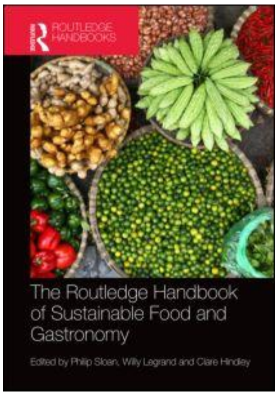

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FOODS FROM AQUACULTURE

Varied and growing

Ricardo Radulovich

Introduction

Thousands of years ago hunting and gathering evolved into agriculture, a most powerful, controlled food-production strategy that greatly enhanced the natural productivity of the land. Nowadays aquaculture, already a global industry with far-reaching international trade, is becoming the evolution from just fishing and recollecting in the aquatic environment towards more controlled aquatic food production. This is happening as a response to dwindling fisheries and increasing demand for aquatic food. Of course, this change of paradigm is afforded by technology and as problems and opportunities arise, scientific and engineering solutions allow the continuous growth of the industry—to yet unpredictable levels.

The sustainability of this rapid growth of aquaculture varies among the different production options. Although naturally the eco-friendliness of producing filter-feeding shellfish and seaweed at sea is very high, effects on environment and biodiversity from large and intensive fish and shrimp farming operations can be significant. Also, there are threats from external variables, among them climate change, including ocean acidification, but also freshwater shortages and limited supply of fishing catch that is used in feed. Yet the industry is striving to guarantee its sustainability, realizing the implications of growth in a changing world, controlling its own negative externalities and promoting positive ones, while moving some operations offshore, developing new feeds and clean production technologies, and establishing standards and certifications that guarantee best practices and product quality. These issues will be discussed throughout this chapter and a final section contains key references and links to sites dealing with sustainability and certification.

Unlike agriculture, which almost totally replaced hunting and gathering, given the vast expanses of the ocean and of some lakes, as well as the myriad of freshwater bodies that are traditionally fished, at least for the time being fishing and recollecting from the aquatic environment will continue until eventually, perhaps, controlled food production through aquaculture will largely overtake the more unpredictable fishing and recollection—which, together, are known as ‘capture’—from the sea and other water bodies.

In fact, what may well happen, and is already happening, is that fisheries themselves will evolve towards incorporating or even becoming one or more forms of aquaculture. An example of this are current methods of aquaculture-assisted fisheries, which consist of releasing laboratory-raised or laboratory-manipulated fish fingerlings, lobster juveniles, or bivalve seeds to restock populations that eventually will be captured (or recaptured)—in a sort of sea ranching. The other way around, fisheries-assisted aquaculture is in fact a major form of aquaculture whereby juveniles of some species (that are hard to reproduce or to be raised from larvae) are captured and grown in controlled conditions such as cages or ponds. Such is the case for, for example, milkfish, tuna, eel, and spiny lobster farming.

Other major aspects of this food-production revolution are that close to 85 percent of world aquaculture is produced in Asia, particularly in China (De Silva and Davy, 2010), and while 87 percent of capture fisheries (of which 85 percent is fish) is marine and only 13 percent inland, this is not the case in aquaculture, where 70 percent is inland fish or freshwater production and only 30 percent of production is marine, of which 76 percent is of mollusks (FAO, 2012). In the case of seaweeds, which are often treated separately from fisheries and aquaculture, although their harvest from the natural environment is recollection and their cultivation is a type of aquaculture, close to 99 percent of the—rapidly growing—production comes from only seven Asian countries. All this indicates, among other considerations, that there is extraordinary room for growth outside of Asia, that mollusks, crustaceans, and seaweeds are becoming far more available, and that freshwater fish will continue to dominate markets, at least for some years to come—something that renders the term "seafood" inappropriate and favors the term "aquatic food," leaving "seafood" for the increasingly more expensive true food from the sea, whether captured or cultured.

A distinction between capture and cultured fish production may also be in order, particularly for marine fishes since long-favored properties such as flavor, meat firmness, and oil content may differ significantly. For example, in controlled-feeding conditions, salmon do not naturally develop a typical flesh color and must be fed with colorants. A similar case may be made for meat firmness and even its red color for active swimmers like tuna, which is not fully developed in controlled conditions. This, coupled to some limitations to the expansion of marine fish farming, which will be discussed below, indicate that choice-captured marine fishes, such as tuna, sea bass, grouper, snapper, and others, may become increasingly more costly products. However, this may be offset, at least partly, as captured seafood becomes more under scrutiny for a variety of reasons, including limitations in traceability given the fact that it is almost impossible to know what fish have eaten and thus accumulated without testing.

World fisheries' capture of fish, mollusks, crustaceans, and other creatures, grew to circa 90 million tons (MT) around 1990 and has stagnated since then, particularly in the marine sector. The FAO (2012) considers that 87 percent of the world's fishing stocks are either fully (57 percent) or over- (30 percent) exploited. As a response to this, animal aquaculture grew at a rate of 8.8 percent per year since 1970 from 2.6 MT to 66.7 MT in 2012, when it reached 73 percent of the tonnage produced by capture (Table 20.1). In fact, it is considered that, in a few years, overall fish food production via aquaculture will surpass that from fisheries.

Mollusk production via aquaculture (Table 20.1), which is mostly marine bivalves, has more than doubled that from capture, while crustaceans and others (like sea urchins) are already similar in quantities between capture and aquaculture. In the years to come, supply of marine mollusks, crustaceans, and others from aquaculture will continue to grow and dominate the market, abundantly providing the commonly consumed oysters and shrimps as well as many other species.

However, the situation is far from static and both freshwater and marine aquacultures are evolving fast, in a rather fierce competition with other food sectors and under heavy attack from environmental and biodiversity concerns. For example, Duarte et al. (2008) describe the recent domestication of hundreds of freshwater and marine animals and marine plants,

Table 20.1 Comparison between capture and aquaculture production (data in million tons)

Group	*1970*			*2012*		
	Capture	*Aquaculture*	*% aquac./capture*	*Capture*	*Aquaculture*	*% aquac./capture*
Fin fish	50.6	1.5	3.0	77.5	44.2	56.9
Mollusks	2.7	1.1	40.7	6.9	15.2	219.7
Crustaceans	1.9	0.01	0.5	6.3	6.5	103.7
Other	0.2	0.0	0.0	0.6	0.8	133.3
Total	55.4	2.6	4.7	91.3	66.7	73.0
	Harvested	Cultivated	%	Harvested	Cultivated	%
Seaweeds	0.9	1.0	108.6	0.8	20.9	2635.2

Data from FAO (www.fao.org/fishery/topic/16140/en).

and the FAO (2012) states that about 600 aquatic species are raised in captivity, including frogs and reptiles, in about 190 countries. This large variation, of course, places importance on paying attention to the different species being produced and marketed, perhaps expecting that as the industry and markets mature there will be a reduction in the number of species being cultured, leaving fewer "winners" or predominant species. Or perhaps not, and variation will continue to cater for ever growing sophisticated markets. As already evidenced for major groups in Table 20.1, production through aquaculture for some individual species is also much higher than their capture counterpart. For example, aquaculture supplies almost 100 percent of the total production of Atlantic salmon and oysters.

The often-forgotten dark horse of aquaculture is seaweed cultivation, yet it may soon grow to become the main form of aquatic food production (because seaweeds, just as crops on land, are, through biosynthesis, the true producers of food, while animals really only transform existing food—albeit into a higher quality). With an exponential rate of growth, in which tropical countries have grown the fastest in the past two decades, already 21 MT of fresh seaweeds are produced in the world via cultivation, representing 96 percent of the world's production of seaweeds, compared to 0.8 MT harvested from the wild. In 1970 production via cultivation was equivalent to that from harvest, yet in 2012 cultivated production was 26 times that from natural harvests (Table 20.1). Thus, with seaweeds in particular, aquaculture is making the strongest difference between captured and cultured. According to Chopin (2012: 24), "The use of seaweeds as sea vegetables for direct human consumption [represents] 76% of the tonnage and 88% of the value." Yet this is not the case for tropical seaweed cultivation, which is still mostly for hydrocolloids, with recent efforts toward their use as food (e.g., Lee, 2008; Radulovich et al., 2013).

Besides the many achievements and the extremely large potential, there are, of course, many problems related to aquaculture that must be considered, yet most of these pertain to aquatic food production in general, whether natural or partly controlled. Given the nature of the aquatic environment, water and whatever is dissolved or suspended in it (e.g., chemicals, microbes, silt) travels with waves, tides, and currents. Aquaculture, however, since it normally entails keeping what is being produced in one place, while feeding it and caring for it, allows for better traceability and control than fisheries. Even little- or non-moving animals like bivalves are subjected to moving waters that require constant monitoring to know what they brought with them. Complete control through intensive, self-contained recirculating aquaculture systems makes a difference in this respect—yet, to an extent, this takes the "zest" away.

Among undesirable situations, toxins in the marine environment, produced, for example, by dinoflagellates that cause ciguatera (ciguatoxins and others) or by some phytoplankton blooms (e.g., red tides) must be considered as they accumulate permanently in carnivorous fishes (up the trophic chain) and temporarily in filter feeders like bivalves, respectively. In freshwater environments, although not excluding marine ones, parasites and pathogens that affect humans find ideal vectors in fish and plants. Adding to chemical contaminants from industry and agriculture, heavy metals from natural sources prove a concern. Besides mercury, which accumulates in fish oil, arsenic—common in waters near volcanoes—can accumulate in aquatic organisms, including, for example, clams that inhabit muddy bottoms (like the geoduck clam, *Panopea generosa*, from the Pacific Northwest of the USA) and some seaweeds (like hijiki, a species of *Sargassum* from the coasts of Japan). Spoilage from poor post-harvest handling of produce, normally a problem in fisheries related to the time elapsed from catch to port and to poor facilities aboard, is far more controlled in aquaculture since harvest can be better synchronized with rapid and even live transport to adequate processing and storage plants. Also, in general, harvest and slaughter from aquaculture tends to be more humane than what many fisheries offer.

Increases in greenhouse gases, besides indirectly raising ocean temperature and promoting sea-level rise, directly promote ocean acidification, which decreases the strength of the calcareous shell of mollusks—something that is already affecting production in many sites. These processes may emphasize the shift from fisheries into aquaculture for a variety of species in order to maintain and increase supply, since species to be farmed can be largely chosen and established according to varying conditions. Complementarily, aquaculture may implement some measures designed to counteract these effects, such as, for example, shifting production to less-affected areas and providing an adequate environment during the initial stages of bivalve development for proper shell-setting.

In general, implementation of good practices, usually as part of certification programs that aim at guaranteeing the quality and safety of aquatic foods, is gaining importance. These programs range from registering aquatic production to the most advanced certifications, such as best practices, HACCP, organic, and kosher (e.g., to be kosher, fish species must have both fins and scales, therefore all other aquatic animals like catfish, eels, shrimps, and oysters, as well as sturgeon's caviar, are not), and can be public and/or private. Some of the major organizations and programs related to aquaculture and certification are referenced at the end of this chapter.

Compliance with a variety of other requirements, some of which reflect societal trends, can also be of relevance to aquaculture products, similar to when tuna fisheries had to adapt to exclude dolphins, and shrimp fisheries now adapt to excluding turtles and abandoning bottom trawling. One factor that leads to criticism of the culture of carnivore fishes such as salmon and tuna, as well as other marine and even choice freshwater species and crustaceans, is that their feeds are largely based on fish meal and oil, for which a sizable share of capture fisheries is devoted (indeed, turning them into luxury products). While fish meal can be more easily replaced with other sources of protein, to date fish oil has proven irreplaceable if quality of fish meat is to be maintained—although important efforts are being made to achieve substitution. The main problem is that substituting fish meal and oil in aquaculture feed may lead to these fish and shrimp being so different to the point of having a significantly different nutrition profile than their wild counterparts (e.g., see Toppe et al., 2012; Bowyer et al., 2013). This issue is threatening the sustainability of this branch of the industry.

An interesting spin-off from this situation is that fish oil from forage fish and krill (a shrimp) are being offered as nutritional supplements on their own, rich with omega 3s and antioxidants and free of bioaccumulation of mercury and other contaminants suffered by high trophic level fish. Oil from microalgae is also being used in this manner.

The use of chemicals and pharmacological products to produce fish (like hormones, antibiotics and parasiticides) is a significant concern that must be more openly publicized. Another important issue is whether species being cultured are native or not, or of too-narrow a genetic makeup, or even if they have been genetically modified, since their inevitable escape can affect native biodiversity. Overall, green or eco-friendly aquaculture, although more costly, is better positioned, particularly for higher markets.

Thus, as capture dwindles, controlled food production in aquatic environments is undergoing rapid evolutionary processes to complement and even substitute fisheries to a large degree. Of course, in many ways, products from aquaculture are not the same as those from fisheries, and this entails an adaptation challenge to the food industry. Many of the limitations regarding the choice of species being farmed or, rather, not farmed, have to do mainly with the inability to reproduce the species, at least with the regularity and reliability needed to establish a farming operation. As these limitations and others are slowly overcome, more species with high market demand are beginning to be farmed on significant scales, to the point where economic factors will become the major determinant. In the meantime, of course, production will continue to be dominated by those species that are easy to reproduce or their reproduction has already been mastered, like most of the freshwater fishes. Reproduction, and with it farming, of several marine species like salmon and many bivalves has already been mastered.

On the other hand, capture of juveniles or seed from the wild affords considerable—although in most cases limited—farming, as is the case for eels, tuna, and lobster. The culture of milkfish (*Chanos chanos*) in onshore ponds and waterways, however, traditionally conducted in Asia by capturing millions of fingerlings from the coastal sea, is an example of a sizable aquaculture option that developed without mastering reproduction—although currently great effort is being devoted to mastering milkfish reproduction in order to guarantee sustainability.

It is, however, important to consider that aquaculture is, overall, a young industry that is constantly striving to improve and adapt. Therefore, what may be true today can rapidly change, so far usually for the best. Excellent examples of this are the appearance of new-coming species, in both marine and freshwater environments. While most farmed fish species grow at rates of around 1kg/year or even less, newcomer cobia (*Rachycentron canadum*), a tropical marine fish, can grow up to 4kg/year. A freshwater species from the Amazon, *Arapaima gigas*, can grow much faster (reputedly, up to 20kg/year) and is becoming an important substitute for other freshwater species. All of this, of course, must be at some point compared to animal production on land. For example, chicken grow to 3kg in six weeks, explaining some differences in prices. On the other hand, as some problems are being identified, like the cases of arsenic accumulation or ocean acidification mentioned above, it is important for those involved in aquatic food products to keep abreast of developments.

After these introductory notes, the rest of this chapter is devoted to describing in some more detail the main and most interesting species being farmed within each major group. After that follows a brief section of concluding remarks describing current developments, some of which may determine the future of the industry.

Fish

As pointed out, the major difference to date is that the most common fish being cultured are freshwater species produced in freshwater ponds, although increasingly intensively in tanks and caged in large water bodies such as lakes. A reason for this is that aquaculture began in freshwater. Comparatively, considering reproduction, management, feed requirements, and harvest, it is far easier to produce fish in freshwater ponds than at sea.

As seen in Table 20.2, three types of freshwater fish dominate production worldwide: carps, tilapias, and catfishes. Most production comes from Asia and their price is comparatively low—although some tend to be marketed at higher prices. However, to any fish connoisseur, their taste and other characteristics are rather bland, yet this freshwater fish production satisfies the most basic market demands for fish meat.

An important characteristic of the main cultured freshwater fish species is that they are mostly of low to medium trophic level—omnivorous and some even herbivores or to a degree filter feeders—so their feed is often low cost and to a large extent produced *in situ* (through fertilization of ponds, adding chemical fertilizers or agricultural residues that promote the growth of plankton and from that a vigorous trophic chain, something called "green water"

Table 20.2 Main or most interesting fish species in aquaculture.

Freshwater

Carps: family *Cyprinidae*, several species: silver, grass, common, bighead, and rohu carps.
Tilapias: several species, main one being farmed is Nile tilapia, *Oreochromis niloticus*; others, *Tilapia* spp.
Catfishes: important species, pangasiid or pangasius catfishes (*Pangasius* spp., *Pangasianodon* sp.), channel catfish (*Ictalurus punctatus*) and European catfish (*Silurus glanis*).

Other interesting groups of freshwater fishes are:
Trout (several species, among them the rainbow trout, *Oncorhynchus mykiss*), relatively important in colder freshwater production.
Sturgeons (family *Acipenseridae*, at least two important genera, *Acipenser* spp. and *Huso* spp.), which |are also a subtropical to colder water group of slowly growing species (taking from five to eight years to reach maturity), produced both for meat and for their roe, which is made into caviar. Their aquaculture is growing and already caviar prices have fallen to about a third of their past peak. Some expect that in a few years close to 100 percent of the world's caviar will be from aquaculture.
Arapaima (*Arapaima gigas*), mentioned above, a fast-growing species from the Amazon, is gaining terrain.
Barramundi or Asian seabass (*Lates calcarifer*), produced in Asia, Australia and New Zealand, both in freshwater and seawater.
Eels (*Anguilla* spp.), the farming of which is growing, even though due to their complex lifecycle they are not bred in hatcheries but they are recollected from the wild in an early stage known as glass eel for the stocking of aquaculture ponds or recirculating tanks.

Seawater

Salmon[1] (Atlantic salmon, *Salmo salar*, also Pacific and Coho salmons, *Oncorhynchus* spp.).
Milkfish (*Chanos chanos*), produced mostly in Asia.
Cobia (*Rachycentron canadum*), a tropical species that is gaining terrain.
Tuna (*Thunnus* spp.), several species are being farmed, both bluefin and yellowfin, capturing juveniles and raising them in pens at sea. Breeding efforts are under way.
Grouper (several genera in the subfamily *Epinephelinae*, mainly *Epinephelus* spp.), there is already a long tradition of farming groupers in Asia and other regions.
Grey mullet (*Mugil cephalus*), traditionally grown in onshore ponds.
Several other species, including snappers, sea bass and sea bream.

The FAO provides factsheets on 64 cultured aquatic species at www.fao.org/fishery/culturedspecies/search/en.

aquaculture (see Neori, 2011)). Thus (excepting tilapia in intensive production) they do not require to any large extent fish meal and oil in their diet as carnivores do. In that sense freshwater fish production is quite sustainable, and several advanced production, harvest, and postharvest techniques make it financially viable as well—including, for example, the all-male production techniques for tilapia.

However, since besides exchange requirements water is lost from ponds by evaporation and seepage, freshwater fish require thousands of liters of water for each kilogram produced. This very high water requirement has slowed down the expansion of freshwater aquaculture and, together with many complications arising from any large industry—including market saturation and many quality-related considerations, such as releases of polluted water from ponds—has increasingly placed freshwater aquaculture in a state of controversy. The usually unreported use of antibiotics and other chemicals in overly intensive freshwater fish production, as well as other unhygienic conditions, must be considered and reliable certifications are essential if quality is to be guaranteed.

In spite of the many limitations already discussed, marine fish production is, nonetheless, gaining momentum and technology is facilitating its growth. The main or most promising marine species being farmed to date are shown in Table 20.2, where most of them are notably carnivorous and high up in the trophic chain—mainly because of their high value that makes their costly and risky farming at sea financially viable (which is not exempt from similar problems to freshwater aquaculture, such as, for example, parasites). Exceptions to the carnivore rule are traditional production of milkfish and grey mullet in onshore salt- and brackish-water ponds. Due to ease of reproduction and high market prices, the first group of marine species to be grown in caged farming directly at sea was salmon (mainly Atlantic salmon, but others as well, like Pacific and Coho salmons). Many attempts have followed with other species, yet to date reproduction and high-quality feed remain a limiting factor. Although reproduction has been achieved to a large extent beyond doubt for a few species (e.g., cobia mentioned above, groupers and others like snappers), some marine fish farming operations rely entirely on the capture of juveniles from the wild—being in that sense a "fattening" or ranching operation. Tuna is a good example of this, although efforts to reproduce them are under way.

Besides active research towards finding suitable oils to replace that from fish in feed, perhaps from seaweeds or even from microalgae, a tendency may be to culture "down the trophic chain" (analogous to "fishing down the trophic chain"), growing omnivores, "forage" fish like filter feeding sardines, anchovies, and menhaden, and herbivore fishes like rabbit fish, instead of the more tasty and nutritionally superb yet very expensive, although perhaps unsustainable, carnivores like salmon and tuna.

While for several reasons marine aquacultured choice fish and even crustaceans may differ in several characteristics from their natural counterparts, this is not at all the case for bivalves, which get their feed from passing water. Size is another concern. For example, many aquacultured fish species are grown to a minimal profitable size, like plate-sized, harvesting as soon as possible in order to decrease risk and guarantee profit. On the other hand, besides being stagnated or dwindling, so their continued supply at best will remain similar to present levels, marine fisheries are not without quality problems that go well beyond poor post-harvest handling. A balance is certainly hard to achieve and a dynamic posture on fish will guarantee the best choices.

Crustaceans

Production of marine crustaceans through aquaculture has grown in the last years to the point that it has now surpassed capture. It has centered for decades now on shrimp farming in onshore ponds with sea- or brackish water. Catering mainly to USA, European, and Japanese markets, this industry grew mostly in Asia and Latin America to an annual production of 6.5 MT in 2012, already 103.7 percent that of capture crustacean fisheries which have stagnated at around 6 MT since 1998 (Table 20.1).

Most crustacean aquaculture is based on two species of marine shrimps, *Penaeus vannamei* (Pacific white shrimp) and *Penaeus monodon* (giant tiger prawn). Both belong to the *Penaeidae* family, from which several other *Penaeus* species are also farmed (like the Indian white shrimp, *Penaeus indicus*), some in growing quantities.

Given the size of the industry, shrimp farming in many thousands of hectares of onshore ponds has been related to several environmental problems. To begin with, it has been established by destroying mangrove forests and other natural coastal formations (something for which there is probably no way back). The other major environmental problem is the disposal of effluent waters loaded with nutrients and organic matter. While also plagued by production variability due to diseases that can wipe out entire areas, as well as toxins that may develop in pond water, the industry is evolving towards certified better farming practices and growing more in intensive production than in new farming areas. That, together with the alternative of farming shrimp in cages at sea that has been recently developed (e.g., Radulovich, 2010), coupled to an increased interest in growing shrimp in tanks using recirculating methodologies (something that allows the industry to be established in just about any location), guarantees a stable and growing supply of shrimp.

Moreover, improved shrimp-farming techniques allow the production of larger shrimp, since limitations in size have normally been due to poor conditions related to crowding and low oxygen in onshore ponds.

Aquaculture of crabs, mainly also in onshore ponds with sea- or brackish water, is in second place in importance, although far less sizable than shrimp. Besides the sturdiness of the crab and fast growth rates for meat, this has the incentive of the soft-shell crab upper-end market, and the supply is growing. Crab species being cultured include the blue crab (*Callinectes sapidus*) and the mud crab (*Scylla serrata*). Some freshwater crabs are also produced but in limited amounts.

Lobster aquaculture is placed in a distant third place, limited because of complicated reproduction from complex developmental stages. Spiny lobster (*Panulirus* spp.) is being produced in cages or ponds, taking juveniles from the wild. Ongoing efforts allow that lobster aquaculture may become more common in the future, not only as reproduction in hatcheries develops, but also as restocking efforts increase opportunities to obtain juveniles from targeted areas.

There is considerable farming of freshwater prawns, mainly the giant river prawn, *Macrobrachium rosenbergii*, grown mainly in China but other places as well, such as in the USA.

Mollusks

The surprising winners in animal aquaculture, so far and compared to their captured counterpart, have been marine mollusks (*phylum Mollusca*), particularly bivalves (order *Bivalvia*) like mussels and oysters, though there are other important *Mollusca* groups described below. As indicated earlier, close to 100 percent of the oysters being marketed worldwide come from marine aquaculture—most of it directly at sea—and the trend continues with sophisticated techniques (such as, for example, triploid and tetraploid oysters). Although some freshwater bivalves are cultured, this is an extremely small fraction compared to marine production.

Historically for centuries cultured in Europe, as seen in Table 20.1, already in 1970 mollusk culture at sea represented 40.7 percent of what was recollected from the wild (1.1 over 2.7 MT), while in 2012 the aquacultured tonnage of mollusks more than doubled what is recollected (15.2 over 6.9 MT). This is largely due to a combination of ease of reproduction (in some cases, like with mussels, it only requires keeping ropes near spat fall areas where they get covered with juveniles that settle on them) and of farming (including the advantage that they are mostly immobile), greatly aided by the fact that bivalves don't need to be fed since they are filter-feeders—indeed lowering costs and simplifying an operation. All these great advantages lead to this branch of the industry growing, with many species being produced (described in Table 20.3), and it will probably be some time until the market saturates. What used to be expensive oysters and other bivalves are becoming far more common and affordable.

Important issues already mentioned are that bivalves, as filter-feeders, will also take in a variety of contaminants that may accumulate, some permanently, others temporarily. Another issue also discussed above is that ocean acidification is making it hard for mollusks to construct their calcareous shells. The main point, however, is that the industry may have a low ceiling related to how much bivalves will be incorporated into diets in spite of price and supply—dictated by some inelasticity of demand that may have to be modified.

Aquatic gastropods are another major branch of the *Mollusca phylum*. They are called univalves or snails. Although there are many freshwater species, some of which are edible and a few are cultured (like the applesnail, *Pomacea canaliculata*, considered an invasive pest),

Table 20.3 Main bivalve groups and species being cultured

Mussels (family *Mytilidae*): blue mussel, *Mytilus edulis*, Mediterranean mussel, *Mytilus galloprovincialis*, and New Zealand greenshell mussel, *Perna canaliculus*, among others.
Oysters (family *Ostreidae*): particularly the Pacific or Japanese oyster, *Crassostrea gigas*, already produced in nearly 100 countries, and others like the American or Atlantic oyster, *Crassostrea virginica*, the European flat oyster, *Ostrea edulis*, and the rock oyster, *Saccostrea glomerata*.
Clams (true clams belong to the *Veneridae* family, which are "infauna" in that they live buried in mud or sand): included are hard clam, *Mercenaria mercenaria*, Manila clam, *Tapes philippinarum*, grooved-shell clam, *Ruditapes decussatus*, littleneck clam, *Protothaca staminea*, and the Japanese clam, *Venerupis japonica*.
Other "clams" (from different families but sharing the "infauna" characteristic): the sizable Pacific geoduck clam, *Panopea abrupta* (family *Hiatellidae*); the surf clam or macha, *Mesodesma donacium* (family *Mesodesmatidae*); and the large group of the razor clams (family *Pharidae*), among which the Atlantic Jackknife, *Ensis directus*, the Chinese razor clam, *Sinonovacula constricta*, the razor shell, *Ensis arcuatus*, and the pod razor, *Ensis siliqua* are cultured.
Scallops (family *Pectinidae*): with several species being cultured, such as Yesso scallop or Japanese scallop, *Patinopecten yessoensis*, the Pacific scallop, which is a hybrid, *Patinopecten caurinus* x *yessoensis*, the giant or sea scallop, *Placopecten magellanicus*, the Northern Bay Scallop, *Argopecten irradians*, the Chilean scallop, *Argopecten purpuratus*, and the great scallop, *Pecten maximus*.
Ark clams or blood cockles (family *Arcidae*): extensively cultured is the blood cockle, *Anadara granosa*, although there are several other *Anadara* spp. being farmed.
True cockles (family *Cardiidae*): some are cultured to an extent, among them the common cockle, *Cerastoderma edule* and the basket cockle, *Clinocardium nuttalli*.

the majority of the interest is on sea snails. Two gastropod seafood groups that are being cultured are the abalone (several species of the genus *Haliotis* are being farmed, from cold to tropical waters), which is gaining terrain and feeds on seaweeds, and the conch, of which the Queen conch (*Lobatus gigas*) is a major representative already being farmed in the Caribbean.

Within yet another group of *Mollusca*, the cephalopods (octopi, squids), the farming of octopus (several species of the genus *Octopus*) is proceeding at speed given high market demand, and soon there may be stable supplies of this otherwise overfished group.

Echinoderms

The phylum *Echinodermata* is composed of marine animals of which sea urchins and sea cucumbers are being farmed due to increasing demand and thanks to the development of technology.

Sea urchin roe is a luxury food product and their culture in both cold waters (e.g., the green sea urchin, *Strongylocentrotus droebachiensis*) and tropical waters (e.g., the tropical sea urchin, *Tripneustes gratilla*) is proving easy. Moreover, they feed mostly on seaweeds, therefore in some ways lowering production costs and making them less dependent on external feed sources.

Sea cucumbers (class *Holothuroidea*), of which the harvested product is referred to as *bêche-de-mer*, have a strong market in China and, while overfishing has depleted populations, this has promoted a growing aquaculture. Interestingly, since sea cucumbers are mostly bottom-dwellers and detritus eaters, they can be grown together with other species, like in shrimp ponds or fish cages, feeding on refuse and leftovers. Several species are being produced, including the Japanese sea cucumber, *Stichopus japonicus*, the sandfish, *Holothuria scabra*, the greenfish, *Stichopus chloronotus*, and the prickly redfish, *Thelenota ananas*.

Reptiles and amphibians

These two groups are cultured in a very limited manner, all cases in freshwater. Among them alligator farms are famous and their viability depends on production for leather and tourism rather than for meat. Another aquatic reptile being cultured for food, mainly in China, is the soft shell turtle (*Trionyx sinensis*). Within amphibians, some frog species (*Rana* spp.) are being produced for their legs, although their production in controlled conditions is difficult, in many ways due to their need to be fed live feed.

Seaweeds (macroalgae)

A very strong newcomer into marine aquaculture and increasingly as a food is seaweeds (formally known as macroalgae, singular "macroalga"). While in 1950 cultivated tonnage was 10.4 percent of that harvested from the wild (0.03 vs. 0.33 MT), in 2012 cultivated tonnage was more than 26 times that harvested from the wild (20.9 vs. 0.8 MT), most of it used as food. While only seven countries in Asia produced 98.9 percent of the world's seaweed output, already a total of 31 countries and territories reported significant seaweed farming in 2010 (FAO, 2012). One hundred and forty-five seaweed species are known to be used for food and 101 species for hydrocolloid production (Zemke-White and Ohno, 1999). These are agar, alginate, and carrageenan, commonly used in the food industry as thickeners and for water retention (Bixler and Porse, 2011).

Classified as red, brown, and green, there are estimated to be between 8,000 and 10,000 seaweed species worldwide (Lüning, 1990; Thomas, 2002). Consumption of seaweeds by man is ancient practice. There is evidence that they were used for food and medicine more than 14,000 years ago in southern Chile (Dillehay et al., 2008). An early report from Hawaii (Reed, 1907) describes not only that "many tons of these seaweeds are gathered and eaten," but that they were cultivated by reseeding them in different locations to increase their abundance. Nutritional properties of seaweeds include high protein content of adequate digestibility and a balanced amino acid composition, polyunsaturated fatty acids, vitamins (including B12 precursor), and high fiber and mineral content (e.g., Black, 1952; McDermid and Stuercke, 2003; MacArtain et al., 2007; Matanjun et al., 2009; Van Ginneken et al., 2011).

The growing interest in cultivated seaweeds for human food has resulted in a variety of recent publications. Among these, Lee (2008), Mouritsen (2013), and Radulovich et al. (2013) describe the use of seaweeds as food, while Winberg et al. (2011), Radulovich et al. (2013), and Redmond et al. (2014) describe cultivation methods.

Microalgae

Several microalgae types and species are being cultured worldwide for food and other uses. The activity originated with the well-known spirulina, which is a cyanobacteria also known as blue-green algae, and is now placed in the genus *Arthrospira* (*maxima* and *platensis*). Spirulina is very high in protein of adequate amino acid distribution and provides several other nutritional benefits, including high-quality oil. Other important microalgae being cultured for food or food supplements, among them polyunsaturated fat (including omega 3s) and antioxidants, are, for example, *Chlorella vulgaris* and *Dunaliella salina*. Their high productivity, however, although initially leading people to believe that they would be an answer to growing food and even fuel limitations, requires some stringent conditions that greatly increase costs. Therefore, their use as "food" in general is restricted at present, while their use as food complements and as sources of nutraceutical compounds may grow.

Other plants

Freshwater bodies, like lakes and dams, are now eliciting increased interest for controlled food production, with caged fish aquaculture and aquaculture-assisted fisheries among them. Yet perhaps the most promising techniques are based on plants. Besides what is being termed "aquatic agriculture," growing land plants in floating conditions (related in a sense to "aquaponics," which is hydroponics using the water from controlled freshwater fish aquaculture), there are some direct efforts at cultivating aquatic plants (which like seaweeds carry the misnomer of "aquatic weeds") beyond growing them on freshwater aquaculture ponds as animal feed.

Several of these species, including some freshwater green macroalgae, tend to grow fast and have an excellent nutritional composition. In particular, water hyacinth (*Eichornia crassipes*) is the fastest growing, has a very wide distribution, and is well known for blocking waterways and surfaces. However, water hyacinth, but others as well, accumulate small and sharp crystals of calcium oxalate in their tissue, presumably as a defense mechanism against herbivory, something that renders them inedible. Some recent efforts aim at either learning how to make aquatic plants edible or identifying or even forging strains through genetic means that are low in or have no calcium oxalate. If these attempts are successful, the world can count on a highly productive new aquatic crop.

Conclusion

Aquatic food production is already a global food industry and it certainly is growing in the number of cultured species, quantities produced, and quality. Moreover, given that 70 percent of the planet's surface is covered by water, while land food production is increasingly limited by water availability, aquatic foods may well be more important in the years to come, perhaps to the point of becoming a second agriculture (e.g., see Radulovich, 2011). In fact, once sizable portions of these water surfaces begin to be properly used, mostly the ocean but also lakes and other freshwater bodies, there will probably be no shortage of food at the world level that some fear. However, for this to be true, production must be based on new aquatic plant growth, which will be the food in itself or the feed to grow aquatic animals. Seaweeds, of course, are first in line, and there is ample room for selection and improvement in turning them into more palatable and useful crops.

Regarding animal aquaculture, freshwater production of fish will continue to dominate for some time, probably until marine aquaculture takes over. Most likely, however, the long-term emphasis on fish production will shift to lower-trophic animals that do not require feeds heavy in fish meal and oil to develop properly—except, of course, as far as the adaptation to alternative feed sources will allow. This will also be true to an extent for crustaceans, which are carnivores to a large extent. Bivalve production, however, will continue to grow unfettered until it eventually reaches some limitations, like market saturation.

Integrated strategies to manage fisheries, aquaculture, and conservation together will probably provide new avenues to recover and perhaps increase fisheries while sustainably increasing areas for aquaculture. This will provide a continued and increasing supply of aquatic meat and plant products that will affect eating habits and food supply in novel ways. Moreover, possibilities based on the extensive marine biodiversity go far beyond commonly known and farmed species, with growing applications of genetic engineering and marine biotechnology in a range of products, such as nutraceuticals (see, e.g., OECD, 2013).

Overall, it may well be that we are entering an aquatic age and we must, simply, evolve.

Links to aquaculture organizations and certification

Additional to each country's associations and other organizations, some of those with international involvement are:

The World Aquaculture Society, www.was.org.
The European Aquaculture Society, www.easonline.org.
The Global Aquaculture Alliance, www.gaa.org.

For quality concerns and certifications

Alongside each country's regulations for production and import/export, there are several private (some public/private) efforts to guarantee sustainability and standards being applied to fishery and aquaculture products.

- The Norwegian Ministry of Fisheries and Coastal Affairs (2009) provides an excellent example of a strategy at the national level to achieve environmental sustainability of their aquaculture industry.

- The FAO (www.fao.org) has been greatly involved in the issue and is the leading world authority. There is a recent FAO publication on aquaculture standards and certifications, freely available online (FAO, 2011). In another FAO document, Toppe et al. (2012) address biosecurity concerns related to aquatic foods.
- The World Fish Center (www.worldfishcenter.org) and the Network of Aquaculture Centres in Asia-Pacific (www.enaca.org) are two additional organizations involved in better management practices and certification issues. Certification of aquaculture, however, is not without critique (e.g., see Bush, 2013).

The following sites are devoted to aquaculture certification:

- Best Aquaculture Practices (BAP) certifications, through the Global Aquaculture Alliance (www.gaa.org), the Aquaculture Certification Council, www.responsibleseafood.org, and www.aquaculturecertification.org.
- Aquaculture Stewardship Council (ASC) standards and certifications, www.asc-aqua.org.
- Organic aquaculture certification, www.naturland.de.
- Perdikaris and Paschos (2010) provide an interesting short review of organic aquaculture.

Note

1 Salmon spp. begin and end their life in freshwater, living at sea in-between.

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