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Atlantic cod aquaculture: Boom, bust, and rebirth?

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Abstract

The commercialization of a new species through aquaculture is much more complex than the mastery of the production process, or closing the loop, as it is sometimes referred to. Commercial aquaculture is a layer within the global seafood industry, much as wild capture is; however, it places human control at a much earlier phase in the life cycle of the harvested product. As an important species on both sides of the Atlantic, the commercialization efforts for the culture of Atlantic cod are described for four locations, Norway, United Kingdom, New England, and Atlantic Canada that highlight many similar technical challenges and the progress made from the late 1980s through 2012. We also describe some of the marketing challenges faced and how they differ. Technically, the species has been commercialized. Hatcheries and farms in all four countries were successfully established. However, there are clear differences in access to capital for research and industrial expansion from both the private and public sector, social acceptance of farmed fish, as well as the impacts on sales when marketing farmed cod in the context of a global seafood supply. Lower cost species substitution, from either the farmed or wild catch, is also a factor that can have a significant impact on long-term successful commercialization.

KEYWORDS
aquaculture, atlantic cod, atlantic cod aquaculture history

1 | INTRODUCTION

Atlantic cod (*Gadus morhua)* spawning was first recorded in Gloucester, MA, in 1878 and continued in subsequent years aboard the hatchery ship Fish Hawk, operated by the United States Fish Commission (American Association for the Advancement of Science, 1899; NOAA Fisheries, n.d.). During these efforts, cod eggs were collected, hatched, and released, and similar procedures were practiced in the 1880s by the Norwegian sea captain G. M. Dannevig, as well as in 1890s in Newfoundland, Canada. Over the years, much was learned about the cod fishery from these efforts on both sides of the Atlantic, as it grew into the dominant species landed in many ports; a species that many fishermen thought was impossible to overfish. However, our knowledge of the fishery and our ability to use ever increasing efficient capture technologies proved this was not the case, and by the late 1980s, Canada's cod fishery had collapsed, and the New England cod fishery was not far behind (Milich, 1999; Pershing et al., 2015). According to the NOAA landings statistics, Atlantic cod fishery landings had declined from over 75 million pounds (34 million kg) in 1988 to just over 2 million pound (0.9 million kg) in 2019 in the New England region. However, as a comparison, Pacific cod landings nearly doubled at the same time frame from 269 million pounds (122 million kg) to nearly 464 million pounds (210 million kg).

During the 1970s and 1980s, salmon aquaculture research and commercial aquaculture began to take hold (Asche & Bjørndal, 2011), and by the 1990s, it was a fast-growing industry. It had the luxury of having decades of government subsidized research to acquire the knowledge and technology necessary to produce trout and salmon juveniles for recreational fishery restocking. This knowledge was transferred to the commercial aquaculture sector and enabled rapid growth of salmon farming as we know it. This is very important, as the newer, alternative species had to pay for their culture experience through trial and error, without as much historical support, or knowledge beyond the production of yolk sac fry. This created a longer launch pad to commercialization and profitability.

The bass (*Dicentrarchus labrax*) and sea bream (*Sparus aurata*) industry in the Mediterranean, however, was also launched around the mid-70s and proved to be a successful culture model for marine species, especially at the hatchery level (Shields, 2001). With the decline of numerous popular marine species, including Atlantic cod, and the previous successes with marine finfish aquaculture, researchers, and entrepreneurs began to investigate the culture of additional species.

In the United Kingdom, Atlantic turbot (*Scopthalmus maximus*) grew into a successful product and production migrated to Spain where warmer waters decreased time to harvest and therefore cost of production. Other marine species began to be commercialized including Atlantic cod, haddock (*Melanogrammus aeglefinus)*, sablefish (*Anoplopoma fimbria*), cobia (*Rachycentrom canadum*), and flatfish species, such as Atlantic halibut and the flounders of the *Paralichthyid* genus, summer flounder (*P. dentatus*), southern flounder (*P. lethostigma*), olive flounder (*P. olivaceous*), and California halibut (*P. californicus*). Olive flounder (*Paralichthys olivaceous*), familiar to many as hirame at sushi restaurants (also known as Japanese, Chinese, or Korean flounder), grew into a 40,000 m.t. per year in industry (Hamidoghli et al., 2020).

Atlantic cod seemed a natural species to complement the production of Atlantic salmon, allowing the salmon farmers to produce another cold-water species in the same locations and with the same equipment. As cod produce antifreeze proteins that salmon do not, they would also be a possible candidate for sites that experience super chill that could kill salmon.

Converting from salmon farming to cod farming would require minimal capital outlay for being able to diversify and expand production. From the late 1980s to the early 1990s, commercial cod hatcheries and farms were established in Canada, New England, the United Kingdom, and Norway. Indeed, cod farming appeared to be so promising, over 400,000 m.t. were expected to be grown in Norway and investors were backing new cod farming ventures, buying up as many concessions as possible (Bevanger, 2002). The future looked promising, but the new industry had not been stress tested, yet, in the commercial sense. Could the hatcheries keep up with high-quality juveniles that would allow ventures to meet their business plan projections? How hard will deformities, early maturation, and disease impact the industry once densities and fish handling increase?

This article is a retrospect of the commercial cod farming boom and bust that took place in four locations: New England, Atlantic Canada, Scotland, and Norway from approximately 1985–2012. Technical challenges, particularly at the hatchery, created international cooperation and information sharing among some of the industry participants. For this reason, we believe to better understand the status of Atlantic cod culture in the United States, you have to understand it in the context of an international effort. Commercial cod farming during this period also had a presence in Ireland, Iceland, and the Faroe Islands; their stories follow a similar pattern. Ireland notably focused on organic cod farming (FitzGerald et al., 2011).

One of these locations, Norway, arguably the catalyst for cod farming, is making a bit of a comeback building on the experience and knowledge gained during the pioneering days. Where will this new phase of the industry go, and will the other regions of the world take a second look? To answer this question, we will look at each of the four locations and the different challenges they faced during their attempts to launch major commercial aquaculture industries.

2 | COD AQUACULTURE IN NORWAY

2.1 | Commercial culture history

In Norway, the first culture trials with Atlantic cod were carried out as restocking programs in the late 1880s with large releases of hatchery-produced yolk sac larvae (Rognerud, 1887). As the financial support for this activity was from investors with limited culture knowledge, proof of larval survival was needed for continued support, and this was demonstrated by rearing about 5,000 cod fry in a 2,500 m^3 pond on natural zooplankton at the hatchery in Flødevigen, on the south coast of Norway. About 100 years later, the same method was applied on the Norwegian west coast at Austevoll, for the purpose of producing cod fry for aquaculture. In 1983, about 60,000 cod juveniles were harvested from the "Hyltropollen" lagoon system (Kvenseth & Øiestad, 1984; Øiestad, Kvenseth, & Folkvord, 1985), giving a kick-off to start the interest in cod farming. However, it appeared that the production capacity in such lagoon systems, also called "the extensive method" (van der Meeren & Naas, 1997), was 1–2 fry per m^3 of pond or lagoon water. A few commercial cod farms were established for both juvenile production and ongrowing to harvest size of pond-reared cod fry, but commercialization was restricted by limited juvenile production capacity, lack of optimized formulated feed, early sexual maturation with subsequent growth reduction, and limited market opportunities due to a healthy wild cod population (Engelsen, Asche, Skjennum, & Adoff, 2004; Svåsand, Otterå, & Taranger, 2004). The Institute of Marine Research (IMR) in Bergen continued to maintain cod broodstock and a lagoon production system (Blom, Otterå, Svåsand, Kristiansen, & Serigstad, 1991) and was well situated for the second "cod boom" at the millennium, spurred by promising Canadian research on intensive fry production in indoor hatcheries increasing prices due to declines of the wild stocks.

Meanwhile, the IMR lagoon system produced cod fry for sea ranching investigations and stock enhancement programs (Svåsand et al., 2000), but also supplied 3–5 commercial farms with cod juveniles. Furthermore, research projects were initiated with some of these facilities to investigate the possibility of overcoming early sexual maturation in farmed cod by using light (Taranger, Aardal, Hansen, & Kjesbu, 2006), as successfully implemented in Atlantic salmon farming. Inspired by the growth of sea bream (*Sparus aurata*) and sea bass (*Dicentrarchus labrax*) aquaculture in southern Europe, trials with intensive production of cod juveniles based on live feed production of rotifers and *Artemia* were carried out during 1990–1993 by the companies PB Nutrition ARC and Salar AS at Bessaker north of Trondheim, together with several Norwegian Research institutions (Svåsand et al., 2004). Despite a high number of metamorphosed fry produced in these large-scale experiments, high mortality was observed due to cannibalism caused by suboptimal rearing and feeding conditions. This, together with a general skepticism that cod farming was economically viable, ended further exploration of cod as a new species for aquaculture at that time.

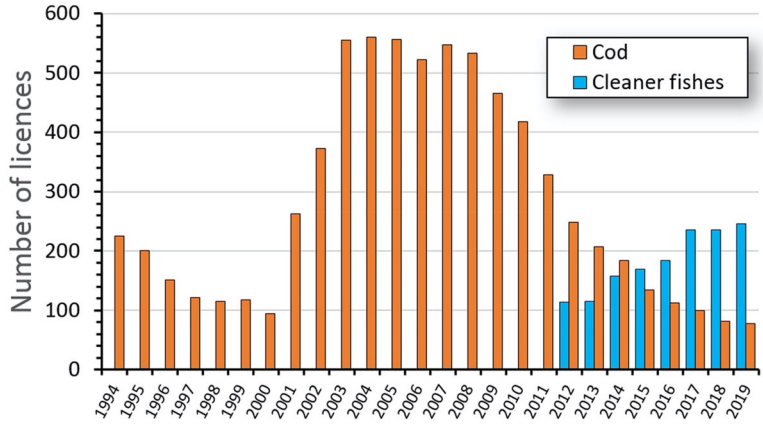

FIGURE 1 Number of aquaculture licenses, both hatcheries and cage farms, issued by the Fishery Directorate in Norway for Atlantic cod and cleaner fishes which confines various species of wrasses and lumpsucker (*Cyclopterus lumpus*).
Source: The Norwegian Fishery Directorate (www.fiskeridir.no)

The improvements of intensive larval fish and live feed culture techniques and nutritional enrichment of rotifers and *Artemia* during the 1990s laid the foundation for a substantial increase in the production of European marine finfish species, from 3,900 t of sea bass and sea bream in 1990 to greater than 150,000 t in 2000. In Norway, Atlantic halibut juvenile production benefitted from the global focus on larval fish nutrition and hatchery development, and lead to culture of other cold-water, marine species. When year-round cod spawning and juvenile production was made available by photoperiod manipulation (Norberg, Brown, Halldorsson, Stensland, & Björnsson, 2004; van der Meeren & Ivannikov, 2006), a second cod boom was initiated in the very beginning of the new millennium. Licenses for establishing cod hatcheries and farms for on-growing to market-size increased quickly from 94 in 2000 to 560 at the end of 2004 (Figure 1).

2.2 | Technical and biological challenges, and progress

The high number of licenses issued indicated that many companies wanted to take part in the Norwegian "cod adventure," but knowledge and experience with intensive start-feeding of larval cod were somewhat limiting. Despite this, full-scale hatcheries were built to supply the demands from the on-growing farms, because the continuation of the (net-pen) licenses was dependent on active operation within a few years following approval. This resulted in production of low-quality juveniles in some cases and the net pens were stocked with all the juveniles available from the hatcheries, including cod fry with bone deformities and slow growth. Adverse public reaction followed as deformed cod started to escape from the farms and referred to as "monster cod" by the media (Norway Police to Investigate Monster Fish, 2010). Fishermen catching such cod claimed that "even the cat wouldn't eat them."

Bone deformities remain a problem for many cultured fish species and reduce profitability when they occur in high frequency. It became a general opinion that the frequency of bone deformities in cod fed natural zooplankton (mainly copepods) by the extensive method in lagoon systems appeared to be lower than in cod from intensive fry production start-fed on rotifers and *Artemia*. However, not all the bone deformities were visible from the outside, and it was found that the position of the deformities on the cranial and vertebral regions seemed to differ between the two production methods (Fjelldal, van der Meeren, Jørstad, & Hansen, 2009). Even wild cod had bone deformities, however, but at much lower prevalence than in farmed cod. The underlying causes for bone deformities were unclear and remain a challenge, but rearing environment, such as temperature and water currents, nutrient deficiencies (e.g., minerals and vitamins), and interactions with gene expression, have been the focus of extensive research in the last decades. From the mid-1990s through the mid-2000s, the frequency and severity of deformities became less

of a production concern at commercial hatcheries, as they transferred the knowledge from the research sector into practice.

Slow growth during the labor-intensive larval start-feeding period may also reduce hatchery profitability, and larval growth rate is clearly related to nutrition (Busch, Falk-Petersen, Peruzzi, Rist, & Hamre, 2010; Karlsen et al., 2015). Besides superior growth, skin pigmentation appeared to be more marked in copepod-fed cod larvae (Busch, Peruzzi, Tonning, & Falk-Petersen, 2011). For these reasons, research had been initiated to extract the clues of why copepods were better fed than rotifers and *Artemia* (van der Meeren, Olsen, Hamre, & Fyhn, 2008), with extended emphasis on how enrichment could improve the nutritional quality of both the live and formulated feeds used in intensive production of cod juveniles. However, a closure of this challenge also remains, although important progress has been carried out on enrichment media and protocols. Regarding feed for the on-growing phase, gadoids store excess dietary fat in the liver in contrast to salmonids, clupeoids, and scombrids that store fat in the muscle tissue. Thus, cod requires less lipid and more protein in the feed than salmon to avoid the so-called "fat liver," and an optimal feed for this phase of cod farming was required along with the immediate need for presenting a high-quality farmed cod product for the consumers.

In contrast to salmonids, cod is a marine fish that readily spawn in the net pens (Jørstad et al., 2008). As sexual maturation is not controlled and cod fry were moved along the entire Norwegian coast, this could become a threat to the genetics of local wild cod stocks. Another risk factor for negative impacts on native cod gene pools was escapes of cod from the cage farms (Jørstad et al., 2014). Cod were in fact observed to bite holes in the nets (Damsgård et al., 2012). The cod genome has been mapped (Johansen et al., 2009), and new molecular methods for gene diversification and expression have appeared and expanded quickly in the last decade. Emerging knowledge about local cod stock structure from genetic studies indicated genetic separation among cod populations over short geographic distances (Barth et al., 2018), but care should be taken not to generalize this to be applicable for all fjords with cod populations along the Norwegian coast. Both escapes and sexual maturation with subsequent spawning in the net pens directly affected the farm economics during the second cod boom (2000–2010) in Norway. Furthermore, prevention of sexual maturation in cod during the first 2 years of on-growing in sea cages (precocious sexual maturity) at a commercial scale seemed difficult to control with an artificial light regime in the presence of a natural light cycle (Skulstad et al., 2013). Losses in somatic growth at the expense of gonadal growth during sexual maturation were a major constraint to economic success in Atlantic cod farming. Additionally, precocious sexual maturity proved to be an animal welfare issue, as some individuals had problems of releasing eggs and developed what was later called "egg bound" (Árnason & Björnsson, 2012; van der Meeren & Ivannikov, 2006).

Diseases also continue to pose problems for Atlantic cod culture. In 2004, a new bacterium belonging to the genus *Francisella* sp. caused mortality in Norwegian cod aquaculture (Nylund, Ottem, Watanabe, Karlsbakk, & Krossøy, 2006). Farmers experienced large losses because the intracellular *Francisella noatunensis* caused the systemic granulomatous inflammatory disease (Francisellosis) that could not readily be treated with antibiotics (Furevik, Pettersen, Colquhoun, & Wergeland, 2011). The Norwegian Food Agency mandated all fish to be slaughtered if Francisellosis broke out in a cod farm. Francisellosis was also observed in escapees from cod farms, which posed a threat to wild cod stocks or other cod farms within the same or neighboring fjord systems. Francisellosis seemed to be most common in the southern part of Norway, an indication that temperature could play an important role in bacterial uptake and disease outbreak (Bakkemo, Mikkelsen, Johansen, Robertsen, & Seppola, 2016).

Francisellosis, escapees, fry quality, slow growth, and lack of control with sexual maturation followed by eggbound mortality or spawning in the net pens all became threats to the new cod farming industry after the millennium. Attaining a maximum production of 21,000 t in 2010, cod farming in Norway ended in a collapse from 2011 to 2014 (Figure 2). It is not possible to point at a single factor for the collapse. However, many cod hatcheries were not shut down but converted to hatcheries for cleaner fishes, such as lumpfish (*Cyclopterus lumpus*) and ballan wrasse (*Labris bergylta*) needed for biological delousing in the salmon aquaculture industry after the salmon louse became resistant to the chemical delousing agents (Børretzen Fjørtoft et al., 2017).

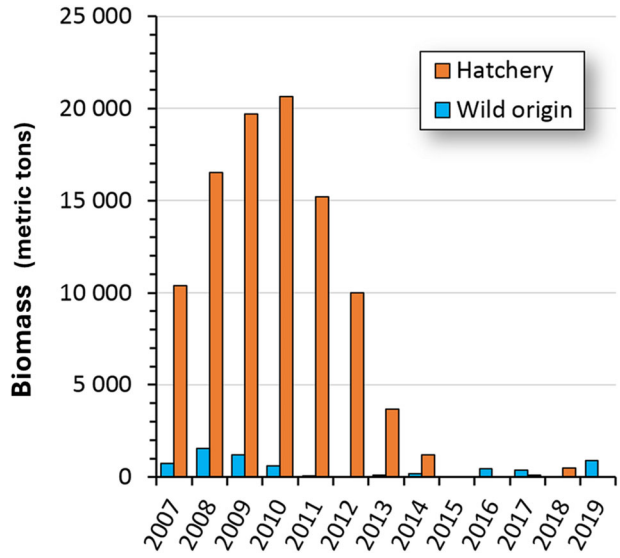

FIGURE 2 Sales of farmed cod in Norway 2007–2019, originating from both hatchery-reared juveniles and wild-caught cod put in cages for on-growing.
Source: The Norwegian Fishery Directorate (www.fiskeridir.no)

2.3 | Market challenges and opportunities

Cod has not traditionally been regarded as a high-value product, although some segments in the market seem to be willing to pay very good prices for cod (Engelsen et al., 2004). The situation with decline in the wild stocks in the 1990s, created a surge for cod with historical high prices around the millennium. Thus, the second cod boom in Norway appeared in a window of opportunity with unknown duration. However, the biological and technical constraints mentioned earlier made cod farming very costly, requiring a price for the product that was in the upper segment of what the market was willing to pay.

The collapse in cod farming in Norway coincided with the world-wide economic crisis emerging in 2008 and changes in the world's seafood market. From 2004 and onward, global production of another whitefish species, pangasius (*Pangasianodon hypophthalmus*), increased rapidly to 1.4 million tonnes in 2008 and rising up to 1.7–2.0 million tonnes during 2011–2014 (Subasinghe, 2017). This product would compete with cod in the supermarkets in Europe and the United States, the primary markets for farmed cod. Additionally, annual catches from the largest wild cod stock, the Northeast Arctic cod in the Barents Sea, also doubled from 2007 to about 1 million tonnes in 2012 and 2013. However, the benefit of farmed cod is that it can be delivered fresh year around, but this requires a certain quantity and regularity of supply as demanded by the seafood companies. Despite this, the unfortunate changes in the world sea food market and economy halted the profitability in cod farming in Norway after 2008 through its decline to 2014.

2.4 | Current commercial status

After the collapse of Norwegian cod farming, potential future hatchery production remained viable as the facilities remained operational, because several hatcheries converted to cleaner fish production (Figure 1). Furthermore, an increasing interest in live holding or capture-based aquaculture (CBA) of cod that can deliver a fresh and high-quality product out of season for the wild cod, has developed the last decade (~2008–2015) in Norway (Humborstad et al., 2016). However, over the last 2 years (2019–2020), a new interest for farming all life stages of cod has emerged, particularly in the northern regions of Norway, and farmed juvenile cod from two hatcheries have been transferred to sea cages in three farms for on-growing, with plans for up-scaling the production in 2021 among three

different cod farming companies. The two hatcheries, the governmental National Cod Breeding Program operated by The Norwegian Institute of Food, Fisheries and Aquaculture Research (NOFIMA) near Tromsø and the private company Havlandet Marin Yngel AS (HMY) in Florø, have kept broodstocks of cod and carried out breeding programs over 5 and 6 generations, respectively, selecting for faster growth, disease resistance, and delay of sexual maturation; HMY and NOFIMA are now capable of delivering cod fry on demand for industry.

2.5 | Promise and outlook for the next decade

While the cod boom 20 years ago was basically initiated with wild cod, the new interest in cod farming is based on broodstocks selected for specific traits to overcome the previously experienced problems. In the media, HMY and NOFIMA both claim great progress regarding increased growth rate and reduction in bone deformities. NOFIMA also claims that their cod is calmer and show less stress in the hatchery tanks, have less mortality in the sea cages, and are less prone to escape (The Cod Has Become Livestock, 2019). However, a vaccine or treatment of the Francisellosis disease needs to be developed, and the claimed progress must be put to a test in full scale farming trials which is now under way. One of the cod farming companies, Norcod AS, has plans for a production of 30,000 t annually by 2025. Any development of a new cod farming industry will also face new challenges, and the success will be dependent on how the production costs balance with what the market is willing to pay. Prices equivalent with farmed salmon have recently been seen, but in the future, this may change if or when the production surges.

Another interesting aspect is that HMY is planning ongrowing of up to 200 t of cod in a land-based farm with recirculation (RAS) technology. This will solve the problem with precocious sexual maturation, and HMY says they already produced cod up to 25 kg without maturation by controlling photoperiod. RAS farms may reduce costs if access to sea areas becomes difficult due to environmental issues and lack of social acceptance, and it may reduce the susceptibility to diseases like Francisellosis.

Cod farming will also compete for feed ingredients in a market where there is a goal for expanding Norwegian salmon farming to 5 million tonnes by 2050 if environmental issues, for example, the salmon louse problem, can be overcome. Salmon is already using up to 70% terrestrial feed ingredients due to lack of supply from marine sources, and currently no prospects are fully developed to expand the access to such ingredients. This implies competition for expensive and limited marine feed ingredients and understanding how cod biologically will cope with increased fractions of terrestrial ingredients in the feed.

To conclude, breeding programs on cod should continue and future cod farming may benefit from planned, incremental growth while addressing the challenges discovered over the last 20 years and avoiding another cod farming collapse. This may enable high enough production volume of each company for a stable and season-independent delivery to the market. More research is needed on feed composition, cod biology and physiology, farming technology that supports fish welfare, and disease and parasite problems. All these are necessary to produce a product of the quality required to compete in the upper segment of the cod market.

3 | COD AQUACULTURE IN THE UNITED KINGDOM

3.1 | Commercial culture history

In the late 1990s, declines in cod catches, particularly in the North Sea and Irish Seas, led to sharp increases in cod prices. This was highlighted by the Seafish Industry Authority, a public body supporting the seafood industry, in a series of reports. There followed a series of meetings in Norway and Scotland attended by the salmon farming community looking at the potential for farming cod. As salmon prices were falling, the salmon industry was keen to have an alternative species to farm.

In 2001, Marine Farms through its subsidiary, Lakeland Smolts Ltd, and Stirling University set up a joint venture hatchery, Machrihanish Marine Farm Ltd, to produce about 1 million cod juveniles for companies interested in growing cod. This was completed in 2003 and opened in style by Princess Anne. In 2002, Nufish, a cod hatchery near Sandwick in Shetland was also started by Peter Tarrant and Denis Blackmore, two technicians from the Greek seabass and seabream industry. In 2002, the Johnson brothers, Ivor and Angus who had been successful salmon farmers for several years, set up a company Johnson Seafarms to farm cod in the Shetlands. Their prospectus was circulated in the investment community in London (not the normal route to finance aquaculture) and proposed to set up several cod companies (cod1, cod2, etc.), with a year class of cod juveniles which would be grown on to market size over 3 years. The Johnsons were paid a management fee for looking after the fish. At harvest, the investors, who got large tax breaks for such investments, could either cash in or re-invest in one of the other cod companies.

In the frenzy that followed, in 2005, Johnson Seafarms and Nufish were acquired by a consortium of Milestone Capital and Kaupthing Singer and Freidlander, the U.K. subsidiary of the Icelandic bank Kaupthing. In total £21 M was raised for the purchase of the company and its future development. The new company was called No Catch and produced organic cod for the U.K. market. The management of Laurent Viguié and Karol Rzepkowski were very market oriented and launched cod steaks under the name "No Catch – just cod" in Tesco and Carrefour supermarkets retailing at £20/kg (about twice the wild cod fillet price).

By 2005, there was one main ongrower, No Catch, and 4 hatcheries, Nufish, Machrihanish Marine Farm, Mannin Seafarm (Isle of Man owned by Nick Fullerton), and Ardtoe (owned by Tim Atack and Jim Treasurer). Several other salmon farmers bought small quantities of cod from the hatcheries to conduct trials (Lakeland Marine Farm and Wester Ross Salmon).

Early results looked promising with high fillet yields reported (50% vs. 35% for wild fish) and good acceptance by the market which preferred the stocky farmed cod to wild fish with long thin tail fillets. Costs of production were estimated at £2–2.50/kg and farmed cod prices rose to £4+/kg head on gutted versus £2.60 for the equivalent wild product; the first time that a farmed fish was more expensive than its wild equivalent.

At the height of the industry in 2006, hatchery production rose to about 2 million juveniles and about 1,000 m.t. of production, but in 2007/8, a "perfect storm" involving several factors combined to kill off the industry in the United Kingdom.

- First, technical problems resulting in deformities and early maturation plus the high price of vaccines and organic feed were pushing up the costs of production
- Second, supplies of wild cod improved due to increased catches in the Barents Sea fishery to 1 M tonnes by 2013 and the price of wild cod dropped to below the break-even price of farmed fish.
- The financial crash of 2008 severely affected the banking sector, particularly the Icelandic banks. This put pressure on No Catch to repay its loans from Kaupthing. The company went bankrupt with debts of over £40 M

With the collapse of the only serious ongrower, hatcheries were left with surplus juvenile stocks. Although some were sold to Norwegian buyers, the majority had to be culled. Hatcheries then ceased operation, although many were subsequently used for cleanerfish production. If the industry had been larger, it may have survived these events, but as was shown in Norway it only prolonged the inevitable.

3.2 | Technical challenges

The main technical challenges in the hatcheries were similar to Norway's, including high larval mortality, problems with weaning, cannibalism, and deformity.

Water quality issues at the Machrihanish hatchery caused high larval mortalities, which was improved by converting to recirculation (RAS) and using clay in later years, but the hatchery never fulfilled its production goals during

the early years. Nufish also had early problems but later produced good quality juveniles with low deformities using live phytoplankton. Water quality was affected by a severe landslide in the local loch. Mannin produced good fish as did Ardtoe but in smaller quantities.

The main ongrowing technical problems again were similar to those already stated. However, in regard to disease, *Vibrio*sis was of most concern. Initial vaccination was ineffective, as early vaccines lacked protection against *Vibrio anguillarum* Serotype 2b. Commercial vaccines for this bacterium strain were not licensed in the United Kingdom, but had to be produced autogenously, using isolates from moribund fish, which made them very expensive.

3.3 | Market challenges and opportunities

Positives

- Only organic farmed cod was marketed in the United Kingdom and well received by fish buyers
- Fillet yields were good (50% vs. 35% for wild fish)
- Early farmed cod sold at higher prices than wild cod
- The continuity of supply was highly rated by fish buyers
- Consumption of cod in the United Kingdom at the time was about 170,000 t/year of which 20,000 t was prime fillet. This was the target market for the farmer

Negatives

- One problem was that the U.K. public had been told that cod was a threatened species so avoided buying it, preferring haddock. (Today cod is less expensive than haddock in the fish and chip shops.)
- Public was not used to paying high prices for cod
- In general, farmed fish in the United Kingdom is not considered a premium product

3.4 | Current commercial status

At present, there is no cod farming in the United Kingdom and very little interest.

3.5 | Promise and outlook for the next decade

As long as there is a reasonable supply of inexpensive cod from the wild, it is unlikely that cod farming will reappear in the United Kingdom. There is possibly a niche market for organic cod (similar niche to halibut).

One problem is that the authorities will need to ease restrictions on cod farming. For example, licenses for cod were restricted to 1,000 t/year, compared to salmon farms at 1,500 t/year, because it was thought that the higher protein content of cod feed would cause more pollution.

One positive attribute is that there were few diseases passed between cod and salmon. This is important as cod would have to be grown together with salmon. With the current market situation, it is unlikely that salmon farmers would take this risk.

Cod does not suffer from sea lice so may have more of a social license to farm in sea pens, not requiring expensive and environmentally controversial chemical treatment to remove lice (currently the biggest issue with salmon farming).

One problem in the United Kingdom was that apart from No Catch, there was little appetite to finance cod farming. It is difficult to see how this will change in the future.

4 | COD CULTURE IN NEW ENGLAND

4.1 | Commercial culture history

Founded in 1995 by Christopher Duffy and George Nardi, GreatBay Aquaculture (GBA) initially produced juveniles of marine species for commercial aquaculture. Its first species, summer flounder (*Paralichthys dentatus)*, was a technical success, but the challenge to build a North American land-based ongrowing industry for flatfish proved to be an insurmountable challenge during the late 1990s when dot com bubble investors were looking for returns in less than 12 months. However, the salmon industry in Maine and New Brunswick was open to species diversification, especially with a species, such as cod, that could take advantage of the existing farm infrastructure. GBA was fortunate to find established cod broodstock held at the NOAA Lab at their Narragansett Laboratory in Rhode Island that needed a new home. GBA also captured wild broodstock locally for domestication.

In 2000, GBA began to produce Atlantic cod at its Portsmouth, New Hampshire, hatchery working collaboratively with NOAA and academic researchers from the Narragansett Laboratory in Rhode Island and the University of New Hampshire (UNH). After a year of trial productions, survival rose from an average of 5% or less, to 30% or greater. In 2001, GBA began to supply the Open Ocean Aquaculture (OOA) Project at UNH with juvenile stock for growing in submersible net pens moored in 55 m of water off the Isle of Shoals, 6 miles offshore from Portsmouth, NH (Intrafish, 2008, 2012).

The UNH OOA project utilized submersible spar cages called Sea Stations, supplied by Net Systems, Inc., Bainbridge Island, WA. While the cages were excellent at containing the fish and being able to submerge during storm events, the functionality of the cage for partial harvesting, as an example, was a challenge for a species with a swim bladder such as cod (Chambers & Howell, 2006). During a partial harvest, the cage would be brought to the surface faster than the cod could regulate the gas in its swim bladder, causing barotrauma, highlighting the need for a controlled ascent cage system for cod.

GBA was fortunate to receive significant grant funds from the National Oceanographic and Atmospheric Administration (NOAA) and the United States Department of Agriculture (USDA) and often partnered with research institutions. Significant Atlantic cod research has also been conducted at the University of Maine's Center for Cooperative Aquaculture Research and at UNH. This research (Brown, Kling, & Skonberg, 2007; Neves & Brown, 2015; Rillahan, Chambers, Howell, & Watson, 2011; Walker, Fournier, Neefus, Nardi, & Berlinsky, 2009) focused on topics that would assist the development of the industry, including breeding, fish health, and genetic improvement. Production of commercial quantities of juveniles was no longer limiting the New Hampshire commercial hatchery producing over a million juveniles per year.

In 2010, an NOAA funded project sponsored the development of a cod farming curriculum and a 13-week training program for commercial fishermen interested in transitioning to farming Atlantic cod in Maine. This certificate program, named the Cod Academy, required the fishermen to learn all aspects of farming and related animal husbandry. It included studying a syllabus created for this purpose, classroom participation as well as hands on work at the nursery and cage farm site. The course culminated in their development of a business plan for a proposed cod farm business. The training was rigorous and only about 25% of the fishermen that started the training finished the program. This program included the participation of GBA, University of Maine, and Coastal Enterprises, Inc. in addition to the Maine Aquaculture Association (MAA), under the leadership of Sebastian Belle.

Salmon farming ventures in the region using traditional surface cages in Maine and New Brunswick stocked trial cages with hatchery produced cod juveniles, including Stolt Sea Farms in Maine, Cooke Aquaculture in New Brunswick and GreatBay Aquaculture of Maine, the sister company of the Portsmouth, New Hampshire hatchery. However, as these fish were now being raised commercially, certain culture challenges, discussed below, that while not unexpected, slowed its acceptance as an alternative to salmon.

Stolt Sea Farms had stocked one cage in a grid with nine other cages holding salmon. When the young cod had a *Vibrio* outbreak, one that the attending veterinarian was not overly concerned with as all the salmon had been

vaccinated and mortality was extremely low, the managing director of Stolt Maine had a decision to make. Not a technical one, as the science indicated the fish were protected, but an economic one. The cod trial was promptly terminated, as any risk above zero was not acceptable economically to the salmon operation.

At Cooke Aquaculture, during the mid-2000s, over 1 million fish were stocked into over 40 cages with Atlantic cod supplied by GBA. Harvested fish were featured by Cooke at the Boston Seafood Show, Boston, MA.

At sea, both fish health and early maturation presented further challenges. An endoparasite, *Loma morhua*, caused significant mortality and early maturation slowed the overall growth of the stock. Bacterial disease was kept in check through vaccination, primarily against *Vibrio anguillarum*, *Vibrio harveyi*, and *Photobacterium* sp. These problems, however, were able to help inform the breeding program for Atlantic cod as part of the Cod Genome Project.

GBA of Maine stocked 10 cages with Atlantic cod and sold most of their harvested product to the domestic Chinese market in Boston and New York as live market size fish. However, all live fish had to be tagged with a tag that had all production data traceable from farm harvest back to the hatchery, as Atlantic cod is managed by a Federal Fishery Management Plan, and the fish were being transported interstate. Each member state of the Atlantic States Marine Fisheries Commission through which the fish would pass had to agree to this and the tagging program, as well as NOAA. This was very important as the size of legally harvested wild fish was too large a product for the live Chinese market that requested a plate size fish of about 2 pounds or about 1 kg. This created a new and unique market for the farmed cod. The acceptance of the tag was key to avoid poaching concerns from illegal fishing of undersize cod from the fishery and to permit the sale of the nonconforming farmed fish.

While demonstrating commercial promise from the 1990s forward, in both Canada and the United States, cod aquaculture received a large blow in 2008 with the global economic crash—both Cooke Aquaculture and GreatBay Aquaculture were forced to curtail developing projects. At the time Cooke had multiple sites licensed, stocked, and producing cod, and GBA of Maine had a second site permitted, ready for expansion with one 10-cage site already producing year-round. For Cooke, this meant the curtailment of the cod program, and for GBA, it meant splitting up the cod hatchery and farm operations in 2010. GreatBay Aquaculture of Maine continued to farm cod for the live market and GreatBay of New Hampshire focused on the production of juvenile species, both warm-water and cold-water fish, for domestic and international clients.

4.2 | Technical challenges and progress

Atlantic cod broodstock respond very well to environmental cues, are very prolific volitional spawners, so egg production was rarely a problem. The technical challenges are similar to what had been observed elsewhere.

In addition to the challenges at the hatchery to overcome deformity and cannibalism, gas management (i.e., O_2, CO_2, N_2) has proved critical to cod production at the hatchery level. The larvae are sensitive to supersaturation, particularly from dissolved nitrogen. The partial pressure of nitrogen gas must be maintained at 100% or less (King & Nardi, 2002).

Cod larval survival in intensive production also benefitted from weaning directly to dry diets from rotifers, skipping the *Artemia* phase. The transition was more uniform onto the dry diet as it appeared larval cod reluctantly weaned from *Artemia*.

Nodavirus or VNN, a virus found throughout the marine environment, effects many marine species that are cultured, such as European sea bass and grouper species. In one production run, GBA lost over 600,000 juveniles in the process of discovering Atlantic cod is susceptible to this virus. It is now advised that all hatcheries set their UV dose to 150–200 mJ/cm^2 to inactivate this virus.

During grow out in the sea pens, disease, primarily *Vibriosis* (*V. anguillarum*), was an issue during warm water months at the farm site in Maine; however, once an autogenous vaccine was developed, this issue was well managed. Unlike in Europe, autogenous vaccines are a viable option and affordable to the farmer in the United States.

Parasites were not a major issue, but periodic issues with sea lice, and *Loma morhua* were observed at the farm sites that did account for some mortality. The sea lice presence on the fish were seasonal and farms did not have to treat pens on any regular basis.

Uniformity at harvest was an issue, as the industry was still growing progeny from domesticated wild broodstock; this highlighted the need for a breeding program. Early precocious maturation, as noted by others, particularly of females also reduced farm productivity. While technically feasible to stock a 5–10 g juvenile in a protected location, it became apparent that stocking a larger, better graded juvenile would perform better at sea.

4.3 | Market challenges and opportunities

The market in North America is very good for cod; however, the market will readily substitute Pacific cod for Atlantic cod. While the two species are similar, their market pricing is quite disparate. Atlantic cod, once primarily a fish and chips favorite, is now on menus at the highest price point, creating an incentive for substitution. The principal cod market, even in New England is now filled by lower cost Pacific cod from Alaska. As GreatBay Aquaculture of Maine sold its farmed cod into the fresh market, its competition was Pacific cod, and that pricing would not support profitable farm raised production. As the price of Atlantic cod rose, whether or not it was farm raised, buyers would substitute Pacific cod as American consumers could not tell the difference between the cods. As a result, working with a live fish distributor that serviced the Chinese markets in Boston and New York, GBA developed a market for 1 kg live Atlantic cod. While an excellent high value, niche market, this limited overall growth potential for the industry in the region.

4.4 | Current commercial status

There are no active cod farms in the New England region. Legacy broodstock from the breeding program with the University of Maine is being held at the Center for Cooperative Aquaculture Research in Franklin, ME.

4.5 | Promise and outlook for the next decade

In New England, Atlantic cod may enjoy a niche aquaculture market to supply the live market, but unless production costs can be lowered, and the price of whitefish that compete with it in the marketplace rise, the outlook is not very promising for large scale growth.

5 | COD CULTURE IN CANADA

5.1 | Commercial culture history

Atlantic cod was the principal species in a fishing industry that was the backbone of Newfoundland's economy and was an integral part of the social and economic fabric of Newfoundland since the arrival of Europeans in the fifteenth century. The failure of this fishery and subsequent announcement of a moratorium in 1992 had catastrophic impacts on Newfoundland's rural economy and way of life and spurred a great interest in developing cod aquaculture. Unfortunately, the history of cod farming in Newfoundland is described by a lack of long-term commitment and a chronic lack of capital that frittered the advanced place Newfoundland companies and researchers held as leaders in the development of this potential new industry.

In 1890, under the direction of Adolf Nielsen, Newfoundland investors opened the first cod hatchery in the province. Like those in Norway and elsewhere in the North Atlantic, vast numbers of hatched larvae were released over a six-year period as an enhancement effort to improve cod fisheries that had declined significantly. Financing for the program ceased in 1896 and the hatchery was closed.

Cod is an iconic species from Newfoundland whose return to abundance in the wild has been devastatingly slow to the communities that depend upon it. In July of 1992, the collapse of the Grand Banks cod fishery put 40,000 people out of work. In Newfoundland, the decimation of the cod fishery preceded that in New England by more than a decade, and hence the efforts to culture Atlantic cod to market size also first began in Newfoundland in the 1980s. A moratorium on the cod fishery was initially projected to last for 2 years to allow the stocks to recover, but by 1994, it was clear that it was to be prolonged much further and, in fact, is still in place today.

Cod grow-out in Canada initially was born out of the trap fishery for cod, the idea developed by Mr. Cabot Martin was to increase the size of the cod by feeding them forage fish, such as capelin (Pynn, 1999). The larger fish would get a higher price than the smaller fish. In July of 1993, cod farming courses were sponsored in 12 Newfoundland fishing communities by Sea Forest Plantation Ltd. and the Aquaculture Unit of the Marine Institute. While much was learned during this seasonal grow-out period, including aspects of fish health as it related to parasites and bacterial pathogens, including *Vibrio*, the market did not react favorably as the quality of the fish flesh was softer and exhibited gaping of the fillet muscle.

Sea Forest Plantation Ltd. (SFP) founded in 1986 by Jonathan Moir, initially grew wild caught cod from the trap fishery developing aquaculture techniques for the farming of cod in Newfoundland, harvesting around 350 m.t. per year until 1991, when the collapse of the trap fishery and the moratorium on cod harvesting eliminated the supply of small fish. SFP then established a cod hatchery and in 1996 produced its first commercial quantity of juveniles. A major milestone for the cod farming industry.

A total of 20,000 cod fry were produced in 1996. The hatchery was expanded in 1997 with a nursery facility capable of producing up to 500,000 juveniles. However, in May of 1997, the hatchery was destroyed by a fire which set back the whole commercial development by several years. The company relocated their hatchery, research, and production to the Ocean Sciences Centre of Memorial University and were able to produce 6,000 juveniles later in the season. In 1999, 50,000 cod were produced and moved to a land-based RAS broodstock system originally intended for halibut, constructed by Newfoundland Aqua Ventures, for partial grow out. Once again, the investment needed to move the fish to cage culture dried up when the investors refused to provide further injections of cash that were required to transfer the fish to cages and continue rearing them to market size.

Northern Cod Ventures looked to take up the cod torch in Newfoundland, starting to build a hatchery capable of producing up to 10 million cod juveniles in Bay Roberts, but with construction nearly complete, hoping to open in 2002, the final investment could not be found, as the original backers ran into financial difficulties, and the facility never went into production as planned.

With no commercial cod hatchery capable of producing sufficient quantity of juveniles in Newfoundland, Memorial University's Department of Ocean Sciences, under leadership of the late Dr. Joe Brown ended up playing a substantial role in the advancement of cod aquaculture in North America, particularly with advancing broodstock genetics and juvenile production. The CAD $12.3 million publicly funded Commercialization of Atlantic Cod and Support for the Atlantic Halibut Industry Project provided significant resources to continue the effort to establish commercial cod farming in Newfoundland.

The project in Newfoundland that addressed production and technology issues as well as best practices, included:

- Broodstock Development
- Live Feed Standardization
- Larval Rearing Protocols
- Fish Size and Time of Transfer to Sea
- Live Transportation
- Underwater Lighting-Early Maturation

- Grading at Sea and Net Changing
- Diets and Feeding Related Issues

Farm cage sites that were stocked with juvenile cod, collaborating with researchers were located in Hermitage Bay from 2001 to 2003, and McGrath's Cove from 2005 to 2008. In 2009, the Government of Canada through the Department of Fisheries and Oceans, along with the Province of Newfoundland and Labrador, Memorial University and Cooke Aquaculture (Cooke) announced a CAD $8.5 million project to establish a cod demonstration farm on the south coast of the Province.

In 2003, Cooke Aquaculture in New Brunswick converted one of its salmon farms, Kelly Cove, to farm Atlantic cod, establishing farming operations with juveniles supplied principally by GreatBay Aquaculture's hatchery in Portsmouth, NH. This was soon followed by a second site, Fundy, and a sea pen-based nursery site, named L&J. Cooke also converted a land-based RAS nursery in Mink Cove, NS, from salmon to cod to take the small fish from the hatchery to trial a larger size juvenile for cage stocking. Cooke continued to develop its cod operation through 2008 but post the economic recession and with numerous production challenges remaining and less government money available, Cooke backed out of cod aquaculture as it became a distraction to the ever-growing salmon farming industry.

In 2007, Cooke harvested 100 m.t., then 200 m.t. in 2008, and in 2009, the company harvested 1,050 m.t. of Atlantic cod.

The Grand Harbor Cod Company, Ltd. on Grand Manan Island, New Brunswick, was a Joint Venture (JV) with GBA to establish a sea pen nursery to supply farms in the Maritime Provinces. It was established in 2003, but in the winter of 2005 an icing event caused the catastrophic loss of the juveniles as ice crystals pierced the gills of the juveniles. The fish had missed their 2004 fall stocking in deeper water cages, and the JV never recovered.

Memorial University of Newfoundland, Department of Ocean Sciences, Huntsman Marine Science Center as well as the Department of Fisheries and Oceans' Biological station in St. Andrews, NB actively supported key research projects to support the growth of the industry in Canada. The most significant of these projects was known as the Cod Genome Project funded by Genome Atlantic (Trippel et al., 2009) to help advance the domestication of Atlantic cod, the CAD $18.1 million Atlantic Cod Genomics and Broodstock Development Project (CGP) was established to develop Atlantic cod family-based selective-breeding programs in Newfoundland and Labrador, and New Brunswick, Canada. In parallel, a large-scale genomics initiative was also undertaken.

The Atlantic Cod Genomics and Broodstock Development Project was a unique 4-year initiative that brought together key participants from industry, universities, government, and not-for-profit organizations in a partnership on cod aquaculture. The CGP was managed by Genome Atlantic with funding provided by Genome Canada, the Atlantic Canadian Opportunities Agency, Fisheries, and Oceans Canada, provincial funding bodies in the Atlantic provinces, industrial partners, and participating institutions. Industry partners included Cooke Aquaculture, GreatBay Aquaculture, and the Newfoundland Cod Broodstock Company.

In 2011, after the termination of the Cod Genome Project in 2010, cod farming activities in Newfoundland ceased, as the only company remaining in Newfoundland did not have the financial resources to continue farming in the sea.

The Newfoundland Cod Broodstock Company continued operations and in 2012 shipped cod eggs to Chile where they were raised in a hatchery adjacent to Puerto Montt. Fish were transferred to the ocean in 2014 and the project continued there until 2018. The last fish were removed, and the project terminated in early 2020. Growth performance in Chile in the cages was significantly better than in Newfoundland due to more stable water temperatures and a better-quality diet.

5.2 | Technical challenges and progress

In New Brunswick, the technical challenges were similar to those reported elsewhere in this review, such as deformity, fish health, early maturation, and the need for a long-term focused breeding program. In addition to Vibriosis,

Aeromonas, or furunculosis was also encountered in grow-out. In the trials performed at Cooke Aquaculture comparing stocking of small versus larger juveniles, it appeared the benefits of growing a larger juvenile on land, 100 g versus 10 g, including less time in the cages to harvest size, ability to administer intraperitoneal or IP vaccines and better grade and cull prior to stocking outweighed the higher juvenile cost of production.

Unfortunately, the loss of interest in, and lack of funding for, cod aquaculture in Newfoundland after the termination of Cod Genome Project has resulted in the breeding gains made with F1–F3 generations have been lost. Consequently, any future development will have to start with wild broodstock. As Norway maintained its broodstock development program the gains made from elite broodstock selection has clearly paid off in improved performance. There is renewed interest in cod farming in Norway which is now seen as an economically viable opportunity.

Technical challenges overcome in the hatchery:

- Survival increased from 2 to 3% in 1996 to consistent and predictable average survival through weaning of greater than 30%.
- Survival improved through all stanzas of development from first feeding, through weaning directly to dry diets from rotifer.
- Variable growth rates were gradually eliminated through the selection of breeding programs and improved production protocols.

Other technical challenges that continue in grow-out:

- Cage grow-out in Newfoundland never experienced problems with escapes from fish chewing on nets that was experienced in Norway, possibly because of the stock selected for production.
- Siting for cod aquaculture is a challenge in Newfoundland. Inshore waters have temperatures that fluctuate from -1.5°C to $+20^{\circ}$C. Specific sites may experience higher temperatures for periods during the summer with pronounced stratification that extends to 20 m deep, necessitating deep nets.
- Occasional offshore wind events can drop the temperature in summer from $+20^{\circ}$C to -1°C in a matter of hours resulting in *Vibrio* outbreaks due to the thermal stress, although this has been alleviated using vaccines. Growth performance is affected by high temperatures and there are only a few months when temperatures are within the ideal range of 8–12°C.
- Global warming may open new more northern sites that have little concern for ice formation in the winter and much lower temperatures in the summer than experienced on the south coast.
- Early maturation and increased mortality of females due to being egg bound reduced harvest yield and challenged economic viability.
- The combined effect of virtually no feeding from January through to April and potential spawning of early maturing fish can cause a drop in overall biomass of up to 30% post spawning.
- Compensatory growth post spawning does not gain back the cost of the lost weight over the winter and spring.
- Some parasite problems were experienced including *Loma morhua* and *Lernaeocera branchialis* but these are not major impediments and both can be addressed with good site selection.

5.3 | Market challenges and opportunities

There is a strong market for cod, but as a white fish it was difficult to maintain high prices with market pressure from both Pacific cod and rebounding fisheries in Iceland and Norway pushing price levels downward. In addition, the lucrative live markets in Toronto, Boston and New York were expensive to supply from Newfoundland.

- Initially, Sea Forest Plantation showed there was a market for farmed cod that generated an improved price over wild fish.
- Fillet yield was compromised by time of processing, duration of rigor and many other post-harvest issues that affected marketability.
- After the moratorium the market for cod contracted rapidly and was swiftly replaced by less expensive substitutes such as Alaskan Pollock, and other farmed whitefish such as tilapia and Pangasius.
- Barents Sea cod quotas recovered in the late 1990s and replaced Newfoundland in the fresh and premium frozen fish markets.
- Both the above-mentioned factors placed a downward pressure on price.
- Markets wanted consistent higher volumes than could initially be produced.
- There are niche markets for farmed cod directed to the white tablecloth and high-end retail sectors; however, the required capital investment is significant and the performance issues previously experienced in grow out will be dependent upon a selective breeding program.

5.4 | Current commercial status

There are no active cod farms in the Atlantic Canada region.

5.5 | Promise and outlook for the next decade

Cod is an iconic species in Atlantic Canada but is most often associated with fish and chips and subject to whitefish species substitution, whether that is from haddock, Pacific cod, pangasius, or imported Atlantic cod. Continuation of genetic breeding programs are necessary and controlling early maturation still requires work. The cost of production may be decreasing and many of the culture challenges known, but only a strong market price will induce another run at commercial cod aquaculture in Canada.

6 | CONCLUSION

As an aquaculture production species, Atlantic cod is technically a proven candidate. The broodstock reliably spawn massive numbers of eggs through photothermal manipulation. Hatchery survival rates exceed 30%. Their principal fish health issues are known, as well as their nutritional needs. Their genome has been mapped and selective breeding programs have advanced their commercial viability. As an added benefit, farmed cod are free of cod worms, this alone would save the processing industry millions of dollars annually.

In Canada, the United States and Britain cod do not command a premium price, sufficient to have overcome the development hurdles described earlier, nor maintained active breeding programs. For this reason, we believe we will see the resurgence of cod aquaculture coming from Norway and the interest from the other regions will not take off until market forces better align. In many parts of Europe and Norway, premiums are paid for fresh, quality fish, including cod. Norway has continued to invest in breeding programs for cod that make farming more economically viable. In December of 2020, a new Norwegian cod farming company Norcod AS made its first commercial harvest and has announced plans to harvest 10,000 m.t. in 2022 and 30,000 m.t. by 2025. The latter is clearly an example of a country that continued to support, over the long term, the generational species improvements gained through selective breeding. Cod breeding programs in both Canada (CGP) and the United States (NOAA, S-K Industry Grant), 4 and 2 years, respectively, while making important advances, were too short lived to have long lasting effects for moving the industry forward.

As described earlier, it is a long process to bring a species to commercialization and requires a long-term focused program to support fish health, nutritional research, and genetic improvements of key traits. The probability of success is increased when both the public and private sector make long-term commitments to the species commercialization, both biologically and economically. As even with all this, the market forces will be the final arbiter.

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