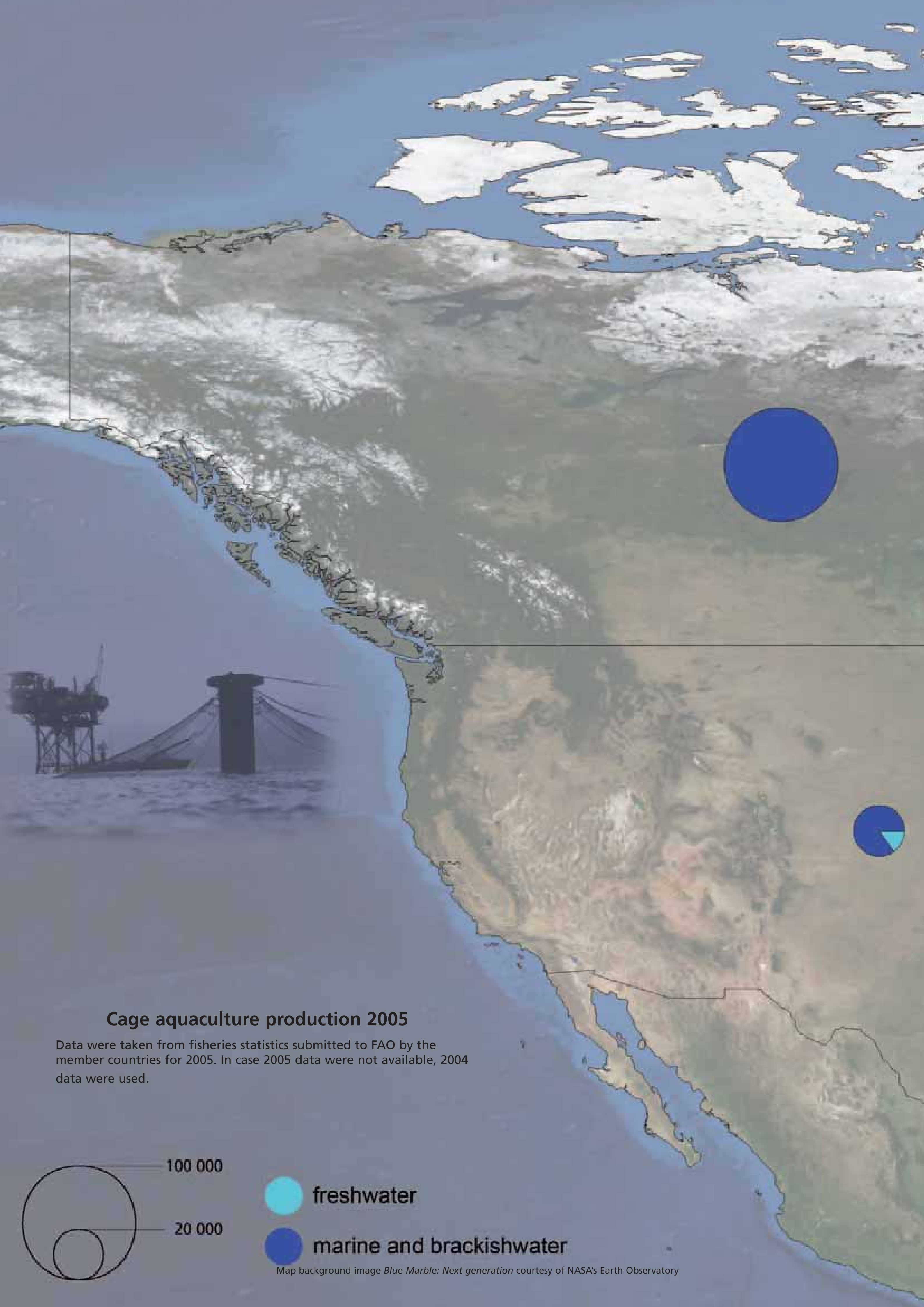
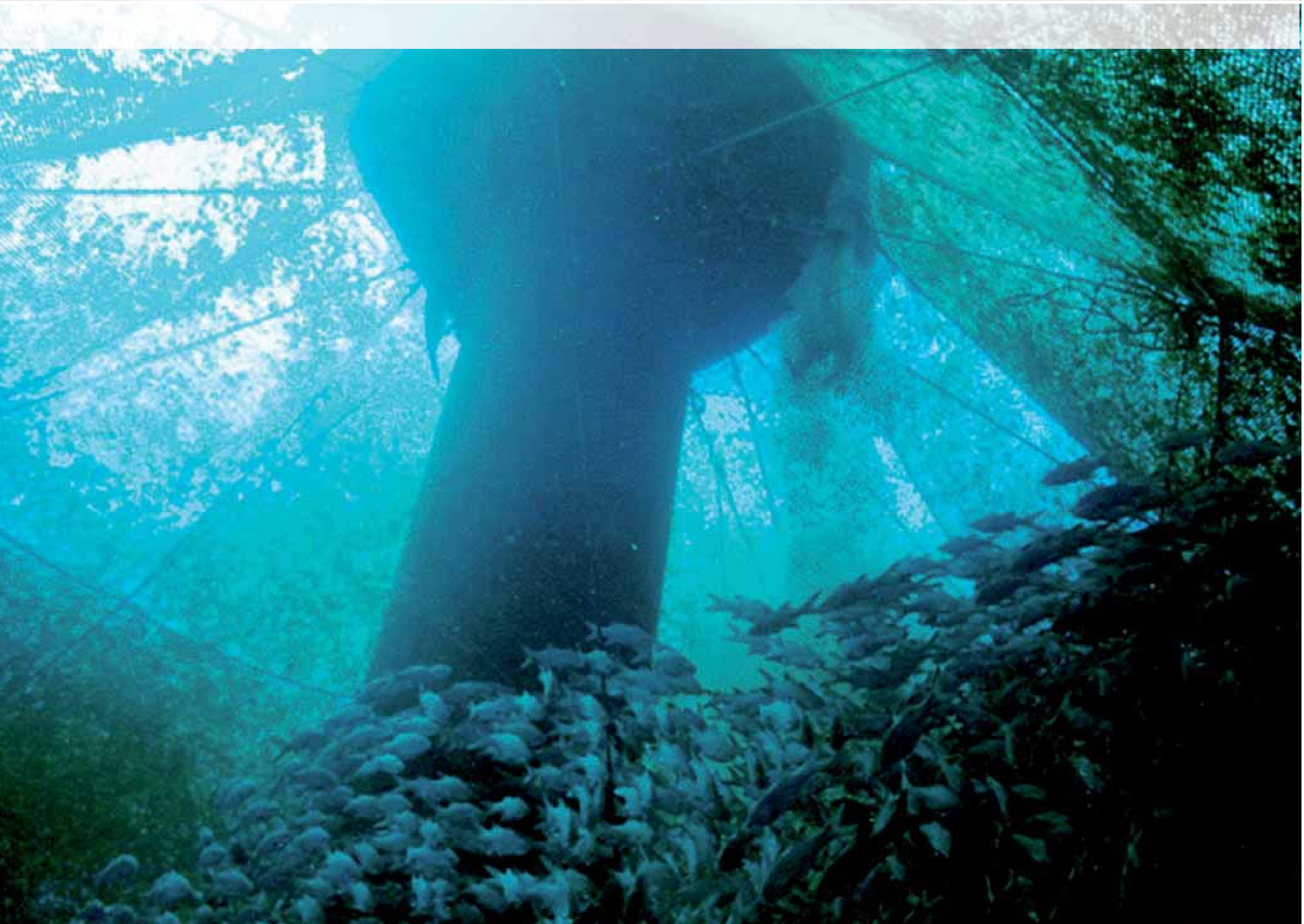



## Cage aquaculture production 2005

Data were taken from fisheries statistics submitted to FAO by the member countries for 2005. In case 2005 data were not available, 2004 data were used.

# A review of cage aquaculture: North America



# A review of cage aquaculture: North America

**Michael P. Masser[1] and Christopher J. Bridger[2]**

**Masser, M.P. and Bridger, C.J.**
A review of cage aquaculture: North America. In M. Halwart, D. Soto and J.R. Arthur (eds). *Cage aquaculture – Regional reviews and global overview*, pp. 102–125. FAO Fisheries Technical Paper. No. 498. Rome, FAO. 2007. 241 pp.

## ABSTRACT

This paper is an overview of the status and future prospects of cage aquaculture of marine and freshwater finfish in North America (excluding Latin American countries), covering Canada and the United States of America. Cage culture has a fairly recent history in North America compared to Asia. After four decades of evolution and growth, North American cage culture production and diversity is growing and future development and sustainability appears bright. Main species cultured are Atlantic salmon (*Salmo salar*), steelhead trout (*Oncorhynchus mykiss*), chinook salmon (*Oncorhynchus tshawytscha*), coho salmon (*Oncorhynchus kisutch*), rainbow trout (*Oncorhynchus mykiss*), channel catfish (*Ictalurus punctatus*), arctic char (*Salvelinus alpinus*), blue catfish (*Ictalurus furcatus*), cutthroat trout (*Oncorhynchus clarkii*), yellow perch (*Perca flavescens*), hybrid striped bass (*Morone* spp.), sunfish (*Lepomis* spp.) and tilapia (*Oreochromis* spp.). The total estimated aquaculture production in 2004 was 6 300 tonnes and 105 000 tonnes in freshwater and marine environments, respectively. No official data is available related to production and value of specific species in cage culture in freshwater or marine systems in the United States of America because such operations occur on private land or data cannot be kept anonymous (e.g. only one salmon producer in Washington State). Total production levels are tabulated by species and not by culture system employed. In all freshwater species cases, open pond aquaculture dominates the industry with cage culture activities providing a negligible quantity of production.

A great deal of public research and private innovation in cage culture technology, development of new species, and advancement of management techniques have taken place in North America. However, much more technological development will have to take place if open ocean aquaculture is to meet its projected potential. Currently, Canada leads the United States of America in expansion of commercial cage aquaculture and in developing policies, regulations and public perceptions that accept and promote the future growth and sustainability of its industry. The USA is making slow progress in developing policies that could permit cage aquaculture in the marine environment. However, the prospect of utilizing public freshwater sources for cage culture in the United States of America appears dismal. Most United States state natural resource agencies, which regulate access to public water bodies, have no desire or public/political pressure to allow or promote cage culture in public waters.

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## BACKGROUND AND AIM OF STUDY

This paper presents an overview of the status of cage aquaculture in North America, with examples of historical and current cage farming and impediments to future development. Cage aquaculture has experienced enormous evolution and growth in North America over the past four decades. We have chosen to discuss cage aquaculture in North America primarily based upon water salinity (i.e. freshwater versus marine) rather than by country. We felt that this approach ensures common topics are discussed together in a more logical arrangement. Within this framework, specific examples and discussion points by country are discussed as appropriate.

The information presented comes from numerous sources, including current research of the US Cooperative State Research Education and Extension Service (CSREES) Regional Aquaculture Centers and National Oceanographic and Atmospheric Administration (NOAA) Sea Grant, Government of Canada and provincial government agency statistical sources, scientific and popular literature (FAO, 2006) and recent reviews of cage aquaculture (Huguenin, 1997; Beveridge, 2004).

## HISTORY AND CURRENT STATUS OF CAGE AQUACULTURE IN NORTH AMERICA

Canada and the United States of America cover a vast area of land that occupies approximately 91 percent of continental North America. The two countries extend temperate and sub-tropical environments, three oceans and is the home of disparate cultures. Aquaculture production for both countries combined including all species was 577 641 metric tons having a total farm-gate value of US$1.46 billion in 2003 (compiled data from the above sources). Cage aquaculture operations exist throughout the two countries in marine and freshwater environments raising a wide diversity of species.

In Canada, aquaculture production was 145 018 metric tons valued at Can$ 518 million in 2004. Species raised in cages (salmon, steelhead trout and other marine species) recently accounted for approximately 70 percent of the total production volume but nearly 84 percent of total aquaculture value (Statistics Canada, 2005).

The scale and value of cage aquaculture operations is largely attributed to the rapid growth of the Atlantic salmon sector compared with 1986 data (Figure 1). Grow-out of other finfish species (including chinook salmon, coho salmon, trout, steelhead, cod and other species) has remained low despite industry and government investments to diversify the marine aquaculture industry. Atlantic salmon is raised in waters along both the Atlantic and Pacific coasts of Canada. British Columbia, Canada's only Pacific Ocean province, accounts for the majority of all Atlantic salmon production despite being a non-native species to the region and having initial grow-out trials and commercialization along the east coast of Canada in the Atlantic Ocean (Figure 2). Expansion of the Atlantic salmon industry is expected to increase as companies continue to make use of economies of scale and attempt to offset decreasing average prices. Prices have plummeted in recent years in large part due to increasing international competition and an excess of product in the marketplace (Figure 2).

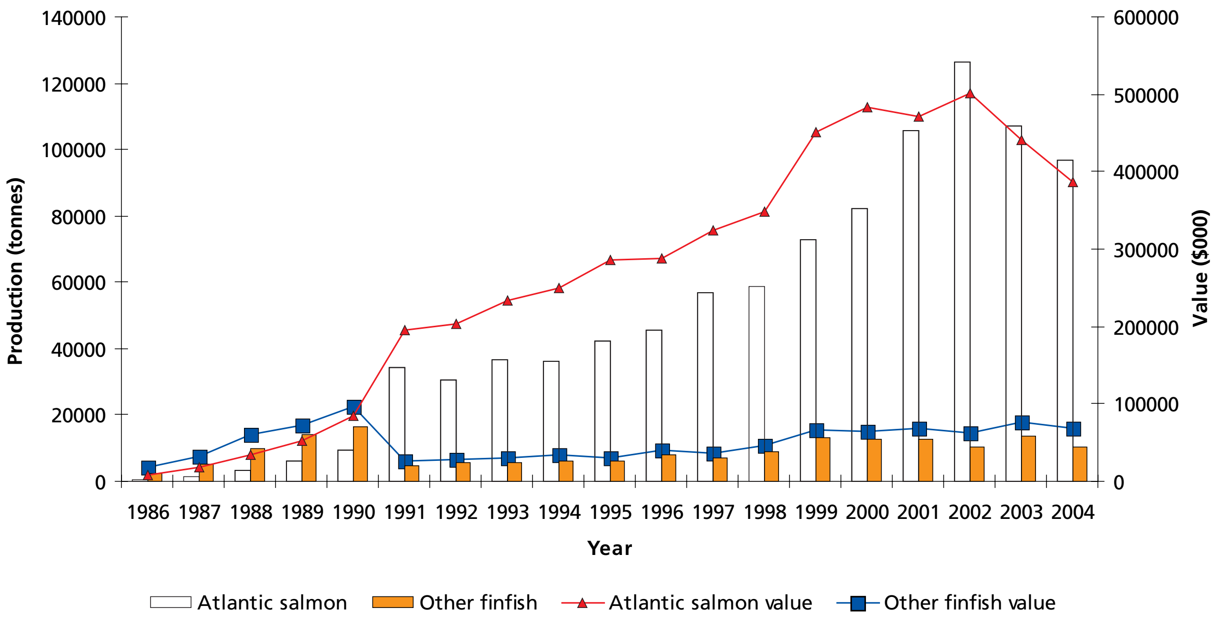
The total area licensed for aquaculture production in Canadian waters for all species is approximately 30 971 hectares or equivalent to a square measuring of 17.6 km x 17.6 km (OCAD, 2003).

This small patch of water resource produced approximately 14 percent of all Canadian seafood landings in 2003. The opportunity for continued growth of the Canadian cage aquaculture industry is tremendous having a total national coastline of 202 080 km. Given an appropriate regulatory policy framework coupled with increased environmental stewardship and consumer confidence, conservative projections for anticipated growth expects an increase in aquaculture product value from Can$0.5 billion in 2000 to Can$2.8 billion by 2010–2015 (anticipated multiplier effects of this value should equate to Can$6.6 billion to the Canadian economy [OCAD, 2003]).

Cage culture of Atlantic salmon (*Salmo salar*) in Canada followed its inauguration in Norway in the 1970s. The first attempts at full-cycle culture in marine cages occurred in the 1970s off Nova Scotia and New Brunswick, but failed due to lethal winter temperatures. A later successful venture was conducted in the southwest Bay of Fundy through a cooperative agreement between private enterprise and the provincial and federal governments. Their first production was 6 metric tons in 1979, which convinced other private investors to engage in Atlantic salmon aquaculture in the region (Saunders, 1995).

Farm-raised Atlantic salmon represents the single largest crop from the entire New Brunswick agri-food sector at 23 percent of total agriculture revenue (equivalent to the provincial production of potatoes, poultry, vegetables, fruits, berries

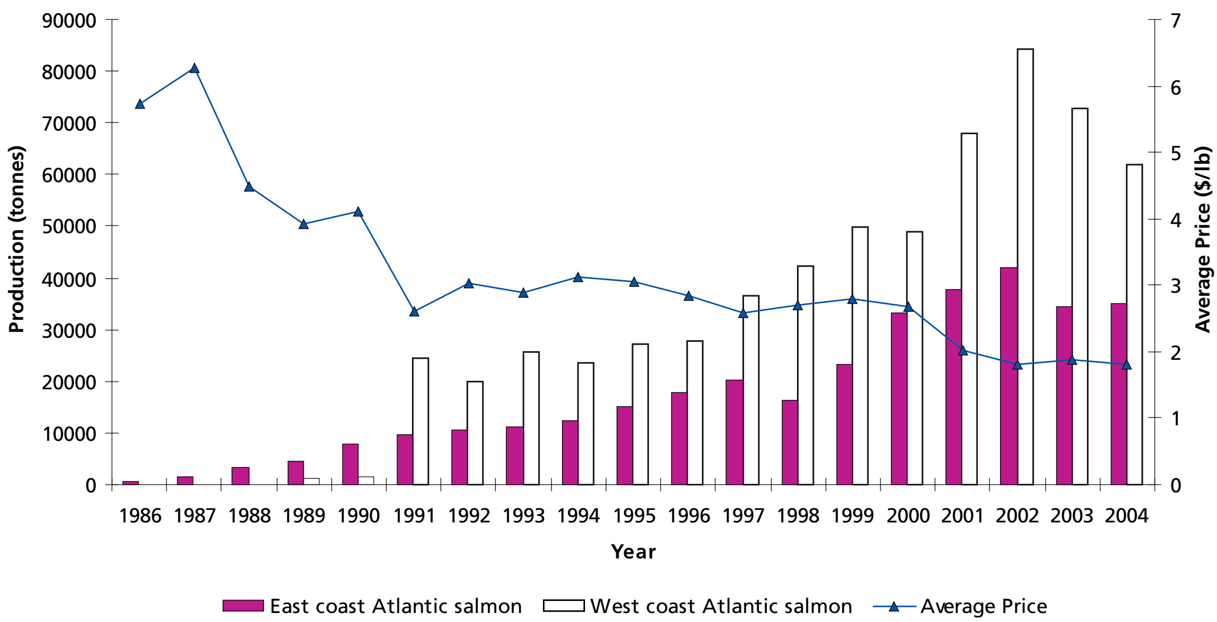
FIGURE 1
**Total Canadian finfish aquaculture production and value 1984-2004**




and grain combined) and a farm-gate value of Can$175 million in 2004. This level of production requires the services of 1 849 individuals in direct employment including hatcheries, marine grow-out, processing, direct services and administration (NBDAFA, 2005).

Steelhead trout (*Oncorhynchus mykiss*) was initially cultured off Cape Breton, Nova Scotia in the 1970s. Atlantic salmon production off Nova Scotia has been slower to develop than New Brunswick and is impeded today off much of the province owing to cold winter temperatures

FIGURE 2
**Atlantic salmon production in British Columbia along the west coast of Canada compared with Atlantic salmon production in all east coast provinces including Newfoundland and Labrador, Nova Scotia, New Brunswick, Prince Edward Island and Quebec. Production statistics are superimposed with annual values for average price per pound**



(most Atlantic salmon aquaculture is presently concentrated in the Bras d'Or Lakes, the Annapolis Basin, Shelburne Harbor and parts of St Margaret's Bay). Steelhead trout are raised in the Pubnico and Lobster Bay areas and the Bras d'Or Lakes. These two species combined accounted for approximately 36 percent of the total Nova Scotia aquaculture production sales in 2004. This value is lower than the 67 percent produced in 2003 due to industry financial difficulties and several catastrophic ice and superchill (extremely cold seawater) events during the winter of 2004. However, the industry recovered and the figures for 2005 were back up at 67 percent (http://www.gov.ns.ca/nsaf/aquaculture/stats/index.shtml).

Salmonid aquaculture (involving Atlantic salmon and steelhead trout) was not initiated in Newfoundland and Labrador until the mid-1980s. The present salmonid aquaculture is concentrated on the south coast in Bay d'Espoir and Fortune Bay. Grow-out of cod (*Gadus morhua*), the practice of catching small wild cod and feeding them to market size in ocean cages, was implemented in the 1980s following collapse of the once rich Grand Banks groundfish fishery. Research trials of cod egg-to-plate grow-out continued in 2004 with little more than 50 000 cod fingerlings stocked in sea cages along the province's south coast (NLDFA, 2005).

Salmon aquaculture in British Columbia began in the early 1970s with chinook (*Oncorhynchus tshawytscha*) and coho (*Oncorhynchus kisutch*) salmon operations. The industry gradually switched to Atlantic salmon cultivation owing to poor economic returns and reduced growth rates and stocking densities associated with Pacific salmon species. Anti-salmon farming organizations gained momentum throughout the 1980s and early 1990s culminating in 1995 when the second moratorium on aquaculture expansion was initiated and held until completion of a review of salmon aquaculture in British Columbia by the Environmental Assessment Office (the first moratorium on new site approval occurred in 1986 and resulted in the Gillespie inquiry). This review was finalized in 1997, following broad public consultation and literature analyses, with an overall conclusion that "salmon farming in British Columbia, as presently practiced and at current production levels, presents a low overall risk to the environment". The Salmon Aquaculture Review provided 49 recommendations to the Minister of Environment, Lands and Parks and Minister of Agriculture, Fisheries and Food as a means to move forward (EAO, 1997). Opposition to the local salmon aquaculture industry did not end with this review and expansion of the British Columbia salmon aquaculture industry has been slow despite the lifting of the moratorium. Salmon production in sea cages represents a very important industry to rural coastal British Columbia communities with 61 774 metric tons produced in 2004 valued at Can$ 212 million (Statistics Canada, 2005).

Marine cage culture in the states of Maine and Washington occurred in tandem with their neighboring Canadian provinces of New Brunswick and British Columbia, respectively. In both cases, marine aquaculture expansion has been stifled by continuous anti-aquaculture demonstrations mainly by a few environmental NGOs in Maine while Washington opposition tends to originate from those supportive of the wild salmon fishery. In both cases, these organizations are influencing policy for rural coastal areas that would otherwise benefit from having aquaculture operations along these working coastlines. Most United States coastal states lack the intricate coastline of Canadian marine provinces, the latter having numerous islands, bays, inlets and fjords for aquaculture development. Recognizing these limitations coupled with complex user conflicts for limited coastal space and a growing seafood trade deficit resultant from increasing dependence on foreign seafood products, the USA has invested quite substantially in the development of open ocean aquaculture since the late 1990s. On 10 August 1999, the United States Department of Commerce approved an Aquaculture Policy (http://www.nmfs.noaa.gov/trade/DOCAQpolicy.htm) to promote the development of an environmentally sustainable and economically feasible aquaculture industry with a vision:

> *"To assist in the development of a highly competitive, sustainable aquaculture industry in the United States that will meet growing consumer demand for aquatic foods and products that are of high quality, safe, competitively priced and are produced in an environmentally responsible manner with maximum opportunity for profitability in all sectors of the industry."*

Today a nascent aquaculture industry is operating in the open ocean off the coasts of Hawaii (Ostrowski and Helsley, 2003) and Puerto Rico (O'Hanlon *et al*., 2003). The University of New Hampshire has operated a government funded research site off the coast of New Hampshire since 1997 (Chambers *et al.*, 2003). The Gulf of Mexico region has also witnessed previous attempts at open ocean aquaculture, but no industry yet exists in the region (Chambers, 1998; Kaiser, 2003; Bridger, 2004).

## CURRENT SITUATION OF CAGE FARMING

### Freshwater cage culture farming systems

Freshwater cage culture in North America is often limited to private impoundments, as few states or provinces allow commercial fish production in public waters. No official data is available related to production and value of specific species in cage culture in freshwater systems in the United States of America because such operations occur on private land or the data collected would not be considered anonymous. Total production levels are tabulated by species and not by culture system employed. In all species cases, open pond aquaculture dominates the industry with cage culture activities providing a negligible quantity of production. In the United States of America, a few states (e.g. Oklahoma, Oregon and Arkansas) allow cage culture in public waters on a special permit basis. In Canada, freshwater cage culture is practiced in some public waters (i.e. Lake Huron, Ontario) through a permitting system.

#### *Cage design and construction*

Freshwater cages tend to be relatively small in volume as compared to marine cages but rearing densities are typically higher. Freshwater fish cages in the United States of America are typically utilized in private impoundments with no natural water flow. Freshwater cages usually range in volume from 1 m³ up to 7 m³ and are made from small mesh (i.e. 13–25 mm) nylon netting, solid plastic mesh or plastic coated welded wire mesh. Cage frames have been constructed from wood, polyvinyl chloride (PVC) pipe or galvanized steel with flotation provided by styrofoam, PVC pipe or plastic bottles (Figure 3) (Masser, 1997a).

#### *Species and farming systems*

North American freshwater cage culture historically was limited to rainbow trout (*Oncorhynchus mykiss*) and channel catfish (*Ictalurus punctatus*). Raceway and pond culture industries are well developed for these species. Many universities have broadly researched cage culture of these two species and some private production has grown fish in marginal areas where topography, springs/groundwater and/

FIGURE 3
**7 m³ freshwater cage used for channel catfish aquaculture**

COURTESY OF M. P. MASSER

or infrastructure were not suitable for traditional pond or raceway culture. Most freshwater cage culture is practiced in private watershed type impoundments. These typically release water only during heavy rainfall events and most discharge is during the cooler and wetter winter months. Exceptions to private impoundment culture include the Lake Huron and Columbia River production facilities discussed below.

Currently most marine cage culture operations are located close to shore although the home base of operations might be located a considerable distance away. These nearshore sites are located in deep-water fjords, protected coves, or bays with sufficient currents to limit localized water quality problems. The industry trend has been to develop more exposed high-energy sites. In a few instances cage culture operations are sited further from land thereby increasing the exposure of the cage systems to the oceanographic conditions.

Densities in small freshwater cages are high, ranging from 200 to 700 fish/m³ depending on species cultured and preferred market size. Production levels vary with species produced but usually range from 90 to 150 kg/m³ (Masser, 1997b). Common problems in freshwater cages are localized poor water quality and diseases (Duarte *et al.*, 1993).

Commercial cage production of catfish has never developed into a substantial industry (i.e. only 0.002 to 0.003 percent of the total United States catfish production) compared to open-pond culture in the United States of America. Most of the cage production is scattered throughout the South, Midwest and West and are small-scale, family operations producing fish for personal use and/or local niche markets. Alabama has had a viable cage catfish industry in its Piedmont region since the 1990s (Masser and Duarte, 1994), but currently has only 30 to 40 farmers producing 50–100 metric tons per year. These producers organized to form the Piedmont Association of Caged Fish Producers and trademarked a brand (i.e. Piedmont Classics) in 1993. However, trademarking did not result in an increase in sales or markets. The major reason for poor sales is probably related to the small size of cage operations and the higher sale prices necessary for producers to profit.

Traditionally these producers have marketed their catfish in the round for US$2.20/kg while pond-raised fish are sold for less than US$1.65/kg. An additional problem is the smaller size of fish produced. Typically, caged catfish seldom grow to over 0.6 kg in size in a single growing season and suffer high mortalities if over-wintered. Therefore, most cage-produced fish are marketed as small whole fish, while the industry (i.e. pond-raised) standard is a 0.8 to 1 kg fish processed and marketed as a fillet. The higher price and whole fish product make the cage fish non-competitive except in small-scale local niche markets.

Large catfish cage operations have existed on private lakes in central Missouri and in one public lake, Lake Texoma in Oklahoma (Lorio, 1987), but are no longer in operation. These failed because of diseases, slow growth, and/or water quality problems (Veenstra *et al.*, 2003). No surveys have been conducted since the early 1990s to determine the catfish production in cages. However, estimates would put total cage North American cage production of catfish at 300–500 metric tons per year.

Cage culture of rainbow trout in the United States of America is minor compared to raceway culture. There are scattered individuals producing trout in cages for local niche markets in the east and upper midwest. In Washington State on the Columbia River 16 river miles (9.4 km) below Grand Cooley dam is the single largest caged trout operation in the USA with 80 000 m³ total growing volume provided from numerous large cages (1 000–6 000 m³). Its annual production is in the range of 1 800–2 000 metric tons with maximum production of 30 kg/m³. Stocking density varies based upon fish size.

Other attempts at large-scale cage culture of rainbow trout and chinook salmon (*Oncorhynchus tshawytscha*) were attempted from 1988 to 1995 at two abandoned iron ore pit lakes in the state of Minnesota (Axler *et al.*, 1998). These operations met with strong and emotional opposition related to perceived pollution of the regional aquifer, which supplied water to nearby communities and recreational lakes. The operations were closed due to bankruptcy in 1995. Part of the reason for bankruptcy was the inability to meet new restrictions on water quality imposed by state regulators after permitting the operation. Approximately 2 000 tonnes of fish were produced during the seven years of operation. Later studies showed that the mine pit lakes totally recovered with minimal remediation and with no lasting impacts to the aquifer (Axler *et al.*, 1998).

In Canada, arctic char (*Salvelinus alpinus*) was cultured in cages in Newfoundland, Nova Scotia, Prince Edward Island and Ontario in the early 1990's (Glebe and Turner, 1993; Proc of Arctic

Char, 1993). Currently none of these facilities are producing arctic char in cages. Failures appear to have been caused by combinations of water quality, limited markets, and environmental concerns.

In Ontario, Canada, rainbow trout are cultured in large marine type cages in Georgian Bay of Lake Huron (Figure 4). Culture of rainbow trout started in this area in 1982 and has grown to 3 500 tonnes today. Currently ten sites in the Bay are utilized producing a market size trout averaging 1.2–1.4 kg (Figure 5). Cage culture in Georgian Bay represents over 75 percent of the total trout production in the province of Ontario (Figure 6). Total farm-gate value in 2004 was US$17 million or a value of approximately US$4.00/kg (Moccia and Bevan, 2004). The smallest farm consists of six cages measuring 15 m x 15 m with a production of 160 000–180 000 kg/yr. Operations smaller than this do not appear to be economically viable. The largest farm operation consists of twenty cages measuring 15 m x 25 m with a production of 450 000 kg/yr. Site investigations, water quality monitoring, permitting and oversight by government regulators are required for these operations.

The Arkansas Department of Game and Fish Commission produce catchable size fish in cages for stocking into public waters at three sites: Lake Wilhelmia, Pot Shoals and Jim Collins. Species produced include channel catfish, blue catfish (*Ictalurus furcatus*), rainbow trout (*Oncorhynchus mykiss*) and cutthroat trout (*Oncorhynchus clarkii*). Annual production is approximately 900 000 fish with a combined weight of 230 tonnes. Annual cost of production is US$2.09 per kg.

Other species currently cultured in freshwater cages include yellow perch (*Perca flavescens*), hybrid striped bass (*Morone* spp), sunfish (*Lepomis* spp) and tilapia (*Oreochromis* spp). The culture of these species is primarily limited to private impoundments for personal consumption or sales to small-scale local niche markets. Therefore, there is a lack of information as to the quantity of these species produced or their value.

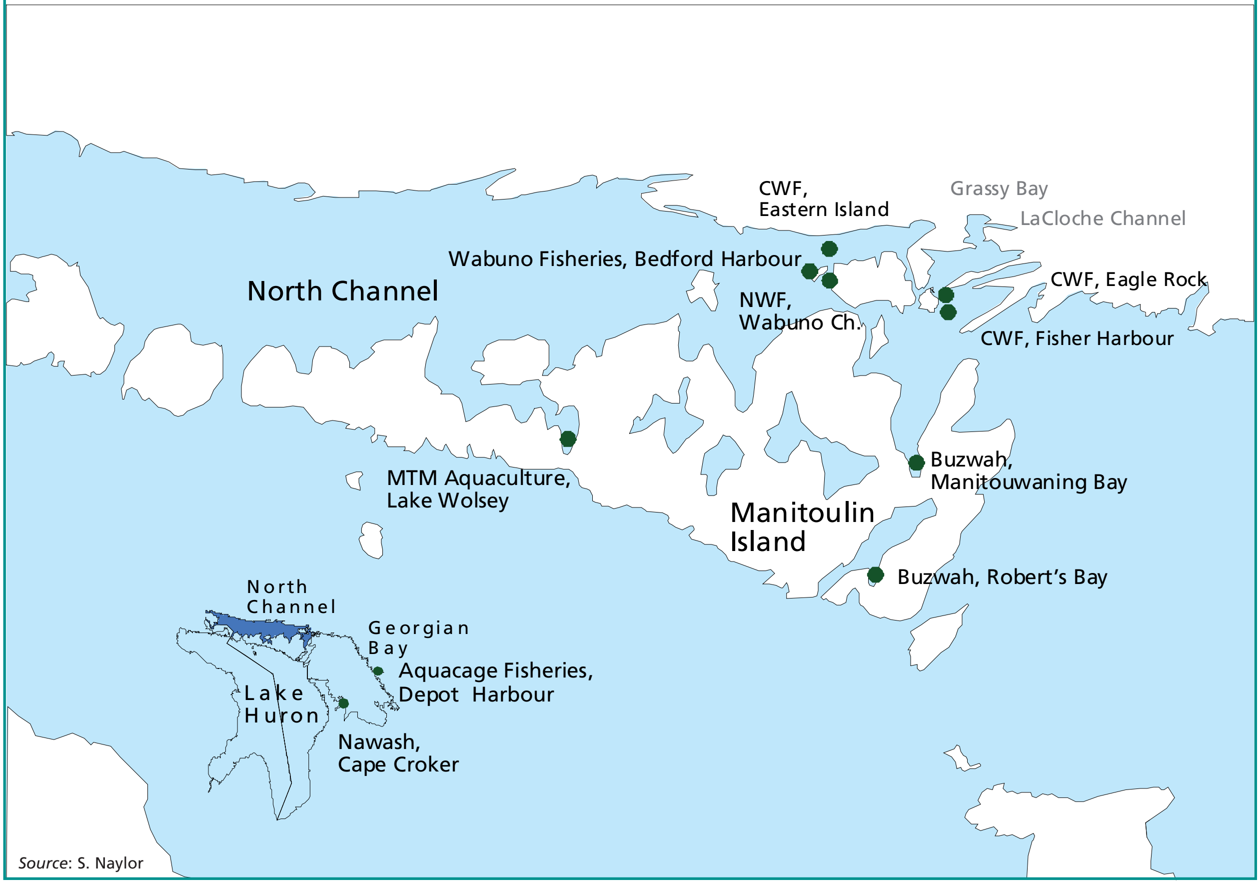
## Marine cage culture farming systems

Marine cage aquaculture systems vary immensely throughout Canada and the United States of America. Main criteria considered when choosing

FIGURE 4
**Freshwater rainbow trout cages in Georgian Bay of Lake Huron, Ontario, Canada**

COURTESY OF S. NAYLOR

FIGURE 5
**Map of freshwater rainbow trout cages in Georgian Bay and other sites in Lake Huron, Ontario, Canada**




*Source*: S. Naylor

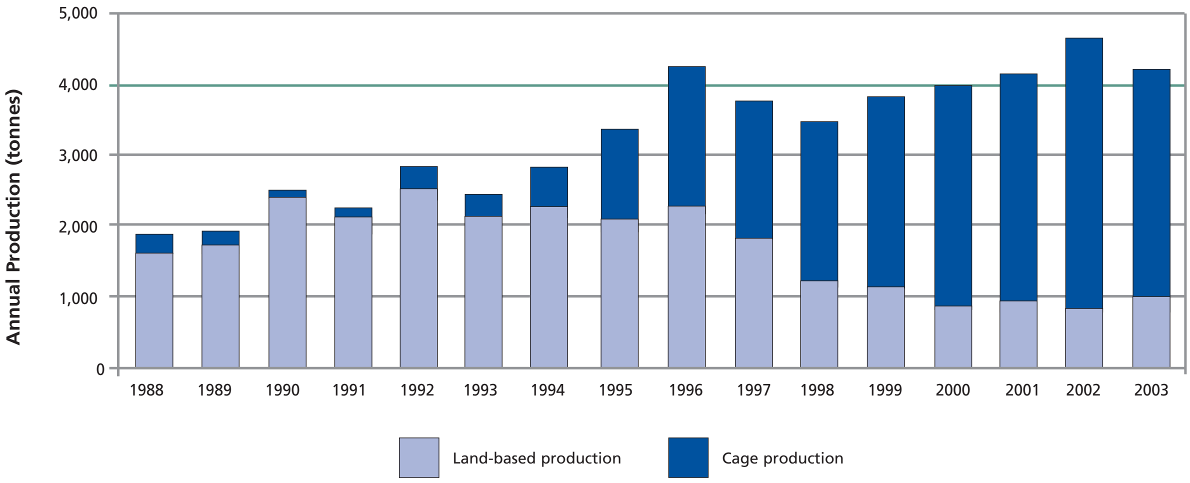
a marine cage farming system include: water body characteristics, degree of exposure, scale of operation, target species, market and economic outlook, and whether the farm is to be operated at or below the surface. Further, specific peripheral support systems (such as feed delivery systems and moorings) are chosen based upon many of the same criteria, but bottom soil characteristics, anticipated environmental loads, and in some cases the absolute need for an integrated system design whereby all individual components act as a single unit to minimize effects from environmental loading also must be considered. Indeed, marine aquaculture operations located in protected coastal bays and fjords have been successful at gradually increasing the scale of their operations coupled with increased technological sophistication. However, if a move to open ocean conditions occurs it will not be accomplished by simply moving existing coastal systems offshore. To the contrary, the entire system must be considered in a holistic manner from the outset to ensure operation efficiency and worker safety while reducing risks to the fish stock, capital infrastructure, the environment and other user groups of the open ocean.

### *Cage design and construction*

In recent years, the global cage culture industry has witnessed a surge of novel containment system designs. Despite these innovative concepts, marine cage culture operations raising commodity species such as salmon at coastal sites is reasonably uniform throughout North America and the globe. Nearly all of these cages can be classified as "gravity" type cages according to the classification scheme proposed by Loverich and Gace (1998).

In North America these cages have a surface collar structure from which a net is supported and hung into the water column (Figure 7). These collars are generally constructed of steel or high density polyethylene (HDPE) in coastal aquaculture systems in Canada and the United States HDPE is preferred in Atlantic Canadian operations owing to the reduced capital costs associated with using this material and the fact that HDPE collars are considered wave conformers (i.e. bend as necessary with passing energy as opposed to remaining rigid). Steel collars are hinged to allow some wave conformation between connecting cage units. Steel collars also offer stable work platforms

**Figure 6**
**Comparison of Ontario land-based and cage aquaculture production between 1988 and 2003**




*Source*: Moccia and Bevan, 2004

by providing a walkway along their sides that might be used by workers for feed and equipment storage and a stable platform to manage the farm operations. This is not the case for HDPE collar cages where two flotation rings are at the water surface. HDPE cages are not conducive to safe worker use and are not designed for storage thereby requiring separate barges on site.

Nets are typically hung from the inner plastic ring or inner portion of steel cage walkways while predator nets might be draped from the outer plastic ring on HDPE collars or the outer portion

FIGURE 7
**Standard surface-based HDPE collar cage used in the salmon aquaculture industry**


COURTESY OF C. J. BRIDGER

of steel cage walkways. Gravity cages do not have rigid nets and bagging occurs at times of high tidal current thereby decreasing the total cage volume. Indeed, Aarsnes *et al.* (1990) observed that up to 80 percent of the expected growing volume in surface collar cages may be lost in currents of 1 m/sec (approximately two knots). This issue was traditionally minimized by attaching weights to the lower portion of the net at frequent intervals to reduce net deformation. More recently, bagging has been eliminated by deploying a sinker tube from the surface collar and attached to the lower portion of the net to maintain the overall shape and cage volume.

Marine cages are moored as a group, or flotilla, typically within submerged grid mooring systems (Figure 8). These grids frequently provide upwards of eight mooring lines connected to each cage to maintain its position within the grid.

Salmon aquaculture cages have large growing volumes thereby providing an excellent return on investment. For example, a smaller surface-based HDPE cage might have a 100 m circumference with a net depth of 11.21 m and, therefore, provides a total growing volume equal to 8 925 $m^3$. A larger cage of similar structure with a 120 m circumference and having a net depth of 20 m will provide a total growing volume of 22 921 $m^3$. Assuming a target final stocking density of 15 and 18 $kg/m^3$ these volumes will hold 133 875 kg (133 metric tons) and 412 578 kg (412 metric tons) of salmon per cage, respectively.

In British Columbia, the salmon aquaculture industry is experiencing a constant campaign from anti-salmon farming environmental NGOs. Their efforts have stifled industry expansion over the past few years while government scientists have studied salmon farming and its environmental impacts to develop science-based policy as a way forward. While science strongly indicates that responsibly managed salmon farms have limited negative impacts on the ocean environment one company has been developing a novel cage design that could conceivably eliminate any risk of deleterious environmental consequences. Future Sustained Environment Aquaculture (SEA) Technologies Inc. was founded in 1994 to develop an enclosed water-tight SEA system that is supplied with water pumped into the fish grow-out enclosure from optimum locations, including depth, to regulate temperature, oxygen levels, and overall water quality while increasing waste management capabilities and minimizing fish escapement (Figure 9; http://futuresea.com). In 2001, Marine Harvest Canada began tests to compare the Future SEA system with conventional steel cage systems as part of the British Columbia Salmon Aquaculture Policy Framework. Over the 14-month trial period the

FIGURE 8
**Typical near shore submerged grid mooring system maintaining multiple cages within a flotilla**

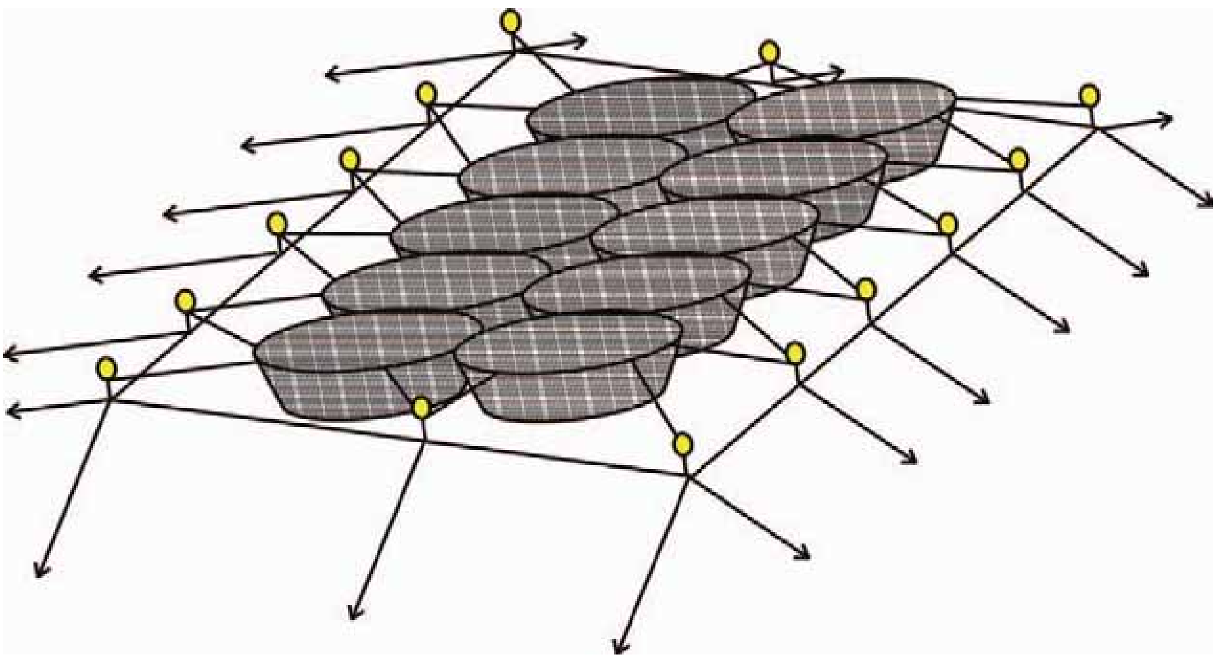
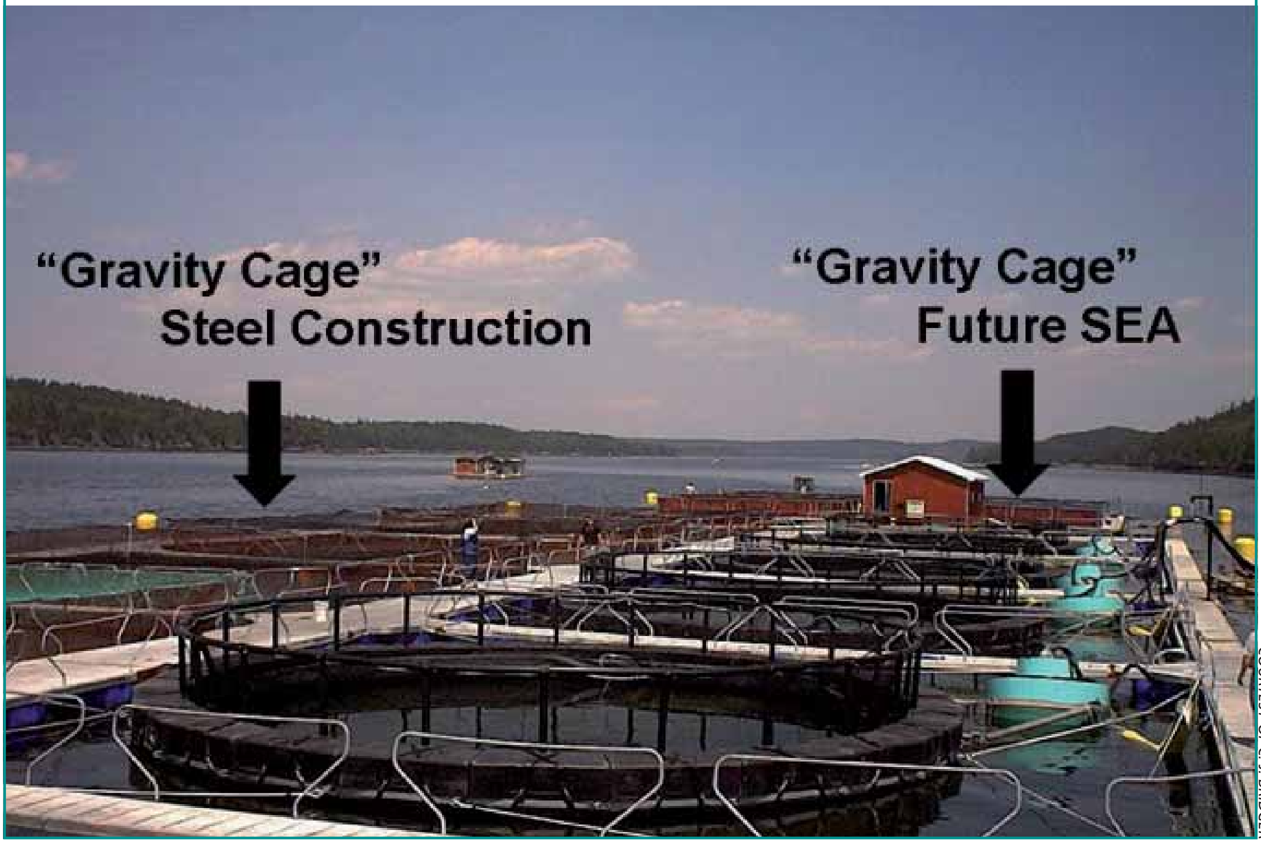


FIGURE 9
**Comparison of standard surface-based steel collar cages and the Future SEA system**




SEA system performed well and comparable to conventional steel cages with regards to survival, feed conversion and overall fish health (Hatfield Consultants Ltd, 2002). The future SEA system did not perform as well economically, however, with the farm gate cost of production for the system being 29 percent higher compared with conventional steel cage systems. This level of increase translated to a difference of US$0.85/kg at the time of harvest.

Numerous cage designs have been proposed and deployed in open ocean conditions in North America. In the USA, the predominant cage system at the moment is the Ocean Spar Sea Station cage (Figure 10; http://www.oceanspar.com). The Sea Station is a self-tensioned cage around a single spar buoy (Loverich and Goudey, 1996). Detailed descriptions of the Ocean Spar Sea Station cage can be found in Tsukrov *et al.* (2000) and Bridger and Costa-Pierce (2002). The experimental cages used in the Gulf of Mexico (Bridger, 2004) and New Hampshire (Chambers *et al.*, 2003) provide a growing volume of 595 $m^3$. Sea Station volumes up to 35 000 $m^3$ have been designed (Loverich and Goudey, 1996) although the largest used commercially to date provides a 3 000 $m^3$ internal volume (Ostrowski and Helsley, 2003; O'Hanlon *et al.*, 2003) but recently a 5 400 $m^3$ cage has been introduced for use by Ocean Spar. Ocean Spar Sea Station cages are all operated well below the water surface in the United States of America. Submerged operations in high-energy open ocean sites do seem intuitive to avoid or at least minimize environmental loads experienced at the surface. On the surface, wave particles rotate at a diameter equal to the wave height and therefore provide the greatest amount of wave energy. This rotation decreases with increasing depth thereby reducing the environmental loads affecting aquaculture structures operated well below the water surface. Tsukrov *et al.* (2000) further substantiates this point by reporting mooring line tension to be 60 percent less for submerged cages compared to surface positions under identical environmental loads. Equally important is the ability of submerged operations to minimize oceanographic effects on contained fish. However, benefits associated with submerged operations have also come at a price as no turn-key or proven farm management options

FIGURE 10
**An Ocean Spar Sea Station cage moored offshore in the Gulf of Mexico adjacent to a gas production platform**


PHOTO COURTESY OF T. REID

are presently available. Numerous farm operations will need to be automated to minimize reliance on scuba diving to perform such farm chores. Until such automation occurs to provide safe and efficient farm management options, submerged operations will have no other option but to remain at a relatively small scale while relying upon divers.

Another innovative example is the Aquaculture Engineering Group in New Brunswick, Canada (http://www.aquaengineering.ca). This company has developed a 'swing site' configuration that also deploys a current deflector to reduce oceanographic conditions experienced on-site. Key to the system's design is the continued use of conventional surface-based cages widely accepted in the salmon farming industry.

Inventory and record keeping are critical for optimal farming practices. Maintaining a record of the number of mortalities removed from the cage and frequent estimates of growth (and calculated biomass) is required for calculating feeding rates, determining quantity of medication to be provided when necessary, and for planning production and harvest schedules. In the least sophisticated operations, a random sample of the entire population is removed from the cage at a meaningful time interval (monthly), anesthetized and weighed to gather necessary growth data.

More technologically advanced farms do not actively disturb the fish stock to reduce stress. Alternatively, fish sizing technologies using video or acoustic image analysis is employed that measure individual fish without physically disturbing them.

***Species and farming systems***

By far, Atlantic salmon (*Salmo salar*) is the species of choice for marine cage culture operations in North America. This species is native to the Atlantic Ocean but a vast quantity of Atlantic salmon is farm-raised along the Pacific coast of Canada.

Other salmonid species raised in sea cages are chinook salmon (*Oncorhynchus tshawytscha*), coho salmon (*Oncorhynchus kisutch*) and steelhead trout (*Oncorhynchus mykiss*). Atlantic salmon in particular is farmed at such a great volume that it has become a commodity species. While this is excellent news for the consumer wanting to purchase wholesome, nutritious and affordable seafood this greatly reduces the profitability of salmon farming operations. Given the reality in which they operate, many salmon farming enterprises have directed a substantial amount of time and investment into species diversification both to supply a broader range of products to the consumer and reduce risks associated with producing only one species all the time.

Candidate species for salmon producers include Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) in the Atlantic Ocean and sablefish or black cod (*Anoplopoma fimbria*) in the Pacific Ocean.

The United States of America possesses a varied environment that is also home to a variety of candidate aquaculture species. In New England, many of the same species are candidates as those studied by present salmon producers for their aquaculture potential.

Further along the United States Atlantic Coast and into the Gulf of Mexico the list of candidate aquaculture species impressively expands to include: cobia (*Rachycentron canadum*), greater amberjack (*Seriola dumerili*), red snapper (*Lutjanus campechanus*), and red drum (*Sciaenops ocellatus*). In the United States Pacific (including Hawaii) equally appealing candidate species for grow-out include Pacific threadfin (*Polydactylus sexfilis*) and kahala amberjack (*Seriola rivoliana*).

## REGIONAL ISSUES

### Freshwater cage culture

Issues that negatively impact small scale cage producers are:

1) limited or no access to large bodies of water (i.e. no public water bodies);
2) higher price paid for fingerlings and feed because of the small size of operations and a location typically outside of traditional aquaculture areas;
3) lack of processing and marketing infrastructure; and
4) diseases.

While high quality fingerlings and commercial feeds are available, usually the cost of shipping and small quantities needed increase the production cost far above what is paid by larger commercial pond or raceway producers.

Finding and servicing niche markets is also difficult for small-scale producers with limited physical and financial resources and/or marketing experience. Where cooperatives and associations have attempted to buy in bulk and market to larger buyers, they have not succeeded probably due to the higher production costs and therefore higher sales prices.

No environmental problems have been associated with freshwater cages in private impoundments. Associated water quality, escapement and other ecological impacts are contained within the impoundment. Private impoundments generally have multiple uses including recreation and livestock watering, are seldom if ever drained, and usually only discharge water during the winter-rainy season. Therefore, few conflicts exist with cage culture practices. Most fish species cultured are native species, with the exception of tilapia. Tilapia production in cages is restricted in only a few states (e.g. Texas and Louisiana). Most states have no restriction on tilapia culture since they will not survive North American winters.

The larger cage operations in public waters for rainbow trout in the province of Ontario and Washington state have gone through an extensive permitting process and are regularly monitored for water quality and other related environmental impact issues. The owner of the operation in Washington felt that he had spent US$1.5 million to set up and permit his farm (Swecker, personal communication). Issues with site location, public perceptions, permitting costs, environmental NGO's involvement in permitting and negative public dialog, and the lack of clear policies and legal frameworks for permitting in most states in the United States of America, has and continues, to hinder development of cage culture in public waters. It is estimated that the cage permitting process in Ontario would require one to two years and a cost of around US$60 000. This cost is primarily for the site evaluation studies necessary to obtain a permit. Permitting involves several Federal and Provincial ministries and numerous Acts (Moccia and Bevan, 2000). Objections or conflicts with shoreline property owners (NIMBY = not in my backyard, syndrome) surface as the major problem faced by cage culture entrepreneurs attempting to obtain permits. Therefore, locations where these types of operations have been or can be permitted at freshwater sites in North America are extremely restricted and future expansion is likely limited.

### Marine cage culture

Marine cage culture operations are established in many areas of North America. However, total production from these operations is somewhat limited when compared with potential and anticipated growth over the next decade. Numerous constraining issues will need to be addressed before the promise of many of the involved industry sectors comes to fruition.

Marine cage culture systems used in protected bays and fjords are largely a known entity. However, the industry trend in both Canada and the United States of America is for expansion to more exposed open ocean conditions where they experience fewer human conflicts. Near shore aquaculture technologies and operations will not be able to simply move to these new high-energy environments and ensure continued worker safety and efficient farm operations. Novel open ocean aquaculture technology has been developed over the past decade to begin meeting the needs of this new cage culture sector. However, much technology development remains. One of the critical needs for development is the automation of farm operations. Dependable automation will at minimum ensure fish are effectively fed during inclement weather, but will also be important for other farm chores including fish sizing, net cleaning, mortality removal, fish health monitoring and cage/mooring inspections. Fish feeders might also incorporate technology for long-distance communication to enhance control afforded to site managers. Adoption of these technologies will ensure that site visits will only be necessary for general maintenance and feed delivery when conditions are safe.

***Social aspects***

Industry expansion for marine cage culture will require access to additional space for sites. This aspect is quite different from much of the freshwater cage culture that occurs on private land. In marine aquaculture, the operations are located in the ocean – a resource always considered to be common property. Marine cage culture companies will have to conduct their business in such a manner that the public is informed at all times. This does not imply that company accounting should be open to public scrutiny. However, industry plans for a region or coastline must be discussed within open public forums to ensure that public concerns are addressed at each stage of expansion. In addition, appropriate integrated coastal zone management plans must be developed. Areas appropriate for aquaculture should be chosen that also minimizes interactions between traditional uses of the marine environment including capture fisheries, tourism, land owners rights, shipping, extractive industries, and areas having frequent visits by marine mammals. An excellent example of this sort of exercise was recently published concerning expansion of the salmon aquaculture industry in the Bay of Fundy (Chang *et al*., 2005).

Marine aquaculture also presents an excellent opportunity to maintain coastal communities that are presently reliant upon over-harvested commercial fisheries. Many of these wild fish harvesters represent a highly trained workforce that have extensive knowledge of the ocean, boat handling, net mending and maintenance, and fish harvesting and quality control that aquaculture companies can easily adapt to their own operations. In these cases, previous wild fish harvesters would require some basic training associated with standard farm operations and fish health management. Numerous Atlantic cod fishermen converted to cod grow-out aquaculturists in Newfoundland and Labrador following the collapse of the northern groundfish stocks (these operations entailed live capture of small cod for further grow-out in sea cages prior to harvest for market). These operations have for the most part ceased to exist owing to limited access to small cod around the province for grow-out. However, this experimental period demonstrated that wild fish harvesters can easily adapt to the needs of aquaculture enterprises if the opportunity exists.

In addition to employing wild fish harvesters, any region developing an open ocean aquaculture sector will reap the economic benefits associated with the production and sale of fish grown in marine cages. Recent economic analyses concluded that a single farm operation directly employing only seven individuals for offshore production will provide an additional annual regional economic output of at least US$9 million and provide additional employment for at least 262 persons, related to processing, feed production, distribution, etc. (Posadas and Bridger, 2004). These impacts must be conveyed to local policy makers to ensure many of the coastal communities presently devastated by collapsing wild fisheries have a new source of sustainable income for generations to come.

The aquaculture industry must also become more proactive in shaping public perception of their industry. At present, the environmental NGOs are winning battles for public sympathy on many fronts. The aquaculture industry must rely on science-based information to garner public support while resisting involvement in the usual environmental NGO antics including the use of manipulated, outdated, and/or misleading information regarding aquaculture and its practices. Increased public trust will open additional markets for farm-raised products and potentially allow industry expansion to new sites that are presently contested.

### *Economics and markets*

Aquaculture industry consolidation is a global phenomenon as large multi-national companies seek appropriate economies of scale throughout their entire production and supply chain. This allows them access to increased market-share in the competitive global marketplace for seafood products. In Canada, industry consolidation is recently most pronounced on the Atlantic coast (the Pacific coast has also experienced several rounds of industry consolidation in the past). Here, a local salmon aquaculture company has been successful at industry consolidation within Southwest New Brunswick and Maine while also expanding its operations through new site development in Nova Scotia and Newfoundland and Labrador. Such industry consolidation will undoubtedly result in greater efficiency but also some local loss of employment. However, this degree of consolidation will also ensure a greater degree of control over the company's entire production chain while gaining additional access to its primary market in New England.

The United States of America represents the main export market for Canadian aquaculture products. Aquaculture companies in Canada are well aware of this; in a recent survey of British Columbia aquaculture firms, proximity to markets and the Canadian/US dollar exchange rate ranked as the top two of 35 business factors considered (PricewaterhouseCoopers, 2003). Having direct access to the United States market greatly benefits the Canadian aquaculture industry. However, this dependence also subjects the Canadian aquaculture industry to the vagaries of international factors such as fluctuating currency exchange rates. The Canadian dollar has steadily appreciated against the United States dollar over the past four years – in 2002 the United States exchange rate averaged 1.57 but decreased to 1.21 in 2005. This rate of appreciation is substantial and represents a net loss of 36 cents on each dollar of sales between 2002 and 2005. This loss drastically diminishes industry profit in the absence of increased market prices, production and economies of scale, or efficiency.

### *Ecological and environmental aspects*

Aquaculture operators must act as professional environmental stewards to ensure a pollution-free environment to raise fish and earn a profit. Without a clean, consistent water supply the product to be grown would be stressed with resultant slow growth rates and potential high mortality. Potential environmental impacts associated with marine cage culture operations can be grouped into four broad categories:

1. *Benthic and water column impacts* – Benthic and water column impacts are often associated with poor site selection, management decisions, site overproduction, or some combination of the three. These effects are reversible and can be mitigated through careful farm management and by adapting a site fallowing policy between successive grow-out cycles (McGhie et al., 2000).
2. *Impacts on the frequency of harmful algal blooms* – Fish farming activities will result in increased nutrients in the surrounding environment. However, most studies to date have concluded that aquaculture activities sited in preferred locations have not resulted in increased abundance of phytoplankton species (Parsons *et al*., 1990; Pridmore and Rutherford, 1992; Taylor, 1993). In fact, Arzul *et al*. (2001) reported inhibited phytoplankton growth when in the presence of excretion from selected finfish species (sea bass and salmon). These results were in stark contrast to the excretion from shellfish species (oysters and mussels), which stimulated phytoplankton growth rates.
3. *Impacts to local and migratory marine mammals* – Unlike fishing gear, entanglement of marine mammals into aquaculture gear has not been frequently documented and therefore generally represents a low concern of aquaculture operators. However, when such interactions occur the costs to both the aquaculture site (in lost stock and negative public perception) and the marine mammal involved tends to be great. The aquaculture industry must do everything possible to avoid such incidents.
4. *Escapement and implications to wild populations* – Aquaculture companies can only remain in business if they manage to contain their fish stock for sale. The most logical approach to mitigate impacts of escaped aquaculture fish is prevention. Myrick (2002) discussed escapement of cultured species in general while Bridger and Garber (2002) specifically reviewed salmonid escapement occurrence, implications and solutions for mitigation. In cases that escapement does occur, salmonid escapees –

specifically steelhead trout – have been observed to remain in the vicinity of aquaculture cages and displayed a homing response to aquaculture facilities if escapement occurs away from established aquaculture sites (Bridger *et al*., 2001). These results indicate a much lower risk from escapement to wild stocks than portrayed by environmental NGOs. Further, developing recapture strategies to return escapees to cages for additional growth and decreased economic losses should be feasible.

### *Policy and legal frameworks*

Policy and legal frameworks associated with marine cage aquaculture differs immensely based upon the specific jurisdiction involved. In Canada, both federal and provincial levels of government have a role in developing and ensuring the aquaculture industry has the ability to expand while being managed in an environmentally and socially responsible manner. In recognition of this joint role, Canadian Ministers of Fisheries and Aquaculture (national and provincial) have agreed to Interjurisdictional Cooperation and creation of a Canadian Action Plan for Aquaculture that commits both levels of government to improve the regulatory environment, strengthen industry competitiveness, and increase public confidence in both industry and government. In nearly all cases, provincial government departments have assumed responsibility for site allocation of aquaculture in the oceans through federal-provincial Memoranda of Understanding. Many provincial departments have created appropriate Bay Management Plans and single year class management systems (i.e., one generation of fish on a site at a time) to improve fish health management and environmental quality.

In the United States of America, all marine cage aquaculture to date occurs within specific state waters. States manage aquaculture industries individually, which can result in some inconsistency between states. "Offshore aquaculture" serves as a legal term in the United States of America, which refers to aquaculture operations sited in United States federal waters. Federal waters represent the expanse of ocean existing outside of state waters within the United States Exclusive Economic Zone, typically occurring three miles outside of the furthest state controlled land (including islands) to 200 miles offshore. The existing policy framework for aquaculture in United States federal waters has been frequently cited as the prime reason for no industry development. Presently unregulated, Senate Commerce Committee Co-Chairs introduced S. 1195, the National Offshore Aquaculture Act of 2005, on 8 June 2005 to:

> *"…provide the necessary authority to the Secretary of Commerce for the establishment and implementation of a regulatory system for offshore aquaculture in the United States Exclusive Economic Zone and for other purposes."*

Introduction of this Act represents the first of many essential steps necessary for aquaculture to be established in United States federal waters. Following adoption, the Department of Commerce will have authority to create the necessary regulations to govern an offshore aquaculture industry. This process will require many years, numerous public comment periods and revisions prior to completion.

## THE WAY FORWARD

The importance of markets cannot be overemphasized. As discussed earlier, Canada looks to the United States of America as its main export market. Many other countries also export heavily to the United States of America and Canada, so international development and competition is expected to drive seafood markets in developed countries. Many "unfair trade" issues have already surfaced with seafood imports to the United States of America. These will undoubtedly increase in the future as competition and a perceived "fair playing field" will be fought in political arenas.

The United States of America probably more than Canada or most other countries has had a great deal of opposition to marine cage culture in public fresh and near-shore waters. Therefore, as discussed earlier, aquaculture farmers must take a more proactive role in engaging the public and countering non sustained accusations of environmental NGOs. They must develop public trust and work closely with legislators and public officials, demanding scientific studies and a science-based policy for future development.

The prospect of utilizing public freshwater sources in the United States of America for cage culture is remote. Most United States state natural resource agencies, which regulate access to public water bodies, have no desire or public/political pressure to promote cage culture in public waters.

It appears that most expansion of cage aquaculture in the United States of America will involve open ocean cages. At the moment, new open ocean aquaculture entrants are limited in many jurisdictions and the species of choice frequently has limited competition from wild harvests thereby yielding excellent demand for cultured products. At some point, these direct benefits to early business entrants will diminish as candidate species become a commodity and established markets are flooded. Operators using many of the existing or proposed open ocean aquaculture cage systems may experience economic difficulties in raising commodity species owing to limited growing volume with new cage designs and high capital outlay costs. These operators will have to become more efficient in their farm operations or deploy more cost-effective cage technologies to be profitable. Cage manufacturers will be required to design and supply systems that are indeed lower cost per unit volume. Some companies are already considering these possibilities.

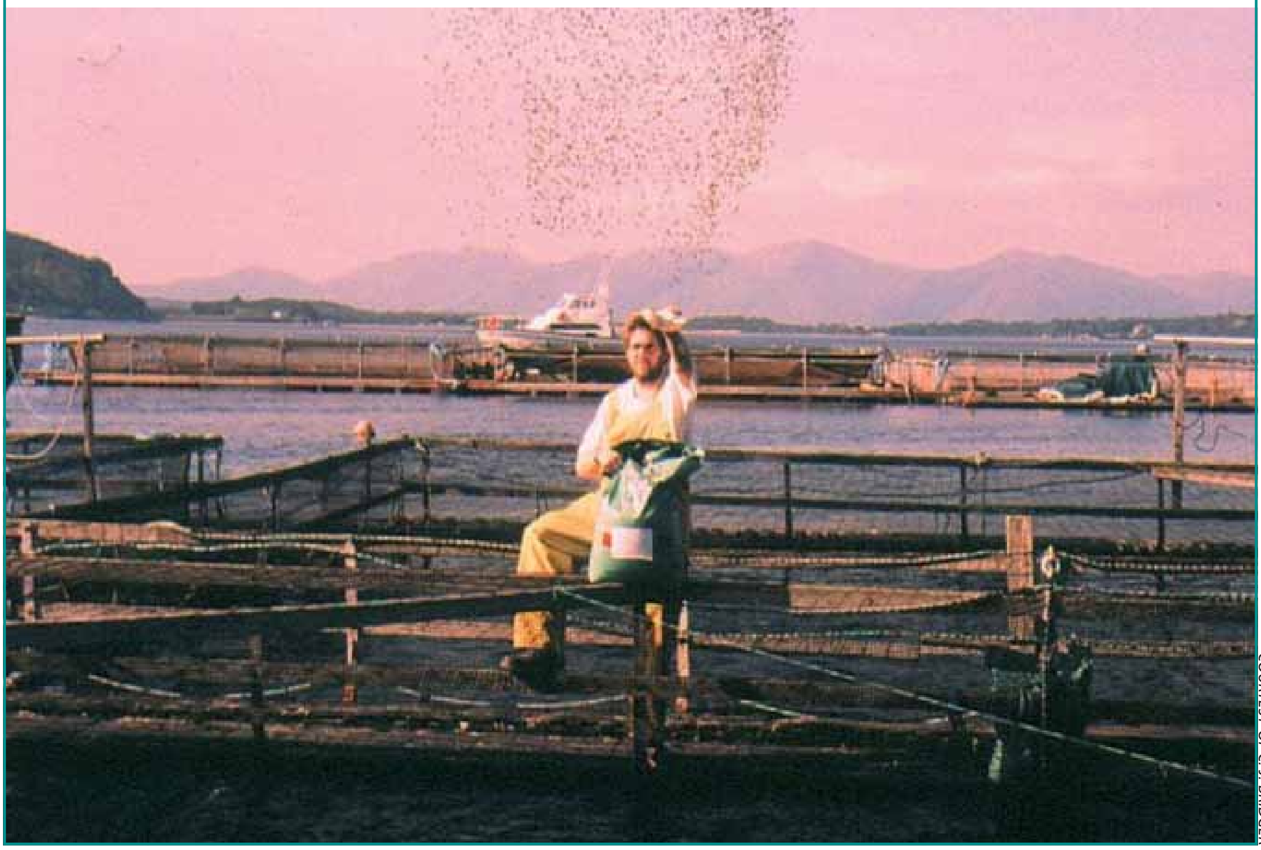
Other peripheral support systems are critically important for coastal marine cage culture operations, most importantly feed delivery systems. Marine cage culture operations in North America are all intensive, i.e. requiring feed inputs. However, few fish are hand fed (Figure 11).

Nearshore operations have reached a scale of operation that requires minimizing manual labor costs. In such cases, service vessels ferry feed to the site (either daily quantities or sufficient amounts for multiple days that are stored on barges or rafts moored on site) and onboard blowers are used for feed delivery to each cage, typically twice a day. Camera systems have been adopted by much of the industry to provide efficient feeding by monitoring for excess feed (e.g. falling through the stock of fish or change in fish behavior). Larger sites have increased their feed capacity through deployment of cone or silo barges that store large quantities of feed and use computer controlled centralized feeding technology to provide individual cages with appropriately allocated amounts of feed. Feed barges are moored on site either using their own independent mooring system or integrated within the cage flotilla mooring.

Many of the new open ocean cage designs have not concurrently developed effective feed delivery systems. In some cases, feeding is performed from a boat through a feed hose extending to the cage. For other sites, feed barges have been considered and modified for open ocean conditions. Finally, novel spar type feed buoys have been constructed

FIGURE 11

**Fish farmer manual feeding fish stocked in a standard surface-based collar cage. Manual operations are popular on smaller sites that do not require automation to achieve economies of scale**



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and tested for use in high energy environments. Regardless of the final concept, all industry experts accept that vessel based feed delivery is a short-term strategy and onsite feed storage and delivery systems will need to be adopted for industry expansion.

Open ocean aquaculture operations must become dependent on technologies that will size fish using video or acoustic image analysis that measure individual fish without physically disturbing them. These must also minimize the amount of time wasted on site for fish sizing when other more urgent tasks must be performed during limited periods of good weather.

A further benefit to deploying video technology to open ocean sites would be the potential use of these same images for reconnaissance fish health surveillance. In these cases, video imagery might be analyzed to look for the presence of gross anatomical fish health signs that would prepare an industry veterinarian prior to visiting the site and potentially solve issues before it becomes unmanageable without severe economic consequences. Ideally, the same video data could be collected for feed delivery, fish sizing and fish health management thereby decreasing the necessary technology investment required.

Food quality and safety are paramount issues of importance to North American consumers. Environmental NGOs have accused aquaculture farmers of using illegal chemicals and have pressured regulatory agencies to increase surveillance measures for seafood. This trend will continue and it behoves North American cage culture producers to develop, self-impose and adhere to strict quality assurance standards. Industry and researchers need to work together to develop novel and non-chemical means of dealing with fish health issues. Finally, organic aquaculture standards need to be developed/legally established in the United States of America so that local producers can service these highly lucrative niche markets.

## CONCLUSIONS AND RECOMMENDATIONS

Cage culture in North America may be poised on the brink of rapid expansion if the current policy changes and regulatory improvements continue to develop. Particularly, Canada has made significant progress in the last decade toward improving the regulatory setting and public perception of cage aquaculture.

Cage aquaculture in the marine environment in the United States of America lags behind Canada but newly proposed policy legislation could start development in United States federal waters. Cage culture has a short and, in particular in freshwater, a somewhat disappointing history in much of North America and will probably not expand rapidly in the near future. While the opportunity for marine cage culture to expand is good, the United States of America lags behind Canada in sustainable implementation and guidance. Impediments of governmental regulations and inconsistencies of policy, environmental concerns, aesthetics, and market uncertainty need to be addressed before sustainable development can progress.

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