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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.