Aquacult Int (2016) 24:757–766
DOI 10.1007/s10499-016-9994-z

Challenges and emerging technical solutions in on-growing salmon farming

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Received: 3 November 2014 / Accepted: 12 March 2016 / Published online: 23 March 2016

Abstract Farming of Atlantic salmon has grown rapidly from its start in the early 1970s until today, with production approaching two million tonnes. Sea cages are the dominant production system for the on-growing stage of salmon farming. It represents an effective production system with lower investment and running costs than land-based systems. The development and improvement of the sea cage farming system has been one of the most important factors for the growth of the salmon farming industry. However, during recent years certain problems related to their placement in the open marine environment have proved highly challenging, increasing operating costs and impacting on industry public relations. The problems are mainly due to parasites, diseases and escape of fish. In this article, emerging technical solutions for solving those problems are described.

Keywords Salmon · Aquaculture · Sealice · Escapes · Technology

Abbreviations

RAS	Recirculating aquaculture systems
IMTA	Integrated multitrophic aquaculture
MAB	Maximum allowed biomass

Guest editors: Elena Mente and Aad Smaal/European Aquaculture Development since 1993: The benefits of aquaculture to Europe and the perspectives of European aquaculture production.

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Introduction

The worldwide production of farmed Atlantic salmon has increased rapidly since its inception in the early 1970', approaching two million tonnes per annum in 2012 (FAO 2012; Asche et al. 2013). Output growth throughout most of this period has been supported through reduction in production costs, although these have stabilized in recent years. Indeed, in Norway, production costs increased between 2005 and 2014 (Directorate of Fisheries, Norway 2015). The production cycle for salmon is well understood and controlled (Stead and Laird 2002; Lucas and Southgate 2012), and effective farming technologies have been developed (Beveridge 2004; Lekang 2013), resulting in profitable production. The production is typically carried out in two phases, a freshwater phase in tanks on land from egg to smolt, ready to live in sea water (typically 100 g), and a grow-out phase until harvesting (4-6 kg approximately). In the grow-out stage, when the salmon becomes bigger and the need for space and exchange of water increases, the farming takes place in open sea cages. With good management and at adequate scale, these represent an effective and economic system. The development and improvement of the sea cage farming system has been one of the most important factors for the growth of the salmon farming industry. However, in recent years, significant problems and constraints with cage farming of salmon have proved difficult to overcome and probably account for some of the increase in production costs. Some of the larger salmon-producing companies are now searching for alternative production technologies for the on-growing salmon phase.

This article aims to describe the technical solutions (under development and recently developed) that tackle the problems related to sea cage farming of salmon.

Cage-based salmon production

Cage-based production, not only for salmon but also for a number of other species, is increasing worldwide. The growth is mainly in seawater farming, although in some countries in fresh water. A general trend is to utilize increasingly exposed offshore sites. Cage-based farming requires lower capital investment per unit of production and, at adequate scale, has lower operating costs than other methods of intensive aquaculture (Beveridge 2004; Halwart et al. 2007). The investment cost per cubic meter of farm capacity is low, and no energy is needed to ensure a proper water exchange, resulting in a low carbon footprint. This of course requires that the cages are located on a site where the speed of the natural current satisfies the essential levels of water exchange.

Problems with net cage farming

Cage-based farming can have negative environmental consequences. Cages are directly exposed to an open environment, so the stock can be affected by environmental factors and the wider environment can be directly affected by the production in the cages. This is mainly through the release of nutrients and organic matter which is dispersed into the environment. However, as long as this release does not exceed the self-cleaning capacity of the site, no negative accumulation occurs (Cross 2013; Telfer et al. 2013). Modeling these environmental services in order to predict the carrying capacity of individual sites has proved an effective mean of management [e.g., the MOM system (Modelling–Ongrowing fish farms–Monitoring) Ervik et al. 1997; Hansen et al. 2001]. There is also the potential to locally enhance carrying capacities through management approaches such as IMTA (integrated multitrophic aquaculture), which is described later.

Two problems that have been particular points of focus in recent years with respect to on-growing salmon in sea cages concern the control of diseases and parasites and the escape of fish. Sea lice (mainly *Lepeophtheirus salmonis* and *Caligus rogercresseyi*) is the parasite that has caused the largest problems in recent years, while amebic gill disease (AGD—e.g., *Neoparamoeba* sp.) has also emerged as a major problem for most salmon-producing countries (Bustos et al. 2011; Hamish 2014). Pancreas disease (PD) is probably the most important viral disease affecting global Atlantic salmon production.

For the Norwegian salmon industry, the severity of these problems is so great that the majority of the on-growing salmon producers are looking for alternative solutions and technologies. The government of Norway also have these problems on their agenda. A number of new "green salmon farm licenses" have recently been distributed to the aquaculture industry. To obtain such licenses, there is a requirement that technology and production methods must clearly decrease the possibilities of fish escape and they should better address the sea lice problem. Conversely, some farming companies have seen a reduction in their production license capacity (reduction in maximum allowed biomass, MAB), because they have not been doing enough to combat problems with sea lice. For these reasons, the development of new production methods and technologies that could prevent and control the problems with parasites and escape of fish has been stimulated. Emerging solutions can be grouped into those that target the sea lice problem, the ones that reduce the possibilities for escape of salmon, and the systems targeting both problems.

The combat against sea lice

In Norway, where intensive cage farming is dominated by on-growing salmon production, there is a great fight against sea lice. The same situation occurs in most of the countries producing salmon. Sea lice are not only creating problems for the farmed fish inside the cage, but can also affect wild fish in the surrounding area (Marty et al. 2010; Torrissen et al. 2013). Additionally, resistance has emerged against all licensed chemical treatments (Bergheim 2012; Igboeli et al. 2014).

In some instances, the sea lice problem has become so great that the fish in the cages need to be slaughtered. Therefore, a number of new management methods have been recently developed and some are still under development (Grøntvedt 2014).

Biological treatment with wrasse to clean the salmon from sea lice is a method that has been tested for over 20 years, but has been more widely adopted in recent years (Bjordal 1991; Skiftesvik et al. 2013). Also new species (lumpfish) feeding on sea lice have been introduced to optimize the biological treatment at lower temperatures (Imsland et al. 2014). The industry is currently moving from initial reliance on limited supplies of wild caught "cleaning fish" to more secure and sustainable use of aquaculture produced stocks. Another relatively new method exploits the fact that motile stages of sea lice mainly inhabit near surface waters. A plankton net or skirt, which is a semi-closed tarpaulin, is hung around individual cages reaching 5–10 m depth (Stien et al. 2012; Frank et al. 2013; Lien et al. 2014). In this way, the motile sea lice larva is inhibited to enter into the cages. An alternative solution under development is to individually clean each fish mechanically by a water jet (Flatsetsund Engineering AS 2014). A more advanced system that is under development is the sea lice laser canon, a combined camera and laser canon which is placed inside the cage. When a sea lice are detected on a fish, a laser beam is fired to kill the sea lice (Beck Engineering 2014). Practical methods for cleaning using fresh water are under development by other companies as the sea lice will drop off from fish when they are held in freshwater (Powell and Kristensen 2014). A thermo-cleaning treatment of the fish with hot water for a short period is also under development (OCEA 2014).

There is considerable interest at present in the development of integrated multitrophic aquaculture (IMTA) which could, for instance, combine sea cage salmon farming with other biological cultures (Troell et al. 2009; Chopin et al. 2012; Lander et al. 2013; Leonczek 2013; Irisarri et al. 2015). Poly-culture is regarded as positive with respect to the environmental impact of the sea cage farming, because other organisms can feed on the waste products from salmon farms for their own growth, resulting in an increase of total yield. However, the production of such combined systems compared to a monoculture of salmon needs to be further assessed with respect to its economical sustainability over a long period of time. However, there may be another positive impact on salmon culture, which also could improve the overall production results. The inclusion within an IMTA system of blue mussels, which can feed on the early life stages of sea lice parasites and other disease organisms (Bartsch et al. 2013; Molloy et al. 2014), could significantly reduce the disease load on the salmon. In this way the addition of bivalve culture to the farming system will function as a barrier for parasites passing through the sea cage farm.

In addition to the development of technical solutions and improved production systems, it has been shown that different salmon strains have different natural resistances against sea lice. Based on this, breeding programs for selecting the strains with higher resistances against sea lice have been developed (AquaGen 2013; Salmo Breed 2014).

Avoiding fish escape from traditional offshore sea cages

The escape of selectively bred farmed fish from open sea cages represents a problem because of the risk of genetic mixing with the local strains (Jonsson and Jonsson 2011; Liu et al. 2011; Sepúlveda et al. 2013). Local strains have evolved to adapt to the wild conditions in the area for generations. The numbers of escapee fish are especially critical when the local wild population is small or is declining. If a large number of farmed salmon escape in an environment where the wild salmon population is low, the consequences for the wild strains could be substantial.

There are several ways to reduce the possibilities of escape (Prevent Escape 2014). Research from Norway shows that bad management or failure of operational or maintenance routines are a major reason for escape (Jensen et al. 2010). Improving management and routines is therefore an important factor to reduce escape (Thorvaldsen et al. 2015). In Chile (Sepúlveda et al. 2013), the following reasons for escape were listed: severe weather conditions (29 %), theft (21 %), structural failure of netpens, and deficient handling of incidents (18 %). Several technologies have been utilized to reduce the possibilities for fish escape. Use of double nets (Moe et al. 2009) and use of thicker treads in the net of the bags are examples that could reduce opportunities for fish to escape. Double nets and thicker treads may however have a negative impact since they reduce the water exchange, and thus, they can increase the environmental loads on the farming area (Moe et al. 2005).

Stronger materials than the traditional multifilament polyamide may also be used to avoid thickenings of the nets to ultimately avoid reductions of water exchange. Several materials can be mentioned here such as polyethylene terephthalate (PET), steel, copper, and zinc (Moe et al. 2009; Tsukrov et al. 2011; Cha et al. 2013; Dwikartika and Casanova 2013; Gansel et al. 2013). The strength of the mooring lines may also be improved, for instance, by using aramid (Kevlar) or CNT threads in the ropes (Handy 2012). Better monitoring of the environmental forces acting on the cage structure, including net bags and mooring lines, will also help to create better designs and to select the correct materials. This can be achieved, for example, through the installation of tension sensors on the mooring lines (Priour and Degres 1995; European Commission—CORDIS (Community Research and Development Information Service) (2014); Wu et al. 2014).

A new method under development is to install electrical wires in the threads of the net bag (Maitri and Kevin 2013; Havtek 2014). By continuously monitoring an electrical current through these wires, eventual failures and holes in the net bag can be detected quickly. This system can be installed in the entire net bag or only in the areas of greater mechanical stresses.

In large sea cages, on moderately exposed sites, bottom rings (sinker tubes) are commonly used to maintain the shape of the net bags in the water. However, this may represent a problem because the net bag can be exposed to physical wear in the connection points between the bottom ring and the net bag. The result may be damage of the net bag and an escape of fish. Improved designs that better integrate the sinker tube into the overall cage, net, and mooring design (e.g., Aqualine Midgard System, Aqualine 2014) are expected to eliminate this problem.

Besides the focus on improving technologies, there have been developments and tests of the production of sterile triploid fish, where the consequences of any escape may be lower for the wild salmon populations. Newly released information from commercial farming of triploid salmon so far seems promising when using an adapted diet (Norway Royal Salmon ASA 2015; Forskning 2015).

Alternative production systems

Closed sea cages

A method to avoid problems with sea lice, microorganisms, algae, jellyfish, and the general problems with the environmental impact of cage farming, is to utilize sea cages without the openings of the nets, using “closed” materials. This is referred to as “closed sea cages” or “semi-closed sea cages.” The concept behind such systems is that they should be cheaper to build and to operate than land-based tanks. The pumping of water into such cage units represents one of the additional production costs compared with traditional sea cages. However, this involves a lower pump head than would be the case with land-based tanks, resulting in lower production cost. Another important factor is that no land area is needed for the farming units. Establishing large tank-based farms on the shoreline can potentially produce large environmental impacts which can be avoided if closed sea cages are used. An example could be the modification of the natural landscape if blasting is needed to level the ground for the farm. Also, the energy and carbon footprint used to make land-based farms are larger than the footprint of closed sea cages, due to the fuel needed for construction machinery and transport of heavy construction materials, etc. Often, it is also of general interest that the public shall have access to the shoreline.

Several materials have been used, and some are still under development to build closed sea cages (Chadwick et al. 2010; Ping et al. 2014; Sveen 2014). Examples are bags made of tarpaulin, polyethylene, or domes cast in fiberglass. Concrete or steel may also be used for these types of constructions, but the cost and environmental footprints increase. Commercial results from such designs are still limited.

Land-based on-growing

To move on-growing farms on-shore is another solution to the problems with escapes and sea lice. A land-based farm will have greater security against environmentally caused cage failures (e.g., waves and water currents). In land-based farms it is also possible to add a double security by building a wall around the tank area (requirement for smolt farms in Norway). If a structural failure occurs in a land-based tank, the salmon will have less possibility to escape. As with closed sea cages, it is also possible to treat the inlet water or to take water from depths with reduced concentrations of parasites, and by this reduce the sea lice problem. An additional advantage of moving the farm on-shore, it is that by having the outlet water channeled, it is easier to handle and treat the waste effluent.

In the 1990s there was also an interest for moving on-growing salmon farms on-shore. Around 10 commercial land-based on-growing Atlantic salmon farms with capacities above 10,000 m^3 of effective farming volume were established in Norway and Iceland (Lekang 1991; Lekang and Fjæra 1992). Seawater was oxygenated and pumped through large on-shore tanks. The economic results from these establishments were negative, and the farms either closed down their activities or they went bankrupt after some years. Even if theoretically they should be profitable, results from real production cases show the opposite. Problems were related to maintaining high fish densities and creating effective systems for movement of fish between tanks. Capital investment and running cost are also substantially higher on a per m^3 farming volume basis, so require a higher effective fish density to be profitable.

The main difference between the original land-based farms and those that are being established today is that new builds are typically recirculating aquaculture systems (RAS) (Summerfelt and Christianson 2014). This allows them to operate at higher water temperatures which lead to better growth rates, and potentially a higher stock turnover per m^3 of farm volume. The pumping cost may also be slightly reduced due to lower lifting head, avoiding the need to lift large volumes of sea water from sea level into the farm tanks. Pump pressure head is only needed to compensate the head loss in the RAS circuit. However, a RAS plant requires higher investment cost than a traditional flow through farm and until now, no commercial size land-based farms have run for long enough to document their production results and economics over time.

Offshore cage farming

There are trials and a new impetus for moving the traditional sea cage farms to far more exposed sites. By doing that, it is possible to increase both the size and number of sites. The distance between farms could also be substantially increased, reducing the possibilities for interactions among the farms. This could help prevent or at least minimize the problem of transfer of parasites and diseases between farms. Using offshore cage farming could reduce the risk of genetic mixing or of parasites and diseases from farmed fish affecting the local wild salmon as a consequence of not having escapee farmed salmon in the fjords. The fjords are the required path for wild salmon to move between the oceans and rivers.

As waste dispersal and hence the self-cleaning capacity will be much higher in exposed sites, the total farmed biomass could be increased. By having a higher biomass, and a higher total production, the cost per kg fish can be reduced. However, the investment cost would be higher because the equipment must tolerate more aggressive currents and larger waves (Ocean Farming 2015).

Combining offshore aquaculture facilities with other offshore facilities such as wind farms and oil and gas production facilities is an interesting possibility to reduce the overall installations and running costs (Mee 2006; Benassai et al. 2014).

New production regimes; increased smolt size: production of postsmolt

Another strategy undergoing trials is to increase the size of smolts before transferring them to the open sea cages. The rationale for this is to make the fish stronger against possible sea lice attack. By setting out a larger fish, nets with a larger mesh size can be used which reduces the necessity for changing nets during the production period. This will reduce the number of handling operations where there is a critical risk of fish escape. The overall time fish spend in open sea cages will be reduced as well.

Several Norwegian smolt production plants are today increasing the size of the production facilities to provide possibilities for increasing the smolt size above the traditional 60–100 g. Two strategies are available for the farms. One is to produce larger size smolts, up to 250 g, and the other way is to keep the fish until the first stage of the on-growing phase on the smolt farm, producing a postsmolt. The production of a larger size smolt will however increase the requirement for freshwater, which is already a constraint for many smolt farms. The solution here is the use of RAS systems which will also contribute to higher fish growth rates through the use of higher water temperatures. Sea water can also be used in a RAS land farm, and the produced fish could reach higher weights (e.g., 1 kg). However, the economically optimal size for transfer is not known. By using such systems, the typical boundaries between smolt farms and on-growing farms for salmon will be redrawn. It could either be that the smolt farms would start producing postsmolt for later transfer to on-growing farms, or that the on-growing farms have their own department for early on-growing, where they grow ordinary smolts. This can be done in land-based farms or in closed sea cage farms. In this way, the industry could change its structure from smolt and on-growing to a future three-stage model, (1) ordinary smolt production, (2) an early on-growing/postsmolt, and (3) an on-growing (grown fish), three farms on three different sites.

Future perspectives

To continue the growth in farmed salmon production, there is a need to find solutions for the on-growing phase concerning both the environmental and economic sustainability, especially to tackle the problems with parasites, diseases, and fish escapes. Therefore, the development of new technologies and production methods will continue. The future will probably hold a greater diversity of production methods and technologies. The development of land-based systems with different percentages of water reused, closed cage technology, and sea cage technology tolerating larger mechanical stresses will continue. The efforts will also include an increased number of production sites, which is required to continue the growth in salmon production. The typical two-stage salmon production process may be re-drawn, and there will probably be a variety of production regimes. This will also set new requirements for the production license system and which fish sizes and water quality criteria to include.

Besides new technologies and new production methods, the most important contributor to ensure a further economically sustainable growth in salmon farming will be vaccine development. This has so far been very effective for a number of diseases in salmon aquaculture. It will also be interesting to follow the production of triploid salmon regarding production economy. If both prove to be successful, they will be an important contributor for the future growth of farming in sea cages.

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