Growth potential of farmed cod

(Vaxtargeta eldisþorsks)

AVS-project R 10028-09.

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Summary.

A long term rearing experiment was launched in the spring of 2008 to compare different start-feeding protocols and study the link between early- and long term growth performance of farmed cod. Two ambitious aims were set for the project i.e. to reach a mean weight of 5 kg in 30 months from hatch in land-based rearing and 4 kg in 32 months from hatch in a sea-cage in the East-fjords. These predictions were based on the growth model for cod published by scientists at the MRI in Iceland in 2007.

Several different start-feeding protocols were applied and growth was measured at weekly intervals during the larval- and early-juvenile stages. During the juvenile stage several experimental groups were formed for long-term monitoring of growth performance. Two groups (A and B) were reared at optimal temperatures (8-14°C) while the third (C) was reared at low temperature (8°C). Groups A and C were start-fed with Artemia while group B was not. Group A was subsequently size-graded into two categories (A and A+). The AVS-project had a time-frame from June 2009 to December 2010 and two main tasks were defined, 1) Land-based rearing trial and 2) Sea-cage rearing trial.

In task 1 the long-term growth performance of four groups (A+, A, B and C) was monitored from hatch until 30 months post-hatch (mph). At 100 days post-hatch the mean weights of the groups were 9.1, 5.9, 1.7 and 1.5 g, respectively. The weight increase became absolutely linear from the second year onwards. At 30 mph groups A, A+, C and B measured 3.4, 3.1, 2.2 and 1.8 kg in mean weight and the absolute linear growth rates were 2.5, 2.2, 1.7 and 1.5 kg per year, respectively. The von Bertalanffy growth function provides a good fit to the growth performance and curiously predicts a much lower maximum size for farmed cod, compared to cod in the wild. The growth performance of group A (3.4 kg in 30 mph) is probably the best ever reported for a group of intensive cod but was still far below the original 5 kg target.

In task 2 some 934 large juveniles (470 g) were transported by boat to one of the East-fjords, Berufjörður, and released into a cage among one-year older fish. When the cage was harvested in December 2010 only 24% of the juveniles were recaptured and the mean weight was 2.2 kg. This may have been the best growth performance of hatchery-produced cod in Iceland to date but still far below the optimistic target of 4 kg.

Even though the growth performance in the study was lower than predicted it can be claimed that the main aim was successfully achieved. The results show how the early growth performance limits the long-term performance and effectively prove that the growth potential of farmed cod is in fact restricted by nutritional deficiencies during start-feeding. Cod farming based on growth-restricted juveniles will never be economically viable and the obvious conclusion is that a semi-intensive start-feeding strategy (including copepods in the diet) is required to produce cod juveniles with un-restricted growth potential.

Skýrsluágrip.

Í þessu verkefni hefur verið fylgst með vexti og afdrifum eldisþorsks sem var alinn frá klaki í Tilraunaeldisstöð Hafrannsóknastofnunarinnar vorið 2008. Höfuðmarkmið verkefnisins var að sýna fram á það hvernig vaxtargeta eldisþorsks ræðst þegar á fyrstu stigum eldisins. Stefnt var að því að leysa vaxtargetu eldisþorsksins úr læðingi og ná 5 kg meðalstærð í eldisstöðinni á aðeins 30 mánuðum frá klaki. Jafnframt var stefnt að því að ná 4 kg meðalstærð í sjókví á 32 mánuðum frá klaki. Þessar spár voru byggðar á vaxtarlíkani Hafrannsóknastofnunarinnar frá 2007.

Á lirfu- og ungseiðastiginu voru gerðar vikulegar stærðarmælingar og á seiðastiginu voru síðan myndaðir sérstakir tilraunahópar með mismunandi forsögu. Tveir hópar (A og B) voru aldir við kjörhitastig á fyrstu stigum (8-14°C) en sá þriðji (C) var alinn við lágt hitastig (8°C). Hópar A og C voru frumfóðraðir með Artemíu en hópur B fékk enga Artemíu. Hópur A var síðan flokkaður í tvo stærðarhópa (A og A+). AVS-verkefnið var myndað í kringum þessa seiðahópa og tímaramminn var frá júní 2009-desember 2010. Verkefnið skiptist í tvo verkþætti, 1) Landeldi í Grindavík og 2) Kvíaeldi á Berufirði.

Í verkþætti 1 var fylgst með vaxtarsögu fjögurra seiðahópa (A+, A, B og C) allt frá klaki til 30 mánaða aldurs frá klaki. Mikill munur var á vexti hópanna á fyrstu ævistigum og við 100 daga aldur var meðalþyngd hópanna 9.1, 5.9, 1.7 og 1.5 g. Með tímanum breyttist röð hópanna og þyngdarvöxtur varð nánast fullkomlega línulegur á öðru æviári. Við 30 mánaða aldur voru hópar A, A+, C og B orðnir 3.4, 3.1, 2.2 og 1.8 kg að meðaltali og hinn línulegi vöxtur hópanna nam 2.5, 2.2, 1.7 og 1.5 kg á ári. Von Bertalanffy vaxtarformúlan lýsir vextinum vel og samkvæmt henni er hámarksstærð eldisþorsks mun minni en hjá villtum þorski. Vöxturinn hjá hópi A (3.4 kg á 30 mánuðum) er að öllum líkindum sá besti sem mælst hefur hjá stríðeldisþorski en var engu að síður langt undir væntingum um 5 kg meðalþyngd.

Í verkþætti 2 voru 934 stórseiði (470 g) flutt með báti til Berufjarðar og sett í sjókví saman við ári eldri fisk. Þegar kvíin var tæmd í desember 2010 fundust aðeins 24% af seiðunum aftur og meðalþyngdin var orðin 2200 g. Þetta er raunar besti vöxtur eldisþorsks sem náðst hefur í kvíaeldi á Íslandi en engu að síður langt undir upphaflegum væntingum.

Þrátt fyrir að vöxtur eldisþorsksins hafi verið minni en vonast var til þá er óhætt að fullyrða að höfuðmarkmið verkefnisins hafi náðst. Niðurstöðurnar sýna vel hvernig vöxtur á lirfustigi takmarkar vaxtargetu hjá eldisþorski og færa sönnur á það að vaxtargeta eldisþorsks er almennt verulega skert vegna næringarskorts á lirfustigi. Augljóst er að þorskeldi sem byggist á vaxtarskertum seiðum getur aldrei orðið arðbært. Nauðsynlegt er að frumfóðra með næringarríkari fæðudýrum (krabbadýrum) til þess að hægt sé að leysa hina miklu vaxtargetu eldisþorsks úr læðingi.

1. Introduction.

Cod farming is a new and developing industry in Iceland. Farming of wild-captured cod has been practised for many years and about 1,000 tons of on-grown cod are being harvested each year. Cod juveniles were first stocked in sea-cages in 2002 and after the catching of wild juveniles was abandoned in 2009, all cod juveniles have been supplied by intensive hatcheries. Full-cycle cod farming in Iceland is now solely based upon hatchery juveniles from the Icelandic selective breeding program (Icecod ltd) which can supply juveniles 2-3 times per year. The Marine Research Institute (MRI), however, also supplies cod juveniles upon demand from its research hatchery in Grindavík. Full-cycle farming has, however, not properly taken off yet as only 300-400 tons are being harvested from cages per year (Gunnarsson 2011). The industry has struggled with problems such as high mortalities and poor growth rates. The growth performance of the hatchery juveniles appears to be limited and there is some concern that their disease resistance might be compromised as well. This project is designed to target these problems and concerns.

As this project covers all the stages of the life-cycle of cod it is useful to define terminology and succession of the life-stages according to Steinarsson (2004). In the production process the cod will move between four successive stages of development: egg, larva (4-12 mm), early juvenile (12-45 mm) and juvenile (>45 mm). At the MRI it typically requires 16 weeks from fertilization to vaccinated 5 g fry and the entire process can be divided into three parts: incubation (2 weeks), hatchery (8 weeks) and nursery (6 weeks).

There are currently three different strategies or methods available for the production of cod juveniles for aquaculture: A) Extensive production in lagoons, pens or ponds (wild zooplankton diet), B) Semi-intensive production in tanks, ponds or bags (rotifers, Artemia and zooplankton) and C) Intensive production in tanks in land-based hatcheries (rotifers and Artemia diet). Strategies A and B have been used on a relatively small scale in Norway for almost 30 years and also in the Faroes for several years (Svåsand et al. 2004, Kolbeinshavn 2008). In this report the juveniles will be defined as intensive, semi-intensive and extensive, depending on the production strategy. The term ”zoovenile” will be used for the semi-intensive and extensive juveniles start-fed with wild- or cultured zooplankton (copepods).

The intensive hatchery strategy was largely adopted from bass and bream hatcheries and has grown to dominate the market in recent years. This strategy has been considered the only realistic method to mass-produce juveniles for a large-scale farming industry. Cod larvae are stocked in tanks at high initial densities (50-150 larvae/litre) and fed enriched rotifers (*B. plicatilis*) and Artemia (*A. fransiscana*) before being weaned on a micro-particulate artificial feed (Steinarsson 2004). The traditional late-weaning protocol prescribes rotifers until 30-35 days-post-hatch (dph) and Artemia until fully weaned at 45-55 dph (Moretti et al. 1999).

Many Norwegian cod hatcheries have, however, excluded Artemia from the hatchery diet and rather wean the larvae directly from rotifers onto artificial feed as early as day 25-30 dph.

The early-weaning protocol has produced relatively high and stable production levels in Norway (King 2007, Rosenlund and Halldorsson 2007) but usually at the cost of reduced growth performance. Available information from the Norwegian hatcheries indicates a common 100 dph benchmark size of only 1-2 g for early weaned juveniles (King 2007, Øie 2009b). This compares poorly with benchmarks of 4-7 g for late-weaned juveniles at MRI-Iceland (Steinarsson 2004) or 10-12 g for zooveniles from Lofilab in Norway (Øie 2009b). Furthermore, the long-term growth performance of early weaned juveniles has been largely inferior to the performance of zooveniles in Norwegian sea cages (Björnsson et al. 2007). Data from Icelandic cod farms have shown a strong correlation between juvenile benchmark sizes and long-term growth performance in sea cages (Gunnarsson and Steinarsson 2007).

Laboratory studies have indeed confirmed the poor growth performance of the early-weaned juveniles (Fletcher et al. 2007). The larval stomach starts to develop at about 15 mm SL i.e. around 35 dph (Pedersen and Falk-Petersen 1992). Feeding with formulated diets before the stomach is developed usually results in reduced growth rates (Callan et al. 2003, MacQueen-Leifson 2003). A major obstacle is the rapid leakage of nutrients from formulated micro-particulate diets, especially water-soluble proteins needed by the larvae (Hamre 2006). A high deformity incidence has routinely been associated with intensive juveniles of various species, such as Atlantic cod (Hamre 2006, Imsland et al. 2006, Holmvaag-Hansen 2011), Atlantic halibut, turbot and Japanese flounder (Dedi et al. 1997, Hamre et al. 2002, Koven 2003, Haga et al. 2004).

The evidence presented above suggests that the suppressed growth performance may be caused by nutritional deficiencies in the start-feeding diet. It has been shown that cod juveniles (zooveniles) that prey upon copepods during the larval stage, either in tanks (Otterlei et al. 1999) or marine lagoons (van der Meeren et al. 1994, Finn et al. 2002, Svåsand et al. 2004), grow faster than the intensive hatchery juveniles (Folkvord 2005). Similar results have been found for other marine species, notably halibut (Næss et al. 1995; Hamre et al. 2002) and turbot (Iglesias et al. 1987). Imsland et al. (2006) found a significant difference in long-term growth rates of zooveniles and intensive cod juveniles and the zooveniles also had less deformities.

Zooveniles have also been shown to outclass intensive hatchery juveniles in survival and viability (Svåsand et al. 2004). Inadequate fatty acid composition of rotifers used during early first feeding is identified as one factor causing later reduced growth, survival and viability of cod juveniles. The fatty acid composition of rotifer phospholipids (PL) is not optimal for larval cod which cannot efficiently utilise DHA, an abundant PUFA in copepods, from tri-acylglycerides. Copepods have an ideal PL-composition and cod larvae should preferably be start-fed live feed with a copepod-like PL-fatty acid composition (Hamre 2006, Øie 2009, Larssen et al. 2009). Furthermore, the lipid- and protein levels may be too high and too low, respectively, in rotifers and especially Artemia, to sustain optimal growth rates of cod larvae (Hamre 2006).

Several studies have suggested that restricted muscle growth during the larval stage of marine fishes may permanently affect their long-term growth potential (Weatherley and Gill 1987, Weatherley 1990, Galloway et al. 1999, Johnston 2006). In Atlantic salmon *Salmo salar*, early thermal experience produced up to a 20% difference in the final fibre number (FFN) between temperature treatments in the adult fish (Johnston et al. 2003, MacQueen et al. 2008). In the study by Galloway et al. (1999) DHA-deficiencies in the larval diet were shown to have negative effects on the muscle growth of cod larvae, resulting in reduced larval condition and perhaps ultimately in reduced long-term growth potential. Larssen et al. (2009) concluded that DHA-deficiencies in the early larval stages may irreversibly affect growth potential, health and viability of older stages.

The ultimate maximum size of teleost fishes has been shown to be directly linked to the dynamics of muscle growth. The ultimate size of the fish appears to depend on the cessation of new muscle fibre recruitment in the fish which has been shown to occur at approximately 44% of ultimate maximum fork length over a range of species (Weatherley et al. 1988). This means that after this benchmark size is reached, growth no longer occurs through hyperplasia (new muscle-fibres) but only through hypertrophy (enlargement) of existing muscle-fibres (Martell and Kieffer 2007). The highest somatic growth rates during larval stages have been associated with an increased contribution of hyperplasia to axial white muscle growth (Galloway et al. 1999).

Based on the available information it may seem like the obvious choice to base cod farming on juveniles fed as larvae with copepods in lagoons, pens or hatcheries. These methods have been practised successfully in Norway and the Faroes for many years but have eventually been considered an unviable option to produce juveniles on a large scale. Wild zooplankton is only available seasonally and has proven difficult to grow and harvest commercially. Some copepod species are, however, being grown experimentally in Norway and Canada, and they might eventually become available as co-feed in cod hatcheries (Kjørsvik et al. 2004, Engell-Sørensen et al. 2006, Øie 2009, Holmvaag-Hansen 2011). It remains unclear, however, if and when the productivity of copepod cultivation will be brought up to the required commercial levels. Until then, the research effort should largely be focused on improving the nutritional properties of the intensive start-feeding diet and matching the properties of the wild zooplankton diet.

The long-term growth performance of intensive juveniles in Iceland, Norway, Scotland and Canada has invariably been less than predicted from the growth model of

Björnsson et al. (2007). In Iceland, intensive cod juveniles are reported to reach 1.5-2.0 kg in 30 months from hatch, while the model easily predicts 3.5 kg in mean weight (Kristjánsson et al. 2004). Very impressive growth rates have, however, been reported for zooveniles both in Norway (Solgaard 2005) and the Faroe islands (Kolbeinshavn et al. 2012), where the farmed cod reaches up to over 4 kg in mean weight after only 27 months from hatch. These growth rates conform well to the growth model, which comes as no surprise since it was partly based on growth trials with wild-captured larger cod and furthermore tuned to fit better with growth data for Norwegian zooveniles (Björnsson et al. 2007).

High losses of stocked juveniles are a major problem in Icelandic cod farming, with routine losses of 30-70% from stocking to harvest (Jónasson 2011). The majority of the losses appear to happen in the first few weeks or months after stocking and can be traced to various causes such as diseases, predation and low quality of the juveniles (Kristmundsson et al. 2011). The timing of stocking, with respect to sea temperature and daylength, may also be of importance and there have been some late summer stockings with only 20-30%% losses (Kristjánsson et al. 2004, Kristjánsson 2011). In comparison, Codfarmers AS in Norway routinely report total losses 30-40% from their large-scale stockings of intensive juveniles, more or less irrespective of season (Codfarmers AS 2011). A total stocking loss of less than 20% has been defined by many as an acceptable loss and a desirable target for cod farming.

The present study was designed to tackle some of the challenges discussed in the introduction. Two separate tasks were formulated:

- Task 1. *Growth potential and feeding efficiency in land-based farming.*

This task is aimed at testing the long term effects of various start-feeding protocols and studying the link between early- and long-term growth performance. The original ambitious target was to rear a group of farmed cod to 5 kg in 30 months post-hatch but reduced to 4 kg after the first year of the study.

- Task 2. *Sea cage trial in Berufjörður.*

The goal of this task is to test the stocking of large juveniles into sea-cages in one of the East-fjords of Iceland. The ambitious target was to grow the juveniles to 4 kg in 19 months from stocking.

The questions being raised are: Is the long-term growth potential of hatchery produced juveniles directly affected by their previous larval growth performance? Which start-feeding protocol is optimal in terms of survival, morphology and long-term growth potential? Can the elusive 3 kg harvest size be reached after two summers in Icelandic sea-cages by stocking larger juveniles?

2. Material and methods.

2.1. Hatchery production protocols.

The cod juveniles used in this study were produced at the MRI-hatchery in Grindavík in February (group D), April (group A) and May (groups B and C) 2008. Groups A, B, C and D were hatched from the egg on 22 April, 16 May, 7 May and 15 January, respectively. The hatching date was defined as day 0 (or 0 days from hatch). Group A, B and D eggs (mean egg diameter 1.45, 1.33 and 1.42 mm, respectively) were obtained from the Icecod hatchery in Hafnir and incubated at 7°C in black 25-L silos. The group C eggs (mean egg diameter 1.45 mm) were stripped and fertilized from wild catch and incubated at the MRI-hatchery. The mean standard length (SL ± SD) of larvae at hatch was 5.0, 4.5, 5.0 and 4.8 ± 0.1 mm in groups A-D, respectively.

Figure 1. The Aquaculture Research Station of the MRI in Grindavík.

The larval rearing of groups A, B and D was conducted in black-coloured fibreglass tanks (3,200 L) stocked with 150-250,000 larvae per tank (initial stocking density 47-69 larvae per L). The culture water had a stable salinity of 32-33‰ and the rearing temperature was gradually raised from an initial 8°C up to 14°C by the end of the early juvenile stage. Group C larvae were stocked into four 150-L larval silos (7,500 per silo) for 35 days post-hatch and then moved to larval tanks. The rearing temperature of group C was held at 8°C from hatch until 120 dph when the temperatures were matched to those of the other groups. The tank culture water was shaded with *Nannochloropsis* algae paste from Reed Mariculture (2 x 30-40 ml per day). The photoperiod was fixed at 24:0 (L:D) through the entire hatchery stage. The photo-irradiance (converted from maximum illuminance on surface) was increased gradually from an initial 1.6 to a maximum of 8.0 µE m^{-2} s^{-1} in two weeks from hatch. The hatchery tanks are equipped with an automatic cleaner-arm and the debris was siphoned twice a day. Surface skimmers were cleaned twice a day.

The larvae were fed live enriched rotifers (*Brachionus plicatilis*) from 2-35 dph in three daily rations (9:00, 15:00 and 20:00). The rotifers were enriched with a 50:50 mixture of Algamac 3050 and Algamac Enhance (Aquafauna Biomarine) for a period of 6 or 16 hours, depending on ration. The rotifers were then carefully washed on a sieve before being offered to the larvae. In cases where Artemia (*Artemia fransiscana*) was offered to the larvae, feeding with live Artemia nauplii started on 15 dph and feeding with enriched meta-nauplii started on 22 dph. The Artemia were enriched with the Algamac blend from 22-27 dph. After 27 dph the Artemia was enriched alternately with ORI-Gold and ORI-Pro (Skretting Norway) for 20 or 26 hours, depending on ration. After 35 dph the larvae in group A were partly fed on-grown Artemia, enriched with ORI-Pro for a further 24 hours.

All groups were fed rotifers and the micro-particulate starter feed *Gemma Micro Diamond* from Skretting Norway (55% protein, 15% lipid). Groups A, C and D also received Artemia but the early weaning group (group B) was not fed any Artemia. Groups A, B, C and D were fully weaned onto dry-feed by 48, 35, 51 and 50 dph. The starter feed was introduced two weeks in advance of weaning, gradually replacing the live feed. The starter feed was later replaced by Wean-Ex nursery feed from Biomar Denmark (63% protein, 14% lipid). Dry feed was fed with automatic suspension feeders and offered continuously outside regular working hours (8-16:00).

Larval samples for standard length, dry weight and anatomy were collected weekly and survival calculated at transfer to nursery tanks (49-55 dph). For measurement of dry weight, 10 larvae were pooled and dried for 48 hrs at 70°C on a pre-weighed net-piece before being weighed to the nearest µg on a Sartorius micro-balance. All groups were size-graded at the end of the hatchery stage to prevent cannibalism but the grades were normally re-united before the long-term trials started. Five separate experimental groups were finally formed from these four start-feeding groups (Table 1).

Table 1. Overview of the experimental groups used in the study. 'Rot' stands for rotifers, 'Med'. stands for medium size grade. Group E belongs to the previous year-class (2007).

Group	Origin	Hatching date	Mean hatch length (mm)	Live start-feed	Weaning age (dph)	Size grade	Initial number	Rearing units
A+	Icecod	22.04.08	5.0	Rot/Artemia	48	Top	178	Tanks/cage
A	Icecod	22.04.08	5.0	Rot/Artemia	48	Med.	277	Tanks
B	Icecod	15.05.08	4.5	Rotifers	35	Med.	120	Tanks
C	Wild	15.05.08	5.0	Rot/Artemia	51	Med.	87	Tanks
D	Icecod	05.02.08	5.0	Rot/Artemia	50	Med.	549	Sea cage
E	MRI	22.04.07	4.8	Rot/Artemia	26-30	Med.	28,000	Sea cage

2.2. Land-based farming trial in Grindavík.

In order to investigate the long-term effects of the different start-feeding protocols (see section 2.1), sub-populations from groups A, A+, B and C (see Table 1) were reared and monitored at the MRI until the age of 30 months post-hatch. The sub-groups were *Vibrio*-vaccinated (dip) at 3-5 g mean weight and then reared separately in 300-L tanks until transfer to three 5 m^3 tanks at 30-40 g mean weight. Group A was used in a salinity trial from 14 August – 16 September 2008 where four sub-groups were reared at 5, 10, 20 and 30‰ salinity. After the trial, the juveniles were returned to full salinity without any prior acclimation. All fish were inter-peritoneally tagged with Trovan passive transponder tags (Trovan Ltd.) at 10-30 g mean weight. At 203 dph (350-500 g mean weight) the groups were mixed at random and reared in two separate 5 m^3 tanks until 13 months of age, when they were moved to a 30 m^3 tank for rearing until the end of the experiment.

Rearing temperatures were kept close to optimal at 9-12°C during the first year but lowered and maintained at 8°C after transfer to the 30 m^3 tank. Lights were provided 24 hours a day and oxygen saturation maintained at 100-120% at all times. The fish were fed to satiation with Wean-Ex nursery feed (Biomar Denmark) and later with commercially available dry feed (Laxá Ltd.) with automatic feeders and supplemented with hand-feeding each morning. The composition of the feed varied for different pellet sizes, with f.ex. 45 and 48% protein and 23 and 20% lipids in 4 and 12 mm pellets, respectively. Sensors were used to measure temperature and oxygen (Oxyguard® Handy Polaris), pH (Oxyguard® pH) and light intensity (Testboy® TV332).

The progression in live weight and total length was monitored with regular measurements of all individual fish. The fish were anaesthetized with MS-222 and identified with a pit-tag reader (AEG ARE H5) before being weighed and measured. At the approximate ages of 12, 15, 19, 26 and 30 months from hatch, a small sub-sample of fishes was killed to measure the sexual maturation and the liver index of the groups.

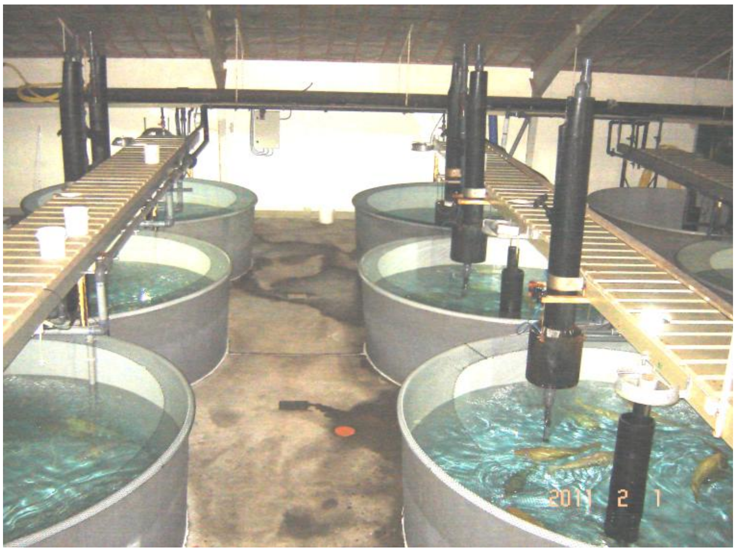

Figure 2. The rearing tanks used in the land-based trial from approximately 7-13 months post-hatch.

2.3. Sea cage farming trial in Berufjörður.

On 7 June 2009 some 934 juveniles (group D) were transported by boat (Papey, HB-Grandi) from Grindavík to Berufjörður on the east coast of Iceland (Fig. 3).

Figure 3. The transfer of the juveniles from Grindavík to Berufjörður. A) Loading of the "Papey" on 7 June 2009. The juveniles were stocked into six 600-L fish tubs. B) Arrival and release of of the juveniles into the sea cage in Berufjörður on 8 June 2009. Feeding boat in the background.

The mean weight at the time of shipping was 470 g and all the juveniles were fin-clipped for identification (third dorsal fin removed). No mortalities occurred during transport and the juveniles were stocked into a cage holding 9,500 farmed cod (group E) from the previous (2007) year-class. The mean weight of group E was approximately 350 g at this time. The cages were serviced by boat on a daily basis and divers monitored the integrity of the cage on a regular basis. The fish were fed commercially available dry feed (Laxá Ltd.) through pipes connected to an anchored feeding boat and supplemented with hand-feeding. The composition of the feed varied for different pellet sizes, with for example 45 and 48% protein and 23 and 20% lipids in 4 and 12 mm pellets, respectively. Dead fish were regularly removed from the cage. The sea temperature in the cage varied seasonally from a low of 2-3°C in January-April to a high of 7-8°C in August-September. The yearly mean temperatures in 2009 and 2010 were 4.67°C and 4.39°C, respectively. No external lighting was provided.

Growth rates and other vital statistics were monitored with regular measurements in June and December each year. A supposedly random sub-sample of fish from both groups was collected from the cage and brought on board the boat for identification and separation into two fish tubs. All the sampled fish were killed and subsequently brought to land for a detailed analysis in a local processing factory in Djúpavogur. The parameters measured included wet weight, gutted weight, total length, liver weight, gonad weight and deformities. Figure 4 shows photos from one of the samplings as well as the beautiful sunset in Berufjörður in December 2009.

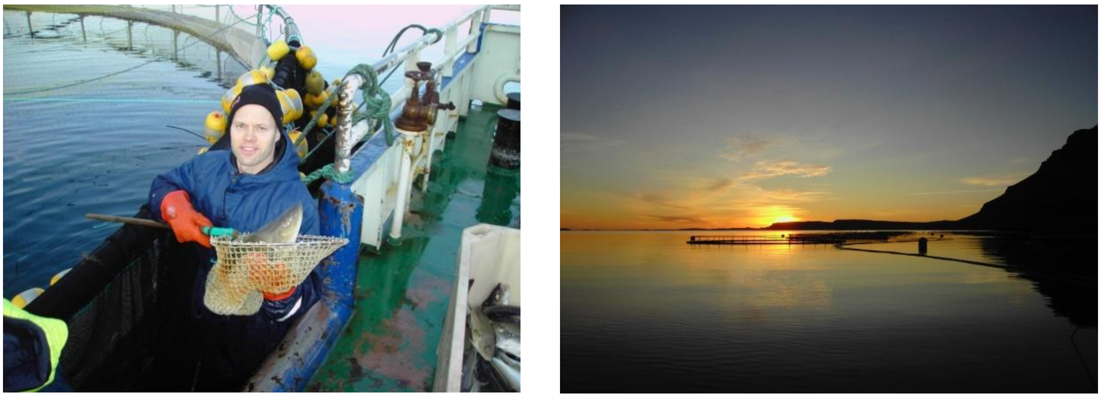

Figure 4. Sampling from the sea cage in Berufjörður in December 2009. A) Agnar holding a sampled cod from the cage. B) Sunset in Berufjörður in December 2009. Mount Búlandstindur on the right.

2.4. Data analysis and statistics.

The instantaneous growth coefficient (g) was calculated according to the following formula: $g = 100(\ln W_2 - \ln W_1)/(t_2 - t_1)$, where W_1 and W_2 are the weights of the fish at times t_1 and t_2. Daily weight specific growth rate (G) was calculated as percent per day according to the formula: $G = 100(e^g - 1)$ (Houde and Schekter 1981). The calculations were based on dry weights for larvae and wet weight for juveniles and larger fish. Standard length (SL) was used for larvae and total length (L) for juveniles and larger fish. The Length increment (L_I) was calculated as mm per day according to the formula: $L_I = (L_2 - L_1)/(t_2 - t_1)$, where L_1 and L_2 are the lengths of the fish at times t_1 and t_2. The Absolute growth rate (ABS) was calculated as kg per year according to: $ABS = 365((W_2 - W_1)/(t_2 - t_1))$, where W_1 and W_2 are the weights (kg) of the fish at times t_1 and t_2 (in days). Fulton's condition factor (K) was calculated according to: $K = 100(W/(L^3))$, where W is the wet weight (g) and L is the length (cm). The gonadosomatic index (GSI) was calculated according to the formula: GSI = 100 × [(gonad weight, g)/(gutted body weight, g)]. The hepatosomatic index (HSI) was calculated according to the equation, $HSI = 100 \times (LW \times W^{-1})$, where LW is the weight of the liver.

The von Bertalanffy growth function (VBGF) describes change in length (L) as: $L(t) = L_\infty(1 - e^{-K(t-t0)})$, where t is time, L is length, K is the growth rate and L_∞ ('L infinity'), is the asymptotic length at which growth is zero. The parameter t_0 is included to adjust the equation for the initial size of the organism. The VBGF can also be used to describe fish weight (W) as a function of age, after transforming the equation with the length/weight relationship: $W(t) = a*L^b(t)$, where a is the condition factor and b is the power quotient. Thus, "the weight-based VBGF" can be written: $W(t) = W_\infty(1-e^{-K(t-t0)})^b$, where the "asymptotic weight" (W_∞), corresponds to the asymptotic length (L_∞) (Sparre and Venema 1998).

Due to time constraints and the large volume of data, all the results presented in this report have not been fully statistically analysed yet. Full statistical analysis will be performed later, in the process of publishing the results in scientific papers.

3. Results.

3.1. Larval- and early juvenile stages.

3.1.1. Survival.

There was a consistent problem with poor egg quality from Icecod in the 2008 spring season and the survival rates in the larval tanks were extremely low. In the late weaning tanks the average survival to viable juvenile was 4% (group A) but only 2% in the early weaning tanks (group B). The survival from wild eggs was higher i.e. 6% from silos (group C) and 10% from tanks. A total number of 95,000 vaccinated juveniles were produced from eleven hatchery tanks.

3.1.2. Length growth performance.

Measurements of standard length (SL) during the larval- and early-juvenile stages were transformed to total length to allow for direct comparison into the juvenile stage (<45 mm). Figure 5 shows the development in total length over the first 70 days post-hatch (dph) for groups A and B. Group A was late-weaned (fed rotifers and Artemia) but group B was early-weaned (fed rotifers only).

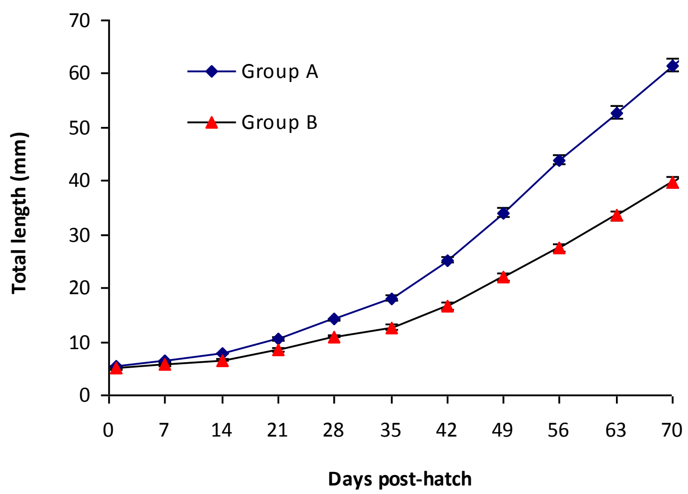

Figure 5. Mean total length (L) of groups A and B during the first 10 weeks post-hatch. Vertical whiskers show the standard error around the mean.

Groups A and B are not directly comparable due to differences in mean standard length at hatch (5.0 and 4.5 mm, respectively). The relative difference was maintained initially but group A began to pull further away after Artemia was offered from day 15 onwards. During 35-70 dph the relative length ratio between groups A and B was approximately 1.5 to 1. As the larval stage is defined to end at 12 mm SL, the duration of the larval stage (D) was about 27 days for group A and 36 days for group B. After the completed larval stage there was a clear ontogenetic shift in the growth of both groups and the daily length increment (L_I) increased dramatically (Fig. 6).

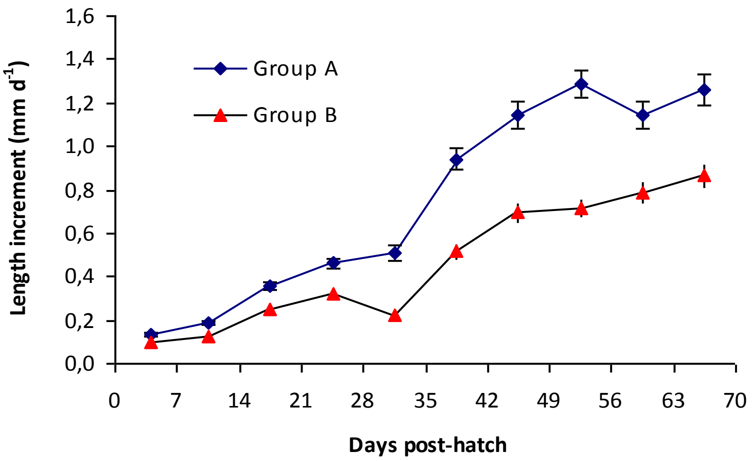

Figure 6. Mean daily length increment (L_I) of groups A and B during the first 10 weeks post-hatch. Vertical whiskers show the standard error around the mean.

The daily length increment (based on standard length) of group A reached a maximum of 1.3 mm per day at 7-8 weeks post-hatch, which corresponds to the end of the early-juvenile phase (45 mm SL). Group B was still rising at the end of 10 weeks post-hatch as it still had about a week left of the early juvenile phase. A temporary decline in the growth rates of both groups was observed around weaning (at 4 and 8 weeks post-hatch for groups A and B, respectively).

3.1.3. Weight growth rates.

The mean dry weight of both groups increased exponentially after the completed larval stage but the rise was much steeper for the late-weaned group A (Fig. 7).

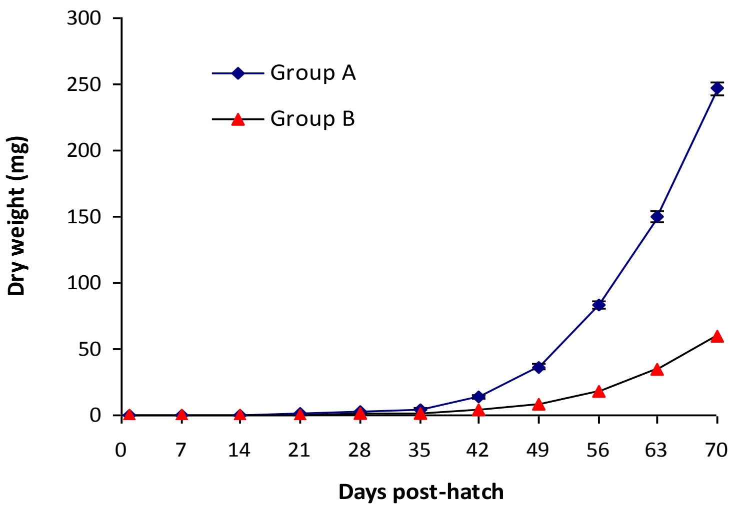

Figure 7. Mean dry weight of groups A and B during the first 10 weeks post-hatch. Vertical whiskers show the standard error of the mean.

At the end of the hatchery stage (56 dph) and further at 70 dph the mean dry weight in group A was about 4 times higher than in group B. Incidentally, the benchmark dry weights observed in group A at 8 and 10 weeks post-hatch (83 and 247 mg, respectively) are probably the highest ever reported for intensive cod juveniles. Group B still compares well with the intensive cod larval performance reported in the literature (see Steinarsson 2004).

The observed differences in larval growth performance are further reflected in the weight specific growth rates (Fig. 8).

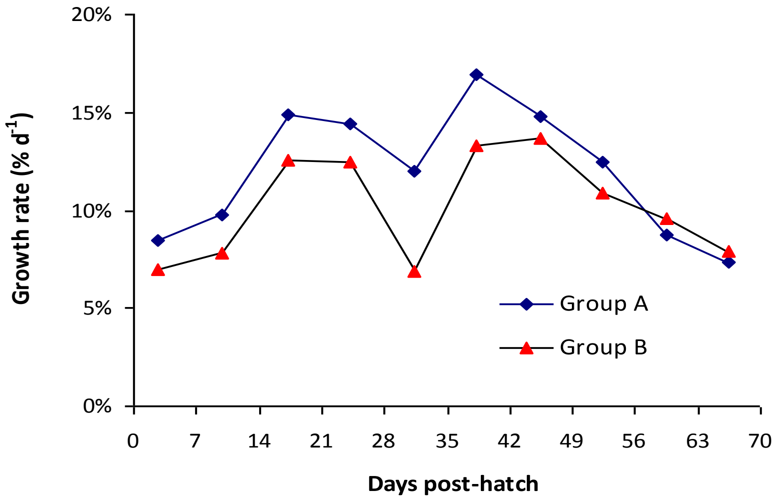

Figure 8. Mean daily weight specific growth rates of the three start-feeding groups during the first 10 weeks post-hatch. Vertical whiskers show the standard error of the mean.

The weight specific growth rate was consistently higher for group A until about 8 weeks post-hatch, after which group B grew slightly faster. A temporary decline in growth rates was observed in both groups between 4-5 weeks post-hatch, especially in group B which was being weaned at the time. The growth rates of group A peaked at about 18% per day after 5-6 weeks post-hatch and again these may be among the fastest growth rates ever reported for intensive cod juveniles (see Steinarsson 2004).

3.1.4. Early benchmark sizes.

To facilitate the direct evaluation of growth performance during the early developmental stages it is useful to list up and compare the mean sizes at various age benchmarks. As long-term growth performance may reflect the early growth performance it is important for the cod hatcheries to measure up their performance to an available reference list. Table 2 shows mean benchmark sizes observed in this study during the first 100 days post-hatch. The growth performance of groups A (late-weaned) and B (early-weaned) are included in the table. Benchmark sizes are presented as standard length (SL), total length (L), dry weight (DW) and wet weight (WW), according to the applied method of measurement in each size category.

Table 2. Mean benchmark sizes of groups A and B during the first 100 days post-hatch (dph). Dry weight (DW) is calculated from standard length (SL) according to Finn et al. (2002) and Steinarsson (2004). Total length (L) and wet weight (WW) of early juveniles (49-70 dph) is based on standard length and dry weight, respectively, multiplied by 1.1 and 0.006, respectively.

	SL (mm)		L (mm)		DW (mg)		WW (g)	
Dph	A	B	A	B	A	B	A	B
0	5.0	4.5	-	-	0.10	0.07	-	-
7	5.8	5.1	-	-	0.16	0.11	-	-
14	7.1	6.0	-	-	0.31	0.18	-	-
21	9.6	7.8	-	-	0.83	0.42	-	-
28	12.8	10.0	-	-	2.12	0.95	-	-
35	16.4	11.6	-	-	4.68	1.51	-	-
42	23.0	15.2	-	-	14.0	3.62	-	-
49	31.1	20.0	34.1	22.0	36.6	8.88	0.22	0.05
56	40.0	25.0	44.0	27.5	83.3	18.3	0.50	0.11
63	48.0	30.5	52.8	33.6	150	34.7	0.90	0.21
70	56.0	36.0	61.6	39.6	247	59.0	1.48	0.36
80	-	-	73.5	50.0	-	-	2.41	0.61
90	-	-	84.0	59.0	-	-	3.89	1.10
100	-	-	94.5	67.0	-	-	5.93	1.73

As mentioned before, groups A and B are not directly comparable due to differences in egg size and ultimately standard length at hatch. The growth performance of these groups, however, provides a valuable reference for comparison with other studies.

3.2. Land-based farming trial in Grindavík.

3.2.1. Mortality, tag loss and deformities.

The natural mortality during the long-term rearing trial was low in all the groups. Upon transfer to the large tank on 12 October 2009 the numbers in group A were randomly reduced and deformed or maladjusted fish were culled and discarded from all the groups. Table 3 shows the number of surviving fish in groups A, A+, B and C at all successive sampling dates from 10 March 2009.

Table 3. Survival and mortality during the land-based rearing trial. **T**he number of surviving fish is indicated for each date. The overall natural mortality is indicated in the last column.

Group	10.03.09	22.04.09	12.10.09	17.02.10	07.07.10	07.11.10	Natural mortality
Group A+	176	172	167	138	133	121	4.0%
Group A	50	50	50	34	33	29	3.4%
Group B	57	55	53	45	43	34	8.8%
Group C	101	90	87	66	63	59	13.8%

In addition to manual grazing and culling, some fish were also selected for sampling at 7 June 2010. Groups A and B were scanned for deformities at around 150 dph and deformities were manifested differently among the groups. Head deformities were the most common category overall and dorsal fin deformities were common among the early-weaned group B juveniles. The incidence of early visible head deformities in groups A and B was 11 and 35%, respectively. All discarded fish were subsequently excluded from the calculation of group means and the final analysis of growth performance was based on final survivors only, i.e. fish that could be traced back to the juvenile stage.

3.2.2. Long-term growth performance.

The analysis of long-term growth performance is only based on those fish that ultimately survived until the end of the rearing trial. Subsequently, the mean growth-performance of the original groups is skewed positively by about 5-6% as the discarded fish were often slow-growing due to deformity or disease. Figure 9 shows the mean weight trajectories of all groups from tagging to the end of the experiment at 30 months post-hatch.

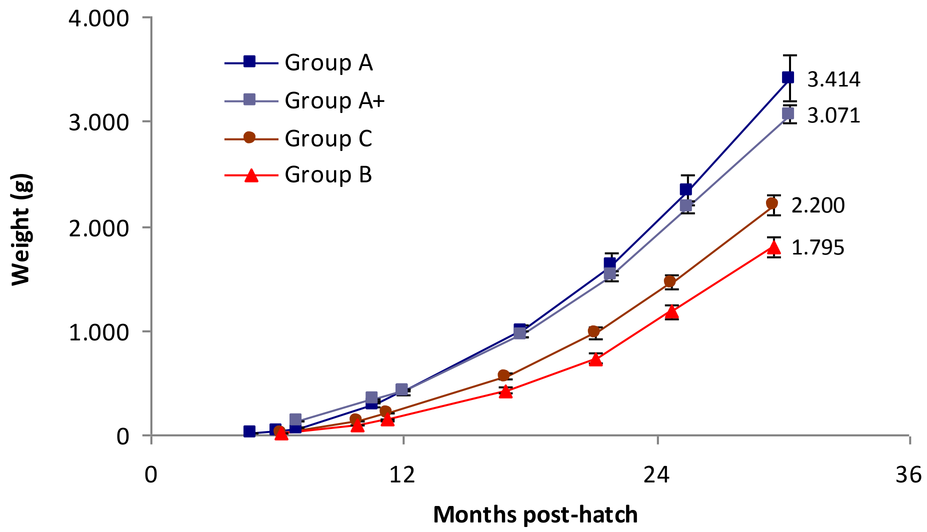

Figure 9. The progression in mean weight of all groups from initial tagging to the end of the experiment at 30 months post-hatch. The mean weights are based on final surviving fish only. The final mean weight of each group is indicated with the values adjacent to the final label.

The most obvious observation from Figure 9 is the superior growth performance of the late-weaned A-groups. Interestingly, the medium-grade (A) gradually caught up and overtook the top-grade (A+) and the low-temperature group (C) finished well ahead of the early-weaned group (B). The performance of group A is the best ever reported for any intensive hatchery cod. A mean weight of 3.4 kg after only 30 mph is probably the highest benchmark weight reported from either research trials or industrial farming.

3.2.3. Long-term effect of low salinity exposure.

At the end of the hatchery stage (at 50 dph) group A was split into top-grade (group A+) and medium-grade (group A). Juveniles from group A were later used in a series of experiments involving rearing at different salinities, ranging from 5-30‰. After the last trial the tagged juveniles were mixed together into one group and later re-used as a research group in the present study (group A). All the juveniles could therefore be traced and categorized according to their previous salinity exposure. Figure 10 shows the long-term growth performance of the salinity subgroups (A5, A10, A20 and A30).

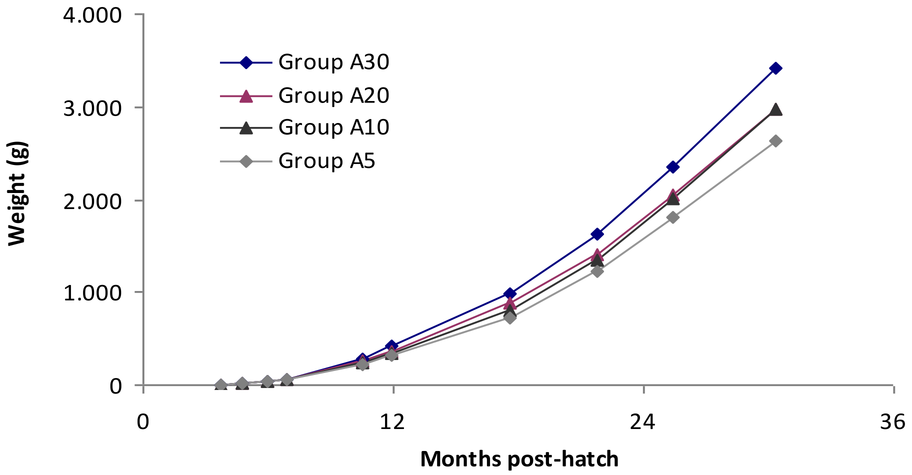

Figure 10. The progression in mean weight of all salinity sub-groups of group A from initial tagging to the end of the experiment at 30 months post-hatch. The group label indicates the previous salinity exposure of the subgroup. The mean weights are based on final surviving fish only.

The long-term rearing of group A gradually revealed a surprising finding, i.e. that the growth performance differed between the salinity subgroups. At 30 mph the mean weight in the high salinity group (A30) was about 15% higher than in the medium salinity groups (A20 and A10) and about 25% higher than in the low salinity group (A5). This observation led to the obvious conclusion that the growth potential of groups A5-20 had been compromised by their previous salinity exposure. The most likely explanation is that a sudden salinity shock may have had these adverse long-term effects (see Discussion). This is an interesting observation and shows that environmental extremes during the juvenile stage can potentially cause a permanent negative effect on future growth performance. It was therefore decided to exclude subgroups A5-20 and use only subgroup A30 to represent the actual growth performance of group A. Originally, 50 out of 263 juveniles belonged to group A30 and at the final weighing the numbers had been reduced further to 29 fishes.

3.2.4. Long-term effect of early grading.

As mentioned in the last section, group A was originally split into two grades, i.e. top-grade (A+) and medium-grade (A). Group A+ held fewer individuals, with approximately 10% of the population. At the time of grading (56 dph), the mean weight of the top-grade was 55% higher than that of the medium grade and the same relative difference was further maintained at 100 dph. In the salinity trial group A was reared at sub-optimal temperatures (9°C) and as a result group A+ was more than 100% larger in mean weight at the time of its tagging (7 mph). Figure 11 shows the long-term growth performance of groups A and A+.

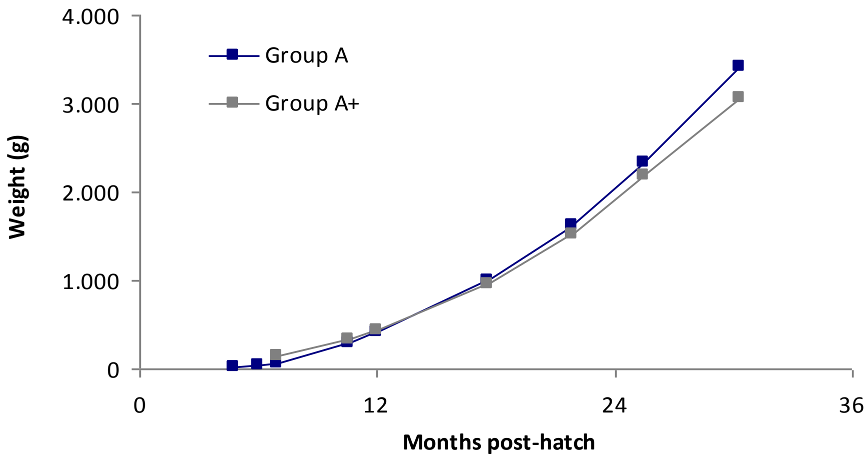

Figure 11. The progression in mean weight of the two original size-grades of group A from initial tagging to the end of the experiment at 30 months post-hatch. The mean weights are based on final surviving fish only.

The long-term rearing of group A gradually revealed another surprising finding, i.e. that the medium-grade (A) gradually overtook the top-grade (A+) and eventually group A outweighed group A+ by about 10% at 30 mph. The top-graded A+ had been expected to excel and maintain its original lead in the long-term trial but the group did not live up to these expectations. This result leads to speculations about the long-term benefit of early grading. Further, as all the fish were PIT-tagged they could be traced and ranked individually in successive measurements (Table 4).

Table 4. The correlation between early- and final size rank in groups A and A+. Values show the coefficient of variation (R^2) between present and final size rank at the indicated ages (in dph).

Age (dph):	113	146	182	211	321	364	537	665	775	925

R^2 (group A):	0,16	0,33	0,47	0,55	0,70	0,69	0,86	0,91	0,98	1,00
R^2 (group A+):				0,39	0,59	0,60	0,71	0,82	0,94	1,00

Table 4 shows that for both A-groups there is a relatively weak stability of individual size rank. The size rank of juveniles has a very low correlation with the final rank and it is only at 12-18 mph that the correlation has become reasonably good. The instability of individual rank leads to the conclusion that individual growth rates must fluctuate considerably relative to their group means (see Discussion).

The relatively poor long-term growth performance of group A+ may also lead to speculations about the benefit of rearing juveniles at optimal temperatures for growth. Group A was reared at sub-optimal temperatures during 3-6 mph but still managed to overtake group A+ in the long run (see Fig. 11). It is a valid speculation whether the enhanced juvenile growth performance resulting from optimal temperature rearing may in fact ultimately lead to a permanent reduction in the long-term growth performance (see Discussion).

3.2.5. Long-term effect of early weaning.

The long-term effect of early weaning was the main focus of the present study. Groups A and B are, however, not directly comparable due to differences in mean standard length at hatch (5.0 and 4.5 mm, respectively). This initial size difference lead to a difference in the early larval growth performance of these groups (see Figures 5-8). Nevertheless, these two groups provide a good example of the high and low extremes in long-term growth potential (Fig. 12).

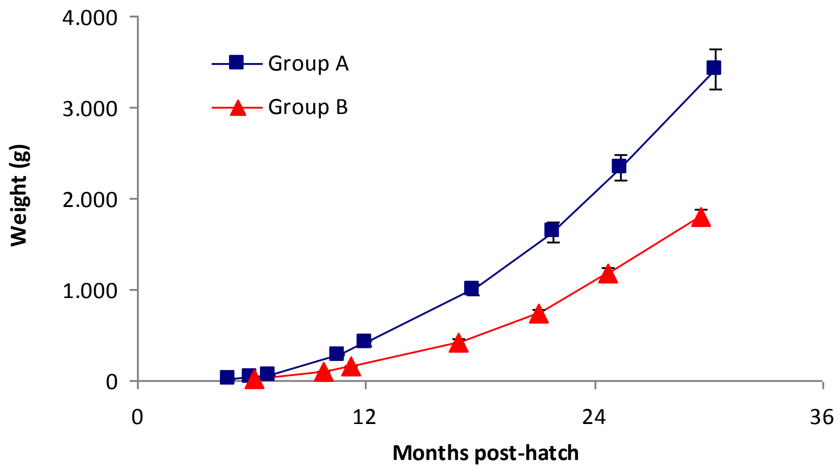

Figure 12. The progression in mean weight of group A (late-weaned) and group B (early-weaned). The mean weights are based on final surviving fish only. Vertical whiskers show the standard error of the mean.

The most striking observation from Figure 12 is the huge difference in the potential growth performance of two groups of perfectly healthy cod juveniles. Ever since the late juvenile stage there has been a more or less consistent two-fold difference in the mean weight of these two groups. At 30 mph one group measures 3.4 kg while the other measures only 1.8 kg in mean weight. This difference in growth performance can be traced back to the early life stages (see Figures 5-8) and primarily ascribed to the suppressing effect of early weaning (see Discussion). Clearly, the early weaning strategy applied in the present study was not satisfactory in terms of juvenile quality and cannot be recommended to cod hatcheries.

Based on the different growth performance of groups A and B, one might expect a corresponding difference in size-specific growth rates. However, since the late juvenile stage the growth rates of these groups have been remarkably similar (Fig. 13).

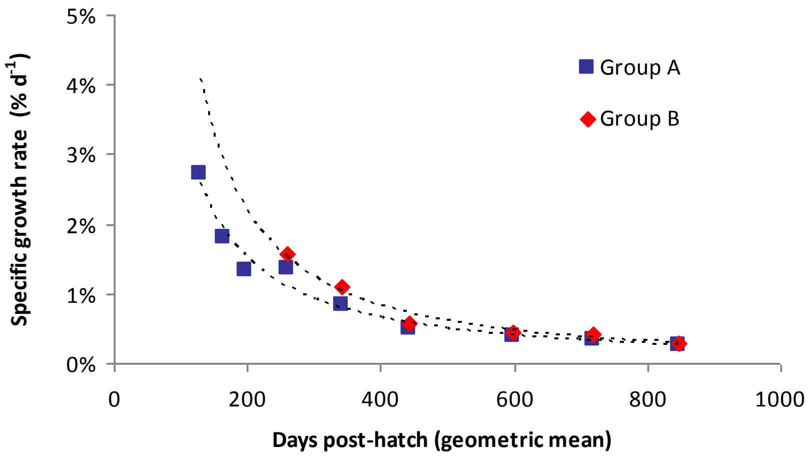

Figure 13. Mean weight-specific growth rates (G) of groups A and B between weighings. The mean weights are based on final surviving fish only.

Figure 13 shows that in spite of a permanent two-fold size difference the weight-specific growth rates (G) of both groups have been almost identical after every weighing. The unavoidable conclusion is that the growth rate appears to be age-dependent and not weight-dependent. As a natural consequence, the initial weight ratios established during the juvenile stage did not change considerably throughout the experiment.

3.2.6. The von Bertalanffy growth approximation.

The von Bertalanffy growth function (VBGF) is the most widely used growth model in fisheries studies. It is, however, rarely used to describe the growth performance of farmed fish and no references can be found for its use to describe the growth of farmed cod. When applied to weight growth, the typical VBGF growth curve has a temporary linear phase in the mid-size range. The long-term weight trajectories of all groups in the present study have all become almost perfectly linear with age after about 16-18 months post-hatch. It was therefore rational to approximate their growth performance by the weight-based VBGF. Figure 14 shows the VBGF approximation of groups A and B.

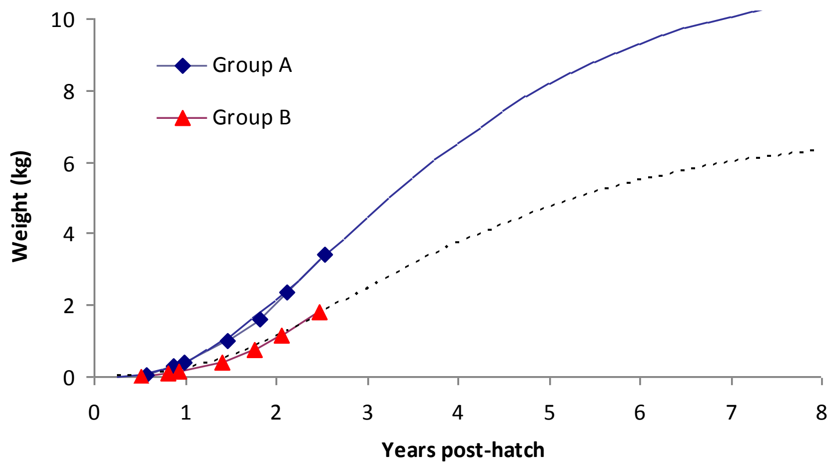

Figure 14. The progression in mean weight of group A (late-weaned) and group B (early-weaned) described and forecasted with the weight-based von Bertalanffy function. The mean weights are based on final surviving fish only.

The VBGF growth curves in Figure 14 start to deviate from linearity after the third year from hatch and are predicted to reach their potential maximum weight asymptotically in about 7-8 years from hatch. Group A is predicted to maintain its advantage and the maximum mean weights (W_∞) predicted by the equation, are 11.4 and 6.9 kg for groups A and B, respectively. These predictions are of course based on only 2.5 years of growth and may therefore be subject to considerable prediction error. Still, it is safe to conclude that these maximum weights are much lower than commonly reported for wild cod (see Discussion).

3.2.7. Benchmarking growth performance.

Benchmark sizes can be a useful tool to compare the growth performance of cod from different locations or experiments. Table 5 shows the mean weights of groups A, B and C at various benchmark ages.

Table 5. Mean live weights of groups A, B and C at various age benchmarks post-hatch. The values for 36 and 48 months post-hatch (mph) are calculated from the respective von Bertalanffy equations.

	Age in days (dph) or months (mph) post-hatch.								
Group	100 dph	150 dph	180 dph	12 mph	18 mph	24 mph	30 mph	36 mph	48 mph
Group A	5.93	25.3	43.0	422	1,156	2,162	3,303	4,463	6,558
Group B	1.73	8.0	13.5	188	565	1,114	1,760	2,436	3,702
Group C	-	-	18.9	258	751	1,381	2,165	2,972	4,479

The 100-day benchmark may be an ideal indicator for the future growth potential. The 100-day benchmark weight of group A is very impressive but due to sub-optimal rearing temperatures and -salinities the 150- and 180 day benchmarks are somewhat less impressive. After the 1-year mark, however, all the benchmarks for group A are probably the highest ever reported for a group of intensive cod juveniles. They are about twice as high as reported benchmarks from Icelandic cod farming but still they are much lower than reported benchmarks for fast-growing semi-intensive juveniles (see Discussion). The benchmarks of groups B and C are more in line with the reported growth performance from commercial cod farming. The performance of group C is surprisingly good and impressive in view of the low temperatures applied during the early life stages.

3.2.8. Individual growth performance.

As all the fish in the study were individually tagged, their growth performance could be monitored. Figure 15 shows the final individual weight trajectories from group A.

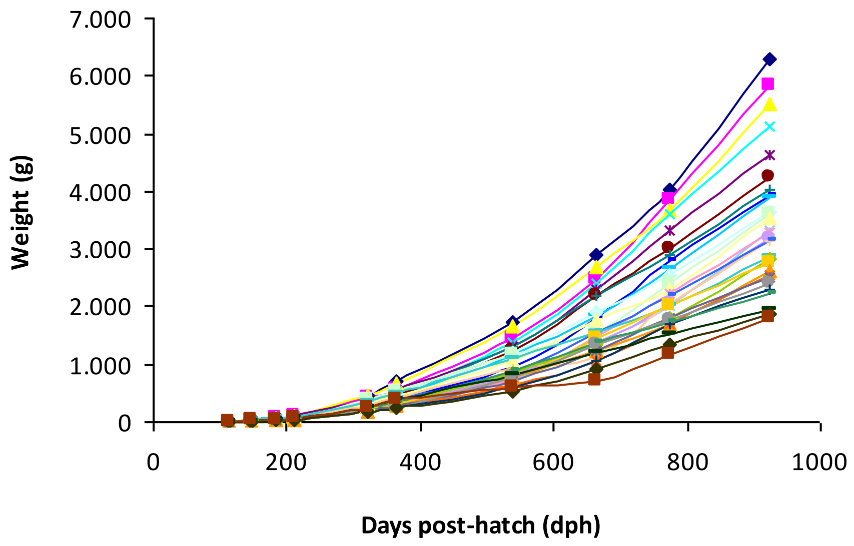

Figure 15. The individual growth trajectories from group A. Each trajectory is based on measurements from one single tagged fish. Only final surviving fish are included.

A plot of many overlapping growth trajectories is not easy to decipher but is included here for one group to underline the large variation in individual growth performance. It would indeed be very valuable to be able to safely identify and separate the winners from the losers already at the juvenile stage. By simply removing the bottom 25% of the group, the final mean weight can be increased by about 15% which translates into a two-month reduction in rearing time to harvest (see Discussion). Such effective size-grading could potentially have increased the final mean weight of group A from 3.4 to 3.9 kg.

During the last 12-18 months of the trial the absolute growth rate (ABS in kg/year) remained more or less constant for each group. The absolute growth rates therefore provide an excellent point of comparison between different groups of cod. There was, however, a large variation in the absolute growth rates within the groups (Fig. 16).

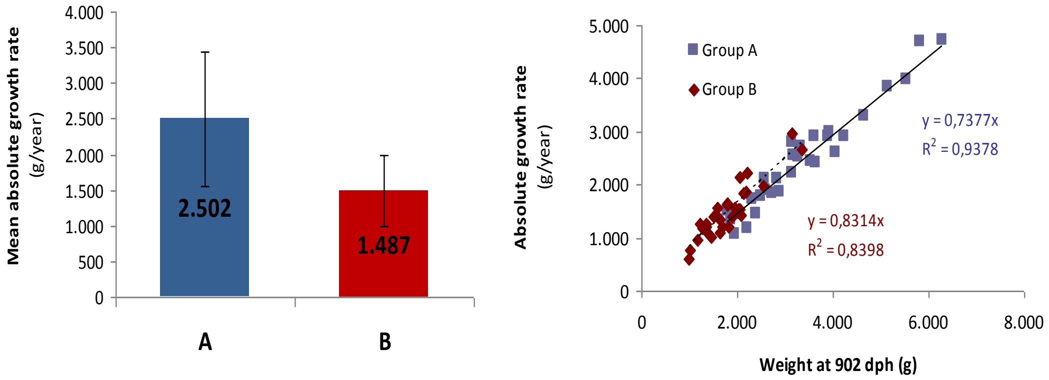

Figure 16. A) The absolute growth rates (ABS) of groups A and B during a part of the linear growth phase (537-775 dph). Vertical whiskers show the standard deviation. B) Absolute growth rates of tagged individual fish plotted against weight at 902 dph. The upper (blue) and the lower (red) regression equations apply to groups A and B, respectively.

Figure 16a shows the large variation in the absolute growth rates among individual fish within the groups. The coefficient of variation was 37.8 and 33.4% for groups A and B, respectively. Figure 16b further shows the wide range of individual absolute growth rates in group A (1.1-4.7 kg per year) and group B (0.6-3.0 kg per year). The fishes on the upper end of the spectrum, with growth rates of 4-5 kg per year, compare well with wild fish and could potentially grow to reach 20-30 kg. The fishes on the lower end are on the other hand very growth-suppressed and will struggle to reach even the modest maximum size of 3-4 kg. The absolute growth potential will invariably match the actual weight of the fish at 26 and 27 mph in groups A and B, respectively.

3.2.9. Length growth.

Length trajectories were made for all groups, from the early juvenile stage to 30 month old fish. They were then fitted with the von Bertalanffy growth function (Fig. 17).

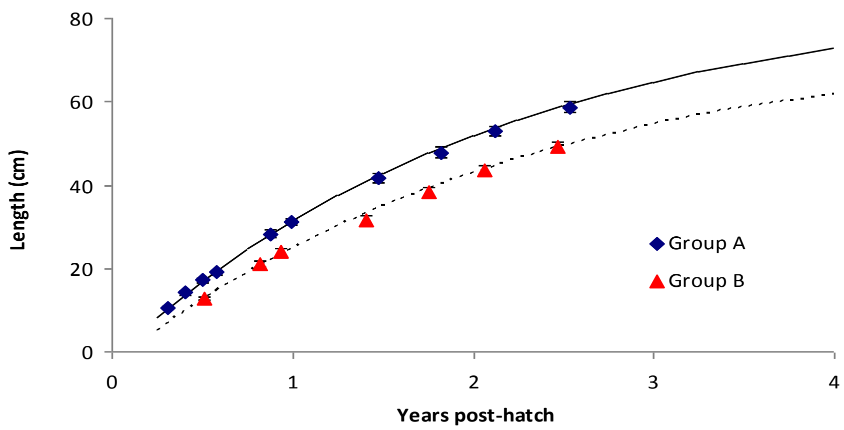

Figure 17. Mean length trajectories for groups A and B fitted with the von Bertalanffy growth function and forecasted until the end of year 4 post-hatch.

The von Bertalanffy growth function gives a good fit to the length growth trajectories. The parameters t_0 (years), K and L_∞ (cm) are 0.0, 0.47 and 87.0 for group A and 0.07, 0.45 and 75.0 for group B. This means that groups A and B are predicted to reach a maximum mean length of only 87 and 75 cm, respectively. Furthermore, they are predicted to reach their maximum length in only 7-8 years from hatch. The predictions from figure 17 are startling when compared to wild Icelandic cod which are known to grow continuously for at least 10-15 years and reach lengths of more than 120 cm (Jónsson 1992).

The daily length increment of groups A and B peaked at 1.3 and 0.9 mm per day at the end of the early juvenile stage (Fig. 6). The reverse trend has been seen during the grow-out phase with the length increment gradually decreasing for both groups A and B.

At each sampling date some fish were sampled for total length also and at the final weighing all fishes were measured for total length. A length-to-weight relationship can therefore be plotted for the entire land-based trial (Fig. 18).

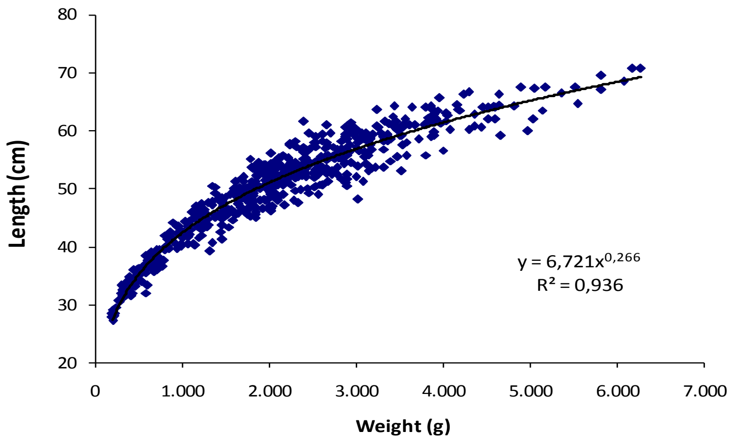

Figure 18. Total length versus wet weight for all the groups in the land-based trial based on samples from all sampling dates. The data is fitted with a trendline and the corresponding equation is shown.

Figure 18 reveals the large variation observed in the length-to-weight relationship. For each given length there is roughly a two-fold variation in wet weight and condition i.e. a 50 cm fish may weigh in at anywhere between 1.5 to 3 kg. This may reflect the large periodical fluctuation in growth rates among individual fish (see Discussion).

3.2.10. Feeding efficiency.

Feeding efficiency was only monitored for one growth period during the late juvenile stage (for 43 days during March and April 2009). The fish were at that time split into three groups or combinations i.e. groups A+, A and B/C in three separate tanks. The feeding efficiency is presented by the biological feed conversion ratio (BFCR) i.e. feed consumed per live mass produced (Fig. 19).

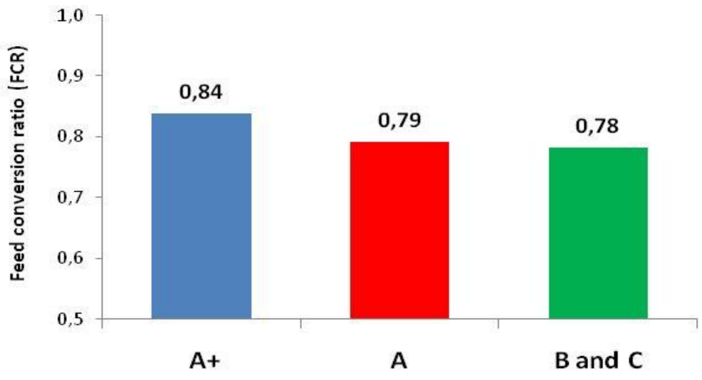

Figure 19. The biological feed conversion ratio (BFCR) of groups A+, A and B/C during 43 days on the late juvenile stage.

The groups are not directly comparable due to differences in mean weight (360, 278 and 133 g in geometric mean weight for groups A+, A and B/C, respectively). The specific growth rates were 0.59, 1.10 and 0.81% for the same groups, respectively. After taking the size difference into account, it can be concluded that groups B/C show a relatively high and un-efficient FCR in view of their smaller size. This may indicate that poor growth performance is indeed also accompanied with poor feeding efficiency (see Discussion).

3.2.11. <u>Sexual maturity and liver index.</u>

Starting in February 2010 (22 mph), samples were taken at each sampling to measure the sexual maturity of the fish. To make a long story short, the gonadosomatic index (GSI) was very low throughout the trial i.e. only 0.3, 1.1 and 1.1% at 22, 25 and 30 mph, respectively. It can be concluded that the 24:0 photoperiod applied was truly effective in holding back the sexual maturity. A considerable variation was, however, found in the hepatosomatic index (HSI) of the groups (Fig. 20). The difference can probably in most part be explained by the size differences between the groups (see Discussion).

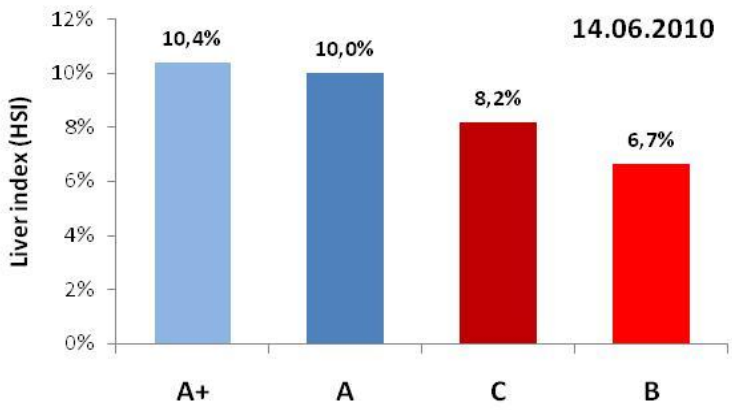

Figure 20. The hepatosomatic index (HSI) of groups A+, A, C and B in June 2010.

3.3. Sea cage farming trial in Berufjörður.

3.3.1. Mortality.

In June 2009 some 934 large juveniles were transferred by boat to a sea cage in Berufjörður. No mortalities occurred underway and the juveniles were stocked into a cage with fishes from the previous 2007 year-class (group E). A total of 83 fish were removed via regular sampling from the cage and at the final harvest in December 2010 some 145 survivors were counted from the cage. The assumption that all sampled fish would have survived until harvest translates to a poor 24% survival from the trial. It is however likely that some fishes may have escaped identification by the workers doing the harvesting and that the survival may therefore be somewhat under-estimated. This is unfortunate but still we have to conclude that the total mortality may have been as high as 76%, which is very similar to the total mortality in group E reared in the same cage. Veterinary diagnosis of dead fish has revealed bacterial infections (mainly *Aeromonas salmonicida*) as the main mortality cause (Kristmundsson et al. 2011, Theódór Kristjánsson, pers. comm.).

3.3.2. Growth performance.

The growth-performance of the stocked juveniles was monitored by sampling every six months after stocking (Fig. 21).

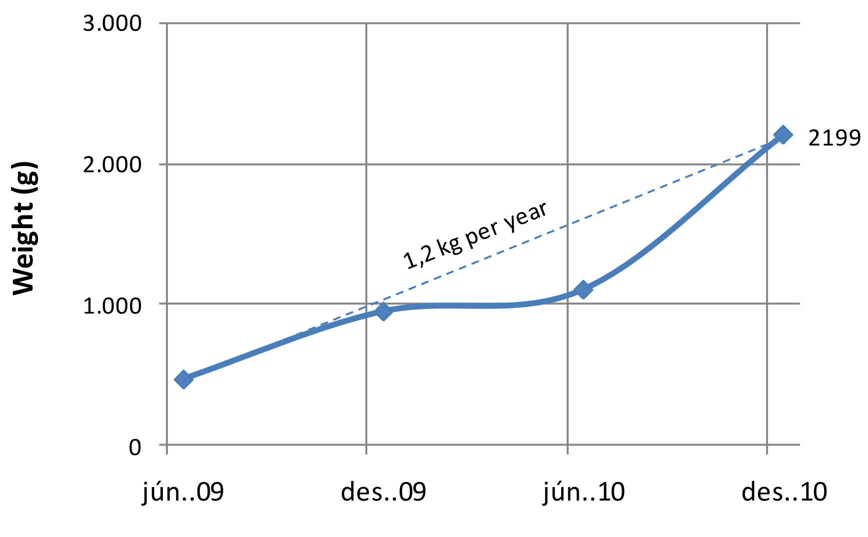

Figure 21. The growth performance of group E in a sea cage in Berufjörður. The dashed line shows the absolute growth rate (ABS) during the trial, indicated above the line.

Figure 21 shows that the fish had a distinctly seasonal growth pattern reflecting the seasonal variation in sea temperature at the cage site. The mean weight was effectively doubled during each summer when temperatures peaked at 7-8°C in August-September. The growth was, however, stagnated during the late winter-months when the temperatures became as low as 2°C in Feb-April. The mean weight at harvest was 2.2 kg which was admittedly well below expectations. The mean absolute weight increase during the 18 month trial was therefore approximately 1.2 kg per year. Still, this is to date the best growth performance of farmed cod in this area (see Discussion). Due to the high stock losses and short rearing time, the juvenile yield was only 0.72 kg per stocked juvenile and only 0.24 kg per stocked juvenile per year.

3.3.3. Sexual maturity and liver index.

A sub-sample of fish from the cage was analyzed every six months after stocking. All surviving fish were sampled after harvest in December 2010. The vital statistics measured included condition, liver and gonads (Table 6).

Table 6. Results from sampling from the sea cage rearing trial in Berufjörður. Listed results include: number sampled, wet weight (W), total length (L), condition factor (K), gutted weight index (GWI), hepatosomatic index (HSI) and gonadosomatic index (GSI).

Date	Sample	W (g)	L (cm)	K	GWI	HSI	GSI
15.06.2009		470	33,9	1.21			
15.12.2009	50	952	41.3	1.35	78.3%	10.6%	3.5%
15.06.2010	33	1,104	45.9	1.14	81.7%	9.7%	1.5%
15.12.2010	145	2,199	54.2	1.38	76.6%	12.1%	6.6%

The final sampling revealed more males (76) than females (69) but the females were about 6% larger in mean weight (2,267 g) than the males (2,136 g). The maturity incidence was over 95% for both sexes but the GSI was higher for males (8.7%) than females (4.2%). The HSI, on the other hand, was higher for the females (12.9%) than the males (11.4%).

There was a large seasonal variation in fish condition as measured by the Fulton's condition factor (K). The fish condition peaked in December each year, about 3 months after the annual peak in temperature in September (Fig. 22).

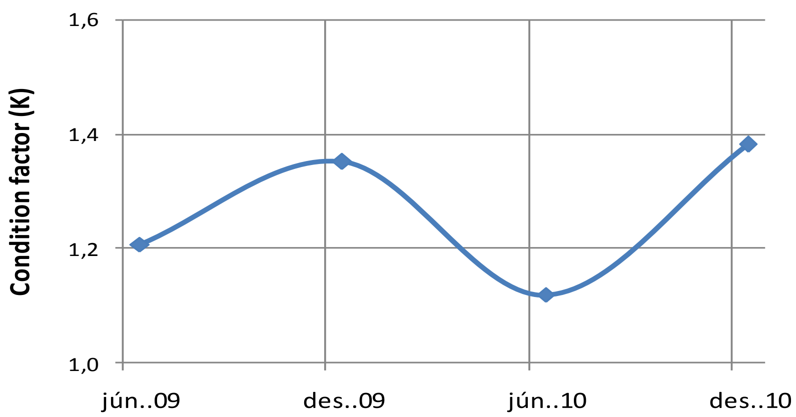

Figure 22. Seasonal variation in mean condition factor (K) of group E in a sea cage in Berufjörður. Fulton's condition factor $K = W/L^3 \times 100$, where W = wet weight (g) and L = total length (cm).

4. Discussion.

This project is one of two recent projects at the MRI that are possibly the first research projects to monitor cod populations under controlled conditions in a land-based facility from hatch to market size (the AVS-project OPTILAR is the other one). Regular measurements during the larval stage provided data which could in turn be compared with individual growth trajectories during the entire grow-out stage. Viewing the entire life-cycle as a whole opens a new perspective on the growth of cod and has led to some interesting new findings from this project. A complete understanding of the underlying growth dynamics is crucial if the aquaculture industry is to fully exploit the large innate growth potential of cod.

4.1. Growth and rearing performance in the study.

4.1.1. Larval- and early juvenile performance.

The performance of the hatchery phase in terms of survival was rather disappointing as only 2-4% of the stocked larvae from brood-stock eggs ultimately survived to viable juveniles. Meanwhile, the survival from the single batch of wild collected eggs was 10%. The poor survival from the brood-stock eggs can surely be ascribed to poor egg quality because the survival in Icecod’s hatchery was even lower at the same time.

The growth performance during the early life-stages varied widely between treatment groups and was primarily affected by the weaning strategy but also by egg size, origin and rearing temperature. The performance of the late-weaned group (A) was excellent and the early benchmark sizes were the highest ever reported for intensive cod juveniles. A maximal weight-specific growth rate of 18% per day and length increment of 1.3 mm per day were relatively impressive. The 8 week benchmark dry weight of group A was 83 mg compared to 18 mg for the early-weaned group B. The MRI-hatchery in Iceland has previously reported 8 week benchmarks of 56 mg (Steinarsson 2004) and 52 mg (Steinarsson et al. 2012) for late-weaned juveniles. Various studies have reported 8 week benchmarks of only 8-10 mg for intensive juveniles (Baskerville-Bridges and Kling 2000b, Puvanendran and Brown 2002, Callan et al. 2003). An 8 week benchmark of 48 mg has been reported for wild-caught Icelandic cod larvae based on otolith readings (Begg and Marteinsdottir 2000).

The performance of group A, however, fades in comparison with copepod-fed juveniles (zooveniles). Zooveniles in Norway have been reported to reach 130 mg (Otterlei et al. 1999) and 160 mg (Finn et al. 2002) and a benchmark of approximately 180 mg can be extrapolated for Faroese zooveniles (Kolbeinshavn et al. 2012). This comparison indicates that the superior long-term growth performance of zooveniles can be traced back to limitations in the early growth dynamics. The poor larval growth performance in many intensive hatcheries may perhaps be traced to sub-optimal rearing- and feeding protocols, such as unsuitable enrichment feeds, early weaning and low rearing temperatures.

4.1.2. Land-based rearing trial.

From the aquaculture perspective the overall performance of the fish is simply a product of growth and survival. The natural mortality in the land-based trial was very low in group A (3-4% total mortality) but relatively higher in groups B and C (9-14%). Deformity-based culling was relatively high in groups B and C (10-15%). The growth performance during the land-based rearing trial was very variable between groups with a two-fold difference in final mean weight at the end of the study. The long-term growth performance of the late-weaned group A was probably the best ever reported for intensive cod juveniles. By assuming a 10% total stocking loss, due to natural mortality and deformities, the juvenile yield in group A can be calculated as 2.55 kg per stocked juvenile or 1.39 kg per juvenile per year. By comparison, the juvenile yield from commercial cod farming in Norway and Iceland is typically around 0.9 and 0.6 kg per juvenile per year, respectively (see Table 7).

The growth performance can be put into context by comparing reported mean weights at 27 months post-hatch (mph) from growth studies and cod farming. It must be kept in mind that temperature and climate conditions vary widely between the various locations. The zooveniles from the Faroes are in a league of their own, reaching a mean weight of 4 kg (Kolbeinshavn et al. 2012), while zooveniles in Norway have been reported to reach 3.3 kg (Solgard 2005), 1.9 kg (Imsland et al. 2007) and 1.7 kg (Imsland et al. 2006a). After 27 mph intensive juveniles in Iceland have been reported to reach 2.8 kg (Group A, present study), 2.7 kg (Steinarsson et al. 2012), 1.5 kg (Group B, present study) and 1.4 kg (Kristjánsson and Steinarsson 2007). In Norway, the mean weight of Codfarmer's F3-yearclass can be extrapolated to 2.3 kg (Codfarmers AS 2011) at 27 mph, while research studies have reported 1.4 kg (Imsland et al. 2006b). Canada has reported 1.6 kg for their intensive juveniles (Powell 2008) and Ireland has reported 1.2 kg at 27 mph (Bolton-Warberg and FitzGerald 2011).

The comparison shows the wide variation in the growth performance of farmed cod. The late-weaned juveniles from the present study compare very well with other intensive juveniles but not so well with the best performing zooveniles. The variable performance of the Norwegian zooveniles, however, shows that a start-feeding diet of copepods does not necessarily produce fast long-term growth rates. Codfarmers AS in Norway (the world's largest cod farming enterprise) report relatively good growth rates for intensive juveniles.

The growth model of Björnsson et al. (2007) has been widely used to describe the growth of farmed cod. The model was based on growth trials with intensive juveniles and wild-captured larger cod and furthermore tuned to fit better with growth data for Norwegian zooveniles. Growth predictions from the model were compared to growth performance of groups A and B, as well as to the growth of zooveniles and wild-captured cod (Fig. 23).

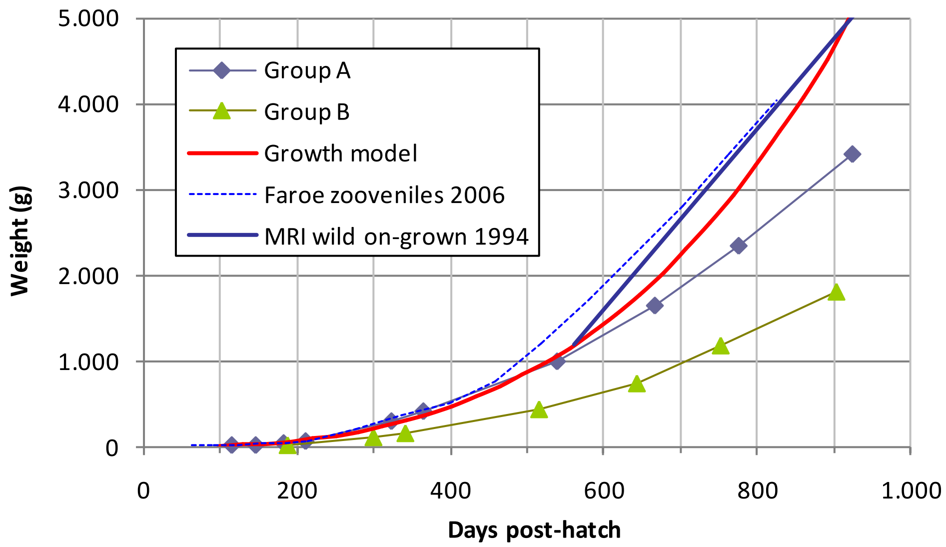

Figure 23. Weight trajectories of groups A and B fitted with the growth model (whole red line) of Björnsson et al. (2007). The dashed blue line shows the growth of semi-intensive "zooveniles" in the Faroe islands (Kolbeinshavn 2008) and the whole blue line shows the growth of wild-captured Icelandic cod in land-based tanks (Björnsson and Steinarsson 2002).

The model initially provided a reasonably good fit to the growth of group A but at about 20 months post-hatch the model went sky-rocketing, while the actual growth remained linear. The model, on the other hand gave a reasonable long-term fit to the growth of both the zooveniles and the wild-captured cod, that follow a much steeper linear path of almost 4 kg per year, leaving the intensive juveniles far behind. The usability of the model for describing the growth performance of semi-intensive cod has further been confirmed in a recent article by Kolbeinshavn et al. (2012).

The first growth model published by Björnsson and Steinarsson (2002), which was based on trials with intensive juveniles only, has on the other hand been reported to provide a better fit to the growth of intensive juveniles (Bolton-Warberg and FitzGerald 2011). The observed linear weight increase of large cod clearly does not agree with the exponential nature of the growth model. In view of the good fit provided by the von Bertalanffy growth function, as presented in this paper, it may be sensible to base a new growth model on an application of this function.

A very similar scenario was presented for the results from the OPTILAR-study, where the intensive juveniles failed to match the prediction of the growth model (Steinarsson et al. 2012). It may, however, be claimed that the performance of the best performing intensive juveniles is gradually approaching the full innate growth capacity. Through continued and focussed research effort there is some hope that the present gap may be closed in the coming years, bringing the quality of the intensive juveniles up to an acceptable level for aquaculture.

4.1.3. <u>Sea cage rearing trial.</u>

The rearing performance during the ocean-based grow-out phase was disappointing in terms of both survival and growth rates. The ultimate total mortality was measured as 76% but this figure may however be over-estimated due to human error during harvesting from the cage. Still, it is safe to say that the mortality was very high and similar to the total mortality in the 2007 year-class reared in the same cage. Veterinary diagnosis of dead fish has revealed bacterial infections (mainly *Aeromonas salmonicida*) as the main mortality cause. It was indeed unfortunate that this is the highest mortality ever recorded for a single year-class of farmed cod in Berufjörður. Other year-classes in Berufjörður have routinely suffered 30-40% mortalities and even lower if stocked in late summer (Theódór Kristjánsson, pers. comm.).

The growth performance in the sea cage trial was fitted with the growth model of Björnsson et al. (2007) and furthermore, compared to the performance of the 2007 year-class, reared simultaneously in the cage (Theódór Kristjánsson, pers.comm.) (Fig. 24).

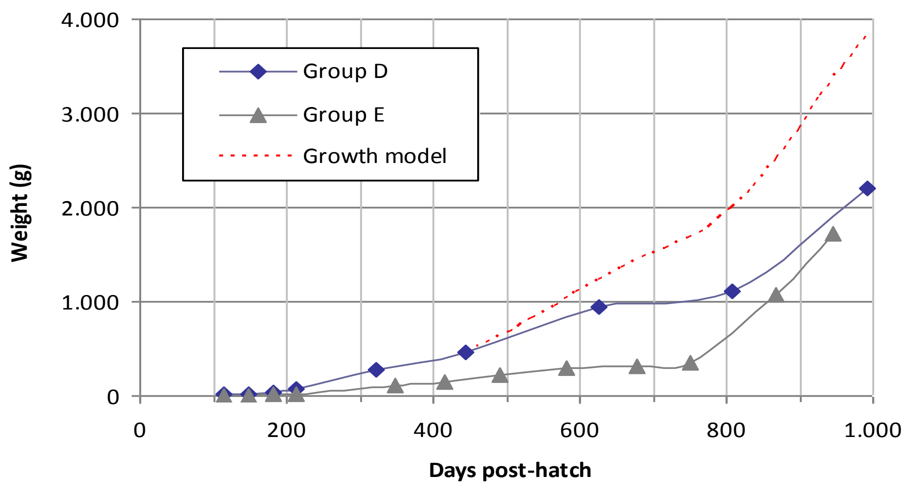

Figure 24. The growth performance of group D juveniles (2008 year-class) in sea cages in Berufjörður fitted with the growth model (dashed red line) of Björnsson et al. (2007). The grey line shows the performance of the 2007 year-class, reared in the same cage (Theódór Kristjánsson, pers. comm.).

The growth model is fitted to the initial weight of group D which was three times higher than the mean weight of the 2007 year-class (group E) at the same age. The temperature input is based on temperature recordings from the cage site (year average 4.5°C). At the end of the study (33 mph) the mean weight of group D was 2.2 kg, while the model predicted 3.7 kg. After a slow start group E grew very fast during the second summer at sea and almost caught up with group D and after still another year in the cage the harvest weight of group E was 3.2 kg. This comparison therefore shows that group D failed to maintain its original advantage over group E and also failed to match the growth model.

4.2. **Growth potential of farmed cod.**

4.2.1. The critical stage for growth potential.

All the evidence from this study indicates that the long-term growth potential is determined during the early life-stages. The early growth performance sets the pace for future growth and launches the juvenile cod onto a fixed path of pre-determined growth potential. A fixed reduction in the long-term growth potential of the early-weaned juveniles could be traced all the way back to the larval stage when their growth was stunted during weaning. All the growth measurements from the larval- and early juvenile stages therefore lead to one clear conclusion: The late-larval stage, especially 15-35 dph, appears to be critical for deciding the long-term growth potential. It is therefore important to optimize rearing and feeding conditions during this period to enhance both short-term and long-term growth performance.

An interesting analogy appears to exist between the duration of the larval stage (D) and rearing time to 3 kg. A larval stage of 27 and 36 days for groups A and B, respectively, was curiously reflected by 27 and 36 months, respectively, to a mean weight of 3 kg (predicted for group B).

Studies of cod larvae have indicated that nutritional deficiencies during the larval stage can lead to poor muscle cell recruitment and ultimately to a permanently reduced long-term growth potential in the fish (Weatherley 1990, Galloway et al. 1999, Johnston 2006). This may be the underlying reason behind the long-term growth-suppression found in the present study. There is indeed an urgent need for detailed studies on the link between early muscle growth dynamics and long-term growth performance in cod and other farmed species.

4.2.2. Effect of egg- and larval size.

The eggs incubated and hatched during this study were of variable size and origin. The first batches of brood-stock eggs in the spring of 2008 were approximately 1.45 mm in diameter (hatching into group A) while the last batches used were approximately 1.32 mm in diameter (hatching into group B). This means that the egg volume was about 30% larger in the first eggs and the larvae were 10% longer at hatch (5.0 and 4.5 mm, respectively). The size of the wild-collected eggs (hatching into group C) was similar to the first brood-stock eggs. Analysis of early larval growth performance in the different groups indicates that the initial relative size difference is at least maintained and even compounded during the larval- and early-juvenile stages. Based on the evidence presented in this study (and in the OPTILAR-study) this should have negative implications for long-term growth performance. This is, however, a controversial issue and some more direct evidence is needed to back up this theory. It is very important to investigate this matter further by running long-term rearing trials with juveniles hatched from different sized eggs. The results from such experiments could easily be very important for cod brood-stock management.

4.2.3. Effect of early weaning.

The results from this study are in line with the results from the OPTILAR-study where early weaning was found to have negative long-term effects on the growth potential of farmed cod. In the OPTILAR-study the eggs were of same size and origin but still a 50% difference was observed in final mean weight. In the present study the difference is even larger as the late-weaned groups reached a 90% higher mean weight at the final weighing. Some part of this difference may be explained by the initial differences in egg size and larval hatch length. Nevertheless, the study confirms the early larval growth suppression caused by the early weaning process with drastic associated negative effects on long-term growth performance. The early growth performance has lasting effects and in fact, the final size ratios are practically a reflection of the initial size-ratios after the early juvenile stage. The early-weaning strategy applied in the present study can therefore clearly not be recommended as it will produce lower quality juveniles both in terms of growth potential and deformity incidence. The strategy may of course be developed and improved in the future but meanwhile it may be wise to prioritize the juvenile quality and use the late-weaning strategy.

4.2.4. Effect of start-feeding diet.

The large difference in the growth performance of intensive- and semi-intensive juveniles can only be explained by fundamental nutritional differences between the start-feeding diets. Nutritional studies have revealed various deficiencies in enriched rotifers and Artemia compared to the typical nutritional profile of natural zooplankton, especially in n-3 PUFA (fatty acids) and various minerals and trace elements like magnesium, selenium and iodine (Hamre et al. 2008, Busch et al. 2011). Furthermore, copepods contain higher levels of dry matter, protein, pigments and free amino acids and cover a much wider size range than rotifers and Artemia (van der Meeren et al. 2008). Many studies have indeed reported inferior growth rates of marine larvae fed rotifers vs. a diet of natural zooplankton (Imsland et al. 2006, Wilcox et al. 2006, Rajkumar and Kumaraguru vasagam 2006). A semi-intensive diet of rotifers and copepods may be the protocol required to sustain maximal growth rates and produce juveniles of sufficient quality for aquaculture (Larssen et al. 2009).

The results from the present study and the OPTILAR-study (Steinarsson et al. 2012) indicate that a diet of enriched rotifers may sustain adequate growth rates initially but only for about two weeks after hatching. After that the zooplankton diet produces much better growth rates than the intensive hatchery diet of enriched rotifers and Artemia. It has been suggested that rotifers are simply too small to support optimal growth in cod larvae exceeding 7 mm SL (Busch et al. 2011). Prolonged feeding with rotifers only, may lead to stagnated growth at around 24 dph (MacQueen-Leifson 2003) but on the other hand it may have adverse effects to shift too early to Artemia (Shields et al. 2003). Another problem with rotifers is their high sinking rate in larval tanks, even after temperature acclimation, often leading to low prey availability (O'Brien-MacDonald 2006).

4.2.5. Effect of abrupt salinity changes.

The present study yielded a surprising finding about the long-term effect of abrupt salinity changes. One of the groups had previously been used in a salinity trial (SALCOD) with salinities from 5-30‰ before being returned again to full salinity (33‰) without any prior acclimation. When the individual growth performances from these sub-groups were traced back to the salinity experiments, a long-term effect on growth performance was revealed. The growth performance of the low salinity groups was clearly negatively affected by their previous salinity shock treatment.

A similar but more drastic effect has been seen in salmonids, that when prematurely transferred to seawater may cease to grow and become stunted. The osmoregulatory problems associated with premature transfer to seawater appear to cause growth hormone (GH) resistance in salmonids (Björnsson et. al. 2011) concomitant with growth retardation, caused by down-regulation of hepatic GH receptors. The cause of the observed growth retardation in cod may perhaps be the same albeit with less severe consequences for cod than salmonids.

No mortalities or visible external damage was, however, noticed among the juveniles and thus the damage went unnoticed. This finding shows that the juveniles must be handled very carefully, including proper acclimation to salinity changes. This particular experiment was however fortunate as it lead to this interesting finding, which may in turn lead to improved husbandry techniques in the farming of juveniles.

4.2.6. Effect of size grading.

The long-term monitoring of tagged fish from the juvenile stage to harvest size lead to another important finding: The individual weight rank in a group of juvenile cod has very little correlation to the ultimate size rank, come harvest time. The only logical reasoning that may explain the poor rank correlation is that the individual growth performance may actually fluctuate considerably over time. The results from the present study indeed show that the growth of individual fishes fluctuate considerably over time and that size-ranks are very unstable during the first year of life.

Figure 25 shows a random example of individual growth performances from group A, where the individual weight-specific growth rates have been matched against the mean growth rate, defined as 100%. These relative growth rates fluctuated over time around the group average. A possible explanation may be that each juvenile periodically shifts between periods of *hyperplasia* (new muscle-fibres) and *hypertrophy* (enlargement of muscle-fibres). Every individual fish would thus exhibit a periodical growth pattern and continuously run up and down the ranks. As hyperplasia is known to cease at about 44% of maximum fork length in various species of fish (Weatherley and Gill 1988), this might explain why growth appears to become more uniform after about 1-2 years post-hatch.

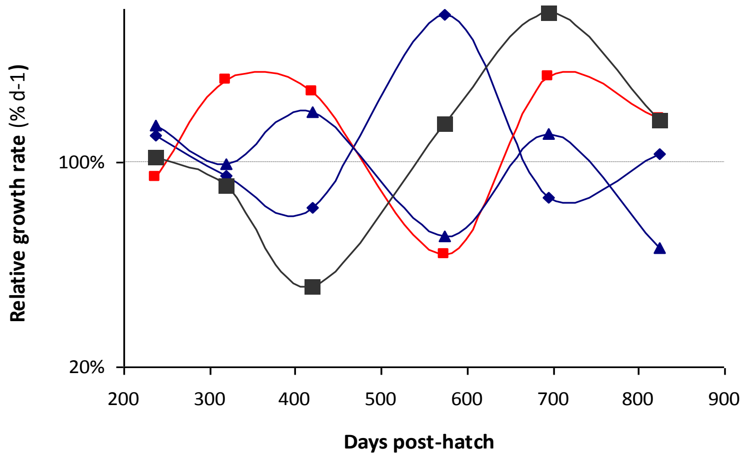

Figure 25. A random example of four individual growth performances from group A. The smoothed lines show the individual growth rates in relation to the average growth rate at each weighing.

Fluctuating growth rates may explain why the early culling of juveniles, based only on size criteria, will only produce a small long-term advantage. From an aquaculture point of view it would of course be desirable to size-grade effectively already at the juvenile stage. For example, if the 25% slowest growers could be removed effectively from the population the final harvest size could be increased by approximately 15% or alternatively, the rearing time shortened by about two months. Effective early size-grading may perhaps be an overlooked possibility to easily enhance the growth performance in cod farming.

A more systematic approach may be required to effectively size-grade a population of juveniles. A serial, early grading system with four separate size classes can be suggested as a solution to this problem. By splitting each class serially into two size-grades and promoting/demoting each grade to the next class, the fast- and slow-growing fish should gradually aggregate in the top- or bottom classes, respectively. In other words, the juveniles should gradually move up or down the class rank according to their long-term growth potential. It would be interesting to bring this grading system to the test because it could be an effective method to identify the losers at an early age and increase the long-term growth performance of the population.

4.2.7. Age dependency of growth potential.

After analyzing the results from the present study, the ultimate conclusion regarding growth potential becomes obvious: The growth potential of cod is entirely age-dependent. The alleged size-dependency of growth rate may be an artifact masked by the correlation between age and size. Busch et al. (2010) arrived at the same conclusion from their studies on larval cod. Size-at-age after 2-3 months from hatch appears to be a decisive factor controlling the long-term growth potential of cod and probably many other marine fish species as well. This means that the growth potential of cod is extremely vulnerable to variations in external factors that may overrule the underlying genetic growth potential. This may be a fundamental difference between an r-selected species with small eggs (like cod) and a K-selected species with large eggs. The small larvae from the r-selected species are directly exposed to the elements and the larva must create its own fortune during the early developmental stages.

4.2.8. Growth potential and feeding efficiency.

Age dependent growth potential does effectively mean that potential growth rates are identical at a given age, irrespective of fish size. This for example means that a healthy 30 mph farmed cod weighing 3 kg and ready for harvest does in fact have the same weight-specific growth rate as a healthy 1 kg cod of the same age (close to 0.3% per day at optimal temperature). Studies on many fish species, such as Atlantic salmon (Thodesen 1999) and channel catfish (Burch 1986), have shown that there is a direct positive correlation between growth rate and feed conversion. Consequently, as the growth rates decrease with increasing age of the fish so does the feed conversion become gradually less efficient. A slow-growing fish will take longer to reach the harvest size than the fast-growing fish and therefore exhibit lower mean growth rates and poorer feed conversion. Based on the approximate relationship between age and feed conversion, a 7-8% lower FCR (feed conversion ratio) would be expected for the fast growing cod in the previous example. As feed costs are by far the biggest single cost factor in aquaculture, this would represent a very significant cost benefit for cod farming.

4.2.9. The von Bertalanffy growth approximation.

The linear weight increase of the cod in this study conforms nicely to the weight-based von Bertalanffy growth function (VBGF). Growth predictions based on the VBGF lead to the same conclusion as the OPTILAR-study; the maximum asymptotic size of the intensive cod appears to be much smaller than for the Icelandic cod stock in the wild. The predicted maximum weights (W_∞) of groups A and B are only 11.4 and 6.9 kg, respectively, while the maximum weight of Icelandic wild cod is often given as 20-30 kg (Jónsson 1992). This applies to group means while individual fishes can either become smaller or larger. These predictions are of course based on only 2.5 years of growth and may therefore be subject to considerable prediction error. Still, it is safe to conclude that these maximum weights are much lower than commonly reported for wild cod. All available data thus points in one direction, that the growth potential of the intensive juveniles appears to be seriously compromised. The scope for growth in the intensive juveniles appears to be very limited and their maximum attainable size is much smaller than for their wild conspecifics. The continued long-term rearing of fish from the present study will gradually provide evidence that may support this hypothesis.

4.2.10. Absolute growth rates.

The initial exponential growth of all groups started to fade during the second year of life and the growth trajectories became almost perfectly linear (see Figures 9-12 and 23). The absolute growth rates (ABS) during this linear phase were determined as 2.5 and 1.5 kg per year for groups A and B, respectively. In comparison, absolute growth rates of 1.7 and 1.2 kg per year were reported for intensive cod from the OPTILAR-study (Steinarsson et al. 2012). A linear weight increase after year 1 can also be read from long-term growth results reported for Irish hatchery-cod, growing by 1.1 kg per year in sea cages for up to three years in a row (Bolton-Warberg and FitzGerald 2011). Also for Faroese semi-intensive cod, growing by 3.5 kg during one year in sea cages as shown in Figure 23 (Kolbeinshavn et al. 2012). It can be concluded that the best growth performance in the present study is very good compared to other intensive juveniles but still compares poorly with fast-growing semi-intensive juveniles (Solgard 2005, Kolbeinshavn et al. 2012).

A linear weight increase has also been reported for other marine species. Björnsson (1995) reported linear absolute growth rates of 3.2 kg/year and 1.4 kg/year for female and male Atlantic halibut, respectively. Interestingly, Imsland et al. (2005) reported a very moderate weight increase of 1.2 and 1.6 kg per year for un-sexed intensive Atlantic halibut (>1 kg) reared in tanks at 27 and 15‰ salinity, respectively. This indicates that intensive halibut juveniles may be just as growth-suppressed as intensive cod juveniles.

4.3. How to advance cod farming in Iceland.

4.3.1. Juveniles production strategies.

Cod farming is a virtual marathon, compared to the farming of many other species, like sea bass, sea bream, turbot and flounder. Long-term growth potential is therefore of particular importance for cod farming and should not be compromised lightly. The efficiency of the cod hatchery should not be based upon productivity and immediate costs alone. The growth potential is what primarily determines the value of the juvenile and should therefore be given first priority. Other important quality traits for aquaculture such as viability, disease resistance and feeding efficiency are also known to correlate positively with growth potential. It is therefore obvious that the most important challenge facing cod farming today is the large-scale production of juveniles with adequate growth potential. All potential production strategies should therefore be considered and compared without prejudice.

This study has confirmed the superior performance of zooveniles when compared to traditional intensive juveniles. The enhancement of the early growth performance is clearly the key to produce "fully charged" juveniles that have sufficient growth potential for cost-efficient full cycle farming. Production strategies based on zooplankton-feeding should therefore be seriously re-considered as viable alternatives to the intensive hatchery strategy. The extensive strategy is only possible once a year as it is totally dependent on season.

4.3.2. The intensive hatchery strategy.

The intensive hatchery strategy has the advantage of being an indoor operation and being based on easily cultivable prey. The strategy can furthermore be practised at any time of year which makes off-season production easily possible. It is therefore likely that this strategy will continue to be used to produce cod juveniles for years to come. The research effort should be focused on improving the nutritional properties of the start-feeding diet and matching the properties of the wild zooplankton diet. Enrichment protocols and feeds must be improved, and co-feeding with cultured copepods is an interesting option for the future.

The OPTILAR-study concluded that moderate stocking densities (65-70 larvae/litre) should be applied in the hatchery and that a productivity of 10 juveniles per litre start-feeding volume was a reasonable target without compromising growth potential (Steinarsson et al. 2012). The early-weaning strategy applied in this study and the OPTILAR-study, excluding Artemia from the diet, was unsuccessful as it produced lower long-term growth rates and a higher deformity incidence. The early weaning strategy may be developed and improved over time but presently it would be wise to prioritize long-term growth potential over hatchery efficiency. An intermediate weaning strategy, with Artemia feeding until 40-45 dph, appears to be sufficient to convey important advantages in terms of growth and anatomy.

4.3.3. The semi-intensive hatchery strategy.

The semi-intensive strategy may perhaps be the single most attractive strategy for the future as it combines the advantages from both the extensive- and the intensive strategies. The method is being used in many countries in the production of various species, like turbot, gilthead seabream and European flounder and in all instances the juvenile quality is excellent (Iglesias et al. 2007). The semi-intensive method has been used successfully for cod in Norway and the Faroes and has produced juveniles of exceptional quality (Solgard 2005, Kolbeinshavn et al. 2012). Enclosed large plastic bags (10 m^3) have been stocked with larvae at low densities (7 larvae/L) and supplied with copepods harvested from a surrounding lagoon. Backup-feeding with rotifers and Artemia ensures sufficient prey availability when needed and usually the juveniles have been fully weaned in only 5 weeks post-hatch (Hamre et al. 2008, Busch et al. 2011).

The semi-intensive strategy may, on the other hand, become possible out of season if the large-scale cultivation of copepods becomes technically possible. The main challenge is to master a year-round cultivation of copepods on a scale large enough to sustain large scale production. The cultivation of copepods is currently the focus of several research projects in both Norway, Greece and Iceland (Kjørsvik et al. 2004, Engell-Sørensen et al. 2006). The best option would be the year-round commercial availability of copepod eggs, or otherwise the zooplankton would have to be harvested from fertilized lagoons or cultivated seasonally. The strategy of choice can of course be different between countries and locations.

An interesting option for Iceland might be to use greenhouses and perform the semi-intensive production in land-based raceways, supplied with sea-water and geothermal water for heating. Off-season production would be possible through the use of electric lights and geothermal water. A greenhouse with eight 200 m^3 raceways might theoretically produce 1.6 million juveniles per run, based on a modest productivity of only 1 juvenile per litre. With three runs per year the capacity would thus be approximately 5 million juveniles per year. In comparison, the productivity of the semi-intensive method in Norway and the Faroes has ranged from 1-2 juveniles per litre. The semi-intensive method might be the ideal production method for Iceland which is rich in the resources needed, such as land, borehole-water, geothermal water and moderately priced electricity.

4.3.4. Land-based juvenile rearing.

The results of the study indicate that the growth performance of the juveniles should be maximized until at least 3 months post-hatch in order not to compromise long-term growth potential. This means that optimal temperatures and high-quality feed should be applied during the nursery stage (approximately 50-120 dph). Care must be taken not to underfeed the juveniles and all excess handling should be avoided. It is recommended to use the 100-day benchmark weight to compare and predict the growth performance of intensive juveniles.

After graduating from the nursery the growth potential of the juveniles may already be carved in stone and nothing can further be done to enhance it. Logic may even demand that the growth can deliberately be slowed down during the juvenile stage as the growth loss will most likely be fully recovered later. The rearing of juveniles at optimal temperatures may in fact be unnecessary and even wasteful, as the farmed cod will ultimately harvest its full potential in the grow-out phase anyway. Furthermore, if the juveniles are properly size-graded and deliberately underfed, a land-based farm may carry a much higher number of juveniles. This theory should be tested as it may be of utmost importance for the economics of land-based rearing of juveniles. If valuable resources are being wasted in the juvenile rearing, this must be rectified as soon as possible.

4.3.5. On-growing in sea-cages.

The results from the sea cage trial in the present study were disappointing, both in terms of growth performance and stock losses. A total loss of over 70%, as seen in this study, is unusually high and obviously far from being acceptable. Observed total losses of intensive cod stocked in sea cages are routinely 30-40% and as a rule of thumb approximately 1% of the original stock is lost per month of cage rearing (Theódór Kristjánsson, pers. comm.). Bacterial diseases and parasite infestations have been identified as the main cause for natural mortalities among caged cod (Kristmundsson et al. 2011). It is obvious that the disease resistance of farmed cod must be increased through improved husbandry and genetic selection but not least by improving the growth performance and shortening the rearing time. To reach the acceptable target of less than 20% losses, the rearing time from stocking to harvest should preferably be reduced by one whole calendar year.

In the main Icelandic farming grounds the mean yearly temperature is only 4-5°C which means that the growth capacity of the farmed cod is only 60-70% compared to an optimal mean temperature of 7-8°C (according to the growth model of Björnsson et al. 2007). In Norway, where the temperatures are higher, intensive cod routinely require 32-34 months from hatch to reach a 3 kg harvest size (Codfarmers AS 2011) whereas in Iceland some 40-42 months may be required to reach the same size. The results from the present study furthermore indicate that the stocking of larger temperature-boosted juveniles does not produce any significant long-term benefit.

It is therefore obvious that the only way to effectively produce farmed cod within a time-frame of only 32-34 months in Iceland is to stock juveniles with greater growth potential. This can be achieved primarily through improved start-feeding strategy and secondarily through selective breeding. A semi-intensive hatchery technology may be required to unleash the full growth potential of the farmed cod. An off-season juvenile production strategy may furthermore lengthen the effective time-frame for rearing by about 4-6 months. Predictions from the model of Björnsson et al. (2007) show that by stocking off-season juveniles during their first summer, land-based costs are minimized and potential harvest size increased by up to 20-25%.

The most feasible strategy for Icelandic full-cycle cod farming would thus be based primarily upon semi-intensive, off-season juveniles. The benefits can be numerous for the farmers, including larger harvest size, higher sale price, less mortalities, lower feed cost, lower juvenile cost and lower running cost. The intensive hatchery strategy should of course be developed and improved further but the semi-intensive strategy should be seriously considered as an option for Iceland. Disease resistance and genetic growth potential must also be improved through a continuous process of selective breeding.

4.3.6. Added value from the study.

All changes in growth performance and mortalities have a direct effect on production costs from farming. An improved growth performance will shorten the rearing time to harvest, increase the biomass turnover, increase production and revenues, reduce mortalities and improve the biological feed conversion. Reduced mortality will reduce the juvenile costs, the labour costs and the feed costs through an improved economic feed conversion.

In the original application, the AVS-factor of the study (Added Value of Seafood) was defined as new knowledge that might potentially lead to an ambitious 50% reduction in the variable operational costs in the full-cycle farming of cod in Iceland. This target was to be reached primarily by a reduction in the juvenile costs and the feeding costs. It was further proposed that the juvenile yield in Icelandic cod farming could be increased up to about 3 kg per juvenile. The results from the present study can be used to calculate the variable costs from theoretical cod farming situations and further compared to actual examples from commercial cod farming. The variable factors primarily affected by growth performance and losses are revenues, juvenile costs and feed costs (Table 7).

Table 7. A theoretical cost/profit analysis for groups A, B and D from the present study, compared to typical examples from commercial cage farming of cod in the Faroes (zooveniles), Norway and Iceland. All calculations are made on the basis of individual fish performance. Price assumptions: juveniles (120 ISK per juvenile), feed (200 ISK per kg) and sale price (450 ISK per kg whole cod). BFCR: biological feed conversion ratio, EFCR: economic feed conversion ratio. Profit = Revenues – juvenile costs – feed costs.

	Group A (tank)	Group B (tank)	Group D (cage)	Faroes (cage)	Norway (cage)	Iceland (cage)
Total stock losses (%)	15%	25%	76%	20%	35%	40%
Time 50 g to 3 kg (months)	22	32	36	19	26	36
Harvest yield (kg per year)	1,64	1,13	1,00	1,89	1,38	1,00
BFCR	1,05	1,12	1,20	1,05	1,20	1,20
EFCR	1,13	1,25	1,58	1,15	1,38	1,40
Juvenile yield (kg/juvenile)	2,55	2,25	0,72	2,40	1,95	1,80
Juvenile yield (kg/juv/year)	1,39	0,84	0,24	1,52	0,90	0,60
Revenues (ISK/year)	626	380	108	682	405	270
Juvenile costs (ISK/year)	141	160	500	150	185	200
Feed costs (ISK/year)	362	275	311	429	374	275
Juveniles + feed (ISK/year)	503	435	811	579	559	475
Juveniles + feed (ISK/kg)	308	387	811	305	404	475
Profit (ISK/year)	123	-56	-703	104	-154	-205

The calculations in Table 7 provide a theoretical example to show the dominating effect that growth performance and losses have on the most important variable costs. In the land-based trial the greater growth performance of group A produces much higher revenues than group B and turns a theoretical profit. The extreme stock losses and high EFCR of group D from the present study result in low revenues and high costs, which ultimately produce a large economic loss. The combination of fast growth (zooveniles) and low mortalities in the

Faroe example results in high revenues and a theoretical profit. The relatively high stock losses and high EFCR's in the examples from Norway and Iceland lead to a net operating loss in both cases. This comparison thus confirms the importance of juvenile quality and growth potential for the economy of cod farming.

It can be debated whether the results from the present study will lead to an added value of seafood by leading to a reduction in the variable production costs from the industry. The sea-cage trial was obviously not successful as the variable costs were approximately 8 times higher than the ultimate revenues! The variable costs from the land-based trial were, on the other hand, much lower and incidentally, the variable costs were about 50% lower in group A than in the Icelandic cage example. Furthermore, group A had about 20% lower variable costs than the early-weaned group B, thereby demonstrating the economic significance of juvenile quality. The juvenile yield from the land-based trial was very high but would have required a couple of months more to reach the target of 3 kg per juvenile.

4.3.7. The aims of the study.

In the original application, poor growth performance and high stock losses from sea cages, were identified as the main problems facing Icelandic cod farming. It was suggested that the suppressed growth potential of early weaned juveniles together with the sub-optimal temperatures applied during the land-based juvenile rearing were causing the poor growth performance. It was further hypothesized that boosting the growth juveniles with optimal temperatures during the land-based rearing would effectively increase the juvenile stocking size and that this initial size advantage would then be carried on to harvest. It was hoped that this way the elusive 3 kg harvest size could be reached after two summers at sea. These aspirations were, however, shown to be unrealistic as the growth performance of the boosted juveniles fell well short of the target. It must be concluded that, at present, the growth potential of intensive cod juveniles is insufficient to sustain adequate growth performance in the cold Icelandic fjords.

The primary aims defined in the original application were: 1) To investigate the relationship between larval growth performance and long term growth performance/feeding efficiency, 2) Grow a group of cod juveniles in land-based tanks to a mean weight of 5 kg in 30 months from hatch and 3) Grow a group of cod juveniles from a mean weight of 700 g to 4 kg in 19 months in a sea-cage in Berufjörður. It can be claimed that aim 1 has been successfully reached. The importance of early growth performance has been demonstrated and the results on the long-term growth dynamics are extremely interesting. Aim 2 was, however, far from being reached as the best group "only" reached a mean weight of 3.4 kg in 30 mph. This was still the best long-term growth performance ever reported for a group of intensive cod juveniles. Aim 3 was also far from being reached as the sea-cage group only reached a mean weight of 2.2 kg after 19 months in the cage. This poor performance can partly be explained by a lower initial weight, being only 470 g in stead of 700 g.

The ambitious original aims were based on predictions from the growth model of Björnsson et al. (2007) but the model has since been shown to overshoot the performance of intensive juveniles. The model is based on trial results with wild collected cod and further tuned to fit better to the reported growth of Norwegian zooveniles. Now, in retrospect, it must be admitted that the aims defined for this study were far too optimistic. The difference in growth performance of intensive- and semi-intensive/wild juveniles was much greater than originally anticipated.

4.3.8. Project evaluation- Lokamat (in Icelandic).

Í þessum kafla er framkvæmt lokamat á verkefninu samkvæmt fyrirmælum frá AVS-sjóðnum:

1. Hver er afurð verkefnisins?

Afurð verkefnisins er á formi þekkingar. Í þessu verkefni var í fyrsta sinn svo vitað sé fylgst með eldisþorski með reglulegum mælingum frá klaki og upp í markaðsstærð. Fiskurinn var allur einstaklingsmerktur og alinn við kjöraðstæður og stöðugt hitastig árið um kring sem eru aðstæður sem erlendar rannsóknastofnanir geta yfirleitt ekki státað af. Verkefnið var því um margt einstakt og gaf einstaklega skýra mynd af vaxtargetu þorsksins. Niðurstöður verkefnisins sýna það vöxtur á lirfustigi hefur varanleg áhrif á langtíma vaxtargetu og að eldisseiði eru almennt verulega vaxtarskert. Verkefnið sýnir jafnframt að eldisþorskur hefur línulegan þyngdarvöxt sem hefst á öðru aldursári og stendur í nokkur ár. Ennfremur að eldisþorskur hefur mun minni hámarksstærð en þorskur í villtri náttúru. Fjölmargt fleira mætti tína til eins og kemur fram í þessari lokaskýrslu.

2. Er afurðin einkaleyfishæf?

Nei.

3. Þarf að huga að eignarétti?

Nei.

4. Hvað verður gert við afurðina?

Óumdeilt er að um er að ræða nýja þekkingu sem nýst getur við þróun þorskeldis en jafnframt við fiskrannsóknir almennt. Gera má ráð fyrir að niðurstöður verkefnisins verði til þess að aðferðafræði við framleiðslu þorskseiða til eldis verði tekin til endurskoðunar á Íslandi. Mikilvægt er að þeir aðilar sem koma að þróun og uppbyggingu þorskeldis skilji hvaða þættir liggja að baki vaxtargetu eldisfisksins og taki ákvarðanir í samræmi við það. Hægt er að skýra stærðfræðilegan grunn vaxtargetunnar með einfaldri þríhyrningafræði í hnitakerfi og mun verkefnisstjóri kynna þær hugmyndir á næstu vikum og mánuðum. Vonir standa til þess að hægt verði að skrifa nokkrar athyglisverðar vísindagreinar þar sem þessar hugmyndir verða kynntar.

5. Stóðust áætlanir um afurð verkefnisins?

Áætlanir um nýja þekkingu stóðust algjörlega en aftur á móti stóðust væntingar um vöxt eldisfisksins ekki þær væntingar sem gerðar höfðu verið. Þegar verkefnið hófst var ekki vitað að stríðeldisseiði (alin á hjóldýrum og Artemíu) væru vaxtarskert og allar vaxtarspár voru því byggðar á vaxtarlíkani Björns Björnssonar o.fl. (2007). Vaxtarlíkanið var hins vegar aðlagað að vexti svokallaðra pollaseiða (alin á villtu dýrasvifi) frá Noregi og samanburður hefur nú leitt í ljós að slík seiði hafa mun meiri vaxtargetu en stríðeldisseiðin. Hin skerta vaxtargeta stríðeldisseiðanna í þessari tilraun varð hins vegar til þess að hægt var að rekja rót vaxtargetunnar aftur á lirfustig þorsksins.

6. Stóðst verkefnið tímaáætlun?

Upphafleg tímaáætlun stóðst algjörlega hvað varðar allar framkvæmdir. Úrvinnsla gagna og skýrsluskrif hafa hins vegar dregist um rúmt ár og ítrekað hefur verið sótt um frest fyrir skil á lokaskýrslu. Um er að ræða mjög ítarleg rannsóknagögn og verkefnisstjóri hefur jafnframt þurft að sinna ýmsum ófyrirséðum aðkallandi verkefnum sem hafa tafið verkið.

7. Stóðst verkefnið fjárhagsáætlun?

Eins og fram kemur í meðfylgjandi fjármálauppgjöri hafa ýmsir kostnaðarliðir þróast öðruvísi en áætlað hafði verið og þá ýmist til hækkunar eða lækkunar. Umfang fóðrunar varð mun minna en áætlað var en á móti komu miklar hækkanir á fóðurverði. Fóðurkostnaðurinn varð engu að síður um 700 þúsund krónum minni en reiknað var með. Úrvinnsla og skýrsluvinna varð aftur á móti mjög tímafrek þ.a. launakostnaður varð um 700 þúsund krónum meiri en áætlað var (aukning um einn mánuð sérfræðings). Aðrir liðir voru nokkurn veginn á pari þ.a. heildaruppgjör verkefnisins hljóðaði upp á 103% af fjárhagsáætlun.

8. Stóðst verkefnið framkvæmdaáætlun, var allt gert sem átti að gera?

Í stuttu máli sagt þá stóðst framkvæmdaáætlun verkefnisins algjörlega og var í fullu samræmi við það sem upphafleg áætlun gerði ráð fyrir.

9. Var afrakstur verkefnisins sá sami og vænst var í upphafi?

Í upphaflegri áætlun voru skilgreind mjög metnaðarfull (bjartsýn?) markmið varðandi langtímavöxt eldisþorsksins og óhætt er að segja að þau markmið hafi ekki náðst. Engu að síður var vöxtur fisksins sennilega sá mesti sem nokkurn tímann hefur náðst í eldi stríðeldisþorsks, hvort sem litið er til innlendra eða erlendra rannsókna eða eldis. Afrakstur varðandi nýja þekkingu var hins vegar í fullu samræmi við uphafleg markmið.

10. Hvað kostaði verkefnið?

Heildarkostnaður verkefnisins var samkvæmt fjármálauppgjöri 9.108.900 krónur.

5. Conclusions.

The results from the present study suggest that the long-term growth performance of farmed cod is affected by various factors, such as egg size, start-feeding diet, hatchery temperatures, juvenile rearing temperatures, salinity exposure, deformities and size-grading. The start-feeding diet seems to be the single most important factor and apparently the intensive start-feeding protocol is presently not able to meet the full nutritional requirements of the larvae during the critical larval stage. As a result, the long-term growth potential of hatchery juveniles appears to be seriously compromised and much smaller than reported for either wild or zooplankton-fed juveniles. It appears that the developing cod farming industry is largely being supplied with growth-suppressed juveniles. As a consequence the required rearing time in sea cages becomes overly long and the fish struggle to reach harvestable size.

The high survival and relatively good growth performance in the land-based trial was better than ever reported from any research- or commercial rearing of intensive cod juveniles. Land-based rearing of cod until harvest is, however, not considered economically viable and sea-cage rearing is presently the only realistic option for cod farming (Eðvaldsson . The results from the sea-cage trial were not encouraging but informative nonetheless. Due to the low ambient sea temperatures in the Icelandic farming grounds, the growth potential is temperature-limited and therefore the innate growth potential must be maximized. It is very important to reach harvest size in no more than 32-34 months from hatch to minimize losses and reduce costs but, regrettably, there is no indication that this target can be reached in Iceland in the near future based on the farming of intensive juveniles. It can be concluded that Icelandic codfarmers should focus on the production of juveniles with un-restricted growth potential. This may perhaps be achieved with a semi-intensive hatchery technology.

The results from the present study may suggest that cod farming can be potentially feasible in Iceland but only if it is based on high quality juveniles. The biggest challenge of the cod farming community in the coming years is clearly to unleash the innate growth potential of farmed cod and create the necessary foundation for a viable farming industry.

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