Aqua reports 2021:9

Feasibility and potential for farming and conditioning of wild fish fed with by-catches in Sweden

Örjan Östman, Arne Fjälling, Maria Ovegård, Sven-Gunnar Lunneryd, Helena Röcklinsberg, Albin Gräns, Aleksandar Vidakovic, Anders Kiessling

Sveriges lantbruksuniversitet
Swedish University of Agricultural Sciences

Institutionen för akvatiska resurser

Feasibility and potential for farming and conditioning of wild fish fed with by-catches in Sweden

Örjan Östman	Swedish University of Agricultural Sciences (SLU), Dept. Aquatic Resources
Arne Fjälling	Swedish University of Agricultural Sciences (SLU), Dept. Aquatic Resources
Maria Ovegård	Swedish University of Agricultural Sciences (SLU), Dept. Aquatic Resources
Sven-Gunnar Lunneryd	Swedish University of Agricultural Sciences (SLU), Dept. Aquatic Resources
Helena Röcklinsberg	Swedish University of Agricultural Sciences (SLU), Animal Env. and Health
Albin Gräns	Swedish University of Agricultural Sciences (SLU), Animal Env. and Health
Aleksandar Vidakovic	Swedish University of Agricultural Sciences (SLU), Animal Nutrition and Manag.
Anders Kiessling	Swedish University of Agricultural Sciences (SLU), Animal Nutrition and Manag.

This report has been reviewed by:

Peter Ljungberg, Swedish University of Agricultural Sciences (SLU), Dept. Aquatic Resources

Erik Petersson, Swedish University of Agricultural Sciences (SLU), Dept. Aquatic Resources

The report has been financed by:

SLU Aquaculture, SLU.aqua.2019.4.2-369

The authors are solely responsible for the content of this report and does not include any opinion by SLU Aquaculture.

Editor:	Noél Holmgren, Swedish University of Agricultural Sciences (SLU), Dept. Aquatic Resources
Publisher:	Swedish University of Agricultural Sciences (SLU), Dept. Aquatic Resources
Year of publication:	2021
Place of publication:	Lysekil
Illustration:	Magnus Falklind
Title of series:	Aqua reports
Part number:	2021:9
ISBN:	978-91-576-9872-8
Keywords:	Aquaculture, ethics, fish, fishers, law, sustainability

Abstract

Small-scale fisheries face problems with declining fish stocks in poor condition, increasing interactions with seals and cormorants and partly non-efficient distribution systems, resulting in low profitability. One potential method to increase the value of their catch is rear the fish in farms until fish reach a size that render a higher price. This may not only provide a higher value of each animal but also a steadier supply of fish to consumers and retailers. In addition, by-catch of unwanted species may be used as feed ingredient to the farmed fish. This will not only cut the costs for the feed but is also a more sustainable alternative as it will both make use of by-catches that otherwise is discarded, and recirculate nutrients on a regional scale instead of importing new nutrients.

Farming of wild caught fish and shellfish (grow-out or capture-based aquaculture) constitute a large part of aquaculture on a global scale. Except for eel is this type of aquaculture still limited in Sweden and Europe, with relatively little development. Here we make an overview of species that could be interesting for farming of wild caught fish, and identify benefits and challenges.

The species we find most suitable for further development are cod, perch, whitefish, pike and pikeperch for which we can identify evident benefits of farming. In common for all these species is the need for an efficient feed system to ensure early and rapid weight gain and minimizing initial mortality. We speculate that a feed based on insect larvae could be one way to improve the feeding system for several species of wild caught fish.

However, there are ethical and welfare issues related to farming wild born fish. As wild caught fish are not domesticated for life in captivity they can suffer from distress and increased susceptibility and transmissions of disease. Safeguarding the health and welfare of fish in capture-based aquaculture is a key to making it economically feasible, as an increased value for the end-consumers is necessary to compensate the fishermen for the additional costs associated with farming of wild caught fish. In addition, removal of wild fish may also impede natural stock size and recruitment of the natural stocks. Although our aim is to develop a farming system where local by-catches is used as a feed ingredient, local eutrophication effects and water pollutions (feed and fish residues) can cause degradation of local water quality.

In conclusion, we find potential for farming of wild caught fish with local-by-catches as a feed ingredient. To be economically feasible there is a need for developing feeding systems, investigate stress responses and ethical and sustainability aspects important for marketing of such products.

Svensk sammanfattning

Småskaligt fiske står inför flera problem med vikande kommersiella fiskbestånd, ökad påverkan av säl och skarv, och delvis ineffektiva distributionssystem, vilket resulterar i låg lönsamhet. Ett sätt att öka värdet på fångsten kan vara att använda vildfångad fisk i vattenbruk för att få dem att växa i storlek och ge ett högre pris, men också stadigare tillgång på fisk till konsumenter. Dessutom, om bifångster av oönskade arter kan användas som foder kan detta inbära sänkta kostnaderna för fodret samt möjliggöra ett bättre utnyttja av bifångster. Om bifångsten används som foder istället för att slänga tillbaka den är det också ett effektivt sätt att återcirkulera näringsämnen på en regional skala, istället för importera näringsämnen i form av foder av fisk från andra områden.

Användande av vildfångad fisk och skaldjur i vattenbruk utgör en stor del av vattenbruket på en global skala. Men i Sverige och Europa är denna typ av vattenbruk fortfarande väldigt liten. Här gör vi en analys och översikt över olika arter som skulle kunna vara intressanta för vattenbruk av vildfångad fisk.

De arter som vi tycker är mest lämpade för vidare undersökningar är torsk, abborre, sik, gädda och gös där vi kan identifiera tydliga fördelar med att använda vildfångad fisk i vattenbruk. Gemensamt för alla dessa arter är behovet av ett effektivt fodersystem för att säkerställa tidig och snabb viktökning och minimera initial dödlighet. Vi spekulerar i att ett foder baserat på insektslarver kan vara ett sätt att förbättra utfodringssystemet för flera arter av vildfångad fisk.

Det finns dock flera etiska- och hållbarhetsfrågor relaterade till vattenbruk av vildfödda fiskar. För det första är fisken inte domesticerad för ett liv i fångenskap vilket kan orsaka skadlig stress, minska motståndskraft mor sjukdom och en ökad risk för sjukdomsöverföring. Detta är en mycket viktig aspekt för marknadsföring av vildfångad fisk i vattenbruk för att uppnå ett mervärde för slutkonsumenterna för att kompensera för kostnader. Dessutom kan avlägsnande av vild fisk också påverka de naturliga bestånden och rekryteringen negativt. Även om vårt mål är att utveckla ett system där lokala bifångster används som foderingredienser, kan lokala eutrofieringseffekter och vattenföroreningar orsaka försämring av den lokala vattenkvaliteten.

Sammanfattningsvis anser vi att det finns en potential för uppfödningen av vildfångad fisk med lokala bifångster som foderingrediens. För att vara ekonomiskt genomförbart finns det ett behov av att utveckla utfodringssystem, minimera skadliga effekter av stress, och etiska och hållbarhetsaspekter som är viktiga för marknadsföring av sådana produkter.

Table of contents

1. Introduction

On a global scale, grow-out farming or conditioning of wild caught fish (capture-based aquaculture) is estimated to constitute around 20% of the world's total aquaculture production (Lovatelli and Holthus 2008). Except for short time storage over a few days, farming or conditioning of wild caught fish and shellfish is generally uncommon in Sweden (Ungfors & Lindegarth 2014). However, there are several potential advantages of farming wild born fish, such as a control of the production chain with a more steady supply, less discard of low value fish (by-catch), and better quality of fish products with increased and steady revenues (Ungfors & Lindegarth 2014). Better quality and revenue can be achieved by improving their condition, or to let the fish live until prices are higher. In Norway, conditioned wild cod can pay 30-45% higher price than at catch (Dreyer et al. 2008). Compared with traditional fish farms, rearing of wild caught fish terminates the needs for hatcheries that can be costly and technically challenging steps in the production chain. Wild fish farming is also a way for small-scale mixed fisheries to increase the value of the part of catches that have low value. Farming of wild fish could reduce the need to fish in order to achieve an acceptable income potentially improving working conditions, and at the coast produce fish without disturbance of seals and cormorants stealing the catch and/or destroying fishing gears. To reduce the risk of local eutrophication due to fish feeds, by-catches from local fisheries can be used to feed the farmed fish, or as a source for the fish feed, to circulate nutrients locally within a fishing and farming area instead of being discarded.

In this report, we investigate which wild fish species may be suitable for grow-out farming in Sweden, and synthesize knowledge from places where it has been tested. We also review potential welfare hazards associated with farming of wild caught fish, ethical and legal aspects of feeding by-catches, and identify the main knowledge gaps and constraints for developing farmed wild fish in Sweden today.

2. Farming of wild caught fish/shellfish in a bio-based circular system

Since the 1990's aquaculture has globally become an increasing important source of food and income as production has increased, whereas catches from wild stocks have stagnated (FAO 2016). Today aquaculture constitutes almost 50% of total aquatic animal production (including for non-human consumption) (FAO 2016). In Europe, most of the aquaculture occurs in *in situ* cages or ponds with domesticated strains born in hatcheries, the main exception is eel (Nielsen & Prouzet 2008). This may cause problems with escapees from cages (Olaussen 2018) and local eutrophication and pollution effects from increasing nutrient loads from the fish farms (Grigorakis & Rigos 2011; Edwards 2015). At the same time, parts of catches of wild fish, i.e. by-catches and residues are not used for human consumption due to low economical value because of undesirable size (usually too small), lean, or just a species with low market value (Cashion et al. 2017). Adding value to current low value fish products could result in better sustainable use of both natural resources (wild stocks) and income to fish producers.

Farming of low value fish with fish feeds based on local resources is one way to get a more efficient use of by-catches and residues that can improve income to fishing companies while avoiding problems of (in sea-based farming) escapees and eutrophication and pollution of aquatic habitat (Fig. 1). In addition, if local by-catches are available those can be a viable option as ingredients in fish feed for land-based farming. In this way, a larger part of the catch can be used instead of being discarded.

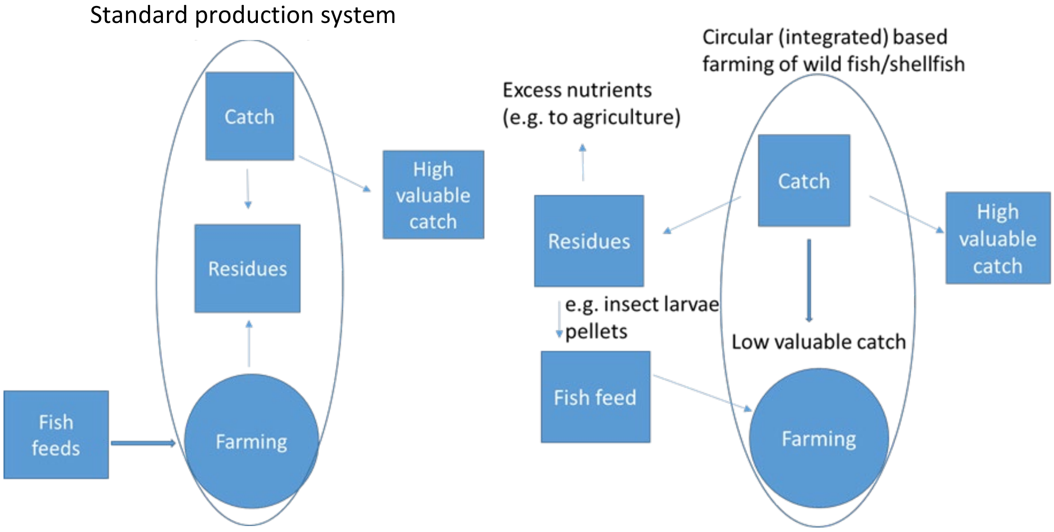

Figure 1. Schematic flow chart of biomass and nutrient in two systems: a conventional "modern" fish production system (left) and in an integrated farming system of wild fish/shellfish (right). The standard system: production of wild fish (Catch) is on a local scale separated from production in fish farming as feeds are based on external inputs from other ecosystems. The circular system: low valuable fish and residues from wild catches is transferred back to fish farming which become less dependent on external inputs.

From a *financial* point of view, a circular or integrated system, farming of wild fish and shellfish can contribute to fish producers' increased income in different ways. A larger part of the catches can be used since part of it can be sold later to a higher price than if sold at catch, thanks to improved quality through an additional feeding period. Further, some species are easy to catch at a specific time of the year, e.g. during spawning migrations, which may render a relative low price due to temporarily high supply or poor quality after spawning. Storage of wild fish and selling it at another time with less supply and higher prices could therefore smooth out and increase yearly revenues.

Farming wild fish and shellfish, however, comes with certain costs, which differs between farming methods and species (Ungfors & Lindegarth 2014; Wikberg & Wikner 2014). There will be additional costs for feed, but also for infrastructure and time for feeding attending the cultures. In addition, there are challenges regarding how to get wild fish to eat commercial fish feeds (Sæther & Bogevik 2017), stress responses to being in relative high densities in cages/tanks/ponds. There is also an increased risk of spread of diseases in cultures as wild individuals may carry pathogens, which may also increase the risk of spreading infectious diseases to the wild fish populations (Shea et al. 2020).

Also from an *ecosystem* perspective, there can be positive effects of farming of wild fish fed with locally originated feeds. In particular, a larger part of the catch can be used and not discarded. For some species, it may be possible to use only males and put back females to ensure reproductive potential of wild stocks. Additionally, when catching fish or shellfish for farming, the fishing procedure and handling of fish have to be selective and gentle, otherwise the fish would become injured or die (Olsen et al. 2012) Suitable fishing gears for this would likely be fish traps, fyke-nets and seines. Another positive side-effect would be that these fishing gears tend to have lower by-catches of seabirds and sea-mammals than for example gill-nets (Vinther 1999; Österblom et al. 2002; ASCOBANS 2012).

Finally there are some *ethical, legal* and *sustainability* issues that need consideration. As to the latter, farming of wild fish aims to improve fish growth it will likely be more effective to start farm smaller fish that may not be matured. This means that the wild but farmed fish may never be able to reproduce, which contradicts the principle that minimum size of catch should be larger than size at maturity to avoid impaired recruitment (ICES 2017). Thus, it is important to ensure that the catch of premature fish in an area is not so large that it will affect the reproductive potential of the stock. It is not possible to provide any recommendation of how much that is, which hence needs to be judged from case to case. Further, there are both ethical and legal issues related to holding wild fish and potentially feeding them with live fish, some of which are high-lighted below (section 3 and 5.2).

This report aims to identify research and development required to overcome these issues with farming of wild caught fish and shellfish in a circular bio-based production system.

3. Legal aspects

Before starting a grow-out farm with wild fish there are several ethical and legal aspects to consider. A common factor for most successful species in aquaculture, much in parallel with other livestock, is that the animals used have a long history of breeding programs where specific traits, e.g. high stress tolerance and growth, have been selected for, making them better suited for a life in a farm. As this is impossible when considering grow-out farm with wild fish the suitability of the candidate species needs to be evaluated and some species will be more difficult to keep than others. Another obvious parallel is that once a fish is kept in captivity they are also covered by the legislation in the Swedish Animal Welfare Act (SFS 2018:1192). This means they 1) should be treated well and protected from unnecessary suffering and disease (Chapter 2, section 1), and 2) accommodated in an environment that is appropriate and promotes health and permit natural behavior (Chapter 2, section 2).

In addition, all aquaculture in Sweden is obliged to follow several different legislation acts and permits (Svenskt Vattenbruk 2018). According to the Swedish Fishery Act (1993) a permit is required to set out or move fish in order to prevent invasions of non-native fish and transmissions of diseases. For farming of the wild born fish considered here, this is not a major problem as the farmed fish comes from local catches.

Aquaculture that uses more than 40 tons fish feed per year require, according to the Environmental Protection Act, a full environmental assessment, which can be substantial (Svenskt Vattenbruk 2018). With < 40 tons of feed per year, only a notice to the local municipality is required. This applies irrespective of form and origin of fish feed. A more thorough overview over permits required in Sweden is available in Ungfors & Lidegarth (2014).

The Swedish Board of Agriculture is responsible for regulations regarding animal welfare and prevention of diseases in aquaculture. This is the same for all aquaculture irrespective whether fish or shellfish originate from hatcheries or the wild. The Swedish Animal Welfare Act (SFS 2018:1192) requires that all farmed animals must be continuously controlled and monitored for well-being and a number of diseases (Svenskt Vattenbruk 2018). It is the Administrative County Boards that judge that standard is high enough to ensure good welfare for all farmed fish, irrespective if from hatcheries or the wild. Because wild fish mainly feed on living prey in the wild, a feed based on living prey could eventually facilitate the transition to farming conditions and, subsequently, to a feed based on dead prey or commercial feeds. This is, however, not allowed as there is a clear statement from the Swedish Board of Agriculture (2010) that live feeds (of vertebrates) is forbidden for animals, including feeds for wild animals (Swedish Board of Agriculture 2005). Thus, even adding living prey to augment densities of a species under natural like conditions is forbidden. However, naturally occurring prey in areas where farmed fish has been artificially augmented is today likely legal as long as the prey is not forced and can escape, for example through a mesh.

Finally, the Swedish Board for Food Safety controls that the slaughtered fish is not contagious and is the same irrespective of the origin of the fish product. From a legislative perspective there is no major difference between farming domesticated strains or wild born fish. However, that fish are wild born will need to be considered from a welfare perspective that may require specific adaptions relative farming of domesticated strains.

4. Previous experience of farming of wild fish

Cod is the species where farming of wild fish has been most extensive in Northern Europe (Ungfors & Lindegarth 2014), of which most have occurred in Norway (reviewed in Sæther & Bogevik 2017). This is a relative short term farming (< 12 weeks) that is more to consider as a live storage or conditioning of cod for marketing reasons. Common feeds is smaller fish like herring and capelin that is common and inexpensive to use.

A major issue for farming of wild caught cod has been to get them to start eating the feed (including fish) and it can take 3-4 weeks before they start eating the provided feed (Sæther & Bogevik 2017). To use them with a feed it is better to provide them small portions of feeds frequently than single large feeds (Sæther & Bogevik 2017).

Trials with dry feeds suggest a poor willingness for ingestions, and experiments have been terminated because cod did not feed on the provided feed (Sæther & Bogevik 2017). Consistence and texture of the feed seems important, when dry feeds were soaked in water ingestion increased, which however, can increase the feed residue as soaked feeds dissolve in the water. Still fewer ate the softened feed relative a fish eating control group and they grew slower (reviewed in Sæther & Bogevik 2017). Thus, wild caught cod accept fish to a higher degree and grew faster than when fed dry or soft feeds. Cod in general require a feed rich in protein as they have difficulties digesting fat and carbohydrates (Sæther & Bogevik 2017).

Although stress or general welfare seems not to have been explicitly studied, there are observations of "welfare" diseases of wild caught cod in farming systems, such as enlarged liver (Sæther & Bogevik 2017). In experiments, cod fed with energy rich food (minced herring) had lower utilization and uptake than cod fed with whole fish, although they grew similar. Sæther & Bogevik (2017) conclude that cod should have a feed including less energy-rich tissue (i.e. whole or chopped fish) for the cod's stomach to "work with" for an efficient digestion of the feed.

In conclusion, Sæther & Bogevik (2017) identify two main issues for getting profitability of farming of wild caught cod: 1) Getting wild caught cod to start feeding, and, 2) availability and price of this is prone to changes between seasons and years. A more predictable feed that cod readily accept early in the farming phase is required for improved farming, and preferably with a feed allowing automated feeding.

In a pilot study of farming of wild caught cod on the Swedish west coast in a land-based recirculated aquaculture system (RAS) there was an initial problem with high water temperatures (Ungfors & Lindegarth 2014), and a cooler water was required. Smaller cod were especially sensitive to the handling and transport from the gear to the RAS facility. High mortalities (> 2/3 of the cod died) during the trial was observed, which is thought to be an effect of the salted tap-water used, mortality ceased when sea water was used instead (Ungfors & Lindegarth 2014).

In this trial at the Swedish west coast, cod was fed frozen shrimps and small herring, and some individuals seemed to start eating whereas other seemed reluctant to this food. Shrimp seemed to be much preferred over herring, but the study could not estimate weight increase as too few cods were used and they were sensitive to handling at the onset of the trial (Ungfors & Lindegarth 2014). They concluded that it is important to use cod of similar size to avoid larger cod preventing smaller from feeding, as well as avoiding cannibalism.

Some conclusions regarding farming of wild caught cod based on previous studies are: 1) Collect and handle cod in cooler water condition, i.e. avoid summers, and ensure cooler water as they are sensitive to water temperatures > 15°C. 2) Smaller (unclear to what size) cod are more sensitive to handling and transport than larger cod, 3) An efficient feeding system is required to ensure high and stable growth of cod at a low cost that also must facilitate the cod to start eating on the feed. Economical calculations suggests that the economic feasibility for RAS farming of wild caught cod at the current situation is low, unless substantially higher prices can compensate for the costs (Wikberg & Wikner 2014).

5. Potential risks and problems – needs for future research

Besides the obvious problems of getting wild caught fish and shellfish to eat, grow and survive to a reasonable cost to ensure fish products can be sold with profit there are several risks and ethical issues related to farming of wild fish.

5.1. Farming and stress in wild fish

Captivity of wild fish may be stressful to the fish as they are used to swim large distances and some species (e.g. pike) are solitary and may rarely encounter conspecifics, but in captivity densities would increase substantially and social interactions as well. Although a higher supply of food may partly result in decreased aggressive interactions among individuals, stress levels tend to increase with density in fish farms (Conte 2004). It is therefore important to follow up on how stress levels change over time and relates to control groups.

5.2. Ethical aspects

Fish and shellfish production is related to a number of ethical challenges such as i.e. overfishing, biodiversity loss, by-catch and discard, eutrophication, working conditions, food security (reviewed by Eurogroup for Animals 2018). Further, a number of fish welfare issues are at stake, such as suffocation in wild catch, transport, stunning and slaughter in aquaculture. Hence, on a general ethical note, the entire practice of fish production for human consumption can be questioned. Some positive effects such as beneficial health effects of fish consumption (Omega 3), employment and livelihoods through small-scale fisheries however may be regarded as a chance to balance the negative effects (Röcklinsberg 2015). Considering wild caught fish farming some of these challenges remain, but there is also a set of specific ethical challenges to be considered (see Röcklinsberg et al. 2019).

A *first* issue of wild caught fish farming is related to the possibilities of making a livelihood as fishers. Keeping wild caught fish until they have either an ideal size, or the market demand is high, may lead to increased price control, thanks to choice of time period for slaughter and choice of target species, and thereby reducing price fluctuation and meeting consumer demands, and thus improving the fishermen livelihood situation. Their situation may also be improved by the possibility to choose more freely, and related to weather conditions, when to go out fishing.

A *second* ethically relevant point is the welfare of the individual fish. Wild fish have the full freedom of moving and interacting, or not interacting with other individuals, but also the risks of being prayed on, or lack of suitable food. Once caught and caged their spatial freedom is restricted. If they start to feed, however, food is available without much effort. These aspects can be ethically weighed in different ways largely depending on whether the value of 'freedom to move and interact' or the value of 'being satisfied, i.e. basic health' is given priority. Both are relevant aspects of the concept of animal welfare, whereby the former is linked to possibilities to perform natural behavior and the latter to biological function, or health. The third standard aspect of animal welfare, affective state or subjective experiences, is then still missing, but should be included in an overall welfare assessment, albeit much more difficult to assess in fish than in mammals. Its relevance is clear when considering the difference between domesticated and wild fish. The latter are adapted neither to confinement induced stress nor standard feed, and they are not used to high densities or handling, and normally eat living prey.

To feed with live feed would not only be legally prohibited in some countries, but also evokes a *third* ethical concern. Is it ethically justified to farm one wild fish species with live feeds of another species (e.g. fish/insect)? Depending of species the necessary welfare conditions can be met in a better or less good way, but the principal issue of feeding with living prey, and hence inducing stress in some individuals, for the sake of keeping others alive is relevant to pose. Further, it evokes sustainability (mainly environmental and economic) concerns. On the other hand, feeding is a necessary condition for high welfare of wild caught fish as they would otherwise starve, and for some species (e.g. pike) feeding with processed feed, such as pellets is difficult. Some species (e.g. whitefish and perch) are likely more prone to accept insect based feed, which relates to a *fourth* issue; what feed, if not living prey, is ethically sustainable and justified?

Many insects such as black soldier fly (*Hermetia illucens*), crickets (e.g. *Gryllus bimaculatus*) and meal worms (*Tenebrio molitor*) are high in protein, and some also low in fat, with a much lower climate impact than other animal based protein sources, and hence increasingly proposed for human consumption. Hence, the general ethical challenge of feeding fish with food suitable for human consumption has not been solved.

Benefits in terms of improving fish farmers' situation, and the improved health of fed fish have to be weighed against these mentioned ethical concerns as well as against the risk of diseases, but a deeper ethical analysis will be needed to elaborate on these issues in more detail.

5.3. Feeds

Earlier attempts of farming wild fish have suffered from the problem to get the wild fish to start eating in captivity. The wild fish we analyse here are mainly feeding on living fish prey (piscivores). Therefore, feeding with their natural prey (incl. invertebrates) may be required, at least, initially. However, this can be expensive and it is ethically and legally questionable to feed living prey to farmed fish as prey will have little or no way to escape predation and might be very stressful for prey before they become consumed. It is also risky from a parasite transmission perspective.

If natural prey, preferably dead, can be given only periodically while the wild fish get used to other feeds it can be relative cheap method to start feeding the fish. Instead of a feed based on natural prey, an alternative would be to use the local by-catches as an ingredient for the fish feed. Previous examples show that there may be problems getting wild fish to start feeding on artificial feeds. An alternative is to use the fish meal from local by-catches as fodder for insects, which are then used as feed for the wild fish. Insects and insect larvae, depending on life stage and substrate grown on, can have a protein and lipid content very similar to the requirements of some carnivorous fish species (Nogales-Mérida *et al.*, 2018).

Our aim is that the feeds in the farming of wild caught fish should be based on local by-catches or residues to have a circular nutrient flow to mitigate eutrophication and pollution from farming. However, investigations are needed in order to evaluate which fish species of by-catches, or combination of species, can be suitable for use in feeds or as substrates for feed.

Important aspects to consider are if one type of by-catch is more suitable for handling and fish growth than others and if there are seasonal variation in possibility and condition of by-catches. Suitable species for feeds in coastal areas may be herring and sticklebacks that are abundant pelagic species, high in fat content but have seasonal occurrence at the coast. Sticklebacks are not generally caught in any larger quantities as a by-catch because of their small size, but a reduction fishery has been proposed (Bergström et al. 2015). Cyprinids (e.g. roach, bream, bleak), sculpins and gobids are other species with low commercial value that can be used as a substrate for fish feeds. An especially interesting species to study as a substrate for fish feed is the round goby (‘*svartmunnad smörbult*’), an invasive species that has increased exponentially in some parts of Swedish coastal waters (Hallin 2014). A fishery targeting round goby could prevent potentially negative effects of the round goby on native species.

5.4. Diseases

Wild fish and shellfish are carriers of a number of naturally occurring pathogens in fish (Pettersen et al. 2015). Substantially increasing densities may risk in increased pathogen transmission causing increased pathogen prevalence and abundance among farmed fish that can result in poor growth and quality and increased mortality. On the other hand, the ability to treat and control feeds such that it is pathogen free may lower the incidence of some especially food-borne pathogens.

It is not studied how diseases may be regulated and spread in explicitly farming of wild born fish, but there are several studies showing that increasing fish density increase disease spread (reviewed by Krkošek 2010, 2017). Risks of disease outbreaks, which can substantially diminish production, is though, an important issue to consider and study in the future.

5.5. Eutrophication and pollution

One obvious problem with any type of *in situ* farming is local eutrophication effects and pollution. As fish must be fed there will be a local increase in nutrient flows at the site of the farming. Here we suggest to generally try to delimit this problem by using by-catches from the surrounding area as the main ingredient in the fish feed to circulate nutrients at a regional scale. However, some local eutrophication can come to occur as nutrients become concentrated to one site. Using sites that are deeper, exposed to some waves or currents can dilute nutrients over larger water volumes and mitigate local eutrophication and pollution (Edwards 2015; Olaussen 2018).

It can therefore be necessary to study water quality (nutrient levels and absorbance) and local eutrophication effects, increased abundance of primary producers, in transects from the farming site. Water quality is easily measured from a water sample, and eutrophication effects can be estimated by measuring biomass of primary producers (algae) on bottom attached tiles over a season or plastic bands in the water column over a couple of weeks.

Semi-enclosed farming of fish in sea-based cages that collects residues of feeds and faeces reduces nutrient leakage and pollution, although solved nutrients will still be released. However, investment costs are high and currently this method is mainly considered suitable for relative large faming facilities (> 1000 ton/year), but technical developments may increase the use of semi-enclosed farming also for smaller facilities (Ungfors & Lindegarth 2014).

A solution for minimizing eutrophication and pollution from aquaculture is so called "Multi-trophic farming", i.e. culturing of different species are integrated in the same farming system. One such example is aquaponics where fish/shellfish and plants are farmed in the same facility so that plants can use the residues from the fish. Other configurations are possible where one species "clean" the water of residues (e.g. algae, mussels) from the farmed species to minimize the outflow of nutrients and pollutants from a farming facility. However, today there is no such specific system available for farming of wild caught fish, but could of course be an option if possible.

6. Potential stocks of wild fish feasible for farming (target species)

We here identify some species and areas where we think a farming of wild fish can potentially be economically and ecologically sustainable.

6.1. Cod (*Gadus morhua*)

We see the potential for farming of wild cod as being good, if the problems are solved regarding handling, feeding systems, and economy. The cod in the eastern Baltic stock have shown a decline in condition during the last decades (Limburg & Casini 2019). Fishers are also struggling with seals damaging both fishing gear and catches. There is an ongoing pilot project in Blekinge led by SLU Aquatic Resources, together with a fisher, to enhance small-scale coastal fisheries. Lean cod with a low or none commercial value are caught in seal safe cod pots and traps, which not only prevents seal damages but also minimizes injures on fish due to gear use, compared to nets and trawls. Fish are stored in sea pens and fed for two months with locally caught herring. By using a locally caught feed the transport of nutrients is kept on a small local scale, and the fishermen are given a possibility to get an economical return using their bycatch, which is normally thrown back in the sea. Preliminary analyses show that cod start eating only after a few days in the sea pens. On average around 50 individuals per sea pen, with a starting biomass of about 30 kg, are fed every second day (if weather allows) with 1-2 kg defrosted herring cut in 1-2 cm pieces. After 54-70 days in the pens, without exploring biological and temporal differences, surviving cod have on average increased 193 grams (38%) in body mass with a high variability and 1.8 cm in length. There were problems with mortality due to high temperature and at one occasion also a disease, which had to be handled.

Even if there was a low economical profit, the fisher would have liked to continue if not a fishing ban on cod had taken place. The amount of feed was of the same size as the final outcome of cod in good condition with high commercial value, which increased the fishers' economic turnover (Lunneryd et al. in prep). One challenge is to develop a feed that is high in protein that cod accept early on and can be distributed automatically in the feeding system to lower labour costs.

6.2. Perch (*Perca fluviatilis*)

Perch is an abundant fish species in many lakes and along the Baltic Sea coast, and is popular for human consumption. However, large part of the perch biomass constitutes perch that is too small for human consumption, and perch is easiest to catch during spawning migration in spring. Therefore, farming of smaller individuals and perch from spring migration during summer can be one way forward to increase income from perch fisheries.

Perch is generally a robust species that survive handling and treatments, and is readily used for experimental purposes, where survival of juvenile perch and older is above 90% (Fontain et al. 1997). However, there have been previous attempts of farming perch (from a hatchery) on a small but commercial scale, but has not been entirely successful. According to the farmers the main problem is that the profitability has been low relative other species because of their relative slow growth. One way to improve growth could be to replace conventional feeds with fish feed based on insect larvae as an interesting approach that may result in lower initial loss due mortality and faster growth.

A potential interesting case is perch fisheries in the Bothnian Bay where vendace (siklöja) fishery is the main source of income but very limited in time (sept-oct), and results in large amount of residues as only the roe is used for human consumption. Here a potential circulation of fish products could be that the vendace residues in fall is processed to fish feeds during winter, eventually by using it as food for insect larvae that is formed into a fish feed, see below. During spring perch is caught in fish traps or fyke-nets and farmed during summer and fall with the fish feed, and to be sold during winter when prices are higher due to short supply.

In a pilot project at Forsmark wild caught perch had survival rates >95% when experimentally fed with insect larve of the black soldier fly or flour beetles, which was much higher compared to when fed a traditional fish feed pellets (Östman, unpubl.). However, in this study perch did not grow well and further development is needed.

6.3. Whitefish (*Coregonus lavaretus*)

In Lake Vänern whitefish has high levels of dioxin and are not allowed to be sold, but the stop in whitefish fisheries has resulted in an increased abundance of whitefish. One way to mitigate the problem of high levels of toxins may be to farm the whitefish and feed them with detoxified feeds. In general for hydrophobic substances, as dioxin, the main bioaccumulation occurs through the diet in contrast to hydrophilic chemicals where food is less important (Hall et al. 1997; Mackay & Fraser 2000). Estimates show that more than 85% of the hydrophobic toxins in fish comes through the food pathway (Hall et al. 1997). Therefore it is, in theory, possible to feed whitefish with non-toxin feeds *in situ* cages.

One possibility is to farm whitefish large enough for sale to get a reduction in dioxin levels under threshold levels. Currently, nothing is known about how fast dioxin may leave the body of whitefish. Estimates on lean fish (like carp) show reduction time for a 50% reduction of dioxin can be several hundreds of days (Kuehl et al. 1997). The first step would be to monitor toxin levels in wild whitefish from Lake Vänern when fed on a non-toxic diet, and if the process can be speeded up by for example starving them first. Ideally, whitefish would be fed with feeds based on resources originated from Lake Vänern to avoid eutrophication, but as this may be toxic and involve extra costs to extract, an external input feed can be considered. Alternatively, if the time for toxin reduction is large, it may be a better option to farm smaller sized whitefish on a toxin-free diet and let them growth in cages such there is a dilution of toxins in the body.

Previous experience have shown that whitefish are relative sensitive to handling and need to be caught in traps or fyke-nets to not be injured. Besides that whitefish is considered to be a species that is relatively easy to farm and accept feeds and there is a commercial farming of whitefish especially in Finland (Kankainen et al. 2016). Pilot studies could be done in experimental facilities, for examples at SLU Dept. Aquatic Resources at Drottningholm.

6.4. Pike (*Esox luscius*)

In lakes and along the Baltic Sea coast may pike be an interesting species for farming, either as food or as a conservation action to regain larger pike (Berggren et al. Unpubl.). With static gears, like fyke-nets, catches are highest during their spawning migration in spring. Farming of pikes could therefore be a way to even out the incomes over the year and also get a higher price in autumn and winter when there is less supply of pike. What may be a problem for farming of wild pike is that it may require a feed of living fish, or at least food items that resembles living fish. Also cannibalism will likely be a problem but little is known about farming of pike.

The status of pike stocks are variable and in many areas there are activities to support local stock with restocking of young pike. However, the scientific evidence suggest this to be an inefficient way to improve stock status, but also that the larger they are the more likely stocking is to have an effect (Guilleraut et al. 2017). An alternative method could therefore be to rear juveniles to larger size before stocking them. This would clearly introduce new problems of how to feed them and potential domestication of behavior but could be interesting to investigate further.

6.5. Pikeperch (*Sander lucioperca*)

In some larger lakes and coastal areas pikeperch is of economic importance for fishing companies due to the high price. In the great lakes Mälaren and Hjälmaren new fishing regulations have resulted in a substantial increase in stock sizes and profitability is so high that farming of pikeperch cannot be considered as commercially feasible. However, at the coast, stock status is generally poor, mortality high and local fishing bans are discussed. Thus, for the coastal areas it could be interesting to farm pikeperch because of the relative high price and use local by-catches of cyprinids as ingredient in the feed. One evident problem though is the poor status of many coastal pikeperch populations making it difficult to catch substantial number of pikeperch to farm, which may threaten natural populations. However, there are pikeperch larvae from freshwater available that could be used in farming, but as pikeperch display a strong local genetic structure there is an evident risk that escapees from an *in situ* farming could have negative genetic effects on local pikeperch populations.

Pikeperch has been stocked in several sites along the coast but seem to have a low success. Also for improved stocking success farming of pikeperch could be a potential alternative if it is possible to farm them to larger sizes without losing wild behavior. Farming for stocking must, however, be done on individuals from a local stock to avoid introgression and outbreeding effects in local adapted pikeperch populations.

6.6. Other species

There are pilot studies and projects of other species for farming of wild individuals that we have not explicitly considered here but we think is worth mentioning. At Gothenburg University there is a developmental project for farming wolffish (or catfish, mainly the spotted wolffish *Anarhichas minor*). Also several species of shellfish (oyster, mussels, crayfish, Norwegian lobster, European lobster) are currently being investigated as farm animals.

7. The future for farming of wild fish and shellfish

Although there are obvious advantages of farming wild caught fish and shellfish, many issues and problems must be solved, including taking ethical and welfare concerns into consideration as well as fulfilling legally claims. In this overview we try to identify the most prosperous species to work with in Sweden (focusing mainly on the Baltic Sea and lakes), but for farming of wild fish to be commercially, and ecologically, viable there is a clear need for developing farm and feeding systems in tight collaboration between researchers and fishermen/women.

There is already much infrastructure and facilities available for conducting research and development of farming of wild caught fish. Regarding research facilities the department of Aquatic resources at SLU has several experimental ponds and large outdoor tanks at Drottningholm that can be used to study growth and interactions. This facility is located by Lake Mälaren and is hence mainly suitable for freshwater species. The same department also has a research station at the Biotest basin outside the Forsmark nuclear power plant that is suitable for sea-based experiments and studies.

The Department of Aquatic Resources has an extended network with fishers that can be useful for implementation studies and small-scale production trials. This network is also important to have access to fish based substrates for fish feeds in captivity. The Department of Animal Nutrition and Management at SLU has the knowledge and facilities for producing fish feeds and assessing quality, an important step to develop fish feeds from local by-catches suitable for farming of wild fish, whereas the department of Animal Environment and Health at SLU has facilities for measuring stress and welfare of fish, as well as performing a continued and deeper ethical analysis.

In this review we have identified several issues that need to be addressed. In our view, none of these issues should be impossible to overcome but will require substantial development work. In the end, the future for farming of wild caught fish is all about whether it is possible to ensure the welfare and improve the value of the farmed fish/shellfish relative the value in the catch and the additional cost for the extra work In general, there is a trend of many consumers being willing to pay a high price for a local product with a high quality which improves the equation.

References

ASCOBANS. 2012. *Strategies for the Prevention of Bycatch of Seabirds and Marine Mammals in Baltic Sea Fisheries*. 19th ASCOBANS Advisory Committee Meeting Galway, Ireland, 20-22 March.

Bergström, U., Olsson, J., Casini, M., Eriksson, B.K., Fredriksson, R., Wennhage, H., Appelberg, M. (2015). Stickleback increase in the Baltic Sea – A thorny issue for coastal predatory fish. *Estuarine, Coastal and Shelf Science* 163: 134-142.

Board of Agriculture (2010). *Om utfodring av levande djur*. Internet: https://www.jordbruksverket.se/download/18.32b12c7f12940112a7c80006315/1370041089149/Levande%20F%C3%B6da%2031-6812-10.pdf. [Visited: 2018-11-28]

Cashion, T., Le Manach, F., Zeller, D., & Pauly, D. (2017). Most fish destined for fishmeal production are food-grade fish. *Fish and Fisheries* 18: 837-844.

Conte, F.S. (2004). Stress and the welfare of cultured fish. *Applied Animal Behaviour Science* 86: 205-223.

Dreyer, B.M., Nøstvold, B.H., Midling, K.Ø. and Hermansen, Ø. (2008). Capture-based aquaculture of cod. In Lovatelli, A. & Holthus, P.F.E (eds Capture-based aquaculture. Global overview. *FAO Fisheries Technical Paper*. Rome. No. 508: 298.

Edwards, P. (2015). Aquaculture environment interactions: past, present and likely future trends. *Aquaculture* 447: 2-14.

Eurogroup for Animals. (2018). *Looking Beneath the Surface: Fish Welfare in European Aquaculture*. Available at: https://www.eurogroupforanimals.org/sites/eurogroup/files/2020-02/Fish-Welfare-in-European-Aquaculture-2.pdf [visited 2021-02-24].

FAO. (2016). *The State of World Fisheries and Aquaculture 2016*. Contributing to food security and nutrition for all. Rome. 200 pp.

Fontaine, P., Gardeur, J. N., Kestemont, P., & Georges, A. (1997). Influence of feeding level on growth, intraspecific weight variability and sexual growth dimorphism of Eurasian perch *Perca fluviatilis* L. reared in a recirculation system. *Aquaculture* 157: 1-9.

Grigorakis, K., & Rigos, G. (2011). Aquaculture effects on environmental and public welfare – The case of Mediterranean mariculture. *Chemosphere* 85: 899-919.

Guilleraut, N., Hühn, D., Cucherousset, J., Arlinghaus, R., Skov, C. (2017). Stocking for pike enhencement. In (eds. Skov & Nilsson): *Biology & Ecology of the pike*. CRC Press, Boca Raton, Florida.

Hall, B.D., Bodaly, R.A., Fudge, R.J.P., Rudd, J.W.M. and Rosenberg, D.M. (1997). Food as the dominant pathway of methylmercury uptake by fish. *Water, Air, and Soil Pollution* 100: 13–24.

Hallin, A-K. (2014). Svårt stoppa flytande invasioner. *Mijlötrender – Invasiva arter*. SLU, Uppsala.
ICES (2017). *Technical Guidelines - ICES fisheries management reference points for category 1 and 2 stocks*. DOI: 10.17895/ices.pub.3036.
Kankainen, M., Setälä, J., Kause, A., Quinton, C., Airaksinen, S., & Koskela, J. (2016). Economic values of supply chain productivity and quality traits calculated for a farmed European whitefish breeding program. *Aquaculture Economics & Management* 20: 131-164.
Krkošek, M. (2010). Host density thresholds and disease control for fisheries and aquaculture. *Aquaculture Environment Interactions* 1: 21-32.
Krkošek, M. (2017). Population biology of infectious diseases shared by wild and farmed fish. *Canadian Journal of Fisheries and Aquatic Sciences* 74: 620-628.
Kuehl, D. W., Cook, P. M., Batterman, A. R., Lothenbach, D., & Butterworth, B. C. (1987). Bioavailability of polychlorinated dibenzo-p-dioxins and dibenzofurans from contaminated Wisconsin River sediment to carp. *Chemosphere* 16: 667-679.
Laikre, L., Palm, S., & Ryman, N. (2005). Genetic population structure of fishes: implications for coastal zone management. *AMBIO* 34: 111-119.
Limburg, K. E., & Casini, M. (2019). Otolith chemistry indicates recent worsened Baltic cod condition is linked to hypoxia exposure. *Biology Letters* 15: 20190352.
Lovatelli, A. & Holthus, P.F.E. (2008). Capture-based aquaculture. Global overview. *FAO Fisheries Technical Paper*. Rome. No. 508: 298.
Mackay, D. & Fraser, A. (2000). Bioaccumulation of persistent organic chemicals: mechanisms and models. *Environmental Pollution* 110: 375-391.
Nielsen, T., & Prouzet, P. (2008). Capture-based aquaculture of the wild European eel (Anguilla anguilla). Capture-based aquaculture. Global overview. *FAO Fisheries Technical Paper* 508: 141-168.
Nogales-Mérida, S., Gobbi, P., Józefiak, D., Mazurkiewicz, J., Dudek, K., Rawski, M., Kierończyk, B. & Józefiak, A. (2018) Insect meals in fish nutrition. *Reviews in Aquaculture* 11: 1080-1103.
Olaussen, J. O. (2018). Environmental problems and regulation in the aquaculture industry. Insights from Norway. *Marine Policy* 98: 158-163.
Olsen, R. E., Oppedal, F., Tenningen, M., & Vold, A. (2012). Physiological response and mortality caused by scale loss in Atlantic herring. *Fisheries Research* 129: 21-27.
Österblom,H., Fransson,T. & Olsson,O. (2002). Bycatches of common guillemot (*Uria aalge*) in the Baltic Sea gillnet fishery. *Biological Conservation* 105: 309-319.
Pettersen, J. M., Rich, K. M., Jensen, B. B., & Aunsmo, A. (2015). The economic benefits of disease triggered early harvest: a case study of pancreas disease in farmed Atlantic salmon from Norway. *Preventive Veterinary Medicine* 121: 314-324.
Röcklinsberg, H. (2015) Fish Consumption: Choices in the Intersection of Public Concern, Fish Welfare, Food Security, Human Health and Climate Change. *Journal of Agricultural and Environmental Ethics* 28: 533-551.
Röcklinsberg, H, Gräns, A., Kornum, A. and Gjerris, M. (2019). Ethical aspects of fish farming. In: Vinnari, E and Vinnari M. *Sustainable governance*

and Management of food systems. Ethical perspectives. Wageningen Academic, pp: 267-272.
Sæther, B-S. & Bogevik, A.S. (2017). Kunnskapsstatus; fôr til villfanget, levendelagret torsk. *NOFIMA Rapport 6/2017*. ISBN: 978-82-8296-488-3.
Shea, D., Bateman, A., Li, S., Tabata, A., Schulze, A., Mordecai, G., ... & Krkošek, M. (2020). Environmental DNA from multiple pathogens is elevated near active Atlantic salmon farms. *Proceedings of the Royal Society B* 287: 20202010.
Svenskt Vattenbruk. (2018). *Lagstiftning*. Internet: http://www.svensktvattenbruk.se/amnesomraden/attdrivavattenbruk/lagstiftningtillstand/lagstiftning.4.72cfa6d614df7504e82d867f.html. [Visited 2018-11-28]
Swedish Board of Agriculture (2005). *Anpassningar till nya EG-bestämmelser om livsmedel, djurhälsa, foder, djurskydd och växtskydd m.m*. Regeringskanliet Ds 2005:31. ISBN: 91-38-22404-06.
Swedish Fishery Act [*Fiskeklag*] (1993). *SFS- 1993:787*. https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/fiskelag-1993787_sfs-1993-787.
Swedish Law on Animal Welfare [*Djurskyddslagen*] (2018). *SFS- 2018:1192*. https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/djurskyddslag-20181192_sfs-2018-1192
Ungfors, A. & Lindegarth, S. (2014). *Småskalig marin fiskodling och Levandelagring-Beskrivning av teknik och ekonomi*. Samförvaltning Norra Bohuslän.
Vinther, M. (1999). Bycatches of harbour porpoises (*Phocoena phocoena* L.) in Danish set-net fisheries. *Journal of Cetacean Research and Management* 1:123-135.
Wikberg, D. & Wikner J. (2014). *Möjlighetsstudie för småskalig,miljöanpassad marin fiskodling i kustvatten ekonomisk – beräkningsmodell*. Vattenbrukscentrum Norr AB.