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Salmon Welfare Index Model (SWIM 1.0): a semantic model for overall welfare assessment of caged Atlantic salmon: review of the selected welfare indicators and model presentation

Lars H. Stien[1], Marc B. M. Bracke[2], Ole Folkedal[1], Jonatan Nilsson[1], Frode Oppedal[1], Thomas Torgersen[1], Silje Kittilsen[3], Paul J. Midtlyng[3], Marco A. Vindas[4], Øyvind Øverli[4] and Tore S. Kristiansen[1]

1 Institute of Marine Research, Bergen, Norway
2 Wageningen UR Livestock Research, Lelystad, The Netherlands
3 Norwegian School of Veterinary Science, Oslo, Norway
4 Norwegian University of Life Sciences, Ås, Norway

Correspondence
Lars H. Stien, Institute of Marine Research, PO Box 1870 Nordnes, 5817 Bergen, Norway.
Email: lars.stien@imr.no

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Abstract

A semantic model for overall welfare assessment of Atlantic salmon reared in sea cages is presented. The model, called SWIM 1.0, is designed to enable fish farmers to make a formal and standardized assessment of fish welfare using a set of selected welfare indicators. In order to cover all welfare relevant aspects from the animals' point of view and to create a science-based tool we first identified the known welfare needs of Atlantic salmon in sea cages and searched the literature for feasible welfare indicators. The framework of semantic modelling was used to perform a structured literature review and an evaluation of each indicator. The selected indicators were water temperature, salinity, oxygen saturation, water current, stocking density, lighting, disturbance, daily mortality rate, appetite, sea lice infestation ratio, condition factor, emaciation state, vertebral deformation, maturation stage, smoltification state, fin condition and skin condition. Selection criteria for the indicators were that they should be practical and measureable on the farm, that each indicator could be divided into levels from good to poor welfare backed up by relevant scientific literature. To estimate each indicator's relative impact on welfare, all the indicators were weighted based on their respective literature reviews and according to weighting factors defined as part of the semantic modelling framework. This was ultimately amalgamated into an overall model that calculates welfare indexes for salmon in sea cages. More importantly, the model identifies how each indicator contributes (negatively and positively) to the overall index and hence which welfare needs are compromised or fulfilled.

Key words: animal welfare score, aquaculture, diagnostic, scientific literature, sea cage.

Introduction

The problem of how to assess the welfare status of fish is an ongoing debate and no consensus has been reached on definitions or assessment methodology (Ashley 2007; Huntingford & Kadri 2008; Segner *et al.* 2012). However, food and aquaculture authorities ask for methods that can be used to assess fish welfare and thus check the fulfilment of laws and regulations. A number of EU projects and national projects related to fish welfare have been or are being performed. These use a range of approaches from studies of fish behaviour to microarrays and a number of welfare related indicators have been suggested, but without an integrating model and theory, much confusion remains as to how the indicators can be scored, weighted and integrated into an overall welfare assessment (OWA).

To gain the best possible assessment, an OWA model should be based on observations of the animals, their biological and physical environments, and the available scientific knowledge (Bracke *et al.* 1999b; Anon 2001), and the selected welfare indicators (WIs) should be species specific, validated, reliable, feasible and auditable (EFSA 2009). There are two closely related approaches for creating OWA models; risk analysis (EFSA 2006a,b; Bracke *et al.* 2008) and semantic modelling (Bracke *et al.* 2002a,b). The prime objectives of risk analysis are to identify hazards, their consequences and probabilities of occurrence, and to find critical control points in the production process to avoid welfare risks, e.g. stress, injuries, disease and mortality. Semantic modelling follows a principally different approach, focusing on welfare defined as the quality of life as perceived by the animals themselves and is searching for indicators of the degree of fulfilment of the animal's welfare needs and the effects on the animals' wellbeing. Since semantic modelling considers both positive and negative aspects of welfare it is a risk–benefit analysis (Bracke *et al.* 1999a,b,c, 2008).

This paper describes a first attempt to apply semantic modelling to review commonly used WIs for farmed Atlantic salmon (*Salmo salar* L.) and to propose a science based model and tool for OWA in the sea cage phase. Atlantic salmon is chosen as the case species given its great importance in aquaculture and since there is a reasonable amount of scientific knowledge available. The model is named SWIM 1.0, an acronym for Salmon Welfare Index Model, where no. 1 states that it is the farmer's version and .0 states that this is the pilot version which may be revised and upgraded later. A web application (http://www.imr.no/swim) was constructed in order to facilitate author collaboration when updating the model's scientific database (statements from the literature) and the model itself. The web application will also support updating the model with results from future research, such that SWIM will be a dynamic and up-to-date model. The model is primarily intended as a tool for fish farmers to assess fish welfare in sea cages, but will be expanded with WIs that can be measured by farm veterinarians (SWIM 2) and fish welfare experts (SWIM 3). For use by fish farmers it is important that the WIs are limited in number, feasible and practical to use. The indicators employed in the current version and their weightings in the model may change in future versions as knowledge of different WIs expands.

The semantic modelling concept

The semantic modelling concept for the purpose of formalized assessment of animal welfare was first introduced by Bracke *et al.* (1999a,b,c), and is based on the meaning (semantics) of available scientific information about the animals' welfare needs and how these are related to animal welfare. This includes scientific descriptions of housing systems in terms of both environment based and animal based measures, and how these affect animal welfare. Semantic modelling was first applied to assess housing systems for dry sows (Bracke *et al.* 2002a,b), but it has also been applied to assess overall welfare in laying hens (De Mol *et al.* 2004, 2006; Shimmura *et al.* 2011), for tail biting in pigs (Bracke *et al.* 2004a,b), for enrichment materials for pigs (Bracke *et al.* 2007a,b; Bracke 2008), in dairy cattle (Ursinus *et al.* 2009) and for wallowing in pigs (Bracke 2011; Bracke & Spoolder 2011).

In view of the ongoing debate about fish welfare, it is necessary to clarify definitions and underlying assumptions that the semantic modelling of animal welfare rests on: Welfare is here defined as 'the quality of life as perceived by the animals themselves', and the ability to experience welfare is seen as part of the emotional monitoring system that guides animals (with advanced central nervous systems) in getting what they need and avoiding harm and dangers in an effective way. In order to survive an animal must fulfil its basic needs; e.g. nutrition, respiration, thermoregulation etc., and to this end, animals continuously assess their state of need. The qualitative welfare experience is created by the reward and punishment systems in the emotional brain, and involves experience, memories and re-evaluation of needs in anticipation of physiological, psychological and behavioural requirements (Berridge 2004; Panksepp 2005; Korte *et al.* 2007). There is growing evidence that teleost fish, and hence salmon, can feel pain and that they possess functional equivalents of the limbic and dopaminergic nervous systems – systems that are linked with emotion, memory, spatial relationships, primary consciousness, reward, cost–benefit estimation and decision-making (Sneddon 2003; Braithwaite & Huntingford 2004; Chandroo *et al.* 2004a,b; Håstein *et al.* 2005; Braithwaite & Boulcott 2007; Broom 2007; Galhardo & Oliveira 2009; Braithwaite 2010; Torgersen *et al.* 2011). In short, there are strong indications that also fish are able to experience states of welfare.

Based on this we assume that salmon experience a continuum of welfare states, which may vary from very poor to excellent and that are closely related to the degree of fulfilment of the salmons' welfare needs, i.e. needs monitored by the emotional brain. An OWA should be in accordance with the needs-assessment performed by the animals themselves. However, since we cannot tap directly into the animal brain, we must assess their state of need and emotionality based on observations of the animals and what we know about the way they respond to a variety of environmental conditions. This implies using scientific knowledge about animal physiology and behaviour to surmise their welfare state (Bracke *et al.* 1999c).

Welfare relevant needs of farmed Atlantic salmon

We used a slightly modified version of the semantic modelling procedure described in Bracke *et al.* (2002b). First, based on the list of needs presented in Bracke *et al.* 1999c we formulated a list of known welfare needs for Atlantic salmon in sea cages (Table 1). The physical welfare needs include respiration, osmotic balance, nutrition, good health and thermoregulation. Behavioural welfare needs describe motivations to perform specific behaviours to get an immediate reward or for which the mere performance is rewarding and are behaviours that have evolved to fulfil more ultimate goals related to survival, growth or reproduction (Jensen & Toates 1993). For Atlantic salmon in sea cages we include behaviour control, feeding, safety, protection, social contact, exploration, kinesis, rest, sexual behaviour and body care. To avoid confusion, we must emphasize that the distinction between physical and behavioural needs, and also the distinctions between needs, is not absolute and that overlaps exist.

Linking of welfare indicators to welfare needs

In order to cover all welfare relevant aspects from the animals' point of view we searched the literature for feasible welfare indicators suggestive of the fulfilment of the welfare needs and 17 WIs were selected for inclusion in the SWIM 1.0 model. All the WIs were linked to at least one of the needs and all welfare needs are linked to at least one WI (Table 2). This was done to make sure that all the indicators concern the degree of fulfilment of the welfare needs and that the assessment covers all welfare relevant needs from the salmons' point of view.

Welfare indicator literature review, ranking of levels and weighting

The next step of the semantic modelling procedure is to collect relevant scientific statements, obtained from a systematic literature review (Bracke *et al.* 2002b). In this review we used the selection criterion that the statements are relevant to assess the fulfilment of needs of Atlantic salmon kept in sea cages. Sources include ISI Web of Knowledge^{SM}, Google Scholar^{TM} and various books and reports on the topic. As far as possible the statements are species specific and for the post-smolt sea water adapted life stage of Atlantic salmon. Based on the review the WIs were scaled on at least two levels from best to worst. According to semantic modelling these levels must be mutually exclusive and cover the model's domain, i.e. in our case on-growing of Atlantic salmon in sea cages. Each WI-level must also be linked to at least one scientific statement that provides the scientific basis of the weighting of the model: Firstly, the levels are ranked within each WI to create indicator scores (IS):

$$\mathrm{IS}_{i,j} = \frac{\mathrm{NL}_i - \mathrm{RL}_{i,j}}{\mathrm{NL}_i - 1} \tag{1}$$

where $\mathrm{IS}_{i,j}$ is the score of the j-th level of the i-th WI in the model, NL_i is the total number of levels of indicator i and $\mathrm{RL}_{i,j}$ is the rank number of level j. Next, the scientific evidence is used to assign weighting scores (WS) using weighting categories (WC) (Table 3). This is a somewhat subjective, but systematic, scoring based on an assessment of the intensity, duration and incidence of the welfare impact as implied by each scientific statement that has been linked to the WI. The WC's classify welfare performance criteria, e.g. pain, illness and reduced survival (Table 2).

Table 1 List of Atlantic salmons basic needs, adapted from Bracke *et al.* (1999c)

	Need	Explanation and relevance for salmon
Physical needs	Respiration	Uptake of oxygen and release of carbon dioxide by pumping water over the gills
	Osmotic balance	Maintaining homeostasis of body cell fluids
	Nutrition	Intake of food containing the required energy, amino acids, minerals, vitamins etc.
	Health	Absence of disease, illness and malfunction
	Thermal regulation	Optimization of metabolism and temperature, including thermal comfort
Behavioural needs	Behaviour control	Ability of the fish to freely position themselves (including regulation of buoyancy) and respond to stimuli
	Feeding	Regular access to food
	Safety	Possibility to avoid perceived danger
	Protection	Possibility to keep the body undamaged from physical injury
	Social contact	Predictable interaction with conspecifics
	Exploration	Possibility to search for resources and information
	Kinesis	Being able to swim (physical activity)
	Rest	Possibility of reducing activity level or 'sleep'
	Sexual behaviour	Homeward migration, breeding behaviour, spawning, etc.
	Body care	Scratching, parasite cleaning, etc.

Table 2 The most significant links between the selected welfare indicators and the welfare needs of Atlantic salmon in sea cages

Needs	Respiration	Osmotic balance	Nutrition	Health	Thermal regulation	Behaviour control	Feeding	Safety	Protection	Social contact	Exploration	Kinesis	Rest	Sexual behaviour	Body care
Welfare indicator															
Temperature	*				*										
Salinity		*		*											
Oxygen	*														
Water current	*					*							*		
Stocking density				*		*				*			*		
Lighting						*					*		*		
Disturbances								*	*						
Daily mortality				*											
Appetite			*	*			*	*							
Sea lice				*					*						*
Condition factor				*			*					*			
Emaciation state		*	*	*			*					*			
Sexual maturity stage		*												*	
Smoltification state		*		*											
Vertebral deformation			*	*											
Fin condition				*					*			*			*
Skin condition				*					*						*

The weighting factor (WF) of each welfare indicator i in the model was subsequently calculated as proposed by De Mol *et al.* (2006):

$$\mathrm{WF}_i = \left(\sum_{\mathrm{wc}} \max(\mathrm{WS}_{\mathrm{wcl}})\right)_{\mathrm{ILbest},i} - \left(\sum_{\mathrm{wc}} \min(\mathrm{WS}_{\mathrm{wcl}})\right)_{\mathrm{ILworst},i} \quad (2)$$

where $\mathrm{IL}_{\mathrm{best},i}$ is the best indicator level and $\mathrm{IL}_{\mathrm{worst},i}$ is the worst indicator level of the i-th welfare indicator, $\mathrm{WS}_{\mathrm{wcl}}$ is the weighting score assigned to the indicator level based on the scientific statements; *wc* identifies the weighting categories linked to the indicator level. A special case is made up of WI-levels that are so detrimental for welfare that welfare is poor (minimum), no matter which levels are selected for the other indicators. These levels are called knockout levels, and if present the overall welfare index (OWI) is defined as 0. Knockout levels are not included when calculating WFs.

As much as possible each indicator was reviewed as stand alone, i.e. if an indicator level has an effect on another indicator the resulting change in fish welfare is attributed to the second indicator and not the first. As an example, high stocking densities may lead to poor oxygen levels if the water in the cage is not sufficiently replenished. The low oxygen level has a direct effect on the fish and this is hence the primary WI in this specific example. Each section below reviews a WI, and each review section includes a ranking and weighting paragraph. For each weighting the WS is given in parenthesis behind its respective WC. The WIs and WCs have been given capital first letters in these paragraphs for easy recognition. This is done in detail for the first WI, i.e. the temperature-indicator, but only for the best and worst level for the remaining indicators. The WSs are expert opinions based on the reviews, but the reader is free to challenge these decisions.

Temperature (°C)

Temperature governs the metabolic rate of salmon, and thereby acts as a controlling and limiting factor together with oxygen for the fishes' physiological performance including their capacity for dealing with stressors. The relevance of water temperature as a welfare indicator is evident from tolerance limits and temperature preferences of Atlantic salmon in sea cages. A temperature preference in temperature stratified conditions in sea cages of about 17°C is suggested by Johansson *et al.* (2006, 2009), which correspond well with the finding that the Atlantic salmons' selected temperature in a horizontal temperature gradient increased with acclimation (5–20°C), showing a final preference at about 17°C (Javaid & Anderson 1967). In the available range between 11 and 20°C, caged Atlantic salmon individuals and groups clearly avoided water warmer than 18°C as well as water colder than 12°C (Johansson *et al.* 2006, 2009; Oppedal *et al.* 2011a,b). The temperature tolerance is highly dependent on fish acclimatization states, and in general Atlantic salmon can adapt to a range from 0

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Table 3 Weighting categories used in the weighting procedure of semantic modelling with brief descriptions and ranges of weighting scores (WSs). Adapted from Bracke *et al.* (2002b)

Weighting category	Brief description	Range of WS
HPI	Evidence of activation of the HPI (hypothalamic pituitary interrenal) axis indicative of stress	−5 to −1
Illness	Evidence of health problems, including increased mortality, but excluding skin lesions, fin damage and abnormalities in body shape (see 'pain')	−5 to −1
Pain	Evidence of pain including skin and fin damage	−5 to −1
Reduced survival	Evidence of reduced survival related to physiological requirements (other than through specific health problems), e.g. longevity, deprivation of food, poor environment	−5 to −1
Abnormal behaviour	Evidence of disturbed behaviour and or apathy	−3 to −1
Aggression	Evidence of aggression such as bite marks and attacks	−3 to −1
Avoidance	Evidence of avoiding stimuli (which are perceived as dangerous/noxious)	−3 to −1
Frustration	Evidence of blocked behaviour or deprivation	−3 to −1
Negative performance	Evidence of decreased performance (that is likely to indicate negative affect), including (re)production effects, but excluding specific survival aspects related to physiological necessities, HPI-activation and illness	−3 to −1
SAM	Evidence of SAM (sympathetic adrenal medullary) activation (indicative of negative affect), e.g. increased heart rate and (nor)adrenalin levels	−3 to −1
Demand	Evidence that the fish are willing to spend effort to obtain food or other recourses	1 to 5
Natural behaviour	Evidence of (potential positive reward from) behaviour as seen in (semi) natural conditions	1 to 3
Positive performance	Evidence of healthy, fit fish	1 to 3
Preference	Evidence of choosing one resource over another (e.g. in a preference test)	1 to 3

to 20–23°C provided sufficient oxygen levels and gradual transitions between temperatures are applied (Priede 2002; EFSA 2008). An Icelandic stock of Atlantic salmon survived 1 month with water temperatures <0°C before mortalities started to occur at −1.4°C (Skuladottir *et al.* 1990). On the opposite end of the scale Goncalves *et al.* (2006) observed increased mortality already at temperatures slightly above 18°C in the case of full-strength seawater, and Hevrøy *et al.* (2011) found more than 50% reduction in feed intake, growth and feed utilization after 2 weeks at 19°C compared with salmon at 14°C. This shows that the margins are small between temperatures that salmon seem to prefer and what may be harmful to them (with exponential effects occurring in the upper range). Comparing Atlantic salmon reared at 6, 10, 14 and 18°C for 12 weeks following transfer to seawater, Handeland *et al.* (2008) found that growth rate, feed intake, feed conversion efficiency (FCE) and stomach evacuation rate were significantly influenced by temperature and fish size. The highest growth rate was seen in the 14°C group (1.53% d^{-1}). No differences in growth were found between the 10 and 18°C groups (1.35% d^{-1} vs. 1.29% d^{-1}), and lowest growth rates were observed for the 6°C group (0.78% d^{-1}). However, in a recent study, 16°C induced a long-term reduced growth rate compared with 10°C following vaccination (Grini *et al.* 2011).

Based on this review we propose that the temperature WI can be divided into six levels, which can be ranked for welfare as follows: (1) 10–15°C, (2) 7–10°C, (3) 16–17°C, (4) 3–6°C, (5) ≤2, ≥18, short term and (6) ≤2, ≥18, long term. These are temperatures within the normal seasonal range Atlantic salmon experience in sea cages. Atlantic salmon have Positive performance (3) and show Preference (2) for level 1: 10–15°C. 7–10°C is ranked as level 2 since Performance and Preference is less compared with level 1. 16–17°C ranks as level 3 since here the salmon is susceptible to harm, but above 3–6°C as level 4 since salmon prefer the third to the fourth level. Very high (≥18°C) and low temperatures (≤2°C) are associated with avoidance (−2), negative performance (−3), illness (−3) and reduced survival (−3) giving a total WS of −11 for level 5. Very high and low temperatures can be lethal if they persist for a long time. Level 6 is therefore a knockout level. Finally, Equation 2 gives a weighting factor of 16 (Eqn 2: WF = (3 + 2)−(−2−3−3−3), Table 4) for the temperature WI.

Salinity

During the smoltification process salmon develop tolerance for brackish and seawater salinity. Adult, non-migratory Atlantic salmon is little affected by salinity (Bakke *et al.* 1991; Johansson *et al.* 2006, 2009), unless damage to the skin and disease impair their osmoregulatory ability (Grimnes & Jakobsen 1996; Boxaspen 2006). Mature salmon have altered osmoregulation in adaptation to a hypo-osmotic environment before re-entering freshwater in nature (Persson *et al.* 1998) and may therefore experience osmoregulatory challenges in high salinities. Small salmon display a preference for the halocline (Oppedal *et al.* 2011a) and may benefit from access to brackish water (Handeland

Table 4 Welfare indicators (WI) with levels from best to worst, the associated indicator level score (IS), the sum of the weighting scores assigned to the best and worst level and the calculated weighting factor (WF), see Eqn 2. Levels with indicator score *K* are knockout levels, i.e. levels that result in severely reduced welfare regardless of other WIs

		WI	#	Levels	IS	Σ	WF
Environment	Sea cage	Temperature (°C)	1	10–15	1.00	5	16
			2	7–10	0.75		
			3	16–17	0.50		
			4	3–6	0.25		
			5	≤2, ≥18, short term	0.00	−11	
			6	≤2, ≥18, long term	K		
		Salinity	1	Access to brackish water	1.00	1	3
			2	Adult fish with no access to brackish water	0.50		
			3	Small post smolts, maturing or clearly impaired fish with no access to brackish water	0.00	−2	
		Oxygen (%)	1	>80%, all temperatures	1.00	1	17
			2	70–80% for warm water (≈18°C), 60–80% (≈12°C), 50–80% cold water (6°C)	0.50		
			3	60–70% for warm water (≈18°C), 40–60% (≈12°C), 30–50% cold water (6°C)	0.00	−8	
			4	<60% for warm water (≈18°C), <40% (≈12°C), <30% cold water (6°C)	K		
		Water current (BL s^{-1})	1	<0.9	1.00	1	3
			2	0.9 – U_{crit},	0.00	−2	
			3	≥U_{crit}	K		
		Stocking density (kg m^{-3})	1	<22	1.00	1	8
			2	22–26	0.66		
			3	26–32	0.33		
			4	>32	0.00	−7	
		Lighting	1	Optimal	1.00	2	4
			2	Suboptimal	0.00	−2	
		Disturbances	1	None	1.00	1	11
			2	Light	0.67		
			3	Moderate	0.33		
			4	Severe	0.00	−10	
Animal		Mortality (% day^{-1})	1	At or below 10 percentile curve	1.00	3	21
			2	Below benchmark curve	0.75		
			3	At the benchmark curve	0.50		
			4	Above the benchmark curve	0.25		
			5	At or above the 90 percentile curve	0.00	−18	
			6	At or above the 90 percentile curve, long term	K		
		Appetite	1	Good appetite	1.00	6	11
			2	As expected	0.50		
			3	Poor appetite	0.00	−5	
	Individual fish	Sea lice	1	No lice	1.00	1	11
			2	Light infestation	0.66		
			3	≥0.05 pre-adult or adult lice cm^{-2} fish	0.33		
			4	≥0.08 pre-adult or adult lice cm^{-2} fish	0.00	−10	
			5	≥0.12 pre-adult or adult lice cm^{-2} fish	K		
		Condition factor	1	>1.1	1.00	3	6
			2	0.9–1.1	0.50		
			3	<0.9	0.00	−3	
		Emaciation state	1	Not emaciated	1.00	1	16
			2	Potentially emaciated	0.00	−15	
			3	Distinctly emaciated	K		

Table 4 (Continued)

WI	#	Levels	IS	Σ	WF
Vertebral deformation	1	No external signs of vertebral deformities	1.00	1	10
	2	'Short-tail' of normal weight	0.50		
	3	'Short-tail' of low weight.	0.00	−9	
Sexual maturity stage	1	Not mature	1.00	1	9
	2	Precocious male	0.66		
	3	Mature male	0.33		
	4	Mature female	0.00	−8	
Smoltification state	1	Fully smoltified	1.00	1	9
	2	Parr, access to brackish water	0.75		
	3	Parr, incomplete smoltification, 10°C	0.50		
	4	Parr, incomplete smoltification, 14°C	0.25		
	5	Parr, incomplete smoltification, 7°C	0.0	−8	
	6	Parr, incomplete smoltification, 20°C	K		
Fin condition	1	Normal healthy fins, nothing to comment	1.00	3	13
	2	Scar tissue or slight necrosis	0.66		
	3	Moderate current skin damage and/or necrosis including splitting and/or thickening	0.33		
	4	Severe skin damage and/or necrosis with bleeding and/or inflammation and/or exposed fin rays and severe tissue loss	0.00	−10	
Skin condition	1	Normal healthy skin, nothing to comment	1.00	1	15
	2	Scar tissue, healed	0.80		
	3	Scale loss (dislocated or missing scales)	0.60		
	4	Superficial wound or ulcer <1 cm^2	0.40		
	5	Superficial wound or ulcer >1 cm^2	0.20		
	6	Penetrating and/or multiple wounds or ulcers possibly infected	0.00	−14	
	7	Large open wounds, life threatening	K		

et al. 1998) as osmoregulation is relatively costly for them. Swimming in brackish water may also help the salmon to avoid sea lice infestation (*Lepeophtheirus salmonis*) (Hevrøy *et al.* 2003; Plantalech Manel-La *et al.* 2009) as the infectious larvae of sea lice do not tolerate low salinities (Bricknell *et al.* 2006). Salinity has been suggested as a factor regulating swimming depth in adult salmon, but current evidence suggests that salinity is unimportant in determining vertical distributions in immature fully smoltified seawater-transferred Atlantic salmon (Johansson *et al.* 2006, 2007; Oppedal *et al.* 2011a).

To conclude, there is little evidence that salinity levels have significant effects on the welfare of adult Atlantic salmon in sea cages. We do, however, suggest three levels for the Salinity WI: (1) Access to brackish water, (2) Adult fish with no access to brackish water (in a sea cage containing 10–400 000 individuals it is likely that some fish have compromised osmotic balance) and (3) Poorly smoltified, maturing or impaired fish with no access to brackish water. These fish (level 3) will show Preference (1) for brackish water, and otherwise have negative performance (−1) and reduced survival (−1). In accordance with limited evidence for strong effects on fish welfare the calculated WF is only 3 (Eqn 2, Table 4).

Oxygen saturation (%)

For this welfare indicator it is necessary to first explain why we use oxygen saturation (%) and not oxygen concentration (mg L^{-1}). These measures are of course related, but as oxygen solubility decreases with temperature and salinity, the oxygen concentration corresponding to any level of oxygen saturation varies. Both concentration and saturation are meaningful metrics of available oxygen in the water. Any oxygen that is to be utilized by fish tissues must be extracted from the water ventilated by the fish over its gills, and at any given saturation, cooler and less saline water contains more oxygen. However, the diffusion gradient of oxygen over the gills depends on oxygen saturation of the water, and at any given concentration of oxygen, the higher saturation in warmer, more saline water aids oxygen uptake over the gills. Also, a considerable strength of using saturation as the operational welfare indicator is how intuitive inferences can be drawn from such readings without any knowledge about temperature, salinity and solubility: 80% oxygen tells us that the fish is offered 80% of what is found in pure water at equilibrium with air.

Stevens *et al.* (1998) found that the routine oxygen uptake of juvenile Atlantic salmon in freshwater at 12–13°C was not limited by water oxygen saturations above 38%. This is confirmed in recent studies in sea water (reviewed in Oppedal *et al.* 2011a) showing that at 18, 12 and 6°C 400 g salmon post-smolt are not able to maintain routine metabolic rates below approximately 60%, 40% and 30% saturation, respectively. Below these thresholds mortality will commence in farmed salmon if oxygen levels are not improved. The difference between the routine and the maximum metabolic rate (the maximum theoretically possible oxygen uptake under the present conditions) acts as a buffer against factors such as stress, disease and feeding, which narrow this metabolic scope (e.g. Helfman *et al.* 1997; Priede 2002). Salmon will therefore migrate vertically in sea cages to avoid hypoxic zones (Oppedal *et al.* 2011a). A summary from several hypoxia trials (WEALTH 2008) concluded that immune responses are reduced at levels below 55% oxygen saturation, and Sundh *et al.* (2010) found that the intestinal function was clearly disturbed at a level of 50% for salmon kept at both 9°C and 16°C. Furthermore, studies with full-feeding Atlantic salmon held in seawater at 16°C and given fluctuating oxygen levels from 90 to 70% showed reduced appetite, fluctuating from 90 to 60% also initiated acute anaerobic metabolism and increased skin lesions, fluctuations from 90 to 50% additionally initiated acute stress responses, reduced feed conversion and growth, and fluctuations from 90 to 40% additionally caused impaired osmoregulation and mortalities (Remen *et al.* 2012). Moderate environmental hypoxia also has an effect. Crampton *et al.* (2003) and Bergheim *et al.* (2006) found that salmon displayed reduced growth at 75% oxygen in 9°C water and at 85% in 15°C water, respectively, compared with fish kept at 100% oxygen. This high sensitivity of growth rate to oxygen availability suggests that even modest reductions in oxygen saturation may start causing welfare problems.

Based on this review we suggest that oxygen levels above 80% do not cause welfare problems for salmon in sea cages, but instead are associated with Positive performance (3). We divide the dissolved oxygen (DO) WI into four level combinations of oxygen saturation and temperature (Table 4), including one knockout level. The worst level, excluding the knockout is set to: 60–70% and ≈18°C, 40–60% and ≈12°C or 30–50% and ≈6°C. This level is associated with avoidance (−3), negative performance (−3), illness (−3) and reduced survival (−5). This gives a total WF of 17 (Eqn 2, Table 4).

Water current (measured as body lengths per second)

The water flow through a sea cage replenishes oxygen used by the fish and flushes out metabolites and suspended solids such as faeces and excess feed (EFSA 2008; MacIntyre *et al.* 2008). The swimming capacity of Atlantic salmon depends on factors such as body size and metabolic scope (Grøttum & Sigholt 1998). Observations from sea cages show that during daytime salmon cruise at 0.3–0.9 BL s^{-1} (Juell 1995; Dempster *et al.* 2008, 2009; Korsøen *et al.* 2009), while they typically slow down during darkness to 0–0.4 BL s^{-1} (Korsøen *et al.* 2009). Salmon reared in raceways with a fixed current (28 cm s^{-1}) for 8 months prior to harvest showed nearly 40% higher weight gain compared with control fish farmed in ordinary cages (Totland *et al.* 1987). Intensity of exercise has been found positively correlated with disease resistance (Takle *et al.* 2010) and improved cardio-vascular capacities (Jørgensen & Jobling 1994; Davison 1997). Although water current typically is measured as m s^{-1}, in regard to fish welfare it makes more sense to measure it as BL s^{-1}. High currents can drive small salmon (400–800 g) to exhaustion already at 1.6–2.2 BL s^{-1} (McKenzie *et al.* 1998; Deitch *et al.* 2006), although some can manage 3.0 BL s^{-1}(Lijalad & Powell 2009). We were unable to find data on larger Atlantic salmon, but studies in Sockeye salmon (*Oncorhynchus nerka*) indicate a critical swimming speed U_{crit} of about 1.35 BL s^{-1} for larger salmonids (Steinhausen *et al.* 2008). It should be noted that the above studies using swimming tunnels were performed on starved fish and that fully fed, commercial fish probably have lower thresholds due to less available scope for activity.

In conclusion, the water flow through sea cages must be sufficient to secure replenishment of oxygen. While saturation with oxygen per se is a separate WI, water currents also affect swimming speeds of the fish. We suggest dividing the water current WI into three levels: At level 1 (<0.9 BL s^{-1}) currents provide exercise and give positive performance (1), at level 2 (0.9 – U_{crit}) welfare may be reduced, and when the water velocity is so high that it exceeds critical swimming speed (U_{crit}) then water flow may even be lethal for the fish (knock-out, level 3). We were not able to find any literature about swimming speeds between the comfort zone and the U_{crit}s (level 2), but it is reasonable to assume that forced swimming leads to loss of control and hence frustration (−2) over time. It is also reasonable to assume that U_{crit} in addition to size depends on the state of the fish, for instance how adapted it is to high water currents. The farmer must, in other words, know the ability of the fish or use a U_{crit} of 1.3 for safe margins. In accordance with scant evidence for the direct effects of water current on fish welfare we get a WF of only 3 (Eqn 2, Table 4).

Stocking density (kg m^{-3})

Stocking density, defined as the total biomass of the fish divided by the sea cage volume, is typically used by authorities to set upper limits for what is allowed in sea cages (e.g. 25 kg m^{-3} in Norway). Despite its frequent use as a production parameter there are relatively few studies on how different stocking densities affect salmon in sea cages. Turnbull *et al.* (2005) examined densities ranging from 10 to 34 kg m^{-3} at a sea farm and found no negative effects on the salmon, measured as a combined score of body condition, fin condition, plasma glucose and cortisol, up to an inflection point at about 22 kg m^{-3}, and no substantial negative effect on these parameters below 32 kg m^{-3}. These findings were largely confirmed in a tank study by Adams *et al.* (2007) and a sea cage study by Oppedal *et al.* (2011b). Adams *et al.* (2007) found negative effects on welfare for a stocking density of 35 kg m^{-3} compared with 25 kg m^{-3}, and Oppedal *et al.* (2011b) found declined feed intake, growth rate, feed utilization and a greater number of cataracts when the stocking density exceeded 26.5 kg m^{-3}. Unfortunately, these three studies provide limited information about the oxygen saturation of the water or the presence of endemic infections, which both may have been important reasons for decreased fish welfare at the higher densities (Johansson *et al.* 2006; Oppedal *et al.* 2011b). A tank study indicates that low stocking densities of only 57 individuals may lead to aggression and reduced welfare (Adams *et al.* 2007), but this has not been confirmed for low densities in sea cages holding a higher number of individuals (Turnbull *et al.* 2005; Johansson *et al.* 2006; Oppedal *et al.* 2011b). Johansson *et al.* (2006) showed that salmon in sea cages at high stocking densities (18–27 kg m^{-3}) have limited abilities to position themselves at preferred temperatures compared with fish at lower densities (7–11 kg m^{-3}) and as a result grew less. Oppedal *et al.* (2007, 2011b) showed that salmon may congregate into very tight schools, with a local density above 180 kg m^{-3}, in order to avoid high temperatures. This illustrates that crowding of fish may be a response to an underlying factor, i.e. competition for limited resources within the cage and/or lack of ability to avoid sub-lethal/lethal conditions, which seem to be far more relevant problems than stocking density per se.

Although the literature shows that salmon may congregate at extreme densities, we take as given that high overall densities limit the fish's freedom to move in the cage. Low stocking densities (below 22 kg m^{-3}) will therefore give more natural behaviour (1). At higher densities welfare becomes incrementally worse until above 32 kg m^{-1}, where there is a substantial effect on negative performance (−2), pain (−1), illness (−1) and activation of the HPI-axis (−3). We divided the stocking density WI into four levels from <22 kg m^{-3} to above 32 kg m^{-3} and calculated a WF of 8 (Eqn 2, Table 4).

Lighting

Underwater lights are widely used in the industry to reduce the incidence of sexual maturation (e.g. Oppedal *et al.* 2011a). Maturation is covered as a separate WI (see below), but the underwater lights have also more direct implications for fish behaviour. Atlantic salmon tend to avoid strong surface daylight (Huse & Holm 1993; Fernö *et al.* 1995), but are attracted to night-time surface and underwater lights (Oppedal *et al.* 2001, 2007, 2011a; Juell *et al.* 2003; Juell & Fosseidengen 2004). Lighting the cage at night stimulates the salmon to maintain daytime swimming speeds and schooling behaviour, but the use of only surface lights may result in fish swimming at very high densities near the surface (Juell *et al.* 2003). Using submersible lights at depths (e.g. 15 m) that allow the salmon to spread out both above and below the lights, therefore, improves the welfare of caged salmon (Juell *et al.* 2003; Juell & Fosseidengen 2004; Oppedal *et al.* 2007, 2011a).

Based on this we propose to divide the lighting WI into two levels: (1) optimal and (2) suboptimal. Optimal is the use of artificial lights at multiple depths. Suboptimal is narrow illumination of the cage volume, such as moonlight, artificial lights positioned at only a shallow depth or above the surface. Optimal lighting allows the salmon to utilize the entire water column and hence contributes to positive performance (1) and preference (1). Lack of illumination may force the salmon to school at high densities near the surface at night time and experience frustration (−1) and avoidance (−1) as the other depth layers are not used. WF is calculated as 4 (Eqn 2, Table 4). The lighting WI is defined as optimal during the light season of the year.

Disturbances

Removing fish from the water, for instance when estimating the level of sea lice infestation, is one of the most severe stress events, and induces a high cortisol response (Schreck *et al.* 1997). However, this is usually done on only a few individuals at a time and likely to have little effect on the other fish in the cage. Other procedures may affect the whole group, e.g. delousing by bath (Vigen 2008; Nilsen *et al.* 2010), grading (Juell *et al.* 2008) and transportation (Iversen *et al.* 1998, 2005; Farrel 2005). Studies of wellboat-transportation of smolts (Iversen *et al.* 2005) and live-hauling of harvest fish to processing facilities (Farrel 2005) show that the salmon recover during transportation from the initial handling stress of being loaded. This recovery seems to be crucial for avoiding cumulative and hence long-term stress during their initial period in the sea cages (Iversen *et al.* 2005). Juell *et al.* (2008) observed that crowding, pumping and sorting of salmon in sea cages led to a rapid drop in oxygen levels (not critical) during the procedure. For several days the fish were also more dispersed in the cages than before the treatment and they did not congregate as much in the warm surface layers as before. Appetite was reduced for approximately 5 days, and did not increase with the increasing surface temperatures in May, indicating a strong negative effect of this commercial sorting procedure. During delousing with bath treatment a bottom opened or closed tarpaulin 'skirt' is placed around the cage to keep the therapeutic chemicals inside the cage. Various aspects of this procedure, including the disturbance, crowding, changed environment, skirt and the treatment substance, may affect the fish. Vigen (2008) found that in a group of salmon held at 25 kg m^{-3} the oxygen saturation decreased to around 50% within 45 min after a skirt was placed around the cage, when no treatment substance was added. After the treatment substance (the pyrethroid cypermethrin, Betamax Vet) had been added within the skirt, salmon crowded at very high densities (up to 107 kg m^{-3}) near the surface. Oxygen saturation decreased faster while the swimming speed and gill ventilation frequency were higher and more variable. In a compilation of observations during topical delousing with skirts Nilsen *et al.* (2010) concluded that the salmon avoided the therapeutant by swimming below the enclosed volume when the nets were not lifted. Following delousing, many farmers have reported poor performance of the fish including poor appetite, reduced growth, disease outbreaks and increased mortalities.

We propose to divide the disturbances WI into four levels: (1) none, (2) light, (3) moderate and (4) severe. Level 4 includes disturbances such as pumping of the fish which may lead to activation of the HPI (−3) axis, abnormal behaviour (−3), frustration (−1), negative performance (−1), illness (−1) and reduced survival (−1). Level 3 includes disturbances such as crowding and topical delousing. Level 2 includes disturbances such as activity around the cage that only stresses the fish to a mild extent. Level 1, no disturbances, promotes natural behaviour (1) and the total WF is calculated as 11 (Eqn 2, Table 4).

Daily mortality rate (% per day)

Mortality in farmed animals, including salmon, is an indicator of disease outbreaks, poor environmental conditions, or injuries, all conditions that are related to reduced welfare. Aunsmo *et al.* (2008a) studied fish mortalities in 20 cages (10 sites) in the three first months after transfer and found that the fish died from various reasons including incomplete smoltification (5.6%), precocious males (3.3%), trauma (18.2%), specific diseases (65.6%) or unknown reasons (7.6%). Cage mortality rates were not normally distributed and 73% of the recorded mortalities occurred in only 20% of the cages. The best performing sea cages had a mortality rate, defined as the number of dead fish divided by the total number of fish in the cage multiplied by 100, of about 0.002% day^{-1}, while the worst cages had periods of mortality rates with peaks of up to 2.4% day^{-1} with an average of 0.1% day^{-1}. Production data of fish mortalities in sea water (2009–2011) from mid-Norway were grouped according to smolt-groups ($n = 127$, 65.6 million individuals), where 11% of the groups had >30% mortality, 55.9% had 30–20% mortality, 33.1% had <10% mortality, and the average mortality was 16.1% (Anon 2011a). Disease during the sea water phase accounted for 23.5% of the mortalities, smolt quality related problems accounted for 38% and handling during the sea water phase accounted for 38.5% (Anon 2011a). In an extensive study of more than 88 production cycles in Scotland within one company, Soares *et al.* (2011) developed benchmark mortality curves. The 50-percentile benchmark curve starts at above 0.1% day^{-1} mortality during the first week after transfer, between 0.01% and 0.1% during week 2–40, and then <0.01% day^{-1} until slaughter. Using the 50-percentile curve as a benchmark gives a total mortality of about 11% at the end of production. This is considerably better than the total mortality value of 17% reported by the Norwegian salmon industry and the 21% reported by the Scottish Industry (Aunsmo *et al.* 2008a). For the 10- and 90-percentile curves and more detailed description of the 50-percentile curve see (Soares *et al.* 2011). The main causes of mortalities in Soares *et al.* (2011) were disease (31%), production factors (accident loss, caught in net, cull, failed smolts, jacks, mature, net tear, parr, precocious male, transfer, treatment kill, smolt transfer and suspected cannibalism) (29%), environment (8%), predation (7%) and other causes (26%).

High daily mortality compared with the benchmark is indicative of illness (−5), reduced survival (−5), pain (−5) and negative performance (−3), while low daily mortality indicates positive performance (3). Based on the mortality benchmark study we suggest dividing the daily mortality WI into five levels from best (at or below the 10-percentile curve) to worst (at or above 90-percentile curve (Table 4). Long term values at or above the 90-percentile will lead to extreme mortality and is accordingly considered to be a knockout level. The WF is calculated to 21 (Eqn 2, Table 4).

Appetite

Appetite is defined here as the fish's willingness to forage, and the loss of appetite may be a sign of one or more underlying welfare relevant conditions (Schreck *et al.*

1997; Huntingford *et al.* 2006). Several studies have reported a loss of appetite at seawater transfer (Usher *et al.* 1991; Toften *et al.* 2003), infection or disease (Rodger & McArdle 1996; Damsgård *et al.* 2004), handling (McCormick *et al.* 1998), a deteriorating environment (Bergheim *et al.* 2006; WEALTH 2008) and high stocking density (Oppedal *et al.* 2011b). Many fish farmers use appetite to determine feeding levels. It requires experience in order to interpret the behaviour of the fish. The farmer must assess appetite in relation to water temperature and fish size. Generally, appetite increases with water temperature and decreases with fish size (Austreng *et al.* 1987). Feed companies usually supply farmers with expected amounts of feed under different water temperatures and fish sizes (see above). The responsiveness to food varies with the time of day and season (Kadri *et al.* 1991; Jørgensen & Jobling 1992; Smith *et al.* 1993), and it may be manipulated using artificial photoperiods (Taranger *et al.* 1995; Nordgarden *et al.* 2003; Oppedal *et al.* 2003). Although the feeding regime in general seems to have little effect on growth and the feed conversion ratio (FCR) (Sveier & Lied 1998), suppressed growth was seen in the daily feeding regime of one meal compared with eight meals in the period just following sea transfer (Flood *et al.* 2011). Today, many Salmon farmers use a camera positioned beneath the feeding area, looking up, to assess appetite levels; when the farmer sees pellets reaching down to the camera the feeding is turned off.

Prolonged (weeks to months) poor appetite is clearly indicative of negative performance (−2) and illness (−3), and good appetite suggests demand (3) and positive performance (3). For practical application in the SWIM 1.0-model, we suggest dividing the Appetite WI intro three levels: (1) good appetite, (2) as expected and (3) poor appetite and calculate a WF of 11 (Eqn 2, Table 4).

Sea lice

Farmed Atlantic salmon are parasitized by two species of sea lice; *Lepeophtheirus salmonis* (salmon lice) and, to a lesser extent, *Caligus elongates* (e.g. Pike & Wadsworth 1999). Salmon respond to a sea lice infestation with primary stress responses including elevated blood cortisol and glucose (Bowers *et al.* 2000; Finstad *et al.* 2000). These stress responses occur even though at the infective copepod stage the lice do not yet feed on the salmon (e.g. Finstad *et al.* 2011). Grimnes and Jakobsen (1996) and Finstad *et al.* (2000) did not find severe effects on the fish from extreme infections of sea lice (>1 lice cm^{-2} fish or >100 lice $fish^{-1}$) at the copepod and early chalimus stages, but they did find a sudden increase in mortality after the appearance of the pre-adult stages. Responses to an infestation of pre-adult and adult sea lice include primary stress responses, inflammatory responses, changes in appetite, changes in the skin and gills, compromised immunity, delayed healing of injuries, osmotic problems and tissue self-destruction (Nolan *et al.* 1999; Bowers *et al.* 2000; Finstad *et al.* 2000; Ross *et al.* 2000; Boxaspen 2006; Skugor *et al.* 2008). Sea lice initiate short term physiological effects for the host already at 0.01 lice cm^{-2} fish and long term effects at 0.05 lice cm^{-2} fish (Nolan *et al.* 1999). Grimnes and Jakobsen (1996) found that more than 0.15 lice cm^{-2} fish was lethal, but indicated that the actual mortality limit probably is lower. An extensive 10 year sampling of wild Atlantic salmon in the Norwegian sea revealed no fish carrying more than 10 adult lice (Holst *et al.* 2003). Since a wild smolt leaving the coast has a weight of about 15 g (Finstad *et al.* 2000) or surface area (including fins) of 95 cm^{-2} (Tucker *et al.* 2002: fish surface area (cm^2) = 0.6131*fish weight (g) + 86.144), this implies an upper limit of 0.12 lice cm^{-2} fish.

Infestations of more than 0.12 lice cm^{-2} fish are lethal for the fish (knockout), at lower levels >0.05 lice cm^{-2} fish the fish will increasingly suffer from illness (−3), pain (−1), activation of the HPI (−1) axis, reduced survival (−3) and negative performance (−2) (Table 4). We suggest five levels for the sea lice WI (Table 4), from no lice as level 1 (positive performance (1)), via light infestation as level 2 (only Copepod and Chalimus stages and/or <0.05 lice cm^{-2} fish for the pre-adult and adult stages), to ≥0.08 adult or pre-adult lice cm^{-2} fish as level 4 (Table 4) and calculate a WF of 11 (Eqn 2, Table 4).

Condition factor

Condition factor (*K*) is a standard measurement of fish nutritional status (Bolger & Conolly 1989; Nash *et al.* 2006) and is calculated as $K = (WL^{-3})100$, where W is the weight in g and L is the length in cm. In general terms, a skinny salmon may have a $K < 0.9$ and a fat fish a *K* of 1.5 (Tvenning 1991). During the production cycle *K* changes from just above 1 as smolt (O'Flynn *et al.* 1997; Mørkøre & Rørvik 2001; Oppedal *et al.* 1999, 2006; Fjelldal *et al.* 2009a, b) to 1.6 nearer slaughter (Oppedal *et al.* 1997, 1999, 2006; Einen *et al.* 1998; Rørå *et al.* 1998; Mørkøre & Rørvik 2001) but this may partly be overruled by season phase and delayed by artificial photoperiods (Oppedal *et al.* 1997, 1999, 2003, 2006; Fjelldal *et al.* 2009a, b). Generally, *K* decreases during winter and spring, and increases during summer and autumn. Periods of good growth typically increase *K* (Juell *et al.* 1994; Endal *et al.* 2000), while periods of poor growth reduce *K* (e.g. Juell *et al.* 1994; Einen *et al.* 1999). Also, sea transfer as either spring or autumn smolts may interfere with the seasonal pattern (Mørkøre & Rørvik 2001), but not inevitably (Fjelldal *et al.* 2009a). Farmed fish display higher *K* compared with hybrid and wild salmon given similar farming conditions (Fjelldal *et al.* 2009a). There is a strong and significant positive correlation between *K* and total lipid content in Atlantic salmon (Herbinger & Friars 1991; Einen *et al.* 1998, 1999; Rørå *et al.* 1998; Hamre *et al.* 2004; Peterson & Harmon 2005). *K* is negatively correlated with plasma glucose and cortisol (Turnbull *et al.* 2005). Very high *K* (>1.6) indicates spinal deformation (Gjerde *et al.* 2005; Witten *et al.* 2005; Berg *et al.* 2006; Fjelldal *et al.* 2009b; Hansen *et al.* 2010), but the specific level at which this may occur is difficult to fix due to the variations discussed above. However, within a population, low *K* individuals tend to be emaciated fish while 'normal' *K* values indicate good health, and very high *K* values often indicate deformed individuals.

We propose to divide the condition factor WI into three levels: (1) >1.1, (2) 0.9–1.1, and (3) <0.9. Salmon with *K* above 1.1 have lipid reserves indicating positive performance (3), while salmon with *K* below 0.9 and 1.1 have negative performance (−2) and activation of the HPI (−1) axis. Extreme high *K* (>1.6) may be indicative of malformation, but this is addresses by the vertebral deformities WI (see below) and need therefore not be considered here. Similarly, for extreme low *K* which is addressed by the emaciation state WI (see below). The WF was calculated as 6 (Eqn 2, Table 4).

Emaciation state

Fish may become emaciated due to disease (Stephen & Ribble 1995; Kent & Poppe 2002), poor smoltification (Duston 1994), 'wrong' feeding strategy (at transfer some fish may start to eat zooplankton instead of pellets) (pers. obs.; wild smolt: Rikardsen *et al.* 2004), sea lice (e.g. Finstad *et al.* 2011), stress (e.g. Huntingford *et al.* 2006) and social constraints (Jobling & Reinsnes 1986; Adams *et al.* 2000). Emaciated fish are generally small, very thin fish of poor health, and they may act as a vector for introducing disease to the other (more healthy) fish in the cage. As they are feeding poorly, or not at all, it is difficult to treat them orally (Coyne *et al.* 2006). Emaciated fish are well known to fish farmers (Stien *et al.* 2009; Anon 2011b), but there is little published research on the subject. A study using Floy anchor tags on farmed chinook salmon (*Oncorhynchus tshuwytscha*) individuals that could be captured with a dip net from the surface, showed that these were mainly emaciated and moribund fish (62% died within 24 h) (Stephen & Ribble 1995). Characteristic of these fish were obvious pathological and clinical abnormalities (95% of 366 individuals exhibited gross and/or histopathological abnormalities), and behavioural abnormalities such as swimming into the nets or in circles, swimming separated/apart from the main group, and staying at the surface for prolonged periods of time.

We propose to divide the emaciated state WI into three levels: (1) not emaciated, (2) potentially emaciated and (3) distinctly emaciated (Table 4). No sign of emaciation is evidence of a healthy fish, i.e. positive performance (1). An emaciated fish is very ill and moribund. A positive identification of an emaciated fish is therefore a knockout level for that individual fish. A potentially emaciated fish is a fish showing signs of abnormal behaviour (−3), negative performance (−3) and illness (−3), and is likely to have reduced survival (−3) and experience pain (−3). Based on this we calculated a WF 16 (Eqn 2, Table 4).

Vertebral deformation

The main vertebral deformity in Norwegian salmon farms is pronounced compression of the vertebral column and reduced fork length, commonly referred to as 'short-tail' (Gil-Martens 2010). Multiple causes of vertebral deformities have been identified such as environmental conditions during egg incubation (Wargelius *et al.* 2005), fish size and temperature at vaccination (Berg *et al.* 2006), type of vaccination (Aunsmo *et al.* 2008b), mineral nutrition (Fjelldal *et al.* 2008, 2009b), use of underyearling smolt (Fjelldal *et al.* 2006) and temperature at transfer to sea water (Grini *et al.* 2011). The prevalence of one or more vertebral deformities determined by radiology in harvest sized salmon have been reported in the range of 6.6–73.3% (Witten *et al.* 2005; Fjelldal *et al.* 2007, 2009a, b; Korsøen *et al.* 2009). Hansen *et al.* (2010) found that a low severity of deformed vertebrae (<6 vertebrae compressed) has little effect on growth, but individuals with more than 10 deformed vertebrae were shorter and had a higher condition factor than normal fish, while fish with more than 20 deformed vertebrae in addition showed lower weight than normal fish. Aunsmo *et al.* (2008b) reported that fish with high intra-abdominal lesion scores also more frequently had vertebral deformities and weighed 62% of non-deformed fish at slaughter.

Dependent on the severity of deformation, external examination is a less sensitive method of assessment than radiology, the prevalence has, for example, been assessed as 1.3% vs. 12.4% (Fjelldal *et al.* 2007) and 13–17% vs. 88–94% (Grini *et al.* 2011). Since this version of the SWIM-model is aimed at fish farmers the vertebral deformation WI must be judged by external examination of the individual fish. We therefore suggest dividing the WI into three levels: (1) no external signs of vertebral deformity, (2) 'short tail' of normal weight, (3) 'short tail' of low weight compared with the rest of the population. Level 1 is linked with positive performance (1), while level 3 indicates negative performance (−3), pain (−3) and illness (−3) this gives a WF of 10 (Eqn 2, Table 4).

Sexual maturity stage

Sexual maturation leads to allocation of energy towards gonad build-up and migration. Prior to upstream migration wild salmon have an energy loss of about 60% of their body reserves (Jonsson *et al.* 1997; Fleming 1998). In the wild few survive to breed another year (Fleming 1998). Consequently, sexual maturation is detrimental for salmon production, where artificial photo-regimes are used to prevent maturation (e.g. Oppedal *et al.* 2011a). Sexually mature parr, precocious males, can be present at sea transfer and their presence is linked to increased mortality (Aunsmo *et al.* 2008a). The energy expended for maturation and spawning increases with fish size and females also expend more energy on gonads compared with males (ca 28% vs. ca 4% of total energy reserves, Fleming 1998). Whether mature salmon have a behavioural need to carry out spawning migration is difficult to answer (cf. Huntingford *et al.* 2006), but it is plausible that there is an increase in aggression (Fleming & Einum 2011). With regard to altered osmoregulation in adaptation to a hypo-osmotic environment before re-entering freshwater in nature, Persson *et al.* (1998) found that salmon caught in the estuary (before entering the river) had already adapted to a hypoosmotic environment and that during the upriver migration the gill Na^+, K^+-ATPase activity decreased even further. It is therefore plausible that mature salmon in sea cages to some extent experience osmoregulatory challenges. Besides the energy draining effects of maturation, it has been shown that compared with immature fish mature salmon have a higher prevalence of the parasite *Kudoa thyrsites,* that is a cause of post mortem soft flesh (St-Hilaire *et al.* 1998).

Mature females have invested heavily in the development of gonads and show negative performance (−3) and ultimately reduced survival (−3). Mature males and especially mature juvenile males invest less. Maturity linked aggression (−2) may also reduce welfare. No maturation is presumed to give a positive performance (1). We propose dividing the sexual maturity stage WI into four levels and calculate a WF of 9 (Eqn 2, Table 4).

Smoltification state

During the smoltification process salmon parr develop tolerance for high salinity, enabling the young salmon (now called smolt) to enter seawater with only minor disturbances in osmotic balance (e.g. Stefansson *et al.* 2008; Thorstad *et al.* 2011). The physiological disturbances during exposure to seawater (33 ppt) are greater at high temperatures (>14°C) compared with intermediate temperatures (10°C), while low temperatures (<7°C) may lead to a prolonged period of osmotic stress and increased mortality (Sigholt & Finstad 1990; Arnesen *et al.* 1998; Handeland *et al.* 2000, 2003). For intermediate water temperatures (which are best for welfare) transfer of salmon to full strength seawater before the smoltification process has completed resulted in high mortality (>40%) and stunted growth rates for a period of 1–2 months (Duston 1994), but when transferred to brackish water (20 ppt) mortality was <10% and only temporarily stunted growth rates were observed, and with even less saline water (10 ppt) little to no mortality occurred and no stunting of growth compared with parr continuing in freshwater (Bjerknes *et al.* 1992; Duston 1994). For fully smoltified fish there is little effect of salinity on growth rate and mortality (Duston 1994).

Fully smoltified fish have few problems with osmoregulation in full strength seawater (positive performance (1)). Impaired smolts have negative performance (−3) and reduced survival (−5), especially at low temperatures (<7°C), and knockout for high temperatures (>20°C). This gives six WI levels from worst (incomplete smoltification at high temperature) to best (fully smoltified) and a WF of 9 (Eqn 2, Table 4). As this is a farmer's version of SWIM, the smoltification state must be judged based on the colouration and shape of the fish. Fully smoltified Atlantic salmon have lost their distinctive parr markings, gained a more silvery colour and have a more streamlined shape (Hoar 1988).

Fin condition

Fin erosion refers to damage to, and loss of, the tissue of the rayed fins (Latremouille 2003) and is often found in farmed salmonids. Being externally visible, fin damage represents an intuitive and meaningful welfare indicator easily recognized by farmers and informed consumers (Ellis *et al.* 2008). While most studies on nociception in fish have focused on the head region or the body, Chervova (1997) demonstrated experimentally that fish fins are capable of nociception. Being live tissue capable of nociception mechanical injury to fin tissue is probably associated with pain. In some cases, mechanical fin damage may reflect aggressive behaviour within the rearing unit (salmon parr: Turnbull *et al.* 1996, 1998; Jones *et al.* 2010). Damage to the fins of salmonids is, however, more often caused by chronic infection with biofilm forming bacteria that progressively necrotize the fin edges (Bernardet *et al.* 1998), similar to leprosy in humans not necessarily being painful. Poor fin condition is coupled with a high stocking density, poor water quality, decreased condition factor and increased plasma glucose and cortisol levels (Turnbull *et al.* 2005; Adams *et al.* 2007). The fins fulfil important functions in both locomotion and intraspecific communication in salmonids (Abbott & Dill 1985; Pelis & McCormick 2003) and severe fin erosion thus has the potential to affect behaviour. However, the evidence is scarce or contradictory, and any functional impairment following fin erosion has yet to be demonstrated scientifically. The breakdown of the epithelial barrier during active fin erosion may disrupt osmotic homeostasis and can thus cause severe stress in the fish (Clayton *et al.* 1998).

Fin damage represents injury to live tissue with the potential for inflammation and pain (−5). Damaged epithelial structures may also represent invasion routes for pathogens and thus lead to illness (−3) and negative performance (−2). We propose to divide the fin condition WI into four levels ranging from normal healthy fins (positive performance (3)) without tissue loss to severely damaged fins with tissue loss, which also may be suffering from necrosis, inflammation, bleeding or exposed fin rays (Table 4). The WF calculated in SWIM 1.0 is 13 (Eqn 2, Table 4).

Skin condition

The integrity of the skin-scale complex provides a relatively impermeable barrier to water and electrolytes. Epidermal damage such as scale loss, wounds and ulcers can therefore result in a loss of body water and changed ion balance, which produces an osmotic stress that potentially can be life threatening (Bouck & Smith 1979). There is evidence that ulceration of as little as 10% of the body surface area can result in high acute mortality and that the degree of mortality is directly related to the amount of skin damage (Bouck & Smith 1979). Sub-lethal skin damage might affect the fish energy budget due to increased metabolic cost involved in wound repair, and osmoregulatory perturbations. Such chronic effects can affect growth rates and fecundity negatively; it may also lead to an increased susceptibility to other diseases (Noga 2000). Many situations or management procedures in salmon aquaculture are associated with a high risk for mechanical damage to the skin. Examples are transport, sorting, vaccination, pumping, strong currents and high densities of fish, jelly fish burns, parasites, attack from other fish and predators (Noble *et al.* 2012). Virus- or bacterial infections can often also constitute the underlying cause of skin necrosis or ulcerations in fish. In sea farmed Atlantic salmon several infections are associated with severe or even pathognomic cutaneous symptoms, i.e. winter ulcer disease (infection with *Moritella viscosa*; Lunder *et al.* 1995; Benediktsdóttir *et al.* 2000), atypical furunculosis (atypical *Aeromonas salmonicida* infections; Wicklund & Dalsgaard 1998), Piscirickettsiosis (Mauel & Miller 2002) and salmon anaemia (Totland *et al.* 1996). Several bacteria in the class Flexibacteriae often cause skin lesions and fin erosion in both freshwater or seawater reared fish (Bernardet 1998; Lorenzen 1999) and it has been shown that many fish pathogenic bacteria secrete proteolytic enzymes that cause massive tissue damage (Leung & Stevenson 1988; Ostland *et al.* 2000). It should also be mentioned that the skin provides a first line of defence against pathogens (Segner *et al.* 2012), where the skin mucus prevents aggregation of pathogens by being continuously replenished and by containing various immune factors (Shepard 1994). Epidermal damage such as wounds and non-intact mucus layers therefore represent invasion routes for virus and bacteria (Svendsen & Bøgwald 1997).

Similar to the fin condition WI damage to the skin may cause pain (−5) and represent invasion routes for pathogens leading to infection and illness (−3) and possibly reduced survival (−3) in salmon. Even smaller skin damages may lead to long term negative performance (−3) due to increased metabolic cost involved in wound repair and osmoregulatory perturbation. Both the size of the affected area and the depth (whether it is penetrating or superficial) of skin damage will probably contribute to the severity of the condition. Thus, the indicator is divided into five levels (Table 4) ranging from normal healthy skin (positive performance (1)) to penetrating and/or multiple wounds or ulcers that also may be infected, plus a knockout level for large open wounds. The WF calculated in SWIM 1.0 is 15 (Eqn 2, Table 4).

Final model

The final step of the semantic modelling procedure (Bracke *et al.* 2002b) is to assemble the WIs, the levels and their associated ranks into an OWA-model using the following three formulae for calculating the relative weighting factors (RWFs), indicator welfare scores (IWSs) and the overall welfare index (OWI):

$$\mathrm{RWF}_i = \mathrm{WF}_i \cdot \left(\sum_{j=1}^{m} \mathrm{WF}_j \right)^{-1} \quad (3)$$

$$\mathrm{IWS}_i = \mathrm{IS}_i \cdot \mathrm{RWF}_i \quad (4)$$

$$\mathrm{OWI} = \sum_{j=1}^{m} \mathrm{IWS}_j \quad (5)$$

where m is the total number of indicators in the model, WF_i and WF_j (see Eqn 2) are the weighting factors of the respective indicator i and j, and IS_i (see Eqn 1) is the indicator score given by the assessor (the fish farmer) for indicator i. In the case of one or more knockout levels the OWI is defined as 0. Knockout levels are not included when calculating RWFs and IWSs.

Although, we originally intended that the WIs should be at the sea cage level, the literature reviews made clear that the research on many of the WIs predominantly or exclusively were based on analysis of their effects on individual fish. For example, not the prevalence of sea lice infested fish in a sea cage and the effect on the overall fish welfare in the cage, but the effects on the welfare of individual fish from different sea lice infestation ratios. We therefore divided the indicators into sea cage specific WIs: temperature, salinity, oxygen saturation, water current, stocking density, lighting, disturbances, daily mortality ratio and appetite and individual fish specific WIs: sea lice infestation ratio, body condition, emaciation state, vertebral deformation, maturation stage, smoltification state, fin condition and skin condition (Table 4). Table 5 shows the RWFs for the sea cage and individual fish specific WIs. These RWFs together with their levels and their ISs in Table 4 give a model (or schema) for calculating an OWA score for a sea cage and for individual fish. The first gives an overall score for the welfare conditions in the sea cage, while the second give scores for the respective fishes. We call the model Salmon Welfare Index Model 1.0, abbreviated SWIM 1.0. 1 states that it is the farmer's version and .0 states that this is the pilot version which may be revised and upgraded later.

Example scenario

This scenario is based on a real world example from a sea farm in Western Norway, autumn 2011. The sea cage was 157 m in circumference, fitted with a 35 m deep cone-shaped net containing 140 000 fish with an average weight of 2.3 kg and average length of 55 cm. The water temperature was 14°C, 33 ppt salinity from top to bottom, oxygen saturation was 50% in large parts of the water column, the water current varied between 3 and 12 cm s^{-1} (i.e. between 0.05 and 0.22 BL s^{-1}), stocking density at about 14 kg m^{-3}, no artificial lighting, only light disturbances, mortality at 0.11% and the farmer reported poorer appetite than expected. Using the sea cage WIs from Table 4 this gives an OWI for the sea cage of 0.37 (Eqn 5, Table 6), on a scale from 0 to 1, where 0 is worst and 1 is best welfare. The low OWI indicates low fish welfare. This was affirmed 2 days later when the farmer collected more than 3300 dead fish, i.e. 2.36% of the fish in the cage. This is a knockout value and if the assessment had been performed on the sea cage that day, the OWI would have been set to 0.

For the individual fish specific indicators, an OWA will be based on a representative sample of fish from the cage, but as an example we only look at one imagined representative fish in the current scenario. Figure 1 shows a salmon with no lice, a K of 1.21 (1.6 kg and 51 cm), not emaciated, no external signs of deformity, moderate splitting of the fins and a normal healthy skin. This specific fish gets an OWI of 0.90 (Eqn 5, Table 7) on a scale from 0 worst to 1 best possible welfare score.

Table 5 Relative weighting factors for the sea cage specific WIs and for the individual fish specific WIs in SWIM 1.0

Sea cage WIs	WF	RWF	Individual fish WIs	WF	RWF
Temperature (°C)	16	0.17	Sea lice	11	0.12
Salinity	3	0.03	Condition factor	6	0.07
Oxygen (%)	17	0.18	Emaciation state	16	0.18
Water current (BL s^{-1})	3	0.03	Vertebral deformation	10	0.11
Stocking density (kg m^{-3})	8	0.09	Sexual maturity stage	9	0.10
Lighting	4	0.04	Smoltification state	9	0.10
Disturbances	11	0.12	Fin condition	13	0.15
Mortality (% day^{-1})	21	0.22	Skin condition	15	0.17
Appetite	11	0.12			
SUM	94	1.00		89	1.00

Table 6 SWIM 1.0 applied on the sea cage in the example scenario. The OWI is the sum of the IWS (Eqn 5)

Sea cage WIs	RWF	#	Level	IS	IWS
Temperature (°C)	0.17	1	10–15	1.00	0.17
Salinity	0.03	2	No access to brackish water	0.00	0.00
Oxygen (%)	0.18	3	40–60% (≈12°C)	0.00	0.00
Water current (BL s^{-1})	0.03	1	<0.9	1.00	0.03
Stocking density (kg m^{-3})	0.09	1	<22	1.00	0.09
Lighting	0.04	2	Suboptimal	0.00	0.00
Disturbances	0.12	2	Light	0.67	0.08
Mortality (% day^{-1})	0.22	5	At or above the 90 percentile curve	0.00	0.00
Appetite	0.12	3	Poor appetite	0.00	0.00
OWI					0.37

Figure 1 Image of the fish used in the example scenario. This fish had an OWI of 0.90 on a scale from 0 worst to 1 best possible welfare score (Table 7).

Table 7 SWIM 1.0 applied on the fish from the example scenario. The OWI is the sum of the IWS (Eqn 5)

Individual fish WIs	RWF	#	Level	IS	IWS
Sea lice	0.12	1	No lice	1.00	0.12
Condition factor	0.07	1	1.0–1.5	1.00	0.07
Emaciation state	0.18	1	Not emaciated	1.00	0.18
Vertebral deformation	0.11	1	No external signs of v. deformities	1.00	0.11
Sexual maturity stage	0.10	1	Not mature	1.00	0.10
Smoltification state	0.10	1	Fully smoltified	1.00	0.10
Fin condition	0.15	3	Moderate splitting	0.33	0.05
Skin condition	0.17	1	Normal healthy skin	0.00	0.17
OWI					0.90

Table 8 Results from the first SWIM 1.0 sampling of a commercial salmon sea cage. The OWI is the sum of the IWS (Eqn 5)

Sea cage WIs	RWF	#	Level	IS	IWS
Temperature (°C)	0.17	2	7–10	0.75	0.13
Salinity	0.03	2	Adult fish with no access to brackish water	0.50	0.02
Oxygen (%)	0.18	3	>80%, all temperatures	1.00	0.18
Water current (BL s^{-1})	0.03	1	<0.9	1.00	0.03
Stocking density (kg m^{-3})	0.09	1	<22	1.00	0.09
Lighting	0.04	1	Optimal	1.00	0.04
Disturbances	0.12	2	Severe	0.00	0.00
Mortality (% day^{-1})	0.22	3	At the benchmark curve	0.50	0.11
Appetite	0.12	3	Poor appetite	0.00	0.00
OWI					0.59

Combining the score of the sea cage and the score of the individual 'representative fish' results in an OWI (Eqn 5) given as OWI = (0.37*94 + 0.90*89)/(94 + 89) = 0.62. The conclusion is that the fish welfare at the time of sampling was mediocre. The example representative fish was still fit, but the conditions in the sea cage were very poor.

First sampling using SWIM 1.0

This is the first actual sampling using the SWIM 1.0 model. The sampling was done at a sea farm in Western Norway, winter 2012. The sea cage was 157 m in circumference, fitted with a 45 m deep cone-shaped net containing 100 000 fish with an average weight of 5.8 kg and average length of 79 cm. The water temperature was 7°C, 33 ppt salinity and 100% oxygen saturation from top to bottom of the cage, the water current at the surface varied between 6 and 36 cm s^{-1} (i.e. between 0.07 and 0.38 BL s^{-1}), the stocking density was at about 20 kg m^{-3}, artificial lighting positioned at 10 m depth, recent severe disturbances occurred when 30 000 fish were harvested from the cage, the mortality was at about 0.01% and the farmer reported poorer appetite than expected. Using the sea cage WIs from Table 4 this gives an OWI for the sea cage of 0.59 (Eqn 5, Table 8), on a scale from 0 to 1.

Ten fish were sampled for the individual fish specific indicators. Details for each of the sampled fish (weight, length, condition factor and number of pre- and adult lice) are given in Table 9, together with the assigned WI levels and calculated OWIs. The OWIs varied from a minimum of 0.00 (emaciated fish, Fig. 2) to a maximum of 0.88

Table 9 SWIM 1.0 applied on 10 fish from the first SWIM 1.0 sampling The OWI for each fish is the sum of the IWS for the respective WI levels (Eqn 5)

	Details for fish 1–10									
Details	1	2	3	4	5	6	7	8	9	10
Weight (kg)	6.20	5.85	9.00	2.90	8.25	8.55	5.90	7.16	8.50	1.05
Length (cm)	79	77	82	70	85	87	83	84	85	54
Condition factor	1.26	1.28	1.63	0.85	1.34	1.30	1.03	1.21	1.38	0.67
Number of lice (#)	4	0	4	4	5	11	7	7	7	45
	WI levels for fish 1–10									
Individual fish WIs	1	2	3	4	5	6	7	8	9	10
Sea lice	2	1	2	2	2	2	2	2	2	3
Condition factor	1	1	1	3	1	1	1	1	1	3
Emaciation state	1	1	1	2	1	1	1	1	1	3
Vertebral deformation	1	1	1	1	1	1	1	1	1	1
Sexual maturity stage	1	1	1	3	1	3	1	1	1	1
Smoltification state	1	1	1	1	1	1	1	1	1	1
Fin condition	3	4	2	2	3	2	3	3	2	2
Skin condition	3	5	3	1	3	1	3	5	2	4
OWI	0.79	0.72	0.84	0.59	0.84	0.84	0.79	0.73	0.88	0.00

Figure 2 Image of fish number 10 from the first sampling. This fish had an OWI of 0.00 on a scale from 0 worst to 1 best possible welfare score (Table 9).

Figure 3 Image of fish number 9 from the first sampling. This fish had an OWI of 0.88 on a scale from 0 worst to 1 best possible welfare score (Table 9).

Figure 4 Image of fish number 2 from the first sampling. This fish had clearly been injured during the recent harvesting of fish from the cage and had an OWI of 0.72 due to the low skin and fin indexes (Table 9).

(Fig. 3); median OWI for the ten fish was 0.79. As a further example, fish number 2 is shown in Figure 4. This fish was clearly damaged during the recent harvesting of fish from the sea cage and got an OWI of only 0.72 due to the low skin and fin indexes (Table 9). Combining the score of the sea cage and the median score of the individual fish gives a total OWI = (0.59*94 + 0.79*89)/(94 + 89) = 0.69 (Eqn 5).

Discussion

Methodology

The objectives of this paper were to review basic welfare indicators of sea-cage farmed Atlantic salmon and to generate a semantic model (SWIM 1.0) to enable farmers to assess overall welfare. Although there are many papers published on semantic modelling and on welfare assessment in various species of farm animals, this is the first time a systematic review of scientific statements has been performed and presented on farmed fish. A main advantage of reviewing welfare indicators according to the principles of semantic modelling is that it gave focus to the review, as it was necessary to assess each indicator in terms of what the indicator itself tells about salmon welfare. This prevented long and overlapping essays about each indicator; special cases, and interactions that are an inherent part of a complex problem area such as fish welfare in sea cages.

In order to create an overall model it is necessary to reduce complexity. The advantage of the transparency in semantic modelling is that it shows where these reductions are made and where there is scope for further upgrading with new scientific knowledge. Semantic modelling also supports transparency of the model itself, allowing criticism of underlying principles and specific choices made.

The semantic-modelling procedure used in SWIM 1.0 was derived from Bracke *et al.* (2002b) and De Mol *et al.* (2006). It started with an extensive literature review for statements that are somehow relevant for the welfare of Atlantic salmon farmed in sea cages. This ensures that the formulation of WI-levels and the calculation of WFs are done in relation to unbiased scientific statements, i.e. statements that have not been produced in order to confirm preconceived notions of the importance of different WIs and how welfare should be assessed.

A major criticism of semantic modelling is that it is subjective; i.e. one has to decide on how to divide the indicators into levels, which weighting categories are appropriate for each indicator and one must assign indicator and weighting scores. These decisions are indeed based on a partly subjective interpretation of the meaning of the collected scientific information. This subjectivity is, however, decreasing with increasing quality and the amount of available scientific information; more solid data reduces the freedom of the interpretation of the data. The model and the semantic-modelling procedure itself are objective, i.e. the information is scientifically valid and the semantic-modelling procedure is formalized and has been described and validated in detail elsewhere (Bracke *et al.* 2002b, 2008; Bracke 2008, 2011). It is designed to take the modeller's point of view, as much as possible, out of the equation (Bracke *et al.* 2002b; Bracke 2008; Bracke *et al.* 2008).

The model

This is the first time semantic modelling has been used to create OWA for fish and, although there are several risk assessment schemas for fish farming, there are to our knowledge no schemas for assessing fish welfare. As the SWIM 1.0 model is based on an extensive review of the literature, including the mentioned risk assessment schemas, it would be a circular argument to compare the model with the literature and risk assessment schemas. Based on our expertise, however, we believe that the scoring in SWIM 1.0 has sufficient validity for fish farmers to start using the model. It is, for example, generally agreed that daily mortality is probably one of most important WIs for fish in sea cages and that salinity probably is one of the least important. That said, however, it is anticipated that the model will need further maturation and upgrading. It is also important to note that although the SWIM 1.0 model gives OWIs as output, its main purpose is its use as a diagnostic tool to identify indicators of reduced welfare and which the fish farmer should address in order to improve fish welfare. The next step is to visit several farms and at different times of the production in order to test and calibrate the model, and to gain an overview of how fish welfare varies in commercial sea cages. These will be very extensive studies that warrant their own publication.

We must again emphasize that this is the first version of the model and by its inherent transparency it is open for further upgrading. We hope that readers will have many suggestions for how the model can be improved, for example new WIs, WIs that can be removed, more precise WI-levels, criticism on specific weightings and choices made, studies that should be included as part of the background knowledge database etc. Finally, we plan to make additional SWIM models adapted for use by farm veterinarians (SWIM 2) and fish welfare experts (SWIM 3), where we can use more advanced WIs that require specific expertise or equipment. The goal is that the fish welfare community can build on the SWIMs and in time reach a consensus on how to best assess overall fish welfare in sea cages.

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