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Modelling of Atlantic salmon (*Salmo salar* L.) behaviour in sea-cages: Using artificial light to control swimming depth

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ABSTRACT

Submerged artificial light sources are commonly used to control sexual maturation in farmed Atlantic salmon, but may also be a tool to steer salmon to swim at depths which are optimal for production. In this study, we used an individual-based model of the behaviour of salmon toward environmental variability to simulate the swimming depths of salmon in different seasons, production environments and artificial light regimes. Model outputs agreed with direct observations of salmon swimming depths from literature, suggesting that the model accurately simulated the behavioural mechanisms behind responses toward artificial lights superimposed upon different environmental conditions. We used the model in a series of *in silico* experiments to predict the behavioural effects of submerged artificial lights placed at different depths in environmental conditions typical for coastal waters in winter, spring and summer. The model indicated that artificial lights controlled salmon swimming depths most efficiently in winter. Further, lights may be more efficient in sites with a more homogeneous environment throughout the water column (e.g. open coast) than sites that are thermally stratified (e.g. fjords). Placing submerged lights at the right depths could produce better culture conditions, ultimately resulting in increased growth. With standard measurements of temperature at several depths as a sole user input, the model could act as a tool to inform farmers of which depths to place their lights on any given day or season.

1. Introduction

Modern salmon aquaculture has advanced from small, shallow cages containing thousands of fish placed at sheltered inshore locations to large, deep cages (157 m circumference, 50 m depth) holding 100,000–250,000 individual salmon in more exposed locations (Fredheim and Langan, 2009). Although larger production units offer considerable economies of scale, they introduce distinct challenges for production management that differ from smaller sea-cages, including feeding control (Talbot et al., 1999), photoperiod control (Hansen et al., 1992), sea-lice management (Costello, 2009) and maintaining optimal oxygen levels (Johansson et al., 2007). To counter such production challenges, cage management strategies customised to large-scale production conditions are required. A key element in developing such strategies is knowledge on how salmon behave in response to the culture conditions.

Within the confines of sea-cages, the behaviours of farmed Atlantic salmon are determined by a complex environment containing spatially and temporally varying factors, such as temperature, light, dissolved oxygen (DO) and salinity. Whereas the full effects of DO and salinity on adult salmon behaviour are still not known (Oppedal et al., 2011a), responses to temperature and light levels drive the vertical distribution of salmon within sea-cages outside feeding periods (Fernö et al., 1995; Johansson et al., 2006). Salmon have distinct ranges of preference for water temperature and light intensity, and regulate these factors behaviourally when they are outside their preference ranges (Dempster et al., 2008; Fernö et al., 1995; Johansson et al., 2007). As both temperature and light vary less horizontally than with depth in the water column, this often results in vertical movement. When the most preferable temperature and light levels occur at different depths, salmon may swim at depths that are a trade-off between these factors (Oppedal et al., 2011a). The distributions resulting from these trade-offs tend to be much denser than the initial stocking density of the cage (Oppedal et al., 2011a, 2011b).

The use of artificial light sources is a management strategy originally developed to inhibit fish maturation in cages (Hansen et al., 1992; Oppedal et al., 1997; Porter et al., 1999), but has also been shown to have positive effects on fish growth (Nordgarden et al., 2003; Oppedal et al., 1997, 1999, 2003). Submerged artificial lights also affect fish behaviour (Juell and Fosseidengen, 2004; Juell et al., 2003; Korsøen et al., 2012; Oppedal et al., 2001). Placing light sources

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at specific depths could be a strategy to shift fish vertically within the cage to distribute fish more evenly within the cage or to steer fish away from areas in the cage where conditions are sub-optimal for growth and welfare (Oppedal et al., 2007).

Individual-based (or Lagrangian) modelling (IBM) is a technique in which each individual animal in a population is modelled to produce a group-level outcome. This technique has been applied with great success to other livestock industries (e.g. Pomar and Pomar, 2005; Tedeschi et al., 2004) to improve production efficiency through precision livestock farming (Wathes et al., 2008). An IBM of salmon behaviour in sea-cages has been developed and verified against detailed observational data on salmon distributions (Føre et al., 2009). The model accurately simulates the behavioural trade-offs made by salmon between temperature and natural light levels when positioning themselves vertically in a sea-cage. However, the model does not currently include behavioural responses to artificial light sources which are in widespread use by the industry.

We aimed to model the behavioural effects of artificial lights in salmon aquaculture and verify the model using observational data on the swimming depths of salmon in full-scale sea-cages subject to artificial light sources. We expanded the model of Føre et al. (2009) by adding a new model module describing the responses of salmon to underwater artificial light sources, and verified model outputs against observational data provided by Oppedal et al. (2007). Through a series of simulation experiments using the model, we predicted the effects of artificial light placement depth, season, and water column thermal profiles (stratified versus well mixed), to determine which combinations were most likely to yield growth advantages for commercial production.

2. Materials and methods

The model described below is based on an individual-based model built and verified by Føre et al. (2009) which simulates the behaviours and swimming depths of Atlantic salmon in sea-cages in response to a range of environmental variables. Here, we only briefly explain the main features of the model and detail modifications to adapt the model to account for behavioural responses of salmon toward artificial light sources. The model explanation partly follows the ODD (Overview, Design concepts, Detail) protocol for presenting individual-based models (Grimm et al., 2006).

2.1. State variables and scales

As the model was based on an individual-based (or Lagrangian) approach, the behaviour of each individual fish was modelled explicitly. Individual fish were defined by constant parameters describing their size (body length, *BL*, and body weight, *BW*) as well as dynamic state variables describing their 3-dimensional position and spatial orientation ($\mathbf{r}$), 3-dimensional swimming velocity vector ($\dot{\mathbf{r}}$), stomach contents (x) and the present state of the fish with regards to feeding behaviour (Feeding Mode). Numerical simulations were performed using a fixed time step of 1 s, and had a maximum duration of 24 h. The fish were programmed to respond to an environment consisting of spatially and temporally varying environmental factors (temperature, light and feed), as well as a set of fixed parameters describing the dimensions of the sea-cage. In addition, the fish responded to the presence of other individuals by following two simple rules which were designed to prevent collisions between fish (i.e. avoid individuals that are considered close enough to represent an imminent risk of collision, and align with individuals that are in the proximity but not close enough to elicit evasive manoeuvres). Finally, the swimming behaviour of the individuals was subjected to a stochastic component intended to reflect the response toward factors not described by the model and random fluctuations in swimming patterns. Table 1 contains the most relevant model variables in this study, while Table 2 contains the most relevant parameters.

Table 1
Relevant model variables. '–' denotes dimensionless.

Description	Symbol	Unit
Position and orientation of fish	$\mathbf{r}$	m, radians
Swimming velocity vector	$\dot{\mathbf{r}}$	m s^{-1}
Temperature	T	°C
Total light intensity	I	μEm^{-2}s^{-1}
Natural light intensity	I_n	μEm^{-2}s^{-1}
Artificial light intensity	I_a	μEm^{-2}s^{-1}
Direction of increased light intensity	d	–
Response to cage	$\mathbf{v}_C$	m s^{-1}
Response to feed	$\mathbf{v}_F$	m s^{-1}
Response to temperature	$\mathbf{v}_T$	m s^{-1}
Response to light	$\mathbf{v}_L$	m s^{-1}
Response to other fish	$\mathbf{v}_{SO}$	m s^{-1}
Stochastic component	$\mathbf{v}_{ST}$	m s^{-1}
Reference swimming velocity	$\dot{\mathbf{r}}_{ref}$	m s^{-1}
Swimming velocity in previous time step	$\dot{\mathbf{r}}_{prev}$	m s^{-1}

2.2. Initialisation

In addition to the sequence of events mentioned in Føre et al. (2009), model initialisation was expanded to include the placement of artificial light sources at various depths. This was done by defining their location in the cage, source strength and the coefficient for light attenuation in the selected scenario.

2.3. Input

In Føre et al. (2009), we employed a dynamic model based on latitude and time to simulate diurnal and seasonal variations in light intensity. Furthermore, water temperature was defined by a single vertical gradient representative for the entire duration of a simulation. In this paper, where detailed data sets on temperature and light were available for specific scenarios, a more dynamic environment was obtained by reading the measurement values directly into the model and interpolating the data to produce an environment that was continuous with respect to both time and space. We therefore expanded the model with an option to read in spatially and temporally varying temperature and light measurements from data files.

2.3.1. Total behavioural response

External factors affecting fish behaviour (i.e. the cage, feed, temperature, light and other fish) were organised in a hierarchy based on their assumed importance for salmon (see Føre et al. (2009) for a detailed account of the derivation of the hierarchy). This allowed the fish to perform behavioural trade-offs in which responses toward

Table 2
Relevant model parameters. '–' denotes dimensionless.

Description	Symbol	Unit	Value
Artificial light source strength	I_{as}	μEm^{-2}s^{-1}	Variable
Attenuation coefficient for artificial light	α_a	–	Variable
Influence of previous velocity on present velocity	τ	–	0.65
Low temperature preference threshold	T_l	°C	Variable (13 to 16)
High temperature preference threshold	T_h	°C	Variable (18 to 21)
Steepness factor for response to low temperatures	T_{ll}	°C	−720
Steepness factor for response to high temperatures	T_{hh}	°C	120
Low light level preference threshold	I_l	μEm^{-2}s^{-1}	3.5
High light level preference threshold	I_h	μEm^{-2}s^{-1}	700
Steepness factor for response to low light levels	I_{ll}	μEm^{-2}s^{-1}	−160
Steepness factor for response to high light levels	I_{hh}	μEm^{-2}s^{-1}	1000