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Aquaculture of coregonid species — *quo vadis*?

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Whitefish is well-known for its delicious meat and consumers are willing to pay high prices for it, but local supply is often limited due to fluctuating or declining catches. It is thus expected that whitefish aquaculture production should increase to help meet the demand, provided that insufficient knowledge or other roadblocks do not interfere. Here we use a literature review, expert interviews, and case-study approach to understand the existing knowledge, current production levels, and limitations of whitefish aquaculture in individual countries. As shown through the literature review, there is sufficient technical knowledge to scale-up whitefish production. However, interviews with several experts point out different factors hindering aquaculture production: strict environmental regulations, established production of other freshwater species, and possible competition with fish imports. The failure to establish whitefish aquaculture in Lake Constance underlines this outcome, as there is nearly no chance to establish whitefish aquaculture in this area despite very high demand paired with drastically decreasing supply from capture-fisheries. As a result, at least 50% of whitefish consumed at Lake Constance are imported. This case highlights a common pitfall in environmental management: decisions to forego or reduce local production often results in replacing a product of exceptionally high sustainability (locally produced fish) with imports from other countries.

Introduction

Coregonids have a circumpolar distribution with a considerable number of various ecotypes of high plasticity (Vonlanthen *et al*. 2012). However, because of multiple anthropogenic stressors, coregonid diversity is currently threatened worldwide (Turgeon *et al.* 1999, Vonlanthen *et al.* 2012), leading to declining populations and loss of diversity (Anneville *et al.* 2015). At the same time, consumer demands are high and increasing, resulting in a high economic value of whitefish for local fisheries and a robust market (Mickiewicz & Wołos 2012). Consequently, the development of decreasing stocks and increasing consumer demand provide an excellent basis for increasing whitefish aquaculture.

Much of the knowledge required to raise coregonids exists because of the production of stocking material to enhance coregonid fishery yield through increased cohort size or to stabilize fluctuating stocks. The first reports of rear-

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ing coregonid larvae for stocking purposes date back to 1867 in Finland (Salojärvi 1992) and to 1887 in Germany (Rösch 1993). The basis for farming coregonids (hereafter referred to as whitefish) stemmed from the experience and practical knowledge gathered during the production of stocking material and now, more than 100 years later, the aquaculture of whitefish is part of a growing industry in some countries (Paisley *et al.* 2010).

To eventually initiate whitefish aquaculture at Lake Constance, Germany, a four-year research project between 2011 and 2015 aimed to evaluate the possibility of rearing whitefish in Lake Constance, one of the largest lakes in central Europe. The project was locally motivated because whitefish yields had been decreased constantly since 2005 (Baer *et al.* 2016), while the local demand for whitefish consumption remained very high given the substantial local population and millions of tourists that visit the region each year. This situation resulted in high import of whitefish (40%–50%) to cover the demand (Dreßler 2013). The outcome of the project was that production of a local Lake Constance whitefish strain seemed to be a feasible option (Goebel *et al.* 2021), and that those farmed whitefish could effectively compete with wild whitefish in terms of product quality (Goebel *et al.* 2017b). Therefore, farming of whitefish represents a promising and ecologically sound approach compensating for the current catch decline in the whitefish fisheries of Lake Constance. However, until now no single whitefish aquaculture facility was built. As a consequence and with further declining catches (Baer *et al*. 2016), the high market demand for local whitefish is nowadays met mainly by imports.

The problems with establishing an aquaculture business in Lake Constance — even if general requirements are met (high demand, excellent market, and practical knowledge) — was the motivation for this analysis. Our goal was to identify the reasons for this failure and see whether this pattern restricted to Lake Constance or apparent in other regions as well. First, we review the development and level of knowledge regarding whitefish farming worldwide and identify some common pitfalls in whitefish production. Second, we present available data on aquaculture production and capture-based fisheries for whitefish and analyse possible similarities in other regions. Third, we describe the case of Lake Constance within this larger context. Fourth, we assess the *status quo* of whitefish aquaculture and identify potential reasons for its success or failure based on interviews with experts from countries where research in the field of whitefish aquaculture was carried out. Finally, using the information gathered in these steps, we discuss the future of whitefish aquaculture and related research.

Material and methods

In preparing this overview we used Google Scholar to search for papers applying the following key words: (1) whitefish, (2) coregonus or coregonid, (3) aquaculture, (4) rearing, and (5) artificial. The papers that were published on these topics between 1950 and 2019 were judged for relevance by inspecting their titles and abstracts. In addition, we included all papers dealing with aquaculture of coregonids and published in the proceedings of the previous International Symposia on the Biology and Management of Coregonid Fishes (ISBMCF).

To process the data, we used the Software for Fishery and Aquaculture Statistical Time Series (FishStatJ) developed by the Food and Agricultural Organization of the United Nations (FAO; http://www.fao.org/fishery/statistics/software/fishstatj/en). For the period 1998–2017, we selected the following variables: coregonids (in FishStatJ, European whitefish = *Coregonus lavaretus*, lake (= common) whitefish = *Coregonus clupeaformis*, and whitefishes nei = *Coregonus* spp. not elsewhere indicated), production area (country), and the way of production (aquaculture production or catches).

To analyse the case of Lake Constance, the available published papers, including grey literature and scientific reports, were gathered and summarized. Expert statements from local scientists and personal communications from fishermen, fish farmers, and fisheries managers were used to complement collected information.

Based on the literature information, we selected countries with relevant scientific activities in the field of whitefish aquaculture, and contacted experts on the subject from those countries by e-mail. After presenting an overview of the situation in Lake Constance, we asked them to describe the current state of whitefish aquaculture in their country, to identify reasons for the successful establishment or failure of whitefish aquaculture, and for their personal future expectations. The answers were sorted, condensed and then sent back to the experts for approval.

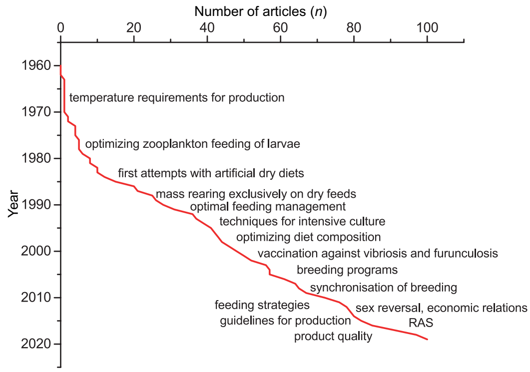

Fig. 1. Number of publications related to whitefish aquaculture and relevant milestones in the past 70 years.

Results

Literature review

In total, we selected 102 papers. The early papers dealt mainly with temperature requirements during the production process, and were published between 1963 and the mid-1970s in the United States (Christie 1963, McCormick *et al.* 1971, Colby & Brooke 1973, Edsall & Rottiers 1976). Those studies were made to improve enhancement fisheries without intention of developing a whitefish aquaculture industry. However, those papers were cited in other studies focused on rearing coregonids under aquaculture conditions and were therefore seen as a starting point. An international workshop on mass rearing of fry and fingerlings of freshwater fishes held in 1979 (Gunkel & Kausch 1979) was the basis for many subsequent studies about the use and necessary improvement of artificial feed for whitefish throughout Europe (e.g. Bogdanova 1980, Dabrowski *et al.* 1986, 1984, Medgyesy & Wieser 1982, Rösch & Appelbaum 1985). In consequence, after 1984 there was a sharp increase in the number of published papers (Fig. 1). In 1986, a large study in Canada made the next step by demonstrating that whitefish could be reared from fingerling to yearling sizes using only artificial trout feed, while keeping mortality below 3% until 14 months of age (Drouin *et al.* 1986). Other studies followed and demonstrated the possibility of feeding whitefish exclusively on commercial dry diets (Champigneulle 1988, Dabrowski & Poczyczyński 1988, Segner *et al.* 1988, Zitzow & Millard 1988, Harris & Hulsman 1991). In the 1990s and early 2000s, researchers focused on finding solutions to other obstacles to large-scale, production-oriented whitefish intensive culture [optimal feeding management (Koskela 1992, Koskela *et al.* 1997), diet composition (Ruohonen *et al.* 2003), rearing techniques (Harris 1992, Kozłowski *et al.* 2000, Enz *et al.* 2001), development of vaccines against vibriosis and furunculosis (Lönnström *et al.* 2001, Koskela *et al.* 2004)] which could be seen as an outstanding advance in whitefish aquaculture. All those studies led to a steady increase in the number of published papers (Fig. 1). In the following years, papers were published to further support whitefish culture and important suggestions for improvements were made in the field of breeding programs (Quinton *et al.* 2007, Szczepkowski *et al.* 2010, Kause *et al.* 2011), synchronisation of breeding (Svinger & Kouril 2014), feeding strategies (Känkänen & Pirhonen 2009, Siikavuopio *et al.* 2010, 2012, 2013, Leithner & Wanzenböck 2015, Esmaeilzadeh-Leithner & Wanzenböck 2018, Ostaszewska *et al.* 2018), product quality (Boiteanu *et al.* 2016, Suomela *et al.* 2016, Goebel *et al.* 2017b), diet composition (Suomela *et al.* 2017), sex reversal (Król *et al.* 2017), economic relationships (Kankainen *et al.* 2016), and the production of modern aquaculture farms (Szczepkowska *et al.* 2014, Lindholm-Lehto *et al.* 2019). Based on the above findings, guidelines for production of whitefish at a commercial level were also published (Whitelaw *et al.* 2015, Fischer *et al.* 2018).

The past International Symposia on the Biology and Management of Coregonid Fishes (ISBMCF) resulted in 27 papers on whitefish aquaculture published in proceedings 2–5 held between 1984 and 1993, while in the following

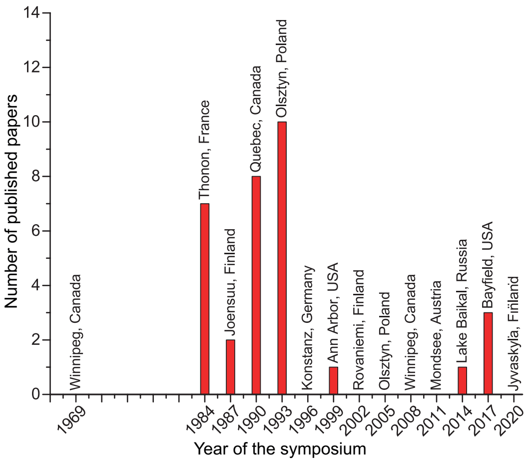

Fig. 2. Papers dealing with aquaculture of whitefish published in the proceedings of the International Symposia on the Biology and Management of Coregonid Fishes (symposium locations above the bars).

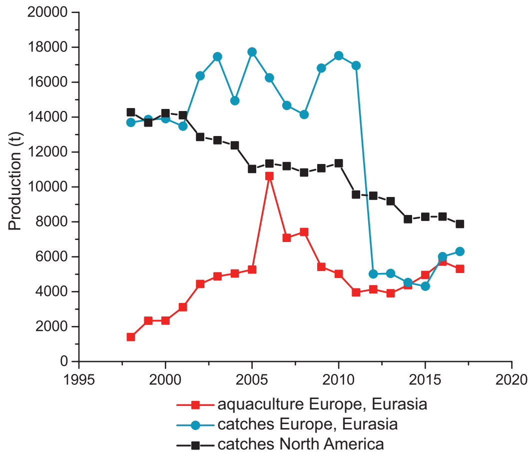

Fig. 3. Worldwide aquaculture production and catches of whitefish in 1998—2017.

proceedings (6–13), only 5 papers dealing with this topic were published (Fig. 2).

Aquaculture and catch statistics

The FAO statistics included data on whitefish aquaculture production (in tonnes) from 8 countries [five in Europe (Denmark, Czech Republic, Latvia, Finland, Austria), and three in Eurasia (Russian Federation, Kyrgyzstan, Belarus)]; and capture-fisheries (in tonnes) from 17 countries [two in North America (United States, Canada), three in Eurasia (Russian Federation, Kyrgyzstan, Armenia), four in central Europe (France, Switzerland, Germany, North Macedonia), and eight in the Baltic region in Europe (Denmark, Estonia, Sweden, Finland, Poland, Latvia, Lithuania, Russian Federation)]. The catches (in tonnes) for the Baltic fleet of the Russian Federation were reported separately and were not included in the reports for Eurasia.

According to the FAO statistics, the catches of whitefish in Eurasia, Europe and North America constantly decreased between 1998 and 2017 (Fig. 3), falling from around 14 000 t to less than 8000 t (Fig. 3). In contrast, between 2007 and 2017 the worldwide aquaculture production increased and stabilized at the mean level of around 5700 t (Fig. 3).

In Eurasia, the largest catches and aquaculture production in was reported for the Russian Federation (Fig. 4), while other countries like Kyrgyzstan, Armenia or Belarus produced much less (Fig. 4.). In 2012, the catches in the Russian Federation sharply decreased, which was also the main reason for the sharp decrease in the total catches in Europe and Eurasia combined (Fig. 3). According to Litvinenko *et al.* (2016), the main reasons for the decline were pollution of whitefish feeding and wintering grounds by the oil industry, and longer periods of low water levels, followed by a fishing ban on certain whitefish species. The aquaculture production in the Russian Federation decreased after 2006 and, despite its slight increase afterwards, never reached the highest value of 2006 again (Fig. 4).

As of 2012, more whitefish was produced in aquaculture than captured (Fig. 4). Between 2015 and 2017, an average of 4500 t were produced in the Russian Federation, representing around 85% of the worldwide aquaculture production of around 5300 t. According to an expert estimation (N. Smeshlivaya, State Research and Production Center of Fisheries, Tyumen, Russian Federation, pers. comm.), around 4000 t of whitefish were produced in small lakes of the forest–steppe zone of the Urals and western Siberia, around 1000 t were grown in net cages per year in the northwestern region of the country (Karelia, Leningrad region) and some smaller amounts in recirculating aquaculture systems (RAS) in western Siberia.

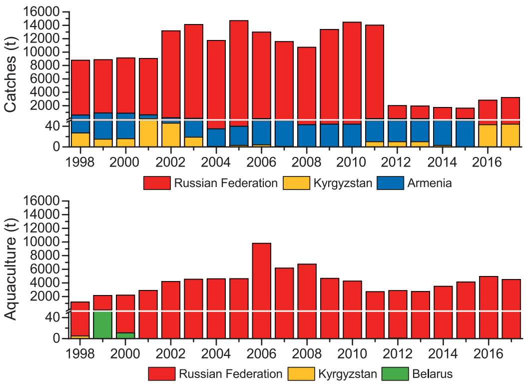

Fig. 4. Catches and aquaculture production of whitefish in Eurasia in 1998–2017.

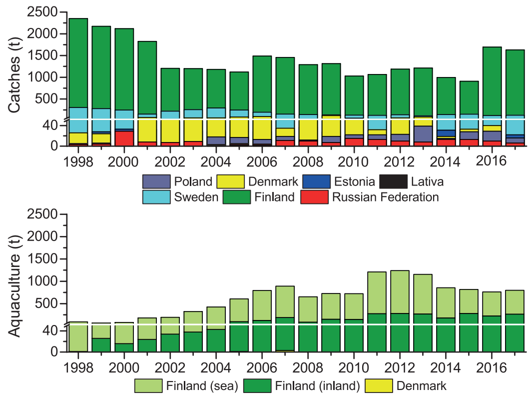

Fig. 5. Catches and aquaculture production of whitefish in the Baltic region in 1998–2017.

Apart from the Russian Federation, only Finland reported a relevant aquaculture production (Fig. 5). Between 1998 and 2017, around 800 t were produced in this country, representing 15% of the worldwide aquaculture production. Most whitefish were reared in net cages in the Baltic Sea, with more limited production in earthen ponds or raceways (P. Heinimaa, Natural Resources Institute Finland, pers. comm.). In addition, Finland reported a relatively stable whitefish catches of about 1400 t annually from the Baltic Sea, which is more than that for the other countries in the Baltic region combined (Fig. 5). The catches in the Baltic Sea region remained relatively constant (1000–1500 t) during the past two decades, and no correlation with the aquaculture production was apparent (Fig. 5).

According to the reports of the countries in central Europe, since 1998 the overall catches of whitefish have remained at a relatively constant level (Fig. 6). The decrease in Germany was outweighed by the increase in France (Fig. 6). The aquaculture production of whitefish in central Europe is small, and only the Czech Republic reported double-digit production (in tonnes) that constantly decreased in the years 1998–2017 (Fig. 6).

The case study of Lake Constance

The total surface area of Lake Constance is 536 km^2. The lake is divided into a large (472 km^2) and deep (max = 254 m, mean = 101 m) Upper Lake, and a small (63 km^2) and shallow (mean = 16 m) Lower Lake. Here, we deal solely with the better documented warm-monomictic pre-alpine expanse of the oligotrophic Upper Lake Constance (hereafter referred to as Lake Constance) which has had supported and regionally important fishery for many centuries.

A minimum of 30 fish species live in the lake (Eckmann & Rösch 1998), of which about 10 are targeted by fisheries (Rösch 2014); however, whitefish (*Coregonus* spp.) are the economically most important species. The whitefish yield decreased from around 300–600 t before 2012 to less than 150 t (Baer *et al.* 2016) in 2012–2018. In 2019, the yield fell further to below 60 t (Gugele *et al.* 2020). The reasons for the decline include the decreasing nutrient load (Baer *et al.* 2016) and the invasion of the non-endemic three-spined stickleback (*Gasterosteus aculeatus*) (Roch *et al.* 2018, Rösch *et al.* 2018). As a result, already in 2012, at least 50% of all whitefish consumed at Lake Constance originated from other countries, including Italy, Finland, and Canada (Dreßler 2013).

In 2011, a four-year study was commissioned by the German Federal Environmental Foundation (Deutsche Bundesstiftung Umwelt) to determine if future whitefish aquaculture in or near Lake Constance could meet the local demand. The basic concept to be tested was that local fishermen would found a cooperative aquaculture enterprise to produce fish locally (whitefish raised in Lake Constance and geneti-

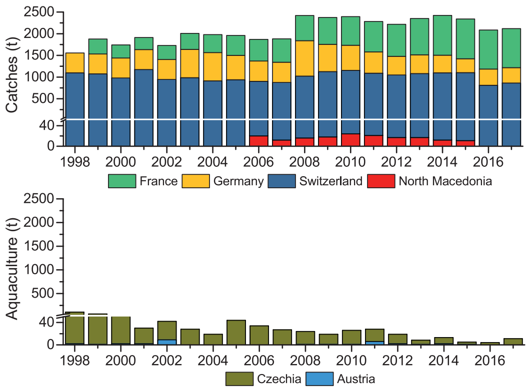

Fig. 6. Catches and aquaculture production of whitefish in central Europe in 1998–2017.

cally originating from local stocks). These fresh, sustainably produced whitefish would then be sold through the fishers' existing direct marketing networks, while maintaining important elements of the traditional fishery.

To this end, we identified a local strain suitable for aquaculture (Goebel *et al.* 2021) able to feed exclusively on dry feed while performing well in the *in-situ* temperatures and at adequate stocking densities (Goebel *et al.* 2017a). We also successfully tested a vaccine against furunculosis, and developed handling guidelines (authors' own data). In addition, no significant differences in flavour, texture or odour between farmed and wild whitefish were found, with the farmed fish, however, having superior levels of healthy fatty acids (EPA & DHA; Goebel *et al.* 2017b). Furthermore, consumers preferred the clear, white flesh of the farmed fish as compared with the pale, slightly grey flesh of the wild ones (Goebel *et al.* 2017b).

During a visit with aquaculture experts from Norway (Nofima, Tromsø), the economic feasibility of building land-based farms was evaluated and a cost-effectiveness study was conducted. The outcome of this evaluation showed that such farms (existing or newly built) carry an extraordinarily high economic risk (besides others, due to high initial investment). Thus, installation of net cages seemed the only viable solution. The plan included the use of existing hatcheries at Lake Constance, built for producing stocking material for the lake, to raise whitefish fingerlings to 20–50 g which could then be transferred for further growth to net cages in Lake Constance. With 10–12 net cages (circumference 40 m, depth 20 m), around 500 t of fish per year could be produced to meet the local demand. Possible negative effects, like spreading of diseases or transfer of the genetic material to the wild stock due to escapes, seemed to be negligible if a local strain and modern aquaculture techniques were used. Eutrophication or changes in the quality of drinking water were also expected to be minor: based on the assumptions that 750 t of trout feed is needed to produce 500 t of whitefish and that 4 kg total P is suspended per 1 t of feed (Dalsgaard & Pedersen 2011), a total amount of around 3 t P would be discharged into the lake as a result of cage farming. Considering that around 1500 t of P is washed into the lake per year, the surplus from whitefish aquaculture would be an increase of onlt 0.2% P per year. Based on the information gained during this project, it seemed that all necessary prerequisites were in place to establish aquaculture with minimal ecological and economical risks. However, aquaculture production has not been established in Lake Constance due to existing legislation and opposition from various groups. First, the majority of local commercial fishers opposed the idea of aquaculture. Some operate as the 13th generation family businesses and wish to continue their centuries-old way of life. They see the traditional capture fishery as much more in line with regional and personal tastes and habits, arguing that they are fishers, not farmers. Therefore, only a small group of local fishermen, trout farmers, and private persons founded a cooperative aquaculture enterprise in 2017. Furthermore, shortly after the founding the water supply companies, the Water Quality Protection Commission of Lake Constance (Internationale Gewässerschutzkomission für den Bodensee, IGKB), several non-governmental conservation organisations, as well as angling and fisheries associations complained about aquaculture plans, and a public/societal discussion in newspapers and digital media began that was mostly critical of aquaculture. In addition to this opposition, existing environmental laws and guidelines already set high barriers: the so-called "Lake Constance guideline" — an agreement between all bordering states about the way how to protect the lake — prohibits aquaculture in the lake. In addition, areas identified as suitable for the net cages were in special zones protected by the Flora-Fauna-Habitat Directive (FFH Directive), making environmental impact statements indispensable. The cooperative is still trying to fulfil all requirements to commence a small pilot project, but the installation of those pilot cages seems to be a distant prospect.

Expert interviews

According to the geographical origin of papers dealing with aquaculture of whitefish, experts from Austria, Canada, Czech Republic, Finland, France, Germany, Norway, Poland, Russian Federation, Switzerland, and USA were chosen and interviewed. Those interviews (Table 1) strongly suggested that the knowledge in all countries is high, and while in some countries whitefish have already been raised in earthen ponds for centuries (e.g. Austria, Czech Republic, and Poland), relevant production currently exists in two countries only (Finland, Russian Federation; Table 1). Furthermore, in countries with small production, the chance for its increase is apparently low. The future of whitefish aquaculture in countries where production is currently high was said to be moderate (Finland) and excellent (Russian Federation). Reasons for low or moderate chances of increasing production included sufficient catches of whitefish from the wild, strict environment laws, and competing aquaculture products. In two countries (Austria, Czech Republic) predation by cormorants was stated as an additional reason, but only on a local scale. In Finland, existing laws and guidelines make it possible to increase production, but the process of issuing necessary permissions is slow. Moreover, local production meets the demand within the country, and prospects for export seem to be low. Only experts from the Russian Federation expected considerable expansion of the whitefish aquaculture industry in their country in the near future.

Discussion

Capturing of wild fish for local consumption is one of the most environmentally sustainable forms of animal food production as suggested by benchmarks for ecological impact such as protein-energy return on investment, greenhouse-gas emissions, and land area requirement (Tyedmers 2004, Hilborn *et al*. 2018). However, as the case of Lake Constance clearly shows, in some places catches from the wild cannot meet the demand by consumers which leads to high import levels. In 2012, with catches above 400 t, at least 50% of all whitefish consumed at Lake Constance came from other countries. Current catches are now below 60 t, and local fisherman and other marketers must import much higher amounts that mostly come from Italy (Lake Garda), Canada or Russia. Due to the fresh fish demand, those imports come primarily by plane or truck, an increasingly controversial practice in terms of ecological footprint and sustainability (Madin & Macreadie 2015). Mixed origin of whitefish may also confuse consumers into thinking that the fish they eat is fresh from the lake, while in reality it may have been transported as a fresh or frozen fillet from another continent.

Most of these drawbacks could be avoided through developing local aquaculture production using a native strain, which also would help to avoid issues such as genetic introgression. In addition, as shown in the literature review and expert statements, the knowledge to produce large quantities of whitefish exists: none of the interviewed experts identified a single technical issue that had to be solved before whitefish production could start in their country, which was also evidenced by the decreasing number of publication on whitefish aquaculture. Taking the above into account, there must be other reasons for farming of whitefish remaining a niche business.

Based on some expert judgements and the experience at Lake Constance, environmental laws make the establishment of a whitefish aquaculture industry difficult. These locally strict laws ironically lead to increasing import rates and related ecological costs elsewhere and/or on a different scale: a fish which is not caught or produced and sold locally, causes ecological problems elsewhere (Hilborn 2013). Nevertheless, it has to be stated, that strict environmental laws and improved management has in many cases increased the local availability of whitefish (Winter *et al.* 2007, Chapra & Dolan 2012). Such efforts have resulted in stable or even increasing yields of coregonids (Gerdeaux *et al*. 2006), as the catches (in tonnes) for different countries show (e.g. France, Switzerland; Fig. 6), and local experts considered those stable catches an important reason for the lack of whitefish aquaculture in their countries. Therefore, environmental policy could help to protect one of the most environmentally sustainable forms of animal food production, namely inland fisheries (Song *et al.* 2018). This would suggest that improving and protecting water and habitat quality should be the first priority in resource management, while expansion of aquaculture facilities has to be balanced against ecological costs. As the case of Lake Constance shows, the ecological costs of aquaculture and its other possible negative impacts appear to be manageable,

Table 1. Outcome of an expert questionnaire about the *status quo* and the chance for establishing whitefish aquaculture (i.e., production of fish for consumption) in different countries.

Topic/question	Response choices	Nationality of experts
Knowledge level regarding whitefish rearing and aquaculture	(**a**) some experience with coregonid rearing but mostly focused on hatcheries for conservation rehabilitation and enhancements	Canada, France, Germany, Switzerland, USA
	(**b**) same as in **a** plus substantial experience/tradition in whitefish aquaculture	Austria, Czech Republic, Finland, Norway, Poland, Russian Federation
Status quo of whitefish farming	(**a**) at this time, there is no or only minor commercial aquaculture production of whitefish	Austria, Canada, Czech Republic, France, Germany, Norway, Poland, Switzerland, USA
	(**b**) substantial production that is constant or increasing	Finland, Russian Federation
Chances of establishing or developing whitefish aquaculture in the future?	(**a**) low, only as a niche product	Austria, Canada, Czech Republic, France, Germany, Norway, Switzerland, USA
	(**b**) moderate	Finland, Poland
	(**c**) high	Russian Federation
Reasons for low or moderate chances in the future?	(**a**) severe restrictions by (environmental) regulations	Austria, Finland, Germany, Norway, Switzerland, USA
	(**b**) fisheries still harvest adequate amounts of whitefish from the wild to meet market demand at a much lower cost than commercial aquaculture production systems	Austria, Canada, France, Germany, Switzerland, USA
	(**c**) other species (salmon, rainbow trout) have higher potential	Austria, Canada, Finland, France, Norway
	(**d**) predation (cormorants)	Austria, Czech Republic
	(**e**) slow granting of permits to increase production in open waters (net cages) and low export potential	Finland
Reasons for high chance of increasing production in the future?	No special environmental legislation and limited restrictions on fish farming, sufficient space, high demand	Russian Federation

but policy decisions are not always based solely on scientific studies and available data. In addition, emissions from local production could be much lower compared with those related to fish import (Ziegler *et al*. 2013, Farmery *et al*. 2015, Parker *et al*. 2018). The low ecological footprint of local production to meet local demand has been shown for other species, like salmon (Pelletier *et al*. 2009), rainbow trout (Samuel-Fitwi *et al*. 2013) or salmonids (Philis *et al*. 2019), but not for whitefish. Such studies could help to highlight the advantages of local aquaculture production. In addition, studies regarding consumer behaviour could help determine how the demand for locally caught or farmed whitefish compares with that for imported. Such studies could also help to understand consumer demand in a way that might decrease the ecological footprint of fish consumption, especially in areas where whitefish is widely consumed and the import levels are high. Such studies would provide information to the decision makers, politicians, NGOs, and fishermen on opportunities and ecological costs of replacing capture production with either aquaculture production or fish imports.

The future of whitefish aquaculture worldwide also depends on the production of other species such as salmon or rainbow trout. These species can replace whitefish and, according to the statements of local experts, can be produced at much lower costs. This may be one reason for the decreasing whitefish catches not being automatically followed by increasing aquaculture production of whitefish as evidenced by statements from experts from countries with decreasing whitefish yields (e.g. USA, Canada). Additionally, based on the established production cycle and the increasing market for salmon and trout (Garlock *et al.* 2020), it is highly unlikely that existing farms will switch to new species like whitefish. In southern Germany, for example, no single trout farmer has switched to whitefish farming despite the seemingly very high demand. On the other hand, the consumer behaviour could change over time: for example, in Norway some traditional seafood was replaced by newly available, processed seafood products and an increasing prevalence of aquaculture products was observed (Scholderer & Trondsen 2008). If the catches of whitefish are decreasing and/or whitefish are substituted by other aquaculture products, the general demand for whitefish in the future may decrease as well.

To summarize, the knowledge required to start and/or to intensify commercial whitefish aquaculture production is available. However, even after more than 50 years of studies, relevant whitefish production exists only in two countries (Finland, Russian Federation). Strict local environmental laws, sufficient local catches of wild whitefish, and replacement of whitefish by other aquaculture products seem responsible for this outcome. In some cases, such as Lake Constance, the lack of established whitefish aquaculture illustrates a common pitfall in environmental management: local environmental protection can result in increasing imports that offload environmental costs to other locations or in ways that are less apparent locally.

In conclusion, studies aimed to improve the production process of whitefish in commercial farms would have little effect on the industry development. Urgently needed are studies that quantify and point out benefits of locally produced whitefish.

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