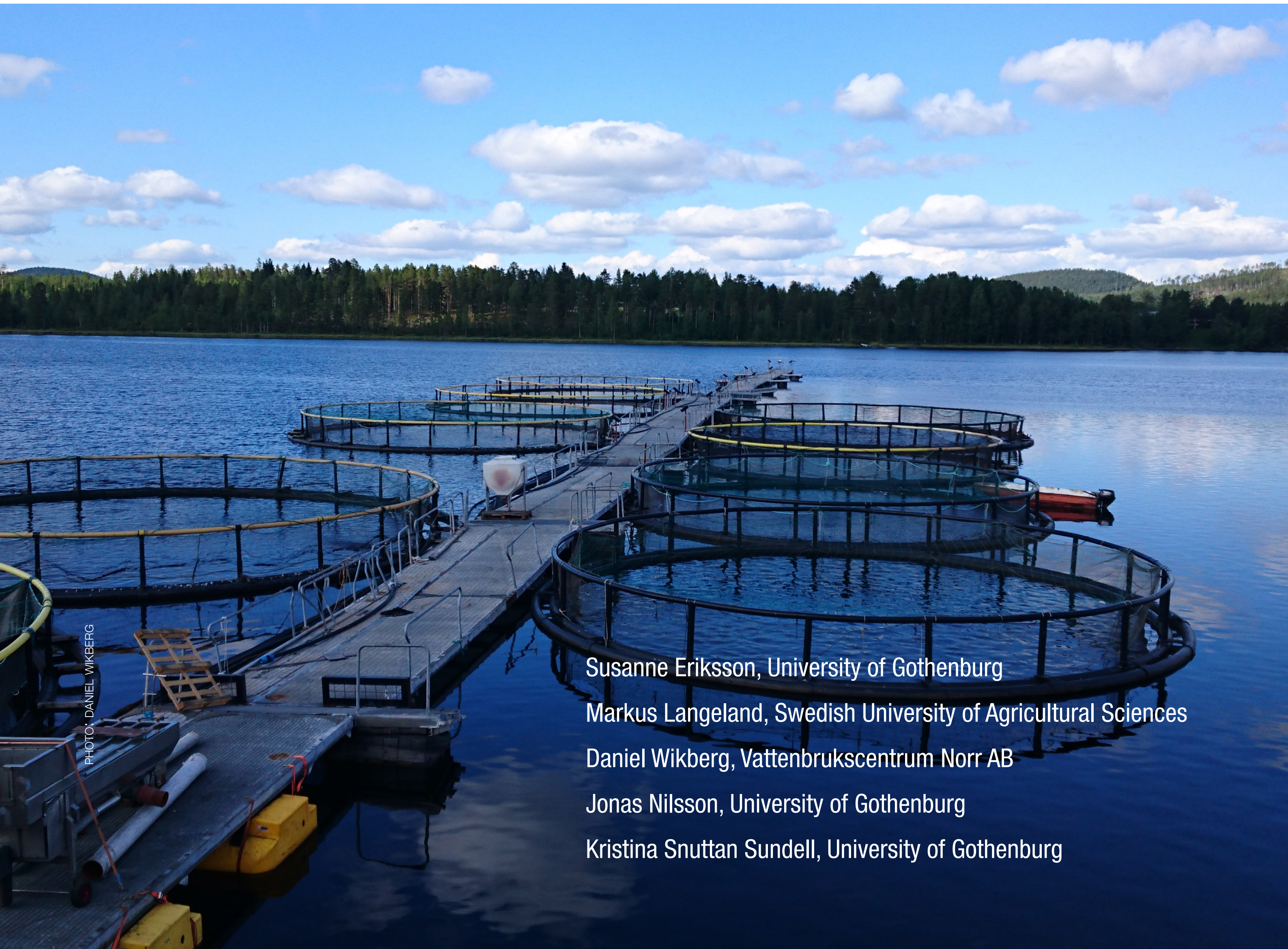
OVERVIEW OF FARMING TECHNIQUES FOR AQUACULTURE IN SWEDEN

– environmental impact, production systems, species and feeds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Susanne Eriksson, University of Gothenburg
Markus Langeland, Swedish University of Agricultural Sciences
Daniel Wikberg, Vattenbrukscentrum Norr AB
Jonas Nilsson, University of Gothenburg
Kristina Snuttan Sundell, University of Gothenburg

2017 report by [1]Susanne Eriksson, [2]Markus Langeland, [3]Daniel Wikberg, [4]Jonas Nilsson, [1]Kristina Snuttan Sundell
[1]SWEMARC & Department of Biological and Environmental Sciences, University of Gothenburg, [2]Department of Animal Nutrition and Management, Swedish University of Agricultural Sciences, [3]Vattenbrukscentrum Norr AB, [4]Department of Law, University of Gothenburg on behalf of the Swedish Agency for Marine and Water Management.
Consultants:
Tina Hedlund, Aquanord AB, Krokom, specialising in open systems for intensive fish farming in open systems and their environmental impact, as well as location and monitoring
Daniel Bergfors, Umlax AB, specialising in practical expertise relating to intensive fish farming in open systems
Reviewed by:
Anders Alanärä, Professor, Department of Wildlife, Fish, and Environmental Studies, Swedish University of Agricultural Sciences
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PREFACE

This reported been produced by the University of Gothenburg (GU), the Swedish University of Agricultural Sciences (SLU) and Vattenbrukscentrum Norr AB (VBCN) on behalf of the Swedish Agency for Marine and Water Management (HaV), and describes available and potential techniques for aquaculture in a Swedish environment. This report provides a review of existing knowledge relating to farming techniques and their impact on the environment on the basis of scientific aspects and published data. The review provides a description of techniques that can be used in Sweden to farm aquatic organisms (fish, molluscs, shellfish, algae) in freshwater and seawater environments as well as in land-based production systems. The report describes whether the techniques are industrially accessible or at the experimental stage, and also indicates the current state of knowledge in the field.

The review of existing knowledge will constitute one of the documents for the Swedish Agency for Marine and Water Management's guidance efforts, but it does not represent any stance on the part of the authority. The authors are responsible for the report's content and summaries.

Gothenburg, November 2017

Björn Sjöberg
Head of Department, Swedish Agency for Marine and Water Management, HaV

Swedish Agency for Marine and Water Management

SUMMARY

The technical development of environmentally sustainable forms of production is progressing rapidly in the field of aquaculture, in terms of both the more traditional open systems and the more recent, semiclosed and closed production systems. Different techniques are appropriate in different habitat types, but a number of techniques may also be appropriate for one and the same habitat. Furthermore, the most appropriate technique also varies depending on the species and size of the fish that are farmed. A number of production systems with potential are still merely at the prototype stage, but many others are undergoing constant development and are being operated on a lesser commercial scale as they undergo technical development.

This report provides a review of existing knowledge and an overview of various farming techniques that are currently in use at commercial fish farms, being tested on a smaller scale or at the prototype stage; but all of them could potentially be used in Sweden. The report also includes a description of the general environmental impact of the various technique types, focusing in particular on aqua feed ingredients currently used in aquaculture, and some potential feed ingredients for the future. The farming techniques are undergoing constant, rapid development in terms of water treatment systems, facility types, water consumption, diversification of species, integration between species, and so forth. These new techniques offer major potential for reduction of environmental impact, but they but may need to be developed through continued research and technical innovations.

The majority of Swedish aquaculture production currently takes place in open systems, using a tried and tested farming technique where the farm is in direct contact with the environment around it. Sweden has a small number of large-scale fish farmers who work with open cages and produce hundreds or thousands of tonnes of fish annually. Most of their environmental impact is due to emissions of nutrients and organic matter in metabolites, faeces and feed residues. Fish cages are open production systems with a natural flow-through system and hence oxygen supply. Placing production systems of this type in nutrient-loaded environments – eutrophic or hypertrophic environments – is less appropriate. Although the local environmental requirements are in place, with good water circulation and a moderately nutritious (mesotrophic) environment, the general conditions in the recipient should be taken into account as dissolved nutrients can be transported into adjacent areas by means of currents. Land-based open facilities with flow-through systems are used primarily for producing fish for consumption. Water is allowed to pass freely through some of these facilities, while others remove a majority of the particulate material before the water is discharged to the recipient.

Open, extensive farming also takes place in marine and brackish water environments, where the organisms are attached to the farming substrate (e.g. lines or nets) or in cages on the bed and absorb nutrients and feed directly from the water or the bed and bind into biomass. Blue mussels are farmed on a commercial scale (~1500 tonnes), mainly on the west coast. Farmed organisms of this type extract nutrients from the environment and constitute a positive ecosystem service when harvested. Co-farming of fish and extractive species also constitutes elements of IMTA (integrated multitrophic aquaculture); integrated, sea-based, multi-species production systems where the extractive species can balance out the net effect of fish farming that involves the addition of nutrients. They can also provide protective farming in nutrient-loaded environments. There are more potential extractive species in the marine environment (such as ascidians, oysters, the brown alga sugar kelp and detritivores) than in brackish water and freshwater environments. There is further potential for co-farming through the flow of nutrients from land-based aquaculture up on land to farming of plants (aquaponics) and the flow of nutrients from various types of aquaculture for farming of insects, but these systems are not discussed in this report.

Smolt production takes place on land in the Norwegian salmon industry. There is a development towards production of larger smolt and production in more closed systems. The final grow-out usually takes place in traditional open cages in the sea. However, this too involves technical developments resulting in more closed/controllable systems in the sea. The major driving forces for these technological developments are to reduce infections by parasites and pathogens, reduce the number of escapes and increase productivity by improving the health and welfare of the farmed fish. The emphasis is on increasing the barriers – i.e. reducing the exchange between farmed fish and their surroundings – and increasing control of the environment inside the farm. This leads to reduced impact on the environment, such as effects on the ecosystem due to emissions of nutrients, while also resulting in a more stable, more accurately adapted environment for the farmed organisms.

New types of semiclosed or closed production systems provide alternatives for greater control and optimisation of the environment for the fish, reduced exchange and hence less impact on the environment in the form of escapes and nutrient load, for example. In semiclosed production systems in seas or lakes, the fish are enclosed in a hard or soft outer shell and have no direct contact with the surrounding environment. Water is pumped into the farm from any depth beneath the farm and discharged via specific outlets. Most of the total solids are deposited and/or filtered on their way out from the culture chamber and dealt with, while nutrients and dissolved organic substances pass out. This technical development is particularly apparent in Norway, so as to be able to increase the numbers of fish that are farmed in closed systems there. Reducing the parasitic pressure from salmon lice is one of the major driving forces for the development of semiclosed systems in Norway, as the water is brought in from areas that are deeper than those in which salmon lice exist. However, this is not a problem in many water zones in Sweden as salmon lice exist only in the marine environment. This method has potential as far as Swedish aquaculture is concerned, but semiclosed systems are still relatively new on the market and experience is limited.

Land-based systems are available in many forms: flow-through systems with or without treatment of the outgoing water, partial or fully recirculating systems (e.g. RAS, biofloc and aquaponics). Farming aquatic organisms in seas/lakes and waterways requires little energy, but the species farmed need to be adapted to the prevailing natural conditions, such as climate and water quality. If farming is transferred to land, the environment can be controlled more effectively and the number of potential species increases. Biological expertise, technical development and uncertain financial outcomes from investments limit what can be farmed in practice. Initial factors such as the cost of investment in construction and, later, energy costs for heating, cooling, pumping, water treatment, oxygen, etc. constitute more specific costs for land-based farms.

The direct environmental impact of closed and recirculating systems on land is low, and escapes are more or less non-existent. However, there is always a certain amount of water exchange, and the environmental burden from wastewater and sludge is primarily dependent on the treatment capacity of the facility. One disadvantage is that dependency on technology and expertise with closed, land-based production systems is greater compared with traditional open systems. Land-based farming for food production is taking place in Sweden at present, on scales ranging from tens to hundreds of tonnes. Truly large-scale production is not up and running as yet, but a number of smaller companies and research initiatives do exist.

The use of chemicals in Swedish farming is relatively low for all types of production system, but a certain amount of treatment of fish/fry or disinfection of water/equipment does take place. Use of pharmaceutical agents in Swedish aquaculture is generally low. Antibiotics are only used in the event of outbreaks of disease, and these are prescribed by veterinary surgeons in Swedish aquaculture. The total amount of active antibiotics used at fish farms in Sweden between 2010 and 2015 was equivalent to half or less of the corresponding figure for other Swedish meat production.

The amount of fishmeal in aqua feeds has been reduced significantly since the mid-2000s, but despite this the majority of fishmeal produced goes to the aquaculture industry. This is due to the overall increase in production volumes in aquaculture. Fishmeal has primarily been replaced by various types of vegetable protein, particularly soya, and an increasing proportion of the feed is made up of raw materials from residual flows, such as fish protein and oil from slaughterhouse waste, but these are unable to meet all of the growing need for feed ingredients. Alternative feed ingredients have to be identified and trialled in order to devise a form of aquaculture that is sustainable in environmental terms. New feed sources must meet the nutrient requirements of the fish/animals, be highly digestible and palatable and – not least – be free of substances that impair absorption, metabolism or health. Inclusion of fish oil has also been reduced, but not at the same pace as with regard to fishmeal.

In the long term, aquaculture feeds must be based on raw materials that do not compete directly with human consumption, and on circular nutrient flows (cycles) where nutrients are not lost, resulting in impact on the environment. As things stand at present, Swedish fish farmers are referred primarily to the major feed producers, which are very much controlled by finances and – not least – large volumes of raw materials, and ensure that the raw materials are approved and included in feeds. This is why innovations in terms of feeds may take a relatively long time to reach the commercial market at competitive prices.

BACKGROUND

The world's population is expected to exceed 9½ billion people by 2050 (United Nations, World Population Prospects 2017[1]). Producing nutritious food for everyone, in an eco-friendly way, is one of the greatest challenges faced. Fish consumption per capita has more than doubled since 1960, and wild fish stocks are overfished in many instances. This is why aquaculture has undergone massive development in order to meet the growing demand for fish and shellfish; and nowadays more than half the fish consumed globally is farmed (FAO, 2016). That said, aquaculture is a relatively small industry in Sweden, although it is the fastest growing food sector on a global level. Hence a great deal of farmed fish is imported to Sweden. A number of international and national reports and publications indicate that there is increasing interest in developing Swedish aquaculture, and an increasing need to do so.

The Swedish Board of Agriculture's 2012-2020 strategy, entitled "Svenskt vattenbruk – en grön näring på blå åkrar" [Swedish aquaculture – a green industry on blue fields] highlights aquaculture as a future industry offering major potential for growth. In the associated action plan, the Swedish Board of Agriculture has identified for each action a convening organisation responsible for commencing cooperation with regard to the action by communicating with other designated implementers. This is in line with the EU's objective, whereby every member state will have its own aquaculture strategy. The Swedish Board of Agriculture's vision is that *"Swedish aquaculture is a growing, profitable and sustainable industry, with ethical production"*. This vision is also shared by the government's Maritime Strategy (August 2015), which emphasises *"Sweden's opportunity to take advantage of technical achievements within companies and projects with a view to promoting growth and new jobs. Environmental challenges can be turned into advantages by ensuring that Sweden is a potential leader in the field of environmental technology, and Swedish companies may gain competitive advantages with eco-friendly solutions. Hence the government wishes to support the development of sustainable aquaculture"*; along with the recently presented Food Strategy "En livsmedelsstrategi för Sverige – fler jobb och hållbar tillväxt i hela landet" [A food strategy for Sweden – more jobs and sustainable growth throughout the country] (December 2016), where the government has identified aquaculture as one of the issues of particular importance if the overall objectives are to be attained. The government's assessment is as follows: *"Marine foods and resources have the potential to meet increased demand. Water zones for sustainable aquaculture, such as fish farms, shellfish farms, oyster farms and mussel farms, should be made available in order to reinforce Swedish aquaculture 'within this strategic area'"*.

Protein production needs to increase globally in order to meet the needs of the growing population. According to the UN body FAO (Food and Agricultural Organization), fish consumption per world inhabitant and year has increased from 10 kg to almost 20 kg over the past 50 years (FAO 2014). This development is being driven by a combination of population growth, increasing incomes and urbanisation. Fish protein is an important nutrient component in certain densely populated countries, where total protein intake levels may be low. The Earth's population is increasing, and most wild fish stocks are fished near or at biologically unsustainable levels, so there is no scope for further expansion of world capture fisheries production. Global catches of wild fish populations have remained more or less stable over the last 30 years at approximately 100 million tonnes, of which 80 per cent was caught in marine waters (FAO 2014).

Over the same period, aquaculture production has gone from modest levels of just a few million tonnes to 74 billion tonnes, which is equivalent to just over half of our consumption of "seafood", and the FAO (2016) has estimated that global aquaculture production amounts to a value of USD 160 billion.

Most of the organisms farmed are fish for consumption (two-thirds), while the rest are invertebrates (primarily shellfish), algae and aquatic plants. On a global level, Southeast Asia dominates the production volumes. The five countries at the top of the FAO's list of farmed water organisms are China, India, Vietnam, Indonesia and Bangladesh, China alone standing responsible for more than half of all aquaculture production on a global level. China has a diversified aquaculture industry, where many different organism types are farmed and a variety of production systems are used. The EU Commission has an integrated sea policy known as "Blue growth" (EU/COM 2013). Aquaculture constitutes some 20 per cent of fish production in the EU and employs around 85,000 people, mainly at small companies in coastal and rural areas. Compare this with Sweden, which employed around 500 people in the farming sector itself in 2015 (Statistics Sweden, 2016). The EU focuses on ensuring that production is sustainable and of high quality and guarantees food safety for consumers. However, the EU's total production since 2000 has remained relatively constant, while global production has increased by around 7 per cent per year over the same period. In 2013, the

PHOTO: KRISTINA SNUTTAN SUNDELL

Figure 1. Atlantic halibut fry (*Hippoglossus hippoglossus*) at a land-based farm in Iceland. The picture shows fry at different stages of development (5 – 8) prior to metamorphosis.

EU Commission devised a reform for a common fisheries policy in order to promote development of aquaculture, among other things, and this was adopted on 1 January 2014. This included strategic guidelines for sustainable development of aquaculture, with collective priorities and general targets for the EU. Four areas were considered priorities: to reduce bureaucracy, to improve access to land and water, to reinforce competitiveness, and to exploit competitive advantages with stringent standards relating to quality, health and the environment.

Working on the basis of these guidelines, the Commission and member states are now working together to increase production and enhance competitiveness. Member states have been encouraged to devise multi-year plans to promote aquaculture. The Commission is helping to chart bottlenecks and facilitate cooperation, coordination and exchange of best practices between member states. The blue growth framework aims to promote responsible and sustainable fishing and aquaculture.

Some countries such as the US have reduced their production over the past few years, primarily due to competition from countries where production costs are lower. Swedish production currently represents just 1 per cent of total EU production, but there should be potential for increased growth as Sweden has both a long coastline and many lakes and waterways. One European country – Norway – is among the top 15 global aquaculture producers. Norway comes in sixth place, with annual production of 1.4 million tonnes. Unlike China's diversified aquaculture, Norway has developed production dominated by a single species; farming of Atlantic salmon at traditional cage farms in coastal areas at sea. In 2012, Norway produced 1.3 million tonnes of fish: compare this with Sweden's modest 12,500 tonnes of fish and around 1500 tonnes of mussels per year (FAO 2014, Statistics Sweden 2016).

Most of the fish consumed in Sweden is imported from Norway (primarily salmon), while a similar amount of wild-caught fish (primarily from the Baltic Sea) is exported as a feed ingredient (Swedish Institute for the Marine Environment 2012), and much of the fish farmed in Sweden at present is also exported. The FAO estimates that more than 600 different species are farmed globally, more than half of which are fish and one-quarter are shellfish (crustaceans and molluscs). Cyprinids are most commonly farmed on a global level. A significant but declining proportion of world fish production (14 per cent, 2014, FAO) is processed to make fishmeal (protein feed) and fish oil (included in aqua feeds or food supplements for humans).

PHOTO: KRISTINA SNUTTAN SUNDELL

Figure 2. Atlantic wolffish egg mass (*Anarhichas lupus*) at a research and development facility in Tromsø, Norway. The egg masses are incubated for up to four months prior to hatching.

Around 25 million tonnes of seaweed and algae are harvested each year for use as foods, in cosmetics, as animal feed additives, as fertiliser or for extraction of thickeners.

Aquatic organisms can be farmed in saltwater, brackish water and freshwater, on land, in waterways and in seas and lakes. Land-based farms a short way away from the coast normally use freshwater, but seawater is also used at land-based farms some distance away from the coast (in Egypt and China, for example). Marine organisms are usually farmed in coastal areas, in tidal zones and at sea (offshore). Aquaculture can be divided into extensive and intensive forms of farming. Extensive farming means that the farmed species lives off naturally occurring food and so does not need be fed. With intensive farming, the animals are fed. These facilities may vary, from relatively simple ponds to technically complex systems involving heating and recirculation of the water. Aquaculture is sometimes linked with environmental problems such as eutrophication, use of chemicals, escapes and the spread of disease. In closed production systems on land, the water is filtered and treated before being returned to the system. This allows nutrients and chemicals to be controlled and reduces the risk of spreading infection between farms. However, these require greater investments and consume more energy than traditional open production systems. Water consumption and treatment, feed ingredients and manufacture, materials and energy for operation of the facility are all important aspects from an environmental standpoint. The summaries "Bästa Tillgängliga Teknologier (BAT) för nordisk akvakultur" [Best Available Technologies (BAT) for Nordic aquaculture] (Heldbo et al. 2013) and "Marin fiskodling på den svenska västkusten: Tekniska lösningar [Marine fish farming on the west coast of Sweden: Technical solutions] (Ungfors et al. 2015) provide detailed overviews of modern farming techniques based on land and sea, as well as the environmental impact of these techniques.

The farming techniques are undergoing constant development, and a number of R&D projects and structured research facilities focusing on different systems have been implemented and presented. In the autumn of 2014, the Research Council of Norway funded a Centre of Excellence for research-driven innovation, known as CtrlAqua (Centre for Closed-containment Aquaculture). Here, research partners and commercial stakeholders work together on research into and development of innovative, semiclosed and closed production systems both at sea and on land. Special trial facilities for research into land-based recirculating production systems have been developed at the Technical University of Denmark, DTU Aqua, in Hirtshals, NOFIMA, Sunndalsöra in Norway and LUKE in Laukaa, Finland. Swedish aquaculture research has increased significantly over the past few years due to increasing interest from the EU and funding from Swedish research funding bodies and universities. However, converting research into commercial production is a long-term process that takes many years to complete.

It is important to point out that the optimum farming technique needs to meet the biological needs of the fish in terms of nutrition, health and habitat, as these are all closely interlinked. Regardless of whether fish are farmed in tanks, ponds, lakes or seas, feeding, management and farming equipment all need to interact so that the fish can be kept in good condition.

The feed used in intensive aquaculture is produced from a large number of different ingredients, with different nutritional and physical properties. Fish feeds have traditionally been based on fishmeal and fish oil from wild-caught fish. Of late, there has been major emphasis on creating feeds made from alternative raw materials that are more eco-friendly and ethically sustainable. Production can be made more sustainable by including increasing amounts of primary producers (terrestrial plants and algae) in the feed. Feed development is also striving to achieve more extensive utilisation of feed ingredients based on recycled raw materials so as to add value for the peripheral flows, which are largely wasted at present. Byproducts from fishing and the processing industry, as well as other industries, can be used. Other feed ingredients tested in various research projects are protein from a variety of other marine sources such as blue mussels, ascidians and brown algae, all of which extract nutrients from the environment in order to form biomass, as well as protein from insects. Feed ingredients can affect the quality of the feed in a number of ways: by changing the nutritional value (e.g. amino acid composition, fatty acid composition, feed conversion capability, etc.) and the physical qualities of the feed (e.g. stability in water, sinking rate, etc.). Both of these factors influence any effect the feed has on the environment if it leaches out in dissolved, particulate or metabolised form.

The environmental impact of aquaculture systems can be reduced by developing new, more controlled production systems, improving water treatment and creating circular nutrient flows by co-farming different organisms, and also by improving the systems that already exist. Impact on the environment and ecosystem is reduced by improving and streamlining open systems in the form of nutrients and organic matter. The overall effects on the environment can be gauged by means of life cycle analyses (LCAs), for example, which compare the amount of energy, natural resources and labour required and determine the extent of the farm's production and emissions according to the various forms of farming.

Swedish consumption of protein-rich foods has been increasing since the 1970s, and average consumption now stands at almost 110 grams per person and day (HMI 2016). It is necessary to go on encouraging development towards more eco-friendly production as long as most of this protein is of animal origin. Aquaculture has the potential to assist with this development.

Method and restrictions

This report is based on data from previous national and international summaries, scientific articles, interviews with farmers and researchers working on ongoing projects, as well as on responses to a questionnaire sent out in autumn 2016 (see Appendix). The questionnaire was aimed at active aquaculture farmers on both commercial and trial scales. This report does not claim to provide an entirely comprehensive view of all farms in Sweden, as the response frequency was not 100 per cent and there has been limited time for follow-up or details. Moreover, this report does not make it possible to view responses from individual companies; instead, the intent is to provide a general view of the techniques currently in use in Swedish aquaculture and the techniques being prepared. This report covers primary production of aquatic organisms, i.e. not slaughter/harvesting, processing or ongoing transport at consumer level. Its content focuses in general on the environmental impact of the various technique types. The report largely adopts a national perspective, but includes examples of techniques from other countries in the north. This report deals only briefly with veterinary aspects. Parts of the report deal with fields where public quantitative documentation is limited. This includes monitoring and financial aspects for newly established technology and aquaculture activities in Sweden.

OPEN SYSTEMS FOR INTENSIVE FISH FARMING

Aquaculture in Sweden largely involves fish farming in open cages, and most of the fish farmed are fish for consumption (Statistics Sweden 2016). The number of rainbow trout farms has almost halved between 2006 and 2015, from 83 to 48, while production has doubled. The number of Arctic char farms has remained relatively stable throughout the same period. Overall, the trend has been for fish farms to become smaller in number but larger in size.

Fish may be farmed for different purposes, and hence production may focus just on one part of the life cycle of the fish or their entire life cycle. In general, fish farming in open systems can be distinguished by whether the fish are being farmed for setting out or food production; but fish are also farmed in open systems for other purposes, including ornamental fish and species for other purposes. In turn, fish farmed for setting out can be used for food production, leisure fishing or stock enhancement. As far as food is concerned, farming may focus on various aspects such as farming roe or fish for consumption.

Market demand can affect farming to a certain degree. For example, different degrees of meat colouration may be preferred, which is one reason why the choice of feed may vary. There is also a great deal of variation between fish species in regard to requirements, behaviour and conditions, involving adaptations and production cycles of varying length, but the farming methodology in open systems is largely the same.

Many of the technical solutions developed for open cages can also be transferred to the new, more closed production systems, particularly as regards semi-closed systems in water.

Techniques and operation

Scientific literature with regard to techniques and operation in open cages is relatively scant, which is why the summary below is based on collective experience and actual practical procedures, equipment and technology currently used for farming fish for consumption in Sweden.

Cage farming

The open cages can be positioned with the top part of the cage above the surface of the water, but they can also be submersible. The latter may be submerged all year round or for parts of the year and be submerged during periods of ice freeze and ice breakup in spring, for example, to reduce the risk of damage. The submersible cages are more costly and more complicated to monitor as the cage and fish cannot be seen from the surface. Traditional cage farming involves net cages mounted on floating structures and secured to the bed using anchoring systems. The local water depth, the bypassing waterflow and the available surface area, together with the farmed biomass and practical conditions, determine the size of the cages used at the farm.

At larger fish farms, the cages are normally circular and have a circumference of around 30-100 metres, but cages with a circumference of up to 200 metres may also be used. The cage depth is normally between seven and 15 metres, but technical development has led to larger farms being able to use larger cages, particularly farms that do not place their cages directly adjacent to land. Fish density in farming

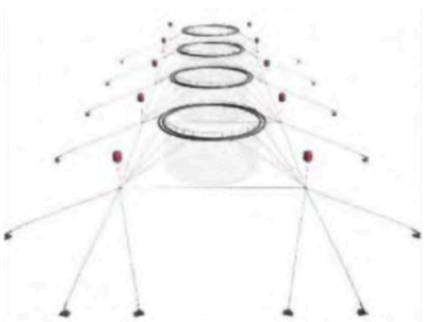

PHOTO: TINA HEDLUND

Figure 3. Basic diagrams showing cage farms. The structure consists of an anchoring arrangement, a floating structure and a net cage.

cages does not normally exceed 30 kg of fish per m^3. Smaller, rectangular cages with a side length of three to 12 metres – or sometimes up to 30 metres – are also used. Smaller cages are normally used as sorting cages, where the fish are sorted and can be kept until slaughter. Depending on conditions, however, the entire farming cage can be towed to the slaughterhouse in many instances. That said, the size of the salmonids set out in cages for further growth has increased over the past few years, which means that an increasing proportion of the life cycle of the fish takes place at land-based facilities (see land-based farms).

The cage mesh size is suited to the species and size of the fish to be farmed. The most common material used for nets is nylon, but polyethylene terephthalate (PET) and Dyneema® are newer materials, the latter exhibiting very high durability. Nets are classified on the basis of durability and are therefore classified for use in different current and wave conditions.

The upper part of the cages is made up of either round floating collars or square bridge systems in order to keep the nets up. The floating structure must be very buoyant, particularly at large farms or at farms located in vulnerable areas. The structure must also be able to withstand the weight of sorting machines, oxygen tanks and any pumps, as well as snow and ice weighing down the structure in winter. The structure must also be able to withstand severe weather conditions involving large or powerful waves. The floating arrangement must also provide a safe, ergonomic workplace for fish farmers. The round or square collars are often made of PVC plastic, while the square bridge systems are made up of wood, steel or concrete structures with plastic/styrofoam buoyancy elements.

Appropriate anchoring arrangements are necessary in order to minimise the risk of damage to the facility. These must be strong, and ideally the anchoring systems should exhibit a certain amount of flexibility so that cages can be relocated and re-anchored within the area if necessary. The anchoring arrangements must prevent the cages moving away from or within the farming area, as well as preventing them from overturning in severe weather. The anchoring arrangements also prevent the cages abrading against one another, thereby preventing escapes. The anchoring arrangements must be designed and adapted to suit conditions on the local beds, and they usually extend about a hundred metres outside the visible part of the farm. The anchoring arrangements are made up of weights or heavy anchors made of metal or cement, for example, and attached to cables, chains or strong hawsers.

The feeding systems at larger fish farms are usually automated. Mechanical equipment is used for the large feed volumes used at farms of this type, and to permit even distribution of the feed ration over the light hours of the day. This equipment may be controlled by compressed air and be made up of large feed silos next to a feeder that releases feed into hoses before compressed air blows the feed on to the selected cage. The feed is spread at the end of the hose so that it is distributed fairly evenly over the surface of the water, ensuring that waste is kept to a minimum. Compressed air feeding can be controlled from land or a special feed barge, which include the complete system containing feed storage, compressors, etc. A sensor can also be fitted to this equipment which interrupts feeding in the event of technical problems; if a feeding tube is fractured, for example. The equipment may also be of sling type, where a feed container is linked to a screw conveyor that pushes feed forward to a sling that then distributes the feed over the surface of the cage.

A number of smaller farms have a simpler arrangement where the feed container is connected directly beneath, with a plate under it that rotates to distribute the feed. This requires the feed container to be located in the middle of the fish unit. All automated feeding is controlled electronically. This is computerised in the more modern systems and controlled via computer and/or smartphone applications where each cage is fed according to the number of fish in the cage, the average weight of the fish, the feed variety, the oxygen content and the water temperature, as well as changes to the latter. The amount of feed to be given is calculated in computer-based models on the basis of the energy requirements of the fish or from growth tables based on empirical data relating to percentage daily growth rate related to the above parameters.

The water temperature is one of the most important factors impacting on fish appetite. That said, the appetite is also affected by other factors such as oxygen content, winds, currents and solar radiation. Fish also grow more quickly at the start of their lives, while the growth rate then declines as they age. There are also major differences in the growth rate between individuals due to genetic variations, which is why fish are sorted at the farm in order to streamline feeding and reduce competition. However, sorting does not take place more frequently than necessary so as to mini-

PHOTO: MARCUS BÄCKSTRÖM

Figure 4. Feeding Arctic char.

mise stress caused to the fish by handling them. This is also the reason why some farmers do not sort their fish at all once they have been placed in the cages. Health is another important factor, as sick or stressed fish lose their appetites. The accuracy of data models and/or growth tables is not tried and tested equally effectively for all fish species. There are well established systems for salmon and rainbow trout, while tables for Arctic char and brown trout – for example – are less standardised. Fish may also be fed manually, which involves throwing the feed manually using a scoop, for example. However, efficient implementation of this at fish farms would be far too demanding. That said, the method is used occasionally to control fish appetite and behaviour.

Fish appetite is monitored every day, and any necessary adjustments to feeding are then implemented accordingly. It is possible to install sensors in the cage in order to streamline feeding and minimise wastage; these monitor the amount of feed that passes through the cage. All technical solutions involve shortcomings, however, and so feeding and other elements of the activity must always be accompanied by monitoring of fish behaviour in order to check their well-being and appetite. Feed consumption is recorded so that it is possible to monitor growth efficiency, known as the feed coefficient or feed conversion ratio (FCR), and to make it possible to calculate nutrient emissions from the activity. Dead fish are removed from cages regularly. Farmers with computerised feeding systems, where the biomass is recorded for each cage, also record the number of fish removed in the data system so as to adjust the amount of feed and the stock value at the farm. Monitoring the number of fish that die at the farm can also be used to monitor the general health of fish and detect any discrepancies. Dead or sick fish create extra work for the farmer and have a potentially adverse effect on the general health of stocks, but also on the surrounding environment.

The procedure for removal of dead fish varies. Traditionally, long-handled landing nets have been used for removing dead fish from the surface of the water. However, some fish tend to sink to the bottom, causing an accumulation of dead fish and impairing the environment in the cage, as well as constituting a substrate for further bacterial growth. These fish have traditionally been collected by rolling the cage, as it is known, which involves lifting one end of the cage and then lifting both long sides so that dead fish on the bottom slide to the other end of the cage. The pocket that forms is then lifted and the dead fish picked out. Larger farms now have technical solutions to facilitate collection of dead fish from cage bottoms. Nets or an additional bottom that can be winched up for emptying can be installed at the bottom of the cage. A different method known as a lift-up system is used to suck the fish up through a hose system from a funnel at the bottom of the cage to a collecting unit. Some farmers use divers to remove the fish. The dead fish are then taken care of and stored without odour, by either freezing them or treating them with formic acid. Depending on the location and the farmer's situation, the dead fish are then sent for incineration or, if possible, to biogas production plants in either Norway or Finland.

Other technical accessories that can be installed in the cages include oxygenation equipment that can be used as required, such as when the fish are particularly stressed during handling. Current formers for creating or controlling currents in the water can also be installed, and protective nets (bird nets) over the cages are normally used to protect the fish from birds, and from mammals as well, in some cases.

Fish are normally sorted at the farm by pumping the fish up from the cage and then passing them through a sorting table. Some form of roller system is normally used at the sorting table, where smaller fish fall between the rollers and larger individuals pass through, and the fish are then directed to different cages. Another method involves dragging a specially adapted net, a Shetland grid, through the cage with a carefully balanced plastic grid system that allows some small fish to pass through while larger fish are swept along. This therefore involves a kind of screening. The Shetland grid may be more gentle as sorting takes place in water, but it is not possible to know how many fish are sorted. Pump sorting over a table allows counters to be connected to the pipe outlet from the sorting table, allowing the fish stock in the cage to be determined. The average weight of the fish is normally also checked during sorting.

Fish can also be pumped without sorting when moving them from one cage to another or pumping them up for slaughter. Manual netting or netting with a crane can also be used when moving fish. The fish can be weighed during dry netting, while netting with a tarpaulin net – wet netting – is more gentle but does not allow the fish to be weighed. Sewing the cages together is another way of transferring fish between cages. Special zipper models are available for this purpose. This is a gentle but labour-intensive method, and it is not possible to either weigh or count the fish.

Figure 5. Example of a net for collecting dead fish.

PHOTO: DANIEL WIKBERG

PHOTO: DANIEL WIKBERG

Figure 6. Transferring fish prior to slaughter.

Offshore farming, including submerged systems

Farms in pelagic areas that are exposed and vulnerable to severe weather conditions require more robust equipment and anchoring. Relocating aquaculture activities to areas further away from the coast (offshore) in order to reduce environmental impact on delicate coastal areas and alleviate conflicts with other activities is one potential future scenario. Offshore farming may also be preferable, rather than areas that may be affected by freezing. Special and robust solutions are usually required for cages or other farming technology that has to be positioned further away from the coast or in deeper waters (Vielma and Kankainen 2013).

Modern fish farming techniques for offshore use are very similar to traditional open cage farming in many ways, but floating closed units are also used. These techniques mainly differ in terms of their appearance and the level of automation. Submersible cages for offshore use may be one option for periodic avoidance of bad weather that affect such farms in exposed locations in winter, for instance.

Submerged production systems are made up of open cages or lines that are submerged beneath the surface to avoid bad weather, freezing, thawing, predation by birds and competition with other activities. These systems have certain advantages in terms of a more stable water quality (temperature, salinity, fewer pathogens, etc.), and the cages do not need to be cleaned as frequently as cages on the surface. Moreover, less stress is caused by high waves and this may improve fish growth, survival and feed conversion. The production season is also extended. As submerged systems do not affect the landscape, they may be more appealing to the local population and less controversial in certain areas. That said, this type of production system has mainly been tested on mussels and oysters in Swedish waters to date.

Environmental impact

There may be both direct and indirect impact on the environment when farming aquatic organisms. Leakage of nutrients, chemicals and organisms from farms has a direct impact, while indirect impact is caused by transportation and consumption of energy and natural resources (such as raw materials for both infrastructure and feed).

Cage farming

In open production systems, the fish are enclosed in net cages that allow the water surrounding the cages to pass through freely, and nutrients, feed residues and faeces from the cage are released into the surrounding environment (Heldbo et al. 2013, Ungfors et al. 2015). Traditional open cage farming is both cost-effective and tried and tested, and there is less of a need for farming equipment than with other farming methods. However, the open cages are in direct contact with the surrounding ecosystem, so there is a greater risk of environmental impact than with semiclosed/closed production systems.

The dimensions, location and maintenance of cage farming facilities are absolutely crucial to the impact of such facilities on the surrounding environment. Topography, currents, physical values (such as salinity, temperature and oxygen level), and above all nutrient status affect how appropriate an area is to accept an increased nutrient burden from open cages.

The nutrients released from the farm are released from faeces and feed residues that may be dissolved or deposited, and also from excretion products via gills and urine (Figure 7). Nutrient emissions from open fish farms can be calculated by means of a model devised by Johansson et al. (2000). This model bases phosphorus emissions on the amount of phosphorus in the feed minus the amount of phosphorus that remains in the fish. This equation is L = P * (FK * CI – CR) * 10, where L = phosphorus emissions (kg), P = fish production (net, tonnes), FK = feed coefficient (i.e. the amount of feed required to produce one kilo of fish), CI = concentration of phosphorus in feed (%), and CR = concentration of phosphorus in fish (%). CR is normally 0.4 per cent. The same formula can be used to calculate nitrogen emissions. A nitrogen CR of 2.5-3.5 per cent in the fish is used in these cases, depending on factors such as the size of the fish (Swedish Environmental Protection Agency 1993).

To calculate the amount of phosphorus to be added per litre of water (the flow-corrected loss of phosphorus (TPin)), the formula TPin = L*1000000/Q is used, where L = phosphorus loss from farming (kg per year) and Q = water flow (m^3 per year). However, the actual increase in phosphorus levels in a lake may be lower than the flow-corrected loss of phosphorus as some of the phosphorus is bound in the bottom sediment due to retention and hence is eliminated from the amount of phosphorus available in the ecosystem.

An increased amount of nutrients helps to increase production in the surrounding water in the form of an increased production of primary producers (phytoplankton, macrophytes and algae), but also an increased volume of zooplankton, which in turn can help to increase fish production (Milbrink et al. 2003, Persson et al. 2008). The benthic organisms in the area may also benefit from the increase in food supply due to the deposited material, provided that the increase in nutrients does not cause imbalance between producers and consumers and lead to overloading of the benthic substrate, resulting in oxygen deficiency. That said, the distribution between different species in the benthic fauna is affected (Nordström and Bonsdorff 2017, Saarinen 2017), so species that feed on sediment are favoured over species that feed on plants and phytoplankton. Overall, correctly dimensioned farming in a water though that is poor in nutrients can help to increase diversity and biomass among the wild fauna in the area (Milbrink et al. 2003). Some of the nutrients in the sediment are released when the sediment is degraded with the assistance of the benthic organisms.

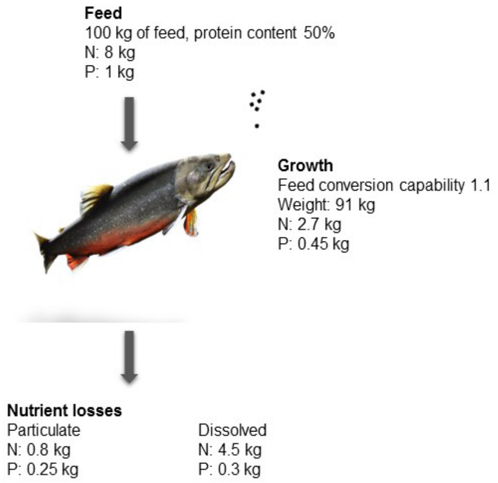

Figure 7. Sample calculation of mass balance from Arctic char with an FCR of 1.1, where 100 kg of feed produces 91 kg of fish.

Trials have been taking place since the mid-1980s involving collection devices beneath the cages with a view to reducing the amount of deposited material in connection with the open cages (Swedish Environmental Protection Agency 1993). Correct dimensioning, location and maintenance are of crucial significance when it comes to minimising environmental impact from cage farming (Alanärä 2012). Dimensioning takes place on the basis of knowledge of the present nutrient status, along with the original nutrient status. Hence the permitted nutrient burden that can be allowed in accordance with the Water Framework Directive without altering the status classification of the water body, can be calculated. Water flow-through in the area, the water body's turnover time and internal flows within the water body are important parameters for assessment of the nutrient burden on the basis of the planned farm's feed consumption, calculated feed coefficient and phosphorus content in the feed (see above).

A proposal based on the Norwegian MOM system (Modelling-Ongrowing fish farm-monitoring, Stigebrandt et al. 2004) has been devised for monitoring sediment in connection with fish farms (Hedlund 2015).

Another, less well-known potential drawback of fish farming is a consequence of modern high energy feeds, as these may release fat that floats on the surface. This appears as a thin film of oil on the surface and may cause inconvenience to bathers and people living nearby as this film of oil may stick to boats, beaches or people bathing and give off a slightly fishy odour. This phenomenon is caused by the fact that the feeds have a different density so that they sink more slowly, thereby maximising the chances of fish having time to consume the feed ration before it falls through the bottom of the cage. Fat is added to the pellets in a vacuum as a final stage in the manufacturing process.

The inconvenience of having a film of oil on the surface is most notable on still, sunny days when locals are moving around the area. Some farmers lay out oil barriers in the direction of the current in order to collect the fat and reduce this inconvenience to a minimum. However, heat, the storage time and problems in the manufacture of the feed may increase the problem by causing more fat to be released from the feed. This is why feed must be stored in conditions that are as cool as possible and for no longer than necessary, and for farmers to make a complaint about feeds supplied to them where the fat has not been absorbed by the pellets.

Open cages also attract wild organisms as there is a certain amount of feed waste from such cages (Carss 1990, Dempster et al. 2010, Holmer 2010, Fernandez-Jover et al. 2011). This may stimulate the quantity of wild fauna in the local area around the farm, and in certain cases biodiversity as well (Karakassis et al. 2006, Buschmann et al. 2006, Kutti et al. 2007, Hargrave 2010). A number of studies indicate positive effects on local fishing (Milbrink et al. 2003, Person et al. 2008, Arechavala-Lopez et al. 2011).

Leakage of phosphorus from feed pellets

Phosphorus is a vital mineral required for normal bone development and in a number of physiological processes. In most fish species, phosphorus deficiency leads to reduced growth, feed conversion capability and bone mineralisation (NRC 2011). The phosphorus content in aqua feeds for the Nordic market was reduced between 1974 and 1989, from 1.7 per cent to 1.0 per cent (Enell and Ackefors 1991). No later summary of corresponding values is available. However, the current high addition of vegetables may have increased the actual phosphorus content in the feed, with a higher proportion of inaccessible phosphorus in the feed. On the other hand, the development of enzymatic additives means that this phosphorus is becoming more available to fish, while the total phosphorus content in the feed is reduced.

In cereals and oilseeds, phosphorus is stored as phytic acid (also known as phytate or myo-inositol hexakisphosphate), which is an inaccessible form of phosphorus for most animals. Between 60 and 80 per cent of the total phosphorus content in a plant may be bound in phytic acid. Phytase (myo-inositol hexakisphosphate) is a phosphatase enzyme that catalyses the hydrolysis of phytic acid to inositol and inorganic phosphorus, which increases the accessibility of phosphorus and other minerals. Phytase is primarily extracted from filamentous fungi and yeast, and phytase from *Aspergillus* species is used in the majority of instances in studies with fish and shrimps. Adding phytase has proven to increase the digestibility of phosphorus in vegetables in both cold and warm water species, for herbivores, omnivores and carnivores (Lemos and Tacon 2015, Kumar et al. 2012).

The optimum amount of phytase to add appears to be between 250 and 1500 FTU per kg of feed (Simons et al. 1990). Most phytases used in aquaculture have a peak activity level (maximum capacity) at a pH of 4.0 to 6.0. This may be a potential obstacle to species that do not have stomachs, e.g. carps and shrimps, which do not have an acidity control function. Hence emphasis should be placed on developing phytases that work effectively even at neutral pH in order to increase the use of phytases in feeds for shrimp and carp, as well as optimising the phytase effect (Tacon and Metian 2015).

Nutrients in the form of dissolved phosphorus, for example (Figure 7), which leaches out into the surrounding water from fish farms stimulates the growth of phytoplankton, increasing the risk of changes in oxygen concentrations. A number of studies involving several different fish species show a clear reduction in phosphorus discharge from fish farms after adding phytase to the feed (Kumar et al. 2012). It has also been demonstrated in salmon that feed based on soya concentrate treated with phytase leads to less phosphorus leakage than fishmeal-based feed (Storebakken et al. 2000). 60-70 per cent reductions in faecal phosphorus leakage have been reported; but most commonly, adding phytase to the feed reduces phosphorus leakage by 30-40 per cent (Tacon and Metian 2015, Kumar et al. 2012).

Escapes, competition and genetic contamination

The risk of escapes varies depending on how the farmed organisms are separated from the surrounding ecosystem. The farmer cannot afford to lose individuals on account of poor equipment, but even if the equipment is inspected carefully at regular intervals and there is a generally low risk of escape, this risk is nevertheless higher in open production systems than in semiclosed and closed systems. There may be many different reasons for damage to cages, such as poor weather in combination with substandard structures, abrasive wear in combination with poor maintenance, damage due to towing cages or propeller damage when transporting the cages using a boat. Deliberate sabotage of cage farms and damage caused by predators may also occur. Regardless of cause, damage to net cages may result in large numbers of fish escaping.

Escapes of domestic species that can reproduce may have major ecological consequences. If farmed fish bred for consumption have a different genetic background to the wild strain and reproduce with the wild strain, this will impact on the genetic signature and qualities of the wild strain and genetic contamination will take place (Bolstad et al. 2017). Even if the escaped fish do not reproduce with the wild fish, they may have an adverse impact on the local ecosystem due to predation and competition for food, for example, or as passive carriers of disease. Rainbow trout are the most common fish for consumption in open production systems in Sweden, but they do not occur naturally in Sweden and in principle are unable to reproduce in Swedish waters. Only a small number of temporary populations of rainbow trout have succeeded in establishing themselves over the years (Pakkasmaa and Petersson 2005). Hence there is no major risk of genetic intervention with wild fish stocks. That said, rainbow trout may affect brown trout populations in tributaries to lakes as they choose the same types of spawning grounds as brown trout in their attempts to reproduce. Unlike rainbow trout, brown trout spawn in autumn but their eggs have not hatched by the time rainbow trout try to spawn in the same areas in spring, which may harm the hatching of brown trout eggs.

A number of more widely highlighted escapes or sabotage have taken place over the past few years. Mechanical damage to the cages has been responsible for most of the escapes. Ice was one of the causes, along with sabotage by animal rights activists. It is difficult to protect against the latter, but some farmers have installed CCTV systems to curb sabotage and being able to prove that it has taken place. Escapes used to take place when towing cages, but the risk of this can be kept to a minimum by applying the correct procedures. However, these escapes due to sabotage and major accidents are estimated to be responsible for just <0.5 per cent of the total amount of fish farmed in cages (data from major escapes between 2012 and 2015, via Statistics Sweden production statistics over the same period). These figures do not include any escapes of individual fish during handling, for example.

Escapes and sabotage result in major costs for farmers as they invest in fish growth with no financial return and have to replace the failed equipment. Good procedures can be used to recapture most escaped fish in the vicinity of the fish farm, depending on the reason for the escape and how quickly it is discovered. However, only some of the recaptured fish can be returned to the cages, depending on the method used. The remaining fish will be damaged when being recaptured and so have to be slaughtered, but on the other hand they will not have any impact on the surrounding ecosystem. Hence recapturing escaped fish does not prevent fish farmers suffering financial losses, other than to a small degree.

Problems with disease and parasite control

Just like wild animals, farmed animals that come into contact with the surrounding environment may contract diseases and parasites. These are a natural part of the ecosystem and are present in the water. Diseases and parasites may increase and cause problems with intensive farming, where large numbers of farmed fish are all kept together. A parasite that has caused major problems in Norway and is financially costly for fish farmers is the salmon louse (*Lepeophtheirus salmonis*).

Salmon lice are not a problem in Sweden as Swedish salmonid production takes place almost exclusively in freshwater or brackish water. However, diseases that may be latent in the water or, to a lesser extent, found in the wild fish population cannot be prevented from reaching the cages containing the farmed fish, even with semiclosed systems. Preventive measures to keep the fish healthy, as well as only setting out healthy fish in the cages, are the only ways in which fish farmers can maintain a healthy fish population at the farm.

Offshore farming, including submerged systems

Nutrient leakage from offshore farms out at sea does not risk affecting the coast in the same way as open systems located within the archipelago. This nutrient leakage, which may involve a risk of environmental impact, does not cease, but the local effects are reduced as the water is frequently deeper and the nutrients are diluted to a greater extent.

OPEN SYSTEMS FOR EXTENSIVE MARINE FARMING

Open systems also include extensive farming of extractive sessile and suspension feeding species such as blue mussels, *Ciona intestinalis* and macroalgae.

Techniques and operation

Mussels

Farming of blue mussels is fully extensive. In other words, the mussels extract all their nutrition from the water in which they grow and no nutrition is added to the farm. In Sweden, the long-line method is most commonly used for farming mussels, which essentially involves hanging out lines to which the mussel larvae can attach themselves (settle) and grow (Figure 8). These lines are anchored at both ends and are some 200 metres long. The lines are kept up using floats (buoys). Lines 5 to 6 metres long or ropes are then suspended from the long lines at approx. five-metre intervals. A single farming unit covers around 0.5 to 1 hectare and is frequently placed in slightly shallower areas (<30 metres depth). The farm is ideally protected to an extent. Other methods have also been used over the last few years, such as mussel-growing ladders and net-based production systems supported by pipes. Net-based production systems supported by pipes use long plastic pipes as floats, and wide-meshed nets are placed on these and hang down into the water. Mussel larvae attach themselves to these nets and grow (Figure 9, Fredriksson et al. 2015). These farms may appear to be less visible as the floats are not all that prominent. The nets do not reach as far down as the lines/ropes, but are frequently around 3 metres deep. Setting out the farming structures at the right time and to the right depth in the sea are important factors in mussel farming (Dunér Holtius et al. 2013). Many animal species multiply at the same time as the mussels, and they compete for space where they can attach and grow. The main competitor to blue mussels on farming ropes is *Ciona intestinalis*, sometimes known by the common name of vase tunicate.

Techniques for submerging mussel farms have been developed so as to protect such farms from ice in winter (Wang et al. 2015). Marker buoys are the only things that can be seen on the surface of the water in this case (see also "Submerged open systems"). Otherwise, these farms work in the same way as long lines or net and pipe systems. In the case of long-line farming, the lines are held up by means of floats that never reach the surface of the sea, while the sinkers hold the lines down at an appropriate depth. With net and pipe systems, the pipes are filled with water so that both they and the nets sink to the bottom. This method has not yet been tried in Sweden, but it has been tested in Denmark, with good results (Fredriksson et al. 2015). It is also possible to farm mussels in cages, but in this case it is necessary to have access to small mussels that have already settled. One advantage of cage farming is that seabirds and suchlike are unable to get at the mussels (Richman et al. 2012). Furthermore, the mussels do not detach as easily and fall to the bottom.

Oysters

Oysters can also be farmed by offering wild oyster fry substrates to which they can attach themselves before then farming them until they are of an edible size. Special structures are used for this purpose, such as "Chinese hats", or oyster hats, comprising plate-shaped PVC discs that are stacked vertically on a PVC pipe, leaving just enough space between the discs to allow the oyster fry to settle (Figure 10). These discs are covered with lime by dipping them in equal parts of water and slaked lime ($Ca(OH)_2$), and this also attracts the fry. Oyster hats have been used and evaluated in Swedish waters, and the results have been good (Dunér Holtius et al. 2014). After being left to settle and grow for about nine months, the oysters are then transferred to cages for further farming in the sea, lying on an appropriate bed. Special equipment is commercially available for mechanical removal of the oysters from the hats for further processing. Oysters (in Sweden the European flat oyster, *Ostrea edulis*) can also be farmed partly on land, in a closed life cycle, where breeding animals are kept and spawning takes place in indoor pools where the temperature and salinity are controlled. The larvae are then reared in larger pools, still indoors, where they are fed on farmed phytoplankton.

During the settling time, the larvae are offered special surfaces that are placed out in net cages in the sea after settling and further growth (to approximately 5 mm). The oysters are moved to larger cages as they grow. The oyster cages can be placed on the seabed or suspended in the water column; and this part of the production cycle is extensive. All nutrition needed for growth is extracted by the oysters from the water column. Farming of the European flat oyster is at the experimental and development stage in Sweden, and commercialisation is

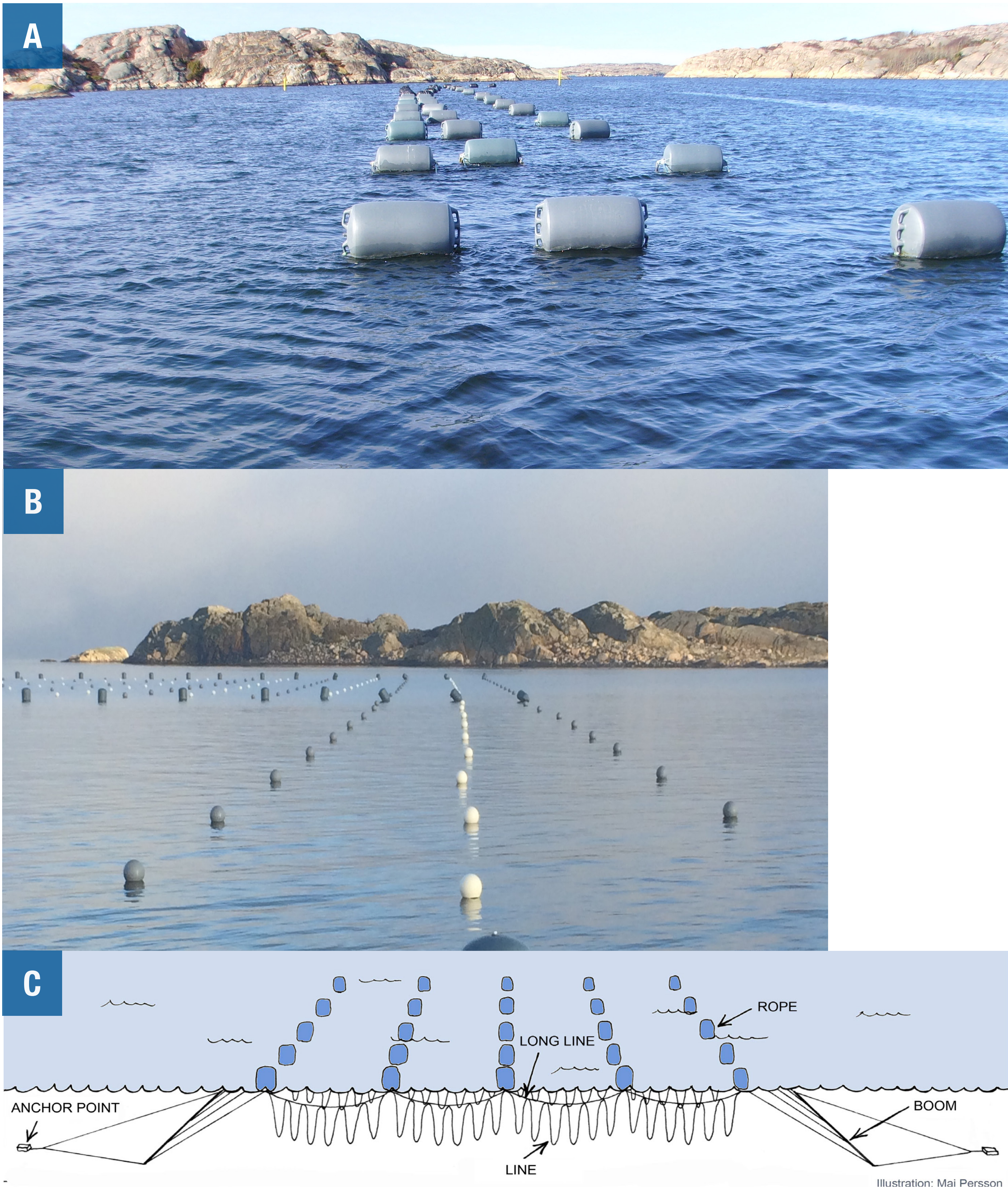

Figure 8. (A) Sea-based open long-line farming for mussels/ascidians. The farm is set out before the larvae settle in may/June. (B) Open rope farming of sugar kelp (marine brown algae). The farm is set out in the autumn and harvested in the following spring before the algae have reached sexual maturity. (C) Basic diagram of a long-line model.

PHOTO: PER BERGSTRÖM

Figure 9. Sea-based open net/pipe farming for blue mussels.

not far off. Only the European flat oyster may be considered for farming in Sweden at present as the Japanese oyster (*Crassostrea gigas*) is an invasive species (Thomas et al. 2016) and so it must not be kept in anything other than entirely closed systems with full treatment to ensure that germ cells or fry are unable to escape into the surrounding waters.

Ascidians

Ciona intestinalis is farmed in Sweden using the same types of line as for blue mussels (see above). Ascidians are chordates (tunicates) and also sessile (immobile), and they often attach themselves slightly more deeply to the farming material and a few weeks earlier than mussel fry (Dunér Holtius et al. 2013).

Macroalgae

Production of macroalgae is now a major industry on a global scale, and farming of several different species is currently being tested in Sweden as well. The greatest development progress has been made with the brown alga sugar kelp (*Saccharina latissima*). Farming of sugar kelp in Sweden currently involves production of small kelp seedlings in land-based flow-through systems to which nutrients are added. The seedlings are then grafted onto thin ropes, which are wound onto thick, more robust nylon ropes and then placed in the sea and anchored to long lines (Nylund pers. comm., Peteiro et al. 2006). Macroalgae grow between autumn and spring, which is why "shifting farming" involving other extensive farming of species such as blue mussels can take place using the same rig as blue mussels settle after the algae have been harvested. There is a test facility for macroalgae at Kosterhavet which, depending on the production system used, has seen growth of up to 15 kg (algae farmed horizontally) or 25 kg (algae farmed vertically) per horizontal metre, which is equivalent to 39 or 65 tonnes respectively of wet weight per hectare. Similar figures have also been published by Scottish and American farms (Gröndahl and Costa-Pierce pers. comm.). It is not possible to farm green algae such as *Ulva lactuca* (which may be of relevance to the Baltic Sea; www.seafarm.se) on ropes in the sea, but conventional techniques can be used (and are used extensively in Asia) which involve farming the algae on fabric cloths instead. This technique is now being tested in the Netherlands (Gröndahl pers. comm).

Environmental impact

It is reported that no chemicals are used and no nutrients (feed) are added to open, sea-based systems used for farming extractive species. That said, a nutrient solution needs to be added to the land-based systems where the first stages of macroalgae, the kelp seedlings, are produced before being set out in the sea.

Mussels

Farming of mussels involves extraction of nutrients from the sea, on average approx. 10 kg of nitrogen (N) per tonne of mussels harvested and 1 kg of phosphorus (P) per tonne of mussels harvested (Bergström et al. 2013, Bergström 2014). This means net uptake of nutrients from the water. The physical structures used for mussel farms also provide other positive environmental effects as they may attract various other sessile species, as well as fish and moving invertebrates that live off the animals that attach themselves to the structures (Suplicy 2018). When mussels filter feed out of the water, they produce faeces which, together with other debris from farms (dead and live mussels, shells, other animals that live in and around the farm, etc.) may increase sedimentation and accumulation of organic matter on the seabed. This accumulation of organic matter may encourage various benthic species to the area with high nutrient and organic matter levels (Nielsen et al. 2016).

Locally, directly beneath the farm, excessively rapid sedimentation may lead to a massive increase in the amount of organic matter, which in turn may lead to oxygen deficiency. However, earlier studies have indicated that this effect is usually very much local (<50 m) to the farm, and that it is eliminated if the farm is moved (Bergström et al. 2013, Bergström 2014). The positioning of mussel farms and local currents are important factors in reducing the effect of local organic debris on seabeds.

Oysters

Oysters also extract nitrogen and phosphorus from the water by means of filtration, in a similar way to mussels, when settled wild fry are used and during the extensive part of the production cycle. However, it is difficult to find any data on the volumes of nitrogen and phosphorus built into biomass per farmed volume of oysters. During this extensive, on-growth phase of the production cycle, the oysters are placed in cages or baskets on the seabed or in structures in the open water column. This results in farming structures added to the environment that can act as substrates for wild organisms. A number of studies have indicated the positive effects of oyster farms as artificial reefs on the wild biota (Peterson et al. 2003, Drent and Dekker 2013).

Macroalgae

Macroalgae assimilate nutrients, primarily dissolved nitrogen compounds, and they have a nitrogen content of between 2.5 and 6.2 per cent of the dry weight when harvested in spring (Sanderson et al. 2012, Handå et al. 2013, Costa-Pierce pers. comm.). No adverse environmental effects of macroalgae farms have been published, to our knowledge. Apart from a certain impact on the landscape, no adverse effects have been identified at the test facility in Koster (Hasselström et al. 2018). However, the people responsible for the R&D facility indicate that a certain amount of biomass may come loose during harvesting, which could lead to local and temporary accumulation of biomass on the seabed and greater oxygen consumption. However, this risk must be deemed small as commercial algae farmers will be striving to use methods that minimise biomass loss (Nylund pers. comm.).

Protective farming/Catch crops

To deal with emissions of nutrients from fish farming, it is possible to implement parallel farming of extractive species which absorb nutrients from the water by filtering or eating nutrients bound to particles (mussels/oysters, detritivores), or by assimilating dissolved nutrients (algae) and thereby acting as catch crops (Buck et al. 2018, Troell et al. 2009). This may take place directly adjacent to fish farms or in the same water zone (defined differently depending on the location) to achieve a nutrient balance in emissions from fish farming, and in this case it is referred to as protective farming. The size of water zones and distance between farms are not easy to define; these factors are dependent on currents, bottom topography and coastlines. However, the number of catch crops can be defined on the basis of mass balance models where the amount of nitrogen and phosphorus released from fish farming is balanced out by farming of extractive species designed to absorb a corresponding amount of nitrogen and phosphorus.

Mussels, ascidians and algae are the catch crops farmed on the west coast at present, but many more species have the potential to operate as catch crops. Mussels grow slightly less well in the Baltic Sea area than they do on the west coast, in full saltwater, but mussels work well as catch crops there, too. There is also potential to farm green algae in the Baltic Sea, although this is still at the experimental stage. When harvesting mussels, it is possible to anticipate extraction of approx. 8-12 kg of nitrogen and 0.6-0.8 kg of phosphorus per tonne of

PHOTO: MICHEL GUENNOC [2]

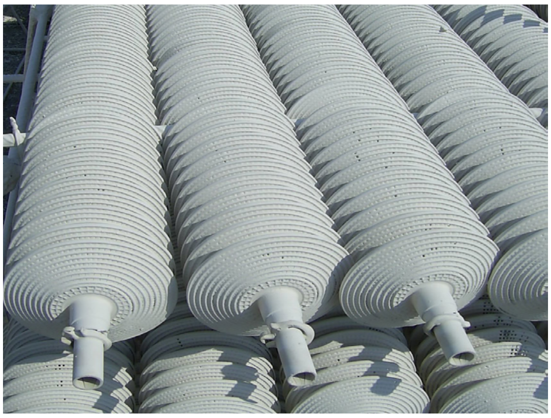

Figure 10. “Chinese hats” for collection of oyster fry before (left) and after (right) setting out.

Species	Production (tonnes)	Volume or area	Total N, kg	Total P, kg	N:P ratio	Sink (reduces more than emissions)	Reference
Fish (FCR 1.1)*	100	3,333 m^3	+5,824	+604	10:1		Converted from emissions in Figure 7
Ciona intestinalis	2,851	0.33 hectare	-7,920	-648	12:1	Nitrogen sink	Norén pers. comm. calculation
Blue mussel	600	2 hectares	-6,000	-600	10:1	-	Bergström et al. 2013
Sugar kelp	275	50 hectares	-6,000	-2,200	3:1	Phosphorus sink	Converted from Pechsiri et al. 2016, Table 1
Diatoms	100		-10,000	-625	16:1	Nitrogen sink	Allert pers. comm. calculation

Table 1. Sample calculation showing emissions of total nitrogen (total-N) and total phosphorus (total-P) from fish farming, with a cage density of max. 30 kg/m^3 water. This describes the volume of catch crops such as mussels, ascidians and algae, in tonnes or by area, that would be needed to compensate for the fish farm in theory. This example reflects conditions on the west coast of Sweden. * FCR = feed conversion ratio.

mussels harvested (see Mussels, oysters and ascidians), and one hectare can produce approx. 300 tonnes of mussels. There may be a major difference in blue mussel growth between different locations due to factors such as different exposure levels and salinity, and the production rate can be doubled in a best-case scenario by selecting the correct location (Bergström et al. 2013).

In Öresund, upscaling calculations from pilot studies (Bucefalos, 2015) have shown that mussel farming using a fine-meshed net – which was the method giving the greatest biomass – gave the following extraction of nutrients per hectare over 2 years: total N = 1652 kg per hectare over 2 years, total P = 165.2 kg per hectare over 2 years. As regards assimilation by algae of dissolved nutrients, the uptake of nitrogen and phosphorus has been quantified from 0.5 ha of farming of the brown alga sugar kelp. Eight months of growth produced 2.5-3 tonnes of algal biomass (dry weight), which was estimated to have absorbed and incorporated approx. 60 kg of nitrogen and 22 kg of phosphorus (Pechsiri et al. 2016). This is equivalent to 20-24 kg of nitrogen and 7.3-8.8 kg of phosphorus per tonne of algae, or 120 kg of nitrogen and 44 kg of phosphorus per hectare. Corresponding figures for farming of sessile microalgae: diatoms, in waters from a land-based fish farm, have demonstrated an uptake of approx. 1.8 tonnes of carbon dioxide, 100 kg of nitrogen and approx. 6.25 kg of phosphorus per tonne of algal biomass (Allert pers. comm.). According to a sample calculation of mass balance (see Figure 7, FCR 1.1), mass balance of nitrogen and phosphorus could in theory be achieved in emissions from a 100-tonne fish farm on the west coast by means of protective farming with 2 hectares of blue mussel farming, 50 hectares of sugar kelp or 100 tonnes of diatoms (Table 1). Uptake of nitrogen in relation to phosphorus (the N/P ratio) varies for the different organisms, and depending on circumstances the catch crop can act as a special sink – i.e. absorb more than is released – for any of the nutrients.

Combined extensive and intensive farming in open systems

Multi-species farming is characterised by farming of multiple species from different levels in the food chain (trophic levels) either together or near to one another. Multitrophic multi-species farming of this type is also known as IMTA: integrated multitrophic aquaculture systems (Troell et al. 2009), where the degree of integration varies from system to system (see also the sections entitled “Mussels, oysters and ascidians” and “Algae” under the heading “Species for farming”) (Buck et al. 2017). A flow of nutrients from one organism to another is created in these multi-species systems, thereby utilising most of the nutrition originally added in the form of feed in the intensive, “fed” farming stage.

Intensive production systems may be open, semiclosed or closed and be located in water or on land. Algae and seed plants, as well as mussels, are examples of common extractive species that can utilise nutrient emissions from fish farms for growth[3]. A combination of filter feeders and algae/plants is normally used in IMTA systems to extract nutrients in both dissolved and particulate form. Benthic creatures such as worms, echinoderms and crustaceans can live off waste feed and faeces beneath fish farms in IMTA models (see Benthic species for IMTA farming). Sugar kelp grows quickly (Broch and Slagstad 2012) and offers major potential for co-farming with fish (Kim et al. 2017). In IMTA trials, Wang et al. (2014) have demonstrated (using stable nitrogen isotopes, δ15N) that much of the nitrogen in the algae came from the nearby fish farm and that growth was 50 per cent higher when the algae were farmed beside the open salmon cages.

In this study, it was estimated that one hectare (10,000 m^2) of sugar kelp could absorb 0.8-1.2 tonnes of nitrogen in a season. These figures are ten times higher than the figures reported for Swedish farms (Table 1, Pechsiri et al. 2016), which may be due to differences in water conditions in the various locations or overestimation in the calculation models used by Wang et al. (2014). Red macroalgae also have potential for IMTA (Buschmann et al. 2008, Abreu et al. 2011, Barceló-Villalobos et al. 2017, Ghadiryanfar et al. 2016). García-Sanz et al. (2010) developed and evaluated a way of using macroalgae as a biomarker in order to study the spread of dissolved substances around a fish farm. By studying the uptake of a stable nitrogen isotope (δ15N) after incubation periods (exposure) of varying length, it was found that the algae should be placed at a depth of approx. 5-20 m and have an incubation period of at least 4 days. It is also interesting to note that studies have shown that mussel growth also increases near to fish farm cages. Reid et al. (2010) showed that mussels have a high absorption capacity for salmon faeces. Mussels that were farmed directly adjacent to the salmon farm grew more quickly than those farmed 200 metres away, and both groups grew more quickly than the reference group (Lander et al. 2014).

Further studies support these results: blue mussels demonstrated a greater growth directly adjacent to a salmon farm, compared with a few hundred metres away (MacDonald et al. 2011). MacDonald et al. (2011) came to the conclusion that it is important to design IMTA facilities carefully if there is to be an actual particulate flow from the fish farms to surrounding algae or mussel farms. This observation is supported by a recent study where six different fish farms in combination with mussel farms tested in the Mediterranean (Sanz-Lazaro and Sanchez-Jerez, 2017). For sugar kelp, a Scottish IMTA study demonstrated the interesting fact that not only was the growth rate of the algae higher closer to the fish farm, but also that the nitrogen content was higher per gram of wet weight at distances closer to the fish farm. This indicates that the nutrient-rich water encourages increased uptake of nitrogen (Sanderson et al. 2012). The degree of integration differs in different multi-species systems (which is why the term "IMTA" may be questioned), but there are tangible advantages with multi-species farming compared with just fish farming, regardless of whether these come about due to direct integration between the various species resulting in a direct flow of nutrients from species to species, or whether this takes place by means of net balancing of nutrients between different species over a wider area.

IMTA may provide better use of farming premises, reduce environmental impact and help to diversify production with better yields on a smaller, local scale with more direct flow of nutrients from one species to another (Folke and Kautsky 1989, Troell et al. 2009, Sanderson et al. 2012). In the Nordic region, multi-species farming has taken and continues to take place at smaller research and development facilities Sweden, while Norway and Denmark are running major research initiatives focusing on co-farming of salmon, blue mussels, algae and benthic animals (Bellona Report 2013)[4,5]. There are also examples of commercial IMTA facilities in both temperate and tropical regions (Neori et al. 2004, Barrington et al. 2009, Troell et al. 2009, Chopin et al. 2012, Cyrus, Bolton and Macey 2015, Fang et al. 2016).

When multiple species from different trophic levels are farmed together in the ways described above, these systems are known as multitrophic; as distinct from polycultures, where species from the same trophic level – different fish, for example – are cofarmed. The objective of multitrophic systems is at least to have a nutrient-neutral net impact on the environment, where the various species balance one another out in terms of emissions and nutrient uptake. All of the species included must also have their own financial value when harvested. The biomass harvested in the form of extractive species can also be used for human food, and/or as aqua feed ingredients, for extraction of high-quality biomolecules and medicines, and for different types of biofuel (Ghadiryanfar et al. 2016).

These systems are complex, so complex calculations and models may also be required to allow the environmental benefits to be demonstrated. For instance, the component organisms may be farmed during different seasons. Fish and blue mussels, for example, do most of their growing between spring and autumn, while sugar kelp grows between autumn and spring. Thus the extractive species will probably not absorb exactly the nutrient molecules emitted by fish farming: instead, these substances will be distributed throughout the surrounding area and undergo biogeochemical changes in the water column before being bound back into organic matter. However, with multitrophic farms the idea is that the net effect of the entire system is expected to be neutral, both temporally and spatially.

Farmers need to choose the right combination of species providing the greatest benefits for the locality. This requires an in-depth knowledge of local conditions such as water depth, topography, currents, spatial and temporal changes in nutrients, temperature, salinity and oxygen levels, as well as freezing. One advantage of multitrophic farms is that farmers can spread the financial risks by farming several different species, but farming several different species may also be a demanding enterprise in terms of both funding and expertise, which is why cooperation involving various farmers is one potential solution.

SEMICLOSED SYSTEMS FOR INTENSIVE FARMING

Techniques and operation

Semiclosed, water-based facilities

In modern, semiclosed production systems in water, the organisms farmed are enclosed in closed containers while the water is pumped from the recipient and flows through the system before then being passed back out into the environment after various treatment stages (Figure 11). This technology is being developed in countries such as Norway, where a number of facilities are producing fish for the market while also working in parallel on constant development of the systems. This technique has also been tested at a number of sea-based locations in Sweden (Mollösund, Sankt Annas skärgård, Figure 12A-B). The containers are either hard and made of materials such as plastic, steel or concrete, or flexible and mobile and made of soft fabric, for instance (Figure 11; Heldbo et al. 2013, Ungfors et al. 2015). The water is pumped into the container from a fairly great depth so as to ensure optimum water quality in terms of temperature, salinity and oxygen saturation, as well as to avoid pathogenic organisms, which in most cases are at depths of 0 to 5 metres.

The effluent water can be treated to remove particulates and/or dissolved material to varying degrees, depending on the treatment technique and flows, before being mixed with the ambient water (Park et al. 2017; Heldbo et al. 2013). This is done by treating particulate material (e.g. feed particles and faeces), by means of grid filters, filter cloths, drum filters and/or sedimentation methods (Figure 12C), which frequently result in extraction of > 80 per cent of the particulate material. The dissolved nutrients are largely passed into the environment. These techniques offer options for connecting further treatment systems, but as far as is known no methods are being used as yet to reduce dissolved nutrient levels; but these techniques are still being developed. These facilities need to be able to withstand stresses due to wind and wave energy and strong currents so that the containers are not fractured or weighed down, allowing surface water to flow in (impaired water quality and increased risk of infection), allowing the fish to escape (Haaland 2017).

The semiclosed systems also include many of the land-based facilities that currently produce fish for consumption. The aim of this is to maintain good control over conception, egg incubation and hatching and to monitor the survival of the fish during the delicate fry stages. The semiclosed systems also include land-based ponds that are supplied with water from nearby water systems by means of gravity and where the surface water is filtered through the soil before it reaches the recipient (Haaland 2017).

Soft shells

Soft, semiclosed sea/lake-based systems are made up of cages made of sealed, durable tarpaulin for open net cages. A number of prototypes are being developed, and several models are available for commercial use. The tarpaulin material is undergoing constant development for optimisation of aquaculture usage, considering factors such as marine environments, mechanical stresses and other challenges[6] (Whyte et al. 2016). The cages are helped to float by means of floating collars. These are often made of plastic, but concrete is also being used to an increasing extent (Ungfors et al. 2015; Ytrestøyl et al. 2013). Deep water is pumped in by means of pumps, while dosed oxygenation takes place when the water is pumped in. The water is passed from the production system through a central bottom pipe, where sludge (deposited material) and dead fish also accumulate and are separated out. Different structures separate off sludge and dead fish in different ways using separate pumps for dead fish, for example, and different separation and transport systems for dealing with sludge. See the separate section under environmental impact from partial and closed RAS for further information about sludge.

ILLUSTRATIONS: KRISTINA SNUTTAN SUNDELL

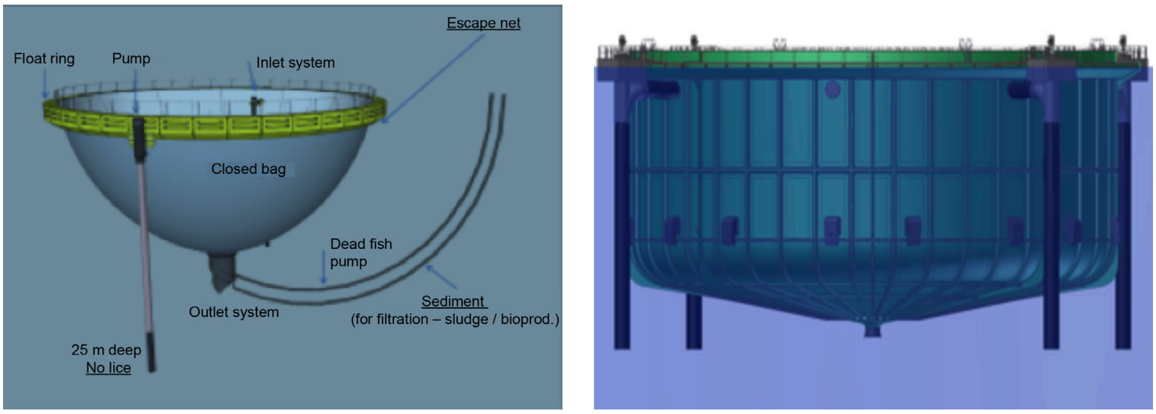

Figure 11. Basic diagram showing two different types of semiclosed production system. (A) Soft, flexible tarpaulin "shell" (Aquafuture). (B) Hard, steel-reinforced fibreglass shell of a diameter of 40 m and depth of 20 m14.

PHOTO: (A) ANETTE UNGFORS (B) MARKUS LANGELAND (C) ANETTE UNGFORS

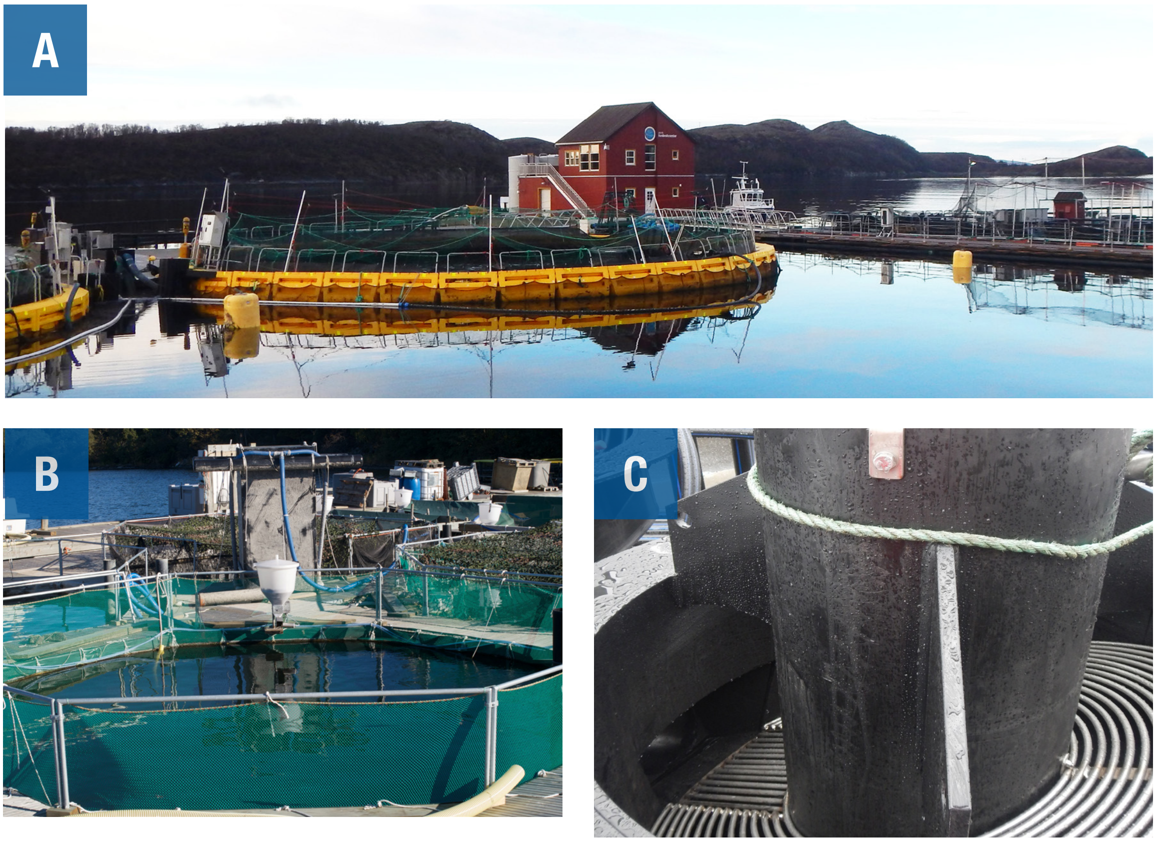

Figure 12. The fish are enclosed in semiclosed production systems while water passes through. Particulate material is dealt with to varying levels depending on the filters and filtration techniques used, while dissolved nutrients salts leave the system together with the water. The container may comprise either (A) a hard shell (B) or a soft, dense bag. The sludge is collected in (C) a bottom valve.

Hard shells

Hard-shelled systems in water are more diverse, and new designs are constantly being developed (e.g. Preline [Figure 12], Neptune, the Egg). The material used is frequently some kind of reinforced glass fibre plastic in various forms. The world's biggest tested prototype to date, Aquafarm's "Neptune", is hemispherical in shape, a cylinder with a rounded bottom (Ungfors et al. 2015) [7,8]. Neptune has undergone constant development since the first prototype was launched in July 2013, and it is now available commercially[8]. However, the shapes of the hard-shell systems vary widely. "Preline", an equally extensively tested prototype, is made up of tubular fish tanks in which the fish constantly swim against a current. This current is adapted in order to provide the ideal swimming speed to promote fish welfare, health and growth (Figure 13; Ytrestøyl et al. 2013; Solstorm 2017)[9]. Another prototype for which permission for testing off the coast of Norway has just been granted is the "Egg" (Lyngøy 2018),[10,11,12] which will be tested in respect of energy consumption as well as fish welfare, infection, parasites and escape. The water volume in these systems may vary between 2,000 and approx. 20,000 m^3 per unit. All or some of the water containing most of the waste, faeces and any uneaten pellets is passed out through an outlet where sludge separation and/or other types of treatment take place. Where appropriate, the rest of the water is passed out through adjustable hatches and holes slightly higher up on the sides of the structure. Powerful pumps are used to pump the water into the facility from the preferred depth. Incoming water is oxygenated automatically by means of an oxygen pump that is controlled by oxygen sensors in the container. The inside of the vertical walls is cleaned at intervals of several weeks using high pressure, brushes, scrapers and/or rotating discs in order to prevent fouling[13].

These new types of farming technique have a number of advantages over open production systems. As regards the health and welfare of the farmed organisms, semiclosed production systems make it possible to keep a close eye on water quality, leading to lower mortality rates compared with open systems (Ytrestøyl et al. 2013; Handeland et al. 2015). Water can be pumped in from any depth, and hence water offering stability in terms of temperature, salinity and oxygen content and containing low levels of pathogens and parasites can be selected.

One restriction with production systems of this type is that they are still relatively untested and undergoing development, along with the fact that they are more expensive structures than nets in open cages and hence the investment cost is higher. Development of semiclosed systems has proceeded rapidly over the past five years, and the farming companies focusing on this technology include large-scale commercial operations for both juvenile growth and farming of fish for consumption, with production volumes in excess of 1000 tonnes a year (Handeland et al. 2015). Besides the initial investment, production should be cost-effective once it is up and running. One challenge involves designing and producing technology that is able to withstand severe storms and ice formation. Semiclosed systems require more monitoring and equipment than open production systems.

Land-based farming with water flowing through

The semiclosed systems also include land-based farms and pond farms that are frequently supplied with water from nearby water systems by means of gravity and where the outgoing water is filtered through technical solutions or the soil before it reaches the recipient. Common pond species in Sweden are rainbow trout, while tilapia, pangasius, clarias and shrimps are common in other parts of the world (van der Blom 2013; FAO 2018; Dalsgaard et al. 2013). Sweden has land-based tank farms where water flows through. In Sweden, land based flow-through systems are used for the majority of roe and fry production for our most important food fish species. The water can be taken from nearby waterways or lakes, and this is referred to here as surface water regardless of the depth from which it is taken. However, it can also be taken from groundwater. Both water intake types have their advantages and disadvantages, and combinations of the two water sources are best for both production and cost effectiveness, if conditions are favourable.

Groundwater maintains an even temperature throughout the year, which means that this water is warmer than surface water in winter and cooler in summer. This means that the fish eggs can be hatched earlier and fry growth therefore commences earlier, but also that hatching and growth are more standardised from production year to production year. There is also no risk of the water temperature becoming too high in summer. However, groundwater frequently needs to be oxygenated, either mechanically or by means of an oxygen gas generator. Various metals often precipitate out of the water when oxygen is added, and these have to be filtered out before the water reaches the production unit. Surface water intake follows the year's natural temperature variation. It is possible to compensate for too low an incoming water temperature by heating the water to the preferred temperature. This uses a lot of energy and results in additional costs for farmers. In the same way, the water may need to be cooled in summer. Surface water normally has a satisfactory oxygen content, but mechanical aeration frequently takes place anyway in order to increase the oxygen level. Incoming surface water may also need to be filtered before it enters the farming facility.

If both surface water and groundwater are available, the different water sources can be combined so that there is no need to pay for heating and cooling. The temperature and farming period(s) can then be controlled and optimised more effectively. Flow-

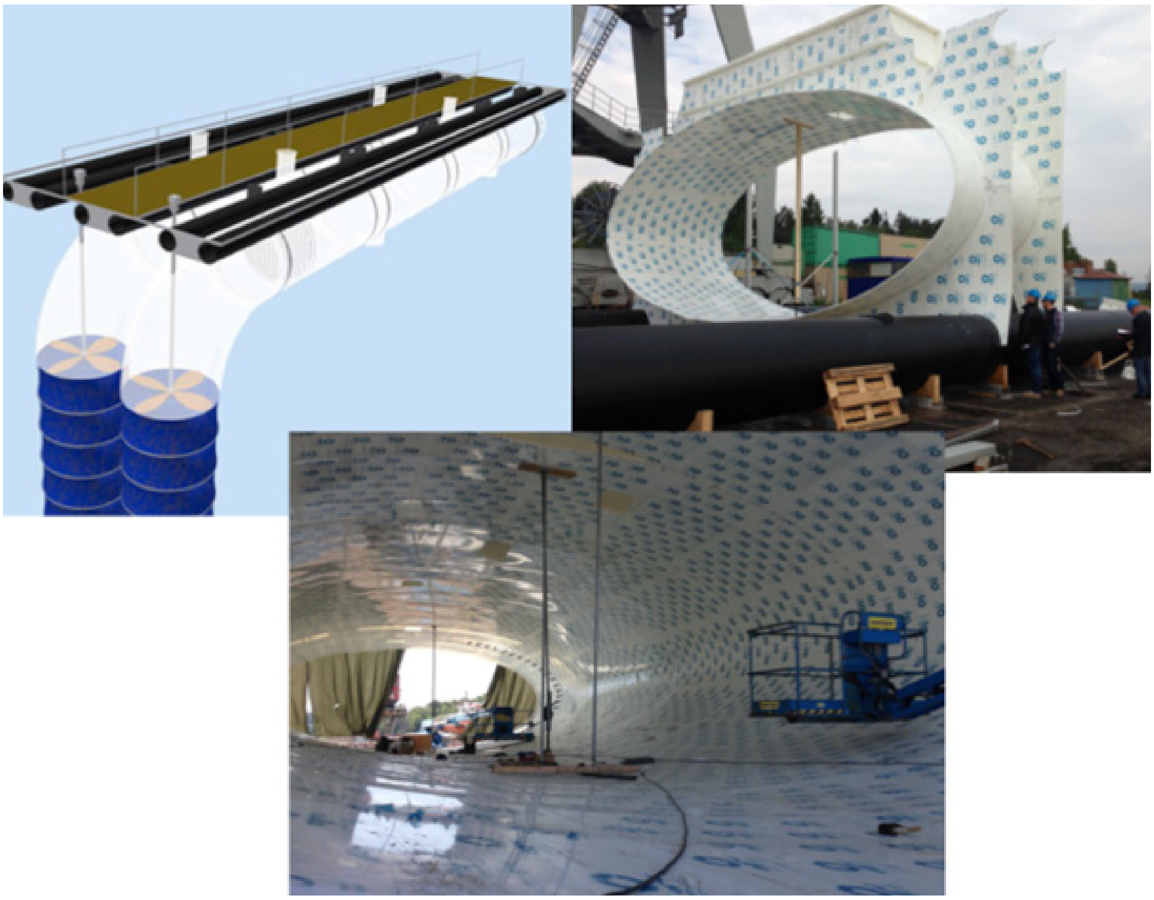

FOTO: HTTP://WWW.PRELINE.NO

Figure 13. Pipe-shaped semiclosed production system where the fish are swimming against a current (Preline).

through facilities are frequently located in areas where the water is gravity-fed so that the cost of pumping water into the facility can be kept to a minimum by utilising the water's natural drop. This is why a number of facilities are located adjacent to hydropower ponds. In these cases, farmers may be required to pay for the reduction in energy production caused by diverting the water that passes to the facility.

Gravity-fed farming plants are at considerably less risk of production downtime due to pump failure and potential adverse consequences due to a shortage of water at the facility.

Broodstock are also kept in pools at the plants or in nearby ponds or – less commonly – in open farming cages. The fish are usually fed using automatic feeders which are activated either mechanically or electronically. Regardless of the method used, the daily condition of the fish determines how the feed ration is optimised.

Farming in ponds

Farming in ponds is most common with facilities producing fish for consumption (FAO 2018). These flow-through systems use surface water, but this may sometimes be mixed with groundwater. In ponds, as with land-based through flow facilities, the fish are fed either manually or using automatic feeders controlled mechanically or electronically.

However manual feeding is more common in pond facilities than in other farming facility types. Regardless of the feeding method use, the daily condition of the fish determines how the feed ration is optimised. Both conventional dry feed and feed with particular buoyancy are used. Waste is prevented by optimising the pellet size according to the size of the fish. Total production at pond facilities is marginal in relation to other production methods (FAO 2018). Farming fish in ponds is relatively inexpensive, but like other fish farming methods the facility requires daily supervision. However, handling of fish – delivery and sorting, for example – may be more labour-intensive and physically demanding than at land-based facilities.

Environmental impact

Semiclosed, water-based facilities

Commercial semiclosed facilities are available to an extent at present, and these also operate in parallel with research and technical development in a number of locations along the coast of Norway. These techniques have also been tested in Sweden on a number of occasions. In the field of salmon farming in Norway, reducing the time spent by fish in open cages in the sea has been one of the driving forces for development of both semiclosed and closed systems. This is partly because the maximum "load-bearing capacity" (space available) for nutrient loading from fish farms in Norway has been reached, and no more permits are being issued for sea-based salmon farming. As a result of this development, more production cycle time is taking place on land in recirculating systems and/or in the sea in semiclosed systems, where nutrients can be dealt with more effectively to a greater or lesser extent, thereby freeing up space so that total production can be increased.

Reducing problems involving salmon lice and other infections at farms, reducing escapes and increasing survival, primarily during the initial period after the fish have been transferred to open cages in the sea, are other important driving forces behind this development. A mortality rate as high as 20 per cent has been reported when transferring Atlantic salmon smolt to open cages in the sea when they reach the traditional size, approx. 100 g.[14] Survival on saltwater transfer has proven to increase if the smolt are of a larger size (200-600 g) when they are set out, and also if they are set out in semiclosed systems for a time first (Handeland et al. 2015, Calabrese et al. 2017).

In semiclosed, water-based systems, the water is pumped into the soft or hard closed "cage" and the outgoing water is passed via filters of various types – different filters for the different systems – but > 80 per cent of the particulate material is normally dealt with before the outgoing water is returned to the recipient. The system currently being tested is reporting values of 80-100 per cent removal of particulate material in the outgoing water. As regards nitrogen and phosphorus, this means that approx. 15-30 per cent of the nitrogen and 65-80 per cent of the phosphorus are dealt with in the sludge. This technique has only been tested on a small number of occasions to date under environmental conditions applicable to Swedish water zones, so it needs to be examined in greater detail in order to establish its potential for Swedish conditions.

As dissolved nutrients are still being released to the surrounding area in outgoing water, it is worth examining in these production systems as well whether integrated farming (IMTA) with extractive species may be appropriate in the local area. One environmental advantage of the technique is that surplus particulate nutrients can be collected, thereby also reducing the organic environmental burden. The fish are entirely enclosed and so there is a low risk of escape, and an additional net can be secured to the outside to further prevent escapes in the event of any damage to or holes in the shell. Incoming water is also pumped through "net bags" to prevent fish being sucked out into the surrounding area if the pump stops. Both these nets and any particulate filters and "escape cages" are cleaned by machine washes, while the cages themselves are washed by brushing and rinsing them.

One of the advantages of large-scale Norwegian tests of semiclosed systems is the massive decline in salmon lice outbreaks, as the proliferation stage of salmon lice remains mainly in the surface water, not appearing in the deep water pumped into the system to any great extent (Johnsen et al. 2014). Some surveys also show that fish behaviour is altered where Atlantic salmon in traditional open systems are aggregated frequently, while it has been noted that salmon are more evenly spread out throughout the cage in a semiclosed system during the daytime. The growth rate has proven to be higher and a lower feed conversion ratio has been measured in semiclosed facilities compared with open cages. A lower mortality rate has also been reported in semiclosed systems (Kolarevic et al. 2014; Calabrese et al. 2017).

Land-based flow-through systems

In land-based farming with water flowing through, outgoing water is normally passed through a mechanical and/or biological filter. Mechanical filtration removes most of the particulate waste, while dissolved nutrients and smaller particles reach the recipient. Flow-through facilities require plenty of access to water. At the same time, a high flow-through rate means that the water passing out from the facility contains low levels of nutrients per litre of water. All or parts of the facility's water can be recirculated in order to reduce the water needed. This increases options for treating the water but also results in a greater need for energy for pumping the water for circulation (see "Closed systems for intensive farming"). Most of the fish for consumption produced at facilities with flow-through systems are set out at farms producing fish for consumption where production in open cages for the grow-out stage.

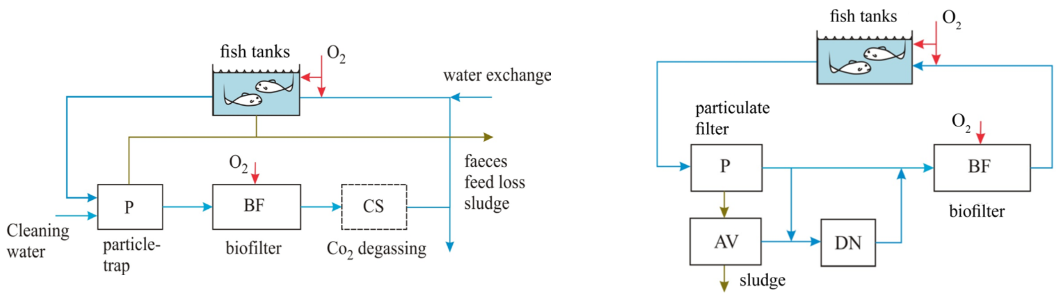

ILLUSTRATION: TORSTEN WIK

Figure 14. Basic diagram showing (A) partial RAS with water exchange, and (B) RAS with complete water recirculation. P = Particulate filter/separator, BF = Biofilter for nitrification and breakdown of organic matter, CS = CO_2 separation, AV = O_2 separation, DN = Denitrification.

Farming in ponds

Outgoing water is not normally treated, but some pond facilities have downstream sedimentation ponds where coarser deposits accumulate. The production volume in ponds in Sweden is low compared with other production systems.

CLOSED SYSTEMS FOR INTENSIVE FARMING

Farming in recirculating systems is taking place on a small scale in Sweden at present, and also in systems where technical development is ongoing. Both tropical and cold water species are farmed.

Techniques and operation

Partial and full RAS

The water in closed recirculating production systems – RAS, Recirculating Aquaculture Systems – is treated over various stages, either entirely or to a great extent, and recirculated back to the fish (Heldbo et al. 2013; Ungfors et al., 2015). This technique is used on land, and so the facility is not subject to wave energy or ice in the same way as water-based systems. The aquatic environment for the farmed organisms can be controlled effectively by means of disinfection, treatment and control of various water quality parameters such as temperature, pH and salinity, and nitrogenous wastes. Essentially, RAS systems can be divided into two main groups: partial recirculating aquaculture systems (recirculating <90 per cent of the water) and full recirculating aquaculture systems (recirculating >90 per cent of the water). RAS facilities can be designed in many different ways, but certain basic functions are always included in partial RAS (Figure 14A) and full RAS (Figure 14B). A high level of recirculation makes stringent demands of water treatment, which in turn may increase installation and operating costs.

The most appropriate type of RAS facility is dependent on the species to be farmed, feed, production volume, temperature and local factors such as water access, emissions levels, access to land, buildings and heating. As a result, investment costs for RAS are high initially and a great deal of technical expertise is required to be able to design an efficient RAS facility. Day-to-day use, operation and maintenance also require more technical equipment and expertise than for open systems. RAS technology offers significant water savings and strong barriers between farmed organisms and the surrounding area, as well as a good production system for organisms as indicated by good survival and growth rates (Terjesen et al. 2013).

Feeding in RAS facilities differs slightly from feeding in open systems. Pellets with different physical qualities such as particular buoyancy are required in RAS facilities. More developed control of feeding is often available here, too, thereby helping to prevent overfeeding.

The effects of overfeeding in RAS systems are frequently more drastic as it affects the various filters and may lead to rapid impairment of the water quality. At RAS facilities, therefore, feed consumption is often lower and more efficient feed conversion has been reported in these systems.

a) Farming tanks

The two most common types are farming channels (long pools) where the water runs from one end to the other and the water quality often declines when approaching the outlet. Round or polygonal tanks are the other farming vessel type, and these are generally considered

PHOTO: (A) ANDERS KIESSLING (B) ELENA GAZEEVA

Figure 15. Land-based production systems with recirculating water, RAS. (A) Swedish farming of perch (B) and sturgeon.

to offer more consistent water quality throughout the entire water volume (Figure 15). It is possible to create a circular current in the water with a correctly angled inflow, particularly in round tanks, thereby creating a current against which the fish can swim (which is good for salmonids, for example), and also provides a better self-cleaning function as particles such as feed residues and faeces accumulate in a centred vortex and can easily be separated by means of a bottom valve (cf. semiclosed systems; Figure 12C). One disadvantage of round tanks is that they require more land space for the same farmed biomass. These tanks are often made of plastic or fibreglass, and sometimes they are made from concrete.

b) Filters and particle separators

The water in an RAS facility can be fed in many different ways to the treatment stages incorporated in the system, but most of the water is frequently fed from the farming tanks to a mechanical filter first, where larger particles and sludge are removed (Figure 16). Drum filters are commonly used, but band filters, disc filters, strainer screens or hydrocyclones are also used. The accumulated particles are compacted in various ways and removed using a sludge separator.

One risk factor with RAS facilities is that tiny particles may accumulate in the water. This may adversely impact on the fish in a number of ways. This may include irritation and damage to the gills, thereby reducing the oxygen uptake of the fish and increasing the risk of bacterial attacks. A certain type of adverse anoxic (oxygen-free) breakdown of organic matter may occur if suspended particles are allowed to accumulate, potentially resulting in a muddy flavour to the fish. Increased particulate levels may also impair visibility in the water, which could affect the attempts of the fish to look for food, reduce food intake and so increase food wastage. However, the opposite is also true, mainly among juveniles of certain species, e.g. Atlantic halibut and cod, where clay or "green water" (phytoplankton, see Figure 19) is added as this encourages food intake. Suspended particles may also affect water treatment in RAS systems by blocking biofilters and impairing UV and/or ozone treatment (Schumann and Brinker 2017). If sand filters or bead filters are used, additional time for backflushing, commissioning, etc. will be required if they are blocked with particulate material. This is why it is important to keep particulate levels low in the water, and this is frequently achieved by means of one of three primary principles for removal of suspended particulate material: sedimentation, filtration and flotation (foaming). Sedimentation takes place naturally when the flow rate is sufficiently low. Large volumes/areas are required in order to achieve a low flow rate, and so sedimentation is not appropriate for indoor farming.

Filtration is a purely mechanical method where the water is passed through a filter with a specific pore size (Holm and Andreassen 2018). Drum filters and band filters are the most common types. Both types require regular flushing of the filters, which in many cases is automated. Flotation is based on a concept whereby tiny particles attach themselves to small air bubbles, which float up to the surface and form a foam, which is then removed. This flirtation method is primarily used at hatcheries and fry facilities, in series with filtration, to remove the tiniest particles remaining. This is known as polishing the water (Heldbo et al. 2013).

Filter arrangements and types may vary in many ways, see Ungfors et al. (2015) for examples of a number of systems available at present. These complex series of filters require continuous control and monitoring of water parameters such as salinity,

PHOTO: ANDERS KIESSLING

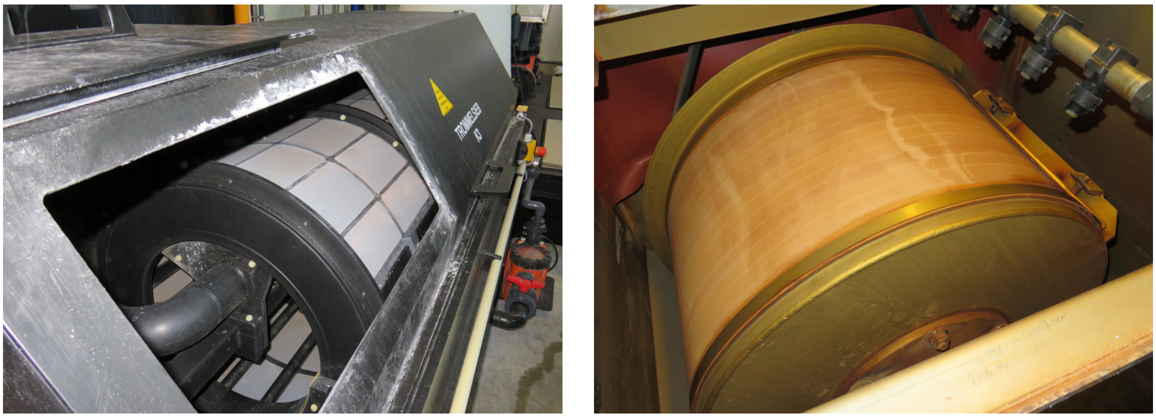

Figure 16. Two different drum filter types for removal of heavier particles and sludge at an RAS facility. The filter on the right is made of brass, which makes it more capable of withstanding saltwater.

temperature, nitrogen compounds and oxygen levels and pumps that guarantee the flow of water in the system, and they can also be used for oxygenation, backflushing and cleaning of filters.

c) Bacterial cleaning stages for partial and full RAS

I. Organic matter

Particulate organic matter that is biodegradable is converted by means of hydrolysis into dissolved organic matter that is more or less readily accessible to heterotrophic bacteria for use as a substrate. The amount of organic matter can be measured by seeing how much oxygen is required for complete breakdown (oxidation) of the organic matter available. This can be done either indirectly by chemical means (COD) or biologically using bacteria (BOD) (Ungfors et al. 2015). The organic matter is broken down in a biogeochemical process where different types of heterotrophic bacteria use oxygen or oxidised inorganic compounds to break down the organic matter and bind it into biomass.

Oxygen is the most effective oxidant and gives bacteria the most energy, so aerobic bacteria have a competitive advantage over anaerobic bacteria. That said, other, more slow-growing bacteria such as denitrifers take over if the oxygen runs out. The active sludge process, which is the traditional municipal water treatment technique, is based entirely on suspended bacteria in open pools. These bacteria form sludge flocs that settle, are dewatered and then removed. This method can also be used in an aquaculture context, but it may be problematic in RAS as sludge flight – which takes place when the flocs do not settle sufficiently quickly – may occur and cause problems with increased particle volumes in the system. Biofilters are normally used in RAS facilities instead. These are also known as bioreactors, and in them the bacteria are attached to a substrate (carrier material) that increases the surface area. This substrate may be made up of sand, stone, plastic or wood in some form (Xiao et al. 2018), which thereby causes the bacteria not to need to settle. The larger the surface area, the more space there is for bacteria, and the carrier material may be either fixed or mobile (Moving Bed Biofilm Reactor, MBBR). The latter has a number of advantages: for instance, the biofilm can be controlled more easily and kept at the ideal thickness, and air is normally used for agitation, thereby ensuring good oxygenation.

II. Nitrification

Nitrogen products are broken down by means of nitrification: this means oxidation of ammonia to form nitrate (NO_3^-) using bacteria, and the reaction takes place over two stages. The nitrogen added to the system comes from proteins in the feed. The main nitrogen product excreted by the animals into the water is ammonia (NH_3). NH_3 is toxic to both fish and crustaceans even at very low concentrations (Roques 2013). Depending on the pH of the water, a greater or lesser volume of NH_3 will be converted into the less toxic form ammonium (NH_4^+). The limit for NH_4^+ in water for fish is 0.5-1.0 mg NH_4^+-N/m³ (see Ungfors et al. 2015).

Nitrification bacteria convert NH_3 over two stages in the presence of oxygen. Firstly, NH_3 is oxidised to form nitrite (NO_2^-), which in turn is oxidised to form nitrate (NO_3^-) (Brailo et al. 2018). As NH_3^- oxidation releases hydrogen ions, it is important for the alkalinity (buffer capacity) of the water to be good so that the released hydrogen ions can be bonded, or buffered. Otherwise there is a risk of the pH of the water falling. NO_2^-, like NH_3, is toxic (Roques 2013), and so it is important to ensure there is no buildup of the NO_2^- concentration; instead, the process has to continue all the way to NO_3^-.

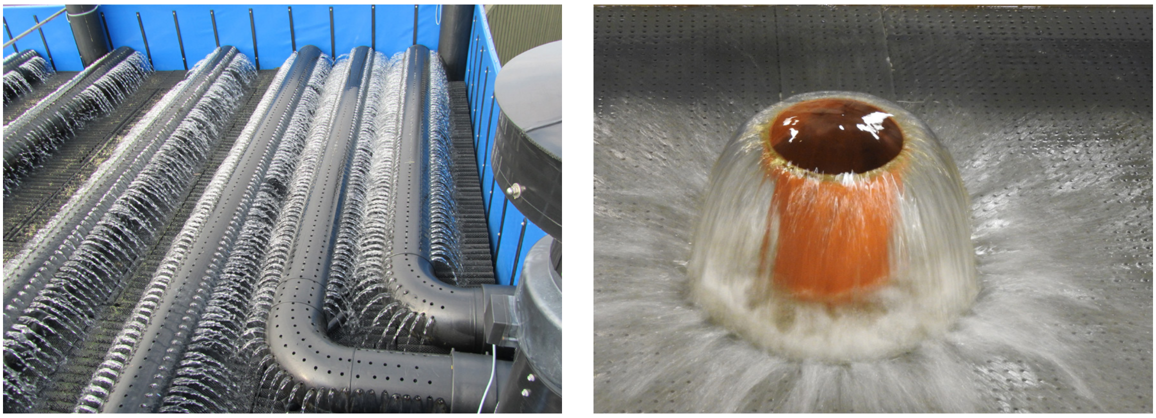

Figure 17. Removal of carbon dioxide for pH regulation. Two different filter types for deaeration of carbon dioxide at an RAS facility. The systems increase the surface between water and air so that carbon dioxide can evaporate to air from the water in a gaseous form, thereby increasing the pH of the water.

Effective oxygenation is important for use of the nitrification bacteria to be optimised. In the bioreactors, the water is allowed to trickle down onto the biobed, aerating the water and thereby increasing the oxygen level. In the biobed, the nitrifying bacteria are allowed to grow on a carrier material that may be designed in many different ways (see above and Ungfors et al. 2015): plastic balls with complex folds that increase the surface area greatly are common. The nitrifying bacteria are autotrophic and use carbon dioxide (not organic matter) as a substrate for their biomass. The bacteria grow slowly, so a biofilter needs to be allowed to mature. In other words, the nitrogen burden in the system needs to be built up gradually to allow the bacterial population to grow to its maximum capacity. An effective biobed has to be built up gradually, and it takes time to optimise it (Rurangwa and Verdegem 2015). All biological water treatment processes are dependent on temperature. This is true of the growth of nitrification bacteria, which declines fairly rapidly as the temperature falls. Room temperature is ideal for nitrification. Bacterial growth rate at 20 °C is approximately halved at 12 °C, and falls to one-third of this level at 8 °C. Therefore, it may be more difficult to achieve stable and high levels of nitrification at temperatures below 7-8 °C. Nitrification is dependent on the number of bacteria, but also on how thick the biofilm is, as oxygen and NH_4^+ need to be able to diffuse into the innermost bacteria in the film; so the larger the surface area, the better (Zhu and Chen, 2002). In water, nitrification is limited more frequently by the amount of available oxygen than by the NH_3/NH_4^+ concentrations. As water may contain more oxygen at low temperatures, this compensates slightly for the lower growth rate of the bacteria (Zhu and Chen 2002). Nitrification in saltwater is slightly lower than in freshwater, which may be due to the fact that saltwater contains lower levels of oxygen than freshwater at the same temperature (Rusten et al. 2006). The best system design is dependent on the salinity and temperature, as well as the farming type, feed, farm size and local factors such as water availability, emissions requirements and access to buildings and heat.

As a number of chemical processes take place in succession, the biofilters are often divided into a number of separate chambers where the organic matter (see I) is broken down in the first few chambers and converted from NH_3/NH_4^+ to NO_2^- and then to NO_3^- in the chambers that follow. In a partial RAS, the concentration of NO_3^- will slowly build up in the system, but NO_3^- is considerably less toxic than NH_3/NH_4^+ and NO_2^-(Roques 2013), which is why fish are able to tolerate a certain increase in levels. The limit for NO_3^- is 50-300 g NO_3^-–N/m³; Ungfors et al. 2015). In the partial RAS, this increase in NO_3^- levels is primarily what determines how much water has to be replaced. Continuous replacement of water ("bleeding") often takes place. This can be done in a number of ways. (Back-)flushing must take place regularly when drum filters, band filters and sand filters are used, and in this case indirect water exchange also takes place as flushing water is also removed with the sludge, although any surplus water is fed back to treatment. If greater water exchanges are needed, this will not suffice. Instead, treated water is drained from the system and new water is fed into the farming tanks. Besides the NO_3^- concentration, the water exchange level is also determined by the pH and alkalinity of the water. Nitrification releases hydrogen ions, which may reduce the pH of the water. This can be adjusted upwards again by reducing the amount of carbon dioxide (CO_2) in the water. The water is trickled over structures that increase the surface area so that the exchange surface between water and air is increased, normally by means of various plastic structures and gravity (Figure 17). Gas exchange can then take place with the ambient air so that carbon dioxide is given off and the pH of the water is increased. However, degassing the carbon dioxide has an adverse impact on alkalinity, which is why some water exchange may be necessary in order to increase the alkalinity as well. Various calcium reactor types, coquina, etc. are also used to increase the alkalinity in the system.

d) Bacterial treatment stages for full RAS III. Denitrification and anammox

The primary difference between the two main groups of RAS systems is that full RAS also involves denitrification/anammox, which means that NO_3^- and/or NO_2^- and ammonium are converted into nitrogen (N_2) that can diffuse out into the air. The recirculation level can increase significantly as this removes the nitrogen from the water (Ungfors et al. 2015). This conversion of formed nitrogen products into N2 also takes place using bacteria in bioreactors. Two primary bacterial groups are able to form N2: the heterotrophic denitrification bacteria that break down NO_3^- into N_2, and the anammox bacteria that combine NH_4^+ and NO_2^- to form N_2 and water. Both can only operate under anaerobic conditions.

Denitrification bacteria need organic matter as a source of carbon for their breakdown activities, but anammox bacteria do not need this; they can use CO2 as a source of carbon instead. These two types of bacteria often occur together in denitrifying, anoxic biofilters. However, anammox bacteria often make a relatively small contribution to denitrification due to their low activity and need for higher temperatures (Awata et al. 2013). However, denitrification using denitrifying heterotrophic bacteria does not seem to be as temperature-sensitive as nitrification, and these bacteria maintain a good rate all the way down to 5 °C (Rusten et al. 2006). A number of research projects are working on potential solutions for optimisation of various combinations, in the same or separate filters, of denitrifying heterotrophic bacteria and anammox bacteria.

The specific demands of various bacteria in terms of an aerobic or anaerobic environment, with or without NH_4^+, with or without organic matter, etc. make it difficult to "simply" add a denitrification stage at the end of the series of filters described for the partial RAS system. For example, nitrification works best if the organic matter content is relatively low, and this is why both organic substances and $NH4^+$ are generally not sufficient at the end of the filter series to allow denitrification to take place, in one way or another. Various solutions are used to supplement a partial system to form a full RAS in various separate loop types, where some of the water is fed to an anoxic denitrification filter directly from the farming tank or directly after the particulate filter, and then on to other filters. Denitrification can also take place in the effluent water, but in this case an external source of carbon usually needs to be added. This can be remedied by adding sludge that has been digested anaerobically, or simple carbon sources such as alcohol. The carbon to nitrogen ratio in the feed, together with fish respiration, are the factors that determine how much NO_3^- can be denitrified without adding external organic matter (see Ungfors et al. 2015, for example).

e) Disinfection

RAS systems frequently include a disinfecting stage as well, where unwanted bacteria, fungi, viruses and pathogens are destroyed. Disinfection is performed either by passing the water past a UV filter and/or by adding ozone gas or chemicals. As RAS facilities utilise "good" bacteria for their water treatment, chemicals are not generally recommended as these can disable the entire biofilter if they have not had time to break down before arriving there via the water flow. Low concentrations of formalin and peracetic acid do not harm nitrifying bacteria to any great extent, but they have an adverse effect on nitrification in high doses (Keck and Blanc 2002, Pedersen et al. 2010, Murray et al. 2014, Ungfors et al. 2015).

Hydrogen peroxide has proven to have a significantly negative effect on biofilter function (Arvin and Pedersen 2015). Instead of chemicals, therefore, methods with a short-lived effect on the passing water and where no chemical byproducts are produced are normally used; UV treatment, ozone treatment and oxidation processes. The more slowly the water flows past the UV lamp, the greater the intensity to which the water and pathogens are subjected. The UV dose is referred to in mJ/cm^2, and for aquaculture purposes this level is generally in the region of 320 mJ/cm^2. UV light at a wavelength of 100-400 nm kills or deactivates most bacterial, viral and parasitic pathogens (Wedemeyer et al. 1978, Sharrer et al. 2005, Skall and Olesen 2011, Janning et al. 2012). Ozone (O_3) is an aggressive gas, more effective than UV light, which speeds up the process and increases the treatment and disinfection capacity. Ozone causes flocculation and settling of particles, and so they can be removed by means of filtration or flotation. Ozone also oxidises dissolved organic substances so that they precipitate and can be filtered out, as well as oxidising toxic NO_2^- to form NO_3^-. No harmful residual products are created, and the ozone gas is converted rapidly into oxygen.

However, when ozone is used the residual ozone has to be removed before it comes into contact with the fish. If necessary,this can be done using UV light as ozone absorbs UV energy and is broken down. The greatest disinfection effect is achieved if ozone and UV light are combined, although individually they are both very capable of killing pathogens (Wedemeyer et al. 1978, Liltved m fl. 2006, Skall and Olesen 2011, Janning et al. 2012, Murray et al. 2014). Another option is to treat the water using AOT (Advanced Oxidation Technology), where bacteria are killed using hydroxyl radicals, reactive oxygen radicals of a kind (Gonzalez 2017). The effect of all these methods is dependent on the water flow; a rapid flow rate will reduce the effect, while a slow rate will increase it. Only one of the land-based closed facilities that responded to the questionnaire stated that they use ozone for water treatment. The gas breaks down quickly and so it has to be produced on site. Moreover, safety systems are required as it may have a carcinogenic effect, and elevated levels should be avoided at the facility. This maybe the reason as to why small farmers and trial facilities use the slightly less effective but safer UV light method.

f) Oxygenation

As all organisms that are farmed in water breathe oxygen, which they need for their metabolism, it is important to maintain constant and plentiful access to oxygen in the farming tanks. Therefore, the oxygen level in the water should be monitored constantly and air or oxygen should be added if necessary. For most fish species, the optimum amount of dissolved oxygen (O_2) is between 4 and 6 O_2 mg/L. Adding air is sufficient if there is a relatively low organic burden on the system, but oxygen usually needs to be added in the case of intensive farming (Figure 18; Summerfelt et al. 2000).

There should be an oxygen sensor in every tank (or in their outlets) that is connected to a control system with automatic oxygen supply and/or alarm functions, so as to ensure that the oxygen level is sufficiently high for farming organisms. As oxygenation, just like any other technique, involves a cost for the facility, it is important to adapt the system to the type of farming and hence the relevant needs. Costs for the selected method can be minimised by using closed-loop regulation based on the measured oxygen level and temperature. In closed systems (and sometimes in semiclosed systems as well), a continuous automated feed is connected to a system that can add extra air/oxygen as required. How much oxygen (in moles or by weight) can dissolve in the water is dependent on the density of the water. This means that low-temperature water with low salinity contains more oxygen at full saturation than high-temperature water with high salinity (Riley and Skirrow, 1975). At normal air pressure (1 bar/101.1 kPa), full oxygen saturation in freshwater at 10 °C is approx. 11.3 mg/L and falls to 9.1 mg/L at 20 °C. The corresponding figures for seawater with a salinity of 35 PSU (3.5 per cent) are 8.8 mg/L and 7.2 mg/L respectively. As organisms' need for oxygen often increases as the temperature rises, this means that farming species at high temperature makes more stringent demands in terms of additional oxygen supply. If the density of the water is changed – by increasing the temperature, for example – this also changes the saturation; and water that was saturated initially then becomes oversaturated, resulting in the formation of gas bubbles. These bubbles of oxygen rise to the surface and may have an adverse impact on the farmed organisms (Stenberg 2016). Additional oxygen is normally supplied at smaller facilities by means of a simple air pump, but air/oxygen compressors are required in the case of larger installations and higher farming density. When compressed oxygen is used, or alternatively an oxygen concentrator and catalysis – where nitrogen and oxygen are separated – the oxygen can be dissolved in the input flow to the point of oversaturation. These types of oxygenation probably use more energy than bubbling. Aeration is needed during certain stages of water treatment, too. During these stages, the water is aerated by trickling it over surfaces or by compressing air in a compressor, for example, before then feeding it to diffusers designed to distribute the air in the form of tiny bubbles. Both of these methods result in a large contact face between the air and the water. The power needed is dependent on a number of factors; friction losses in the diffusers, the efficiency of the compressor and the depth of the water (which determines the counterpressure; Ungfors et al. 2015).

g) Energy requirements

Different energy source types are needed for the purposes of aquaculture: electricity for running pumps and other equipment, fuel for transport and backup generators, and energy for heating and/or cooling. RAS systems are dependent on energy for pumping water and, possibly, for regulating the temperature of the water and heating the premises.

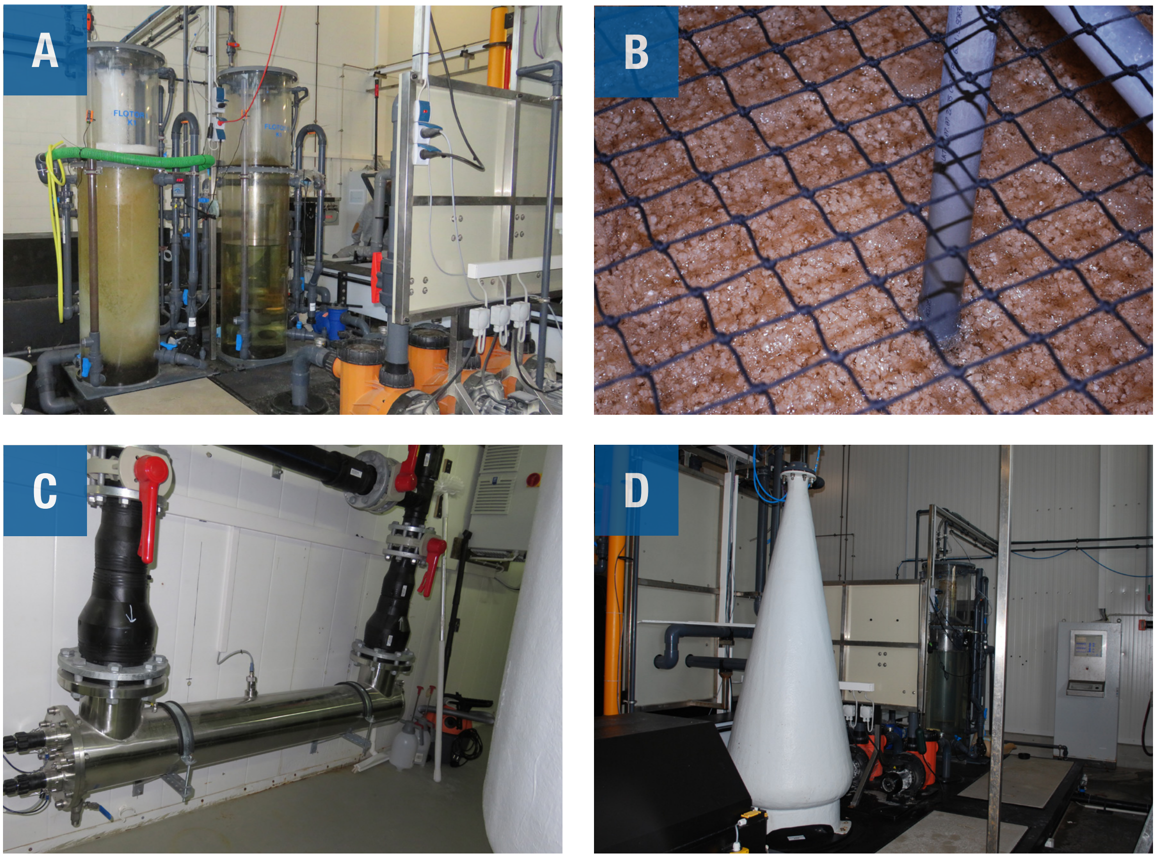

PHOTO: ANDERS KIESSLING

Figure 18. Equipment for water treatment at an RAS facility. (A) Protein skimmers remove loose organic matter (B) Bacteria grow in a moving bed biofilm reactor (MBBR) as a biofilm on a substrate that increases the surface area (plastic balls are used here). Biofilm covers a large surface area over the water and breaks down and treats the water to remove substances containing nitrogen (that are toxic to farming organisms) from the water. (C) Disinfection. The water passes a UV lamp emitting light with a wavelength of 254 nm in order to remove viruses, bacteria, fungi and parasites. (D) Oxygenation of the water. Pure oxygen under pressure is added to the water in an oxygen concentrator.

Aquaponics

Land-based facilities where animals and terrestrial plants are farmed in the same closed water system are known as aquaponics, and ancient traditions are used for this technique. Fish for consumption or shellfish are usually farmed in systems together with vegetables, herbs, mushrooms and flowers. The waste from the fish is used as plant nutrients, and the plants and other organisms – such as bacteria and mussels – are used to treat the water, which can then be recirculated back to the fish. Fish that are hardy and easy to keep and that grow quickly are most common for this type of farming. These include species that live in warm water, such as tilapia and various wels catfish species, but rainbow trout are used as well. The water from the farming tank where the fish are kept is fed to a precipitation tank/biobed where bacteria break down faeces and feed residues to form dissolved nutrients. The water is then fed to the land plants in the system, which are farmed without soil (hydroponics), and the nutrients are then absorbed directly from the water. The water is then pumped back to the fish. Farming of this type frequently takes place in urbanised areas, where land and access to water are in short supply, and these farms are sited in areas that have access to sunlight and are unused; on roofs, for example. Hence these farms also help to bring plant life to the urban landscape. This kind of farming can take place out of doors if weather conditions are favourable, but in the Swedish climate farming in greenhouses is probably more feasible. A lot of energy is used to heat the water, so developments are now considering more energy-efficient greenhouses, and there is also plenty of access to waste heat from buildings and industries that can be used in the urban environment. The proportion of plants to fish in an aquaponic system is approx. 10 to 1, and the plants will also take up quite a large area if they are to compensate entirely for the fish. The plant farming area can be "compressed" by means of vertical farming. This technique is only being used on a small scale in Sweden as yet, in individual households and at demonstration/trial facilities, but commercial systems on a slightly larger scale are being constructed. The containers are normally made of plastic or concrete, and the containers for plants can be filled with inert material such as LECA pellets or pebbles to provide support for the plants. Water in the system is circulated by means of hoses, gutters, automatic siphons and pumps. There are a number of trial and demonstration facilities for aquaponics in Sweden, where plants (leafy greens, tomatoes or tropical plants) are farmed together with fish. Sweden's first commercial sturgeon farm uses in tropical plants such as bananas and papaya trees as biofilters at the RAS facility.

IMTA on land in RAS
Integrated multitrophic farms are also possible in RAS. Trials are currently taking place in Kungshamn and other locations involving farming of diatoms (microalgae) in wastewater from a fairly small land-based RAS fish farm. Certain necessary trace elements and carbon dioxide from the fish farming water and air are also being added so that the algae can grow. The water from fish farming is pumped out of the fish farming facility and into a greenhouse, where it is allowed to flow over flat farming areas in a biofilm system. Diatoms (taken from the local bottom sediment) grow on the surface, and these microalgae treat the water by absorbing nutrients from the water and binding into biomass. The algae can then be harvested and processed for industrial methods (see algae and plants).

Biofloc
In biofloc farming, bacteria and phytoplankton are present directly in the farming water for the fish/crustaceans, where they act as an internal treatment plant, feed and probiotics, in combination. These systems can only be used for species that are adapted to filter/feed from clumped flocs of bacteria (hence the name "biofloc"), such as the whiteleg shrimp and tilapia (Figure 19B). These production systems are entirely closed, land-based systems, with more or less zero emissions (Avnimelech 2009). The bioflocs are made up of microorganisms that circulate and provide food for the shrimps (or filtering fish species such as tilapia).

The bioflocs are made up of microorganisms that live on organic matter with a high protein content, such as legumes. The microorganisms in the system, which needs to be at a high temperature, are intended as a way of supporting the fish or shrimps entirely or of providing a certain amount of support feeding, supplying energy and nutrients to promote high production. The biofloc nutrient composition varies and is dependent on factors such as added nutrients, farming type, farming conditions, salinity, light, ratio of bacteria to phytoplankton, etc. The protein content in different biofloc systems may vary between 14 and 50 per cent on a dry matter basis. The lipid content is normally low, with values between just over 1 per cent and 9 per cent, although the lower range is most common (review by Martínez-Córdova et al. 2015).

Environmental impact
Energy consumption
The amount of energy needed by a land-based RAS facility is higher than for water-based open and semiclosed systems (Ayer and Tyedmers 2009; Badiola et al. 2017). This is mainly due to the pumping of water and, if necessary, temperature control for the premises and water. The water temperature is the factor that has the greatest impact on the growth of aquatic organisms, and increasing the water temperature by a few degrees can significantly increase growth, thereby reducing production time. However, not all species thrive at high water temperatures, and the water may need to be cooled in systems designed for farming of cold water species. The energy needed for cooling or heating the water is essentially proportional to the number of degrees by which the temperature is to be changed (Ungfors et al. 2015, Badiola et al. 2017). A heat exchanger can be used to reduce the energy required for heating or cooling incoming water. The best design involves balancing out the investment and pumping cost on the one hand and the preferred temperature on the other. Various processes in the facility also affect the need for heating and cooling, such as pumps, aeration, evaporation and heat exchange with the ambient air. Unnecessary energy loss is created in the system if there is a major temperature difference between water the and the air. Other energy is required at RAS facilities, too: electricity for lighting, which includes both general lighting and UV light for disinfection purposes. If ozone is used, this is manufactured on site and also requires electricity (Summerfelt 2003). Oxidation processes such as Wallenius AOT, for example, require close contact between water, UV light and the catalyst, which requires reduction of the water flow at certain locations in the system, thereby resulting in pressure losses.

Powerful ventilation of the premises may also be needed in order to deal with high levels of ambient humidity and carbon dioxide. The air may also need to pass through a filter in order to remove particles that may irritate the airways and mucous membranes.

PHOTO: (A) ANETTE UNGFORS (B) SUSANNE ERIKSSON

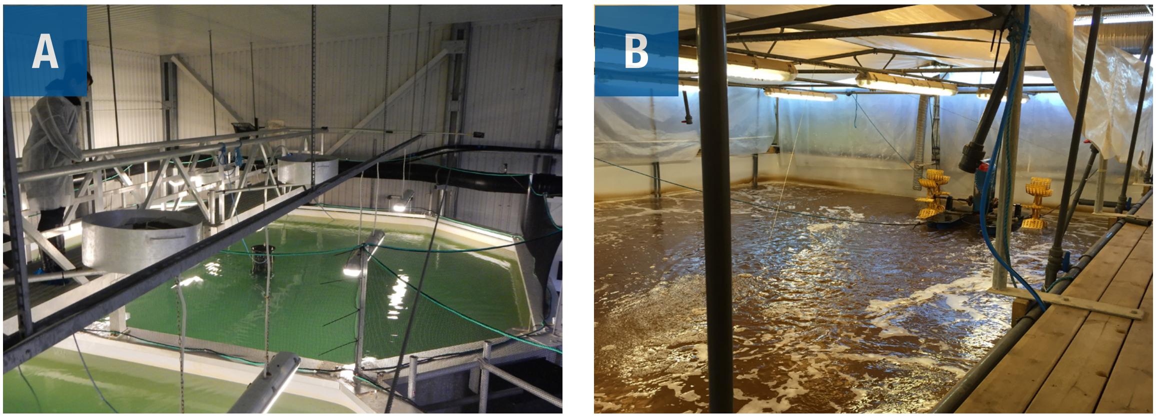

Figure 19. Land-based production systems with (A) farming in green water (microalgae) (B) and closed systems with farming in bioflocs.

Energy consumption may be dependent on many different factors, so it is not possible to provide a general idea of the costs for a RAS system. However, available calculations that have been carried out for large-scale RAS farms in Norway indicate levels of NOK 1.67 per kg of fish (Iversen et al, 2013), or 8% of the total operating costs (Rosten et al, 2013).

Dependence on technology

Land-based RAS systems can maintain a stable and optimum aquatic environment thanks to technical equipment. However, this also involves risks. A power outage or failure of pumps, control equipment, etc. may lead to a rapid change in water quality, with deadly consequences. This in turn may constitute an environmental risk, as the water and dead fish then need to be disposed of. Therefore, there is a major market for advanced control systems, sensors and warning systems for RAS facilities, and new systems are constantly being developed.

Outgoing water

Partial RAS systems may need up to 10 per cent water exchanges every 24 hours, while full RAS systems only need < 10 per cent exchanges every 24 hours, with levels potentially as low as 1-2 per cent (Heldbo et al. 2013, Langeland et al. 2104a; Ungfors et al., 2015). The water in both RAS type is treated mechanically, chemically and biologically before most of it is then returned to the farming pools. As the farming organisms never come into direct contact with the ecosystem outside the facility, pathogen transfer is minimal and genetic contamination due to escapes is more or less impossible.

In partial RAS facilities, the preferred nitrate level limit is primarily what determines how much continuous water exchange is needed, normally between 10 and 20 per cent. This also means that the volume of water fed out from facilities may contain relatively high levels of NO_3: 50 – 300 gN/m³, which is as much nitrate as fish are able to withstand (see the section “Treatment stages for partial and full RAS, II, Nitrification” above). Therefore, the output water needs to be fed to a sewage system for denitrification for a fee, or to be treated further by means of a biofilter with denitrification. The former is most appropriate for outdoor farming in pools or ponds, when emissions and uptake of NO_3^- are then synchronised with the seasons and varying temperatures. If the water is to be denitrified prior to release (post-denitrification), regularly degradable organic substances need to be added as an external carbon source (e.g. alcohol) as the outgoing water has insufficient organic matter for the heterotrophic bacteria that will execute the process. It is also possible to utilise the organic matter in the sludge by hydrolysing and digesting it and then feeding the surplus water to the denitrification stage. Denitrification is an anaerobic process, and some form of agitation is useful as a means of maintaining a high level of efficiency.

The amount of phosphorus and nitrogen pass out from the facility in the output at water is reduced by means of mechanical filtration and heterotrophic and nitrifying biofilters (Langeland et al. 2014a, Ungfors et al. 2015). Emissions are reduced still further if a denitrification stage is also added where nitrogen compounds are converted into nitrogen gas and a phosphorus precipitate, and recirculation levels as low as 1-2 per cent are possible. Phosphorus may be intercepted by means of chemical flocculation, and phosphorus can then be filtered or floated out as it bonds strongly to the flocculant.

Sludge

All water treatment types produce a certain amount of sludge, which is made up of bacterial flocs, faeces and feed residues. This sludge contains a large amount of water, and only a small percentage of it (0.1-5 per cent) is dry matter (Lekang 2013). Water is removed by means of pressing, filtration, centrifuging or drying so that the sludge can be used. The sludge can then be composted in air or digested in airtight containers. Adding lime (burnt lime, CaO, or slaked lime, $Ca(OH)_2$) increases the pH and eliminates both odour and any pathogens.

Sludge from freshwater farms may be appropriate as a fertiliser for agricultural purposes, but according to Mirzoyan et al. (2010) sludge from marine farms may contain too much salt and may therefore be better suited to biogas production (by means of digestion). However, in this respect research is ongoing into options for the use of marine sludge for fertilisation as well, as different crops may have different levels of tolerance to salt (see also Monitoring and supervision). As long as feed and additives do not contain persistent contaminants (such as heavy metals) that exceed the limits, it should be possible to use the sludge produced in closed or partial RAS facilities as a way of providing nutrition for other production; in agriculture, for example. This is what is utilised in integrated systems, such as Aquaponics, where the nutrients are not wasted but are used for food production instead (Enduta et al. 2011). As expertise in this field is still relatively limited, there is a need for further research and investigation relating primarily to sludge management and options for the use of sludge.

Land

One element of environmental impact is the larger area – relatively speaking – required for land-based facilities if they are to be used for farming of large volumes of fish for consumption. Lifting a volume of fish equivalent to a water-based open cage on land requires more space in the form of pools, and hence more land, compared with a lake-based facility where the depth of the cages is significantly greater, thereby providing a greater volume/area.

SPECIES FOR FARMING

According to Statistics Sweden's list of Swedish aquaculture facilities, aquatic organisms worth SEK 487 million were produced for consumption and other organisms for setting out worth a further SEK 68 million were produced in 2016. Most of these organisms were fish: 11,417 tonnes of fish for consumption, at slaughter weight, which is equivalent to a fresh weight of 13,451 tonnes. Besides fish for consumption, the main organisms farmed were mussels, 2317 tonnes in whole fresh weight. Data is reported voluntarily, and according to Statistics Sweden the data is incomplete as a number of farmers have failed to submit information.

According to the trade organisation Matfiskodlarna, their members produce more rainbow trout and Arctic char than they report, and so Statistics Sweden's figures for these species underestimate actual production levels. However, for the sake of simplicity Statistics Sweden's figures will be used below as no other list is available. Commercial Swedish aquaculture currently involves farming of just over ten or so species. Most of the fish produced are salmonids, rainbow trout accounting for approx. 86 per cent of fish production and Arctic char for approx. 15 per cent. These species are followed by shellfish, mainly blue mussels and a fairly small amount of signal crayfish. However, trials are in progress with regard to farming of considerably more species; fish, shellfish, other aquatic animals and primary producers (algae/plants). According to Centrala vattenbruksregistret (the Central Aquaculture Register at the Swedish Board of Agriculture), there are more than 100 farming facilities which together hold farming licences for around 30 different types of fish or shellfish, almost half of these species/variants being salmonids. These facilities are distributed over all counties in Sweden (Statistics Sweden 2016, Centrala vattenbruksregistret 2016). However, trials for the farming of oysters and Ciona intestinalis are taking place solely in the county of Västra Götaland. Some farms are producing several different species simultaneously, and together Jämtland and Västerbotten are responsible for more than half of the fish for consumption produced in 2016. Food fish production since 2010 has increased from 5000-7000 tonnes to a production level of approx. 14-15,000 tonnes. This increase is primarily due to an increase in the farming of rainbow trout and Arctic char. Most rainbow trout farms are small, producing less than 50 tonnes, but most production (95 per cent) takes place at ten or so larger farms operating with production levels in excess of 100 tonnes.

Fry and food fish juveniles are generally farmed in land-based systems, with varying degrees of water recirculation. The fry are small and take up little space, but at the same time they have stringent demands in terms of water quality and maintenance if mortality rates are to remain low. At land-based facilities, water quality (e.g. salinity, temperature, or nutrients for algal and plant growth) and feed (live or dry feed) can be controlled and monitored more easily and thereby optimised to suit the stages to be farmed.

PHOTO: ANETTE UNGFORS

Figure 20. Most of all the fish farmed in Europe and Sweden are salmonids. Salmonids are usually farmed in open cages. This picture shows how the salmon are placed in a cage, with feed pellets floating on the surface. photo: Anette Ungfors.

Salmonids

Rainbow trout (*Oncorhynchus mykiss*) is so named due to the way in which the males change colour during the spawning season. The colours of the fish change, albeit to a lesser extent, even when they are not spawning. They also have pink cheeks and black dots along the entire body. This species is native to North America and the eastern part of the Pacific Ocean and does not occur naturally in Sweden, but rainbow trout stocks have been placed in various waters to an enormous extent on many occasions; this is the most popular fish in Sweden when it comes to angling. The fish in some lakes have escaped from farms, as this is also the most commonly farmed fish in Sweden. Most of the escapes from farms involve rainbow trout, as rainbow trout represent some 80 per cent of the farmed volume of fish in Sweden (Dalsgaard et al. 2013). The first rainbow trout were brought to Sweden back in 1892 (van der Blom 2013). Reproductive stocks have only been established in just over 15 waterways, most of them in southern Sweden, which is why the species is not deemed to be self-reproductive throughout the rest of the country. High pH and low temperature are common to these waterways, benefiting the fish eggs, which are more sensitive to low pH than brown trout (Salmo trutta). Unlike other salmonids, rainbow trout spawn in spring, which counteracts the chances of hybridising with other fish species in Sweden.

Rainbow trout prefer oxygen-rich, clean fresh water, but unlike other salmonid species they can also cope with cloudy aquatic environments with lower oxygen levels. They feed on crustaceans, snails, water insects and flying insects, as well as small fish and fish eggs. There are two rainbow trout varieties: one migrate to the sea (steelhead), while the other lives solely in freshwater (rainbow). The latter variety has mainly been farmed and placed in Swedish waters as they are easy to farm and do not have stringent demands in terms of temperature and water quality. They have proven to be extremely flexible and are capable of living in water temperatures from 0 to 25 °C, but they thrive best in water at a temperature of approx. 16 °C. However, they frequently die after reproducing, unlike the variety that migrates to the sea. They can grow to over 20 kg and live for around 18 years, but they rarely reach these sizes in Swedish waters. The species mainly lives in shoals and normally exhibits no territorial behaviour, which means that farms can maintain relatively high rainbow trout densities without harming the fish.

Arctic char (*Salvelinus spp.*) is a salmonid that lives and thrives best in cold, oxygen-rich waters. They are capable of living in colder waters than other Swedish fish species and thrive there, which is why they both feed and grow throughout much of the winter, unlike species requiring warmer waters. At fish farms, this also means that the farming season is extended in autumn; but it also means that the season can be disrupted in summer if the water temperature rises above the optimum level for Arctic char. In the wild, Arctic char choose to seek out deeper, colder areas in lakes in summer so as to avoid the warmer surface water.

There are a number of different subspecies or varieties of Arctic char that can be crossed. Lake char is the variety that is farmed, and under good conditions this is the fastest-growing variety. Arctic char feed on zooplankton and certain benthic insects, as well as on fish when they grow to larger sizes. However, small individuals and varieties are unable to make the transition to feeding on fish, which normally also impedes their further growth. Arctic char have small scales, with light spots on a greenish silver background. The spectacular red underside is particularly prominent during spawning, and the fins are orange-red in colour, with beautiful white outer edges. They spawn on stone and gravel bottoms in lakes in autumn and early winter. They can grow to more than 10 kg and live for more than 25 years.

Breeding

There are only breeding programmes for two fish species in Sweden: Arctic char and rainbow trout. Breeding and improvement in the production of both animals and plants has resulted in increased growth/production, better meat quality, health and welfare for the animals. The species where it has not been possible to close the life cycle in captivity are still dependent on wild reproduction and fry production (e.g. eels). If the species being farmed would have little impact on the wild ecosystem if it were to get out, this is an advantage in open systems where fish can escape. This is applicable to algae and plants, as well as animals. The farmed organisms are enclosed in semi-closed and closed systems, and if breeding programmes can be devised to increase growth (in animals, this involves increased feed conversion and postponed sexual maturity) and welfare (reduced aggressiveness, resistance to disease and improved health), this is an advantage. However, devising a breeding programme with the desired results is an extensive and protracted process for every new species. This is particularly true of long-lived organisms, normally with late sexual maturity and a long generation time.

The Arctic char breeding programme actually began back in 1982-1985, when an interest in farming Arctic char for consumption began to emerge in Sweden. After a trial period of three years, the most appropriate Arctic char strain could be selected and breeding work could begin (Brännäs et al. 2007).

Sweden is a world leader in breeding programmes for Arctic char farmed in cages. A successful Arctic char breeding programme has been underway for more than thirty years, with original material from Hornavan. Some of the more significant breeding successes include an Arctic char variety that grows considerably more quickly and reaches sexual maturity later than the non-bred Arctic char. This means that in captivity, the fish do not reach sexual maturity until they have reached slaughter size. The colour and shape of the Arctic char have improved, and sizes have also become more homogeneous within populations. In later breeding generations, emphasis has also been placed on breeding individuals that are able to withstand stress, which promotes fish welfare and growth. Breeding work is taking place at the trial station in Kälarne belonging to the Swedish University of Agricultural Sciences, in partnership with Vattenbrukscentrum Norr AB (svb). The third party in this partnership is the industry, which also farms fish in open cages at a number of farms.

This breeding programme has also provided competitive advantages for Swedish farmers working with the selected strain of Arctic char (Arctic Superior). Homogeneous populations with little size distribution permit more efficient handling and feeding, and costs are reduced when there is no need to sort the fish as frequently. Sorting may give rise to stress among fish, so both stress and its consequences – weakened immune systems and poor growth – are reduced with more homogeneous fish sizes. Having longer intervals between sorting operations also means less handling, which may involve fish escaping in a worst-case scenario.

As sexual maturity only occurs at the age of four years, however, breeding work is a time-consuming process that cannot be accelerated. After having been squeezed and fertilised, a breeding generation has no further value for breeding work as its genetic advances can only be used once. That said, these fish can be used as brood fish for commercial roe production. Parts of the breeding generation are also placed with different farmers with a view to providing access to auxiliary populations in case anything happens at the trial station in Kälarne.

A research project is currently in progress where SLU and VBCN will be implementing new trials for the triploidisation of Arctic char. These trials, with the aid of appropriate equipment, will result in higher survival rates. In the long term, triploid Arctic char with no ability to reproduce should be available on the market, thereby eliminating the risk of farmed fish being able to reproduce with wild Arctic char.

There is also a breeding programme for rainbow trout which is being run in partnership between SLU and VBCN. This programme is still at an early stage, but there is a great deal of interest in it among involved authorities, research institutes and the industry. The Swedish National Veterinary Institute (SVA), the Swedish Board of Agriculture and others have specified a need for a Swedish breeding programme for rainbow trout. After eight years of preparation, the breeding generation that was created in 2016 will form a basis for the future breeding programme. Rainbow trout roe is imported from other countries every year, Denmark and Finland being the biggest exporters. Roe produced in Sweden could possibly reduce the risk of disease.

A national control programme that is being devised will increase opportunities for traceability – provided that it is approved by the Swedish Board of Agriculture, that is – and the industry will be encouraged to reduce its importation of roe as a result.

As with the breeding programme for Arctic char, breeding work will focus on similar desirable qualities in the fish. Trials are also planned with a view to examining whether there are any differences between different rainbow trout families as regards feed uptake ability. If these trials are able to demonstrate that there are differences at individual or family level, breeding may also focus on families with a good feed uptake ability, potentially making it possible to reduce the feed coefficient of rainbow trout when they are farmed as fish for consumption. However, triploidisation of rainbow trout has been ongoing for some time in other countries, which is why this technology is already available.

Diversification

An increase in the number of farmed species demands expertise on factors such as farming biology, production conditions, techniques, disease/preventive health work and a study of nutrition (Albertsson et al. 2012, Heldbo et al. 2013, Ungfors et al. 2015). A knowledge of the farming biology of species, along with nutritional needs, appropriate techniques depending on the behaviour and needs of the species and production quality, as well as health and disease control, are needed for farming of new species to have the potential to be economically viable. Farming of new species may also mean that organisms at different life stages will need to be imported to Sweden so as to provide starting material for farming. This is then subject to applicable regulations on the import of organisms (genetic material) to Sweden[15,16].

PHOTO: (A) ALEKSANDAR VIDAKOVIC (B) MARKUS LANGELAND

Figure 21. Long-term breeding programmes. (A) Arctic char. Breeding programmes have produced fish with desirable farming characteristics such as reduced aggressiveness. (B) Perch fish species, such as perch (as shown here) and zander are farmed commercially, but as yet there are no breeding programmes as the species are relatively new established in Swedish fish farming.

Table 3. Commercial or experimental species found in Sweden, and their environmental needs. *In addition, several species that are currently farmed commercially or experimentally in other European countries, and where there has been an interest in starting Swedish farming.

Species	Latin name	Tempe-rature	Salinity	Habitat	Feeding strategy
Fish					
Salmon	*Salmo salar*	Cold	Anadromous	Pelagic	Carnivorous
Salmon trout	*Salmo trutta*	Cold	Anadromous	Pelagic	Carnivorous
Rainbow trout	*Oncorhyncus mykiss*	Cold	Freshwater	Pelagic	Carnivorous
Arctic char	*Salvelinus spp.*	Cold	Freshwater	Pelagic	Carnivorous
***Cod**	*Gadus morhua*	Cold	Marine/ Brackish water	Pelagic-Benthic	Carnivorous
European eel	*Anguilla anguilla*	Cold	Catadromous	Pelagic-Benthic	Carnivorous
Atlantic wolffish	*Anarhichas lupus*	Cold	Marine	Benthic	Carnivorous
Spotted wolffish	*Anarhichas minor*	Cold	Marine	Benthic	Carnivorous
Zander	*Sander lucioperca*	Cold-Warm	Freshwater/ Brackish water	Pelagic	Carnivorous
Perch	*Perca fluviatilis*	Cold-Warm	Freshwater/ Brackish water	Pelagic	Carnivorous
***Turbot**	*Scophthalmus maximus*	Warm	Marine/ Brackish water	Benthic	Carnivorous
Tilapia	*Oreochromis niloticus*	Warm	Freshwater	Pelagic	Omnivorous
African sharptooth catfish	*Clarias gariepinus*	Warm	Freshwater	Pelagic-Benthic	Omnivorous
Sterlet	*Acipenser ruthenus*	Warm	Freshwater/ Brackish water	Benthic	Carnivorous
Crustaceans					
European crayfish	*Astacus astacus*	Cold	Freshwater	Benthic	Omnivorous
European lobster	*Hommarus gammarus*	Warm	Marine	Benthic	Carnivorous
Whiteleg shrimp	*Litopeneaus vannamei*	Warm	Marine/ Brackish water	Pelagic	Omnivorous
Molluscs					
Blue mussel	*Mytilus edulis*	Cold	Marine/ Brackish water	Sessile	Suspension feeder
European flat oyster	*Ostrea edulis*	Cold	Marine	Benthic	Suspension feeder
***Japanese oyster**	*Crassostrea edulis*	Cold	Marine/ Brackish water	Sessile	Suspension feeder
***Great scallop**	*Pecten maximus*	Cold	Marine	Benthic	Suspension feeder
Tunicates					
Ciona intestinalis	*Ciona intestinalis*	Cold	Marine	Sessile	Suspension feeder
Polychaetes					
***Ragworm**	*Hediste diversicolor*	Cold	Marine/ Brackish water	Benthic	Omnivorous
***Alitta virens**	*Alitta virens*	Cold	Marine	Benthic	Omnivorous
Algae					
Cyanobacteria	*Spirulina spp.*	Warm	Freshwater	Pelagic	
Microalgae	*e.g. Chlorella spp, Phaeodactylum tricornutum, Bacillariophyceae spp., Dunaliella salina*	Cold/ Warm	Freshwater/ Brackish water/ Marine	Pelagic/ Benthic	Primary producer
Sugar kelp	*Saccharina latissima*	Cold	Marine	Sessile	Primary producer
Oarweed	*Laminaria digitata*	Cold	Marine	Sessile	Primary producer
***Porphyra spp.**	*Porphyra spp.*	Cold	Marine	Sessile	Primary producer
Dulse	*Palmaria palmata*	Cold	Marine	Sessile	Primary producer
Plants					
Leafy greens (lettuce, herbs, cabbage)			Freshwater		Primary producer
Tomatoes			Freshwater		Primary producer
Tropical plants (banana, papaya)			Freshwater		Primary producer

Species from different parts of the food web have to be included in multitrophic, more or less integrated systems such as IMTA and aquaponics, regardless of whether the farm is sea or land-based. Secondary consumers such as fish or crustaceans produce the residual products (feed residues, faeces, NH_3) on which the rest of the species will grow, and also clear these products from the system. Primary producers such as algae and plants absorb nutrients directly from the water. Suspension feeders such as mussels and other molluscs absorb nutrients in the form of particulate organic matter, in the form of either living microorganisms or dead material (see also IMTA and IMTA on land).

Table 4. Species found in Sweden at commercial or experimental farms. Farming is based on access to larvae/fry/spores that are wild-caught (wild), imported (import) or from Swedish breeding programmes and/or bred in closed life cycle (closed) Production systems Ö = Open, SS = Semiclosed, S = Closed, I = Integrated multitrophic systems, A = Aquaponics.

Species	**Occurring in the wild in Sweden**	**Larvae/fry**	**Farming system**	**Farming**
Fish				
Salmon	All life stages	Closed, wild	SS, S, I	Commercial
Salmon trout	All life stages	Closed, wild	Ö, SS	Commercial
Rainbow trout	All life stages (stocked, occasional evidence of reproduction)	Closed	Ö, SS, S	Commercial
Arctic char	All life stages	Closed	Ö, SS	Commercial
Cod	All life stages	Closed, wild	Ö	Trials (*commercial in Norway, wild, closed*)
European eel	Adults	Wild	S	Commercial
Atlantic wolffish	All life stages	Import	S	Trials
Spotted wolffish	Adults	Import	S	Trials
Zander	All life stages	Wild	S	Commercial
Perch	All life stages	Wild	SS, S	Commercial
Turbot	All life stages	Closed, import	S	*(Commercial, Norway)*
Tilapia	No (tropical)	Import	S, A	Commercial
Walking catfish	No (subtropical)	Import	S	Commercial
Sterlet	No	Import	S	Commercial
Crustaceans				
European crayfish	All life stages	Closed	Ö, S	Commercial
European lobster	All life stages	Wild	Ö, S	Trials
Whiteleg shrimp	No (tropical)	Import	S	Trials/Commercial
Molluscs				
Blue mussel	All life stages	Wild	Ö, I	Commercial (Ö), Trials (I)
European flat oyster	All life stages	Wild	Ö, S	Trials
Japanese oyster	All life stages (invasive)	Wild	S	(*commercial in EU*)
Great scallop	All life stages	Closed, wild		(*trials, commercial in Norway*)
Tunicates				
Ciona intestinalis	All life stages	Wild	Ö	Trials
Polychaetes				
Ragworm	All life stages			Trials *(commercial in EU)*
Alitta virens	All life stages			*commercial in EU*
Algae				
Diatoms	All life stages	Wild	S, I	Trials
Sugar kelp	All life stages	Wild	Ö,	Commercial (Ö), Trials (I)
Oarweed	All life stages	Wild		Trials
Porphyra spp.	All life stages			Trials (*commercial in Norway*)
Dulse	All life stages			Trials
Plants	All life stages			
Leafy greens (lettuce, herbs, cabbage)	All life stages		S, A	Trials
Tomatoes			S, A	Trials
Tropical plants (banana, papaya)			S, A	Trials

Fish fry production

Different species and life stages require different farming techniques. As fry production takes up little space but is demanding in terms of farming biology, this production often takes place in land-based systems with differing degrees of recirculation and treatment of the water (see also Production of fish for consumption in open…). Broodstock, which are sometimes included in breeding programmes, are used for production of eggs and sperm. The fertilised eggs are incubated in silos or trays with water flowing through in order to promote good water quality and oxygenation. Any disinfection (e.g. with Buffodine, 10 min) of the outer layers of the eggs takes place after the eggs have swollen. The incubation time is specific to the species and calculated in degree days (D°; day × temperature in °C). The eggs are then hatched and turn into fry. The eggs are sensitive to vibration, shock and light, for example, and UV light is frequently reduced using light with a long wavelength (orange or red) or darkness in order to reduce the risk of deformations (Zagarese et al. 2001). Dead eggs are removed as they provide a breeding ground for bacteria and fungi (Stickney 2017).

Fry have a yolk sac that provides them with nutrition and energy during the first stage of development. They only start to feed actively when this yolk sac is depleted. The optimum fry feed is entirely dependent on the species, but it varies from live free-swimming rotifers (wheel animalcules) and small crustaceans (artemia or copepods) to formulated feed in the form of granulates or pellets. Many species with small and less developed fry at the time of hatching need live feed initially following consumption of the yolk sac, but they can then be weaned onto dry feed. When this is able to take place is dependent on the species, size and development (Moksness et al. 2004). Feed residues in the water may irritate fry gills and cause bacterial and fungal attacks, and so feeding little and often is recommended for fry.

Farming channels have a relatively large surface area to water volume and permit easy access to the entire area when handling the fish in order to sort them into size, for example (Labatuta and Olivares 2004). The water level is often lower (0.7 to 25 cm) than in standard channels (Labatuta and Olivares 2004), thereby resulting in more efficient water exchange in order to prevent oxygen and metabolite gradients. The density in a channel may stand at 200-400 per cent (two to four layers of fish) of the available bottom area. The larger stages are more robust and are frequently able to withstand greater variation in external factors and increased densities. When the fish have passed the fry stage and become juveniles, they are moved to other tanks or out into open production systems for the grow-out phase. Several sorting operations are frequently needed during the early growth phases as there may be significant differences in size. This is primarily true for cannibalistic species (Kestemont et al. 2003; Szczepkowski et al. 2011).

New fish species – new challenges

Domestic perch fish species

Zander and perch are percides, examples of domestic species that thrive best at higher water temperatures (23 °C ensures optimum growth). They are well known on the market and command high prices. These are species offering potential for Swedish aquaculture (Kestemont & Dabrowski, 1996; Langeland et al. 2014a). However, these species have a fry stage that requires technical adaptation and specialist knowledge, and there is no genetically developed farming material or stable fry availability. As the species require higher temperatures than salmonids, the energy requirement and hence the cost in RAS systems are higher than for salmonids. Therefore, the possibility of combining production of these species in RAS systems with surplus heat is an extremely interesting option. Both species are currently farmed commercially, albeit on a smaller scale, and as yet there is no breeding programme for these species in Sweden.

Marine candidate species

The report by Albertsson et al. (2012) examines the farming biology criteria for establishment of aquaculture of marine fish species on the west coast of Sweden. Commercially promising species were identified from around a hundred Swedish marine species with reproductive populations on the west coast of Sweden. As economic viability is a prerequisite for establishment of aquaculture, the market values of the species were compared with the production cost for salmon (2010 = SEK 23 per kg). Salmon was deemed to be a species for which farming and production costs have been optimised, and so this comparison was able to provide an indication of the minimum cost for farming of other fish species. The level of knowledge of each species and its farming biology and the chances of closing the farming cycle were included in the selection criteria.

Eventually, six species were deemed to be "candidate species" for future farming in Sweden; Atlantic halibut, common sole, turbot, Atlantic wolffish (standard and spotted), pollack and cod. Cod offers good biological farming potential, but the price of cod is currently too low to create the economic criteria, while pollack commands a

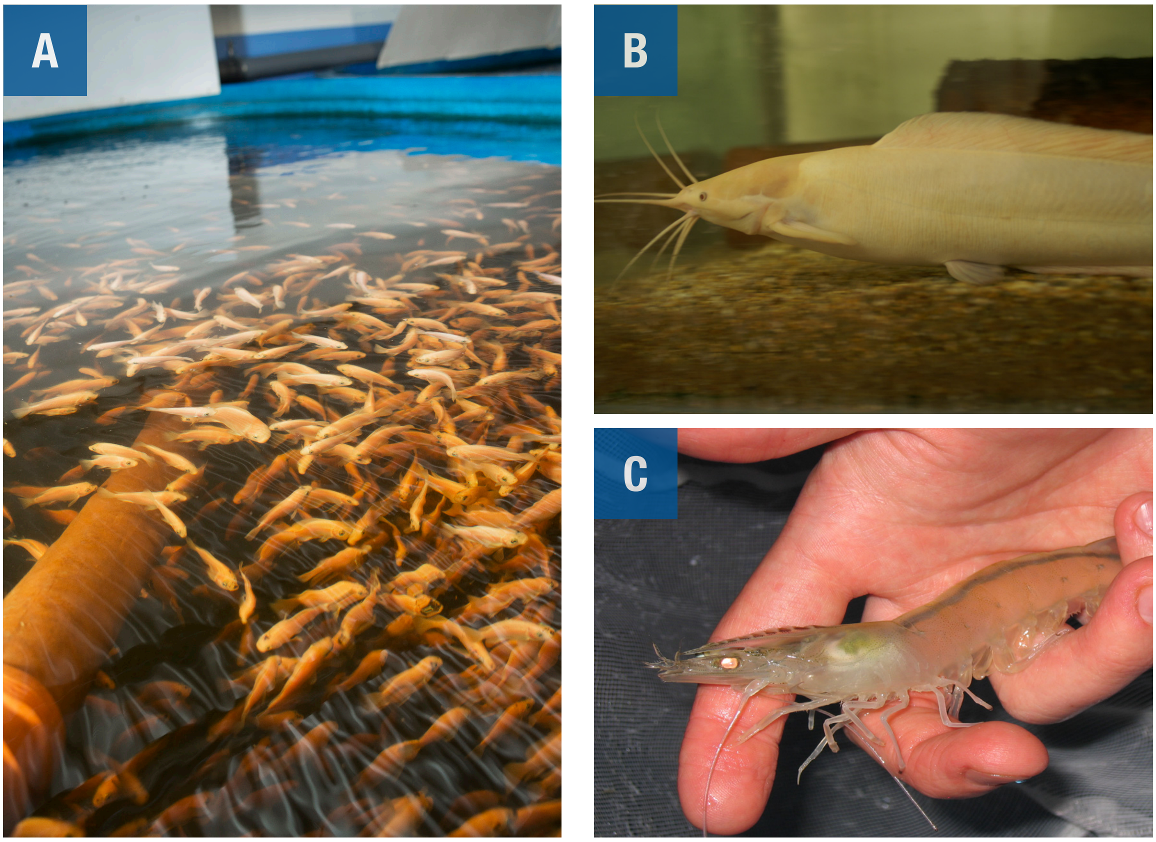

PHOTO: (A) ANDERS KRISTENSSON (B) MARKUS LANGELAND (C) ADAM POWELL

Figure 22. Tropical species are farmed in closed, land-based production systems. (A) Tilapia (freshwater fish) (B) Walking catfish (*Clarias*, freshwater fish) (C) Whiteleg shrimp (king prawn).

higher price but is untested in captivity. Knowledge of the biological criteria for the candidate species was compared with abiotic factors on the west coast. The results of these analyses showed that abiotic conditions on the west coast of Sweden are not ideal for traditional open cage farming for some of the candidate species. As the west coast of Sweden sees relatively major temperature variations, with high summer temperatures – particularly in the surface water – and low temperatures in winter, with freezing, it was concluded that fish farming in open coastal production systems could be problematic and that special technical solutions may be needed. High water temperatures in summer (often in combination with low oxygen levels) may be directly lethal for cold water species such as Atlantic halibut, while low winter temperatures impede the growth of other species. Technical solutions are needed in order to establish successful production systems. These solutions will facilitate regulation of abiotic factors such as salinity, oxygen level and temperature, e.g. by means of land-based farms or semiclosed sea-based farms, where water is pumped up from deeper areas where the water quality is highly stable. All the candidate species are farmed in other countries, entirely or partly in land-based systems. Early fry development always takes place on land, but Atlantic halibut and cod – for example – may be transferred to sea-based cages as they grow. Species that are appropriate for offshore farming should be able to withstand stress as stronger currents and exposure to wind and waves cause greater turbulence in the cages.

Species for semiclosed systems

Both Atlantic salmon and rainbow trout have been trialled in semi-closed systems on the west coast of Sweden. The fish showed good growth during two consecutive grow-out seasons, suggesting potential for farming of different species in sea-based, semi-closed systems. (Ungfors pers. comm.). There is also potential for diversification and farming of new species in water-based semiclosed systems, both in the sea and in freshwater and brackish water. The option of selecting a water intake depth means that optimum and more consistent water quality can be ensured compared with open systems (Ytrestøyl et al. 2013, Handeland et al. 2015; Calabrese et al. 2017). As semiclosed systems take water from deeper areas where the water is at a consistent cold temperature throughout the year, production systems of this type may be appropriate for growth of cold water species such as Atlantic halibut and Atlantic wolffish. This is also true for cod, where water intakes from various depths may be utilised depending on the season: deeper intakes in winter and when summer temperatures are extreme, and intakes that are closer to the surface in spring and autumn. Other water layers in summer ensure good growth for species with temperature optima at higher temperatures, such as common sole and turbot, which is why seasonal farming of these species may work in Swedish waters as well.

Tropical fish species

A number of smaller Swedish facilities for land-based farming of tropical fish species have been started over the past few years. For the most part, the species Nile tilapia and Clarias are being farmed in both closed RAS systems and Aquaponics trials. Both tilapia and Clarias are known to be resilient species, and tilapia in particular is farmed extensively on a global scale. These species are still relatively poorly established as varieties of fish for consumption on the Swedish market, but a domestic market is being built up. Farmers are working intensively to market the species in order to make their farms economically viable. Clarias is marketed as a substitute for eel for smoking purposes as Clarias, just like eel, has a relatively high fat content and can be smoked successfully. Sturgeon are also being farmed now in closed warm water systems on a smaller commercial scale. Sturgeon are farmed for their roe, and also as fish for consumption in some instances. All fry/smaller fish of these species have been imported to date. Closed systems have minor restrictions in terms of possible species. It is possible to farm most species in closed systems as long as the farming biology is known, but that does not mean it is possible to achieve economic viability with all types of farm of this kind. Farming of tropical species requires heated water, which may involve high energy consumption. Therefore, access to inexpensive (and eco-friendly) energy is a must if this type of farming is to be capable of becoming competitive on a commercial level.

Benthic invertebrates

Freshwater crayfish – traditional farmed in ponds

Freshwater crayfish are farmed commercially in either semi-intensive or extensive systems. A number of attempts have been made to farm crayfish in intensive systems, keeping the crayfish indoors in cages until they are ready to be harvested, but these systems have not proven to be economically viable (Rodríguez-Canto et al. 2002; Franke and Hoerstgen-Schwark 2013). In semi-intensive systems, fry production takes place in separate indoor facilities where it is possible to monitor water quality, temperature and the broodstock closely. When the females have been fertilised, they carry the roe until the fry have hatched. The fry are kept in closed systems with heated water and fed on small crustaceans (*Artemia*) in order to achieve a high growth rate with low mortality rate. When the fry have grown slightly and become more robust, they are placed in special fry ponds (earth ponds).

The animals are then normally transferred to a final growth pond, where the crayfish remain until they are harvested. Crayfish can either feed on plants that grow naturally in the pond, or they can be farmed more intensively and fed on dry feed. In this case, extra air frequently has to be added to the pond.

In the case of extensive crayfish production, all reproduction takes place in the pond and so the crayfish are of different ages and sizes. To reduce cannibalism, the pond is provided with hiding places in which crayfish that have recently shed their exoskeletons can seek protection. The density of this form of production is considerably lower than in the case of the more intensive form of production; and there is no control over the parent stock, hence breeding work is not possible. The advantage is that little effort is required, and essentially the work merely involves ensuring that the crayfish are fed during the growth period and checking oxygen and pH levels. The calcium level in the water must be sufficiently high to allow the crayfish to form new exoskeletons. Ice may form on the pond in winter, which is no problem as long as the water does not freeze solid. The low temperature means that crayfish do not grow in winter. Summer, however, brings about maximum crayfish growth before they are then harvested in autumn. Both the domestic European crayfish (*Astacus astacus*) and the invasive signal crayfish (*Pacifastacus leniusculus*) have been farmed commercially in Sweden. However, signal crayfish have been classified as an invasive foreign species throughout entire EU since 2016, and according to new EU regulations for the handling of live signal crayfish, setting out and farming signal crayfish is now prohibited (Figure 23A).

Lobster farming at the trial stage in Sweden

European lobster is farmed at a number of land-based facilities in Europe. However, most of the hatcheries merely farm the lobster for their first few months of life so that they pass the first free-swimming larval stages, and the creatures are then set out in the sea when they have reached the benthic stage, by which time they

PHOTO: (A) MERIKE LINNAMAGI (B) SUSANNE ERIKSSON

Figure 23. (A) Freshwater crayfish are farmed mainly in ponds. Signal crayfish (pictured), however, are now classified as an invasive species and may no longer be farmed (B) Of the marine crustaceans, lobster is considered to have the greatest potential as an aquaculture species and attempts are now being made to upscale farming to a commercial level in land-based systems.

are relatively hardier. The main purpose of farming is to support the wild populations or, as in Norway, to "corral" them in offshore areas that are cordoned off. Lobster farming trials are currently taking place in Sweden. Although lobster farming biology is fairly well documented, there are some good opportunities to improve the process. This is particularly true of the development of ecologically sustainable and economically viable feed and farming at land-based RAS facilities, where nutrients can be dealt with entirely or partly (Powell, Hintchcliffe, Sundell, Carlsson and Eriksson 2017). As lobster can be farmed at relatively high temperatures, 18 to 20 °C , heating the water in RAS systems can optimise growth, accelerating it to levels not seen in the wild (Powell and Eriksson 2016).

Benthic species for IMTA farming

Feed waste and faeces end up under fish and mussel farms, and the local organic burden may increase. A number of benthic animals could thrive and grow well in this environment – provided that the burden is not too great, resulting in oxygen deficiency – as long as the water at the bottom is still oxygenated and of good quality, and they may also help to improve the oxygenation and quality of the bottom environment. These are invertebrates such as echinoderms (e.g. sea cucumbers and sea urchins) and polychaetes that normally live on dead, finely dispersed organic matter (detritus). Crustaceans (both freshwater crayfish and marine species) that live off benthic animals or carcasses (cadavers) and other dead matter are also able to grow well. In Norway, it has been possible to measure increased production of benthic organisms at distances of up to 250 m from salmon farms (Kutti et al. 2008). Echinoderms are marketed mainly as food and for export, and polychaetes have proven to be valuable as bait for fishing (trolling) and biogas. Echinoderms live only in marine environments. There are no freshwater species within this group of animals. Farming of these organisms in Sweden could therefore involve marine RAS facilities on land or as part of IMTA beneath open or semiclosed production systems on the west coast. IMTA experiments show that when sea cucumbers are placed in cages in the water column beneath fish farms, emissions of total organic N and carbon are reduced by ≈ 60 per cent. Sea cucumbers eat fish detritus and feed residues and also have high survival and growth rates (Yokoyama 2013). Polychaetes of the *Nereidae* family are farmed in ponds in the United Kingdom and the Netherlands, for example, and are sold as bait for trolling (Olive 1999). Polychaetes can live on organic faecal material from both fish and mussel farms, and they grow well (Bergström 2014). As these worms dig down into the bottom sediment (bioturbation), microbial activity and oxygenation of the bottom sediment are increased, and so the worms also help to improve the environment beneath farms (Bergström 2014). Crustaceans are also benthic invertebrates where some species dig pathways in the bottom sediment. They are omnivores, which means that they eat both dead and living organic matter. It is conceivable that several commercial marine and freshwater species could be farmed in an integrated manner and/or harvested adjacent to fish farms, such as crab, lobster, langoustine, signal crayfish and European crayfish. Observations in Canada (Archambault pers. comm.) of how lobster fishermen place their pots on the periphery of salmon farms indicate higher lobster density in this area, resulting in better catches in the pots.

Tropical crustaceans (bioflocs)

The whiteleg shrimp is a large tropical shrimp with a complex life cycle and many larval stages. This shrimp is common in captivity, primarily in Asia and the Amer-

icas (FAO Fishery Statistics, 2016). Larvae are currently imported from an American hatchery for farming in biofloc systems in Sweden. These production systems are entirely closed, land-based systems, with more or less zero emissions (Avnimelech 2009). The bioflocs are made up of microorganisms that circulate and provide food for the shrimps (or filtering fish species such as tilapia). The bioflocs are made up of microorganisms that live on organic matter with a high protein content which is added to the system (such as legumes).
The microorganisms in the system, which needs to be at a high temperature, are intended as a way of supporting the fish or shrimps entirely or of providing a certain amount of support feeding, supplying energy and nutrients to promote high production. The biofloc nutrient composition varies and is dependent on factors such as added nutrients, farming type, farming conditions, salinity, light, ratio of bacteria to phytoplankton, etc. The protein content in different biofloc systems may vary between 14 and 50 per cent on a dry matter basis. The lipid content is normally low, with values between just over 1 per cent and 9 per cent, although the lower range is most common (Martínez-Córdova et al. 2015).

Mussels, oysters and ascidians

Filtering organisms, i.e. suspension feeders, trap particles from the water as it flows past. Both molluscs (mussels and oysters) and ascidians filter and live on tiny particles (2-200 µm) in the water, which may comprise both living (such as phytoplankton) and dead material (such as feed waste, faeces and flocculation organic matter). Thus these organisms absorb nutrient particles from the water and build them into their biomass.
Production of blue mussels on a long-line farm on the west coast may amount to over 7.5 kg per metre of line on harvesting (after 1-1.5 years). This gives approx. 300 tonnes of mussels per hectare. Such farming utilises production of phytoplankton from an area approximately 25 hectares in size. Growth is lower when salinity levels are lower, and these mussels frequently failed to reach “normal” consumption size.

A number of regional and European projects are studying farming of mussels in the Baltic Sea for uptake of nutrients, and these are then used to produce feed, fertiliser and biogas (e.g. Baltic Blue Growth, Bucefalos 2015). Blue mussels growing adjacent to salmon farms have proven to have higher feed activity, high absorption capacity for salmon faeces and hence stronger growth (MacDonald et al. 2011, Reid et al. 2010, Lander et al. 2012). As mussels prefer the flow of particles to be as constant as possible, this needs to be taken into account when designing IMTA facilities as emissions from open fish farms may be intermittent, particularly in connection with feeding. Oysters may also benefit from the increase in nutrient availability adjacent to fish farms (Aguado-Gimenez et al. 2014). However, some studies have been unable to demonstrate any increase in growth along a gradient approaching a fish farm (Navarrete-Mier et al. 2010).

These filtering organisms may also filter copepodites, the planktonic dispersal stage of salmon lice, which means that they could potentially reduce the problem of salmon lice in open production systems. Farming of filtering organisms both upstream and downstream of fish farms could therefore be recommended (Ungfors et al. 2015). Mussels also have the potential to accumulate and deactivate ILA, an infectious salmon anaemia virus (Skår and Mortensen 2007). Modelling the production potential for mussels based on specific local data (Ferreira et al. 2009) has been used to estimate the potential nitrogen uptake in a number of countries, over four continents (Rose et al. 2015).

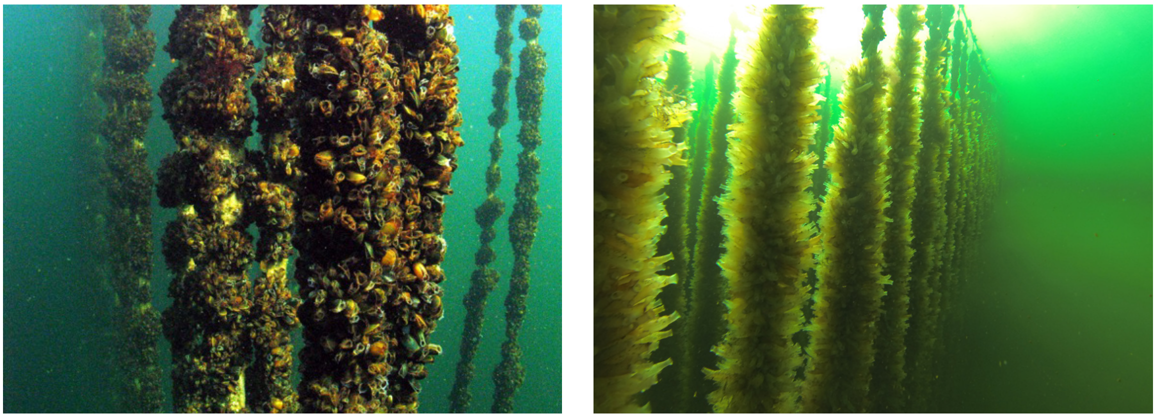

PHOTO: (A) PIA NORLING (B) FREDRIK NORÉN

Figure 24. Marine extractive animal species our farmed by allowing wild larvae to settle on the farming substrate (long lines are used here). The animals filter organic particles out of the water (A) Blue mussel (bivalve) (B) Ciona intestinalis (tunicate)

PHOTO: (A) GUNNAR CERVIN (B) SUSANNE LINDEGARTH

Figure 25. Sugar kelp (marine brown algae) is farmed extensively (A) The tiny sporophytes are grafted onto thin ropes before being placed in the sea. (B) After six months, the algae have grown to more than a metre long and are harvested.

From 12 to 152 grams of N per m² and year (58 on average) can be reduced by means of the farms. Similar models can be applied to Swedish conditions in order to calculate the nutrient uptake from mussel farms. Other calculations show that a farmed mussel contains approximately 1 per cent nitrogen and just under 0.1 per cent phosphorus. When harvesting mussels, this can be used to calculate extraction of approx. 8-12 kg of nitrogen and 0.6-0.8 kg of phosphorus per tonne of mussels harvested. This calculation is based on a mussel meat content of 20-30 per cent (see Protective farming/Catch crops). As with all farming, farming of organisms to reduce nutrients also requires a market for the biomass created. A market for bivalves is found in food, raw materials for animal feed, fish, pigs and poultry, biogas, soil improvement, etc. As ascidians settle on the same type of farming rope as mussels, there may be a risk of farming ascidians instead of blue mussels. Attempts are being made to control species settling on the farming ropes by carefully monitoring water parameters and the presence of larvae in the water during the season. Ascidians are also effective reducers of nutrients. They are annual organisms and so need to be harvested every year. Production at research and development facilities has resulted in approx. 6.6 kg of ascidians (wet weight) per metre of long line, the content of N being approx. 5.5 per cent of the dry weight and the P content being approx. 0.4-0.5 per cent (Norén pers. comm). There was previously no market for ascidians, but options for utilising ascidians in a similar way to blue mussels – for bioactive substances and biogas and as fertilisers – are now being trialled. Moreover, there is major interest in using both ascidians and blue mussels as an alternative feed ingredient with a high protein content, and both organisms are also being tested with regard to the content of various bioactive molecules types.

Algae and plants

Most algae and plants are autotrophic: in other words, they create their own nutrition using sunlight as a source of energy. These organisms also form part of the group of primary producers, organisms that convert inorganic substances into biomass. Dissolved nutrients are bound into algae and plants, and so nutrients are picked up during harvesting and removed from the system (Skjermo et al. 2014). Both microalgae and macroalgae, for example, can be used as extractive species at IMTA farms, where they can reduce the level of dissolved nitrogen and phosphorus compounds adjacent to fish farms (Neori et al. 2004), and they are also a valuable raw material in themselves.

The market for algae rests primarily in the opportunities it offers for use as a feed ingredient, feed additive, ethanol, biogas and food, but its use in textiles is also proposed (Van Hal et al. 2014, Seghetta et al. 2017).

A number of Swedish projects are in progress for evaluation of the potential offered by various species. The brown macroalga sugar kelp (*Saccharina latissima*) grows rapidly and has proven to be a candidate

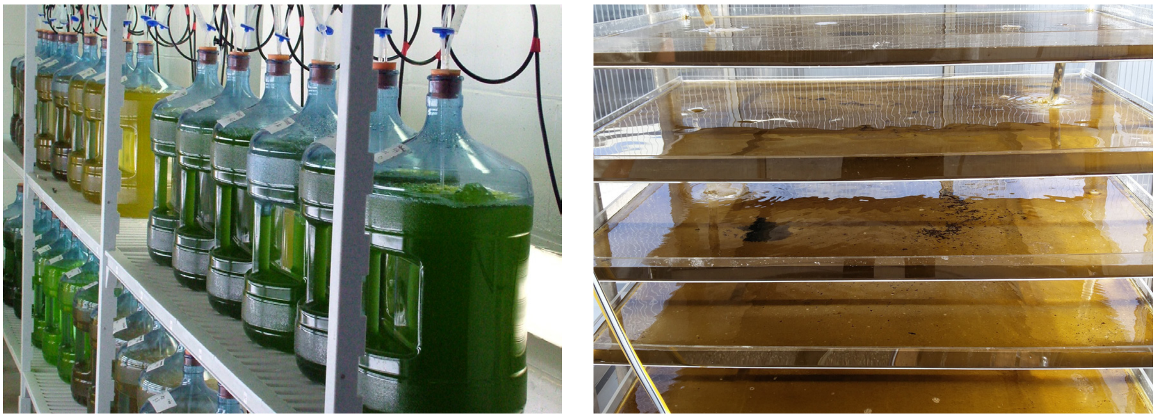

PHOTO: (A) ADAM POWELL (B) MIKAEL HEDBLOM

Figure 26. Microalgae are farmed on land (A) and are used primarily as feed for larval/fry stages of various aquaculture species. (B) Trials are also taking place involving farming of diatoms in biofilm systems. The algae grow on nutrients from RAS fish farming, and the biofilm is harvested once a week for further industrial processing.

species for co-farming with fish (Handå et al. 2013). This alga has been farmed in trials at open farms on the west coast of Sweden since 2014 (Gröndahl pers. comm.), and ongoing projects are studying its growth potential in water from semiclosed fish production systems, as an increase in the availability of dissolved nitrogen has proven to have an additively positive effect on the growth of sugar kelp (Handå et al. 2013).

The green macroalgae *Ulva sp*. (Ben-Ari et al. 2014) and *Enteromorpha sp*. (Martinez-Aragon et al. 2002) are effective biofilters – in other words, they assimilate dissolved nutrients from the water – but their application after harvest is limited to agar or biogas, which commands a relatively low price.

A number of domestic and Asian species of the red macroalga *Porphyra sp*. have demonstrated good growth and uptake capacity and also command a higher price, not least as nori for human consumption (Carmona et al. 2006). Matos et al. (2006) tested the red algae *Gracilaria bursa pastoris*, carrageenan alga *Chondrus crispus* and *Palmaria palmata*, and found that *G. bursa pastoris* grew best, with the most efficient nitrogen uptake, and so this species is recommended for use as an assimilating species in IMTA systems, for farming together with fish and/or shellfish. The number of algae appropriate for farming is limited in the Baltic Sea due to the low level of salinity, but protective farming with certain brown alga species (e.g. *fucus*) and green algae ought to be technically possible even some way up into the Baltic Sea. Microalgae farmed in land-based systems our promising components in land-based IMTA systems. The species *Isochrysis galbana*, *Tetraselmis suecica* and *Phaeodactylum tricornutum* have been trialled in co-farming with turbot and European bass (*Dicentrarchus labrax*), and they grow well and reduce nutrients in the water (Borges et al. 2005). The microalgae can then be harvested and used as feed for mussels (*Tapes decussatus*). Trials are currently also taking place involving integrated farming of diatoms adjacent to a small RAS facility in Kungshamn (Figure 26). The diatoms are being farmed in biofilm systems and grow on nutrients from the fish farm. The biofilm is harvested once a week and the diatoms are processed for various industrial applications (Wulff pers. comm).

NUTRIENT REQUIREMENTS AND FEED

Current production of feed for aquatic organisms is estimated to increase from the current level of 50 million tonnes to more than 65 million tonnes by 2020 and more than 87 million tonnes by 2025 (Tacon and Metian, 2015). For this to be possible, this increase has to take place in an eco-friendly and economically viable manner. Perhaps the most important issue from a sustainability perspective in terms of resources involves the use in aquaculture of fished marine resources, i.e. fishmeal and fish oil in feed, as a number of these origins (mainly anchoveta; *Engraulis ringens* and European sprat; *Clupea harengus*) are deemed to be utilised to the full capacity of the population (FAO 2016), but also the dependency on soya products. Much of the solution involves replacing fishmeal and fish oil in feed with alternatives that are not dependent on finite natural resources such as fertilisers and linear nutrient flows in the form of nutrient losses from farming (SOU 2009:26). However, a number of conditions and demands are defined for the feed ingredi-

ILLUSTRATION: MARKUS LANGELAND

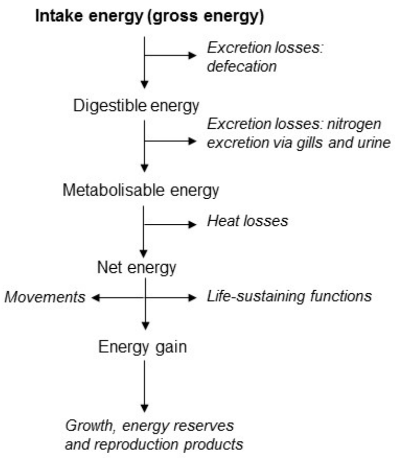

Figure 27. Schematic overview of energy losses in fish. The greatest loss of energy and nutrients is found initially in excrement, and in the next stage with nitrogen excretion via the gills and urine. The energy and nutrients remaining after these processes can be converted in metabolic processes in the animal.

ents that are to replace the fishmeal and fish oil so as to ensure that the feed generates good growth and results in good animal welfare and health for various life stages, while also resulting in high meat quality with minimal environmental burden at a reasonable price.

It is estimated that half of global aquaculture is dependent on the supply of feed, and this is particularly true of fish production in the western world. As intensive aquaculture grows, the need for feed ingredients will grow; and feed already constitutes the single biggest operating expense for any fish farm. It accounts for approx. 50-60 per cent of production costs at modern cage farms, and almost as much at RAS facilities. At present, the increasing price of feed ingredients is the strongest factor driving costs. For instance, the price of fishmeal over the past few years has increased from EUR 1000 to over EUR 1800 per tonne. This is partly due to high demand, but it is also due to major variations in production volume, primarily on account of the El Niño weather phenomenon in the Eastern Pacific Ocean, affecting anchoveta catches.

Development of new aqua feeds has intensified over the past few years, increasingly replacing fishmeal and fish oil with vegetable raw materials or other alternative raw materials. Therefore, the percentage of raw materials from fish has fallen significantly, and the "Fish In: Fish Out" ratio now stands at about 1 on average. In other words, fish farming produces about as much in fish raw materials as it consumes.

The traceability of the feed has been developed in parallel with this so that the raw materials can be traced back to farm or trawler level so as to be able to guarantee that all feed fish comes from sustainable fishing and sustainable populations. All raw materials included in the feed are also thoroughly tested and selected with a view to ensuring that fish find them easy to digest, while also providing a good nutrient balance and minimising excretion products. The feed industry is subject to quality and hygiene inspections and must guarantee that the feed is compliant with food legislation requirements.

The feed must be of good quality in order to streamline the activity and minimise environmental impact. Among other things, this means it is important for the feed to be stored and handled in a manner that ensures it is not contaminated or destroyed. Therefore, premises and equipment used for storage, feeding and transport of feed are generally controlled by means of daily inspections. The feeds must not be exposed to moisture, sunlight, heat and suchlike, but must be transported directly from the truck to the warehouse or silos, where they will be protected effectively. Any discrepancies in feed quality upon receipt will be reported to the manufacturer.

Nutrient requirements

More than 550 different fish and shellfish species are farmed all over the world, with widely differing nutrient requirements , feed-seeking behaviours, anatomy and physiology, resulting in major differences in the ability to digest various feeds. The need for energy, protein, fat, vitamins and minerals is affected not only by the species, but also by the growth phase and sexual maturity of the fish, the ambient temperature, etc. In the case of normal growth and function and under normal production conditions, the nutrient requirements of the most common species are largely known: some 40 species currently account for approx. 90 per cent of production. However, there is still a lack of more detailed information on optimum requirements as regards proteins, amino acids, fatty acids, vitamins and minerals for many species, and this is also becoming more of a problem as new species are introduced to aquaculture. Roughly, species can be divided into carnivores (meat eaters), omnivores (creatures that eat everything) and herbivores (plant eaters). Cyprinids (herbivores and omnivores) and tilapia (omnivores) are some of the most widely farmed fish species in the world, while marine carnivorous fish species (e.g. salmonids, sea bream and sea bass) are the most widely farmed species in the western world. The latter group are the biggest consumers of feeds containing protein and fat sources from wild-caught fish.

Table 4. Differences in different fish species' digestion, illustrated as activity of the starch-hydrolysing enzyme amylase in the liver, intestine and gall bladder of various herbivorous, omnivorous (carp, goldfish and tench) and carnivorous fish species (sea bream, rainbow trout and eel) (Hidalgo et al. 1999). Different fish species have varying ability to digest – i.e. assimilate – starch, a common source of carbohydrate in feed, which is measured as enzymatic activity (U = units).

Fish species	**Liver ($U\ mg^{-1}$ protein)**	**Intestine ($U\ mg^{-1}$ protein)**	**Gall bladder ($U\ ml^{-1}$)**
Common carp (*Cyprinus carpio*)	108.0 ± 7.3	72.5 ± 8.5	4.79
Goldfish (*Carassius auratus*)	23.8 ± 4.2	75.5 ± 15.8	1.61
Tench (*Tinca tinca*)	13.1 ± 1.3	19.5 ± 2.7	-
Sea bream (*Sparus aurata*)	2.7 ± 0.4	1.75 ± 0.28	0.84
Rainbow trout (*Oncorhynchus mykiss)*	0.0	1.30 ± 0.07	0.0
Eel (*Anguilla anguilla*)	0.76 ± 0.08	0.46 ± 0.05	0.067

Besides water, feeds mainly consist of protein, fat and carbohydrates, along with vitamins, minerals, etc. to a lesser extent. The composition of these ingredients is an important factor in ensuring that animals are healthy and grow well. Animals' energy and nutrient requirements and nutritional needs are met by digesting, absorbing and metabolising the nutrients in the feed. The energy from the feed intake is divided into various elements, and energy losses take place over a number of different stages depending on physiological and metabolic processes (Figure 27), as not all energy and nutrients in the feed consumed can be assimilated.

The extent of the losses at each stage is dependent on the ingredients in the feed (how much is absorbed by the animal), their chemical composition and the ability of the fish (animal species) to assimilate the feed. This means that herbivorous and omnivorous species with a longer gastrointestinal system can assimilate complex carbohydrate, for example, more effectively than carnivorous fish with a shorter gastrointestinal system. There are physiological differences as well as anatomical differences. This is reflected by factors such as the digestive enzymes of different species, which catalyse the breakdown of the feed. Amylase, which catalyses the breakdown of starch to form simpler sugars, has been found in the gastrointestinal systems of many different fish species, but with enormous differences in activity (Table 4), and it is usually higher in herbivorous and omnivorous species (Krogdahl et al. 2005). All of these aspects must be borne in mind when formulating a feed. Any nutrients that cannot be absorbed by the fish may burden the ambient environment.

More detailed knowledge of the optimum composition of the feed is relatively well-known for the most common species, and differences in the requirement for protein, amino acids, fatty acids, energy, vitamins and minerals and energy between species and growth phases are presented in Table 5. Amino acids form di-, tri- and polypeptide chains which eventually end up arranged into larger structures, proteins. In fish, some 23 different amino acids are needed to form these structures, of which ten are essential. In other words, fish are unable to create these themselves and they have to be provided with the feed. Different feed ingredients have essential amino acids in different ratios, and this is known as the amino acid profile or – more commonly – protein quality. In a best-case scenario, the amino acid profile should correlate to the needs of the fish. In this case, there will be maximum utilisation of all amino acids and less protein will be needed to meet the needs of the fish. If only a very tiny quantity of an essential amino acid is present, the total protein intake has to increase in order to meet the need for the limiting amino acid, which means that other amino acids are "left over" to a greater extent and can be used for energy, but they will also result in increased excretion of nitrogen to the ambient environment and may also result in reduced growth.

For some species, particularly marine carnivorous fish in intensive production, excluding fishmeal and fish oil in the feed presents a major challenge (albeit a challenge that can be met on an experimental scale), particularly if the feed has to be based entirely on vegetable feedstuffs instead. This is partly due to the fact that this makes the feed less palatable and often results in poorer growth. Furthermore, the amino acids in the alternative vegetable ingredients frequently have lower accessibility and an amino acid and fatty acid profile that does

Table 5. Protein requirements percentage of feed) for various fish species in different size ranges (NRC 2011)

	Weight				
	< 20 g	20-200 g	200-600 g	600-1500 g	>1500 g
Atlantic salmon (*Salmo salar*)	48	44	40	38	34
Nile tilapia (*Oreochromis niloticus*)	40	34	30	28	26
Common carp (*Cyprinus carpio*)	45	38	32	28	28
Rainbow trout (*Oncorhynchus mykiss*)	48	40	38	38	36

not meet the requirements of the fish. Amino acids produced industrially, known as refined or synthetic amino acids, may reduce the losses referred to above by being added in a manner that balances the amino acid profile in the feed. This is why feed researchers are attempting to identify other raw materials that have a similar nutrient content to fishmeal and fish oil and are able to replace these as feed ingredients mainly for carnivorous fish species (see “Animal feed ingredients” below).

Feed ingredients

The feed industry is subject to stringent quality and hygiene inspections, which include analyses of environmental toxins, preservatives, heavy metals and other foreign objects, so as to guarantee that the feed is compliant with food legislation requirements and is “clean” and healthy for the fish and, in the longer term, consumers of the fish.

Use of fishmeal and fish oil

Traditionally, fishmeal and fish oil have been the dominant ingredients in feed for fish and shrimps. Fishmeal has a high protein content, the amino acid profile frequently corresponds to the amino acid requirements of the farmed species, it is highly digestible and it

Table 6. Use (tonnes and proportion of global production) of fishmeal and fish oil in feed for different fish and crustacean species. (Tacon and Metian 2008).

	Fishmeal		**Fish oil**	
Species group	Tonnes (in thousands)	% of feed manufactured	Tonnes (in thousands)	% of feed manufactured
Marine shrimp	1,005,480	27	100,200	12
Marine fish	670,320	18	167,000	20
Salmon	558,600	15	359,050	43
Chinese carp	409,640	11	0	0
Trout (inc. rainbow)	223,440	6	108,550	13
Eel	223,440	6	16,700	2
Wels	186,200	5	33,400	4
Tilapia	186,200	5	16,700	2
Shellfish, freshwater	148,960	4	16,700	2
Carnivorous freshwater species	111,720	3	8350	1
Total	3,724,000	100	835,000	100

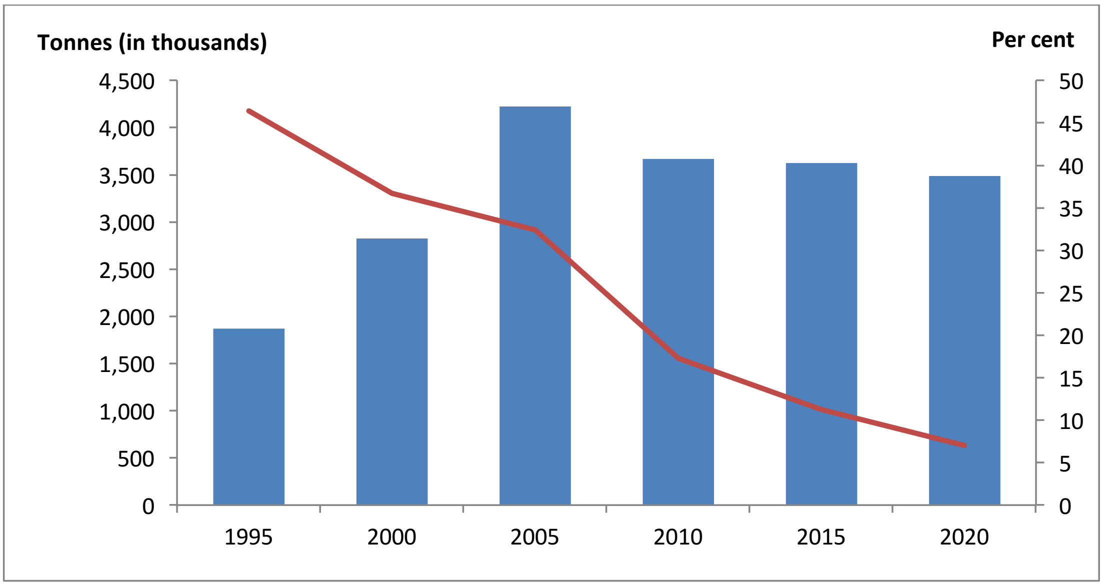

Figure 28. Actual and predicted a) total use of fishmeal in global aquaculture, in thousands of tonnes (columns) and b) average percentage inclusion in feed (lines) (adapted from Tacon et al. 2011).

contains essential minerals and fatty acids. Likewise, fish oil is a source of long chain omega-3 fatty acids which is difficult to replace and also makes the feed highly palatable. As people become more aware of overfishing of marine resources, resulting in shortages of feed fish, intensive efforts have been made to reduce the inclusion of these raw materials in feed.

Many attempts have been made to replace fishmeal with alternatives, and up to 2006 successful attempts had been made to reduce inclusion of fishmeal in feed by 25-50 per cent. This includes both feed for herbivorous and omnivorous species and feed for carnivorous fish species such as salmon, rainbow trout, sea bream (gilt-head bream) and sea bass (European bass), which consumed a total of 45 per cent of the fishmeal used by the aquaculture industry (Table 6). That same year, 88.5 per cent of fish oil on the world market went to the aquaculture industry, of which 43 per cent was used for salmon feed (Table 6). Despite previous successes with replacing fishmeal in feed, the aquaculture industry continued to consume increasing quantities of fishmeal produced on account of increasing feed production for the burgeoning aquaculture industry (Figure 28). However, some 1 million tonnes less fishmeal was produced in 2006 than the average for the previous 20 years, which led to a significant increase in the price. As a result, the industry was forced to adapt rapidly to the new market conditions by including more alternative feed ingredients to a greater extent (Hardy 2010).

Although the aquaculture industry is using increasing amounts of the fishmeal available, the amount of fishmeal in feed has declined. Above all, fishmeal has been replaced with feedstuffs of vegetable origin, soya meal and concentrate, wheat gluten and – to a slightly lesser extent – fava beans, sunflower meal, corn products and pea protein. Much of the production of these raw materials takes place in countries with longer growing seasons than in Scandinavia and the Nordic region. The Baltic sea area is a net importer of protein, primarily in the form of soya (Andersen and Tybirk 2016). Much of the fish oil has been replaced with rapeseed oil for the most part, but use of fish oil has not declined to the same extent as fishmeal, largely due to market demand for high levels of omega-3 fatty acids in the end product (these fatty acids are not found in vegetable oil unless it is genetically modified).

Besides not offering optimum nutritional composition, problems that may arise with new, untested feedstuffs include the fact that they may contain anti-nutrients that directly or indirectly disrupt uptake or metabolism, e.g. in the form of intestinal inflammation and damage to the intestinal mucosa, due to their metabolites (Jutfelt et al. 2007, Knudsen et al. 2008, Geurden et al. 2009, Krogdahl et al. 2010). For new feedstuffs to be considered interesting alternatives to fishmeal, they must contain low levels of fibre and particularly insoluble carbohydrates, starch and anti-nutrients and have a relatively high protein content, with a good amino acid profile and a high level of digestibility, and they must be reasonably palatable as well. Besides this, they must also be readily accessible, priced competitively, easy to handle, transport and store; and not least, they must have the right physical qualities for use in feed production (to be extruded; Gatlin et al, 2007). Alternatives to fishmeal include new plant protein sources and new marine sources, as well as side flows and byproducts from the onshore and offshore animal farming. Vegetables frequently need to be processed or refined to reduce the effect of anti-nutrients and/or improve the nutrient composition. There needs to be greater emphasis on farming of fish and shellfish species with other nutrient requirements (herbivores and omnivores), and in particular on utilisation of residual flows from aquaculture, fishing, agriculture, forestry, industries, etc. in order to create nutrient-rich feedstuffs and innovative sources of protein and lipids (Rana et al. 2009). In the longer term, alternative feedstuffs have to be based on circular nutrient flows instead of linear flows where there is a constant source of nutrient losses, and not least, they must be unfit for direct human consumption, or of no interest.

Vegetable feed ingredients

The main vegetable meal and oil products used in feed production in aquaculture are listed below, in descending order according to global production and market usage (Tacon et al. 2011).

Cereals, including meal and byproduct oils:

- ground or other processed corn, wheat, rice, barley, sorghum, oats, millet, triticale, etc.,
- meal from byproducts from corn gluten, wheat gluten, draff, rice-protein concentrate, rice bran, wheat bran,
- extracted corn and rice oils.

Oilseeds and oils:

- full fat soya (whole soya bean)
- Solvent-extracted meal of soya bean, rapeseed/turnip rape, cotton, peanut, sunflower, palm kernel, coconut (copra)
- byproduct meal comprising soya concentrate and rapeseed protein concentrate
- extracted oils from palm, soya bean, rapeseed/turnip rape, sunflower, linseed, cottonseed and olive.

Legumes and protein concentrates:

- ground or other processed pea and lupin,
- byproduct meal comprising pea/bean protein concentrate and lupin protein concentrate.

Protein-rich soya concentrate was highlighted early on as being a promising alternative for replacement of fishmeal, and it has successfully replaced up to 75 per cent of fishmeal in feed for salmonids. The concentrate contains equally high or even higher levels of the otherwise limiting amino acids lysine, methionine and threonine than in fishmeal. Moreover, unlike whole soya this concentrate does not cause gastrointestinal inflammation in salmonids (review by Hardy, 2010). One problem with soya products is that phosphorus and some other minerals are not available in an accessible form, but are bound into phytic acid. However, this can be remedied by adding the enzyme phytase, which makes the minerals more accessible for the animal. However, soya production has come in for criticism for being part of the reason why large areas of natural land have been turned into agricultural land, resulting in environmental impact such as the release of greenhouse gases, eutrophication, soil erosion and reduced biodiversity. Besides this, large quantities of pesticides that have been prohibited in Sweden for a long time on account of their adverse impact on health are used in soya production. Only a few hectares of soya are farmed in southern Sweden, but new varieties of soya that is suitable for a Scandinavian climate could be farmed here due to climate change and genetic engineering (Poulsen et al. 2016). The major aqua feed companies (Skretting, Biomar and Ewos/Cargill) that produce annual sustainability report states that they only purchase soya from Pro Terra-certified producers, which should mean that their production has taken into account factors such as sustainable environmental, social and economic parameters. Slightly smaller Finnish feed producer Rasio has been named by the WWF as a responsible environmental company[17].

Corn is mostly produced in the US, where most of the crop is used as an energy feedstuff for livestock and the rest is processed to make various foods such as corn oil, starch, syrup, etc., and not least for production of ethanol. A typical corn gluten meal on the market is highly digestible and contains at least 60 per cent crude protein, while in a treated, concentrated form it contains over 70 per cent crude protein. However, lysine levels are frequently low. Corn gluten meal is normally used in feed for salmon and marine species such as European bass and gilt-head bream. The chemical composition restricts inclusion in the feed for these species to a maximum of 20-25 per cent, but the usual rate is between 10 and 15 per cent. Distillers grains are a residual product from the production of ethanol which is used as an ingredient in feed. Unfortunately, its low protein content – normally 28-33 per cent – and relatively high fibre content restrict its use in aqua feeds. Development of a protein concentrate by separating the protein fraction from fibre and starch is currently taking place. Wheat is used widely in the food industry to make bread, pasta, etc., but many of the byproducts from meal production are used as animal feed. Wheat differs from other cereals in that it contains high levels of gluten proteins. Besides its nutritional value, gluten protein is of major significance as a binder in feed, which is particularly important in aquaculture. Wheat used for feed normally has a protein value of around 12 per cent, but it is used primarily as a source of energy due to its high starch content. Around 30 per cent of the amino acid composition of wheat and other cereals is made up of the non-essential amino acid glutamic acid, as well as low levels of lysine and methionine. The byproduct from production of wheatmeal, which is normally used in feed, does however have a number of limitations when used in aqua feeds. When producing the meal, most of the digestible carbohydrates end up in the meal fraction, which means that the byproduct has a high fibre content and the digestible energy value in the aqua feed in general is reduced, particularly in high energy feeds for salmon, for example, due to the fact that it is less digestible. Besides this, the byproduct has a lower gluten content and so its positive qualities as a binder are considerably lower. Barley has been used to a limited extent in aqua feeds, mainly due to its relatively high fibre content, but varieties with a lower fibre content and lower levels of phytic acid have been developed as new varieties have been produced and processing technology has improved. Barley contains 9-15 per cent crude protein, with a lysine content of around 3.6 per cent per crude protein. The protein concentrate, which is a byproduct from the production of ethanol and beta glucans (dietary fibre), has been highly successful. The digestibility of barley products is increasing significantly with modern feed technology in the form of extrusion (Gatlin et al. 2007).

Rapeseed meal (defatted) is a byproduct from the production of rapeseed oil and contains around 35 per cent crude protein, but 12 per cent crude fibre. Furthermore, a protein isolate (rapeseed protein concentrate) is produced that can largely be used to replace fishmeal in feed for salmonids and other carnivorous species as long as the feed is supplemented with amino acids in order to achieve an amino acid profile that meets the needs of the fish. Flavour enhancers such as betaine or blue mussels generally need to be added to feeds containing high levels of rapeseed meal in order to prevent reduced feed intake due to anti-nutrients in rapeseed that reduce palatability.

Legumes such as cottonseed (*Gossypium hirsute*), lupins, peas and beans (mainly faba beans: *Vicia faba*) have a high to relatively high protein content (42-25 per cent crude protein). In general, the lysine and methionine content of legumes is limited, which is why feeds containing these products have to be balanced carefully with other sources of these limiting amino acids (Gatlin et al. 2007, Caruso, 2015). However, there are exceptions that contain relatively high levels of lysine, such as faba beans. Both peas and beans contain a lot of starch, while lupins contain high levels of β-(1.4)-galactan, a polysaccharide that is a non-starch polysaccharide: NSP. In general, fish have little ability to digest and assimilate NSPs. Legumes contain varying levels of anti-nutrients. Some lupins contain saponins, alkaloids, trypsin inhibitors, oligosaccharides and tannins that affect feed uptake, metabolism, palatability, etc. (Gatlin et al. 2007). Rice protein concentrate, with a crude protein content of around 75 per cent and a fat content of around 11 per cent, are another vegetable feed ingredient that could potentially be used to replace fishmeal elements in fish and shrimp feeds (Caruso 2015), but they offer reduced digestibility at inclusion levels in excess of 20 per cent in aqua feeds and 50 per cent in shrimp feeds.

Other vegetables offering future potential that have not been reported at all as feed ingredients in the aquaculture industry as yet may be fractions of red clover, which gives a higher yield per unit area of protein, including both lysine and methionine, than products such as soya. The major challenge lies in concentrating the protein (Poulsen et al. 2016).

PHOTO: (A) ALEKSANDER VIDAROVIC
(B) JAMES HINCHCLIFFE

Figure 29. Alternative feed ingredients with a high protein content (A) Prepupae of black soldier fly. (B) Side flows from the processing industry (herring carcasses are shown here).

Animal feed ingredients

The primary animal meal and oil products from aquatic organisms used in feed production are listed below in descending order according to global production and market usage (Tacon et al. 2011).

- Meal and oils produced from direct fishing and bycatches of fish and shellfish
- (macroinvertebrates),
- Byproduct meal and oils from fish and shellfish produced from products from fishing and/or aquaculture,
- Meal and oils produced from marine zooplankton from wild populations,
- Hydrolysate, ensilage and fermented fish and shellfish produced from aquaculture, fishing, macroinvertebrates, zooplankton and/or residual currents from seafood production,
- Meal produced from caught or farmed marine ringworms (polychaetes).

A growing proportion of fishmeal and fish oil is produced from byflows and/or residual flows from fishing, aquaculture and the food industry. There is currently no definite information on the extent of this. It is been estimated previously that 33 per cent of fishmeal produced in the EU originates from byflows/residual flows (SEAFISH 2009), and non-validated estimates indicate that 25-35 per cent of the global production of fishmeal and fish oil comes from byproducts (FAO 2016).

Furthermore, a number of promising trials have taken place using blue mussels as a feed ingredient for various salmonids (Vidakovic et al. 2015, Langeland et al. 2014b) and turbot (Nagel et al. 2014). Mussels are very similar to fishmeal in terms of nutrient composition, and no differences were found in their high digestibility and palatability and growth and health parameters in control groups of fish that were fed on feeds containing fishmeal and fish oil. Economic criteria for production of mussels and mussel meal, also including toxin analyses, present the biggest challenge in this regard.

Terrestrial animal protein and fat raw materials

- Meal and fat from meat byproducts; made from slaughtered food-producing livestock (cattle, pigs, sheep, etc.) and containing meat and bonemeal, meat meal, dissolved meat and fat, lard and tallow,
- Meal and fat from hen/chicken byproducts; made from slaughtered chickens and hens and containing meal from byproducts, feather meal and chicken fat,
- Meal from blood byproducts; made from slaughtered food-producing livestock and containing blood meal, haemoglobin meal and dried plasma,
- Mixed products from terrestrial invertebrates; produced from wild populations and/or farmed ringworms (*Annelida*), insect larvae/pupae and gastropods.

Protein meals and fats from animal byproducts produced using modern techniques are generally of high nutritional value for fish. Most products are cost-effective alternatives containing a high level of digestible raw protein, energy, fat and a good amino acid composition and are highly accessible to most aquaculture species. Interest in using animal byproducts in fish and shrimp feeds has increased outside the EU, but in Europe products of terrestrial animal origin were prohibited following the BSE crisis in the early 1990s. However, using most animal byproducts in aqua feeds was once again made legal in 2013 (Category 3 ABP, European Commission Regulation No. 1774/2002 and No. 999/2001), and these animal byproducts include PAPs (processed animal proteins). This means animal byproducts or carcasses that are appropriate for direct human consumption but are not used for this purpose for commercial reasons.

Insects, which are rich in protein, fat and energy, have recently been highlighted as a potential feed ingredient for the aquaculture industry (Makkar et al. 2014). More than 1 million different insect species are described, and the nutrient composition differs depending on the species, metamorphic stage, feed, environment and season. A number of fish species from both marine and limnic environments include insects in their natural diet. A number of insect species have the major advantage of high growth, short generation cycles and simple and modest requirements in order to reproduce, they are effective feed converters, and not least they can live on residual flows and/or byflows from industry or food production. Moreover, insect production requires little in the way of water and space. Of 150 insect species analysed, 20 had a raw protein content of between 60 and 78%, while 41 had a crude protein content of between 40 and 78% (on a dry matter basis; Sánchez-Muros et al. 2014). The amino acid composition is often low as regards the essential amino acids histidine, lysine and tryptophan, but with relatively high levels of methionine. In general, insects have a fat content of between 15 and 30 per cent, which is higher than in fishmeal and soya meal. The fatty acid composition can be controlled in insects to an extent by means of the food they eat, which paves the way for new sources of long chain polyunsaturated fatty acids for aqua feeds (Makkar et al. 2014). To date, most emphasis has been placed on the larvae and prepupae of the black soldier fly (*Hermetia illucens*). This two-winged species (order: *Diptera*) is renowned for its effective ability to break down organic waste such as fertiliser and food residues and convert it into high-quality protein and fat. The insects are normally defatted to produce a protein concentrate with a crude protein content of around 70 per cent and a fat fraction. A number of studies involving fish have been carried out, successfully replacing a large proportion of the fishmeal in the feed with insect protein (St-Hilaire et al. 2007, Makkar et al. 2014; Lock et al. 2016). Insects contain varying levels of chitin (aminopolysaccharide), which forms part of the exoskeleton. How different fish species handle high chitin levels in the feed has not yet been charted, and whether this leads to intestinal damage/inflammation must be examined. Insects are not permitted for use as food or feed ingredients in the EU as things stand at present, but there is much to suggest that the law will be changed in this respect before long.

Table 7. Average chemical composition of the primary microorganism groups of interest for aquaculture (percentage of dry matter).

Nutrient	Fungus	Microalgae	Yeast	Bacteria
Protein	30-45	40-60	45-55	50-65
Nucleic acids	7-10	3-8	6-12	8-12
Total N	37-55	43-68	51-67	58-77
Raw fat	2-8	7-20	5-10	3-7
Ash (minerals)	9-14	8-10	5-10	3-7

Microbial feed ingredients

A new type of protein and lipid ingredient in the form of microorganisms or "single cell proteins" has attracted a great deal of interest over the past few years, although trials involving bacteria in aqua feeds have been carried out since the 1980s. Many microorganism types such as yeast, microalgae, bacteria and/or filamentous fungi have a high protein content (Table 7), and in some cases they have an interesting fatty acid profile as well. A number of studies indicate that fish can utilise microorganisms such as yeast very effectively. Moreover, use of this product does not compete with humans as our metabolism is unable to cope with the high levels of nucleic acid found in microorganisms. It appears that most fish can cope with relatively high nucleic acid intake levels, but the cell walls of microorganisms may cause problems as they reduce digestibility and may cause intestinal damage/inflammation (Langeland et al 2014b; Vidakovic et al. 2015). In combination with a RAS system, harvesting nutrients from sludge could be used as a substrate for farming of microorganisms, thereby creating an integrated multitrophic system.

Further development of this could involve farming microalgae in the flow of nutrients from the fish tanks. Microalgae will then be used as feed for rotifers, which will be used as feed for fish fry and larvae. Microalgae have a high protein content, and many species contain high levels of omega-3 and -6 fatty acids. At a later stage, algae could also be harvested and dried for use as protein feeds and as a source of essential fatty acids in dry feeds for larger fish.

Table 8. Chemicals reported to be used in Swedish production systems (questionnaire mailing Appendix). Chemicals with the same field of application are listed separately from one another so that consumption can be listed. Chemical formulae are stated in brackets and brand names appear in italics. Quantities and volumes (where specified) our normalised to the number of tonnes of production per year of the aquaculture organism in question (fish, shellfish or algae). Ö = Open, Ö (land) = flow-through system on land, S = Closed recirculating, A = Aquaponics.

Farming system	Chemicals	Applications	Quantity of chemicals per tonne of farmed organism produced per year
Ö, S	Antibiotics	On diagnosis.	approx. 6 kg of active substance (based on Statistics Sweden figures for production)
Ö (country)	Acetic acid (CH_3COOH) + Peracetic acid (CH_3CO_2OH) + Hydrogen peroxide (H_2O_2) *Ecolab P3-Oxysan ZS*	Disinfection	<0.5 L
Ö (country)	Chloramine-T ($C_7H_7ClNO_2S$ Na) e.g. *Halamid*	Disinfection (oxidising), fry bath	1.4 kg, 0.25 L
Ö (country), S	Formalin (dilute formaldehyde CH_2O)	Disinfection of roe and fry/fish for consumption (not food fish), cleaning	0.25 L
Ö (country)	Iodine (I) *Buffodine*	Disinfection of roe	0.25 L
	O_3)		
S	Soda lye 25% (dilute Sodium hydroxide NaOH)	Cleaning (alkaline)	2h
S	Potassium hydroxide 10-20% (KOH) + Sodium hypochlorite 2-5% (NaClO) *DeLaval Ultra*	Cleaning (alkaline)	<1 L
S	Hydrichloric acid (HCl)	Cleaning (acidic)	<1 L
S	Phosphoric acid 10-20% (H_3PO_4) + Sulphuric acid 5-10% (H_2SO_4) *DeLaval Cidmax*	Cleaning (acidic)	<1 L
S	Sodium carbonate (Na_2CO_3)	pH-adjusting	
	Formic acid (HCOOH)	Ensiling of waste	

Another type of microbial feed placed in a different context is biofloc, which uses an entirely closed system with more or less zero emissions (Avnimelech 2009). A nutritious “soup” made up of microorganisms (bioflocs) is bred in these systems and consumed primarily by regular shrimps or tilapia by means of filtration. The microorganisms in the system, which needs to be at a high temperature, are intended as a way of supporting the fish or shrimps entirely or of providing a certain amount of support feeding, supplying energy and nutrients to promote high production.

CHEMICALS AND PHARMACEUTICAL PREPARATIONS

Fish cages may be impregnated with anti-fouling preparations in some cases, primarily in marine or brackish water environments, as this is largely not needed in freshwater, particularly not in nutrient-poor reservoirs where most cage farming-based activities take place. In freshwater, the cages are washed on land instead using water and a high-pressure washer, or alternatively in large-scale washing machines, or else the cages are wiped down and dirt, fouling, etc. can then be removed and collected. Therefore, more or less no chemicals are used in open cage farms in freshwater environments.

In recirculating systems parasite attacks and disease can be avoided by observing strict hygiene, implementing procedures and ensuring good water quality. The questionnaire responses submitted indicate that most chemicals used in aquaculture are detergents or disinfectants, frequently strong acids with a low pH or alkaline solutions with a high pH (Table 8). As the response rate was not 100 per cent, this table must be viewed as an indication of the chemicals used in Sweden, and not as a comprehensive description of the use of chemicals in the industry. Chemicals are primarily used at land-based facilities nowadays for both large (fish for consumption) and small organisms (roe, larvae/fry, fish for consumption). Some of these land-based facilities are through systems where the water passes through the facility and out into the recipient.

Roe and fry are disinfected in closed baths, but there is no indication of where the water used to treat them then goes. A number of farmers state that they use formalin (formaldehyde dissolved in water) or chloramine-T for disinfecting roe and fry. The dosage is adapted according to the disease, fish size, etc. Chemicals of this type are not used in production of fish for consumption, however. Lime is normally used in the same way as in semiclosed systems to remove the odour of separated sludge. The only information received on pH adjustment of sludge from a land-based facility indicates use of sodium carbonate (Table 8). Nitrification causes acidification, so it may be necessary to add chemicals to increase alkalinity in RAS systems. However, this has not been confirmed in the data received.

No particular use of chemicals has been indicated in entirely closed systems such as aquaponics and bioflocs. One aquaponics facility stated that it used beneficial insects when the farmed plants were attacked, and one biofloc facility stated that mineral supplements (Ca/Mg) were given to the farmed crustaceans.

Fish affected by disease are either given medicated feed prescribed by a veterinary surgeon, or slaughtered. According to the Swedish Board of Agriculture (Ahlberg pers comm.), a total of 10.4 tonnes of antibiotics were sold for livestock purposes in 2014. Of this amount, total antibiotic use at fish farms in Sweden (2015) accounted for just 65.4 kg of active substance. It is not possible to establish the precise distribution of antibiotic use between cage farming and land-based farms, but most antibiotic usage (approx. 70 per cent) takes place at land-based facilities before the fish are placed in cages, while approx. 30 per cent is used at cage farms (Wikberg pers. comm.). Use of antibiotics in fish farming is not permitted for preventive purposes; antibiotics may only be used subject to veterinary prescription (Högfors-Rönnholm 2014). Lists of quantities of antibiotics prescribed are compiled every year. Most active antibiotics are used to treat flavobacteria, where infection can be transmitted both horizontally (from other fish or infected water) and vertically (to offspring). *Flavobacter psychrophilum* causes high mortality rates in fry and fin damage, as well as wounds that may extend all the way into the muscles. This disease is common at low temperatures (<15 °C), and occurs in both freshwater and brackish water. Florfenicol is the

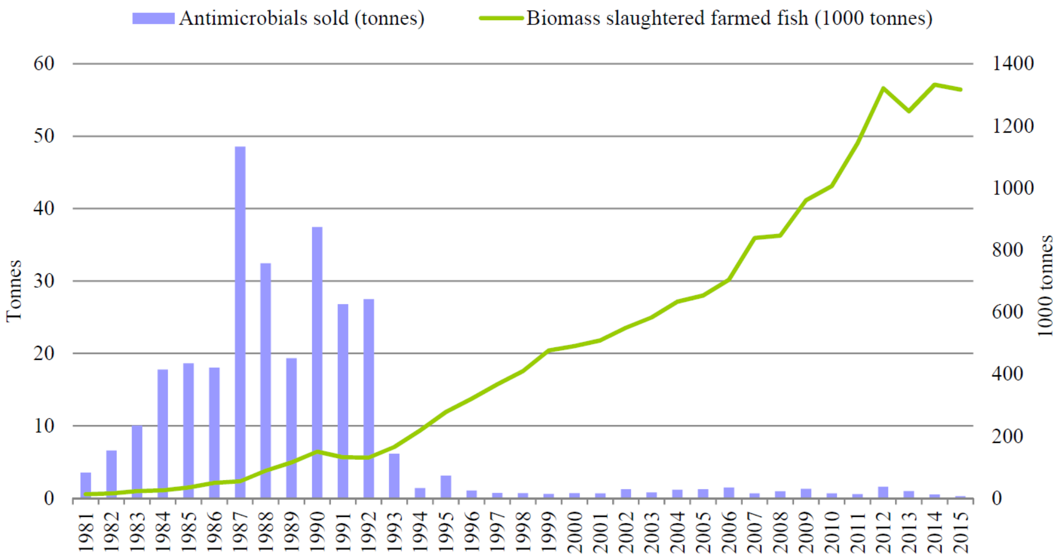

Figure 30. Use of antibiotics at Norwegian salmon farms compared with the amount of fish produced from the start of salmon farming to 2015 (NORM NORM-VET 2015)

active substance in the antibiotic treatment of *Flavobacter psychrophilum*. “Columnare disease” is another common disease caused by flavobacteria (*Flavobacter columnare*). This disease occurs in freshwater and causes damage to fish gills and skin. Oxytetracycline is the active substance for treatment of this disease. Fish farmed in offshore areas and brackish water are normally vaccinated against the most common and/or most important diseases before being placed in cages.

Diseases may be contracted due to the introduction of diseased individuals (at all life stages), contact with infected wild animals, or with feed. Lower levels of many pathogens (pathogenic organisms) frequently occur in water, but farmed animals’ immune defences can effectively prevent infection and subsequent outbreak of disease as long as these levels are not too high (Segner et al. 2011, Sundh and Sundell 2015). There is an increased risk of disease outbreak in the event of increased or additive stress such as poor water quality or a lack of hygiene and procedures, as stress has an adverse impact on organisms’ own defences (Sundh et al. 2009, Segner et al. 2011, Sundh and Sundell 2015). Disease may be spread on tools used to handle individuals, by relocating individuals and by the transmission of various pathogens around the farm in flowing water.

The pathogens that cause disease in fish do not generally affect humans or other terrestrial animals. Use of antibiotics has declined significantly since the mid-1990s as salmonids are vaccinated against common diseases. According to the Norwegian Veterinary Institute’s annual report on the use of antibiotics in Norway, use of antibiotics at Norwegian salmon farms has fallen by 99 per cent since 1987 (NORM_NORM-VET 2105, Figure 30). When vaccinating fish, the fish are anaesthetised and the vaccine is then injected into the abdominal cavity. This may be done manually or mechanically (e.g. NFT-20). Fish are vaccinated against vibriosis and furunculosis, and Alphaject 3000 is a common vaccine. The vaccine dose is 0.01 ml, and depending on the equipment available, fish 10-20 g in size or larger can be injected. After approx. 400 degree days, the fish are deemed to be immune and can be exposed to infection without becoming sick (Lönnström pers. comm.). Small fish fry (<10 g) can also be protected against vibriosis to an extent by means of dip or bath vaccination, where the vaccine is absorbed via the gills or the surface of the body (Dhar et al. 2014)[18,19].

Table 9. Amount of active antibiotic substance prescribed to Swedish fish farms (Ahlberg pers. comm.) and antibiotics in other meat production in Sweden (EMA 2012, 2016). Use of antibiotics expressed as mg of active substance per kg of lightweight. (e.t. = not available).

	Fish farming (g per tonne of live weight)	Other meat production for food (g per tonne of live weight)
2009	1.7	
2010	2.9	15.2
2011	4.0	13.6
2012	4.7	13.5
2013	6.7	12.7
2014	6.0	11.5
2015	5.8	e.t.

In other words, antibiotics are only prescribed and distributed in the feed when disease is diagnosed. Most of the antibiotics in the feed are metabolised by the fish, and the metabolites and some unmetabolised antibiotics that leach out of the medicated feed therefore end up in the recipient. As the amount of antibiotic prescribed is limited, it is particularly important for the farmer to ensure that the feed uptake is as high as possible. This also minimises admissions to the environment. However, the antibiotics prescribed to other food production animals and in other veterinary and medical care do the same thing, which is why the amount from treatment of fish in captivity is negligible. Use of antibiotics for food production in Europe stands at 100 g of active substance per tonne of live weight (i.e. before slaughter) on average (EMA 2012, 2016). In Sweden, this figure is around 11-14 g per tonne for food in general, while in fish farming just half as much (2-7 g per tonne) antibiotic is used as in other food production (EMA 2012, 2016, Heldbo et al. 2013, Table 9). These figures can be compared with approx. 2 g per tonne for Norwegian fish farming, which mainly uses open production systems, and approx. 80 g per tonne for Danish fish farming, which mainly uses recirculating systems (Heldbo et al. 2013, Figure 30).

LOCATION

Farms must be placed in the most appropriate locations from both environmental and socio-economic perspective, encroaching as little as possible upon the environment. As the various production systems have completely different characteristics and needs, and as various water systems have different criteria with regard to abiotic factors, anthropogenic impact, utilisation of land and water areas and other factors, it is not possible to provide general recommendations on the most appropriate location for farms. Open cage farming, for example, generally requires greater nutrient capacity in the recipient than other farming techniques, while RAS facilities – for example – require greater access to land areas for buildings, as well as a good power supply. Therefore, more in-depth analyses of the purpose of the intended farming activity, the scope of the same, the choice of species and the conditions in the potential locations are needed in each individual case if proposals for appropriate geographical locations are to be provided. When planning a fish farm, abiotic factors such as currents, bottom topography, temperature, nutrient levels and, where appropriate, salinity profiles, etc. all have to be charted. Some form of flora and fauna inventory should also be carried out, taking into account plants and animals on the bottom in the water zone that is expected to be affected. The aim of this is to identify whether there are any sensitive species or species requiring particular consideration, and also to provide an overview of the current status in the zone so as to be able to monitor how farming impacts on the environment.

Any farm, be it on land or in the water, affects both the landscape and the water quality in the recipient. Production systems in turn are affected by the water quality at the location of the farm, and good water quality is necessary in order to ensure high production and minimise stress and outbreaks of disease at the farm. When positioning farms, it is necessary to take into account various types of activity in the area such as shipping, recreation and outdoor activities. Roads and a power supply (infrastructure) are also necessary.

The nutrient status of Swedish waters largely restricts the types of production system that are appropriate. The large, regulated lakes in Sweden provide good conditions for lake-based and inland-based fish farms as the nutrient levels in these lakes have fallen due to the hydropower regulation, along with the fact that the reservoirs are normally large and deep. In combination, these factors provide excellent potential for fish farming activities. As a result of the hydropower regulation, most plant and animal life in the littoral zone (the area close to the shore) is knocked out when the water level falls in winter, the area is drained and then freezes solid until the reservoir is refilled in spring and early summer. These areas are the most productive in unregulated lakes, a supply of benthic plants, and they are also home to rich insect life that provides a food base for the fish populations in the lake (Runnström 1955, 1964, Grimås 1962, 1964, Nilsson 1964, Rodhe 1964, Fürst 1968, Andersson 1978, Fürst et al. 1983, 1984, 1986, Svärdsson and Nilsson 1985, Hill & Forsberg 1986, Degerman et al. 1998, Vrede et al. 2006, Persson et al. 2008, Rydin et al. 2008, Milbrink et al. 2011, Markesten et al. 2012). In an unregulated lake, the littoral zone also deals with a large proportion of the nutrients in the water by binding these into biomass production. Regulated lakes, however, do not have this plant and animal life that is capable of binding up the nutrients in the littoral zone, which also reduces biological production as a whole in the reservoir (Runnström 1955, 1964, Grimås 1962, Nilsson 1964, Fürst 1968, Andersson 1978, Fürst et al. 1983, 1984, 1986, Svärdsson and Nilsson 1985, Jensen 1988, Degerman et al. 1998, Milbrink et al. 2003, Vrede et al. 2006, Persson et al. 2008, Milbrink et al. 2011, Markesten et al. 2012). In most reservoirs, former land areas have also been submerged, thereby increasing the volume in the reservoir and hence the turnover time of the water as well. This results in increased sedimentation and hence increased phosphorus retention as well, which is the fixing of nutrients in the benthic substrate (Runnström 1955, 1964, Andersson 1964, 1978, Grimås 1962, Nilsson 1964, Rohde 1964, Grimås & Nilsson 1965, Fürst et al. 1978, 1984, Svärdsson and Nilsson 1985, Jensen 1988, Swedish Environmental Protection Agency 1996, Degerman et al. 1998, Stockner et al. 2000, Milbrink et al. 2003, Vrede et al. 2006, Rydin et al. 2008, Milbrink et al. 2011, Siergieiev 2014, Siergieiev et al. 2014). The overall effect of the hydropower regulation is that instead of being absorbed by the littoral elements of the ecosystem, nutrients sink to the bottom in the deep areas of the lake and are fixed, or alternatively flow out of the lake via the bottom tap in the pond in winter (Swedish Environmental Protection Agency 1986, 1996, Degerman et al. 1998, Rydin et al. 2008, Milbrink et al. 2011, Siergieiev 2014, Siergieiev et al. 2014). In the long run, the ever declining levels of nutrients in the reservoir lead to a reduction in biological production as a whole (Runnström 1955, 1964, Grimås 1962, Andersson 1964, Sundborg 1977, Fürst et al. 1984, Svärdsson and Nilsson 1985, Swedish Environmental Protection Agency 1986, 1996, Ney 1996, Degerman et al. 1998, Stockner et al. 2000, Milbrink et al. 2003, Vrede et al. 2006, Persson et al. 2008, Rydin et al. 2008, Milbrink et al. 2011, Siergieiev 2014, Siergieiev et al. 2014). Adding a certain amount of phosphorus to these reservoirs, e.g. by constructing a correctly dimensioned fish farm, may be considered as a measure for enhancing the biotope as long as the nutrient capacity in the lake is not exceeded. The areas around these reservoirs are also sparsely populated and rarely accommodate other interests, which reduces the risk of conflicts of interest.

Large parts of Swedish coastal areas, primarily in the Baltic Sea area, already have high nutrient loading from the catchment areas and from watercourses, so they are much less capable of being able to withstand an increased nutrient load (HMI 2016). The Baltic Proper is still eutrophied and has shown little or no improvement over the past ten years, despite a considerable reduction in the supply of nutrients. The low turnover of the water, the long dwell time and a lack of water flowing in through Öresund are part of the reason for this (HELCOM 2014). Some 45 per cent of the bottom area in the Baltic Proper, Gulf of Finland and the Gulf of Riga is currently covered by oxygen-poor or oxygen-free water (Havet, 2015/16). In many locations, however, the quality of coastal waters has improved thanks to various measures. The nutrient status is considerably improved in the Gulf of Bothnia and parts of the Bothnian Sea, along parts of the coast but mainly in the open sea areas, which is why conditions for fish farming in open cages are available in carefully selected areas. The Bothnian Sea is demonstrating a declining status (HMI 2016). Total phosphorus levels in the deep-sea area of the Bothnian Sea have increased since the 1970s, while oxygen levels in the deep water have fallen. In the coastal waters, less than half of the water bodies achieve good ecological status in accordance with the assessment criteria in accordance with the Water Framework Directive. As a result of long-term eutrophication, the sediments and bottom water have become rich in organic matter, which increases oxygen consumption when it is degraded. Denitrification in the anoxic sediment layer may be promoted with fluctuating oxygen levels in the water, but a long-term shortage of oxygen (hypoxia) may instead lead to reduced denitrification, which in turn may lead to an increase in the release of phosphorus from the sediments (Jäntti and Heitanen 2012). Of all the Swedish sea areas, the Gulf of Bothnia is least affected by eutrophication (HMI 2016). Total phosphorus levels are low and have also been falling since the 1970s, while the oxygen situation in the deep water is good. Things are slightly worse in the coastal areas, and one in every five water bodies is showing signs of eutrophication. Sweden has a reduction target of 530 tonnes of phosphorus and 9240 tonnes of nitrogen for the Baltic Sea (HELCOM 2013), and according to HELCOM (2014) it is desirable to reduce emissions in the recipient as a whole; that is to say, over the entire area of the Baltic Sea.

The nutrient status is better along the west coast, which offers potential for marine aquaculture. The status in the deep-sea area of the Skagerrak is generally good, both in the water column and at the bottom (HMI 2016). That said, the situation at the coast varies more widely. The status in the water column is generally good, but benthic animals are demonstrating moderate status in many areas in southern Bohuslän. The status is generally good at the coast in the Kattegatt, but slightly poorer down towards Halland and Öresund. The status for benthic animals at the coast has improved over the last few years; except at Laholmsbukten in Halland, which still has a poor status.

The coastal areas are densely populated, and there may be conflicts of interest between aquaculture and other activities such as outdoor recreational activities and boats. Maps showing the suitability of water zones for aquaculture are available for northern Bohuslän (blue general plan), the Kalmar coast (Andersson et al. 2013a; Olofsson and Andersson 2014) and parts of northern Sweden (Andersson et al. 2013b; Olofsson and Andersson 2014). These maps are based on water quality and abiotic factors, as well as on various activities in the areas such as fairways, recreation areas, protected areas (Natura 2000[20]) or marinas.

The nutrient status always needs to be taken into account when selecting production systems for different water zones. Furthermore, for detailed placement individual analyses – which, besides nutrient analyses also include evaluation of other environmental considerations such as energy consumption, transportation, other water quality parameters, etc., as well as social, economic and cultural aspects – need to be carried out so that the best production systems and locations can be selected.

MONITORING OF NUTRIENTS TO THE RECIPIENT

The amount of nutrients released from farming activities is estimated using various calculation models, and impact on the aquatic environment is monitored by sampling water chemistry, checking biological parameters and, in many instances, sampling sediments as well. General recommendations on monitoring the impact of aquaculture on national environmental targets can be found in works such as Fernandes et al. (2001). More specific proposals for the formulation of control programmes for the monitoring of freshwater fish farming are presented in the report entitled “Förslag till modeller för tillståndsbedömning av fiskodling, kontrollprogram och analys av miljöpåverkan” [Proposals for models for assessing the status of fish farming, control programmes and analysis of environmental impact] by Alanärä (2012), but regulatory requirements are amended so models and control programmes need to be updated and developed. One of the calculation models used at present, Vollenwieder OECD (Nordic calibration), is considered to work for computation of point source emissions from fish farms over entire lakes, and making this applicable on a national level has been recommended in order to estimate the potential nutrient capacity in lakes and reservoirs (Alanärä 2012).

The MOM model (Modelling-Ongrowing fish farm monitoring, Stigebrandt et al. 2004) has been developed for marine conditions and is used as a national standard in Norway. This focuses on the water quality in the surrounding environment as well as at the farm. This model accepts a certain amount of local impact from the nutrient load beneath the farm, but the environment must not be affected so extensively that benthic organisms disappear. The model developed for marine conditions cannot be transferred in its entirety to limnic environments. However, it has been used as a starting point for a proposal on how bottom conditions adjacent to fish farms can be monitored, together with the surveys carried out and films created at a number of farms to date. The purpose of the proposal is to standardise the monitoring of the sediment as there are no guidelines for this (Hedlund 2015).

Two national reports (Alanärä 2012 and Andersson et al. 2016) do, however, clearly indicate that there is a major need for ongoing investigation and development work in order to devise more dynamic models that also take into account more parameters, as well as different aquaculture systems and recipient systems.

Environmental impact from open production systems comes from dissolved nutrients and sedimentation of particulate material. It is difficult to measure the precise quantities of nutrients added to the recipient by open systems as these are spread with the water currents, which in turn frequently vary in terms of strength and direction. The essential assessment of the environmental impact and status classification of nutrients is to be based on the water body as a whole. The calculation models used (such as Vollenwieder OECD, Nordic calibration) are adapted for computation of point source emissions from fish farms over entire lakes and provide relevant values indicating the anticipated impact (Alanärä 2012). These calculations can be combined with further parameters such as how much of the particulate waste is eaten by wild fish, or how much of the phosphorus and nitrogen bound in the feed is bioavailable, along with advanced calculations of the spread of nutrients based on current models. This could provide a more detailed view of the impact on various subareas in the recipient (Andersson et al. 2016).

The available nutrients emerging into the recipient impact on primary production in the area, which is why phytoplankton are normally monitored in the recipient control programmes for fish farms. Phytoplankton are also one of the biological parameters for assessment of ecological status classification. An increase in nutrient levels increases the amount (biomass) of phytoplankton, while the occurrence of species may be altered so that the species indicating eutrophication increase. This is reflected in the TPI (Trophic Plankton Index), and also by an increase in cyanobacteria levels. This may impact on the ecological status.

The particulate material deposited from a fish farm has two different effects in the area, which in turn interact to an extent. Nutrients may be released from the deposited material. The effect of this is monitored by sampling the water chemistry and phytoplankton. Benthic fauna samples may indicate the impact from altered nutrient conditions at the bottom of the recipient, but they may also indicate the presence of the other effect that may come about due to the depositing of organic matter; impaired oxygen conditions. Oxygen is consumed as the deposited material is degraded, which may result in oxygen deficiency if the oxygen consumption exceeds the oxygenation capacity of the area. However, as sedimentation takes place within a limited area, any oxygen deficiency due to fish farming does not usually affect the recipient as a whole. Like phytoplankton, benthic fauna are a parameter indicating the status classification of water bodies. While impact on the benthic substrate is limited to the adjacent area, the status classification has to be based on the water body as a whole. Hence the spread and volume of deposited material and the oxygenation of the benthic substrate are often monitored using other methods as well. Filming the bottoms shows the presence or lack of sulphate-reducing bacteria, which in turn indicates whether or not anoxic conditions prevail. These films also show the spread of the sediment, and when combined with measurements of sediment depth they can be used for assessing total sediment volumes beneath fish farms.

Development of semiclosed and closed production systems, both water and land-based, create opportunities for obtaining more precise data for calculating the impact on the aquatic environment as outgoing water can be sampled. The distribution of various nutrients and their forms differs depending on the farming technique used. This also needs to be taken into consideration in development and investigation work for production of new, more complex models for control programmes and monitoring. Development of protective farming by means of filtration and assimilating species also creates further complexity that needs to be included in the models. Both semiclosed and closed systems produce sludge, and handling this usually involves a cost. However, this sludge contains nutrients and may be viewed as a valuable raw material, which is why potential uses for sludge from aquaculture is another field requiring further investigation.

ECONOMIC ASPECTS

The report describes three different production methods for farming of fish. The investment cost varies depending on the production method selected and the facilities needed for the method in question. Norway has semiclosed and closed systems suitable for marine use. These systems are being developed, but they will probably involve higher investment costs than farming in open cages. That said, investment costs for semiclosed systems are probably lower than for similar production volumes in RAS systems, which means that investment costs for production facilities using open cages are significantly lower than for similar RAS systems. Operating costs for semiclosed systems are lower than for RAS systems but higher than for farming in open cages. There are no semiclosed systems for farming in Swedish freshwater areas.

In general, fish farming in open cages gives acceptable returns. After the initial years of establishment, most fish farmers see positive results and stable cash flow. They are frequently also capable of bringing about growth and expansion using their own resources. There are few fish farming companies in Sweden, and a small number of stakeholders are responsible for almost all Swedish production of Arctic char and rainbow trout. Despite this, production has more than doubled over the past few years. Reviewing the annual reports of the seven biggest fish farming companies producing fish for consumption in open cages indicates that all of them made good profits in the five-year period examined (Ekegerd et al. 2014). Price fluctuations for rainbow trout are greater than for Arctic char, but despite this farming of rainbow trout in open cages is profitable. The report (Ekegerd et al. 2014) examined the opinions of different funding bodies on investment in fish farming. The report showed that there are plenty of opportunities for farming companies capable of demonstrating profitability to obtain external capital. Representatives working with risk capital and venture capital are positive about investing in farming of fish for consumption, above all. In other words, the prospects for funding both establishment and expansion within fish farming companies our good.

Commercial, land-based RAS facilities for both cold water and warm water species are operating in Europe, North America and Asia. Relatively few estimates of investment and operating costs are available, and these vary widely as there is a great deal of variation in technology and biology at such facilities. Moreover, technical development and expertise are making rapid progress, which is impacting on investment and operating costs. Most calculations performed for RAS facilities indicate that as things stand at present, there is a need to sell premium products at higher prices in order to achieve profitability. Langeland et al. (2014b) devised a template value for investment costs at commercial RAS facilities. This came in at SEK 90 per kilogram of fish produced, including depreciation, for facilities with a production capacity of 60-300 tonnes per year of salmon, perch and tilapia. The greater the production, the lower the investment cost per unit of fish produced. As technology is advancing, it should be possible to reduce these costs as the technology becomes more established. Operating costs in 2013 were estimated at just over SEK 42 per kilogram of fish produced.

Commercial extensive farming in open marine systems in Sweden at present currently involves farming of blue mussels. Investment costs for a 300-tonne blue mussel farm using long-line systems in Bohuslän is estimated at between SEK 250,000 and SEK 500,000. This means that investment costs of around SEK 1-2 per kilogram are required.

The quality of the end products is of crucial significance to how willing people will be to pay for these products. On the one hand, there is a need to implement predictable production of large volumes with consistent quality. At the same time, some consumers are willing to pay more for small-scale, locally produced products. This may also be the case if production is certified or otherwise guarantees ethical and environmental sustainability. There is a need for in-depth surveys of economic conditions for different production systems.

CONCLUSIONS

It should be possible to develop all aquaculture system types in Sweden, but different techniques are suited to different environments and different species to a greater or lesser extent. Just as with other food production, aquaculture requires resources in order to produce food; both natural resources and economic resources. Technical development, with emphasis on eco-intensive production, is making strong progress and the aim of production systems is to pave the way for ecological, economical and social sustainability. New, more technically advanced systems also require a buildup of expertise levels among both users and authorities. There are currently also opportunities to adapt or adjust conventional methods so as to make them more eco-friendly, such as protective farming of extensive species adjacent to open cages, and/or technical development for collecting nutrients from the open systems as well. On a global level, aquaculture will need to increase in order to meet the protein needs of a growing world population. Sweden has a major opportunity to expand its aquaculture operations and focus on eco-friendly technology, but this is not something that will happen automatically if it initially means that users will have to meet excessively high costs in order to achieve economic viability. Incentives are needed to continue to drive development in a sustainable, eco-friendly direction. Most of the fish eaten in Sweden at present is imported. That said, there are express political objectives with regard to growing aquaculture, research and trials for the development of new and existing production techniques are ongoing, and contractors and both new and established companies are aiming to increase Swedish production of aquaculture products.

Continued development of production systems, such as semiclosed and closed systems, are increasing opportunities for more diversified aquaculture. Species that are able to cope with our Swedish climate and natural seasonal temperature variations can be farmed in open systems. The environment at farms can be controlled in semiclosed and closed systems, which increases opportunities for diversification while also helping to reduce impact on the surrounding environment. However, investment costs relating to closed and, to an extent, semiclosed systems are higher than for open systems. Farming at temperatures optimised for the species may result in consistent high levels of growth and a reduction in feed wasted. Opportunities to control the exchange between farming and the surroundings, along with careful control of the aquatic environment at the farm, reduce the risk of disease and parasite attacks both at the farm and in the recipient, eliminate the risk of genetic contamination and reduce the risk of eutrophication in the local area. The RAS system requires effective water treatment, and this is a major and essential part of the facility. The major dependency of the semiclosed and closed systems on technology demands well-developed control and alarm systems, as well as auxiliary systems, in order to reduce the risk of rapid impairment of water quality.

Having access to water that is appropriate for the species to be farmed is absolutely crucial. Some species are able to withstand fairly major variations in various water parameters, while others are more sensitive, and needs also vary over the life cycles of organisms. In open systems, as well as in semiclosed through systems. The water quality is dependent on where the farm is located; and in semiclosed systems it is also dependent on the depth from which the water is pumped, while in closed and recirculating systems it is dependent on how the water is treated and processed. The effects of any nutrient leakage from a production systems are dependent on the dimensioning of the emissions and also on the conditions in the recipient.

Feed accounts for the biggest operating cost when farming fish and crustaceans, and so it is important to develop more ecologically sustainable feeds at competitive prices. However, factors such is the physical qualities of the feed, reduced nutrient emissions, fish growth and good animal welfare and health must also be taken into account, which is why it takes time to develop new feeds. Development has been progressing for a long time now towards more vegetable elements and less fishmeal and oil, thereby heading in the direction of more sustainable feeds. More innovative raw materials such as marine organisms from lower trophic levels, insect meal and utilisation of more side flows from the processing industry, for example, are alternatives offering major potential as future feed ingredients.
However, further evaluation of these is required before they can be used in large-scale production.

Many areas need to be developed in terms of expertise, such as quality-assured methods for monitoring the effects of production systems and quantifying their emissions, and more in-depth analyses of economic criteria for aquaculture production in relation to species and production methods, for instance.
As farming organisms are also "what they eat" to a certain extent, more needs to be known about any

additives in feed that may originate from the production of the feed ingredient. Furthermore, questions remain to be examined and answered as regards the optimum handling of sludge.

Since the government-appointed inquiry “Det växande vattenbrukslandet” [Sweden: an aquacultural nation in the making] (SOU 2009:26), Sweden has emphasised the need to increase sustainable aquaculture production throughout the country in a number of strategies and visions: “Svenskt vattenbruk – en grön näring på blå åkrar” [Swedish aquaculture – a green industry on blue fields], Swedish Board of Agriculture Strategy 2012-2020, ”En svensk maritim strategi – för människor, jobb och miljö” [A Swedish maritime strategy – for people, jobs and the environment], Government strategy (Aug. 2015) and “En livsmedelsstrategi för Sverige – fler jobb och hållbar tillväxt i hela landet” [A food strategy for Sweden – more jobs and sustainable growth throughout the country], Government bill (Dec. 2016), Sweden has emphasised the need to increase aquaculture production throughout the country, but underlined that this must take place in a sustainable manner. To be able to fulfil these visions and support development of sustainable aquaculture in Sweden, action needs to be taken to coordinate and facilitate licensing and supervision processes, promote development of current techniques and promote adjustment and diversification towards new production system types in terms of techniques, species and feed.

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APPENDIX

Questionnaire mailing

The following questionnaire was sent out on 1 November 2016 via the email list from the national aquaculture conference for 2016 (to 712 recipients). This mailing allowed us to target the broadest possible group of people active in the field of aquaculture. The list included commercial companies, researchers and authorities, as well as individuals and organisations with an interest in aquaculture. The response rate based on the number of mailings was low overall (<10 per cent) due to the extent of the recipient group, but the majority of production currently taking place in Sweden is included as all major farmers responded. Some companies preferred to respond jointly, or verbally. Time constraints meant that follow-up interviews were limited to areas where the information submitted was unclear or needed to be clarified.

Data for Swedish Agency for Marine and Water Management report on Swedish aquaculture

1. Production
    a. Facility type (RAS, closed, semiclosed, open)
    b. Lake/sea-based or land-based
    c. Species
    d. Total production volume
    e. Origin of farming organisms (brood organisms, fry importation, wild-caught, land…)
    f. Risk of escape into/spread throughout the environment (major, minor, non-existent)
    g. Infrastructure (type of container/net, type of material and)
    h. Water type (salinity, temperature)
    i. Volume per species (production volume and water volume)
2. Feed
    a. What percentage of the energy and nutrition requirement is covered by feeding? (In other words, is farming intensive or extensive?)
    b. Type (live, wet feed, dry feed, commercially available, self-produced.)
    c. Chemical composition of the most commonly used feed(s)
    d. Main raw materials in the most commonly used feed(s)
    e. Consumption
3. Water treatment
    a. Type (sedimentation, filtration, biochemical, chemical…)
    b. Infrastructure
    c. Consumption (litres of treated water per hour)
4. Energy
    a. Type (solar, wind, electricity, water, rock…)
    b. Consumption
5. Chemicals
    a. Type (plus function)
    b. Consumption
6. If you are aiming to increase the production volume, what is the main reason for this?

Would your production volume be likely to increase if licensing were based on actual nutrient burden instead of indirect burden calculated by means of feed consumption?

Summary of questionnaire responses

Overview of water treatment/consumption, production, feed conversion (FCR), density per production system. (* estimated figure in full production).
Production systems: Ö = Open, Ö (land) = flow-through system on land, S = Closed recirculating, A = Aquaponics. FCR = Feed conversion ratio (feed used/production). Max. density = kg of farming organisms per m3 of water (kg/m3), or production in tonnes per hectare (t/ha).

System	Infrastructure	Species	Water exchange per day (L/d) Treated water per tonne per hour	Production, tonnes	Feed used, tonnes	FCR	Max. density
Ö	Cage	Rainbow trout	-	12,000	14,000	1.17	25 kg/m3
Ö	Cage	Rainbow trout	-	5,000	6,000	1.2	25 kg/m3
Ő	Cage	Rainbow trout	-	40	50	1.25	9 kg/m3
Ö	Cage	Arctic char	-	2,000	2,300	1.15	30 kg/m3
Ö (country)	Ponds, earth ponds	Salmon trout / Arctic char / Rainbow trout		25-30	30-35	1.17-1.2	
Ö (country)	Fibreglass, plastic ponds	Fish for consumption					
Ö	Line farming	Filtering organisms	-	1,200	-		
Ö	Line and net farming + plastic pipes (polyethylene)	Filtering organisms		5,000	-		
Ö	Net farming	Filtering organisms	-	10	-		80 t/ha
Ö	Line farming	Algae	-	60-70	-		30-35 t/ha
Ö (country)		Filtering organisms	Treatment 4 m3 per hour				
S	Plastic pond	Salmon	Treatment 15 m3 per tonne per hour	1.5		1.1 *	
S	Fibreglass pond	Warmwater fish		36	40	1.1	50-70 kg/m3 230kg/m3*
S	Plastic pond (polypropylene)	Rainbow trout / steglet	Treatment 11 m3 per tonne per hour	35			87 kg/m3
S	Walled ponds	Crustaceans		50			6 kg/m3
A		Warmwater fish, plants	Exchange 10% per day	2	-		
A		Warmwater fish, plants	2 L	0.4	1% of body weight per day		22 kg/m3

Glossary

Adult – Sexually mature organism
Anadromous fish – Fish that reproduce in a freshwater environment but spends their adult lives in a marine environment
Anti-fouling agent – A biocide, a substance that kills living organisms
Anti-nutrients – Substances that inhibit the uptake of nutrients in feed
BOD – (Biological Oxygen Demand) The amount of oxygen consumed during biological breakdown of organic substances by microorganisms
BSE – (Bovine Spongiform Encephalopathy) A disease in the central nervous system of cattle that can be transmitted to humans.
Carnivore – Meat-eater
Catadromous fish – Fish they reproduce in a marine environment that spend their adult lives in a freshwater environment
COD – (Chemical Oxygen Demand) The amount of oxygen consumed during chemical breakdown of organic substances
Detritus – Dead, finely dispersed organic matter
Digestibility – How readily an organism can absorb a feed
Extractive species – Species that extract nutrients from the water
FCR – Feed Conversion Ratio
Fry – An early development stage after hatching and before sexual maturity, found in many fish species and freshwater crayfish
FTU – Phytase unit, the amount of enzyme that releases inorganic phosphate from sodium phosphate per unit time
Herbivore – Plant eater
Hydrolysate – Hydrolysed protein comprising shorter chains of amino acids that are absorbed more readily by the body
IMTA – Integrated multitrophic farming
Innovative – Novel, enhancing, providing renewal
Larva – An early development stage in organisms that undergo metamorphosis, such as flatfish and mussels.
MBBR – Moving Bed Biofilm Reactor
N/P ratio – Ratio of nitrogen (N) to phosphorus (P)
NH_3 – Ammonia
$NH4^+$-N Ammonium nitrogen
NO_2-N Nitrite-nitrogen
NO_3-N Nitrate-nitrogen
NSP – Non-Starch Polysaccharide
Omnivore – A creature that eats everything
PAP – Processed Animal Protein
PSU – Practical Salinity Unit
RAS – Recirculating Aquaculture System
Sessile – Immobile
Suspension feeder – Filter feeder
Svb – A limited company with special limitation on dividends (svb) is a special type of private limited company. The rules aim to ensure that the company's profits primarily remain within the company.
Triploidisation – The number of sets of chromosomes is changed to three from the normal two. Individuals with three sets of chromosomes are generally sterile as chromosome division on meiosis (when germ cells are formed) is unbalanced and disrupted.


PHOTO: MARIA HOLMKVIST