Aquaculture 296 (2009) 373–381

Contents lists available at ScienceDirect

Aquaculture

journal homepage: www.elsevier.com/locate/aqua-online

Long-term culture of Atlantic salmon (*Salmo salar* L.) in submerged cages during winter affects behaviour, growth and condition

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ARTICLE INFO

Article history:
Received 27 January 2009
Received in revised form 24 August 2009
Accepted 30 August 2009

Keywords:
Aquaculture
Submergence
Sea-cage
Buoyancy
Fish welfare
Swimming behaviour
Vertical distribution
Vertebral deformities
Fin erosion

ABSTRACT

In the search for alternative farming methods, we investigated whether large salmon submerged below 10 m in winter conditions behaved normally and performed as well as control fish held in standard surface cages. On average, 2345 salmon of ~3.5 kg were kept in each of six 2000 m^3 sea-cages for 6 weeks; three of which were submerged to 10–24 m depth and three acted as surface controls (0–14 m). Behaviour during both day and night was studied with echo-sounders, and underwater video cameras fitted with infra-red lamps. A sub-sample of fish from each cage was weighed, measured and assessed for fin and snout condition prior to and after the experimental period. In addition, the vertebral column of 50 fish from the control and submerged treatments were dissected and X-rayed to assess vertebral deformities. The submerged salmon seemed unable to re-fill any gas into the swim bladder, as a linear decrease in echo reflection to <5% of pre-submergence levels after 22 days of submergence indicated loss of almost all gas from the physostomous swim bladders and negatively buoyant fish. Around day 22, submerged salmon swam at night time with a distinct 'tail-down, head-up' tilt (26°) compared to the horizontal swimming position of control fish (−3°). Average swimming speed (body length per second) of submerged salmon were 1.3–1.4 times faster (day: 0.77 ± 0.02; night: 0.46 ± 0.02, (mean ± SE)) than control fish (day: 0.54 ± 0.01; night: 0.37 ± 0.02) both during day and night. Almost no mortality was seen, and the submerged salmon maintained similar diurnal vertical migrations as the surface fish, indicating that deep submergence did not exhaust the fish. However, submerged fish fed less efficiently, resulting in lower growth and reduced feed utilization. Fins and snouts of the submerged fish had small, but significantly more erosion than the control fish. Vertebrae in the tail region were significantly compressed in the submerged fish compared to control fish. This could be an early symptom of development of vertebral deformities. The results suggest that continuous submergence below 10 m for longer than 2 weeks reduces the welfare and performance of Atlantic salmon.

1. Introduction

Submergence may solve several of the substantial operational challenges that exist in surface-based fish farming, including those related to heavy storms, ice, algal and jellyfish blooms, salmon lice infestations, hypoxia, unsuitable temperatures, high aluminium levels and biofouling of net cages (Fioravanati et al., 2004, Dempster et al., 2009). Against the backdrop of a projected increase in aquaculture production from 48 million tons in 2005 (FAO, 2006) to approximately 80 million tons in 2050 (FAO, 2008), offshore submersible fish farms may play an important part in the expanding fish farming industry as inshore sites reach full capacity and offshore farming will open an unknown potential for aquaculture (Ryan, 2004). Subsurface technologies have been tested in several production experiments; e.g. in farming of yellowtail (*Seriola* spp.) in Japan, where cages were lowered below 5 m depth to avoid storm damage (Brown, 1983), Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) in the U.S.A (Chambers and Howell, 2006), and cobia (*Rachycentron canadum*) in the Caribbean (Benetti et al., 2008).

The growth and behaviour of fish in submerged cages relative to standard surface systems is however largely unknown; objective comparisons of the performance of fish in commercial-scale submerged cages vs. surface cages have only been undertaken for short-term, shallow submergences (Dempster et al., 2008, 2009). Salmonids, in particular, face challenges during submergence as they have a physostomous swim bladder which must be filled by gulping at the surface to maintain buoyancy (Smith, 1982). Forced submergence in cages denies salmon surface access and may result in negative buoyancy (Dempster et al., 2008, 2009). However, juvenile salmonids (*Oncor- and Salvinus alpinus)* survive in locations with thick surface ice for up to three months in winter (Sutterlin and Stevens, 1992). Therefore, some tolerance for submergence must exist, and may depend upon depth and

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doi:10.1016/j.aquaculture.2009.08.036

pressure, duration and possibly light levels. While the effects of submergence are unlikely to increase linearly with submergence depth, the deeper salmon are forced, the more compressed the swim bladder becomes and thus greater buoyancy challenges may arise.

Previous studies have shown poor welfare outcomes such as exhausted fish, snout injuries, tilted 'tail-down, head-up' swimming and increased mortality, when salmonids have been submerged in small (15–32 m^3) tanks or cages for long periods (20–86 d) and in deep water (4–30 m) (Fosseidengen et al., 1982, Ablett et al., 1989, Osland et al., 2001, Hevrøy et al., 2003). The 'tail-down head-up' swimming position may load the muscles in the tail region to such a degree that some vertebrae become compressed. Similar symptoms (Lordosis) occur in fish forced to swim in strong current (Divanach et al., 1997; Sfakianakis et al., 2006), but have not been investigated in previous submergence trials of salmonids. Understanding the effects of forced submergence of Atlantic salmon is therefore important to ensure the welfare of farmed fish under the range of environmental conditions that sea-cage farms experience. Submergence of cages deeper than 10 m will in most cases force the fish away from unsuitable surface conditions when they occur (Ryan, 2004), but at the same time challenge their buoyancy control.

In general, farmed salmon swim in circular schools at day, and also at night when given artificial lighting conditions (Fernö et al., 1995; Oppedal et al., 2001; Juell and Fosseidengen, 2004; Juell et al., 2003, Oppedal et al., 2007). Towards darkness, salmon normally ascend, become more neutrally buoyant and reduce their swimming activity (Fernö et al., 1995; Oppedal et al., 2001). Submergence will likely inhibit this behaviour; fish may compensate either through increased swimming to generate lift or through tilted swimming. Norwegian spring spawning herring over-wintering in deep water display both increased swimming speeds and tilted swimming to compensate for constant negative buoyancy (Huse and Ona, 1996). Prior to the present study, we measured increased swimming speeds of submerged salmon compared to fish with surface access, possibly to cope with the reduced buoyancy (Dempster et al., 2009). A commercial-scale sea-cage trial showed that salmon of 0.5 kg swam 1.6 times faster when submerged 22 days to 4 m with submerged continuous artificial light in spring, yet growth, feed conversion rate, mortality, body condition and fin conditions were similar to control fish (Dempster et al., 2009). This trial directly measured feed intake, in contrast to other submergence trials with salmon (Fosseidengen et al., 1982, Ablett et al., 1989, Osland et al., 2001, Hevrøy et al., 2003, Dempster et al., 2008). However, a near linear reduction of the swim bladder volume occurred in the submerged fish over the 22 days. Tighter schooling combined with increased swimming speeds was suggested as a behavioural adaption to the reduced buoyancy. So far, the effects of short-term shallow (4 m) submergence on smaller salmon (0.5–1.7 kg) have been documented (Dempster et al., 2008; 2009). However, the effects of submergence during the time of the year when production conditions are potentially most challenging to salmon require further investigation. Deeper submergence of larger fish in the cold and dark conditions present in winter may be expected to cause different responses in terms of growth and welfare.

The aim of this study was to compare Atlantic salmon submerged in sea-cages at 10–24 m to surface-based control cages held at 0–14 m under natural lighting conditions over 6 weeks during short days in mid-winter. The parameters investigated were (i) behavioural effects; (swimming speed and tilt angle during day and night, vertical distribution and buoyancy control), (ii) performance; (mortality, feed intake, growth and feed conversion rate) and (iii) body condition; (fin and snout condition and vertebral deformities).

2. Materials and methods

2.1. Location and experimental design

The experiment was conducted at the *Cage Environment Laboratory* at the Institute of Marine Research field station, at Solheim, in Masfjorden, western Norway (60°N) from 27/11/2007 to 12/1/2008. Six commercial-scale cages (approx. 2000 m^3) were used; 3 for the submerged and 3 for the control treatments. The three control cages were of a standard type used for commercial salmon production (12 m × 12 m × 14 m depth). The three submerged cages were 24 m deep, with a roof of black netting, which consisted of the same mesh as the cage, sewn into the net-cage at 10 m depth, giving them the same effective volume as the surface control cages. A system to remove dead fish (LiftUp AS, Eikelandsosen, Norway) was installed in the three submerged cages, and the control cages had small nets installed in the centre bottom of the net for the same purpose. Submerged and control cages were interspersed at the farm to ensure that fine-scale environmental differences did not contribute to treatment effects.

The experiment lasted for 46 days with one day before (experimental day 1), 42 days of submergence (days 2–43) and three days post-submergence (days 44–46) with all cages at the surface. Fish in the control cages had access to the surface throughout, while submergence began at 10:00 on 28/11/2007 and ended at 10:00 on 09/01/2008. Submergence of cages took approximately 20 min and re-surfacing approximately 60 min per net.

2.2. Environmental variables

At a reference point close to the cages, a vertically profiling CTD (SD204, SAIV AS, Bergen, Norway, www.saivas.no) connected to an automatic winch (HF5000, Belitronics, Lunde, Sweden) was used to determine salinity, temperature and oxygen levels from 0 to 25 m depth throughout the experimental period. One profile was taken every 30 min. The water transparency was measured daily with a Secchi disc. Day lengths were 6.5 h (08:10 to 14:43) the first experimental day, 5.8 h (08:44 to 14:29) at day 24, and 6.3 h by day 43. The computations of sunrise and sunset were made by the Online-Photoperiod Calculator V 1.94 L (http://www.sci.fi/~benefon/sol.html).

2.3. Experimental fish

14,300 Atlantic salmon (Aquagen strain) with a mean weight of 3.5 kg were randomly distributed to the six experimental cages using a well-boat on 20/11/2007, while halfway through pumping 628 fish were put into an extra cage. On 23–24/11/2007, these fish were netted, anaesthetized with MS 222 and measured for weight and fork length, assessed for sea lice (*Lepeophtheirus salmonis*) infestation, condition of all fins and PIT tagged (11 mm Trovan ID 101, BTS Scandinavia AB, Sweden) with the adipose fin being removed in the same operation. Subsequently, 100 of these fish were randomly distributed to each experimental cage. After distribution, cages contained between 2248 and 2481 fish (Table 1).

On days 49–52 (15–18/01/2008), 99–115 randomly chosen fish were netted from each cage after using a 5 × 5 × 5 m casting net pulled up from the bottom to crowd fish at the surface. Following anaesthetization, fish were measured for fork length, weight, sea lice infestation and the condition of all fins. The fin condition was an index from 1 (undamaged) to 5 (complete fin degradation) based on Hoyle et al. (2007). Snout condition was scored as 1 for any sign of skin wear or damage and 0 if no damage was evident. On day 54 (20/01/2008), the triplicate cages of each treatment were pooled into either of two separate tanks in a well-boat, transferred to a commercial processing plant and processed on days 57–58 (23–24/01/2008). The gutted weight of all fish was measured and the numbers of harvested fish within each treatment were 7301 and 6960 from the submerged and control groups, respectively (Table 1). From each replicate cage, 49–84 of the PIT tagged fish were collected and graded for fin condition. The vertebral columns from 50 and 48 randomly selected individuals from each treatment were dissected.