AQUACULTURE:
the Blue Biotechnology of the Future

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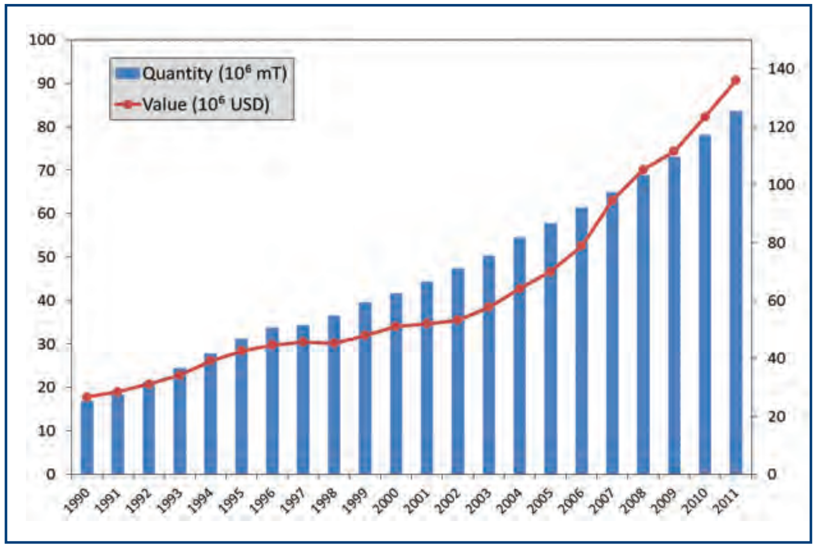
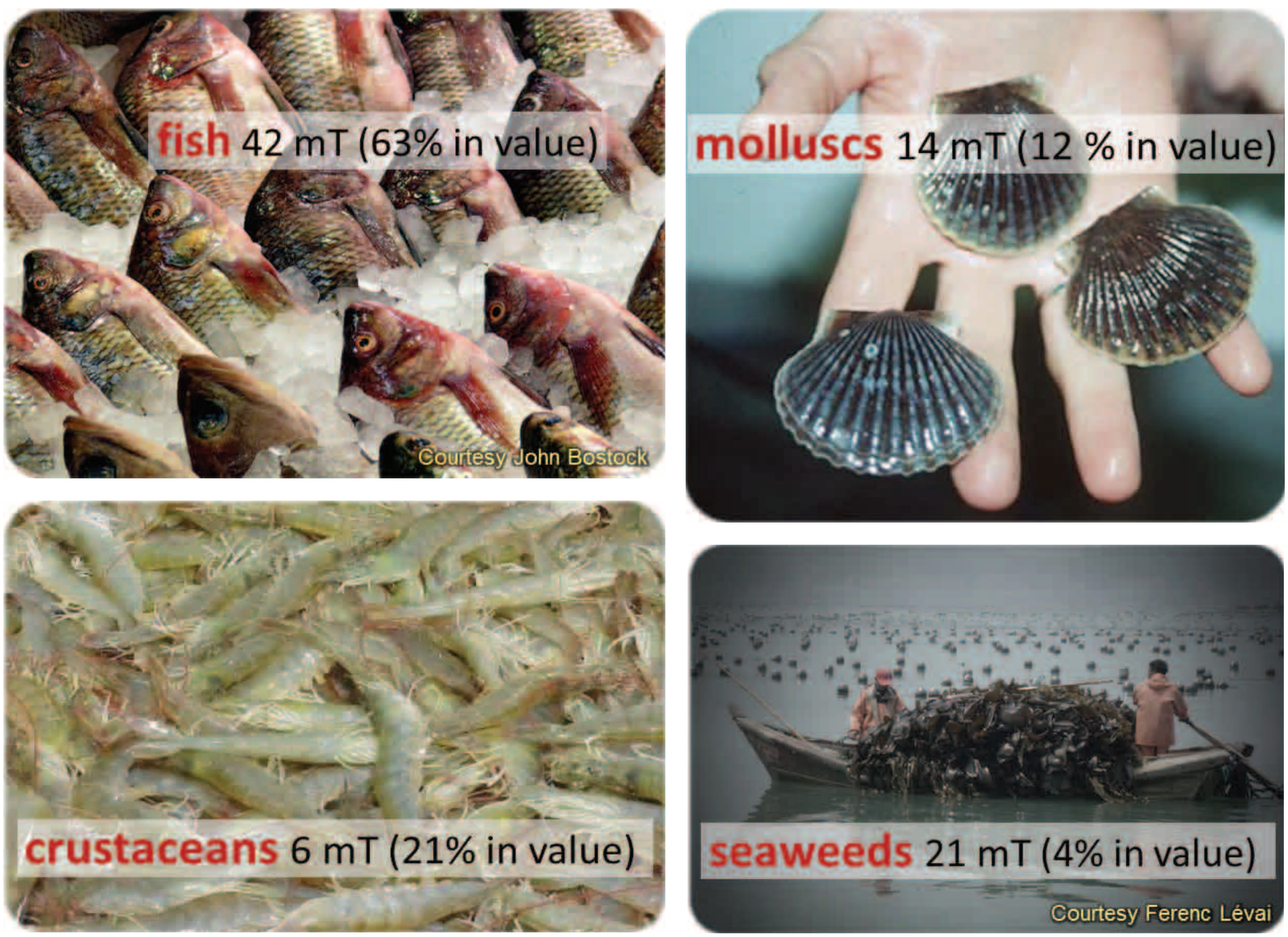
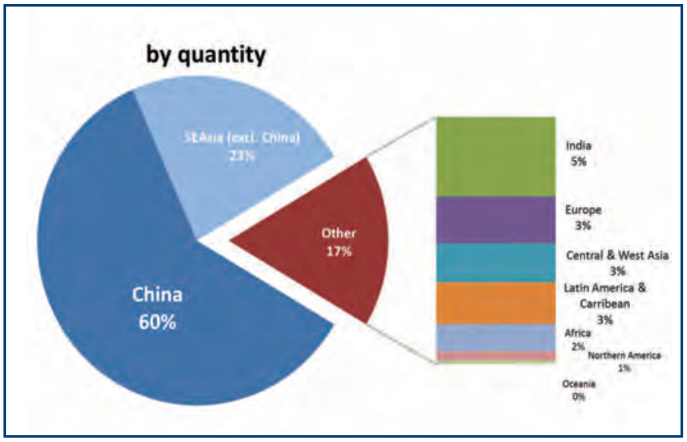
Aquaculture is the fastest growing food-production industry (Fig. 1). It all started in Asia, especially in China, but it was only in the last 3 to 4 decades that spectacular growth took place. Following the FAO global aquaculture production statistics for the year 2011, finfish make up about half of all seafood production, totaling 62.7 million mt with an estimated value of US$ 130 billion. Farmed aquatic algae or

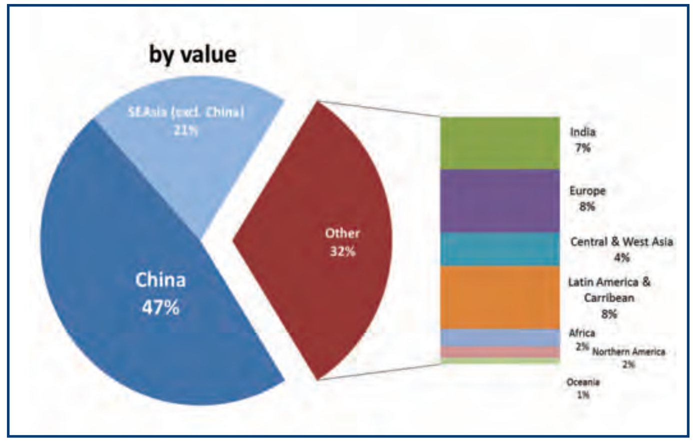


RIGHT, FIGURE 1. *Quantity and value of world aquaculture production of aquatic animals and plants (courtesy Rohana Subasinghe, FAO-Rome, 2013)*

BELOW, FIGURE 2. *Aquaculture products by quantity and value (FAO Fisheries and Aquaculture Department, 2013 Global Aquaculture Production Statistics for 2011 ftp.fao.org/FI/news/GlobalAquacultureProductionStatistics2011.pdf.*



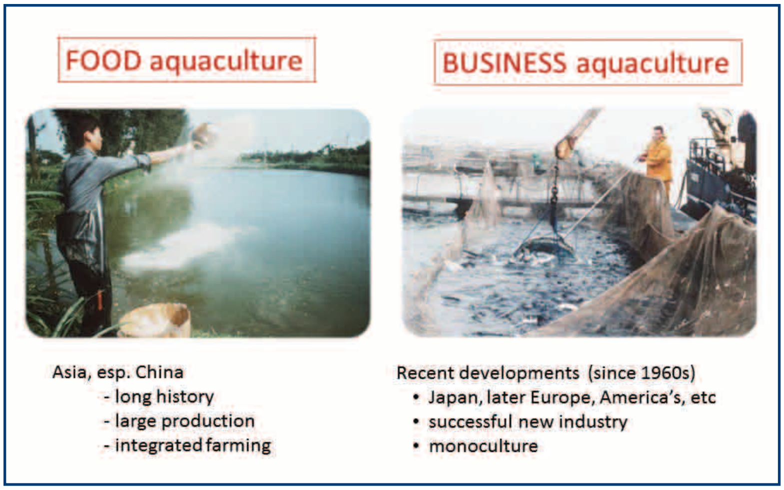


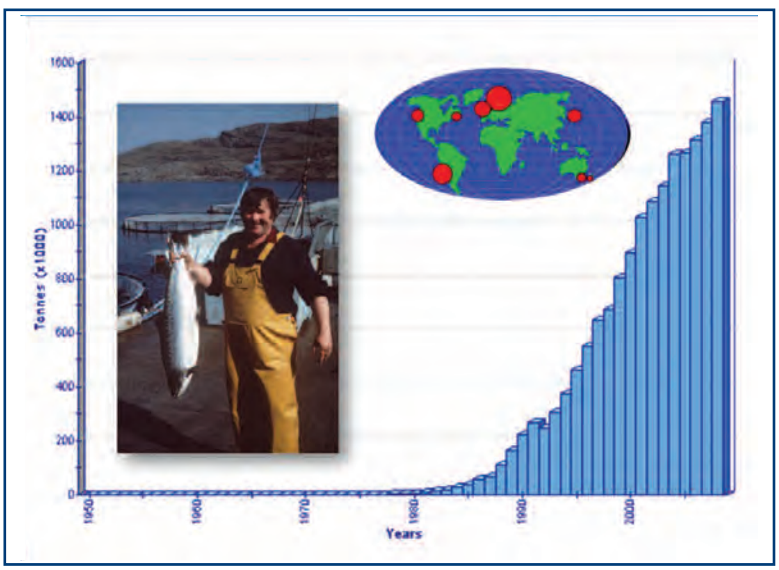


seaweed production was 21 million mt in 2011, worth US$ 5.5 billion (FAO 2013, Fig. 2) By quantity, Asia and the Pacific are responsible for nearly 90 percent of the production but, when expressed by value, Europe and Latin America make up 20 percent because their aquaculture products fetch higher market prices (Fig. 3).

Food Aquaculture and Business Aquaculture

Aquaculture practices can be classified under two categories: "food aquaculture," as practiced for millennia in Asia, and "business aquaculture," the more recent developments that have resulted in new practices with different systems and species (Fig. 4). Food aquaculture is exemplified by the traditional farming of freshwater fish in ponds in Asia. This food security approach is mainly to meet the farmer's personal needs or for catering to very local markets. Until today this pond production practice is very important because it provides close to 15 million mt annually in China alone. Typical for this traditional food aquaculture is the integrated approach: farming of aquatic species in combination with other food production practices. Examples include fish and prawns in the ditches of rice paddies, feeding on periphyton, decaying plant material and insects, or fish integrated with the farming of terrestrial animals, such as chicken, ducks and pigs, using wastes and by-products as direct and indirect food sources.





TOP LEFT & RIGHT, FIGURE 3. *Aquaculture production per region (courtesy Rohana Subasinghe, FAO-Rome, 2013).* MIDDLE, FIGURE 4. *Food aquaculture versus business aquaculture.* BOTTOM, FIGURE 5. *World salmon production (courtesy Yves Harache, 2010).*

Business aquaculture is a much more recent phenomenon. It was pioneered by the Japanese in the 1960s, and taken up later and further developed in Europe, USA, and Australia, in fact everywhere today, even in Asia. The main principle is to engage in the farming of species with high market value following capital-intensive business models. These modern aquaculture industries became feasible from new insights into the biology and life cycle of target organisms, for example, how parental stock could be induced to mature, or how the development of hatchery techniques allow the production of mass quantities of fry in hatcheries, fingerlings that can be stocked in high-density grow-out systems. Similar to the analogous plant and animal farming practices on land, business aquaculture is always practiced as a monoculture. Some typical examples include:

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ABOVE, FIGURE 6. TOP: *Offshore salmon farm producing 12,000 ton/yr in Norway.* BOTTOM LEFT: *Pneumatic feed distribution system.* BOTTOM RIGHT: *Floating 4-store building for feed storage and control room.*

- more or less sophisticated cage structures, in fjords and bays, eventually moving out to more open sea areas;
- land-based systems operated in ponds, concrete raceways or tanks;
- recirculation systems that allow, maybe at a higher cost, production close to large urban markets, often in temperate and cold climates.

Success stories are numerous although most have or are continuing to experience rough times, including Atlantic salmon farming (Fig. 5), the classic example that has set the scene for many other types of business aquaculture. A first example is overproduction in the early 1990s in Norway, resulting in a severe financial crisis that was finally remedied by better marketing efforts, i.e. developing new outlets allowed for further expansion of the industry. Another example with Atlantic salmon has to do with diseases. Although much progress was made in disease control, a lack of basic biosecurity measures has been at the origin of recent devastating problems in Chile, such that it will take years to recover from the present economic setback.

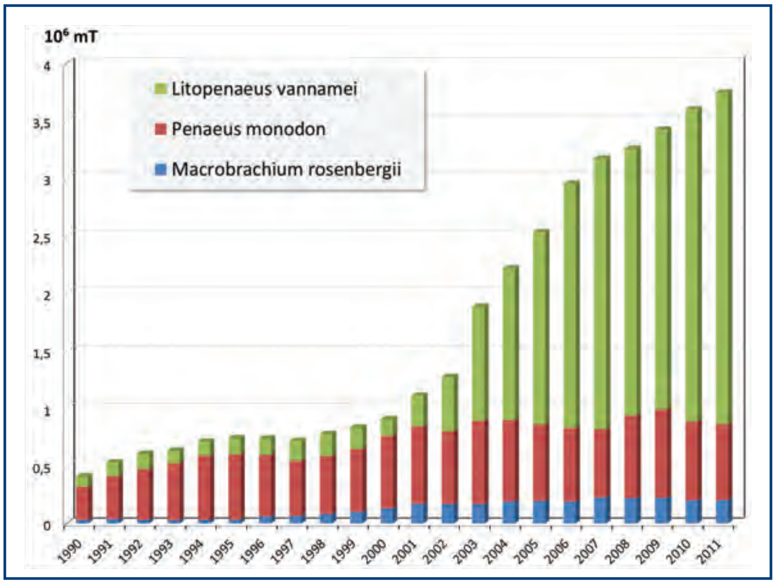
In terms of scale of automation and production size, salmon farming is again leading the way. The farm in Figure 6 is situated offshore of the Trondheim fjord in Norway in a water depth of more than 50 m. The cages have a capacity of 1000 tons each and are operated by a crew of less than 10 people. High automation and thorough specialization are keys to success in this case.

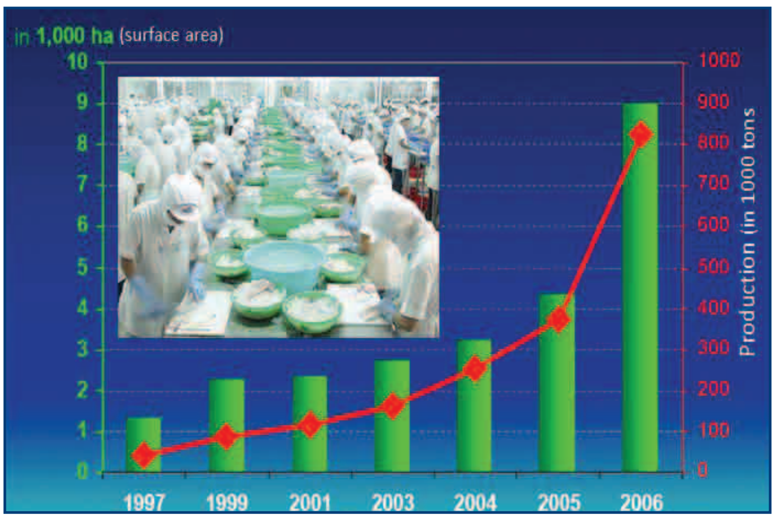
Another success story is penaeid shrimp (Fig. 7). Following very profitable decades in the 1970s and 1980s, shrimp aquaculture experienced a very rough decade in the 1990s with severe disease problems caused by poor management practices and uncontrolled transfers of contaminated broodstock or postlarvae. The introduction of domesticated and SPF white shrimp *Litopenaeus vannamei* enabled more predictable growth of the industry.

Pangasius farming in the Mekong delta in Vietnam will enter history books as a typical example of business aquaculture adopted by a developing country (Fig. 8). Once maturation and hatchery practices were mastered, farming in floating cages and later in ponds expanded at a phenomenal rate. New markets, especially in Europe, were eager to introduce pangasius fillets as a cheap substitute for the more expensive generic whitefish from classic fisheries. It is a success story indeed, but one under serious threat because of biosecurity issues and limited attention to sustainability matters.

Another example of business aquaculture, albeit at a very local level, is the Chinese mitten crab industry (Fig. 9). Following the catastrophe with the white spot syndrome virus disease in the coastal shrimp farming sector in the early 1990s in China, a reconversion to mitten crab seed production really paid off. Annual production output, currently at 700,000 mt, continues to increase as local markets are further expanded and new farming practices, such as the polyculture of mitten crab in rice paddies, are successfully explored, even far inland in western China.

Outside Asia we often forget the success of mollusk farming, with more than 14 million mt annually, and seaweed production, delivering 16 million mt annually. These two latter forms of aquaculture deserve much more attention in the future.





TOP, FIGURE 7. *World shrimp production by species (courtesy Rohana Subasinghe, FAO-Rome, 2013).* MIDDLE, FIGURE 8. *Pangasius catfish farming in Vietnam (courtesy Nguyen Huu Dzung, VASEP-Hanoi, 2010).* BOTTOM, FIGURE 9. *Chinese mitten crab (Eriocheir sinensis) farming in rice paddies in China (courtesy Yong-Xu Cheng, Shanghai Fisheries University, 2010).*

Expectations for Future Aquaculture

What are the expectations for future aquaculture? What are the challenges and threats we face? Are there any opportunities? As world population continues to grow and consumers become increasingly convinced of the health benefits of eating seafood, market demands for aquatic products will further expand in the years to come. Fisheries are stagnating and might even level off, so aquaculture will have to grow even faster. Fresh water will become increasingly scarce in the decades ahead and we should turn more towards the oceans for a sustainable source of our seafood.

Over the past three decades there has been a progressive increase in the contribution of aquaculture

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to global seafood needs (Fig. 10), from less than 10 percent in the 1970s to about 50 percent of what we consume now. This trend will continue as demands increase and fisheries stocks are exploited near or greater than maximum sustainable yields. Calculations based on present per capita consumption and estimated population size 10 years from now reveal that aquaculture will have to provide more than 25 percent more on an annual basis within the next decade. Considering the available global resources for food extraction or production, it is clear that land for crops and pasture will come under serious pressure (Fig. 11). However, the vast area of seas and oceans could be better explored and exploited for mariculture development and eventually play a much more important role in the production of food for humanity. Global primary production is as important in the seas and oceans as it is on land, however, today the marine environment contributes less than 2 percent of the total quantity and only 16 percent of protein to our food supply (Fig. 12). It is largely for historical reasons that aquaculture production today is only slightly greater in marine waters as compared to freshwater habitats (Fig. 13). In future decades we can expect and in fact should promote a significant shift to farming the oceans and seas.

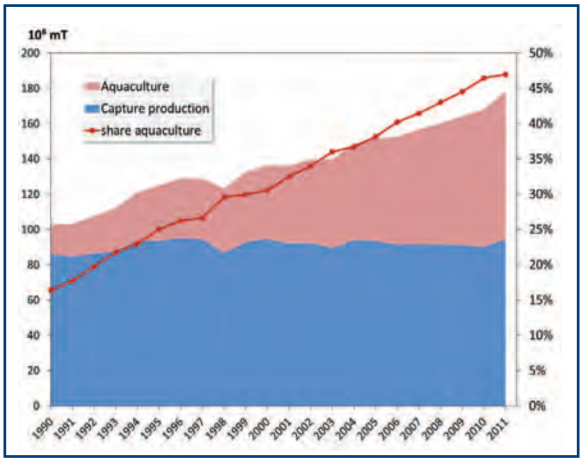
It should be clear that aquaculture is expected to expand very significantly. However, can this be achieved following our current expertise and experience? Can it be accomplished without causing environmental risks or human health problems? The answer is yes but only when we shift into a higher gear. We cannot continue along the empirical path of the past. Perhaps this has been an appropriate approach until now, i.e., trial and error using sound scientific principles. However, with the challenges ahead, we need to develop a more knowledge-based bio-industry. We need to understand the underlying mechanisms of all biological processes responsible for the final production outcome. Only then we can develop a more predictable, reliable, cost-effective and ultimately more sustainable industry.

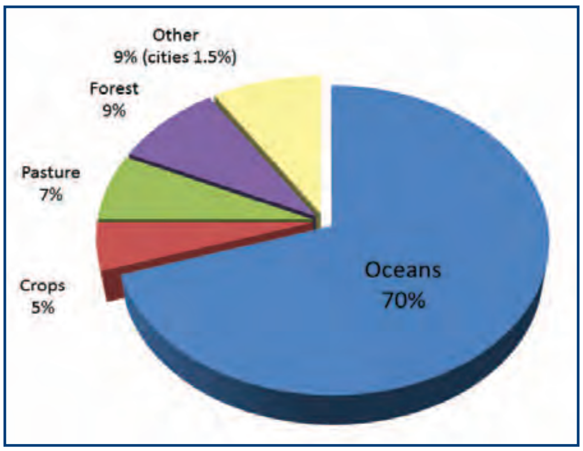
Priority Needs for Future Aquaculture

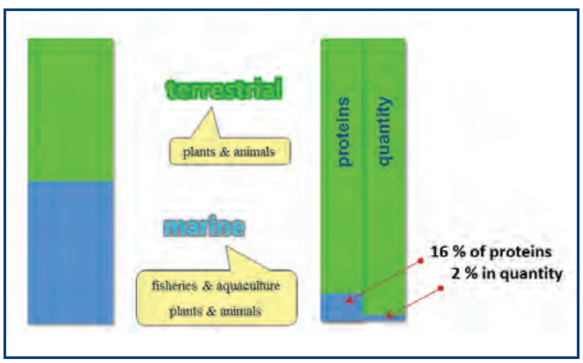
In Table 1 (Fig. 14) I propose a long list of what I consider to be the priority needs for future aquaculture. Most of these are discussed in greater detail in FAO/NACA (2012).

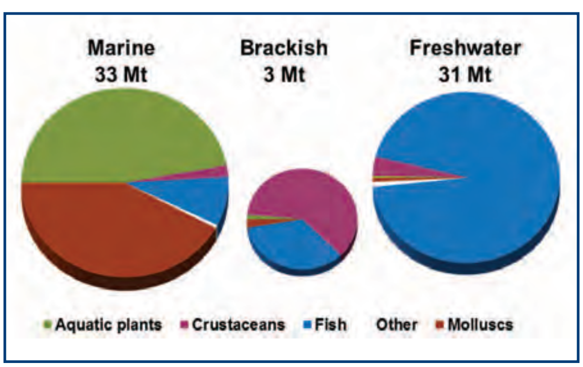
Priority 1 – Domestication. The lack of domestication in aquaculture has placed us many years behind terrestrial animal farming. For many if not most aquatic species, we are still hunting for wild breeders or seed with all the consequences of introducing a lot of variability, i.e. a year of good performers versus a year of poor stock, eventually carrying parasites or even commensals that can turn into nasty pathogens under farm conditions.

Priority 2 – Seed Production. Although many billions of fish and shellfish offspring are produced in more or less sophisticated hatcheries, seed production of delicate aquatic organisms remains a challenge. The predictability of production and especially cost-efficiency can be improved a lot. Consider the example of seabass and seabream hatcheries in the Mediterranean, a sector with an annual turnover of more than 150 million euros. With current levels of survival of only 20 percent at 60 days after hatching, there is much room for improvement. This is not only a concern from a cost-efficiency perspective but also for environmental and overall sustainability reasons.







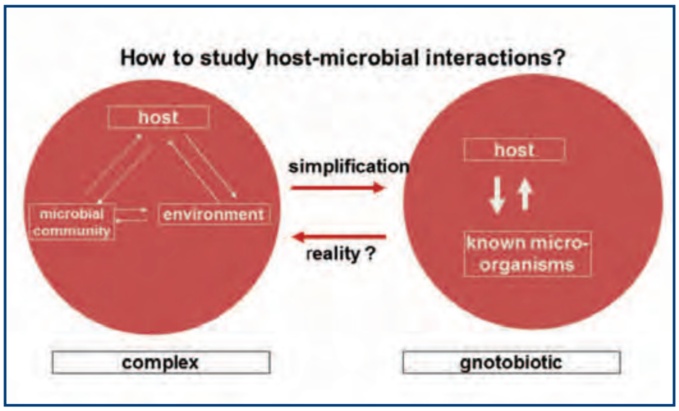


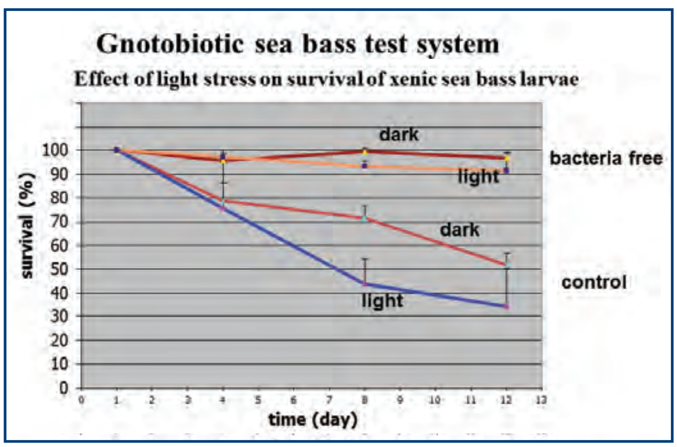
FROM TOP TO BOTTOM. FIGURE 10. *Contribution of aquaculture to world food-fish consumption in 1970-2008 (courtesy Rohana Subasinghe, FAO-Rome, 2010).* FIGURE 11. *Earth's surface distribution and uses (courtesy Patrick Cunningham, as presented at the workshop "Knowledge Based Bio-Economy towards 2020", Brussels, 14 September 2010).* FIGURE 12. *Global primary production and food supply (after Field et al. 1998 and Duarte et al. 2009).* FIGURE 13. *Aquaculture production by species group and environment (FAO - the State of Aquaculture 2010).*

Microbial interference is often cited as the source of problems. Harmful bacteria, not necessarily virulent pathogens, that develop during live food production (microalgae, rotifers, *Artemia*) are carried along with live food into larval rearing tanks where they can interfere with the sensitive physiological development of larvae, especially that of digestive and immune systems. This study of host-microbe interactions requires a different approach from the former "black box" research approach that did not allow the development of reproducible results (Fig. 15).

Interactions between host, environment and microbial communities are just too numerous and complex to unravel under *in vivo* conditions. Similar to work performed with terrestrial animals (mice, pigs and sheep) farmed in bacteria-free conditions, first results with aquatic species prove that much fundamental progress can be made when working with so-called gnotobiotic model systems. To illustrate, European seabass larvae were cultured under bacteria-free conditions for 12 days and fed with bacteria-free, live brine shrimp *Artemia* nauplii (Fig. 16). Under so-called optimal commercial conditions, the classical greenwater approach, unpredictable mortalities occur in the first weeks of larval development and result in large variation in performance. In contrast, bacteria-free conditions are much more stable and result in consistent and very high survival rates throughout the first weeks of larval development. Exposure of larvae to stressful conditions, such as intermittent cycles of light and dark, can result in extra mortalities. Larvae kept under bacteria-free conditions display minimal effects to this kind of stressor. It could be that, at mouth opening, bacteria enter the intestine and activate the wrong triggers, resulting in a negative effect on the physiological condition of larvae.

1. Complete independence from natural stocks through **DOMESTICATION**
2. Improved / more cost-effective **SEED PRODUCTION**
3. Better targeted **SPECIES SELECTION**
4. Development of more efficient stocks through **SELECTIVE BREEDING**
5. More **MICROBIAL MANAGEMENT** for more sustainable production
6. Better understanding of **IMMUNE SYSTEMS** in vertebrates and invertebrates
7. More **INTEGRATED PRODUCTION SYSTEMS** for plant and animal farming
8. **COASTAL AND OFF-SHORE FARMS** of food and energy
9. Full independence from fisheries stocks for **LIPID AND PROTEIN INGREDIENTS** in aquatic feeds
10. More attention for **INTEGRATION** of restocking activities with **FISHERIES** management
11. **SOCIETAL LEVERAGE:**
    1. multi-stakeholder interaction
    2. International cooperation on a win-win basis





FROM TOP TO BOTTOM. FIGURE 14. *Priorities for future aquaculture (from Plenary Lecture by Patrick Sorgeloos "Resources, technologies and services for future aquaculture: a needs assessment for sustainable development" at the Global Conference on Aquaculture, 22–25 September 2010, Phuket, Thailand).* FIGURE 15. *Gnotobiotic culture systems for the study of host-microbial interactions (courtesy Peter Bossier, Laboratory of Aquaculture, Ghent University, 2010).* FIGURE 16. *Survival of European sea bass larvae in gnotobiotic versus standard larviculture control systems in dark and light-stressed conditions (courtesy Peter Bossier and Kristof Dierckens, Laboratory of Aquaculture, Ghent University, 2010 and Dierckens et al. 2009).*

These are valuable empirical observations that can now be further analyzed with molecular tools to unravel gene expression in developing larvae exposed to well-defined conditions.

A multidisciplinary research approach for the study of the possible effects of the magic greenwater technique in fish and shellfish larviculture, as outlined in Figure 17, is needed in different areas of aquaculture research. Only then we can gain more basic insights of underlying biological mechanisms to allow the development of appropriate solutions for application under practical farming conditions.

The ultimate aim should be to develop new hatchery practices (e.g., with regard to microbial steering) and apply innovative products (e.g., substrate for specific bacteria or signal molecules to disrupt their virulence triggers) that ultimately result in more cost-effective hatchery production of certified seed with improved characteristics.

Priority 3 – Species Selection. We need more proactive attention for species selection. We should not aim to increase the number of species farmed but rather be more selective in identifying suitable species for mass markets, such as *Pangasius*, and niche species catering to local markets where value-added products might be in good demand. Working with a more limited number of species should also allow more focus in research.

Priority 4 – Selective Breeding. Selective breeding is another area where we are far behind terrestrial plant and animal agriculture. There is great need to invest in breeding research for key aquatic species. For example, good progress has been made with selective breeding of white shrimp in recent years.

Many of the tools that have been developed in plant genomic

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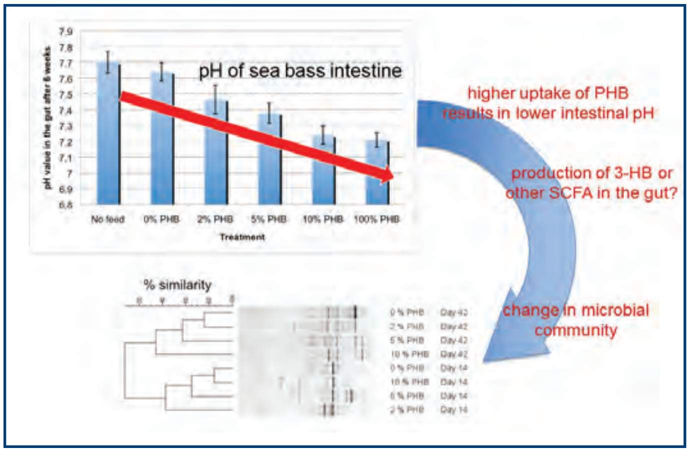

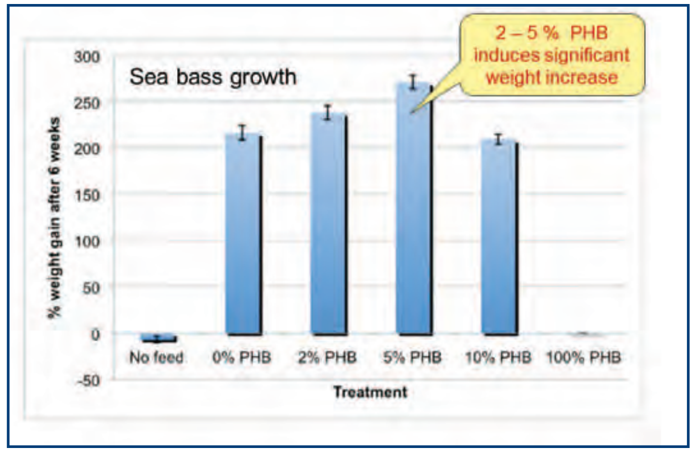

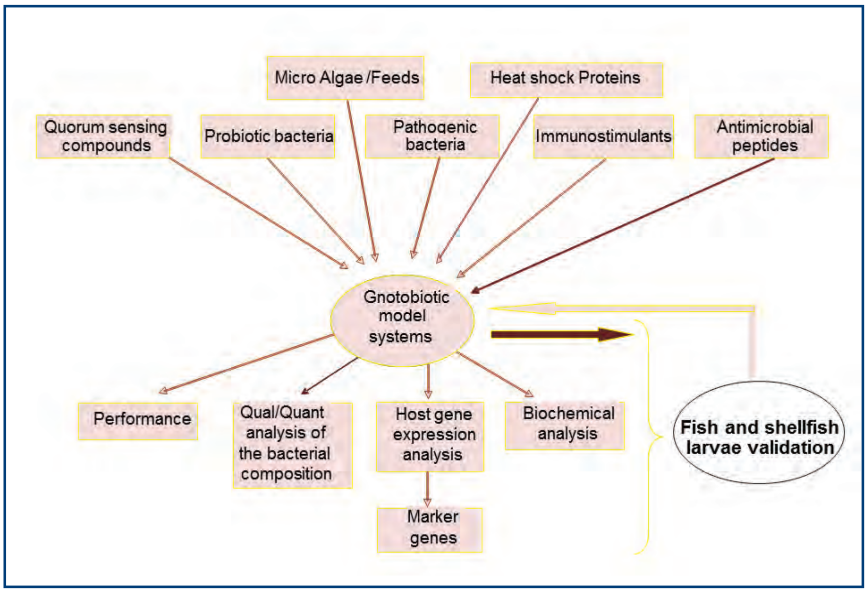

ABOVE, FIGURE 17. *Figure 17. Research approach for the development of innovative microbial management systems in fish and shellfish larviculture.* TOP, FIGURE 18 AND 19. *Dietary effect of polyhydroxybutyrate (PHB) in sea bass nursery rearing (after De Schryver et al. 2010).*

breeding can be applied to aquatic animals to accelerate selection. Genomic sequence comparison with model species can help to identify best breeding aims. Sooner rather than later we can think about selecting and even designing new varieties that are better adapted to, for example, the adverse effects of climate change.

Priority 5 – Bacteria in Aquaculture. Thanks to the availability of new genomic tools, a lot of research has been initiated in recent years on the role of microorganisms in agriculture, in human health and food quality, *inter alia*. Because water is an ideal environment for microbial development, the role of bacteria – beneficial and harmful – in aquaculture systems requires much more research attention. Their role in the aquatic environment, especially in water quality control but also how they convert organic waste matter into nutritious biomass. These so-called bioflocs are rich in protein and often also high in specific micronutrients, such as omega-3 fatty acids and vitamins. Controlled biofloc production could greatly contribute to increased sustainability and more biosecure production systems, through reduced needs for water exchange and more efficient feed conversion. Rather than limiting its application to production of tilapia and shrimp, bioflocs can be more effectively used in multi-species farming. For example, intensive fish or shrimp production and the bioflocs these generate can be integrated with the farming of filter-feeding species that could convert bioflocs into mollusk meat or brine shrimp biomass that can easily be harvested for use as food ingredients for other species.

As with terrestrial livestock (chicken, pigs and cattle), host-microbe interactions can greatly influence production results not only at the start of larval development as discussed earlier but also in juvenile and adult stages. Such interactions can be applied to improve the health status of animals or control the bacterial flora, both in quantity and composition, to impact animal performance. For example, reducing the digestive tract pH of juvenile seabass from 7.7 to 7.3 by delivery and release of a mild organic acid (e.g., butyric acid) results in a significant shift of the microbial composition, as documented by DNA fingerprinting of bacteria, and a larval growth increase of about 20 percent (Figs. 18 and 19). These empirical observations require further nutrition research to reveal the functional role of bacteria in the animal's digestive physiology and most probably its immunology.

Priority 6 – Health Control. Our knowledge of health control in aquatic animals remains very limited, especially in invertebrates, crustaceans and mollusks. Much more basic work using molecular tools should improve knowledge of activation, good functioning and disruption of the animal's immune systems. Only then we will be able to move from empirical trial and error practice today – with all kinds of putative immunostimulants, prebiotics and probiotics – to knowledge-based strategies and products. With some species (e.g., Atlantic salmon), knowledge is well advanced and different generations of vaccines have proven their efficacy. However, vaccines are not a magical solution and scientific progress should only be part of a more concerted effort in health management.

Priority 7 – Ecological Aquaculture. When addressing sustainability issues in future aquaculture developments we must embrace ecological principles and reconsider the monoculture

ABOVE LEFT, FIGURE 20. *"Extractive" versus "fed" aquaculture practices.* ABOVE RIGHT, FIGURE 21. *Coastal shrimp farm in Thailand.* LEFT, FIGURE 22. *Coastal cage farming of yellow croaker in China (inserts: use of 'trash' fish as food source).*

approaches that we have increasingly introduced with the modern forms of business aquaculture. In terrestrial farming a paradigm shift is needed to meet food production needs in the decades ahead, with limited land availability and especially scarce freshwater reserves for plant and meat production. Hydroponics integrated with high-density fish farming in recirculation systems is being evaluated on various continents. Several research agencies are considering demonstration research of integrated farming of terrestrial and aquatic plants and animals, taking advantage of modern tools for sensor-controlled nutrient dosing and heat, energy and water recovery. However, moving away from monoculture will not be easy because the socioeconomic consequences of integrating different food production sectors requires important mentality shifts.

Priority 8 –Marine Aquaculture. As mentioned previously, the oceans and seas make up 70 percent of our global aquatic bioresources. We cannot delay any longer to pay much more attention to the marine environment. It is an opportunity to satisfy seafood market needs and offer aquatic proteins as an alternative to terrestrial meat as a more sustainable food source for humanity in the decades to come. Several think-tanks have concluded that, by the middle of this century, there might not be enough fresh water to continue producing mammalian meat. The time has come to thoroughly reflect about future directions in coastal and offshore farming.

To make a simplistic classification of present-day aquaculture practices, there is so-called "fed aquaculture," e.g., the farming of fish and crustaceans in cages and ponds, and there is "extractive aquaculture," with seaweeds removing inorganic nitrogen and phosphorus and filter-feeding mollusks grazing on organic nitrogen and phosphorus (Fig. 20). Pressure on the environment is very clear in open-flow pond farming of shrimp or fish (Fig. 21) or when trash fish (or formulated feeds) are used in high-density fish cages in shallow coastal waters (Fig. 22).

The empirical practices established in a few coastal regions of China, where initially (starting in the 1950s) only seaweeds were farmed (Fig. 23), are instructive. Later, when mollusk seed could be produced in hatcheries, seaweeds and different mollusk species were grown together. Over the last decade marine fish cages have been added. Some of these areas are vast, encompassing tens of square kilometers of sea surface (Fig. 24). Nutrient flows in these polyculture systems are such that most of these habitats can be classified as oligotrophic environments.

Multi-tropic aquaculture is definitely a part of the future but a lot of effort is required to motivate farmers and industries that operate today in a very competitive world. With what we see in China, we do not have to reinvent the wheel but rather should try to cooperate. Governments should be more proactive in facilitating demonstration projects in cooperation and joint management with private companies. China is furthermore experimenting with polyculture systems with benthic species – different mollusk, sea urchin and sea cucumber species – that benefit from nutrients accumulating under mollusk longlines or fish cages.

The role of seaweeds in bioremediation (Fig. 25) is often overlooked. If the Chinese had not engaged in massive seaweed farming since the 1950s, when domestication and seed production of brown and red algae became feasible, coastal eutrophication today would have become much more critical. Close to ten million tons of seaweeds are harvested every year along China's coast, equivalent to hundreds of thousands of tons of nitrogen and phosphorus that

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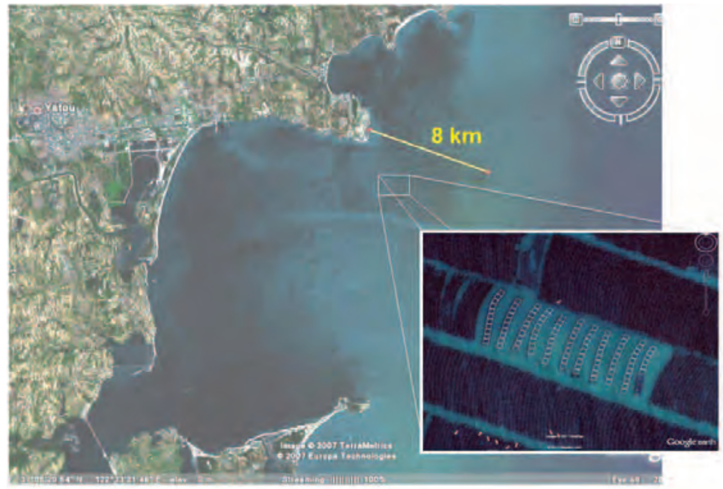


TOP LEFT, FIGURE 23. *Coastal farming of fish (Japanese flounder) in cages, mollusks (scallop, abalone) and sea cucumber in lantern nets and seaweed (Laminaria and Gracilaria) on long lines in the Alian Bay in Shandong province (China).* TOP RIGHT, FIGURE 24. *Aerial view of the Sanggou Bay in Shandong province, China (insert: close up of fish cages surrounded by seaweed and mollusk long lines).* ABOVE, FIGURE 25. LEFT: *Laminaria harvest.* RIGHT: *Seaweed farming on long lines in the Alian Bay in Shandong province (China).*

are removed on an annual basis. Without a doubt, this aquaculture activity has significantly alleviated coastal eutrophication.

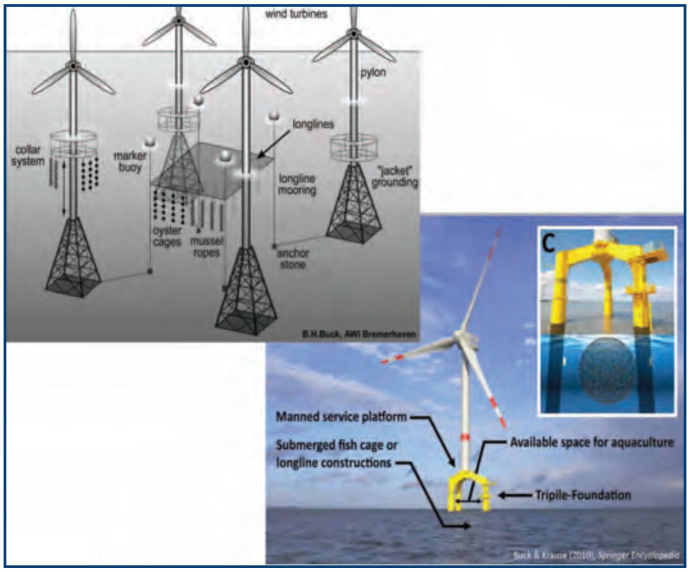
When talking about the need and potential for more integration we should not limit ourselves to aquaculture activities only. New offshore infrastructures are being built for generating energy from wind or waves. This infrastructure could provide facilities for easy integration with cage and long-line farming of fish, mollusk and seaweed species (Fig. 26). Energy and food production sectors could develop interesting synergies.

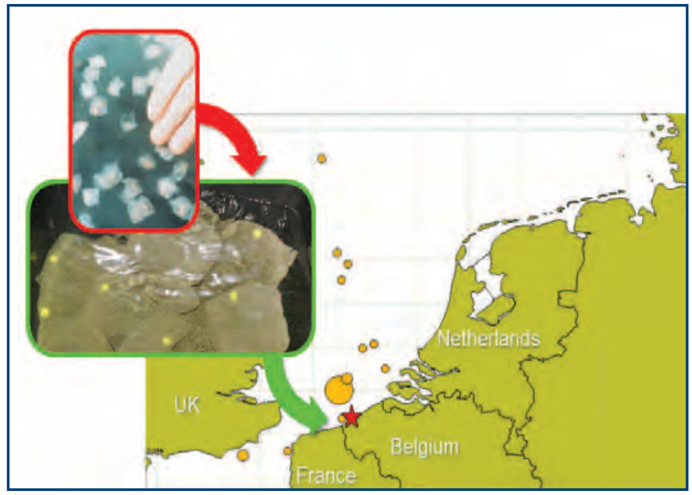
Priority 9 – Replacements for Fishmeal and Fish Oil. Based on recent progress, we can be optimistic that the fishmeal and fish oil paradox in aquaculture is gradually being solved. Much work however is still needed and we might also expect that the approaches followed will differ from region to region.

Priority 10 – Stock Enhancement Programs. More attention is needed to devote to the possible integration of restocking activities with fisheries management. Although this particular FAO Bangkok 2000 recommendation was poorly met, there is much empirical evidence of the benefits of restocking projects in freshwater and marine environments. However, there is also much criticism about possible impacts on biodiversity and overall cost-effectiveness. Fisheries scientists and aquaculture researchers need to come together to engage in a multidisciplinary R&D program to better evaluate the technical and socioeconomic potential, especially now that we have much better analytical tools to evaluate such large-scale experiments. Fishermen are more than eager to cooperate in such studies. For example, local fishermen recaptured 30 percent of released turbot that had migrated within one year from Belgium to all over the North Sea (Fig. 27), indicating excellent support for this rather modest program.

Meeting our Goals

Societal leverage will be critically important to accomplish the priorities outlined above. A multi-stakeholder approach, involving all key players, is needed to decide on priorities and to make sure that all noses are turned in the same direction. International cooperation with due respect for cultural differences is a must and will require more efforts to reach compromises. I am convinced that there are many opportunities between North and South, East and West to develop win-win opportunities, even in sectors where today it looks like tension is building up. One example is the recent creation of the European Aquaculture Technology and





ABOVE, FIGURE 26. *Coastal and offshore farms for food and energy (courtesy Bela Buck, AWI-Bremerhaven, 2010).* TOP RIGHT, FIGURE 27. *Recapture success of turbot restocking project in the North sea (after Delbare and De Clerck 2000).* BOTTOM RIGHT, FIGURE 28. *European Aquaculture Technology & Innovation Platform EATiP: listing of stakeholders.*

Innovation Platform (EATiP). This umbrella organization of all key stakeholders in European aquaculture (Fig. 28) is promoted by the European Commission and aims to establish a strong relationship between aquaculture and the consumer, with the assurance of developing a sustainable industry and fulfilling its role in society at large. With business leaders in the driver's seat and involving all stakeholders, EATiP has recently finalized its vision document Aquaculture 2030 and, based on this, its Strategic Research Agenda. Speaking with one voice, EATiP wants to ensure better leverage to address particular issues, such as legislation and international cooperation. Through its recently established international desk, EATiP wants to become more proactive in exploring and facilitating win-win interactions with other regions in the world, for example with Asian partners in view of the very good relations established between both regions by the ASEM aquaculture platform (see www.asemaquaculture.org). More of these multistakeholder platforms can be set up to stimulate regional interactions in aquaculture.

Notes

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