of ± 0.75 m. Pressure values were registered in bar, with a value of 0 representing the pressure at the water surface. These tags were smaller than the acoustic tags, measuring 8.3 mm in diameter and 25.4 mm in length, and weighing 1.9 g in water. We selected a four minute sampling interval, resulting in a data series that covered about 120 days.

2.4. Experimental setup

We conducted our experiments at the fish farm Rataren (63°46′49.5″N 8°31′02.0″E) near Frøya in mid-Norway over a three-month period (April, May, June). Rataren is a coastal fish farming site which typically experiences currents of around 0.3 m s^{-1}, and lies behind a series of small islands that provide shelter from large oceanic waves and swells. Temperature and light was monitored at 10 min intervals using a string of temperature/light loggers placed at 0.5 m intervals between 0.5–15 m depth (UA-002-64 HOBO, Onset Computer Corporation, Pocasset, MA, USA). There was very little vertical stratification in temperature during the trials, with mean water temperature varying between 6 ° and 10°.

The farm was stocked with fish from the AquaGen strain, which had been put to sea in spring 2013, and had been reared under standard commercial conditions before and during the experiment. The experiment was carried out in two full-scale cages (157 m circumference, 15 m side depth and 25–30 m max depth) stocked with 180000 (cage A) and 150000 (cage B) Atlantic salmon. Initial biomass for the trial period was 361 t (mean weight of 2 kg) in cage A and 232 t in cage B (mean weight of 1.6 kg). The distance between the cages in the farm was about 500 m (Fig. 1A).

Two receivers were placed in the centre of each cage (Fig. 1 B). To maximise the percentage of the cage volume provided with acoustic coverage, we placed one of the receiver units in each cage near the surface facing downwards (d = 3 m, hereafter labelled upper receiver), while the other unit was placed near the cage bottom facing upwards (d = 15 m, lower receiver). This setup was motivated by potential acoustic shadowing of the receiver housing and preliminary simple in-cage range testing of the system.

Fish handling and surgery was made in compliance with the Norwegian animal welfare act, and approved by the Norwegian Animal Research Authority (permit no. 5410). Tags were deployed in early April when water temperatures were just above 5°. Fish were tagged following a commonly used method for equipping fish with acoustic transmitter tags (Pedersen and Andersen, 1985). Salmon were collected from the trial cages by using casting nets sampling from 10 m depth up. A total of 15 and 16 salmon from cage A and B, respectively, were captured and sedated using Benzocaine mixed in sea-water (1:20000) until the fish were observed to be immobile. The fish were then equipped with acoustic transmitter tags (cage A fish IDs 1–15, cage B fish IDs 16–31), 10 of which in each cage were also provided with DSTs (cage A fish IDs 1–10, cage B fish IDs 16–25). In addition, all tagged fish were set up with PIT tags to facilitate easier identification during slaughter after the experiment. Tags were inserted into the abdominal cavity of the fish through small surgical incisions, which were subsequently closed using silk sutures (Ethicon Perma-Hand 2-0) and medicinal glue (Histoacryl). The fish were then kept in a recovery tank with continuously refreshed water until deemed rehabilitated from both sedation and surgery, and then released into the same cages they were collected from.

DST tags were retrieved from the processing plant when the trial cages where processed. PIT-antennae detected the presence of PIT-tags in the processed fish. If a fish carrying a PIT-tag was detected, this fish was removed from the processing line and handled manually.

2.5. Data processing

2.5.1. Hydroacoustic transmitted data

Since the system was a prototype, we also downloaded all data from the receivers manually after they had been collected from the field. We merged the datasets of both receivers in each cage, to produce a single dataset. Duplicate registrations caused by the same acoustic message were identified and combined into a single data point. Such combined data registrations were also equipped with the timestamps and sequence numbers describing their position in the separate datasets of both ARs, as this would enable analyses aimed at identifying eventual effects of receiver placement.

Signal collisions were expected to affect the acoustic reception rates in the cages, and had to be taken into account in our analyses. We therefore calculated a theoretical estimate, T_{EC}, of the percentage of acoustic transmission expected to be lost due to signal collision for the cages. This was done by using a computer simulation programmed in Java which used the transmission interval (50/200), pulse protocol period (4 s) and the number of transmitters in each cage (A: 15, B: 16) as inputs. The simulated tags were programmed to transmit data at random time intervals of between 50 and 200 s, with each transmission event lasting 4 s. If two or more simulated tags attempted to transmit at partially or completely overlapping times, the transmissions of these tags were discarded as corrupted due to code collision and registered as loss. The simulation gave 54% and 57% T_{EC} for cages A (15 tags) and B (16 tags), respectively.

We also divided the telemetry datasets for each cage into several smaller datasets, each containing only the data points received from a specific individual transmitter tag. For each individual tag, we then found the total time interval the transmitter was represented in the data set by subtracting the smallest from the largest timestamp in the dataset. This interval was then divided by the mean time interval between consecutive transmissions (i.e. 125 s), yielding an estimate of the number of acoustic transmissions that this particular transmitter tag was expected to have transmitted, T_{MAX}. By dividing the total amount of data points received from each transmitter by the T_{MAX} for that transmitter, we obtained the proportion of T_{MAX} that was successfully received by the receivers, hereafter denoted as T_{SR}. This percentage together with T_{EC} represented the proportion of the total number of acoustic transmissions that could be accounted for. The remaining percentage of T_{MAX} (i.e. 100% − T_{SR} − T_{EC}) was regarded as data lost due to reasons other than signal collisions (e.g. acoustic noise or signal damping), hereafter denoted as T_L.

To investigate the impact of the number and placement of ARs in a cage we also compared the datasets produced by the ARs at upper (3 m depth) and lower (15 m depth) positions in each cage. We also evaluated eventual time dependent variations in reception by sorting the receiver specific datasets for each cage into 1h-bins from 0 to 24 depending on the time of day data points were received. The number of receptions per 1h-bin was then compared with the mean acoustic noise level indicator value registered by the AR for the same 1h-period of the day.

2.5.2. Tag type data comparison

Unlike the sensors in the acoustic transmitter tags which were pre-calibrated during manufacturing, the sensors in the DSTs were calibrated prior to field deployment. The datasets from the experiments thus had to be manually adjusted by subtracting a bias in value representing the pressure at the water surface (=1 Atm). Since the fish were immersed after their release into the cages, no negative pressure values (indicating negative depths) should occur in the datasets. We thus derived the appropriate bias values for each of the DST tags by finding the most negative value in the datasets and subtracting this value from the entire data series.

We compared the datasets from the DSTs with the datasets collected by the corresponding acoustic transmitters for the fish carrying both tag types co-located. This comparison focused on the main properties of the obtained datasets, i.e. the number of samples received, mean depth and standard deviation in depth.

3. Results

3.1. Fish survival, health and tag retention

General mortality in both cages was at normal levels, with less than 5% mortality for the duration of the experimental period, and the fish populations displayed normal growth rates. Three tagged fish in cage A and one tagged fish in cage B were found dead a few weeks into the experimental period. There were no obvious visual signs of impaired health or lowered growth on the tagged individuals identified at slaughter.

Two individuals originally equipped with both DSTs and acoustic tags were found to only contain one tag when slaughtered. One of the tags had been ejected from the fish, probably through the muscle and skin of the abdominal cavity. Six other acoustic transmitters abruptly started reporting almost constant depths of 30–40 m after first having reported normal depth migrations for the majority of the experimental period. Since these depths could refer to the max cage depth (30 m) or the seabed beneath the farm (40 m), this strongly indicates that the fish died or ejected their transmitters.

Of the 20 fish carrying DSTs, only five (fish 3, 5 and 7 cage A, fish 18 and 25 cage B) were obtained during or after the experimental period, possibly due to tag ejection during the experiment, mortality and difficulties in re-identifying the tagged fish at the slaughter line (i.e. finding 20 fish in 330000 individuals). One of these (fish 3) was obtained in the earliest stages of the experiment through dead fish retrieval and hence did not produce sufficient data to be considered in further analysis.

3.2. System performance

There was little acoustic cross talk between the two cages in the trial. Only 0.4% (1124) of the total number of acoustic receptions detected in cage A (323996) originated from transmitters in cage B, whereas 0.7% (2057) of the total amount of receptions in cage B (317391) came from transmitters in cage A.

3.2.1. Acoustic reception success

When subtracting the transmitters removed from the system due to early mortalities, there were 12 active transmitters left in cage A, while cage B was left with 15. These numbers lead to new estimated acoustic collision fractions T_{EC} of 46% and 54% for cages A and B respectively. Using these estimates, a transmitter specific analysis was conducted for both cages (Fig. 2, Fig. 3).

Although the estimated T_{EC} in cage B was higher than in cage A due to a higher number of surviving tagged fish, T_L was found to be between 5 and 10% for all transmitters in both cages. 90–95% of the total theoretical number of transmissions (T_{MAX}) for all transmitters were hence either received (T_{SR}) or expected to be lost due to signal collisions (T_{EC}).

3.2.2. Spatial and temporal variability in reception

The combined acoustic datasets (i.e. upper + lower receiver datasets) for cages A and B contained a total of 323996 and 317391 verified acoustic receptions during the trial period, respectively. Taking the duration of the experimental period into account, this yielded a mean interval between receptions from a single tag of 275 s in cage A (12 transmitters, T_{EC} = 46%) and 320 s in cage B (15 transmitters, T_{EC} = 54%).

To identify whether receiver placement affected reception rate, we evaluated how the total number of verified acoustic receptions in each cage were distributed between being detected by both receivers, only the upper, and only the lower receiver (Table 1). Between 75 and 80% of the total amount of verified acoustic transmissions received were detected by both receivers in each cage, while the remaining 20–25% was received by only one of the receivers, approximately evenly distributed between the upper and lower receivers.

Although the ratio between percentages detected by both, only upper and only lower receivers was also present in the night and day subsets, the total number of verified acoustic transmissions received at night (i.e. between 21:00 and 07:00) was higher than during the day (07:00 to 21:00) in both cages.

Noise levels were highest between 06:00 and 18:00 in both cages, while the number of received data points was lower for both upper and lower receivers during the same interval (Fig. 4 and Fig. 5). Testing revealed that noise levels were similar irrespective of whether the receivers were powered by the RS-485 line or operating solely on battery power. Mean swimming depth variation was low and within a range of about 2 m for both cages at all hours (8–10 m for cage A, 7–9 m for cage B).

3.3. Comparison with data storage tags (DST)

Two fish from cage A and two fish from cage B carrying both acoustic tags and DSTs were retrieved at slaughter. Swimming depths recorded by the DST tags broadly corresponded with the swimming depth measured by the acoustic transmitters (Figs. 6 and 7). Tagged fish mainly resided between 0 and 10 m depth. Fish with IDs 5 and 7 generally stayed within this range for most of the time. However, both fish occasionally exhibited movement to the deeper layers of the cage (down to 25 m).

Data series from acoustic tags and DSTs were similar for both fish from cage B (Fig. 7 a, b). Vertical distribution patterns of acoustic data points in cage B (Fig. 7 c) differed from those in cage A, in that there seemed to be a larger degree of diurnal variations in the movements of the tagged fish, with a cyclical pattern between staying deep (around 15 m) and within 10 m from the surface. This pattern was recognisable in the acoustic and DST data from the fish with ID 18 (Fig. 7 a), which migrated between 5 and 15 m in a pattern synchronised with the variations in distribution. In contrast, the fish with ID 25 stayed at depths around 10 m throughout the four-day period, with only occasional movements to shallower or deeper sections in the cage (Fig. 7 b).

For all four individuals (Table 2), the mean deviations between DST data and acoustic data over time was between 0.12 and 0.7 m. The number of data points registered by the DST was somewhat higher

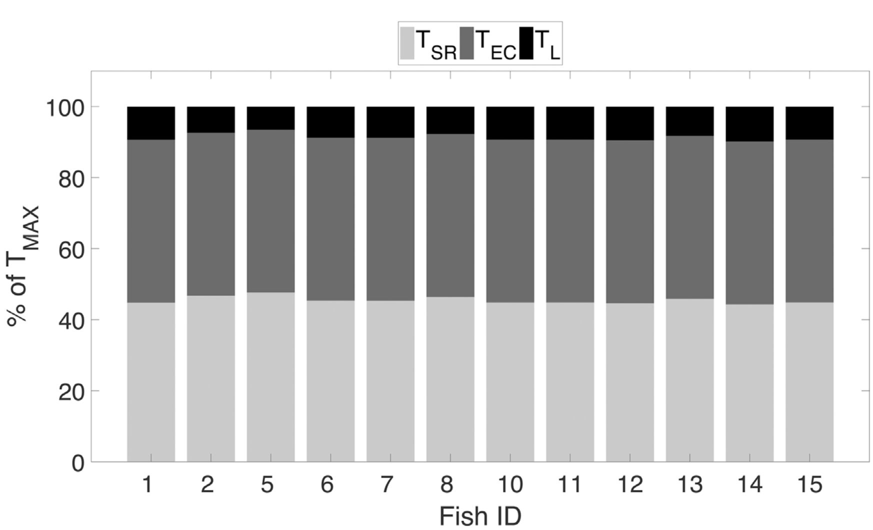

Fig. 2. Transmitter specific reception percentages relative to theoretical maximum number of transmissions(T_{MAX}) in cage A. Light grey represents T_{SR} (percentage properly received by the receiver system), dark grey represents T_{EC} (expected theoretical collision rate, 45.9%), while black represents T_L (transmissions not detected due to other causes).

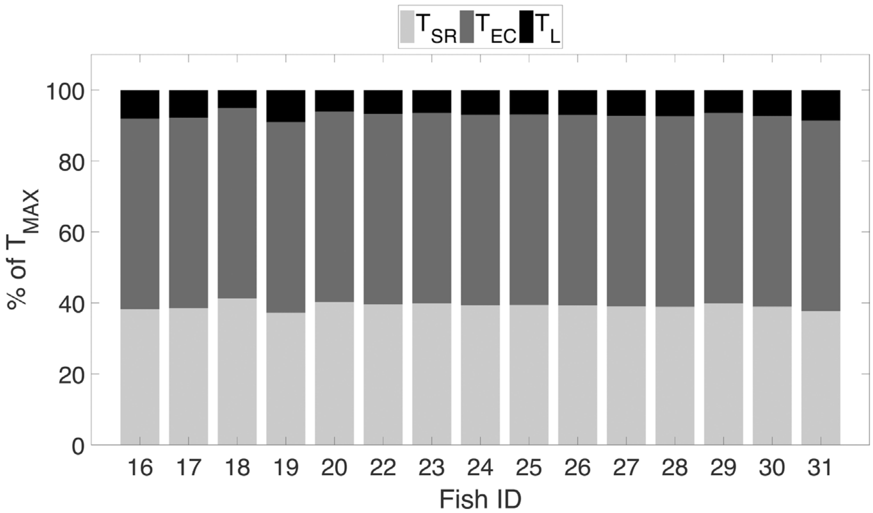

Fig. 3. Transmitter specific reception percentages relative to theoretical maximum number of transmissions (T_{MAX}) in cage B. Light grey represents T_{SR} (percentage properly received by the receiver system), dark grey represents T_{EC} (expected theoretical collision rate, 53.7%), while black represents T_L (transmissions not detected due to other causes).

Table 1
Percentage of total acoustic receptions captured by both receivers, only the upper receiver and only the lower receiver. We have distinguished between day (07:00-21:00) and night (21:00–07:00).

Diurnal period	Cage	Both receivers	Only upper receiver	Only lower receiver
Total dataset	A	75%	10%	14%
	B	80%	11%	10%
Day (07:00–21:00)	A	34%	6%	7%
	B	37%	5%	6%
Night (21:00–07:00)	A	41%	5%	7%
	B	43%	5%	4%

(7–30%) than those received through acoustics. As the fish with ID 18 lost its acoustic tag in mid-June, the analysis for this fish was limited to include only data obtained prior to the tag ejection, hence the lower time interval (60 days) and number of samples registered for this fish. Acoustic transmitters were set up to transmit data approximately twice as frequently (mean distance between samples of 125 s.) as the rate with which the DSTs stored data (1 sample each 4 min).

4. Discussion

4.1. Acoustic telemetry system performance

4.1.1. Acoustic reception

Since the amount of data collected by the prototype system was close to the maximum number of samples theoretically available in both cages with less than 10% loss, we consider acoustic telemetry suitable for obtaining online data on individual fish in commercial facilities.

The low percentage of transmissions from cage A detected by receivers in cage B, and *vice versa*, implies that the distance between the two cages (ca. 500 m) together with the presence of a stocked sea-cage between the cages (Fig. 1A), was sufficient to prevent significant acoustic cross-talk. Low inter-cage acoustic overlap may be essential to achieve acceptable data capture rates in experiments where several cages at the same farm are stocked with fish carrying acoustic transmitters. In particular, this applies when all transmitters in all cages use the same acoustic carrier frequency, as acoustic overlap then could lead to increased signal collision rates in the cages due to transmissions from the other cages. Such challenges could be remedied by assigning each cage with a unique acoustic frequency, and using only transmitters operating on the assigned frequency in each cage.

High reception rates in both cages suggest that placing receivers

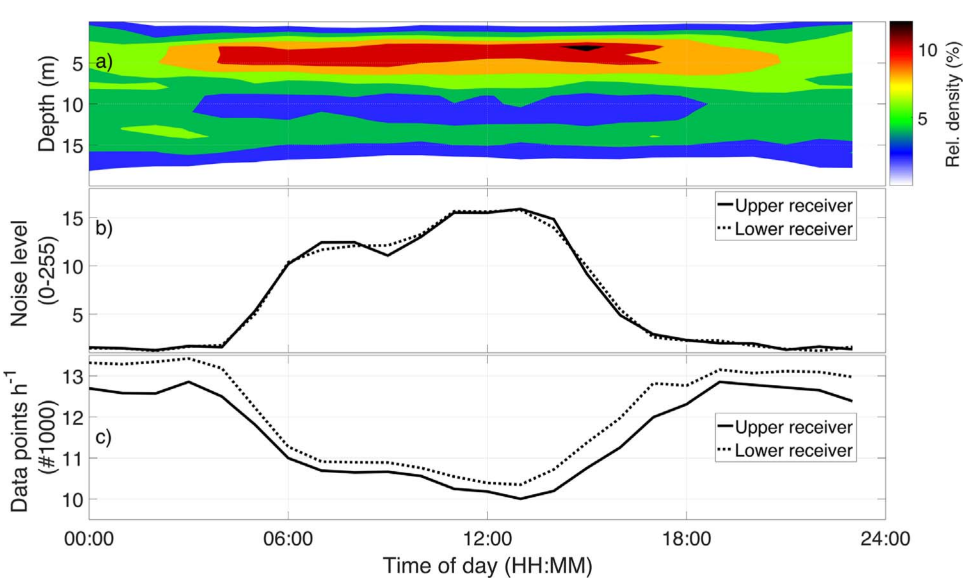

Fig. 4. Hourly values over entire experimental period from cage A; a) vertical distribution of data points in aggregated acoustic telemetry dataset for each hour, b) mean acoustic noise level and c) aggregate number of data points received over the entire experimental period by the upper (solid line) and lower (dashed line) receiver.

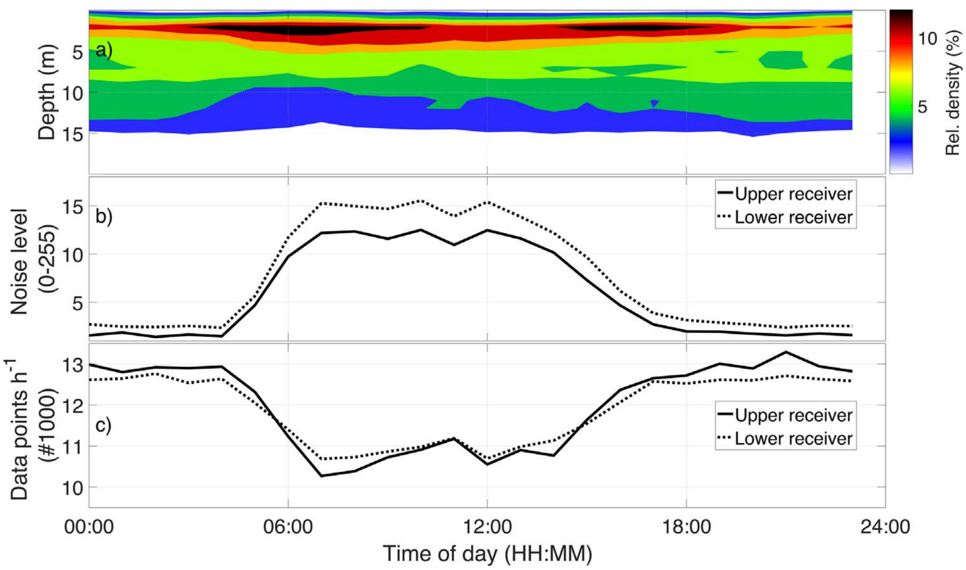

Fig. 5. Hourly values over entire experimental period from cage B; a) vertical distribution of data points in aggregated acoustic telemetry dataset for each hour, b) mean acoustic noise level and c) aggregate number of data points received over the entire experimental period by the upper (solid line) and lower (dashed line) receiver.

close to the surface and near the bottom along the central vertical axis of the cage provided good coverage of the cage volume. Further, there was little difference in reception between the two receivers in each cage, implying that reception conditions were largely independent of receiver deployment depth. While most of the successfully transmitted samples were received by both receivers (75% in cage A, 79% in cage B), the remainder of the signals were only detected by one of the receivers. Although using a single receiver per cage would therefore result in a slightly less comprehensive dataset, a single receiver would still capture more than 85% of the total receptions collected using two receivers. A single receiver would therefore be sufficient to produce knowledge on fish behaviour for fish farm management activities.

Acoustic reception rates per unit time were on average higher at night than during the day in both cages, a difference that varied inversely with the acoustic noise levels registered by the receivers. This suggests that noise at the site was a crucial factor in the ability of the system to monitor the acoustic transmissions. Feed at the farm was delivered in small batches throughout the entire period between 07:00 and 17:00. Feeding systems require high power and could introduce electrical noise in the local power system, which could in turn impact the ARs through their external power supply. However, there were no indications in the datasets that the ARs detected more noise when powered through the RS-485 than when running on batteries, implying that electric noise was negligible. Despite this, the feeding system was probably an important factor behind the increased noise levels during daytime as such systems produce acoustic noise and vibrations in the water.

Since Atlantic salmon rely strongly on vision while swimming and hence are more active during the day than at night (Oppedal et al., 2011), it is likely that higher salmon activity during the day increased the hydroacoustic noise levels observed by the receivers in the cages. This is further implied by the mean noise levels registered by the receiver units starting to increase at 05:00, i.e. hours before any human activity or feeding started at the farm. In addition, the fish swam closer to the surface during the day than at night in response to the feeding schedule applied at the site, a behaviour which matches previous descriptions of the response of Atlantic salmon to feed (Fernö et al., 1995; Juell et al., 2003). Feeding by salmon entails higher activity levels (Ang and Petrell, 1998; Andrew et al., 2002) and may include the fish jumping and breaking the surface, particularly early in the feeding process when feeding motivation is high. Such behaviours may generate acoustic noise suggesting that feeding activity could contribute to increased noise levels.

Despite the observable covariation between reception success and

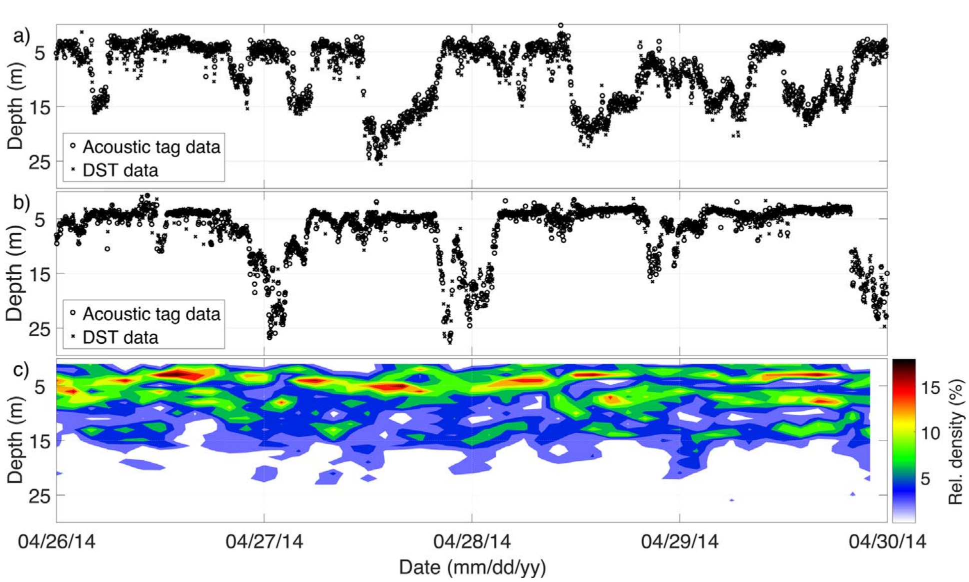

Fig. 6. Illustration of four-day segment of data obtained from cage A during the experiment, each tick on the horizontal bar denoting midnight. a) acoustic data (circles) and DST data (crosses) for fish 5, b) acoustic data (circles) and DST data (crosses) for fish 7, c) vertical distribution of data (based on 12 fish) points in aggregated acoustic telemetry dataset. Different colours denote different relative proportions of data points in%.

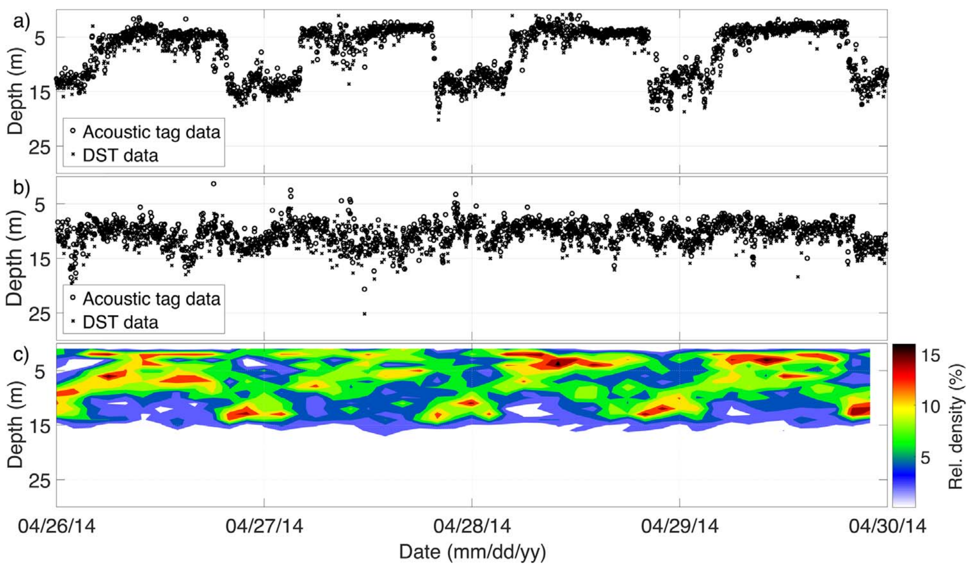

Fig. 7. Illustration of four-day segment of data obtained from cage B during the experiment, each tick on the horizontal bar denoting midnight. a) acoustic data (circles) and DST data (crosses) for fish 18, b) acoustic data (circles) and DST data (crosses) for fish 25, c) vertical distribution of data points in aggregated acoustic telemetry dataset (based on 15 fish). Different colours denote different relative proportions of data points in%.

Table 2
Statistical comparison between the DST data and corresponding acoustic data collected from two individual fish in cage A and two individuals from cage B.

Cage	Fish ID	# Acoustic data points (duration)	# DST data points	Average deviation DST vs acoustic (mean of 10 min periods)
A	5	31334 (97 days)	34201	0.12 m
	7	29844 (97 days)	34201	0.23 m
B	18	16700 (60 days)	21094	0.52 m
	25	23228 (85 days)	30675	0.67 m

acoustic noise, the data loss not related to expected signal interference was very low, implying that total acoustic noise levels were low compared with the signal strength at the site during the experiments. This could be associated with the wind conditions at the site, which were benign throughout the experimental period and rarely exceeded 10 m s^{-1} (Norwegian Meteorological Database, www.yr.no) and a resulting low maximum significant wave height of 0.52 m (measured at a reference buoy close to the farm).

4.1.2. Acoustic datasets vs. DST datasets

Although DSTs are not viable alternatives to acoustic telemetry for online monitoring of fish, they have previously produced useful datasets in experiments on the individual behaviours of salmon in sea cages (Johansson et al., 2009; Korsøen et al., 2012a). We used them to ground truth the datasets produced by the acoustic transmitter tags. Our findings imply that co-located DSTs and acoustic transmitter tags produced matching datasets, as the mean deviations between these (0.12–0.7 m) were lower than the sensor accuracy (0.75 m for DSTs, 0.5–1 m for acoustic tags) for all four fish available for such comparisons.

We retrieved 4 out of the initial 20 DST tags, meaning that the datasets generated by 16 DSTs were lost. This was due partly to tag loss and mortality, but mostly the difficulty in finding 20 PIT tagged fish in a processing plant in amongst 330000 fish. In contrast, acoustic transmitter data was obtained from all monitored fish including those that died during the trial period. As a consequence, the acoustic telemetry system had a higher total data capture success rate than the DSTs. This indicates that the data capturing performance of an acoustic telemetry monitoring system can exceed a system based on DSTs in industrial-scale fish farms.

4.2. Practical considerations for telemetry in full-scale cages

A primary challenge in using individual-based observation techniques to obtain data on animal populations is to ensure that the animals equipped with transmitters are representative for the population from which they are sampled. This is a crucial point when considering acoustic telemetry in commercial fish cages since the population from which the subjects are selected often features a large number of individuals with varying properties and features, some of which are at present not well studied and understood. In this study, we have not explicitly examined the concept of representativeness, but our primary findings suggest that it is technically possible to efficiently monitor a number of fish in a commercial net cage.

In the context of obtaining a representative sample, it is also necessary to consider the sample size. In this trial, 31 fish were equipped with acoustic tags. Although this is a low number compared with the total number of fish in the two cages (330000), acoustic signal collisions were the primary limiting factor behind data loss in the datasets. Given that a similar transmission interval is used in the tags, a larger number of fish equipped with tags would lead to an even higher amount of transmission collisions, and hence more data loss. This means that applying acoustic telemetry to a larger percentage of the population in a sea-cage is difficult to achieve without suffering unacceptable data loss due to acoustic collisions. Solving this challenge is a key factor in achieving a higher data-throughput of acoustic telemetry systems, which in turn is essential to develop commercial telemetric solutions for online monitoring of farmed fish.

One manner in which data impairment due to acoustic collisions may be countered is to employ several different frequencies for acoustic communication rather than sending all data over a single frequency, as was the case in this study. It is then possible to assign fewer transmitters to each frequency, leading to reduced collision rates, while at the same time monitoring a higher number of individuals per cage. This would increase both the data quality obtained and the relationship between sample size and population size, which in turn increases the likelihood that the selected fish constitute a representative selection from the population.

Recent technological developments within acoustic telemetry may also contribute to solving this issue. Modern signal conditioning methods now include approaches for acoustic signal processing which allows untangling signals with different signal strength that are transmitted simultaneously. Such methods could reduce the data loss caused by interference. Both these features have been included in the new Thelma Biotel receiver TBR-700-RT which evolved from the prototype receiver used in the present experiments. The TBR700-RT also features other performance enhancing alterations, including a more accurate clock crystal (10 ppm), and would thus experience less clock drift.

Another approach to improve data retention of acoustic telemetry systems is to reduce the long transmission time (4 s) of acoustic messages by employing more advanced coding and modulation schemes allowing higher bit rates. However, unavoidable trade-offs concerning restrictions on complexity, power consumption and the physical size of the transmitter, while still preserving robustness of the communication protocol, make this approach non-trivial. Developments in areas such as low-power digital signal processing and advanced coding techniques will nevertheless contribute to mitigating these limitations in future.

4.3. Behavioural observations and relevance for commercial farming

Although both cages were of similar size, featured a similar biomass density and were subjected to similar environmental conditions and management regimes, the vertical distribution of the data points over time (and hence the fish carrying the tags) differed between the cages. There were also large variations in the short term individual behaviour within each cage. Whereas both fish 5 and 7 (cage A) appeared to exploit the entire water column over the selected four day interval, their vertical excursions occurred at different times. The difference was clearer for the selected individuals in cage B, as fish 18 exhibited a circadian rhythm while fish 25 stayed within a narrow depth range for the entire sub-period. These observations may indicate the existence of several different behavioural classes or coping strategies within the cage population. This harmonises with previous studies that have found large inter-individual variations in depth behaviour in caged salmon (Johansson et al., 2009), and further illustrates the challenges of using individual-based methods to observe animals in large populations. Tagging a larger a proportion of the population would probably reduce the impact of inter-individual behavioural variation on the resulting dataset.

In demonstrating the efficiency of this technology as a wireless monitoring method in a commercial sea-cage, our study represents the first step towards industrial usage. However, potential industrial applications would also depend on the ability to obtain data that may be used to gain information useful for farm management. Given the low bandwidth of acoustic telemetry, instantaneous sensor values such as present swimming depth (as used in this study), may not produce a sufficient data foundation for decision support. It would probably be more useful to apply tags that derive compound data types describing specific behavioural traits from series of sensor values. For example, acoustic telemetry has previously been used to detect specific feeding responses (Føre et al., 2011) and responses toward the production environment (Kolarevic et al., 2016) in salmon. Although these values were produced in research studies that were not conducted in full-scale environments, such data types would be just as easy to monitor using acoustic telemetry as instantaneous values since the compound variable is computed inside the individual tags prior to acoustic transmission. Similarly, even though physiological sensors such as EMG-sensors (Cooke et al., 2004) may require a more complex tagging procedure, the communication of such data will have no different requirements to the instantaneous data values used in the present study.

5. Future prospects

In Precision Livestock Farming (PLF), principles and technologies from process engineering are used to manage livestock production (Berckmans, 2004; Wathes et al., 2008). Such methods often rely on the capability of automatically monitoring the animals in a population at all times, which in some cases should be done on individuals. There are several examples of research efforts aimed at developing specific technologies for deriving information on individual animals in terrestrial agriculture (Yang et al., 2007; Darr and Epperson, 2009; Tebot et al., 2009). This allows for the application of PLF principles at an individual level, and despite not being completely commercialised, the potential of using such methods to improve animal welfare and production efficiency is considered vast (Banhazi et al., 2012). Although the number of individuals in a commercial fish farm typically far exceeds the number of animals commonly held at terrestrial farms, some of the benefits of individual based PLF principles could be obtained by applying suitable data collection methods. Acoustic telemetry represents one of the few suitable methods for online monitoring the status of individual fish in fish farms. The prototype system presented here could represent a first step toward adapting individual based methods from PLF to the commercial production of finfish.

Despite achieving high reception success relative to the expected theoretical maximum number of detectable signals, our trial only represents a limited subset of the wide range of farm configurations and environmental conditions encountered in modern fish farms. Further studies of a similar scale at other sites and times of the year are required to understand variability in reception success due to farm configuration and environmental influences. For instance, whereas our study was conducted at a site and time where vertical gradients in environmental factors were negligible, many commercial sites, particularly in fjord locations, may frequently experience strong environmental stratifications. As the speed of sound is strongly dependent on water temperature and salinity (Hovem, 2004), this could potentially lead to a more challenging environment for acoustic communication.

Since acoustic noise was one of the primary causes behind data loss in our study, measuring acoustic noise directly using a set of hydrophones that are sensitive to acoustic signals within a wide frequency range would allow further analysis of this factor. This could identify which frequencies dominate the acoustic noise patterns at fish farms, and enable selection of acoustic frequencies for communication that are less likely to be impaired by noise problems.

Although our experiments were aimed at monitoring farmed salmon, the technology and infrastructure system is easily adaptable to monitoring other farmed fish species as well as farm equipment and structural components.

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