THE BLUE REVOLUTION

Aquaculture Feeding Humans with Healthy and Cost-Effective Foods

Cyr Couturier, Research Scientist and Chair, MSc Aquaculture Program, Centre for Aquaculture and Seafood Development, School of Fisheries, Marine Institute, Box 4020, St. John's, NL, A1C 5R3, Email: cyr@mi.mun.ca

KONA BLUE WATER FARMS

Dive inspection of feed silo and ballast system (middle cylinder) of submersible, fully-closed marine fish cage deployed in deep waters off of Hawaii.

AT THE TURN OF THE NEW MILLENNIUM, the United Nation's Food and Agriculture Organization (FAO) noted that aquaculture - the farming of aquatic plants and animals - is the fastest growing food production sector globally. This has recently been reaffirmed by the FAO and experts on food security predict that aquatic farming will play a leading role in supplying much needed, high quality aquatic animal protein to our exponentially growing world population. Aquatic animal protein, from both wild and farmed sources, is the single largest source of *animal* protein consumed by humans at present. Over 140 million tonnes of food grade aquatic protein is harvested from farms and capture fisheries annually, but much of the growth over the past 30 years has been led by aquaculture developments. Estimates are that approximately 70-80% of present-day fished natural stocks are under pressure from over-harvesting, habitat deterioration and anthropogenic activities, not to mention the effects of global warming. This would explain why there have been no substantial increases in *global* capture fisheries landings for nearly three decades. Efforts are underway to develop more environmentally sustainable fish harvesting practices through improved technology, improvements on the limited knowledge of natural fish populations, and better utilization of fishery resources (current discards are estimated at 40 million tonnes as bycatch at sea from capture fisheries and another 5+ million tonnes as fish processing byproducts from wild harvested fish.)

With population growth expanding rapidly, the emphasis will need to be more on aquatic farming to meet the demand for aquatic protein, a demand that has been increasing by 1.5 million tonnes per year on average for the past 20 years. This "blue revolution," termed aquaculture, will not replace wild capture fisheries. Rather, it is seen in most jurisdictions on the planet as a means to supplement our aquatic food bounty while at the same time helping to reduce the pressure on wild stocks. It can be demonstrated that a substantial portion of aquatic food production, both farmed and wild, is energetically more efficient and less costly, has lower environmental footprint, and yields higher rates of animal protein production than many of today's land-based animal protein production. This, combined with global population expansion (people need to eat!) led Nobel Laureate, Peter F. Drucker in 1999 to state: "Aquaculture, not the Internet, represents the most promising investment opportunity of the 21st century."

To put all of this in perspective, the question is not "if" aquaculture should exist, but "how much" and at what rate should it grow, and in what form - intensive, semi-intensive or extensive aquaculture. If we think about it for a moment, the answer is that we need an ever-increasing amount of farmed fish, plants and shellfish to address issues of food security and environmental sustainability for the growing world food demand (need). It is for this reason alone that the largest country in the world, China, with over 1.3 billion people now produces 80% of its fish products from aquatic farming, and accounts for nearly 70% of total world production aquatic food, both farmed and wild.

The global estimates of aquaculture production are staggering, rising from just a few million tonnes in 1970 to 60 million tonnes (MT), today valued at over US $70 billion. This represents 45% of global aquatic food production by volume and more than 50% by value. It is interesting to note that the largest group of fish produced are freshwater carp (~ 25 MT), followed by molluscan shellfish such as oysters, mussels, clams, scallops (~13 MT), seaweeds (~12 MT) and then much smaller groups like salmon, tilapia, shrimp and marine fish, accounting in aggregate for less than 15% of overall volume. With the exception of this latter, smaller group of farmed fish and shellfish, the vast majority of the production globally is what is termed *extensive aquaculture*[1] relying almost solely on natural food production from the oceans, lakes and rivers. The smaller group of fish and shellfish including salmon, shrimp, and tilapia are cultured using either semi-intensive (partial supplement of natural food with prepared diets) or intensive production methods, employing more than 90% of the diet from prepared,

[1] The farming of aquatic plants and animals for at least part of their life cycle.

natural foods. The sustainability of using prepared natural diets, based partially on fish sources of proteins and oils, has come under question in recent years, with fears of over-harvesting wild fish stocks to supplement diets of salmonid fish and shrimp in particular. As explained later in this essay, the use of innovative technologies and approaches has made great strides in efforts to find alternate sources of marine oils and of proteins such that the usage of fish derived proteins and oils is declining rapidly in some of the groups, particularly in the salmonids.

The reader might be interested to know that over 85% of the seaweeds harvested each year around the globe are farmed in extensive culture conditions, and generally considered to have minimal long-term impact on the environment. In fact, farmed seaweed products, such as gel extracts, are used daily by most humans in a variety of forms, including prepared foods (thickeners in ice cream, yogurt, etc.), toothpaste, medical supplies and diagnostics, and even cosmetics. On the employment side, aquatic animal and plant farming provide direct employment for an estimated 10 million people globally, much of it in rural areas, both coastal and inland. The workforce ranges from unskilled labour to highly skilled labour, involving engineers, veterinarians, scientists, technologists, food chemists, and the like. In the developing regions of the world, there is a shortage of skilled labour, and by some accounts this has impeded development.

Additionally, seafood, both farmed and wild, has been shown to be nutritious and healthy, offering valuable sources of cardio-protective omega-3 fatty acids (molluscs[2], salmon, marine fish for example), vitamins (D, B12, etc.), minerals (zinc, potassium, etc.), proteins, all while being low in saturated fats and carbohydrates for the most part (USDA National Nutrient Database for Standard Reference, Release 19, 2006; available online). The recognition of the importance of the nutrient composition of aquatic foods, combined with demographic shifts towards ageing populations in several areas has meant demand exceeds supply for many of these types of products. The Canada Food Guide currently recommends several helpings of fish per week, farmed or wild, to maintain a healthy and balanced diet.

In order to meet this ever-growing need for aquatic food - for subsistence, employment or profit - the farming industry must continuously develop new and innovative technologies to maintain food safety, environmental and social sustainability. The next sections of the essay outline some of the technology initiatives leading the way for this relatively new food production sector.

Farming Technology

A modern industry requires modern technology, and fish farming is no exception. Much of the current technology has been developed with the following in mind: to provide safe, high quality food; to provide sustainable practices that minimize impacts on the environment; and to provide socioeconomic benefits to rural areas of the landscape. Anti-farming critics will say these are motherhood, political statements but the facts speak for themselves: aquaculture is growing globally, providing safe, highly nutritious food, and overall impacts are mitigated or minimized by the advent of technological solutions. There will always be perceived problem areas, but science and technology are assisting with providing solutions, so that we do have a truly sustainable production base for future generations. Some of the following examples will serve to illustrate these points.

Large capacity (140 tonnes per day), ocean going mussel harvesting catamaran (35 m) used in marine mussel farming in New Zealand.

[2] The phylogenetic classification of molluscs is *Phylum Mollusca*.


COOKE AQUACULTURE

The *Martin Searle*, a live transport wellboat (50 meters) for large scale fish movement (smolts or harvest) to and from growing sites.

The more advanced technological developments are highlighted, although the notions of food safety, environmental and social sustainability are acknowledged even at the level of the least technologically advanced methods of production.

Working vessels and harvesting barges employed for large scale commercial aquaculture are designed to withstand rigorous environmental conditions while at the same time providing a high degree of food safety features, for example non-skid, sanitizable surfaces, chilled cargo storage and onboard live holding facilities to ensure the freshest products possible. These vessels often have state-of-the-art navigational and communications tools. Large-scale transport vessels are capable of delivering 500,000 live salmon smolts (~100 grams each, ready for the sea) in one load at distances of more than 300 km with less than 1% mortality.

On the growing side of the equation, equipment has been developed and employed under a wide range of environmental conditions, from subarctic areas with periodic ice flows to open ocean, deep water or high energy sites. Floats and suspension gear for shellfish or finfish operations have been designed to be submerged and employed to depths exceeding 3 atmospheres


CSAR, FISHERIES AND MARINE INSTITUTE OF MEMORIAL UNIVERSITY.

Testing stress points and design features in a model submersible mussel longline in the world's largest laminar flume tank, Marine Institute of Memorial University. Systems like these are being deployed in deepwater areas to avoid ice, winds, and to position shellfish in optimal growing zones.

pressure, or specially fabricated to withstand significant wave and swell conditions to minimize bounce and product loss or equipment stress. New remotely-operated submersible shellfish growing systems, both longlines and rafts, have been developed and are being tested in various parts of the world, and it will not be long before "smart farms" with various detection sensors are in place to find the optimal growing zones within the water column or to lessen the potential impacts of ice, storms, or other hazards on the farms.

Cages employed by Kona Blue Water Farms in Hawaii use fully enclosed, submersible, variable depth ocean cages for rearing a marine fish called Hawaiian yellowtail. The depth of the cages can be adjusted from remote stations, as can the feeding devices. This allows fish to be maintained in an optimal growing zone in the deep waters off of Hawaii, away from boat traffic or sea swells.

90m cages.

In another part of the world, large (160 m circumference), flexible pipe cages have been designed and are used in open ocean, deep water conditions in the cold North West Atlantic waters of Newfoundland and Labrador to grow salmon. Specialized netting consisting of a high tensile strength polymer Dyneema® is employed for the cages; it resists corrosion and UV degradation, limits fouling, enhances water quality in cages, and can withstand extremes in temperature. The netting not only reduces fouling and allows for enhanced growing environments for the fish, but also provides protection of the environment by increasing security against losses from escapees due to its strength and resistance to breakage.

The technology to feed marine finfish has developed significantly in recent years to include automated feed delivery systems with large controlled storage capacities (up to 500 tonnes). Feed delivery is operated remotely by computers with satellite links or by handheld PDAs (personal digital assistants). Underwater camera systems coupled with particle recognition devices ensure that fish are fed optimally and food wastage is minimized, both saving costs and ensuring minimal impact on the environment. Remotely accessible, real-time environmental monitoring systems are becoming increasingly available (e.g., www.smartbay.ca) to assist the industry in selecting appropriate locations for new farms and managing production at farms, which in turn provides input into feeding models.

Inspection of rearing systems for safety, failures, mooring layout and the like is carried out by highly qualified dive teams, but these are being supplemented in some cases by electronic monitoring devices coupled to Underwater Remotely Operated Vehicles (ROVs), similar to those used in deepwater for oil and gas exploration. The ROV systems are being used increasingly to monitor impacts of farming activities before, during, or after harvest to ensure fallowing guidelines are followed.

Habitat Improvements and Mitigating Impacts

Modern aquaculture, particularly the intensive production kind, has faced adverse, if not intense and almost vitriolic criticism from environmental concerns in recent years, particularly in affluent regions of the world. Concerns are wide ranging, from benthic (bottom) impacts, to displacement and impacts on wild fisheries, from habitat destruction to fish health concerns, and finally to food safety concerns. Interestingly, these attacks rarely withstand the scrutiny of science, when more in-depth analyses are conducted. The reality is that the industry is continuously challenged by the market (the consumer), and its survival is dependent on ameliorating its practices to ensure it provides an environmentally and socially sustainable product. Technology is continually assisting with these improvements. After all, fish and shellfish farming rely on good environmental conditions to produce healthy animals and it is in the industry's best interest to maintain impacts on the environment to the minimum possible. Many of the current practices in modern aquaculture have been enshrined in Standard Operating Procedures (SOPs) and Best Management Practices (BMPs) that seek to minimize impacts of one kind or another on the surrounding environment. In most jurisdictions, North American and Europe in particular, adherence to these SOPs and BMPs is under close regulatory oversight to internationally accepted standards of food safety, environmental sustainability and labour force practices.

In fact, in recent years, evidence is pointing to amelioration of habitat and stabilization or even increases in capture fishery production associated with aquatic farming, rather than the declines predicted by some. For example, landings of commercially valuable American lobsters in areas of intensive salmon production in New Brunswick and Newfoundland and Labrador, Canada, have increased substantially, to record levels in some subzones, in spite of predictions to the contrary by fish harvesters. The reasons for these increases in wild fishery catches in salmon farming areas are likely multifold and not fully understood. Theories range from protection of lobster habitat from bottom trawling scallop fisheries, to localized enhancement of lobster habitat near the cage sites, to improved survival of juvenile lobsters due to slightly enhanced nutrient inputs in the areas. These are not the only examples of habitat amelioration and enhanced fish production, and one can find similar examples in shellfish production in China, Japan and France, near mussel farming operations in Prince-Edward-Island, Canada, below oyster raft cultivation in British-Columbia, Canada, and in the Fjords of Iceland where cod ranching is increasingly taking place.

Fish health management has evolved rapidly in the past decade. Like their land-based counterparts, fish and shellfish species grown in intensive culture systems may be exposed to microbial infections, requiring *therapeutant*[3] use. Technological advances in vaccine production have made available a wide range of options against many of the common pathogens for fish production systems so that the use of antibiotic compounds has declined drastically in recent years. Recent figures show antibiotic useage down by nearly 98% in the past 15 years in salmon culture, and relatively few fish farmed intensively today require therapeutants to control microbes. Some estimates suggest as few as 5% of fish (salmon) produced in intensive production are ever exposed to antibiotics during their life; and when they are given therapeutants it is done under the watchful eye of professional veterinarians to ensure proper useage and clearance of compounds from the flesh before harvest. This compares with much, much higher rates of therapeutant useage for domesticated animal meat production, such as poultry, swine or beef industries which the consuming public widely acknowledges to produce safe, high quality protein. Farmed fish and shellfish are one of the few animal food proteins currently produced in intensive culture with little or no antimicrobial compounds employed.

Recent developments in prepared fish diets are equally technologically advanced. High quality diets, that once consisted of 60-70% fish proteins and marine oils, now contain less fish, in some cases less than 20% fish components. Alternate natural protein and oil sources have been sought and tested in diets. Highly digestible vegetable proteins have been substituted for fish in the diets and by changing the nutrient content fish grow as well, or better on the prepared diets. This means that the perceived pressure on wild fish stocks for raw materials in aquafeeds is lessened, although a significant portion of fish meal and oil (more than 50% global supply) still goes into poultry and swine production. The reality is that in spite of 30 years of almost exponential growth in intensive fish and shellfish farming globally, global supply of fish meal and oil has not increased significantly, so major advances in alternate, natural sources of feed ingredients have obviously been made, and will continue to be made. Test diets consisting of 0% fish products have been developed and shown in small trials to provide excellent growth and production in carnivorous fish.

Marine oils containing omega-3 fatty acids (FAs) are essential in prepared fish diets, particularly for marine

[3] Therapeutants are compounds or products used to maintain fish health or treat fish diseases.

species like salmon, cod or even some crustaceans. The traditional supply from wild fish sources is limited, and of variable quality, although significant amounts of fishery discards at-sea do occur from bycatch. In nature, the omega-3 FAs originate from microalgae at the base of the food chain, and it is impractical to filter the ocean to obtain sufficient microalgae to extract the FAs for future supplies. Hence, industry has developed novel ways of mass producing the single cell microalgae in essentially 'bioreactor' type systems that provide a rich source of omega-3 FAs. Extraction methods are being developed to enable sufficient quantities to be utilized in aquafeeds. As production technology develops, costs will come down so that these will be widely available, and eventually lessen the dependency on wild fish stocks.

Enhancing Nature

Nature is, for the most part, unpredictable in terms of food production. Although there are obvious patterns associated with the seasons, there is considerable variability in terms of location, timing, quantity and quality. As populations began to grow, this is one of the primary reasons humans began farming - to provide a means of access and instill some measure of food security. This occurred over 10,000 years ago on land, and perhaps as far back as 3,500 years ago in lakes and ponds in the aquatic realm. Part of the evolution from hunting and gathering to green and blue revolutions of farming entailed an appreciation for the nutrient cycling and energy requirements to produce the organic matter we know as food. Through trial and error, the basic understanding of nutrient and energy flows among different trophic components (feeding levels in the food chain) began to emerge, as far back as several thousand years ago. For the past several hundred years, people in Asia and others parts of the world have used this knowledge to enable the culture of different organisms together, each with different nutrient requirements. For example, it is common to find examples throughout the world of integrated or co-culture, such as fish and rice together, cattle or swine and fish, ducks and fish, shrimp and sea cucumbers, or oysters and shrimp. Closer to home, a good proportion of the so-called organic Boston lettuce is grown in aquaponic systems, combining trout and lettuce. All of these examples have one thing in common - the use and reuse (recycling) of energy and matter using technology to produce food products.

Closer to home, a good proportion of the so-called organic Boston lettuce is grown in aquaponic systems, combining trout and lettuce.

In addition to enhancing production of both land and aquatic species, there is something intuitively attractive about the concept of integrated farming in that it utilizes organisms in different trophic levels to essentially feed upon one another's wastes, thus minimizing impacts on the environment or ecosystem even further. The most recent developments in Northern climates involve so-called integrated farming use adaptations of cage and longline system technology for the extensive culture of seaweeds and filter feeding shellfish (mussels) along with intensive production of marine fish (salmon or cod). All three groups occupy different levels in the ecosystem in terms of nutrient acquisition.

Many of our aquatic systems are enclosed and have relatively poor nutrient recycling between the bottom layers, or benthos, and the upper water column. These exchanges are necessary in the long term for nutrient availability for plankton production, which typically occurs in the surface water layers, and eventually higher organisms, such as fish or shellfish. Deep Fjord systems like in Norway, and deep oceanic waters often contain abundant nutrients in the colder, deep waters that are essentially limited in availability to the surface zones due to poor mixing. Such systems are often considered low level production zones in terms of plankton or fish, compared with more nutrient rich coastal areas.

In recent years, innovative technological approaches have been sought to bring these nutrients from deep waters to the surface where they can mix and enhance production.

One solution being attempted in Norway is to use gravity-fed fresh water in large conduits (2 cubic meters per second or more) and inject this low density water at depths below 20 meters. The resulting density differential causes significant vertical movement of the deeper nutrient rich waters to the surface. Preliminary indications are that algae production has been consistently enhanced by 3-fold over an area of 10 km^2 with this relatively simple system, and experiments are underway to evaluate secondary production of fish and shellfish in these areas. A different approach with the same concept is used in Hawaii with low-cost, low-head, high-volume upwelling tubes that bring cold, nutrient rich waters to the surface into tanks onshore where it can be used for producing algae and other products. These last two studies provide good examples of successful attempts to enhance or improve production in our oceans, by using technologies to manipulate the conditions needed for growth.

Concluding Comments

The preceding essay has attempted to provide an overview of global aquaculture, and some of the applications of technology towards enhancing aquatic food production in our freshwaters and, increasingly, in our marine environment. Global populations will continue to grow and demand high quality, nutritious food that aquatic farming can and will continue to supply. The trends are towards increased use of technology to reduce costs, enhance food safety aspects, and minimize environmental impacts. As technology becomes more and more sophisticated and reliable we will see the further development of automated systems that will assist in removing human error and lessen the potential impact on the environment. This will require highly skilled human resources to fabricate, operate and manage these systems and thus new areas of training will be required. Science will continue to play a pivotal role in creating the knowledge that is needed to ensure the sustainability of aquaculture through the application of novel technological solutions, and the need is greater now than ever.

Cyr Couturier is a Research Scientist and Chair, Aquaculture Programs at the School of Fisheries, Fisheries and Marine Institute of Memorial University and specializes in aquaculture development and science. He has worked in more than 15 countries since 1980 on aquaculture research, extension and training and is a frequent invited speaker at industry meetings, having published extensively on the subject. Cyr is the current President of the Newfoundland Aquaculture Industry Association (NAIA), a leading Canadian producer organization. He may be reached at the following points: Centre for Aquaculture and Seafood Development, School of Fisheries, Marine Institute, Box 4020, St. John's, NL, Canada, A1C 5R3 Email: cyr@mi.mun.ca.