GLOBAL ASSESSMENT OF CLOSED SYSTEM AQUACULTURE

Prepared for:
The David Suzuki Foundation
&
The Georgia Strait Alliance

On Behalf of the Coastal Alliance for Aquaculture Reform

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1. Introduction

EcoPlan International was retained by the David Suzuki Foundation and the Georgia Strait Alliance to provide a review of commercial closed system aquaculture (CSA) technologies throughout the world, emphasizing those technologies and species most relevant to British Columbia. The focus of the report is on finfish, though it is acknowledged that considerable literature and successful examples exist for the use of closed system aquaculture for growing seaweeds, shellfish, crustaceans, and other invertebrate species, as well as for pharmaceutical production.

This report was compiled to provide information to aid in assessing the economic and technical growth potential of aquaculture in the CSA sector. It looks at a variety of technologies and methods used in commercial production as well as several emerging technologies, highlighting some of the major advantages and disadvantages of each.

The study demonstrates that numerous examples exist around the world of commercially successful CSA operations where finfish are grown to harvest size. The major fish are Nile tilapia (*Oreochromis niloticus*), trout (*Oncorhynchus mykiss)*, Arctic char (*Salnelinus alpinus*), Atlantic halibut (*Hippoglossus hippoglossus*), turbot (*Scopthalmus maximus*)[1], barramundi (*Lates calcarifer*)[2], seabream (*Sparus aurata)*[3] and sea bass (*Centropristis striata)* while other species are important in specific locations, such as eel (*Anguilla anguilla)* in Europe, and catfish (*Ictalurus punctatus)*[4] in the United States. Determining production levels for fish reared in CSA is difficult as trade data does not generally disaggregate between pen or net farmed and CSA farmed fish. While in Europe individual countries will place 'eco-labels' to identify their CSA farmed fish, they are not distinguished in trade information. Some fish, such as trout (*Oncorhynchus mykiss)* and turbot (*Scopthalmus maximus)* are almost ubiquitously farmed in CSA; however others, such as seabream, can be either. Also, countries such as the Netherlands employ CSA for all farmed fish regardless of species due to legislation and environmental regulations.

The report was compiled through a series of literature searches in academic and professional journals; web-based and database searches, and through interviews with both commercial companies and researchers. The study was also restricted to literature that was available in English and interviews favoured those individuals who had a commercial perspective as well as research knowledge. This study cannot therefore be taken as an exhaustive account of CSA. To avoid confusion with respect to colloquial names, Latin names are provided alongside colloquial names. A glossary has also been included in the report for reference. In the case that Latin names are not known, the colloquial name is given with reference to the geographic location of its use. All units have been converted to metric and all currency is in US dollars, unless otherwise stated. Also, note that US currency has fluctuated dramatically over the past year. All costs in US figures are therefore taken as an average of the local US currency conversion rate for the year of publication using www.oanda.com/convert/fxhistory.

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[1] Note that there several different species of turbot including the Pacific, Greenland and European (*Psetta maxima*). The *Psetta maxima* is the most common and usually referred to as *Scophthalmus maximus* in trade literature and industry publications.

[2] Also known as Asian seabass.

[3] There are over 125 species in the Sparidae family. The most common of these "breams" for food fish is the Gilt-head seabream (*Sparus aurata)*.

[4] Otherwise known as the Channel catfish. Other species of catfish are referred to in this report – see glossary.

2. Study Overview

The objective of this study is to provide an overview of the current status of closed containment aquaculture with a focus on technologies. This includes technical specifications of systems in commercial production as well as experimental stages, economic statistics related to the volume and value of production, and ecological implications as well as life cycle demands associated with closed containment systems. This study concentrates on finfish where production cycles include harvesting, though it notes several well known species, such as Atlantic salmon (*Salmo salar)*, are raised in CSA until a certain point in their development when they are transferred to net-cages or net-pens. Particular emphasis was given to those examples most suitable to the physical, demographic and economic climate of British Columbia. Consequently, focus was given to examples from other member countries of the Organization for Economic Cooperation and Development (OECD), and in particular in Western Europe, Australia, and North America.

For the purposes of this study, closed system aquaculture (CSA) is defined as:

> **'Any system of fish production that creates a controlled interface between the culture (fish) and the natural environment.'**

The United Nations Food and Agriculture Organisation (FAO) sees little possibility to increase supply from wild capture fisheries to meet growing demand for fish protein (FAO, 2006). Approximately, 75% of the world's fishing grounds are fully exploited, over exploited or severely depleted. Experience from catch fisheries show that for both pelagic and demersal species almost all major fisheries have experienced a shift from high-grade to low-grade fish (Pauley, 1998). Even as wild fisheries productivity declines as a result of over-fishing and other anthropogenic stresses on the marine environment, the global demand for seafood continues to grow, and aquaculture can make a positive contribution to meet increased market demand (Tidwell, 2001; Garcia, 2005).

3. Trends in Aquaculture

Aquaculture has grown enormously over the last 50 years, producing 60 million Mt of product in 2004 with a value of US$70 billion (FAO, 2006). Over the last three decades, aquaculture worldwide experienced 11% annual growth, and currently provides about one third (40 million Mt) of global fisheries production (Naylor, 2005). Asia and the Pacific Region account for 92% of global production; China alone being responsible for 70% (FAO, 2006). Aquaculture is varied throughout the world; East Asia being responsible for the majority of shellfish, crustaceans, and plant production; Central and Eastern Europe for carp (*Cyprinus carpio)*, Western Europe, Chile and Canada for salmonids, and the US for catfish (*Ictalurus punctatus),* (FAO, 2006). Finfish account for approximately half of all aquaculture yields, while algae and invertebrates account for a quarter each (FAO, 2001). Production is dominated by freshwater fish and aquatic plants (FAO, 2006); marine and diadromous fish species account for only 5.3% of the world's total production, but command 14.2% of the world total farmed values (FAO-STAT, 2007). Our findings show that the vast majority of commercial production of finfish in OECD countries is based on open systems; the exact number is difficult to define as production and trade figures are generally not classified as open-system or CSA.

While aquaculture has grown rapidly, increase has slowed in recent years (Funge-Smith, 2001). There are growing opportunities to implement new technologies, new species, and develop new areas, such as South America and Africa (Funge-Smith, 2001). Innovations and proven technologies for closed systems are being applied in parts of the world such as Benin, where Hesy Aquacutlure has recently built an African catfish (*Clarias gariepinus*) farm (Debon, 2007a).

An examination of existing CSA reveals a large and complex range of technologies and methods with no clear distinction in terms of treatment for both incoming and effluent waters. They all however, include a physical barrier between the culture (fish) and the natural environment. These include everything from pond and ditch systems (possibly the earliest form of closed system aquaculture), to constructed impermeable systems, such as raceways or tanks. CSA systems include those using a one time flow-through of water with varying degrees of input and output water treatment methods, to fully 'recirculating' systems where water is largely reused (also known as Recirculating Aquaculture Systems (RAS)). Geographically, these systems are found everywhere from land locked urban centres to sea-based tanks. Systems may depend on municipal water systems, groundwater, lakes or rivers, and the ocean. This range and diversity of existing and emerging technologies is a promising sign for the possibility of closed systems to be successfully adapted to meet specific geographic conditions and respond to social conditions such as consumer demand, policy and legislation.

Modern CSA, and RAS in particular, have been used for commercial production of eels for over 20 years in Europe. However, it has only been since the late 1980's that researchers and civil society groups in North America have increased their efforts to lobby governments to support the development of appropriate aquaculture technology including CSA for finfish in general. In North America, most commercial CSA for 'grow-out' or 'start to finish' finfish production is dedicated to trout, catfish, Arctic char and more recently, tilapia species.

Because the technologies, species and local situations vary so markedly, it is difficult to ascribe definitive strengths and challenges of CSA systems. Clearly, two of the ubiquitous and paramount strengths of CSA are the separation of the fish culture from the environment, and the potential for control of inputs and outputs. With these in mind the challenges and strengths must be balanced together to determine appropriate choices of technology and species for aquaculture production. In general, therefore, the strengths of CSA are:

- Potential to control growing conditions: including temperature, water chemistry and turbidity, disease, etc.

- Stress reduction from control of predation, disease, growing conditions (no temperature or water chemistry fluctuations).
- Potential to influence growth cycles: including shortened time to harvest, size of the species, quality of product, as well as optimum harvest points and ability to plan for harvest; better feed consumption and control of metabolic rates.
- Better Feed Conversion Ratios (FCR): due to greater control of growing conditions and life cycles, as well as water movement. This means less feed is lost and thus nutrient production form lost feed is minimised.
- Greater versatility: options for production location, nearness to market, marginal lands, etc.; production can be tailored to take advantage of local situations such as water temperature, water quality, skilled labour; ability to respond to demographic and consumer shifts (some systems are capable of growing different species – or can be easily transformed; potential for enhancing technology.
- Control of outputs and effluents: treatment and the possibility of reuse as fertilizer or input for other fish systems (in integrated aquaculture).
- Risk reduction: including climate, infection and disease, predation, etc.
- Reduction in certain direct operational costs: associated with feed and disease control from vaccinations and antibiotics.
- Potential for 'clean product': produced without hormones, antibiotics etc.; produced in environmentally friendly way; green and organic labelling.
- Longer average life of tanks and equipment (versus nets) allowing for longer amortisation periods.

The general challenges are:

- Increase in capital costs: research and development can be costly; system start-up is higher than net-pen operations.
- Increase in certain direct operational costs: usually a higher cost associated with certain inputs such as oxygen and maintenance costs associated with chemical balances of the water (note: some flow-through systems based on groundwater sources don't require any inputs or water treatment), careful water monitoring, energy requirements (depending on the technology), input-output water treatment requirements (these are associated with high density farming).
- Complexity of technology: particularly with regards to maintaining water environment and with the use of bio-filters in RAS.
- Risks: potential for rapid chemistry alterations, dependency on monitoring (again, this increases with increased fish densities).

While proponents of CSA consider it an advance towards sustainable finfish aquaculture, they acknowledge there are environmental and social issues surrounding all forms of aquaculture such as those relating to the capture of wild fisheries for feed, energy usage and the associated greenhouse gas emissions, amongst others. The socio-ecological 'footprint' (or fish-print), which is the overall material and energy throughput associated with fish production, needs to be considered and balanced when exploring CSA options. Nevertheless, CSA does address many of the environmental effects of open-pen farming in the Pacific Northwest that have been well documented and acknowledged by policy makers (Phillips, 2005; Brooks, 2002; Buttner, 1992; Naylor, 2003). Many aquaculture operations around the world have caused habitat destruction, water pollution, parasitic infections of wild stock, and unintentional introductions of non-native species. Increasingly, social concerns and environmental impacts associated with the aquaculture industry have resulted in media campaigns discouraging the consumption of farmed seafood (Barrington, 2005).

Part of what is likely to drive the increased use of CSA is consumer demand and stakeholder awareness. In the EU, regulations are increasingly strong regarding what is acceptable, both in terms of environmental impact as well as animal welfare (van Eijk, 2007). Consumer trends indicate an increasing concern for health issues and environmentally sound raised seafood (van Eijk, 2004; Romuel, 2007). Speaking at the Profet Aquaculture Workshop in 2004, the General Secretary of the Dutch Association of Fish Farmers, Wim van Ejik commented "Fish farming is still developing and so we take into account 'from the beginning' the demands associated with food safety, animal welfare and the environment" (van Eijk, 2004). In Europe, one of the major driving forces behind CSA is consumer demand for a product that contains no additives, hormones, antibiotics etc. and is produced in a sustainable way (van Eijk, 2007). In the Netherlands, for instance, environmental and social concerns are reflected in policy and legislation such that 100% of aquaculture is CSA, and due to water constraints, based on recirculating aquaculture systems (Debon, 2007a). To encourage adoption and development of these new technologies the EU has assisted financially with grants, subsidies and tax incentives (van Eijk, 2007; Øiestad, 2007a).

Bio-safety, in terms of controlling disease and maintaining genetic diversity in fish populations, is becoming increasingly prominent in policy development, and emerged as a major theme at the 6th International Conference on Recirculating Aquaculture, Virginia (July, 2006). While this has always been an issue, the intensification of aquaculture production means that this is becoming of paramount importance (Schipp, 2006). CSA addresses bio-safety concerns through control aspects regarding both input and output and the separation for the fish culture from the natural environment.

Albright (2007), a small producer of fresh water Sockeye salmon (*Oncorhynchus nerka*) and Rainbow trout (*Oncorhynchus mykiss*) in Langley (BC), predicts that switching from conventional salmon farming in ocean-based net-pens to enclosed inland freshwater ones would have significant positive outcomes:

- Disease- and antibiotic-free: Unlike conventional commercial fish farms, freshwater fish farms rarely use antibiotics and other chemical therapies because their ground-based water sources do not have common pathogens.
- Improved public perception of fish farming: Inland and groundwater-fed fish farms are not mired in the controversy that shrouds ocean-based fish farming. Recent research done by scientists at Simon Fraser University and elsewhere demonstrates that ocean-based fish farming breeds sea lice in numbers that kill nearby juvenile wild salmon.
- Smaller ecological footprint: While ocean-based fish farms cover several kilometres of seacoast, a typical freshwater farm occupies no more than five acres of land.

4. Technologies and their Deployment

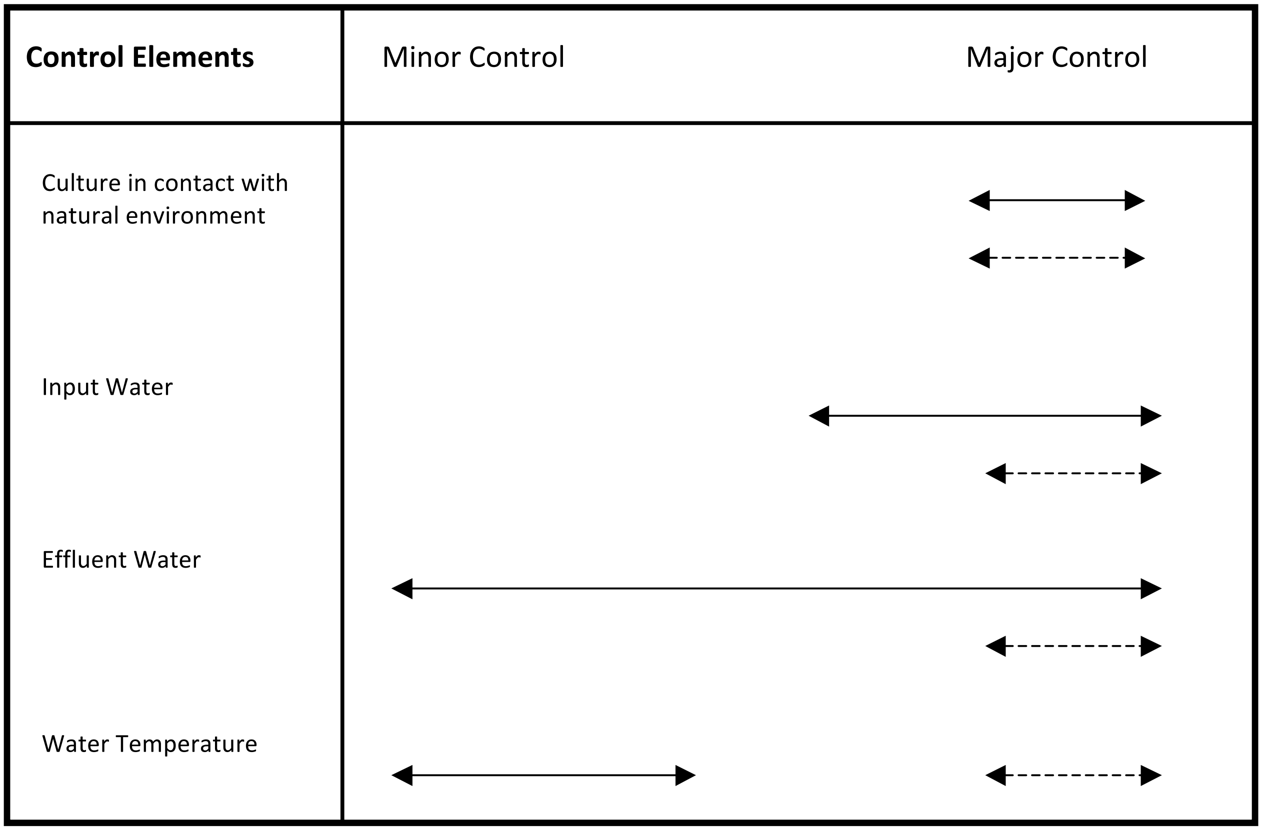
Description of technology and terminology

There are a variety of classification systems and nomenclature regarding CSA technologies. For the purposes of this study, we have classified the spectrum of closed system aquaculture technologies based on: 1) degree of control over input and output waters; 2) shape/layout of system; and 3) location of installation.

1) Degree of control of input and output waters

While all CSA systems have a barrier between the culture (fish) and the natural environment in terms of individual fish, they vary in terms of control with respect to input waters and output wastes, and with regard to water use (Figure 1).

Figure 1: Generalized control elements in flow-through (◄—►) and Recirculating Aquaculture Systems (◄--►)



Flow-through systems allow water flows to enter the system, through the tanks or holding areas, and exit the system. There is a possibility of complete control at both ends. Incoming water is virtually always treated for bacteria, parasites, and disease, and outgoing water is treated to greater and lesser extents (Folke, 1998; Miller, 2002; Piedrahita, 2003; BMP, 2004). Often, treated effluent water is recirculated back to into the system. While there is no clear rule for nomenclature, when approximately 60-70% of this water is recirculated, it becomes classified as RAS (Blancheton, 2000; Queensland, 2007; Schuenhoff, 2003; Troell, 2003). Some systems recirculate more than 95% of their water, essentially replenishing for evaporation and leakage (Debon, 2007a; Desbarats, 2007).

Ponds and channels are considered as closed systems in that while the fish and their holding environments are in contact with soil and the ground they are free from traditional predators, cannot escape to mix with wild species, and any diseases generated in their enclosures can be contained. Water, and thus contaminants can seep into the soil and groundwater (Boyd, 1999).

2) Shape /layout of the system

CSA systems exist in a multitude of different shapes depending on species and scale. Different physical structures determine hydrodynamic flow, area and volume, all of which may be species dependant. Tanks are large structures, usually round for strength, and can be above ground, below ground or suspended in oceans or lakes. A high water volume to container surface area is a common characteristic of tanks. Ponds are analogous to tanks, but dug in the ground with no impermeable barrier.

Raceways are longer structures, sometimes hundreds of meters, where while water flows through them, the residency time of water in any one spot being very small. A low water volume to container surface area characterizes them. This is appropriate for certain species, such as trout, which thrive in a simulated stream flow, and flat fish, such as flounder or sole, which need large surface areas. Channels are analogous to raceways dug in the ground. This is the main method of producing catfish in the US.

Shape will also determine treatment mechanisms while residence time of water will demand different forms of treatment, as will species.

Figure 2: Seven-level shallow tanks for sole (Solea solea) production at Solea BV in The Netherlands *(Photo credit: Albert Imsland, Akvaplan-niva)*

3) Location on land or in open water

CSA technologies can be found in almost any location. Most are on land as tanks, ponds, raceways, and channels. Others are in open water, either ocean or freshwater, and are flow-through tanks. There are, however, exceptions to these especially as new technologies continue to emerge. Also, unless explicitly stated, all species are grown in their native environments, for example Rainbow trout (*Oncorhynchus mykiss*) are generally river fish and thus raised in freshwater.

Summary of findings for general types of CSA

Table 1: Description of technology and examples

Systems/Description	Example Use:	Location/ region:
Land-Based:		
Raceways (recirculating or flow-through)		
Modern raceway systems are made from a variety of materials: concrete, plastic, steel; can be either outdoor or indoor; gravity fed by a stream; partially or fully recirculating.	Trout (*Oncorhynchus mykiss)*	US, Spain, France
	Turbot (*Scophthalmus maxima*)	Spain, (Akvaplan-Niva, Stolt Sea Farms) France, Denmark (UNI-Aqva)
	Seabass (*Centropristis striata*)	France
	Channel catfish (*Ictalurus punctatus)*	USA
	Sole (*Solea solea*), Japanese flounder (*Paralichthys olivaceus*)	Spain, Denmark
Recirculating Tanks		
Tanks can come in a variety of forms. Circular formats have been preferred in many cases because of the self-cleaning properties they provide. Polygon shapes, however, have advantages in being more space efficient. These systems are often modular and scalable, allowing producers to scale-up systems at their own pace and without having to interrupt operations to add greater capacity. Inland recirculating tanks are often located where there is both limited land and water availability, as they can be located in industrial areas and achieve high degrees of water reuse.	Turbot (*Scophthalmus maxima*)	Netherlands (HESY)
	Tilapia (*Oreochromis niloticus*)	El Salvador, Israel (HESY)
	Eel (*Anguilla anuilla*)	Denmark (produces 20% eel consumed by European Market)[5], Croatia and Netherlands (HESY)
	Barramundi (*Lates calcarifer*)	Australia, USA, Russia, The Netherlands, Israel, Denmark, UK
	Jade perch (*Scortum barcoo*)	Australia (Ausyfish)
	Golden perch (*Macquaria ambigua)*	Australia (Ausyfish)
	Murray cod (*Maccullochella peelii peelii*)	Australia (HESY)
	Sleepy cod (*Oxyeleotris lineolatus*)	Australia (Ausyfish)
	Black rockfish (*Sebastes schelegeli*)	Korea (Schipp, 2006)

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[5] http://www.1planet1ocean.org/html/sustainable-aquaculture.html

	Pike perch *(Sander lucioperca)*	Netherlands
	Seabass (*Centropristis striata*)	Greece (HESY)
	Seabream *(Sparus aurata)*	Greece (HESY)
	Trout (*Oncorhynchus mykiss)*	Chile (HESY)
	African catfish (*Clarias gariepinus*)	Benin (HESY)
	Sturgeon (*Acipenser transmontanus*)	Greece (HESY)
Flow-through Tanks		
Flow-through tanks come in similar formats as recirculating tanks. These however are more commonly found where reliable water sources are available and used to harvest species that require certain conditions (i.e. trout).	Arctic char (*Salvelinus alpinus)*	Canada (Icy Waters), Iceland.
	Trout (*Oncorhynchus mykiss)*	Europe, N. America, Chile, Latin America
Inland Ponds and channels		
Ponds - analogous to tanks but dug in the ground (natural). Channels – analogous to raceways but in the ground (natural). Occasionally, these can be lined with membranes or mud but this is generally not the case.	Channel catfish (*Ictalurus punctatus)*	USA
	Tilapia (*Oreochromis niloticus*)	Belize, El Salvador, USA, Australia
	Trout (*Oncorhynchus mykiss)*	Europe, Australia and N. America
	Salmon (*Oncorhynchus nerka)*	Canada (Aqua Farms)
	Barramundi (*Lates calcarifer*)	Australia (Ausyfish)
	Jade perch (*Scortum barcoo*)	Australia (Ausyfish)
	Golden perch (*Macquaria ambigua)*	Australia (Ausyfish)
Primarily Experimental or Development Stage:		
Flow-through Tanks: Open-Water Systems		
These can be found made from a range of materials, in circular as well as square shapes. Hard walled systems are generally made from reinforced plastic, concrete, aluminium. Soft walled are made from plastic.	Ocean trout (*Oncorhynchus mykiss*)	Western Australia (McRobert)
	Rainbow trout (*Oncorhynchus mykiss*) (exp.)	Nova Scotia (SEA)
	Yellowtail kingfish (*Seriola lalandi lalandi*	Western Australia (McRobert)
	Mulloway (*Sciaena Antarctica)*	Western Australia (McRobert)
	Barramundi (*Lates calcarifer*)	Western Australia
	Coho salmon (*Oncorhynchus kisutch)* (exp.)	British Columbia (SEA and SARGO)
	Bluefin tuna (*Thunnus thynnus*) (exp.)	Australia (UNI-Aqua)
	Gilt-head seabream (*Sparus aurata*) (exp.)	Baltimore, US (COMB)
	Chinook salmon (*Oncorhynchus tshawytscha)* (exp.)	British Columbia (SEA and SARGO)
	Arctic char (*Salvelinus alpinus*)	Canada (SEA, and SARGO)

	(exp.)	
	Black cod (*Notothenia microlepidota)* (exp.)	Canada (SEA)
	Walleyed pike (*Sander vitreus vitreus)* (exp.)	USA (Michigan – SARGO)
	Yellowfin tuna (*Thunnus albacares*) (exp.)	Panama (SARGO)
	Cod (*Gadus morhua*) (exp.)	Denmark (UNI-Aqua)
Flow-through Tanks: Land-Based Systems		
Tank systems on land pumping seawater.	Atlantic salmon (*Salmo salar*) (exp.)	British Columbia (Agri-Marine)
	Coho salmon (*Oncorhynchus kisutch)* (exp.)	British Columbia (Agri-Marine)
	Chinook salmon (*Oncorhynchus tshawytscha)* (exp.)	British Columbia (Agri-Marine)
Recirculating Raceways		
Recirculating raceways are operated as land-based (inland) systems. These can be composed of a single level or can be stacked to increase production per floor area of a given occupied space.	Blackspotted seabream (*Pagellus bogaraveo)* (exp.)	Norway
	Cod (*Gadus morhua*) (exp.)	Norway
	California halibut (*Paralichthys californicus)* (exp.)	Spain

Status of development and deployment of technologies

A survey of existing and emerging technologies indicates that this is a sector with a vibrant research and development component. The increasing global demand for seafood products coupled with increasing concern over aquaculture's impact on natural ecologies (manifest as tightening regulation and consumer trends) is encouraging companies to invest in research and development of closed system technologies. In some cases such as in the EU, governments are responding with subsidies to explore and hasten the development and uptake of these technologies. As with many new technologies, early adopters of CSA continue to work to overcome both the technical and financial challenges. To date, the most consistent and notable successes to date in commercial scale closed system aquaculture for food fish production have been achieved by systems using species tolerant of high density conditions and those which command a premium market price (Lazur, 2007).

In **Canada** and the **United States**, CSA technologies are employed to culture a wide variety of both warm-water and cold-water fish in both saltwater and freshwater situations. Currently, most commercial CSA production systems in the United States are small, less than 45 Mt (45,000 Kg) of production per year, providing fresh high quality product at premium prices to niche markets (Harvey, 2005; Lazur, 2007). In **Europe,** commercial production facilities using recirculation are much larger, such as UNI-Aqua's recently completed 8000-10,000 Mt/ year turbot (*Scophthalmus maximus)* farm (Urup, 2007) in Denmark.

The following section describes technologies currently used in commercial operations as well as several demonstration projects. This includes operators as well as the actual developers and manufacturers of the technologies. The bulk of the information from this section has been derived from interviews and proponent websites as indicated.

Land-Based Systems:

Race-ways – Recirculating

NAME:	**Akvaplan-Niva,** Shallow Raceway System Norway (Øiestad, 1999; Øiestad, 2007b)
SPECIES:	11 species have been tested for commercial development, including Atlantic salmon (*Salmo salar*).
STATUS:	Akvaplan-Niva systems have been implemented in commercial operations using turbot *(Scophthalmus maximus)* in Galicia, Spain and Portugal and Dover sole *(Solea solea)* in The Netherlands. Ongoing lab-scale/ pilot scale experimental development with Atlantic halibut *(Hippoglossus hippoglossus),* Spotted wolfish *(Anarhichas minor),* Senegal sole *(Solea senegalensis),* Gilthead seabream *(Sparus aurata),* California halibut *(Paralichthys californicus)* and Japanese flounder *(Paralichthys olivaceus).*
DETAILS:	
This is a hyper-intensive system designed to drastically reduce space requirements by stacking raceways one on top of the other. The outcome is a reported 5-10 times higher production/m^2 of surface area making this system ideal for use in areas with low land availability (Øiestad, 2007b). Recently, this system has been studied as a possibility for instillation in industrial parks for aquaculture (IPA). This is proposed as an economic opportunity to capture economic efficiencies gained through vertical integration "clustering", for instance, landings, processing, and transportation to market (Øiestad, 2007b). The design of the system is almost a standard raceway but with a very low water level (1cm for 100mg fish (such as turbot, halibut & seabream) increasing to 20 cm for fish above 2 kg). Other characteristics include: high fish density (often 100-500 Kg/ m^3), no counter current in the levelled raceways (no jet current), adjustment of water intake with the most remote fish in mind and feeding with floating pellets (pelleted feeds significantly reduces cost of production by eliminating the need to prepare feeds onsite) (Øiestad, 1999). This system has been tested for a wide size range of raceways (7 – 80 m^2) and fish sizes (up to 10kg), normally with growth and survival rates as good as with traditional rearing systems. The results indicate that a variety of fish species can be produced. So far 11 species have been tested, including Atlantic salmon (*Salmo salar*) (Øiestad, 2007a).	
NOTABLE FEATURE:	High fish densities and low energy costs.
PICTURES/ DIAGRAMS:	***Figure 3: Stacked Racks in the Shallow Raceway System at Tustna Kveite AS Facility in Tustna, Norway*** *(Photo credit: Kurt Oterhals)* 

NAME:	**Agassiz Aqua Farms** *Manitoba (*www.agassizaquafarms.com*)*
SPECIES:	Arctic char (*Salvelinus alpinus*), trout (*Oncorhynchus mykiss*), Yellow perch *(Perca flavescens)*
STATUS:	Arctic char – Commercial production; Rainbow trout - has been commercial in the past, currently not raising any significant volume for commercial production; Yellow perch – experimental stage.

DETAILS:

This facility was started in the 1970's as a research centre for the Department of Fisheries and Oceans (DFO).[6] Arctic char from this facility is being sold across Canada at a current volume of 30 Mt/year. Fish are typically grown to 1 Kg but they also produce several custom market sizes for various clients. Raising a fish to 1 Kg requires about 24 to 30 months. They are now trying to expand to a capacity of 150 Mt/yr of Arctic char per year as well as developing a brood-stock Yellow perch *(Perca flavescens)* line. Water comes from a limestone aquifer, 40 meters underground. Water exchange occurs every 72 hours. The company highlights the product as being antibiotic free. The hatchery has been certified disease free for 12 years. While fingerlings and brood-stock 379 l/ min of freshwater, water recirculation used for grow-out stages reduces the water requirement to 76 l/min.

Effluent and discharge treated in a man-made wetland (which has begun attracting migratory birds). Solids are separated through drum filtration and settling chamber then composted (the company is looking into possibilities to prepare and sell compost commercially). The company is also looking into options to use greenhouse components to capture passive solar heating to heat water to the appropriate temperature (depending on species).

Recently, the company has done work with other farmers to set up a new operation in a converted hog barn. This facility will produce approximately 50 Mt/year in a high recirculation facility (76 l/min).

NOTABLE FEATURE:	Long period where fish have been free of disease, and combined commercial and research facility for developing new technology.

PICTURES/ DIAGRAMS:

Figure 4: View of effluent ponds at Agassiz Aqua Farms
(Photo courtesy of Agassiz Aqua Farms)

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[6] The following is taken from www.agassizaquafarms.com and conversations with John Bottomley, President of Agassiz Aqua Farms (see Bottomley, 2007).

Tanks – Recirculating

NAME:	**Aquaculture Developments LLC** Pittsburgh, Pennsylvania based. Exclusive licensees of UNI-Aqua (Denmark) and Fish Protech, Pty. (Australia) in North America.
SPECIES:	Barramundi (Lates calcarifer), salmon, trout, turbot, sole, cod, halibut, Jade perch, Murray cod (Maccullochella peelii peelii), Sleepy cod
STATUS:	Commercial
DETAILS:	

Aquaculture Developments is an engineering consultancy building land-based circulating aquaculture systems. They claim 97-99% water re-use and feed conversion that is 10 times more efficient that in open ponds or flow-through systems.[7] No antibiotics, hormones or other additives are required. This technology has been used in farms that have been commercially successful over a 15-year period.

NOTABLE FEATURES:	Long term economic viability and very good Feed Conversion Ratios.
PICTURES/ DIAGRAMS:	***Figure 5: Interior of barramundi facility in Australia*** *(Photo courtesy of Aquaculture Developments LLC)* 

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[7] The following information is taken from www.aquaculturedevelopments.com.

NAME:	**AquaOptima Norway AS** *Norway* (www.aquaoptima.com)
SPECIES:	Rainbow trout (*Oncorhynchus mykiss)*, Arctic char (*Salvelinus alpinus*), tilapia (*Oreochromis niloticus*), European sea bass (*Centropristis striata)*, seabream, halibut (*Hippoglossus hippoglossus*), Atlantic cod (to juvenile stage only), Japanese flounder (*Paralichthys olivaceus*), Tiger *puffer (Takifugu rubripes)*, barramundi (*Lates calcarifer*), Black sea turbot *(Psetta maxima).*
STATUS:	Commercial
DETAILS:	

AquaOptima was started in 1993. It is a system development, experimental, consulting company.[8] It has built commercial recirculating and flow-through systems in 16 countries for both cold and warm water species such as Rainbow trout (*Oncorhynchus mykiss)*, Arctic char (*Salvelinus alpinus*), tilapia (*Oreochromis niloticus*), European seabass (*Centropristis striata)*, seabream, halibut (*Hippoglossus hippoglossus*), Atlantic cod (to juvenile stage only), Japanese flounder (*Paralichthys olivaceus*), Tiger *puffer (Takifugu rubripes)*, barramundi (*Lates calcarifer*), Black sea turbot *(Psetta maxima).*

AquaOptima has designed and patented a piece of equipment called the Eco-trap. The trap is a modified centre drain for a fish tank that is designed to remove up to 90% solids from the tank using a small amount of water. The EcoTrap comes in a variety of sizes ranging from 110 to 400 mm but can be designed larger if required. Waste collected by the Eco Trap is diverted to an 'Eco-Sludge' collector, located on the side of the tank. The 'Eco-Sludge' is a small swirl separator. The installation of the Eco-Trap system claims to allow for a 50% reduction in the size of mechanical filtration in a system. Its other advantages are that it is a passive, non-mechanical system with little to no chance of failure and reduced energy needs.

Recently, AquaOptima assisted with the installation of a large recirculation system for barramundi in the UK. The Aqua Bella farm located in New Forest, England was constructed in 2004 and is designed to produce 400 Mt of barramundi per year. Harvesting from the facility commenced in March 2006. It is a fully recirculated system comprising of 48 tanks maintaining water at 28 C whilst treating three million litres of water a day. New water is added at the rate of 5% per day. In March 2006 facility anticipated expanding its facility to a 1000 Mt/yr production.[9] The Aqua Bella farm near Southampton, claims to be environmentally friendly as no wild stocks are depleted because they also have a hatchery, there are no additives, and the feed comes from sustainable sources (See: www.aquab.com).

AquaOptima have recently developed a simple method for the construction of large octagonal tanks. The use of large plastic formed, lock in place panels that can be core filled with concrete offers an easily transportable and cost effective solution to tank construction.

NOTABLE FEATURES:	Efficient and rapid waste disposal system for solids. This is important as if the solids can be removed before they begin to break-down there is less need for water treatment. Great variety of types and species, dealing with cold and warm water species requires different technology. Modular concept allows for expansion as market grows etc. The Aqua Bella facility has used their technology and has proven economic success in the UK.

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[8] The following information has been taken from www.aquaoptima.com.

[9] See. http://findarticles.com/p/articles/mi_hb5245/is_200704/ai_n19860493

<table>
<tr><td>NAME:</td><td>Aquatech Solutions
Denmark, with offices in Chile and the Middle East (www.aquatec-solutions.com)</td></tr>
<tr><td>SPECIES:</td><td>Eel (<i>Anguilla anguilla</i>), trout (<i>Oncorhynchus mykiss</i>), salmon (<i>Salmo salar</i>), Pike-perch <i>(Sander lucioperca</i>), sturgeon <i>(Acipenser transmontanus)</i>, seabass (<i>Centropristis striata)</i>, seabream (<i>no species reference provided)</i>, turbot (<i>Scophthalmus maximus</i>), cod <i>(no species reference provided)</i>, Halibut <i>(no species reference provided)</i></td></tr>
<tr><td>STATUS:</td><td>Commercial production for eel (<i>Anguilla anguilla</i>), trout (<i>Oncorhynchus mykiss</i>), turbot (<i>Scophthalmus maximus</i>), Pike-perch <i>(Sander lucioperca</i>); experimental for others.</td></tr>
<tr><td colspan="2">DETAILS:</td></tr>
<tr><td colspan="2">Aquatech Solutions is a development and installation consultancy, and has been in operation for 20 years.[10] They design and install a range of recirculating tank technologies: from flow-through to semi-closed and fully closed systems. Their projects include:
1) A 700 Mt/year pan size rainbow trout production for Danish Aquaculture A/S in Denmark.
2) A 250 Mt/year Pike-perch <i>(Sander lucioperca</i>), production for Amhedegaard Aaledambrug A/S, Denmark,
3) A re-circulation system for existing salmon/ trout incubation system for Patagonia Salmon Farming in Chile,
4) Installation of 3 individual recirculation systems for partly existing and new fish tank system for smolt production of Atlantic salmon <i>(Salmo salar)</i>, Coho salmon (<i>Oncorhynchus kisutch)</i> and trout (<i>Oncorhynchus mykiss)</i> at Super Salmon in Los Fiordos, Mano Negra, Chile.</td></tr>
<tr><td>NOTABLE FEATURE:</td><td>Long-term economically successful large-scale production facilities.</td></tr>
</table>

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[10] The following is taken from www.aquatec-solutions.com.

NAME:	**Baltimore Urban Recirculating Mariculture System** University of Maryland Biotechnology Institute, Center of Marine Biotechnology. (www.umbi.umd.edu), (Romuel, 2007; Zohar, 2007; Zohar, 2005)
SPECIES:	Gilt-head Seabream (*Sparus aurata*).
STATUS:	Currently experimental, commercialization is anticipated in 2008. Also, experimentation with Atlantic salmon *(Salmo salar)* for out-growth (full cycle) is scheduled for 2008.
DETAILS:	

The Baltimore Urban Recirculating Mariculture System is a recirculating, fully contained marine aquaculture system.[11] The core of the system includes biological filtration units that incorporate naturally occurring microbial processes (nitrification heterotrophic/autotrophic denitrification, sulfate reduction and anammox) to control and degrade waste compounds produced by fish (Zohar, 2005). The system collects and digests solid waste products that are derived directly from the fish or by the accumulation of uneaten feed to fuel additional microbial processes whose activities result in the production of methane gas, which can be captured and used as a source of energy. Overall this achieves a 99% containment of effluents (Romuel, 2007; Zohar, 2007; Zohar, 2005).

The system was designed to produce high-value marine fish, to use pre-existing municipal infrastructure and services, to have the ability to locate anywhere, and to maximize the re-use of water. Using this system, two strains of Gilt-head seabream were grown from 0.5 to 400 g commercial size in 268 days (first strain) and to 410 g in 232 days (second strain). Survival rates are claimed to exceed 90% and food conversion rates vary from 0.87 to 1.89. Growing densities ranged from 44 to 47 Kg/m^3 at 7–10% daily water exchange rates. Total ammonia and nitrite levels remained significantly below stressful concentrations (Zohar, 2005). The entire facility occupies 1700 square metres. The total tank water volume of the facility is 205 m^3. Salt used for producing seawater accounts for about 25% of the total production cost (based on a daily discharge and renewal of 10% of the total tank saltwater volume) (Zohar, 2004).

The fact that seabream (*Sparus aurata)* is a non-indigenous species in North America means that it will be allowed to be grown only in fully contained and biosecure systems (Romuel, 2007). Consequently, future production of this species in North America using RAS will not face competition from pond or net-pen production (Romuel, 2007).

Based on experiments to date, it is thought that the system will be suitable for Atlantic salmon *(Salmo salar)* production. Tests on this species are projected to begin at the start of 2008 (Romuel, 2007).

NOTABLE FEATURE:	High effluent cleansing and ability to locate in inner city environments.

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[11] Much of the information included in this section was taken from www.umbi.umd.edu, and from interviews with its proponents.

PICTURES/ DIAGRAMS:

Figure 6: Experimental Baltimore Recirculating Mariculture System *(Taken from http://www.umbi.umd.edu . Numbered systems components are: 1) fish tank, 2) particle removal, 3) sump [left] and pump [right], 4) pH doser, 5) temperature control, 6) biofiltration, 7) protein skimmer, 8) oxygen delivery)*

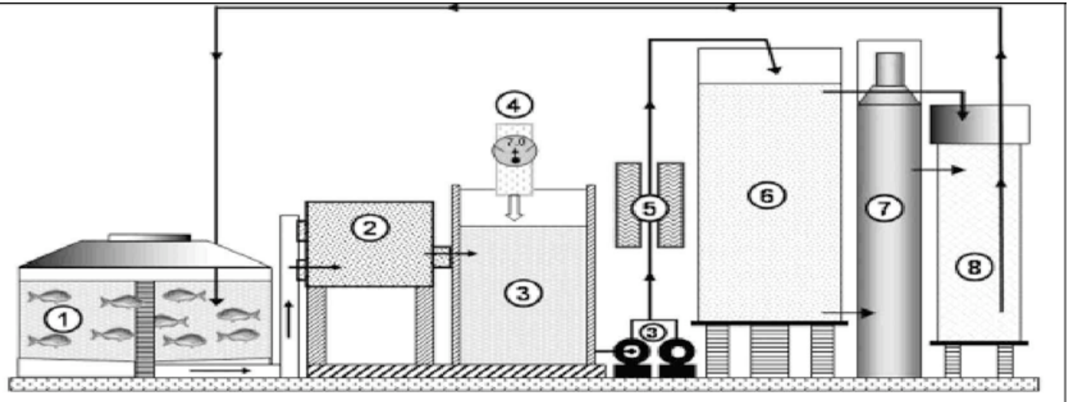

Fig. 10.1. A schematic drawing of the experimental Baltimore Recirculating Mariculture System. Numbered system components are: (1) fish tank, (2) particle removal, (3) sump [left] and pump [right], (4) pH doser, (5) temperature control; (6) biofiltration, (7) protein skimmer, (8) oxygen delivery.

Figure 7: Seabream rearing tanks at the Baltimore Recirculating Mariculture System. *(Taken from http://www.umbi.umd.edu)*

NAME:	**Australis Aquaculture Ltd.** (www.australis.us)
SPECIES:	Barramundi (*Lates calcarifer)*
STATUS:	Commercial
DETAILS:	
The Australis Aquaculture facility in Turner Falls (Mass.) is the largest indoor fish farm in the US.[12] The facility is a recirculation tank system. Current production in on the order of 1000 Mt/yr and delivers its product to Boston, but it is hoping to increase this to 5000 Mt/yr with the potential to export to Europe as well.	
NOTABLE FEATURE:	High value exotic species, bio-safety, and largest indoor fish producer in the US.

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[12] The following is taken from www.australis.us; and personal communication with Josh Goldman.

NAME:	**Billund Aquaculture Service ApS** *Denmark* (Schipp, 2006)
SPECIES:	Eel (*Anguilla anguilla*), tilapia (*Oreochromis niloticus*), barramundi (*Lates calcarifer*), seabass *(no species name provided)*, salmon smolt (Altlantic) *(Salmo salar)*, trout *(no species name provided)* and sturgeon *(no species name provided)*
STATUS:	All commercial – producers of fish product

DETAILS:

Billund Aquaculture has been successfully producing eels for 22 years.[13] They operate in co-operation with Danish researchers. The farms are built on a modular concept to be added onto without major disruption to production. The modules are isolated from each other which increases disease control (Schipp, 2006). Billund has designed two main systems, high intensive and intensive, to accommodate different species.

High intensive:
This design is used for species like eel and tilapia and also hatchery and fingerling units for both freshwater and sea-water fish. The system has a very low exchange of new water (approx. 130 - 260 litres / Kg fish/ day). The required investment level is approximately $12,000 per Mt production. A complete 100 Mt unit, including equipment and buildings would cost $1,200,000. Electricity consumption is estimated at 4-5 kW/ Kg fish.

Intensive:
This system is suitable for species such as barramundi, seabass, salmon smolt, trout and sturgeon. A higher exchange of new water is required at a rate of around 800 - 1000 litres /Kg fish /day. The required investment level is approximately $9,000/ Mt production. A complete 100 Mt unit (including equipment and building) would cost $900,000. The estimated electrical consumption is 1.5-2 kW/Kg fish.

NOTABLE FEATURE:	Low electricity consumption, designs accommodate a variety of fish species, modular design for bio-safety (disease control) and for increased production over time as market develops etc.
PICTURES/ DIAGRAMS:	***Figure 8: Inside Billund Aquaculture's sturgeon farm*** *(Photo courtesy of Billund Aquaculture, 2008)* 

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[13] The following is taken from Schipp (2006).

NAME:	**Cell Aquaculture Systems Europe** *The Netherlands* (Schipp, 2006)
SPECIES:	Barramundi (*Lates calicarifer*)
STATUS:	Commercial

DETAILS:

Cell Aquaculture is an Australian company started in 1999 in Western Australia. They are an engineering consultancy with experimental and commercial projects.[14] Over the past seven years they have researched and developed the EcoCell ‘Hatch to Dispatch’ recirculating system. This is designed to be used as a low cost modular system that can be placed close to large population centres. They are currently targeting both American and European markets. One operation, located in the Netherlands, consists of 16 modular systems located inside a large shed that was previously a chicken farm. The system is capable of producing 66 Mt of barramundi *(Lates calcarifer)*, which they believe is the minimum amount required to make barramundi production economically viable. Systems are designed to handle stocking densities of up to 75 Kg/ m$^{3.}$

The following are details of the company’s modular ‘cell’ system for barramundi production. Each modular system comprises:

- 2 x 10 000 litre tanks and 1 x 4000 litre HDPE tank
- A mechanical filter, which is a home-made belt filter fitted with a 63 µm screen. Screens are attached by Velcro and are removed and cleaned daily.
- A moving bed reactor bio-filter.
- Oxygen stones, supplied from an oxygen generator. Oxygen controlled manually to all tanks – no automatic control.
- 2 x 1 Hp pumps

Other features:

- They are going to use ozone to maintain an oxygen redox potential (ORP) of 120-200mV.
- All feeding is done by hand.
- The farm is designed to be run by 2-3 people.
- The production cycle consists of keeping the fish for two months in the nursery, two months in the 4000 litre tank and then two months in the 10,000 litre tanks.
- Waste is collected and trucked off-site (potential for use as fertilizer).

NOTABLE FEATURE:	Low operation demand on staff, deployment close to urban centres, modular system means production can increase over time, and use of a particular species that grows rapidly.

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[14] The following material is taken from Schipp (2006).

PICTURES/ DIAGRAMS:	***Figure 9: Cell Aquaculture Tanks, Terengganu, Malaysia*** *(Photo courtesy of Cell Aquaculture, 2008)* 

NAME:	**Hesy Aquaculture BV** Bovendijk 35-2 City, Rv Kwintsheul, Ambachtstraat 16-B 2861, Netherlands (Schipp, 2006, Debon, 2007) (http://www.hesy.com)
SPECIES:	Barramundi *(Lates calcarifer)*, Murray cod *(Maccullochella peelii),* eel *(Anguilla Anguilla)*, White sturgeon *(Acipenser transmontanus)*, trout *(Oncorhynchus mykiss)*, Atlantic halibut *(Hippoglossus hippoglossus)*, salmon smolts *(Salmo salar)*, Pike-perch *(Sander lucioperca)*, seabass (*Centropristis striata*), seabream *(Sparus aurata),* European carp *(Cyprinus carpio*), cobia (*Rachycentron canadum)*, Amber jack (*Seriola*),[15] as well as various catfish, tilapia and grunter (a type of Australian perch – see AusyFish below).
STATUS:	All commercial

DETAILS:

Hesy Aquaculture is a private company with over 20 years of experience in the design and operation of intensive recirculating fish farms, they are an engineering consultancy.[16] They have developed systems in over 11 countries, including China, Bulgaria, Morocco and Russia. The smallest system designed produces 2 Mt/year, the largest is greater than 1000 Mt/year. They offer training, operation manuals as well as on-going support as required. They have set up over 85 commercial production units (Table 2).

Based on this experience, they are confident that recirculating systems are cost-effective compared to cage farming. Their systems are designed to rely on gravity flow from a central point, so only one pumping station is needed (Debon, 2007). The water savings are huge, instead of a few hundred m^3 per kilogram fish produced in flow-through systems they need only 50 to 300 litres of new water per kilogram fish produced. They use no antibiotics for their systems as incoming water is treated. Their energy consumption is between 7-8 kW/Kg fish, and in the Netherlands they use their sludge for fertilizer with high salinity tolerant vegetables.

In Europe they have estimated the following costs of production (Schipp, 2006):
Eels (*Anguilla anguilla*): $8.25 / Kg of fish produced
Tilapia *(S. Oreochromis*): $1.5 - 3 / Kg of fish produced
Seabream (*Sparus aurata):* $10.5 - 12 / Kg of fish produced

NOTABLE FEATURES: A large variety of species produced commercially in many geographic and socio-economic settings.

PICTURES/ DIAGRAMS:

Table 2. Summary of recent HESY commercial production units.

Country	Farms	Species
Croatia	1 farms	Eels
Greece	3	Trout, sturgeon, seabass, seabream, mullet
Israel	2	Tilapia, seabass, seabream
Australia	3	Murray cod
Netherlands	14	Pike-perch, turbot,

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[15] Exact species not certain – it may be both Greater and Lesser Amber Jack, as there are several facilities currently operating in the USA.

[16] Much of the following is from www.hesy.com, and from interviews with its president, Mr. Debon.

		sturgeon, eel
Chile	2	Salmon and trout
Benin	1	African catfish

NAME:	**Redfish Ranch Tilapia Farm BC** (http://www.redfishranch.com//)
SPECIES:	Tilapia (*Oreochromis niloticus*)
STATUS:	Commercial
DETAILS:	

Redfish Ranch Tilapia Farm and Hatchery is the only licensed tilapia Farm in British Columbia.[17] It produces live tilapia, primarily for the Asian markets in Vancouver. The current production in just over 100 Mt/yr. It is a recirculation facility with 95% water reuse. They are able to increase production in stages by increasing the number of tanks. Waste goes through drum filters where solids are extracted to septic systems. The effluent water is treated in bio-filters before going through CO2 stripers and being oxygenated for recirculation. The entire facility is on a 10,000 sq foot area. Because tilapia is a tropical fish, temperatures need to be maintained at 28-30 C. Water is heated primarily by propane but passive heating is also being developed. Monitoring is done through sensors.

They receive their broodstock from Idaho. The fish take 6-8 months to reach 0.5 kg harvest size, where they are trucked live to market. Tilapia imports are increasing in BC and have risen from nothing in 1990, to 340 Mt/yr in 1996, to 680 Mt/yr in 2006.

NOTABLE FEATURE:	Use of an exotic species to help develop a niche market.

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[17] The following is taken from http://www.redfishranch.com/

NAME:	**Scotian Halibut, Nova Scotia** (http://www.halibut.ns.ca/)
SPECIES:	Halibut (*Hippoglossus hippoglossus*)
STATUS:	Commercial

DETAILS:

The facility in Woods Harbour, Nova Scotia is land-based, fully contained recirculation facility for halibut (*Hippoglossus hippoglossus*) grow-out.[18] The operation began in 1998 through a partnership between the Icelandic company Fiskey and Canadian investors. Scotian Halibut coordinates this grow-out facility with a nearby hatchery they operate using flow through systems, as fish at these stages are more sensitive to changes in water quality. The time required for the fish to reach market size is approximately 2.5 years (note this is a similar time needed as that for halibut as described by UNI-Aqua, below). The Wood Harbour facility harvests 15-30 2-3lb (0.8-1.3Kg) fish per week. Their target for annual production is 227 to 250 Mt. Most of their product goes to restaurants for sale as high quality, fresh fish. One client restaurant in Toronto sells the fish as live product.

- Modular tanks – each module comprised of 6-7m diam. x 1.4 m high Swede-style tanks, each with water depth of 1.2m
- Design capacity of each module = 50 Mt
- Maximum stocking density (achieved to date) is 60 Kg/m2 (measured per m2 as halibut stack on top of one another (3 deep in this case))
- Temperatures in the tanks are reduced as the halibut grow: from 11-14C when the fish are between 2-25g to between 7-11C once the fish surpass 1 Kg
- Fluidized sand bed bio-filters for filtering waste water
- Dissolved oxygen is injected at 15 psig

NOTABLE FEATURE:	The commercial production of Halibut is significant as a new species to aquaculture, and also in that it is a local species to the region.

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[18] Much of the following is from http://www.halibut.ns.ca/

NAME:	**UNI-Aqua** Denmark (www.uni-aqua.com)
SPECIES	Halibut (*Hippoglossus hippoglossus*) – commercial (as of 1 year) Trout (*Oncorhynchus spp.*) – commercial Turbot (*Scophthalmus maximus*) – commercial Japanese Flounder (*Paralichthys olivaceus*) – commercial Sole (*Solea solea*) – commercial Abalone (*Haliotis spp.*) – commercial Cod (*Gadus morhua*) – experimental (with good potential) Bluefin Tuna (*Thunnus thynnus*) – experimental (entire life cycle)
STATUS:	Commercial
DETAILS:	

UNI-Aqua, of Denmark, is an engineering consultancy and producer, constructing a variety of recirculting tanks for a variety of species. They have deployed their technology in commercial systems in Norway, Spain, China and Australia (Urup, 2007).

Because of the high level of recirculated water, RAS can be located some distance away from the actual shore (important if shore location is costly).[19] A 500 Mt flow-through system will need 12,000 m^3/hr but actual exchange is only 60 m^3/hr (1000 L/min) (Urup, 2007). Control of optimal water chemistry: O2, NH4, CO2-bicarbonate means that aspects of the life cycle can be controlled and maturation can be avoided as in some species, such as turbot (*Scophthalmus maximus*), maturing results in poor feed conversion ratios (www.uni-aqua.com). This also causes fluctuations in meat quality. Because of temperature and input control, the recirculation system performs better than comparable open air flow though systems (See figure 10). They have built a 8-10,000 Mt/year system for turbot (*Scophthalmus maximus*) run by Stolt Sea Farms in Spain (Urup, 2007).

UNI-Aqua has constructed a large turbot (*Scophthalmus maximus*) farm in China using western technology and adapting it to the local Chinese context. They use manual feeding and pumped seawater (Urup, 2007).

NOTABLE FEATURES:	This system claims to grow Bluefin tuna for their entire life cycle (www.uni-aqua.com). Use of wastes: typically, salt from solid wastes is a problem as high salinity is poisonous to crops making it difficult to use as a fertilizer. However, in Denmark solid wastes from their marine species are used as fertilizer as it is mixed with other waste (from conventional animal farms) to reduce salt and spread over a large area (Urup, 2007). 4000 Mt/yr fish production system: will generate 12000 m^3/yr of sludge – 3-4% dry matter. It is high in phosphorous and low in nitrogen and the farmers like it as some of the salts contain micro-nutrients (Urup, 2007). In their experimental tests with halibut, they were able to raise market sized fish in 2-2.5 years (Urup, 2007) (note this is similar to Scotian Halibut, above).

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[19] Much of the following is taken from www.uni-aqua.com, and from interviews with its principal, Mr. Urup.

PICTURES/ DIAGRAMS:

Figure 10: Comparison in growth of halibut *(Hippoglossus hippoglossus)* ***between Flow-through and Recirculation Systems*** *(Photo courtesy of Aquaculture Developments LLC on behalf of UNI-Aqua)*

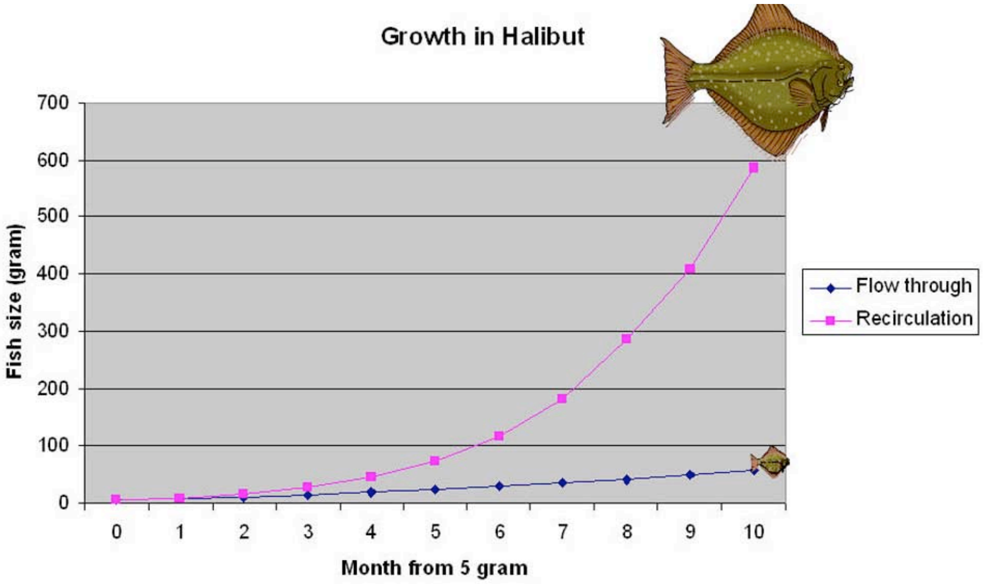

Figure 11: Halibut recirculation system in Dønna, Norway built by UNI-Aqua *(Photo courtesy of Aquaculture Developments LLC on behalf of UNI-Aqua)*

Raceways – Flow-through

NAME:	**Rushing Waters Trout Farm** *Wisconsin, US* (http://www.rushingwaters.net/)
SPECIES:	Trout (*Oncorhynchus mykiss*)
STATUS:	Commercial
DETAILS:	

Trout at the Rushing Waters Trout Farm are grown in paired, steel-reinforced concrete raceways with 15 -20 cm walls and floors.[20] Raceways have an approximate length to width ratio of 6:1 and hold water at a depth of about 1 m. This is a gravity-fed flow-through system with large volumes of cold ($\leq 20^{o}$C) water flow via gravity through a series of terraced raceways and are discharged into a receiving stream. Aeration occurs between raceways as the water flows over a screened outfall and pours into the head of the raceway below. The entire water volume is exchanged approximately every hour.

Nitrogenous wastes must be removed from the raceways by flushing and dilution before toxic levels of un-ionized ammonia gas concentrates in the water. Total alkalinity (>100 mg/L) and pH ($\geq$ 7.5) limits the serial reuse of Kentucky's limestone spring water to 6-8 raceway passes. Waters that are lower in pH and total alkalinity may undergo more reuses before toxic concentrations of un-ionized ammonia are reached.

NOTABLE FEATURE:	Gravity fed water system to keep electrical costs low, and the benefit of using local alkaline waters with a low pH for dealing with ammonia.

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[20] This section has been taken from http://www.rushingwaters.net/.

Tanks - Flow-Through

NAME:	**Icy Waters Ltd** *Whitehorse, Yukon* (http://www.icywaters.com/)
SPECIES:	Arctic char (*Salvelinus alpinus*)
STATUS:	Commercial
DETAILS:	

Icy Waters is a commercial producer of Arctic char. The aquaculture farm has been in operation for 20 yrs.[21] They sell both fish for the consumer market and ova as brood-stock, and have bred a mix of wild and domestic fish to produce a good fish for aquaculture. Production is 200Mt/yr. They employ gravity fed flow-through systems using springs and streams as a water source. Drum filters, settling ponds and wetlands are used to remove particulate matter. Waste sludge is given to farmer's fields, waste from processing is provided to local dog mushers as high oil food or to compost.

NOTABLE FEATURE:	Use of local conditions to grow local variety for international export, and in particular brood-stock. Specialization in a single species. Gravity fed flow-through minimizes pumping costs. Innovative use of waste products.

NAME:	**Silfurstjaran Fish Farm** *Iceland* (Gíslason, 2003; Gústavsson, 2007a)
SPECIES:	Arctic char (*Salvelinus alpinus*), turbot (*Scophthalmus maximus*), halibut (*Hippoglossus hippoglossus*),
STATUS:	Commercial
DETAILS:	

Established in 1988, the Silfurstjarnan Fish Farm is a land-based production system where fish are reared in a number of individual tanks of various sizes and where environments are created for specific species.[22] It is a semi-recirculating system with up to 40% of water reuse. For several years they harvested about 200 Mt/yr of Atlantic salmon *(Salmo salar)*; however, this gave way to Arctic char which has similar growing technology but commands a higher market price. They now produce on the order of 300 Mt/yr of Arctic char. One of the most impressive aspects of the farm is its use of thermal waters to reduce energy costs. After thermal water has passed through a local power generating plant, the cooled water flows to the fish farm where it is used as a heat source. They rely on mixing freshwater, seawater and warm thermal water to provide optimal growth conditions for the fish. Arctic char *(Salvelinus aplinus)*, for example thrive at 16-18 C waters with salinity levels of 10-15 ‰ (Gíslason, 2003)

NOTABLE FEATURE:	Use of geo-thermal heat as an energy source, use of mixing seawater, groundwater, and thermal water to provide an optimal temperature-salinity mixture for fish growth. Iceland is greatly removed from the markets of Europe; nevertheless, they are able to maintain a commercially viable system.

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[21] This section is from www.icywaters.com, and conversations with Icy Waters proponents.

[22] The following is based on personal communication with Mr. Gústavsson (2007a) and reports of Mr. Gíslason (2003).

Inland – Ponds (Flow-Through

NAME:	**Swift Aquafarms** *Agassiz, British Columbia*
SPECIES	Coho salmon (reared in fresh water)
STATUS:	Commercial (small scale)
DETAILS:	

Swift Aquafarms have been rearing salmon for over ten years; and Coho in particular for three years in enirtely in fresh water.[23] They employ a series of 14 ft diameter flow-through tanks. The treatment of waste water is extremely innovative. First, water is passed through a self cleaning 60 micron filter where solids are removed. The effluent is then used to grow watercress and high value wasabi plants. They have also looked at growing hybrid popular for toilet paper and algae that can be used as part of the feed. They have also explored using effluent to grow local crayfish which can weigh as much as ½ pond (200g).
They are expanding to develop recirculating systems.

NOTABLE FEATURES:	Use of fresh water for raising Coho and the integrated approach to aquaculture with profitable by products from effluent and waste. Also, value added products as smoking the fish, or niche market such as restaurants.

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[23] The following is taken from the Minutes of the Special Committee on Sustainable Aquaculture held on October 18, 2006; available from www.leg.bc.ca/cmt/38thparl/session-2/aquaculture/hansard/W61018a.htm#25:1130

NAME:	**Aqua Farm** Langley, BC (Albright, 2007) (http://www.sfu.ca/pamr/news_releases/archives/news10190601.htm)
SPECIES:	Rainbow trout (*Oncorhynchus mykiss*); freshwater Sockeye salmon *(Oncorhynchus nerka)*
STATUS:	Commercial (both)
DETAILS:	

This system involves tank and pond production of trout (*Oncorhynchus mykiss)* and Sockeye salmon (*Oncorhynchus nerka)*, with trout production being 20 Mt/year.[24] Sockeye production is less. Production goes to restaurants in the Vancouver area that want fresh fish (niche market). Sockeye males can grow up to 2.3Kg, and have been cultivated now for four successive life cycles in freshwater only. His tests show that all Pacific salmon, including Coho (*Oncorhynchus kisutch)*, Chinook (*Oncorhynchus tshawytscha)*, Chum (*Oncorhynchus keta*) and Pink salmon (*Oncorhynchus gorbuscha*) can be cultured throughout their entire lifecycle in freshwater.

Most fish are cultivated in flow-through ponds with no recirculation in an area of five acres. Ponds are dewatered at intervals and the sides excavated for solid waste removal that is used as fertilizer (low in nitrogen, but high in phosphorus and micro-nutrients). Incoming water is principally from groundwater wells. Effluent is screened to ensure no escapes, and is treated in a wetland through bio-remediation. There are no antibiotics or additives given to the fish. The feed comes from a local producer, 'UniFeed',[25] and the feed conversion ratio (FCR) is approximately 1.3-1.5.

Albright obtains about $ 10/Kg for trout and $14/Kg for Sockeye salmon (Head-on dressed). Although the Sockeye have white flesh he suggests that demand is high for ecologically reared salmon. Aqua Farms, Westcreek Trout Farm, Silverbrook, Timms, Duriel and N'quatka farms have joined together to create an 'Eco-certificate' for their trout production in the lower mainland of BC.

Albright estimates that the cost of commercially farming salmon in fresh water would be 1.3 times higher than the cost of commercially farming trout in fresh water.

NOTABLE FEATURE:	Sockeye salmon (*Oncorhynchus nerka)* reared entirely in land-based CSA in freshwater. Low pumping and waste treatment costs. Groundwater sources mean that there is little treatment necessary before entry into the ponds.

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[24] The information in this section is derived from interviews with the principle, Dr. Albright (2007), and from the above listed website.

[25] See www.agricoreunited.com/cgi-bin/bvsm/AU2/Farmer/LSS/Unifeed/index.jsp

NAME:	**Ausyfish. Pty. Ltd** *Australia* (www.ausyfish.com)
SPECIES:	Golden perch (*Macquaria ambigua*)[26], Silver perch (*Bidyanus bidyanus*), Murray Cod (*Maccullochella peelii peelii*), Baramundi (*Lates calcarifer*), Jade Perch - Barcoo Grunter (*Scortum barcoo*), and Sleepy Cod (*Oxyeleotris lineolatus*) in recirculating systems (all freshwater species)
STATUS:	Commercial
DETAILS:	
The company has been producing commercial fish since 1988.[27] They have 127 ponds, with three storage dams for water supply, and the systems are mostly gravity fed. They specialise in Australian species, for local consumption and broodstock for export abroad as well. Each species will have its specific benefits. They claim that almost all Golden perch for consumption are now supplied by aquaculture ponds where growing temperatures should not go below 12 C; FCR of 0.8 to 1.7; up to 98% survival rates; and fish feed on plankton in weaning stage reducing feed costs. Jade perch grow twice as fast a Silver perch, generally need temperatures of 27 C, and not below 18C, and grows on wide variety of diets. Sleepy cod can be grown at high densities and can capture market values of $30/Kg. As Sleepy cod tend not to move much there is low production of CO_2 and thus lower costs for aeration, and it also makes them easier to transport live (accounting for high market value). They also grow many ornamental varieties of fish.	
NOTABLE FEATURE:	The focus is on promoting local species and developing sufficient supply to create new markets (Jade perch). Diverse commercial interests, for instance the ornamental fish as well as consumer fish.

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[26] Note they grow all three strains: *Macquaria ambigua ambigua; Macquaria ambigua ssp.*; and *Macquaria ambigua oriens.*

[27] The following was taken from www.ausyfish.com .

NAME:	**Fresh Catch Belize Ltd.** *Belize* (http://www.aquaculture.co.il/Projects/Belize.html)
SPECIES:	Nile tilapia (*Oreochromis niloticus*)
STATUS:	Commercial
DETAILS:	
Aquaculture Production Technology of Israel built the facility.[28] This operation produces tilapia (*Oreochromis niloticus*), supplying 1,300 Mt/yr mainly to US and Mexican markets.[29] The system uses 380 m^2 of land and pumps water from the Sibun river. The project is based on earthen ponds with mechanical aeration, and minimal pumping from the river for compensation against seepage and evaporation losses. The design of the Tilapia Farm is based on 'green-water' re-circulation. In the green-water system fish waste is treated through natural decomposition by bacteria and algae that live in the natural ponds. Ammonia is converted to nitrite and nitrate by bacteria (see waste disposal in section 7 below), the nitrate then being taken up by algae, the algae is consumed by zooplankton which in turn provide a supplement to the fish. Adding water to the fish farm is only required to compensate against losses due to seepage, evaporation and operational uses.	
NOTABLE FEATURE:	The complete 'integrated' cycle of waste to feed for the fish means less waste treatment, less feed, more robust system, photosynthesis of the algae helps maintain oxygen balance (as net O2 producers), much less water consumption, and therefore less possibility for 'interaction' in the system reducing the potential for disease entry. The system has been commercially replicated in El Salvador – see *Aquacoporacion de El Salvador S.A.*[30]

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[28] See www.aquaculture-israel.com

[29] The following is taken from www.aquaculture.co.il/Projects/Belize.html.

[30] See http://www.aquaculture.co.il/Projects/El_Salvador.html

Sea-Based Systems

Flexible Tanks

NAME:	**Aqua-Sphere Closed Containment System.** *Developed by Neptune Industries in Florida City, FL* (Papadoyianis, 2007) (www.neptuneindustries.net)
SPECIES:	Striped seabass (*Morone saxatilis*)
STATUS:	Experimental
DETAILS:	

The Aqua-Cell is a floating, closed-containment seafood production system, and is the first articulated tank system.[31] 'Disruptive technology' is designed to provide an eco-friendly, energy efficient alternative to cages and net-pens. This prototype system designed for Striped Bass has been developed over 8 years in Florida. Aqua-Cell is scalable and modular, and composed of a rigid polyethylene material with neoprene joints between cells that allow flexibility in response to tide, storm surges, etc. The current, first generation prototype is 4.57 m. in diameter with plans for two more generations of prototypes as the company moves towards a commercial scale system. Some other notable features:

- Solid waste is pumped to an anaerobic digester to be converted to methane that is used to run the air lift blowers to pump water.
- Sludge is used as a fertilizer for a hydroponic greenhouse, and waste collected from the bottom of tanks is used to grow edible seaweed.
- The system is very energy efficient as it runs off air lifts (not pumps) – accommodating the use of alternative energy.
- The tanks system is composed of cells that are interconnected with a reinforced neoprene joint, allowing the system to flex upon impact from waves.
- Individual cells have interconnected fish passageways made of flexible tubing or piping. A series of gate valves can be used to move fish from one tank to another without having to net them thereby reducing stress and incidence of disease.
- Neptune Industries has registered a subsidiary in Canada named Aqua Biologics of Canada Ltd.

NOTABLE FEATURE:	Modular components to construct a variety of sides, articulation for stability in wave motion, and easy mobility of fish between adjacent enclosures.

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[31] Information in this section is taken from interviews with Neptune Industry President, Mr. Papadoyianis, and from www.neptuneindustries.net.

NAME:	**Future SEA Technologies** (SEA System™) (www.futuresea.com)
SPECIES:	Chinook salmon (*Oncorhynchus tshawytscha)*, Coho salmon (*Oncorhynchus kisutch)*, Arctic char (*Salvelinus alpinus*), Black cod (*Notothenia microlepidota)*, Rainbow trout (*Oncorhynchus mykiss)*
STATUS:	Commercial
DETAILS:	

The SEA System is a full recirculating system comprising a sea-based flexible bag.[32] This system has been installed for use in British Columbia, Nova Scotia, New Brunswick, Tasmania, Chile, Japan. In B.C. this system has been trialled by Marine Harvest on Salt Spring Island[33] and is currently in use by Middle Bay Sustainable Aquaculture Institute.

The bags are 15m in diameter and range in depth from 7m to 12m (for a total volume range of 1000 m^3 – 2000 m^3). High efficiency pumps reduce the amount of energy required for pumping. Other advantages of the system include ease (and affordability) of transportation from one location to another.
Salmon species can be raised in this system at an average density of 30Kg/ m^3. An operation raising Rainbow trout in Nova Scotia achieved densities of 60Kg/ m^3 while Arctic char in Ontario have been raised at 40 Kg/ m^3. This can be compared with net-pens which generally maintain densities of between 10 and 15 Kg/ m^3 for salmon species.

NOTABLE FEATURE:	Flexible bag system, high efficiency pumps, being tested for salmon rearing

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[32] Information in this section is based on personal communication with Andy Clark, president of Future SEA Technologies, and www.futuresea.com

[33] Information from this trial can be found on the British Columbia Ministry of Agriculture and Lands website at http://www.agf.gov.bc.ca/fisheries/technology/marine_harvest.htm

NAME:	**McRobert Aquaculture Group** *Western Australia* (http://www.mcrobert.com.au/)
SPECIES:	Ocean trout (*Oncorhynchus mykiss),*[34] Yellowtail kingfish (*Seriola lalandi lalandi)* and mulloway *(Sciaena Antarctica)*
STATUS:	Commercial (since 2006)
DETAILS:	

McRobert Aquaculture Group initially developed the Semi-Intensive Floating Tank System (SIFTS) as a product to improve finfish production in the inland saline waterways of Australia, and address many of the current problems within cage farming industries.[35] At the core of the SIFTS development are the McRobert fish handling and waste removal processes. Fish are stocked in SIFTS at densities 4 to 5 times higher than in sea-cages (>80 Kg/ m^3) and sustained by constantly aerated water being pumped through at the high rate of up to four complete exchanges per hour. The impervious liners prevent escapes of fish, eliminate predation and facilitate the capture of solid wastes. The water environment is constantly monitored via a computer-controlled system. A prototype 50m^3 SIFTS deployed into the Ocean Farms site in Fremantle Harbour since November 2006 has capacity to produce up to 50 Mt/yr of fish, including ocean trout, yellowtail kingfish and mulloway for the local market. The system is not suited to tropical waters with large tidal movement but has potential in ponds and sheltered waters.

Whereas SIFTS is designed to grow a "local" product suited to the climate of a particular region, the McRobert Aquaculture Group also designs and installs fully recirculating systems which are biosecure (disease control), intensive, land-based indoor tank-based systems that allow high value species to be grown in any climatic region.

NOTABLE FEATURE:	The use of local species, high densities of fish, and high turnover of water. Although pumping costs must be relatively high (compared to open net) these seem to be out weighted by production volume.
PICTURES/ DIAGRAMS:	***Figure 12: Rotationally moulded SIFTS*** *(Photo provided courtesy of McRobert Aquaculure)* 

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[34] Note that Tasmanian Ocean trout are also known more commonly as Rainbow trout and Steelhead trout.

[35] The following is taken from http://www.mcrobert.com.au/.

Sea Based ‘Hard’ Tanks

NAME:	**Mariculture Systems (SARGO™)** USA (http://www.sargo.net/)
SPECIES:	Coho (*Oncorhynchus kisutch)* and Chinook salmon (*Oncorhynchus tshawytscha)*, Yellowfin tuna (*Thunnus albacares*), Arctic char (*Salvelinus alpinus*) and Walleyed pike (*Sander vitreus vitreus)*
STATUS:	Experimental
DETAILS:	

The basic element of the SARGO fish rearing system is a floating, rigid-wall reservoir with a continuous, external supply of water pumped from any desired depth.[36] Six fish-rearing reservoirs assembled around a service platform comprise a POD. Each service platform contains the pumps, controls, feeding equipment, oxygen supply, waste handling system and other support equipment for its POD. No system is in commercial operation, but there are several in experimental phase. Major testing has been conducted on Coho and Chinook salmon (saltwater), and Arctic char (freshwater); as well as Yellowfin tuna in Panama and Walleyed pike in freshwater lakes in Michigan. Mariculture Systems is also working with Yellow Island Aquaculture on Quadra Island to install a system to raise Chinook salmon. They are projecting this facility to be operational by the spring of 2008. The system is expected to be able to produce market size 3.6-3.9 Kg (8 – 8.5 lbs) in approximately 15 months at a cost that they claim is competitive with net-pen production. They have also previously harvested 2 cycles of Atlantic salmon in Puget Sound (2001 – 2002). These grew to market size 3.6-3.9 Kg (8 – 8.5 lbs) in 10.5 months, outpacing average net-pen production for Atlantic salmon.

Their new 2nd generation tanks are 20 m in diameter and 11.5 m deep with a total of 2500 m^3 usable space. There is a 5ft high level barrier from the open water to top of tank to minimise liquid transfer. Fabric is high density polyethylene with steel reinforcement and fibreglass bottom, which has the particular advantage of very low growth of organisms on sides so there is less drag compared to nets. It is designed to withstand winds of up to 160 km/h.

Water is pumped in locally (either ocean or lake water) and is filtered to remove particulates or any organisms before going into the tank. Their intake pipe can reach depths of 280m with various sections of intake to control temperature and salinity and even water quality. The current waste treatment system is a Type III marine sanitation device (designed for the shipping industry). They are also exploring anaerobic digesters to create methane and wave-energy generators for low cost energy generation. Ultimately, the pods should be entirely self sufficient for ‘far from shore’ open ocean deployment. In tests they have had fairly good feed conversion ratios of 1.15.

NOTABLE FEATURE:	Small energy requirements for pumping, and control of incoming waters through 280 m deep intake pipe, good feed conversion ratios, potential for offshore deployment as it is able to stand up to high winds an waves (note the McRobert CSA system is specifically designed for inland ocean and low tides). Plastic sides reduce barnacle growth, reducing tidal and current effects as well as increasing longevity of tanks.

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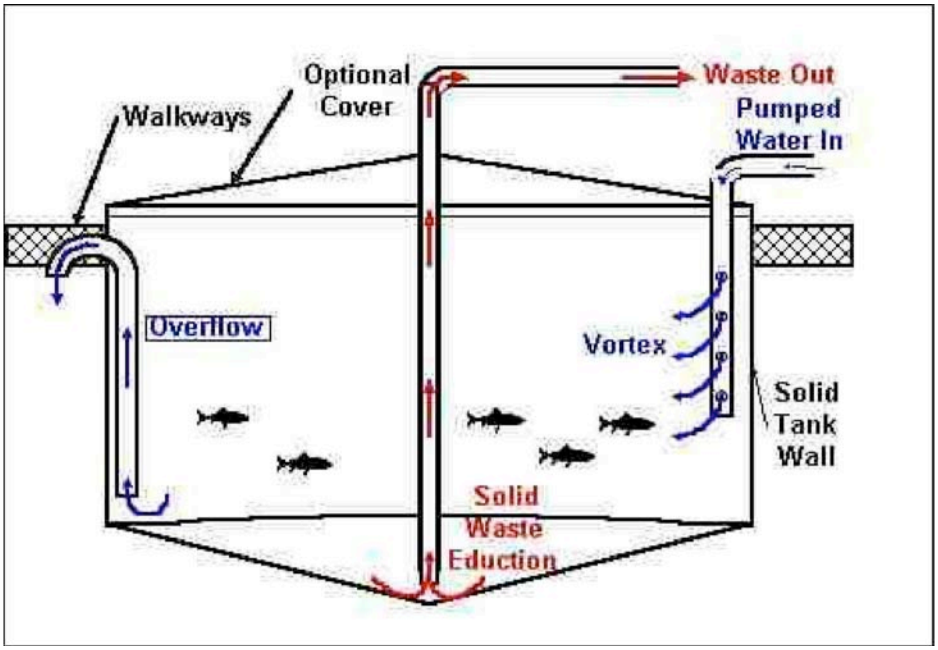
[36] The following information was collected from an interview with D. Meihan, of Mariculture Systems, and from www.sargo.net .

PICTURES/ DIAGRAMS:	***Figure 13: SARGO system*** *(Taken from http://www.sargo.net/)* 

NAME:	**Middle Bay Sustainable Aquaculture Institute** Campbell River, British Columbia (http://www.sustainable-aquaculture.ca/) (Walker, 2007)
SPECIES:	Chinook salmon (*Oncorhynchus tshawytscha)*
STATUS:	Experimental
DETAILS:	

The system being developed at Middle Bay has evolved from the AgriMarine demonstration project in Cedar, BC.[37] This system is composed solid walls made from fibreglass reinforced plastic over high density foam (initially it was concrete). The plan is to install 4 tanks – each with a useable volume of 5500 cubic meters. Each tank is projected to be capable of producing 100,000 fish at a size of 3.5 Kg/fish. The time required for this grow-out is expected to be approximately 16-18 months. Currently, Middle Bay is raising Chinook salmon, though the system will be adaptable to other species (such as sea trout, black cod (sablefish), halibut) and producers may look into these in the future.

Producers at Middle Bay have employed the use of Future SEA Technologies SEA System™ to house fish stock in the interim while they continue to develop their own technology.

NOTABLE FEATURE:	High production levels of 200 Mt/yr for each tank, and harvesting of local species.

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[37] The information in this section was derived from personal communication with Rob Walker, of Middle Bay Sustainable Aquaculture Institute and from http://www.sustainable-aquaculture.ca/

5. Species Grown in Closed System Aquaculture

The following section contains an overview of characteristics pertaining to some of the more common species currently being harvested (commercially or experimentally) in CSA systems.

Abalone (*Haliotis spp.*)
Abalone is susceptible to a range of parasites and requires specific water conditions such as constant and low levels of ammonia at a high pH; low levels of CO2; constant levels of oxygen around 100% saturation in the tanks; and very low turbidity. Because of advantages related to the ability to prevent ectoparasites and the control of incoming water, abalone is especially well suited for CSA.

Arctic Char (*Salvelinus alpinus*)
Arctic char tolerate high-density culture conditions, have an excellent fillet yield, are amenable to niche marketing, and are suitable for production within super-intensive recirculating systems (Summerfelt, 2004). Arctic char are raised predominantly in land-based, closed systems with recirculating water (Summerfelt, 2004). There is some limited production in flow-through systems and net-pens. Arctic char have been shown to be more disease resistant than other salmonids (Marsh, 2006).

Barramundi (*Lates calcarifer*)
Barramundi is a tropical species requiring water temperatures between 20°C and 30°C. Commercial growth rates require temperatures above 25°C. Being euryhaline (able to tolerate a wide range of salinities), barramundi can be grown in salt, brackish or fresh water environments. Barramundi are typically raised at 75 Kg/m^3 (Schipp, 2006). They are reared on dry, pelleted diets; and maximum intakes (and best feed conversion ratios) occur between 27°C to 29°C. The amount of feed consumed by the fish decreases rapidly as the water temperature drops. Barramundi are very robust and hardy and disease is generally not a problem, providing good husbandry techniques are employed. It is a high quality, white fleshed fish, with a high yield of meat to body weight (around 45%) and is high in Omega 3 oils. The development of hatchery technology has provided the major impetus to the barramundi industry's development in recent years.

Cod[38] (*Gadus morhua*) and "Black" (*Notothenia microlepidota)*
Cod is a relatively new species in aquaculture. The total production volume of cod is still relatively low, however, it is a species that could have the potential to grow into a production volume equivalent to that of salmon (www.uni-aqua.com). Cod can be farmed at very high densities but a tank design adapted for cod is necessary and the vaccination program is different from the one used in flow-through systems (Urup, 2007). Marine Harvest has been experimenting with a cod (*Gadus morhua*) hatchery in Norway. In 2005 they produced 2 million 10g fish at a cost of $1.26 each (Shipp, 2006). Note that cod require high levels of fish oil in their diet.

Halibut (*Hippoglossus hippoglossus*), "California" (*Paralichthys californicus)*
Halibut is a new species in aquaculture. It is highly valued, although only well known mainly in Scandinavia, Britain, USA and Canada. Generally, halibut has been grown in containment as juveniles and subsequently transferred to open water cages. Recently, an operation in Norway has begun performing the entire production-cycle on land, with recirculation technology. Using this technology, the production time required for a market size fish can be reduced from 6 years (cage) to approx 2½ years (recirulating system) (Urup, 2007). Furthermore, the overall production costs, including capital costs, of halibut production can be reduced by approximately 30%

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[38] Note that *Gadus morhua* refers to the Atlantic cods, a marine species and similar to "Black" cod of New Zealand. Other 'cods' such as "Murray" *(Maccullochella peelii) and* "Sleepy" (*Oxyeleotris lineolatus*) are freshwater Australian varieties and are of no relation.

using recirculating technology as compared with cage operations (Urup, 2007). Note that halibut require high levels of fish oil in their diet.

Researchers at the Norwegian Institute of Water Research (NIVA) have also been experimenting with halibut. One experiment aimed to control the maturation process in order to maintain somatic (muscle) growth in the fish and improve the FCR. To do this, researchers trialled a feeding regime where fish were starved then fed in 5 week cycle rotations (halibut can live up to one year without feed) (Shipp, 2006).

Salmon, Atlantic (*Salmo salar*)
One of the most grown species in aquaculture in Western Europe, North America and Chile but predominantly in open, net-pen systems. Atlantic salmon are mainly grown in recirculation systems to smolt and post-smolt stages. The AgriMarine farm in Cedar, BC grew two cycles of Atlantic salmon in 2002 and 2003. The Atlantic salmon raised in the second cycle this operation had better feed conversion rates (1.34) and peak densities (36 Kg/ m^3) compared to average Atlantic salmon harvests in net-pen systems (density of 16 Kg/ m^3) (AgriMarine, 2004). The Sargo™ system was also used to grow 2 cycles of Atlantic salmon in Puget Sound before the lease for the property expired.

Salmon, Chinook (*Oncorhynchus tshawytscha)*
Chinook salmon is currently being raised at experimental facilities in British Columbia. Trials at the Middle Bay Sustainable Aquaculture Institute have demonstrated that this species can be raised in CSA facilities at costs on par with those required for net-pen production (Walker, 2007). Future SEA™ as well as Sargo™ technologies have also been tested for Chinook farming. They can be stocked on average at a density of 30Kg/ m^3 (Clark, 2007) and typically grow to 3-3.5Kg in 16-18 months in CSA facilities (Walker, 2007). In 2002, the AgriMaine test facility in Cedar, BC, grew Chinook to a harvest size of 1.6 Kg (3.11/lb) after 13 months (however, they were harvest early to make room for other trials) (AgriMarine, 2003).

Salmon, Coho *(Oncorhynchus kisutch)*
Two production cycles of Coho were grown at the AgriMarine test facility in Cedar, BC in 2002 and 2003. In the first generation, the growth rates (fish reaching 2-3 Kg (4.5-6.8 lbs) in 15 months), survival rates (87%) and feed conversion rates (1.2) were comparable to the performance of net-pen production (Atlantic) salmon. The densities tested (42Kg/ m^3) were more than twice that of net-pen production (max 20 Kg/ m^3). These were produced at a cost of CDN$ 7/Kg (CDN$3.22/lb) (including transportation costs to Victoria) while market value in 2002 was CDN $4.9/Kg (CDN$2.25/lb) (AgriMarine, 2003). Feedback from consumers at the time indicated there would be opportunities to sell this product at a profit (AgriMarine, 2003). The second generation harvest again showed favorable conditions for Coho. The feed conversion rate was higher (FCR 1.6 – believed to have been affected by a longer growth period and overfeeding). The peak density, at 32.5Kg/ m^3, was lower than the first generation but remained higher than typical net-pen production.

Salmon, Sockeye (*Oncorhynchus nerka)*
Aqua Farm in Langley, British Columbia, has raised four generations of Sockeye salmon entirely in freshwater, without the input of anitibiotics of chemicals. The species requires similar growing conditions to trout. The flesh is white and average size to market is 5Kg which is similar to wild caught salmon which average between 3 – 5.5 Kg at maturity (Albright, 2007).

Sole (*Solea solea*)
In Europe, sole is grown primarily in recirculation raceway systems. Sole commands a high market price and is becoming increasingly important species in aquaculture (Øiestad, 2007a; Øiestad, 2007b).

Spotted Wolfish *(Anarhichas minor)*
At the Institute of Marine Research, Austevoll Research Station in Norway, researchers are investigating the high intensity culture of spotted wolfish, in shallow raceways. These fish are being cultured at the high density of 600 Kg/ m^3 (Schipp, 2006).

Tilapia, Nile (*Oreochromis niloticus*)
While there are also the blue tilapia and the Mozambique tilpia, the Nile tilapia is the most commonly used species for aquaculture. This species can be grown at extremely high densities (Schipp, 2006; Holder, 2007), and thrives in saline, brackish or fresh water. Originally from the Middle East and Africa, tilapia require high temperatures (27-20 C). They mature quickly (approximately 6-8 months) and grow between 170 g to 2.2 Kg (Gíslason, 2003) They are a very robust fish with respect to disease and high density numbers and account for the majority of pond system aquaculture for finfish world wide (FAO-STAT, 2007). Tilapia are raised in BC at 100 Kg/m^3 (RedFish, 2007). They are a herbivorous species, meaning they can survive on a plant-based diet (Boyd 2005). Adults do however typically receive feed that contains on average 5% or less fishmeal (Goldburg and Triplett 1997).

Trout, Rainbow (*Oncorhynchus mykiss)*
Rainbow trout are notable for the high densities at which they can be stocked. Typically, they are grown at a rate of 3-5 Kg/L per minute of water flow. In raceways, stocking densities are typically .3 to .7 Kg of fish per litre of water (measured by Kg/litre/flow/min.) (Hardy, 2000). Farms that aerate their raceways and ponds can stock and produce up to 1.2 to 1.8 Kg of fish per litre of water (Hinshaw, 2004).

Rainbow trout are very efficient at converting feed to biomass (Hardy, 2000). Advancements in feed formulations in recent years have led to improved feed conversion ratios and therefore less use of marine resources. In some recirculation systems, Rainbow Trout require relatively little water in the grow-out stage. Water bound to sludge in the system (and subsequently removed) and that volume which evaporates are the only water losses in the system. Water consumption has been found to be as low as 10-20 L of water per Kg of fish produced. This is significant for the fact that it allows the flexibility to locate wherever there is an economical and sustainable supply of production quality water.

Trout is, on average, raised at a density in the range of 150-180 Kg/m^3 in commercial RAS production (Urup, 2007) while flow-through ponds operate with densities in the range of 20-30 kg/m^3 m. Peak levels at +300Kg/m^3 have been seen in RAS systems, without the onset of disease problems, though some fin deformities are observed above 300 Kg/m^3 (Urup, 2007). The SIFTS recirculating tank system used by the McRobert Aquaculture group in Australia raised trout at density of 47 Kg/m^3 (McRobert, 2007).

Tuna, Bluefin (*Thunnus thynnus*)
Tuna has been grown in cage culture for many years using wild caught juveniles. However, with decreasing wild stocks, interest in using captive brood stocks and hatcheries for producing juveniles for grow-out is becoming particularly attractive. UNI-Aqua has been active in Tuna aquaculture (Urup, 2007).

Tuna, Yellowfin (*Thunnus albacares*)
There are attempts underway to grow Yellowfin tuna in CSA open water flow-through systems in Panama. This is very much at the experimental phase (Meihan, 2007). Note tuna require high levels of fish oil in feed.

Turbot (*Scophthalmus maximus*)
Flatfish species such as turbot and halibut are passive fish, and will have similar activity pattern, whether in captivity or in the wild. This makes them excellent choices for aquaculture as they exhibit less stress than other species (Urup, 2007; Øiestad, 2007a).

6. Volume and value of fish grown in CSA

Aquaculture Production in Closed Systems

It is difficult to determine production volumes and values for CSA species as trade data does not generally disaggregate data to reflect the distinction between open and closed system aquaculture. Research revealed some general findings which are helpful in understanding the market for CSA (i.e. the fact that approximately half of all the fish consumed in the Netherlands is farmed; some species such as trout (*Oncorhynchus mykiss)*, turbot (*Scophthalmus maximus*), and Arctic char (*Salvelinus alpinus*) are almost ubiquitously farmed in some form of CSA (Gíslason, 2003); several species are typically reared in CSA until they are smolts or juveniles and then are transferred to open cages or pens for grow-out stages). The following section, therefore, contains piecemeal information that is relevant in determining the value and volume of fish currently being or proposed for production in CSA systems. For organizational purposes, this has been broken down by species and/ or country.

Salmon

Approximately 200 Mt of salmon *(Salmo salar)* were produced in land-based systems in Iceland in the late 1990's before switching to Arctic char (*Salvelinus alpinus*) to capture high market prices associated with this species (Gústavsson, 2007b). In BC, Sockeye salmon is being produced in fresh water CSA and then sold to local restaurants in the BC lower mainland (Albright, 2007). Atlantic *(Salmo salar)*, Coho (*Oncorhynchus kisutch)* and Chinook salmon (*Oncorhynchus tshawytscha)* were raised for two generations in an experimental CSA system in Cedar, BC in 2002 and 2003. They required the following production costs (AgriMarine, 2003): Coho: $6.75/lb (plus packaging, delivery and dressing = $8.80) and Atlantic salmon: $5.98/lb (plus packaging, delivery and dressing = $7.28).

Trout (*Oncorhynchus mykiss)*

In 2004, sales of U.S. farmed food-size trout (note that sales of trout for stocking, fingerlings, and eggs are not included) reached over 24 million Kg ranking trout second in terms of volume for U.S. finfish aquaculture products, behind farmed catfish (*Ictalurus punctatus)* (Harvey 2005). The U.S., however, accounts for only a small amount of overall global farmed trout production which was recorded as 511,000 Mt (FAO-STAT, 2007). The major producing countries for trout include France, Chile, Denmark, Italy, and Norway (Hardy, 2000; FAO-STAT, 2007).

90% of Rainbow trout raised in the US annually comes from flow-through raceway systems facilities (Hinshaw et al. 2004; Bostick et al. 2005), while farms in Canada and Chile raise rainbow trout in open ocean net-pen or cage systems (Bostick et al. 2005).

Turbot (*Scophthalmus maximus*)

Turbot (*Scophthalmus maximus*), as an aquaculture product, is reared exclusively in land-based systems. France and Spain produce the majority of turbot on the market, accounting for 85% of global production. An increase in the volume of turbot aquaculture between 1990 and 1994 lead to a 25% decrease in its market price over the same period (Gíslason, 2003). While the price has stabilized over the last decade, production is still increasing. Note that the price reflected here is to illustrate a trend. The exact figures in terms of fresh fillets, frozen or head-on dressed are not categorised in the FAO database. Moreover, for many species prices per Kg will also vary depending on the size of the fish, further obfuscating the information.

Figure 14: Production and price of turbot, 1990 – 2005 *(Taken from FAO-STAT)*[39]

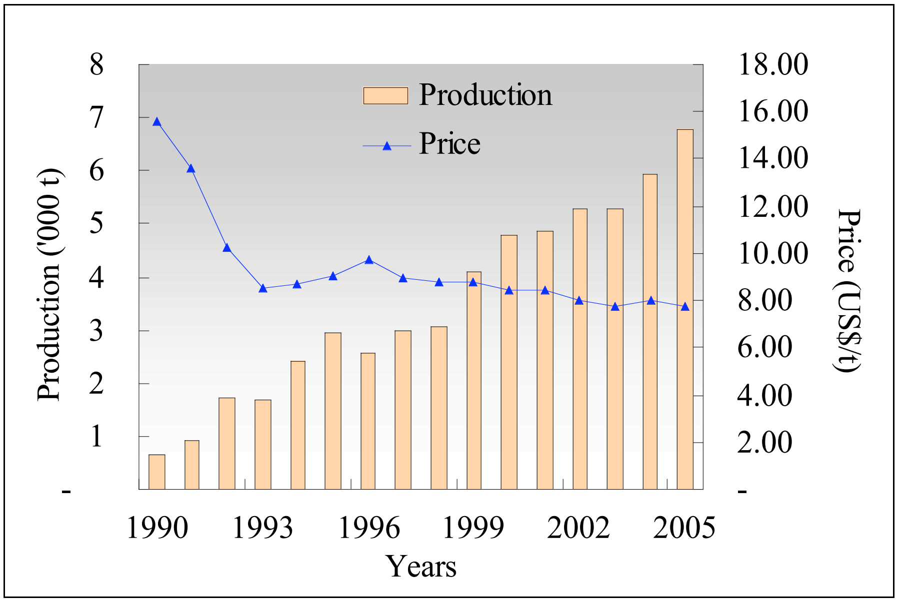
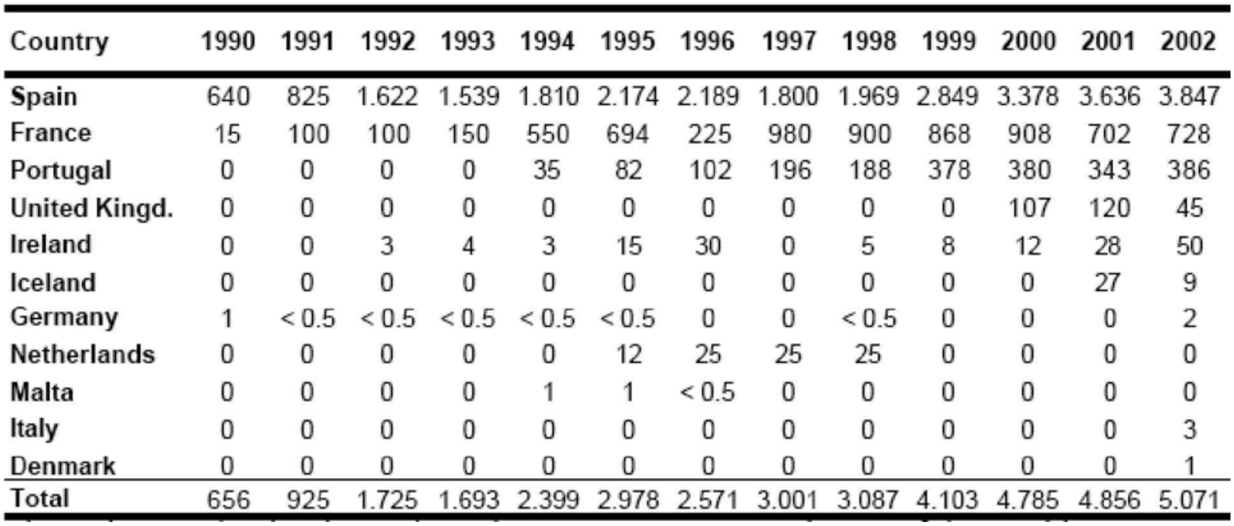


Table 4: Production of turbot *(Scophthalmus maximus)* ***in Europe (Mt/year)*** *(Gíslason, 2003)*



Country	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Spain	640	825	1.622	1.539	1.810	2.174	2.189	1.800	1.969	2.849	3.378	3.636	3.847
France	15	100	100	150	550	694	225	980	900	868	908	702	728
Portugal	0	0	0	0	35	82	102	196	188	378	380	343	386
United Kingd.	0	0	0	0	0	0	0	0	0	0	107	120	45
Ireland	0	0	3	4	3	15	30	0	5	8	12	28	50
Iceland	0	0	0	0	0	0	0	0	0	0	0	27	9
Germany	1	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	0	0	< 0.5	0	0	0	2
Netherlands	0	0	0	0	0	12	25	25	25	0	0	0	0
Malta	0	0	0	0	1	1	< 0.5	0	0	0	0	0	0
Italy	0	0	0	0	0	0	0	0	0	0	0	0	3
Denmark	0	0	0	0	0	0	0	0	0	0	0	0	1
Total	656	925	1.725	1.693	2.399	2.978	2.571	3.001	3.087	4.103	4.785	4.856	5.071

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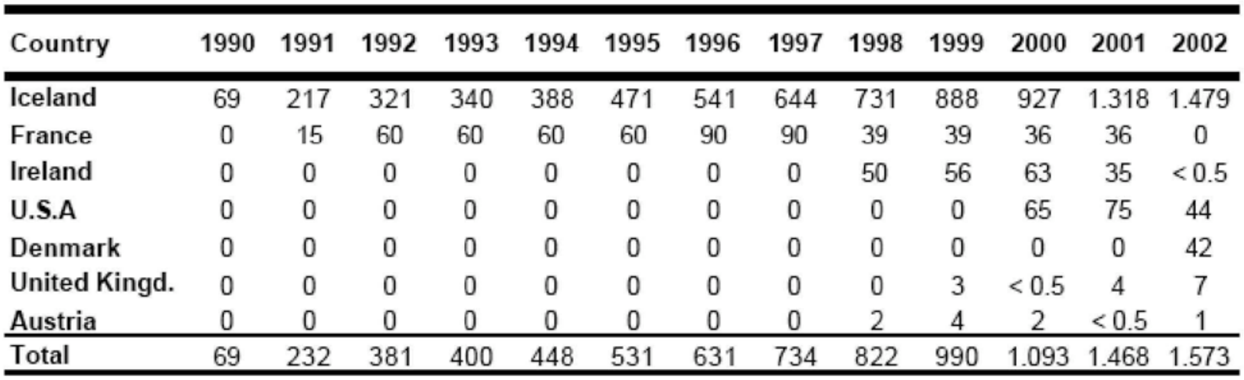
[39] Production costs are not detailed in the FAO site as they are reported by countries. It is assumed to be for 'total' production, including transport to market – also these are thus costs averaged out over numerous facilities each with a unique set of production costs.

Arctic char (*Salvelinus alpinus*)

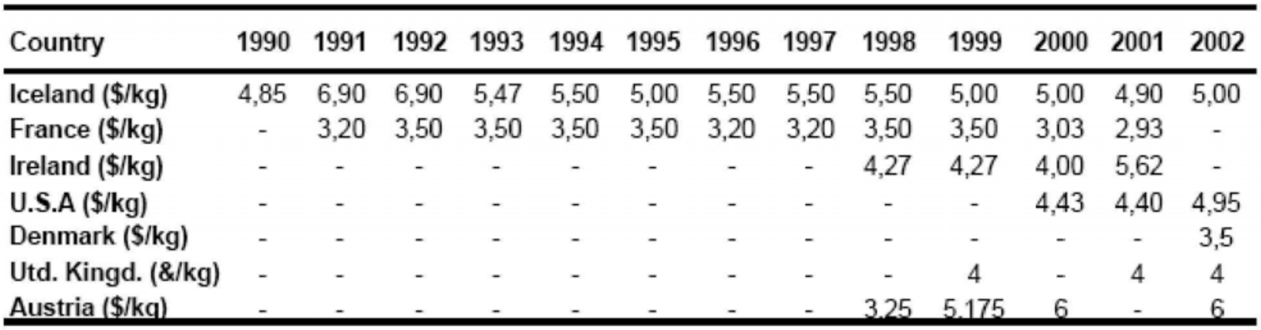
Arctic char aquaculture is predominately based on land-based recirculating systems. In Iceland, char is exclusively produced in land-based systems (Gústavsson, 2007b). Iceland is the largest producer of arctic char with Canada the second largest producer at about 400 Mt/yr (Gíslason, 2003).

***Table 5: Arctic char** (Salvelinus alpinus) **production for selected countries (Mt/yr)** (Gíslason, 2003)*



Country	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Iceland	69	217	321	340	388	471	541	644	731	888	927	1.318	1.479
France	0	15	60	60	60	60	90	90	39	39	36	36	0
Ireland	0	0	0	0	0	0	0	0	50	56	63	35	< 0.5
U.S.A	0	0	0	0	0	0	0	0	0	0	65	75	44
Denmark	0	0	0	0	0	0	0	0	0	0	0	0	42
United Kingd.	0	0	0	0	0	0	0	0	0	3	< 0.5	4	7
Austria	0	0	0	0	0	0	0	0	2	4	2	< 0.5	1
Total	69	232	381	400	448	531	631	734	822	990	1.093	1.468	1.573

***Table 6: Arctic char** (Salvelinus alpinus) **price US$ per Kg fish in selected countries** (Gíslason, 2003)*



Country	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Iceland ($/kg)	4,85	6,90	6,90	5,47	5,50	5,00	5,50	5,50	5,50	5,00	5,00	4,90	5,00
France ($/kg)	-	3,20	3,50	3,50	3,50	3,50	3,20	3,20	3,50	3,50	3,03	2,93	-
Ireland ($/kg)	-	-	-	-	-	-	-	-	4,27	4,27	4,00	5,62	-
U.S.A ($/kg)	-	-	-	-	-	-	-	-	-	-	4,43	4,40	4,95
Denmark ($/kg)	-	-	-	-	-	-	-	-	-	-	-	-	3,5
Utd. Kingd. (&/kg)	-	-	-	-	-	-	-	-	-	4	-	4	4
Austria ($/kg)	-	-	-	-	-	-	-	-	3,25	5,175	6	-	6

The price per Kg of fish was originally taken from FAO statistics (Gíslason, 2003). Note that the price reflected here is to illustrate a trend. The exact figures in terms of fresh fillets, frozen or head-on dressed are not categorised in the FAO database. Moreover, for many species prices per Kg will also vary depending on the size of the fish, further obfuscating the information.

Tilapia (*Oreochromis niloticus*)

Tilapia is becoming increasingly popular in North America, where they are produced entirely in land-based CSA systems. Table 7 shows the importation of tilapia into the US over seven years.

Table 7: Tilapia imports into the US – by product form (Mt) *(Taken from FAO-Globefish, 2005)*

	1997	1998	1999	2000	2001	2002	2003	2004
Whole frozen	19,122	21,534	27,293	27,781	38,730	40,748	49,045	57,299
Frozen fillets	2,499	2,696	4,971	5,186	7,372	12,253	23,249	36,160
Fresh fillets	2,823	3,590	5,310	7,502	10,236	14,187	17,951	19,480
Total	24,444	27,820	37,575	40,469	56,337	67,187	90,246	112,939

US & Canada

In 2005, Harvey found that catfish (*Ictalurus punctatus)*, which are typically reared in flow-through ponds and raceways and are the largest production CSA fish in US (Harvey, 2005). Based on the 1998 US Census of Aquaculture, the bulk of all aquaculture is from flow-through pond systems, with only about 8% of aquaculture production being conducted in recirculating units (RAS). A 2001 survey of recirculation (RAS) facilities in the United States and Canada growing finfish indicated that the number and pounds of fish produced is quite variable, including presence of small, medium and large-sized farms with operations in warm and cold water in both saltwater and freshwater environments. The four fish most commonly grown in recirculation units (RAS) in the United States and Canada are Atlantic salmon *(Salmo salar)* smolts, tilapia (*Oreochromis niloticus*), hybrid Striped bass (*Morone saxatilis*) and ornamental fishes (Delabbio, 2003).

Table 8: Methods Used for Aquaculture Production in the United States: 1998
(Derived from USDA-NASS 1998 Census of Aquaculture
http://www.nass.usda.gov/census/census97/aquaculture/aquaculture.htm Accessed August 12th, 2007
-USDA-NASS, 1998)

Method Used	Number of Farms
Ponds - natural	2,878
Flow-through Raceways or Tanks	617
Cages	117
Net-Pens	50
Closed Recirculation Tanks	328
Ponds-Channels with Prepared Bottoms	338
Other Methods	231
Total Farms	4.028

Success stories and failures

While CSA poses challenges in terms of start-up and production costs, there is no shortage of success stories. CSA operations have been installed in numerous countries for a variety of species that continue to be produced commercially. This section highlights numerous examples of commercially viable CSA systems.

A number of factors are helping to improve the feasibility of CSA systems. The advancement of relevant technologies for CSA is predicted to continue to help improve production efficiencies. Simultaneously, the market price of CSA produced fish could be expected to increase (Holder, 2007). In Europe, for example, food safety concerns and environmental awareness have resulted in some consumers willing to pay a premium for safe and environmentally friendly products (van Eijk, 2007). In Canada, salmon produced in land-based systems in Cedar, British Columbia has successfully brought a premium price, being labelled as 'Eco-salmon' and distributed to some restaurants and seafood stores around Vancouver and Vancouver Island (AgriMarine, 2003). Furthermore, policy and regulatory changes, such as those put forth by the BC Special Committee on Sustainable Aquaculture have the potential to encourage, facilitate and/or mandate CSA through the imposition of fines, taxes and monitoring schemes related to waste discharge, escapement, disease spread, etc.

Spotlight on Successful Operations

Akvaplan-niva. Norwegian (Øiestad, 2007a)
Raceway system for Dover sole (*Solea solea*), seabream (*Sparus aurata)* and turbot (*Scophthalmus maximus*) using the Shallow Raceway System. *(Note: The Akvaplan-niva Shallow Raceway System is being used in commercial operations, Akvaplan-niva is independent of the companies using their system in commercial operations)*

- Aquacria Arousa has been operating a 500 Mt turbot (*Scophthalmus maximus*) facility using Akvaplan-niva's Shallow Raceway System in Galicia, Spain for several years.
- Feed for the turbot (*Scophthalmus maximus*) generally will be about 20-30% of the operational costs. Feed consists of 50% protein, 15% lipids and the rest mix and binder.
- Total for operating costs were $7.5/Kg of fish (including transportation to market), while the sale value for turbot (*Scophthalmus maximus*) is $12-18 /Kg
- Operating costs for the farm were estimated by Mr. Øiestad (2007a) (Table 9)

Table 9: Estimated percentage operating costs for Aquacria Arousa's turbot system *(Øiestad, 2007a)*

Item	% production cost
Juveniles	13%
Feed	23%
Security (sensors and monitoring equipment)	8%
Salary	13%
Processing costs (preparation for market)	18%
O2	4%
Others: admin, maintenance and energy	14%

Stolt Sea Farm (Norway)
Stolt Sea Farms, a branch of Stolt-Nielsen S.A. Norway, has a 4000 Mt turbot (*Scophthalmus maximus*) production facility in Galicia, Spain. They are also exploring potential with California sturgeon *(S. acipenser)* (Øiestad, 2007a).

Inter Aqua Advance ApS (Denmark) (www.interaqua.dk)
Inter Aqua Advance was established in 1978 and was one of the first companies in the world to offer recirculation water treatment systems. As a company, their focus has been on the highest possible water quality, low energy consumption and user-friendly designs. Their system design is now up to its third generation of development. They have a continuing development program and aim toward keeping the systems at a level that is competitive – and cheaper in production cost and management than conventional systems.

- Low head system ~1.5 m vs. 2.5 m
- High recirculation rate of 3000 litres/ second
- A patented low head oxygenation system.
- The biomedia developed by InterAqua, 'curler advance' is claimed to be superior to other plastic media because of its open design which prevents clogging and gives improved nitrification performance.
- Curler advance biomedia is used in the company's Clearwater low-space bioreactor. This bioreactor is designed with an internal airlift system to maintain oxygen, off-gas CO2 and to keep the biomedia moving and operating with a thin, healthy biofilm for improved nitrification performance.
- Recently InterAqua has developed a new, non-mechanical filtration system. Termed 'contact filters' they consist of long raceways filled with sinking plastic media. The media slows the flow of the recirculated water, causing solids to fall out of suspension. The raceways are flushed periodically to remove accumulated wastes.
- Contact filters are already operating successfully in large trout farms in Denmark.
- Simple cost estimate (2005) for a plant producing 600 Mt of fish per year:
  - $4.35 million for the plant
  - $0.6 million for the shed
  - $2.85 million production cost including:
    - Feed $1,386,000
    - Electricity €184,960
    - Labour €431,575
    - Brood Stock €295,537 (species dependent)
    - Maintenance, insurance, ancillary costs etc €123,307

Spotlight on Failed Recirculation Systems

The following list presents examples of failed recirculation systems. These are valuable in highlighting distinctions between issues related to technology, management and policy in influencing the success or failure of a CSA venture. This learning is necessary to maintain or advance the implementation of technologies which may have been associated with a failed venture but have the potential to be successful when installed with other proven technologies, when implemented in an improved management context and/or policy environment.[40]

1. Idaho-based J.R. Simplot Co. closed the doors on its two-year old, intensive tilapia operation, losing more than $20 million in the process. Reason: inadequate biofilter.
2. Bodega Farms shut down its $9.5 million steelhead, Coho salmon (*Oncorhynchus kisutch)* and abalone (*Haliotis spp.*) farm near Bodega Bay, CA. Reason: State of CA would not allow two million fingerlings across the border, and they had no place else to go (no fish, no cash).

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[40] The following list is taken from Timmons (2002) who was paraphrasing and article written by Peter Redmayne (Editor of Seafood Leader, January/February – 1992).

3. Aquaculture Technologies of Louisiana (ATL) went bankrupt abandoning 8 square kilometres of catfish (*Ictalurus punctatus)* ponds in St. Landry Parish. Also they left some $9 million in debts to some 300 creditors. Reason: bad management.
4. NAIAD Corp, largest catfish farming and processing venture in Texas filed Chapter 11 (August of 1991) after starting processing its own catfish (*Ictalurus punctatus)*. Reason: lack of operating cash related to poor cash flow management.
5. Blue Ridge Fisheries (Marinsville, VA) the largest indoor catfish (*Ictalurus punctatus)* operation in the world (at that time, 1991) lost its assets to bank foreclosure. Reason: the RAS was not coast effective. This facility was resurrected as a tilapia facility and is currently a major producer in the Northeast US, essentially under the same management structure).
6. Fish & Dakota lost several hundred thousand pounds of fish and did not reopen its doors. Reason: New management eliminated some of the 24 hour coverage and a power outage and failure of the "automatic" stand-by generator killed the fish.
7. Northern Fresh Fish Cooperative (central NY), last member to lose fish was because his dialer had not been hooked up to alert them of a lack of water (had left a drain open during a cleaning operation); the 2nd to last member went out of business when his well went dry.
8. Perch operation in Western Pennsylvania closed their doors when their new system had finally reached near full design carrying capacity and then the liner in the culture vessel "broke".
9. Southern Pennsylvania perch grower finally gave up after their initial stocking of perch showed growth rates a fraction of what was anticipated.

7. Overview of Factors Influencing the Economics of CSA

The following section contains a summary of some factors found to be influencing the economic feasibility of CSA. This is neither an exhaustive list nor comprehensive analysis; rather, it servers as a brief overview and is intended to provide direction for further research.

Long-term analysis

Some proponents of closed containment systems maintain that the short-term capital investment required for these systems will be offset by gains associated with being able to control losses suffered in open net-pen productions systems due to predation, escapement, etc. Furthermore, over the long-term these systems may require less operation cost whereas net-pen systems face costly labour inputs such as divers. Another long-term consideration affecting the economic viability of closed containment systems is the increasing tightening of regulation which could eventually force larger investments on all sectors of the aquaculture industry (Meihan, 2007; Papadoyianis, 2007).

Diversification

Several of the technologies listed in section 3 of this report are adaptable to a number of different species. This allows producers to capture market highs, rearing fish that at a given time are commanding an attractive market price, while protecting themselves from the lows. As the market for seafood in general increases, opportunities to profit off of new species will expand, benefiting farmers who are able to enter new markets (Quéméner, 2002).

Regulation

Regulation regarding waste disposal is increasingly heading towards tighter restrictions. For example, the EU has recently implemented policies affecting waste disposal (Romuel, 2007). Growing consumer awareness and environmental restrictions have led producers in the direction of re-circulation aquaculture technology (Debon, 2007b). In Denmark, fresh water farms are **required** to use their waste as fertiliser (Schipp, 2006).

Subsidies

The European Union provides subsidies to encourage fishermen to take on aquaculture (Schipp, 2006). As much as 50% start-up financing is available to encourage safe and environmentally sound production (Øiestad, 2007). Other fiscal and tax mechanisms are available to encourage start up of new, environmentally preferable industries.

Licensing

Many countries in the European Union have improved efficiencies around licensing systems which can see farms up and running in a matter of months and thereby making investments in this infrastructure more attractive (Schipp, 2006). The processing time required for approvals and licensing in the Netherlands and Denmark in particular has been significantly reduced (Schipp, 2006).

Labelling and Certification

Increasingly, consumers are demanding to know how their food is produced (van Eijk, 2004) . According to FAO (2006), countries actively producing and certifying organic aquaculture products include Australia, Canada, Chile, Ecuador, Indonesia, New Zealand, Peru, Thailand, and Viet Nam.

In March 2007 the Livestock Committee of the US National Organic Standards Board recommended to the US National Organic Program that aquatic species be included, but cautioned that more dialogue is needed to determine appropriate feeds and whether open water net-pen rearing should be included for organic labels.[41]

Increased consumer awareness regarding the environmental impact of net-pen aquaculture could easily contribute to the creation of opportunities for producers using closed system to capture a niche market. An example would be the price associated with 'fair-trade' coffee. The same might apply to Organic certification or Green labelling in North America.

Economies of scale

Economies of scale may be achievable by moving to large diameter, deep tanks. Tanks of 600 m^3 to one 1000 m^3 have been cited as a standard for profitability (Schipp, 2006).

Improvements in feed utilisation in CSA

Feed technology has improved dramatically over the last decade (Bodvin, 1996; Hardy, 2001; Shpigel, 1993; Tacon, 2004; Tlusty, 2000). In 1994, researchers associated with the North Carolina State University demonstration project created a computer simulation of tilapia production in a small recirculating production system. The results of a model sensitivity analysis indicate that while improvements in the performance efficiency of system components did not greatly affect fish production costs, reductions in feed costs and improvements in the feed conversion ratio caused the greatest reduction of production cost of all of the operational variables investigated (Losordo, 2003). Many CSA, particularly RSA, systems show improving FCR due to control of the water circulation (better uptake), and control of fish environment and ability to control metabolic rates (better internal conversion).

Pumping costs

Numerous companies are designing systems specifically to reduce energy issues associated with pumping. Physical design for a low head (Inter Aqua Advance, SARGO etc.) or a central pumping system with the rest gravity fed (HESY), are some of the means of cost reduction. Clearly, it will depend on location and proximity to the water source. Alternatives for energy production are also being examined such as the generation of energy through wave action and methane capture from waste.

Infrastructure

Scalable, modular systems, such as those being designed by the McRobert Aquaculture Group, amongst others, allow producers to increase (or decrease) production volume at their own pace, thereby reducing risk associated with over capitalisation. The AquaOptima system is another example of this. Using large plastic formed, lock in place panels filled with concrete. Furthermore, with the option to locate systems closer or adjacent to processing facilities and markets, CSA can capture benefits by lowering the economic and environmental costs associated with transportation.

Water Acres

Water acres is a concept that considers the value of near shore versus far from shore areas of water in assessing opportunities for locating industrial activity. Both Neptune Industries and Mariculture (Sargo) Systems are exploring the potential for using CSA in the 'far from shore' open water to achieve production efficiencies. Scarcity, cost and permitting issues around land, especially land adjacent to coasts reduces an operation's

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[41] See http://www.ams.usda.gov/nosb/CommitteeRecommendations/March_07_Meeting/Livestock/AquacultureRec.pdf for details of the recommendations

competitive advantage (Papadoyianis, 2007; Meihan, 2007). This could improve the financial feasibility of CSA, however, the full impact, including ecological sustainability, of this type of operation requires further research.

Weather

Increasing unpredictability in the weather, and in particular water temperatures, have caused producers to look towards greater certainty in production associated with CSA, and RAS in particular (Debon, 2007b).

8. Assessment of Key Ecological Interactions

This section is intended to provide an assessment of the ecological implications of CSA technologies; mainly, interactions between the fish stock and the natural environment; the ecological conditions within the tank; and considerations regarding the life-cycle requirements of CSA systems. Clearly, treatment of incoming water will depend upon its quality and thus the location of the facility and its available water sources. Some farms use groundwater sources, others rain, river, lake or ocean water. Consequently, there is no 'standard' in terms of treating incoming water. Moreover, the species and density of fish will also determine the necessary 'quality' of incoming water, and thus the treatment required. Correspondingly, all these factors influence the issues of parasite and disease control, waste production and treatment, amongst others. Bearing this in mind, the following section is neither exhaustive nor conclusive.

Parasite & disease control

There are more than 100 known fish diseases, many brought on by organisms such as fungi, viruses, bacteria, protozoa, crustaceans, and worms, amongst others (Masser, 1999b, 1999a). Because CSA systems create a barrier between the culture and the natural environment there is control over the possibility for parasites and disease to enter into the holding areas from natural water systems directly. The exception is in natural ponds and channels, where the sides are treated periodically with various bactericides and pesticides when they are periodically cleaned (Boyd, 1999). Nevertheless, disease can enter from human intervention through the brood stock (when applicable) via the equipment, the nets, gloves, and feed etc. The chosen water source is also a considerable factor in disease control as pathogens can enter with water sourced from wild marine environments. Often parasites, such as lice, when introduced can cause stress which makes the fish susceptible to opportunistic infections (Blancheton, 2000; Chatain, 1997; Delabbio, 2003; Lasordo, 2003; Masser, 1999b; Rach, 2000). The actual material of the enclosure can also influence the types of disease and the potential methods of treatment.

Fortunately, CSA provides the opportunity to treat both incoming water and waste waters and is thus optimal for disease control with minor needs for antibiotic use; indeed as noted in section 2 numerous farms use absolutely no antibiotics. All producers ensure that their inflow water is clean, either by choosing a clean source or through treatment. However, it is not the case that all flow-through systems treat their exit waters, and thus the risk of parasites generated in the tanks or ponds could enter the natural environment. There is no ubiquitous system regarding treatment of water for pathogen reduction and removal. The choice of treatment is influenced by:

- Species
- Fish density
- Tank material
- Water hydraulics (residence time and mixing)
- Incoming water quality
- Legislation and regulations
- Cost of treatment

A survey of 139 recirculating operations in North America (including 38 in Canada, and including salmon hatcheries and smolt producers) in 2003 helps to illustrate how the use of prophylactics in disease management varies according to species being harvested and has decreased over time. This showed that 17% of producers employed vaccines as opposed to 30% several years earlier. Sixty-six percent of facilities reported prophylactic use of chemicals on fish while 81% reported therapeutic use (chemical treatments including the use of salt) (Delabbio, 2003). Sixty-one percent of respondents growing Atlantic salmon *(Salmo salar)* currently use vaccines, while only 4% of tilapia growers, 7% of ornamental fish growers and 8% of hybrid Striped bass growers use vaccines on their fish. All of the above mentioned finfish growers reported using vaccines more frequently in the past. Possible explanations for this change of behaviour include: perceived effectiveness of vaccination, cost considerations, change in management and a change in perception of pathogen risk. The high rate of vaccine use in salmon farms is likely due to a culture of use as well as support in vaccine development from both governments and manufacturers for salmonoid products (Samuelsen et al., 1989; Lillehaug, 1990; Lillehaug et al., 1990, Delabbio, 2004). Certain species, such as abalone, may be extremely sensitive to ectoparasites, and therefore require greater control of container water (Urup, 2007). Others, such as tilapia, are known to be very robust, and Arctic char have been shown to be more disease resistant than other salmonids. (Marsh, 2006).

In certain circumstances, the source water for flow-through systems is very clean. Some land based farms operate on ground water sources (Redfish, 2007; Albright, 2007), while open water systems can usually take water from varying depths to minimise parasites and poor water quality associated with surface water on the ocean (Meihan, 2007). The Future SEA Technologies' bag system does not have a filter, but in a recent trial has shown up to a 10-fold reduction in the amount of sea lice inside its pens compared to open net cages (Pendleton, 2005).

Ozone is being increasingly used to help manage water quality in fresh water RAS. Its use in marine systems is also growing in popularity but indiscriminate usage can be problematic. Ozone is a chemical that must be used with extreme caution as it is highly toxic both to humans and to fish. Ozone generated by-products such as bromines can also have potentially toxic side effects when used in marine systems. However, correct usage of ozone can lead to an increase in the reliability of production from hatchery systems (Schipp, 2006). HESY Aquaculture is one of the systems that uses ozone; however, they have observed that certain species are very sensitive to ozone and even moderate levels can result in burns to fish gills (Debon, 2007a). In some raceway facilities where the water is in the tanks for a longer period, incoming water will be treated using a series of bio-filters with supplementary periodic treatment, such as formaldehyde, with high fish densities ensure that pathogen build up does not occur (Øiestad, 2007a)

Interestingly, Ballen wrasse, which have been used in commercial net-pens to control sea lice, are being explored in Norway for use in aquaculture tanks (Schipp, 2006). It should be noted that Wrasse is a species that is exotic outside of the North East Atlantic and this is a crucial factor in determining the appropriateness of its use in the context of disease control.

While recirculating aquaculture systems create optimum environments for fish, they may inadvertently provide favourable conditions for disease occurrence or the reproduction of opportunistic pathogens (Noble, 1996; Timmons, 2002). Disease organisms in recirculation systems recycle with the rearing water, and because no dilution of the pathogens occurs, as in the case of flow-through systems, the rates of infection can be greater (Bullock, 1994) Once a pathogen has become established in a recirculation system it is often extremely difficult to eradicate a disease; the fish rearing system itself becomes an incubator for the disease. In addition, many chemical control treatments commonly used to treat disease problems in flow-through systems are not practical in application with recirculation systems because they affect bacteria that are beneficial and necessary to the bio-filter systems as well as the targeted pathogens (Heinen, 1995; Noble, 1996).

Feed Composition and Conversion Rates

Feed is an important element of fish farming. It generally represents a large portion of the costs, 20-40%, and influences how fast and well the fish develop. There is growing concern regarding the amount wild fish needed to produce quality fish feed (Cho, 1997; Folke, 1989; Hardy, 2001; Naylor, 2000; New, 2002; Tacon, 2004; Tuominen, 2003). A measurement of feed 'efficiency' is the feed conversion ratio (FCR), which is the Kg of feed needed to raise 1 Kg of fish. Reducing the FCR is beneficial as it means that fewer inputs are needed, and less contamination is generated to raise a Kg of fish. There are two principle ways of achieving this:

1. Increase the uptake of the feed (reduce feed loss)
2. Increase the conversion rate within the fish itself

Generally, there are better feed conversion ratios (FCR) for CSA systems as compared to net-pens where feed is lost into the natural environment (Hardy, 2001). Furthermore, better designs in the hydraulics of CSA systems allow for feed pellets to remain in suspension longer. In shallow raceways, for example, water depths have ranged from 7 mm to 25 cm depending on fish size. As a result, food particles pass the vision field of any fish, even those resting on the bottom. To make food more easily available along the length of the raceway, floating formulated pellets have been used as the main staple food. With small juveniles (wet weight from 2 to 100 mg), live food organisms have been used, such as natural zooplankton, brine shrimp *(Artemia salina)*, nauplii and yolk-sac larvae of cod. These food organisms will drift slowly into the vision field of the juveniles (Øiestad, 1999).

RAS, in particular, provides the opportunity to control the fish environment (temperature, salinity, etc.) and thus is metabolic rate of the fish to Increase the conversion rate within the fish itself.

On-farm chemical use

Different systems in different locations will require different inputs and chemical balances. In general flow-through systems use much less chemical inputs than recirculated systems. The high volume of water in flow-through systems reduces the need for chemical applications. However, when applied, systems must be in place to filter or treat chemical flow-through so it doesn't affect wild species downstream. Because of the large volume of water within the system, it is costly to design full waste water in these systems (Kamps, 1999); nevertheless, some flow-through systems have effluents discharged into wetlands for assimilation into the environment providing cheap treatment as well as habitat for natural species. Combining the benefits of good intake water controls with treatment systems designed only to operate in emergencies may be one way to address this issue. Environmental monitoring of flow-through systems with limited treatment will be necessary to judge the real impacts.

By contrast recirculation systems depend upon a greater chemical use, principally to maintain water chemistry, this is for the benefit of the bacteria in the biofilters as much as for the fish. Because of high fish densities dissolved oxygen can decrease rapidly, particularly during feeding when the metabolic rates of the fish increase and uneaten feed with decompose requiring oxygen. Thus constant supply to both the fish and bacteria in the bio-filters are important to maintain fish health and should be at approximately 5ppm. This is usually achieved by introducing water super saturated with oxygen in lower levels of the tank, or along parts of the raceways. Because carbon dioxide is a by-product of fish respiration it must be removed either physically or chemically. The increase in carbon dioxide levels means that the pH of the water is likely to drop. Optimum pH levels will be species dependent, but should generally be maintained between 6 and 9.5 for most fish. Bacteria in bio-filters are generally much more sensitive and require pHs around the 7-8 range. Alkaline buffers, such as sodium bicarbonate and calcium carbonate are typically used. Other chemical in recirculation systems may include salts, including chlorides to reduce nitrate toxicity (Blancheton, 2000; Chatain, 1997; Delabbio, 2003; Lasordo, 2003; Masser, 1999b; Rach, 2000).

Fertilizers and liming materials are the most common substances used in pond aquaculture systems; however, oxidants, coagulants, osmoregulators, algicides, herbicides, piscicides, probiotics, heavy metals and pesticides have all been used to lesser extents (Boyd, 1999).

Using feed with good FCR is important to help maintain water quality. Obtaining a good FCR is important not only from the desire to have more fish for less feed. The feeding rate, feed composition, fish metabolic rate and the quantity of wasted feed affect the tank water quality. As pellet feeds are introduced to the fish, they are either consumed or left to decompose within the system. The by-products of fish metabolism include carbon dioxide, ammonia-nitrogen, and faecal solids. If uneaten feeds and metabolic by-products are left within the culture system, they will generate additional carbon dioxide and ammonia-nitrogen, reduce the oxygen content of the water, and have a direct detrimental impact on the health of the cultured product (Lasordo, 2003; Masser, 1999a; Miller, 2002; Piedrahita, 2003).

Predator kills

Because CSA systems separate the fish culture from the natural environment predator kills are negligible, in all the different forms (mammals, birds, fish, others). In open air systems bird predation is the highest concern (Bevan, 2002; Littauer, 2003; Miles, 2007). In Canada, herons and cormorants pose the greatest threat and have had the highest impact on fish stocks (Bevan, 2002). Predation brings about both direct (kills) and indirect (psychological stresses) damages. The indirect impacts are thought to bring about the economic loss but are the most difficult to isolate and estimate. Common deterrent methods for birds include: exclusions and barriers (nets, wires), acoustic devices, alarms and distress calls, lights, water spray devices, scarecrows and reflectors, silhouettes, human activity, trained dogs and design options (i.e. increase water depth in the tank) (Bevan, 2002).

Also, because of the separation between fish culture and the natural environment, it is reasonable to assume that open water systems (both marine and freshwater) will not need to employ harmful deterrent efforts on mammals or other wild fish species seeking to access the fish culture.

Waste disposal & nutrient loading

The principle wastes generated by all aquaculture are ammonia, nitrates, phosphates, organics (creating high biological oxygen demand), and suspended solids (Cho, 1997; G3-Consulting, 2000; Lee, 2004; Masser, 1999b; Miller, 2002; Piedrahita, 2003). In CSA systems the waste is divided between effluent water and the sludge associated with solid material that does not remain in suspension, such as fecal matter.

Below is a schematic showing the major wastes and their treatment associated with recirculated systems. Flow-through systems will produce the same type of wastes, although in much reduced concentrations (Table 10), consequently their treatment may vary.

Figure 15: Fish wastes and their effects on bacterial and chemical interactions in a recirculating system *(Masser, 1999b)*

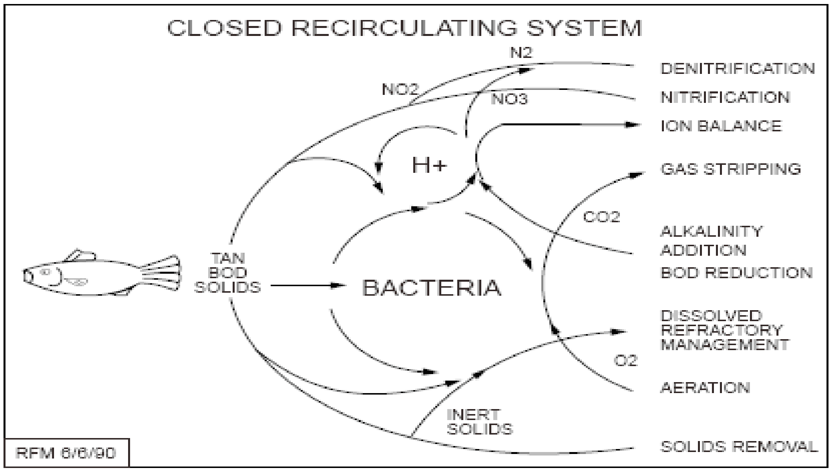

Figure 1. Diagram of fish wastes and their effects on bacterial and chemical interactions in a recirculating system.

Courtesy of Ronald F. Malone, Department of Civil Engineering, Louisiana State University, from Louisiana Aquaculture 1992, "Design of Recirculating Systems for Intensive Tilapia Culture," Douglas G. Drennan and Ronald F. Malone.

Effluent

The wastes in the effluent water from CSA systems are similar in composition; however differ greatly in terms of concentration (Table 10) and thus treatment methods.

Table 10: Effluent wastes by different systems *(from Piedrahita, 2003)*

Hypothetical effluent concentrations for different types of culture systems assuming that no treatment takes place within the systems and the constituents are uniformly distributed in the effluent. The total constituent production is used regardless of whether it is in the solid or dissolved form.

System type	**Water Use**		**Calculated effluent concentration**[a]		
	Kg fish/year (l/min)[b]	**l/Kg fish**[c]	**mg N/l**[d]	**mg P/l**[e]	**Mg TSS/l**[f]
Cold water fish					
Single pass	1.4	375,000	0.2	0.02	1.3
Serial reuse	6	88,000	0.7	0.08	5.7
Partial reuse	50	10,500	5.7	0.67	48
Fully recirculating	160	3,300	18	2.1	152
Warm water fish					
Serial reuse	16	33,000	2.4	0.8	42
Ponds	294	1,800	44	15	780
Recirculating through wetlands	145	3,600	22	7.8	390
Fully recirculating	5,500	105	760	27	13,000

a) Effluent concentrations calculated as: (Constituent production, (Kg constituent)/(Kg feed)) X (Feed conversion ratio, (Kg feed)/(Kg fish))/(Water use, (l/Kg fish)) X (10^6 (mg constituent)/(Kg constituent)). Feed conversion ratios are 1.0 and 2.0 for cold and warm water fish, respectively.
b) After Chen et al. (2002).
c) Calculated assuming a 365-day year.

d) N production. For cold water fish: 0.06 Kg N/Kg feed, assuming a 50% protein feed and 30% N retention as fish biomass. For warm water fish: 0.04 Kg N/Kg feed, assuming a 35% protein feed and 30% N retention as fish biomass.
e) P production. For cold water fish: 0.007 Kg P/Kg feed, assuming a 1% P feed and 30% P retention as fish biomass. For warm water fish: 0.014 Kg P/Kg feed, assuming a 2% P feed and 30% P retention as fish biomass.
f) TSS production. For cold water fish: 0.5 Kg TSS/Kg feed (Chen et al., 1997). For warm water fish: 0.7 Kg TSS/Kg feed (Chen et al., 1997).

In recirculating systems, water is generally cleaned through a combination of bio-filters with denitrifying bacteria, *nitrosomonas* and *nitrobacter,* and through physical aeration. Flow-through systems remove the majority of solid wastes from the waste stream and rely on different types of treatment for effluent waters (ammonia being the most significant waste). Some rely on environmental assimilation for removal of waste and nutrients, while others, like the SARGO™ system, use standard disposal techniques such as those used on ships. Assimilation can be achieved either through direct release into receiving waters, settling ponds, or through biological means, including the use algae, plants etc. in artificial wetlands at the outflow (Miller, 2002). Aqua Farms in Langley, BC is an example of a facility that uses this method. Bioremediation involves co-cultivation of finfish with species capable of metabolizing effluent within a contained or semi-contained aquaculture system. Culturing of the seaweed porphyra for instance, has been used successfully in net-pen salmon aquaculture (Chopin, 1999; Chung, 2002b). Bioremediation techniques have also been demonstrated to be feasible with sponges (Fu, 2006; Milanese, 2003, Gracilaria Zhou, 2006), polychaetes (Licciano, 2005) and bivalves (Gifford, 2004). In the US, some tilapia producers have begun using co-culture with catfish, shrimp or algae (Williams 2000; Fitzsimmons 2001). In addition to dealing with aquaculture effluents, the co-cultured species are often also economically viable – allowing profits to be maximized while lessening detrimental effects of untreated wastes on the environment.

In land based flow-through systems suspended particulate matter and dissolved solids flow out the end of the raceway or tanks in the effluent. The faster the exchange of water, the less suspended solids are in the holding area (Øiestad, 1999). Prior to release into the environment it is common that effluent in flow-through systems includes some form of sedimentation to produce clarified effluent and to concentrate bio-solids or sludge (Viadero Jr, 2005). There are many standard techniques associated with removing suspended and dissolved solids from effluent water, such as flocculation, settling or filtration. Outflow water can also be treated prior to discharge, though it is less common practice in flow-through systems (Miller, 2002).

Sludge

There are two sources of sludge. One is produced in the holding areas, the second is produced by suspended and dissolved solids of the effluent water. In tank systems the greater of the two accumulates in the tank, and in raceways it accumulates from separating the effluent (Øiestad, 1999). The portion of pellet feeds not assimilated by the fish is excreted as a highly organic waste (faecal solids). When broken down by bacteria within the system, faecal solids and uneaten feed will consume dissolved oxygen and generate ammonia-nitrogen. For this reason, waste solids should be removed from the system as quickly as possible. Waste solids can be classified into four categories: those that settle to the bottom (sludge), suspended, floatable and dissolved solids (Losordo, 2003).

There are a multitude to different methods associated with collection of the solids and depend upon the system in place. Virtually all the companies developing aquaculture technologies have developed their own collection systems for sludge waste.

Atlantech Companies (www.aquatech.ca), of Charlottetown PEI, have set up numerous finfish aquaculture installations in Chile and North America. While they design and install complete systems, both flow-through and recirculating, they have a large variety of water treatment components which they claim can be assembled to meet the requirements of many water quality situations. These include a variety of intake filters and intake screens, sand filters, rotary drums (for removal of solid wastes), micro screens, static sieve screens, both UV and Ozone for treatment of intake water, chlorination systems for effluent water, numerous bio-filters which can be designed to run on gravity for energy savings, and a specially designed separator for sludge removal.[42]

The treatment of sludge depends on local environmental conditions and policy restrictions. Generally, sludge from freshwater farms can easily be used as fertilizer as it is high in nitrogen and micro-nutrients. While there is some concern over sludge coming from farms with marine water regarding salt content (Schipp, 2006), this has been overcome by mixing it with other fertilizer (Urup, 2007; van Eijk, 2007). Legislation has assisted in Denmark where it is required that fish waste sludge be used as fertilizer (Schipp, 2006).

Spotlight: Integrated culturing and "Green water" recirculating.

Integrated multi-trophic level aquaculture (IMTA) is a promising area of research because it takes into account interspecies interactions and uptake of nutrients and wastes by integrating filter feeders, finfish, and various macro- and microalgae into aquaculture systems (Dolmer, 2004; Neori, 2004). Multi-trophic aquaculture systems generally involve the addition of extractive species (i.e. requiring no exogenous food input) to existing fed aquaculture systems (e.g. finfish farms). In the context of finfish production, IMTA contributes to environmental sustainability primarily by remediating the nutrient overloading associated with effluent (Bennett, 2006.; Chung, 2002a; Nunes, 2003). This type of system has already proven successful with CSA and tilapia (see the profile on Fresh Catch Belize in section 4).

An offshoot of this practice are 'green-water' recirculating systems, such as that developed by Aquaculture Production Technology (see section 4). The waste produced by the fish is treated by bacteria and algae, which thrive in the reservoirs and earthen ponds (hence - 'green-water'). Nitrates are readily assimilated by the algae, and enter the natural food web. The reservoir acts as a 'sun-lit rumen', and is referred to as a 'green-lung', converting the organic wastes into single cell protein. Algae encourages secondary productivity (e.g. zooplankton), which supplements the diet of the fish (Schipp. 2006).

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[42] See www.atlantec.ca for details on the various treatment units.

9. Environmental Life Cycle and Energy Issues

Choices made about where to set the boundaries when assessing the sustainability of aquaculture operations will have a significant effect on the range of policy options needed. As with all industrial activity, the material and energy requirements for CSA are dependent on other industrial processes each of which have associated material and energy requirements. Although it is beyond the scope of this report to assess the full life cycle analysis issues for CSA aquaculture it is important to note those factors relating to the main material and energy requirements for CSA. These include:

- the fuel source and associated emissions for running the farm,
- energy associated with the transportation of the product to market,
- fuel consumed in catching and processing wild fish used for protein in feed as well as the effect of capture fisheries on the ecology,
- energy implications of growing soya or other vegetable oils for use in the feed
- embodied energy consumed in the making of materials used in constructing the physical infrastructure of the farm

A good deal of research and resulting literature is devoted to assessing the various aspects of aquaculture and its impacts (Anderson, 2002; Asche, 2006; Black, 1997; Brooks, 2001; Bunting, 2001; Folke, 1989, 1992; Folke, 1998; Folke, 1994; Folke, 1997; Garcia, 2005; Gardner, 2003; Hardy, 2001; Haya, 2001; Langdon, 2004; Lindbergh, 1999; Naylor, 2005; Naylor, 2000; New, 2002; Pauly, 2002; Pauly, 2001; Tacon, 2004; Talberth, 2006; Tidwell, 2001; Tuominen, 2003; Wu, 1995). The amount of energy used to create a Kg of fish can be seen as a rough measure of efficiency. The kW/Kg used will obviously be dependent on a number of factors such as density of fish, the type of fish and how fast the fish grow (we could assume tilapia would require less energy than trout for instance), the level of recirculation, to name a few. Each farm will therefore have different kW/Kg values, even between similar fish species. Consequently, comparison between values needs to be cautioned. Nevertheless, knowing the kW/Kg value helps to give and idea of energy costs associated with CSA systems. Hesy Aquaculture suggests that their recirculating systems operate at approximately 7-8 kW/Kg. Billund Aqua Service’s high intensity systems run at 6.5 kW/ Kg and their low intensity at 3.2 kW/Kg. According to Schipp (2006) average recirculating systems run on approximately 8.3 kW/Kg.

Spotlight: Mega-Flow (Israel) (Schipp, 2006)
The Mega Flow system has been developed in Israel and involves large volumes of water being moved around the fish holding system by air. The developers claim it is extremely cost effective to operate. The South Australian Government is investing in a small system at the moment. They claim that for the production of seabream, Mega Flow uses 5.2 KWh per Kg while the average for recirculating systems is 8.3 kW/Kg (Schipp, 2006).

In most systems the largest energy needs are for pumping water and preparing saltwater (from municipal water source, if required (Romuel, 2007). Thus anything that can either directly reduce the pumping needs or offset other energy costs, such as heating, will help with energy savings. Many different techniques have been employed or being explored to reduce energy needs and/or incorporate alternative sources. These include:

- Systems designed to harness gravity for water flow (Hesy Aquaculture).
- Air lifts (Neptune Industries)
- Methane capture (Neptune Industries, COMB, SARGO™)
- Wave energy
- Solar systems
- Passive heating (Redfish Farm)

- Dewatering sludge and use as bio-fuel
- Geo-thermal heating (Sifurstjarnen Farm).

Another issue of concern, particularly in arid countries, is water consumption. This can be measured in m^3/Kg, or l/Kg, of fish produced. Water use can vary considerably from 105 l/Kg for RAS systems to 130,000 l/Kg in single pass flow-through systems. Some systems claim requirements as low as 50 l/Kg (Ebon, 2007).

10. Summary of strengths and challenges

The variety and versatility of the different CSA technologies is encouraging. It demonstrates that CSA can be practiced almost anywhere as it can be adapted to many socio-economic and ecological situations. Clearly, if water savings are a prime concern then RAS could be applied, if water flow is not an issue then there may be cost savings associated with flow-through systems.

Below is a summary of the major advantages of the various systems reviewed in this report, as compared to open net-pens or cages.

Table 11: Advantage and disadvantages of CSA systems (compared with pens)

In General	
Advantages:	• Control of growing conditions: including temperature, water chemistry and turbidity, disease, etc. • Growth cycles: including shortened time to harvest, size of the species, quality of product, as well as optimum harvest points and ability to plan for harvest. • Better Feed to Biomass ratios: due to greater control of growing conditions and life cycles. • Greater versatility: options for production location, nearness to market, marginal lands, etc.; ability to respond to demographic and consumer shits (some systems are capable of growing different species – or can be easily transformed. • Control of outputs and effluents: treatment and the possibility of reuse as fertilizer or input for other fish systems (in integrated aquaculture). • Risk reduction: including climate, infection and disease, predation, etc. • Reduction in direct operational costs: associated with feed and disease control from vaccinations and antibiotics. • Greater fish intensity: better feed consumption and control of metabolic rates, less nutrient development from lost feed. • Potential for 'Clean product': produced without hormones, antibiotics etc.; produced in environmentally friendly way; Green and Organic labelling. • Potential for niche markets: either by species, availability (live to market), or size. • Less area used and ability to use marginalised lands. • Options for variable water sources
Disadvantages:	• Increase in capital costs: research and development is costly, system start-up is higher than net-pen. • Increase in direct operational costs: oxygen inputs and maintaining chemical balances of the water, careful water monitoring, energy requirements, input-output water treatment requirements. • Complexity of technology. • Risks: potential for rapid chemistry alterations resulting in quick and massive die-offs, dependency on monitoring.

Below is a table comparing the relative advantages and disadvantages associated with various CSA technologies as compared to one another.

Table 12: Comparative advantages and disadvantages between CSA technologies

Raceways	
Advantages:	• Stackable for optimum use of space and for use of gravity flow to reduce pumping costs • Designed for species • Less labour intensive to cleaning and feeding • Easy monitoring of fish
Disadvantages:	• If they are very long (200 m) water quality can deteriorate so more monitoring and greater volumes of water are needed. • Additional cleaning of water may be needed • Requires special pellets to ensure food gets the end of raceway
Tanks	
Advantages:	• Large volume to tank area • Easier feeding and good feed conversion ratios • Good control and easy monitoring of fish health and water quality
Disadvantages:	• Need cleaning – high algae growth if flow is insufficient . More difficult to clean as they are usually deeper and harder to access than raceways.
Flow-through	
Advantages:	• Less water treatment for intake water • Less treatment for effluent • Simple technologies for water chemistry
Disadvantages:	• High water use • Less control over water chemistry and temperature
Recirculating Systems	
Advantages:	• Good control of water chemistry and temperature • Low water use • High densities and productivity • Good control of wastes
Disadvantages:	• Higher costs for pumping and treatment • Technically complex • High risk of catastrophic die-off due chemistry alterations
Open water systems	
Advantages:	• Greater available space • Constant temperature • Low pumping costs
Disadvantages:	• Weather and climate dependent • Accessibility • Difficult to monitor fish (because of the relative size and depth of the tanks it is difficult to make detailed monitoring of the health of the fish) • Difficult to clean as they are deep and underwater, and therefore harder to access than land-based systems.
Natural Ponds and Channels	
Advantages:	• Simple technology • Low capital costs
Disadvantages:	• High chemical use of fungicides, herbicides, etc.

	• Competition for nutrients from other organisms that enter • Seepage of water into ground

11. Conclusions

The number of sustained commercial operations illustrates that CSA is a viable means of commercially producing fish for harvesting. The diversity, in terms of location, species and socio-economic conditions, where these operations are found indicate the versatility and innovation associated with CSA technology. Producers of fish and developers of CSA technology are creating commercial operations in countries as varied as Iceland, Morocco and China, in rural areas and in semi-urban zones, using ocean water, groundwater and even municipal water supplies. Practical examples exist for the use of closed system aquaculture for growing finfish, seaweeds, shellfish, crustaceans, and other invertebrate species, as well as for pharmaceutical production. While many CSA operations associated with finfish are hatcheries for fish smolts and juveniles for on-growing in net-pens and cages, increasing development is occurring for raising a variety of finfish fully to harvest size. At this point, the most common species currently being harvested to full size are Nile tilapia (*Oreochromis niloticus*), trout (*Oncorhynchus mykiss)*, Arctic char (*Salnelinus alpinus*), Atlantic halibut (*Hippoglossus hippoglossus*), turbot (*Scopthalmus maximus*), barramundi (*Lates calcarifer*), several varieties of Australian perch (*Macquaria ambigua, Scortum barcoo*, *Sander lucioperca, Bidyanus bidyanus*), seabream (*Sparus aurata, Pagellus bogaraveo)* and seabass (*Centropristis striata), Morone saxatilis*). Also, there are several species having local importance such as eel (Anguilla Anguilla) in Europe, and catfish *(Ictalurus punctatus)* in the US.

The different technologies employed are almost equally as varied. While the basic principles behind water and waste treatment, feeding, and monitoring are consistent; the methods to achieve them are not. Companies such as Atlantech Group and UNI-Aqua, amongst others, have unique designs and products to accommodate local needs for all steps of the operation. Indeed, one can say that there are almost as many different systems as there are operations, each operation being tailored to specific needs. What all CAS systems share, however, is their ability to separate the culture of fish from the natural environment, control their inputs to reduce disease, optimize growth and minimize mortality, and control their outputs to limit external costs to the environment.

At this juncture in the evolution of aquaculture, considerable debate remains as to the adaptability of CSA to the range of commodity species. Technological advancements, regulatory developments and the selection of species will continue to intermingle over the coming years. Local variables such as climate, water availability, alternative energies, access, socio-economic conditions, amongst others, will help determine of the local suitability of CSA. Other factors, such as improvements in energy efficiencies, are already impacting the economic viability and ecological appropriateness of these technologies.

There is convergence among the researchers and producers interviewed and the literature, indicating that CSA is commercially viable for niche market fish, such as live tilapia or barramundi. There is also growing consensus that 'organically' and 'environmentally friendly' produced fish are able to command higher prices such that commodity fish could be moved into a niche market. As evidenced in Europe, environmental and health concerns are increasingly driving consumer demands as well as prompting tighter regulatory conditions for food production in general. While this has been sufficient to move the industry rapidly in Europe, additional measures may be necessary to increase the pace of CSA in North America. The Open Ocean Aquaculture Bill in the US is proposing added costs for open net-pen production (Walters, 2007). This line of action has been echoed by recommendations from the BC Special Committee on Sustainable Aquaculture asking for a complete transition to closed containment aquaculture, and the World Bank call for the internalization of aquaculture costs. Combined socio-environmental concerns, increasing efficiencies of production and regulatory changes are likely to make CSA an increasingly interesting option for future fish production (Walters, 2007; Gústavsson, 2007, Øiestad, 2007a; van Eijk, 2007).

What is clear is that aquaculture will remain an important means of providing fish for the global food supply and that new technologies, trade, consumer demands and regulatory changes will influence the development of CSA.

12. Glossary

Major terms used in this report are as follows:

CSA - Closed system aquaculture is defined as: 'Any system of fish production that creates a controlled interface between the culture (fish) and the natural environment.'

FCR - Feed conversion ratio is the Kg of feed needed to raise 1 Kg of fish. Clearly, the lower the ratio the better the conversion.

RAS - Recirculating Aquaculture Systems

Terms for fish used in this document are the following:

Abalone (*Haliotis spp.*)
Barramundi (*Lates calcarifer*)
Catfish "Channel" (*Ictalurus punctatus),*"African" (*Clarias gariepinus*)
Carp, European *(Cyprinus carpio)*
Char, Arctic (*Salvelinus alpinus*)
Cod (*Gadus morhua*) "Murray" *(Maccullochella peelii),*"Sleepy" (*Oxyeleotris lineolatus*), "Black" (*Notothenia microlepidota)*
Eel (*Anguilla anguilla*)
Flounder, Japanese (*Paralichthys olivaceus*)
Halibut (*Hippoglossus hippoglossus*), "California" (*Paralichthys californicus)*
Mulloway *(Sciaena antarctica)*
Perch, Golder (*Macquaria ambigua)*
Perch, Jade (*Scortum barcoo*)
Perch, Pike *(Sander lucioperca)*
Perch, Silver (*Bidyanus bidyanus*)
Perch, Yellow *(Perca flavescens)*
Pike, Walleyed (*Sander vitreus vitreus)*
Puffer, Tiger *(Takifugu rubripes)*
Salmon, **Atlantic** (*Salmo salar*)
Salmon, Chinook (*Oncorhynchus tshawytscha)*
Salmon, Coho (*Oncorhynchus kisutch)*
Salmon, Sockeye (*Oncorhynchus nerka)*
Seabass "European" (*Centropristis striata),* "Striped" (*Morone saxatilis*)
Seabream "Gilt-head" (*Sparus aurata),*"Blackspotted" (*Pagellus bogaraveo)*
Sole (*Solea solea*)
Sturgeon White *(Acipenser transmontanus)*,
Tilapia, Nile (*Oreochromis niloticus*)
Trout, Rainbow (*Oncorhynchus mykiss)*
Turbot (*Scophthalmus maximus*) Note that there several different species of turbot including the Pacific, Greenland and European (*Psetta maxima*). The *Psetta maxima* is usually referred to as *Scophthalmus maximus* in trade literature and industry publications.
Tuna, **Bluefin** (*Thunnus thynnus*)
Tuna, Yellowfin (*Thunnus albacares*)
Wolfish (*Anarhichas minor*)
Yellowtail kingfish (*Seriola lalandi lalandi)*

13. Company Listings

Agassiz Aqua Farms (p34)
WEB: www.agassizaquafarms.com
PHONE: 204-785-8410
EMAIL: info@agassizaquafarms.com
COUNTRY: Canada
CONTACT: John Bottomley

AgriMarine Industries (see also Middle Bay Sustainable Aquaculture Institute)
WEB: www.agrimarine.com
PHONE: 604-683-7966
COUNTRY: Canada
CONTACT: Richard Buchanan (rbuchanan@sustainable-aquaculture.ca)

Akvaplan-Niva (p12)
WEB: www.akvaplan.niva.no
PHONE: +47-77-75-03-00
EMAIL: info@akvaplan.niva.no
COUNTRY: Norway/Spain
CONTACT: Øiestad, V

Aquaculture Developments LLC (p14)
WEB: www.aquaculturedevelopments.com
EMAIL: info@aquaculturedevelopments.com
COUNTRY: US

Aquaculture Production Technology Ltd. (p40)
WEB: www.aquaculture.co.il
PHONE: 972-5-870-4585
EMAIL: info@aquaculture-israel.com
COUNTRY: Israel

AquaOptima (p15)
WEB: www.aquaoptima.com
PHONE: +47-73-56-11-30
EMAIL: info@aquaoptima.com
COUNTRY: Norway

Aquatech Solutions (p16)
WEB: www.aquatech-solutions.com
PHONE: +45-7588-0222
EMAIL: ole@aquatec-solutions.com
COUNTRY: Denmark
CONTACT: Ole Enggard Pedersen, Managing Director

Aqua Farms (p37)

PHONE: 604-626-6747
EMAIL: Albright@sfu.ca
COUNTRY: Canada
CONTACT: Larry Albright

Atlantech (p69)

WEB: www.atlantech.ca
PHONE: 902-368-7500
EMAIL: info@atlantech.ca
COUNTRY: Canada
CONTACT: A. Desbarats

Ausyfish Pty. Ltd. (p38)

WEB: www.ausyfish.com
PHONE: +69-010-810-670
EMAIL: enquiries@ausyfish.com
COUNTRY: Australia

Baltimore Urban Recirculating Mariculture System (p18)

(University of Maryland Biotechnology Institute, Center of Marine Biotechnology)

WEB: www.umbi.umd.edu
PHONE: 410-234-8800
EMAIL: zohar@umbi.umd.edu
COUNTRY: US
CONTACT: Dr. Yonathan Zohar

Billund Aquaculture Service (p21)

WEB: www.billund-aqua.dk
PHONE: +45-75-33-87-20
COUNTRY: Denmark

Cell Aquaculture Systems Europe (p23)

WEB: www.cellaqua.com
PHONE: +61-8-9336-7122
EMAIL: info@cellaqua.com
COUNTRY: Australia (Head Office)

Future SEA Technologies (p42)

WEB: www.futuresea.com
PHONE: 250-618-0968
EMAIL: clarka@island.net
COUNTRY: Canada
CONTACT: Andy Clark
COUNTRY: Canada

HESY Aquaculture BV (p25)

WEB: www.hesy.com
PHONE: +31-174-220140
EMAIL: office@hesy.com
COUNTRY: The Netherlands
CONTACT: A. Debon

Holar University, Department of Aquaculture and Fisheries (p33)

WEB: www.holar.is
PHONE: 454 4556300
EMAIL: addi@holar.is
COUNTRY: Iceland
CONTACT: Arnþór Gústavsson

Icy Waters (p32)

WEB: www.icywaters.com
PHONE: 867-668-7012
COUNTRY: Canada

JHL Consulting (p27)

PHONE: 250-897-1334
EMAIL info@jlhconsulting.tv
COUNTRY: Canada
CONTACT: John Holder

Mariculture Systems (SARGO System) (p45)

WEB: www.sargo.net
PHONE: 425.778.5975
EMAIL: info@sargo.net
COUNTRY: US
CONTACT: David Meilahn (dmeilahn@sargo.net)

McRobert Aquaculture Group (p42)

WEB: www.mcrobert.com.au/
PHONE: +61-0-8-9433-2900
COUNTRY: Australia

Middle Bay Sustainable Aquaculture Institute (p47)

WEB: www.sustainable-aquaculture.ca
PHONE: 250-286-0019
EMAIL: rwalker@sustainalbe-aquaculture.ca
COUNTRY: Canada
CONTACT: Rob Walker

Rushing Waters Trout Farm (p31)

WEB: www.rushingwaters.net
PHONE: 262-495-2089
EMAIL: info@rushingwaters.net
COUNTRY: US

Scotian Halibut (p28)

WEB: www.halibut.ns.ca
PHONE: 902-471-1113
EMAIL: brianblanchard@klis.com
COUNTRY: Canada
CONTACT: Brian Blanchard

Swift Aquafarm (p36)

PHONE: 604-796-3497
COUNTRY: Canada
CONTACT: Bruce Swift

Neptune Industries (p41)

WEB: www.neptuneindustries.net
PHONE: 561-482-6408
EMAIL: info@neptuneindustries.net
COUNTRY: US
CONTACT: Ernest Papadoyianis

UNI-Aqua (p29)

WEB: www.uni-aqua.com
PHONE: +45-7551-3211
EMAIL: bur@uni-aqua.com
COUNTRY: Denmark
CONTACT: Bent Urup

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