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Development and diversification issues in aquaculture. A historical and dynamic view of fish culture diversification

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SUMMARY – The limitations on fisheries, the increasing demand for aquatic products, and the constant improvement of the biological knowledge on aquatic animals provide interesting opportunities for the domestication of new finfish species. The major historical landmarks of this recent activity are briefly described, emphasizing the cases of trout and salmon farming, yellowtail and marine species. Recent trends in temperate or tropical areas are described, discussing and addressing the major questions affecting finfish aquaculture development. Different aspects of the market (price, quantities), the evolution of product characteristics due to improved rearing practices and the consumer attitude are discussed through practical examples. Thus, diversification not only justifies significant research efforts, offering a solution for facing declining profits, but it has to be considered within a competitive context where some questions are finally addressed, i.e. the relation with the environment or the farming of introduced vs. endemic species.

Key words: Aquaculture, finfish farming, diversification, market, introduced species.

RESUME – *"Développement et diversification en aquaculture. Vision historique et dynamique de la diversification en pisciculture". La limitation des captures par pêche, la demande croissante en produits de la mer, ainsi que l'amélioration croissante des connaissances de la biologie des espèces aquatiques, sont autant de facteurs militant en faveur de la domestication de nouvelles espèces. Les principaux jalons historiques du développement de la pisciculture, une activité récente par rapport aux débuts de l'élevage d'espèces terrestres, sont brievement décrits, avec une attention particulière pour le développement de la salmoniculture (truites et saumons) et des poissons marins (sériole et espèces européennes). Les tendances récentes de la pisciculture en milieu tropical sont décrites, permettant de lister les principales questions qui se posent pour l'avenir de cette activité. Différents aspects du marché (prix, quantités), l'évolution des caractéristiques du produit en liaison avec l'amélioration des pratiques d'élevage ainsi que de l'attitude des consommateurs sont discutées à travers des exemples concrets. La diversification en pisciculture, qui justifie d'importants efforts de recherche, offre des solutions permettant de faire face à la baisse des cours sur les espèces déja produites, mais doit être considérée dans un contexte de concurrence globale, dans lequel les relations de la pisciculture avec l'environnement et le débat sur l'introduction d'espèces non indigènes sont évoqués.*

Mots-clés : *Aquaculture, pisciculture, diversification, marché, introduction d'espèces.*

Introduction

Compared to land-based agriculture, established around 12,000 years ago, aquaculture is a very recent farming activity. Like all other animal productions, it relies on the concept of "domestication" of wild species in order to breed and produce them under human control for various purposes: food, clothing material, working power, company. Historically, domestication was made possible by: (i) the ability to capture wild young juveniles; (ii) the capacity to maintain them in semi-captivity; (iii) the availability of forage to make them grow; and (iv) the learning of social and reproductive behaviour so they can reproduce in captivity.

But unlike terrestrial environments, aquaculture has to face additional difficulties to establish domestication of wild species, due to the characteristics of the aquatic environment: observation of animal behaviour is difficult, and the biology of underwater swimming animals has remained unknown for a long time. Keeping wild fish in captivity appeared much more difficult than fencing ruminants in a grazing area, as more generally, the satisfaction of basic biological requirements for which scientific knowledge was non-existent or weak: access to oxygen which implies water circulation and renewal, appropriate feeding, and creating favourable conditions for reproduction. That is why it took such a long time – *about 8500 years after the beginning of agriculture* – to establish the basis of domestication for aquatic species. It is not surprising that the first species to be domesticated were freshwater fish, easy to isolate from the main water systems, naturally self-feeding and freely reproducing in ponds.

Historical landmarks

Early days

Evidence of some kind of control over the reproduction of captive Nile tilapia (*Oreochromis niloticus*) in irrigation ponds is suggested 1500 years BC in Egypt, by paintings and bas-reliefs found in Theban tombs. Shortly after, carp culture techniques were progressively developed in China, in association with irrigated agriculture, as described by Fan Li 500 years BC. From this early period, carp culture progressively developed both in Asia and central Europe around the 15th century.

It took about 3 millenniums to evolve from the first practices of fish domestication to the discovery of artificial trout fertilization around 1750 in Europe. One more century was necessary before the technology could be rediscovered and extensively used for trout and salmon river stocking and wide dissemination throughout the world.

Initially found only in the Northern hemisphere, salmonid ova – European and North American species of trout and salmon – were intensely shipped to all parts of the world during the second half of the 19th century, to establish acclimatized populations, then a century later, for commercial farming.

Trout farming development

Being the first artificially reproduced fish species, trout provided the first opportunities to develop primitive types of rearing practices in captivity, using earthen ponds and fresh feeds. Initially, there was no established fishery, and thus *no existing market* except in the immediate vicinity of rivers, where trouts were caught and traded. It is interesting to note that when farming really started, it took place almost everywhere with one species only: the North American species of rainbow trout (*Oncorhynchys mykiss*) introduced all over the world, rather than with the local endemic species *Salmo trutta*, *Salvellinus fontinalis* or *S. alpinus.* Production expanded rapidly in Europe at the end of the 60s, towards more intensified and highly mechanized production, and it then expanded to Chile which became the first world producer.

Salmon farming

At the end of the 60s, the Atlantic salmon had become a rare and expensive fish, mainly exploited by recreational fisheries and a few fixed nets, while the world market was relying mainly on Pacific salmon commercial fisheries.

Stimulated by the success of the neighbouring freshwater trout culture in Denmark, the idea of salmon farming in the sea arose in Norway in the 50s. A long experience of smolt production for river stocking allowed the first trials to extend the farming of the species in Norwegian fjords. Sheltered sites provided an ideal environment to develop the production, using the cage technology developed in Japan, and the abundant trash fish material provided by the dynamic Norwegian coastal fishery.

After ten years of R&D, the first significant production of 100 tonnes was achieved in 1970, giving birth to a very dynamic and powerful industry. From 4000 tonnes in 1980, the Norwegian production boomed to 140,000 tonnes in 1990, then expanded very rapidly both in Norway and other European countries, of which Scotland is the second producer. Finally the activity spread to North and South America and even Australia, where Atlantic salmon had been introduced. Today, more than 98% of the Atlantic salmon found on the market comes from farming.

Marine fish reproduction

Following the early works on trout, there was a strong interest in France to promote research on marine biology, through coastal laboratories hosting academic studies on ecosystems and marine biology. Within this framework, and following the works carried out on trout reproduction, many scientific studies were devoted to the reproduction of marine fish between 1848 and 1914, mainly in the Laboratory of the College de France in Concarneau. The works, applied to several marine species such as sole, turbot and cod, provided very valuable scientific documents on larval development of sole and turbot (by Roule, Fabre-Domergue, Bietrix, Anthony, etc.). However, commercial applications to mass production of captive fish, or large restocking programmes failed to develop both in Europe and North America. Subsequently, scientific works were progressively abandoned after the First World War.

The next step forward was made in Japan, with the first attempts to farm yellowtail to commercial size, only using fry captured from the wild, reared in floating enclosures and fed on trash fish. Production developed rapidly between 1960 and 1985 to stabilize around 150,000 tonnes. Forty years after the first trials, production still relies, to a large extent, on the capture of wild juveniles, and hatchery contribution remains limited.

The first case of control of the entire rearing cycle of marine fish was achieved in Japan during the 70s with the Japanese bream (*Pagrus auratus*), the first species to be artificially reproduced from captive brood-stock. Using the same on-growing technology that was used for yellowtail, aquaculture production spreading in the southern part of the archipelago rapidly exceeded that of capture fisheries.

The next step occurred in Europe in the mid 80s when the hatchery technology for seabass (*Dicentrarchus labrax*), seabream (*Sparus auratus*) and turbot production of juveniles became established after 15 years of public research, mainly in UK and France. Once the bottleneck of juvenile availability was solved, production then spread throughout the Mediterranean basin and rapidly expanded to exceed 100,000 tonnes in 2000. Almost simultaneously flatfish culture took off, both in Europe with turbot (*Scophtalmus maximus*) – while the efforts to farm sole failed to result in commercial applications – and Japan with the bastard halibut or hirame (*Paralychtys olivaceus*).

Recent achievements

Tropical marine fish culture

While tropical inland aquaculture has already a long-standing tradition, with the development of tilapia and tropical catfish production, marine fish culture is relatively recent and has appeared only over the last 15 years, especially in South East Asian countries. The main existing activity relies today on the production of the tropical seabass or barramundi (*Lates calcarifer*), an amphihaline coastal species found in the Indian and Pacific Oceans.

Production really took off at the beginning of the 90s with increasing activity in the ASEAN (Association of South East Asian Nations). Still modest, the overall production is probably situated now between 20,000 and 30,000 tonnes. The hatchery technology is now rather well controlled, even if the incidence of nodavirus during juvenile production remains high.

Grouper aquaculture has stimulated a lot of interest from different countries as well as the production of Lutjanids. These species provide today something like 5000 to 10,000 tonnes a year, with large yearly fluctuations. They are due to the fact that most production is realized with captured wild juveniles, while the hatchery technology remains incompletely mastered. Both these products are consumed on local markets of south-eastern or eastern Asia, benefiting from attractive prices for fish delivered live to the restaurants.

Within this scope, the Chinese production, very rarely described in the literature, appears to undergo a very rapid development with the above-mentioned species completed by several sciaenid fish like the very popular yellow croaker, as well as other introduced species mentioned later.

An interesting example of recent progress in the field of tropical aquaculture is that of the red drum (*Sciaenops ocellatus*), a sciaenid species found on the Atlantic coast of southern United States and the Gulf of Mexico. This amphihaline species has stimulated a fair amount of scientific works in the US, in relation with programmes aiming at restocking with hatchery- or pond-produced fry to restore and develop coastal recreational fisheries. But in spite of repeated attempts, aquaculture development has not significantly developed in southern United States. Introduced by the government of La

Martinique in the early 80s as a part of a programme aiming at the assessment of the aquaculture potential of various species of the Caribbean area, the species surprisingly expressed an excellent aquaculture potential in an environment different from its original range, characterized by constant high temperatures (27-29°C) and salinity (37‰). The species has been introduced in the eastern Mediterranean and the Red Sea, Taiwan and China. In this latter country, even if no real statistics are available, it is estimated that it provides a significant contribution to the 300,000 tonnes of marine fish nei, announced by the country in international statistics. The frequent presence of live red drum displayed in the restaurant aquariums of all main big cities suggests that this production may be a few tens of thousand tonnes. More recently, red drum has been introduced by the local administrations of the islands of La Réunion and Mayotte in the South Western Indian Ocean, where the production should reach several hundred tonnes in 2001.

Tuna aquaculture

One of the most significant achievements of the last 5 years is the very rapid development of bluefin tuna aquaculture. This production has its origin in the first trials conducted in Japan by Kinki University during the 70s with *Thynnus thynnus orientalis*, and has had a rapid expansion in Australia – initiated in 1994 – with the south Pacific species (*Thynnus maccoy*) after unsuccessful trials initiated in Nova Scotia (Canada) in the late 80s with the Atlantic bluefin tuna (*Thynnus thynnus*). Even more recently an extremely rapid and significant development of the production of Atlantic bluefin tuna raised in Spain, while other projects (of lesser amplitude) are blooming in Croatia, Italy, Malta, Morocco and Mexico. All these projects are characterized by the same two aspects:

(i) The activity is based on the fattening and growth of captured live tuna in large sea enclosures. The animals come from the established capture fishery, and provide the fish available in the neighbouring migration routes. This covers variable practices, using small size tuna of just a few kilos (Japan), 20-30 kg in Australia or larger sizes (100-200 kg in Spain). The rearing period may vary from several years for small fish to a few months.

(ii) Almost all the aquaculture-produced tuna today is destined to the highly demanding Japanese market which provides attractive prices.

Global production released on the international market is probably approaching 20,000 tonnes, a very spectacular increase in just a few years. In addition to market regulations, sustainability of tuna aquaculture production will rely on the development of stable and guaranteed availability of tuna juveniles. Thus, in the light of rather preoccupying evolution of the stocks and associated resulting quotas, the capacity to provide hatchery reared "domesticated" juveniles appears as a high priority objective. The results obtained by the Japanese institutes – whose captive F1 broodstock reaching the critical age of seven years, may well provide the first "domesticated" F2 generation in the summer of 2001 more than 20 years after the first research started – show the difficulty of the approach, which would justify ambitious international research programmes.

Some remarks and questions

Why separate mass production and niche species?

An artificial and temporary distinction?

When considering prospects for new species, the "type of product" to farm often refers to its anticipated position on the market. Then the alternatives between "niche market products" (NMP = small quantities, high price) and "large market products" (LMP = moderate to cheap prices) are expressed. This duality exists, but when considering the time and resources necessary to establish the technical basis for a new production, is this question really pertinent? It is evident that to face the costs of research, and new technologies, the candidate species must benefit from an initial price which will allow potential profit margins. But the characteristics of an NMP are its high price, necessarily linked to limited supplies (often a few hundred tonnes). Thus, if successful, the production of an NMP will have to face a rapid decline of market prices, which in turn will require large volumes in order to reduce the production price. Then it will no longer be an NMP.

Moreover, when looking at the historical development of the Atlantic salmon industry, and its influence on domestic markets, such as that of France, one may note that from being a *rare and expensive item* in 1970, close to a position of *niche product* (imports of 1000 tonnes in 1970, compared to 10,000 tonnes for Pacific salmons), this fish has become a *commodity product*, with more than 90,000 tonnes imported in 1999, in direct competition with other fishery products of the same price.

Technical characteristics of an aquaculture product evolves with time

Between the initial situation of the first productions of new aquaculture products reaching the markets – using infant non-optimized technology – and what it becomes once the industry has developed and stabilized, there are obviously important differences. That was the case for the seabass industry, first providing only portion-size fish of 350-450 g, corresponding to the highest demand, but also to what the industry could provide considering biological and technical constraints. After 10 years, a significant improvement of technical performance was made, including growth and food conversion, the industry began to provide larger fish (800 or more than 1200 g), corresponding to different segments of the market (other than niche markets) and opening new prospects. This evolution has also been observed in the trout, over a 20 year period, from a situation of an exclusive standardized product, the white flesh-portion size trout, to a much more diversified product, red fleshed and of larger size, opening up many possibilities for transforming the product (steaks, fillets, smoked, prepared, ready to cook, delicatessen, etc.).

Evolution of the market demand

In the meantime, the market itself has shown a progressive evolution, requiring diversified products under diversified forms. The once unique round gutted fish, still appreciated by some regional markets in Europe tends to be completed, or partially replaced by several references for the same product: steaks, fillets, skinned fillets, pre-packed, brochettes, cold or heat smoked, marinated, ready to cook, etc.

Interactions within aquaculture and between aquaculture-fisheries products

Salmon vs. trout?

Historically being different types of products, a cheap white fleshed portion-sized trout as opposed to valuable large size salmon, the two products found their place in different market segments with no or only limited interactions. The major changes which have occurred in the trout industry, especially the production of large size fish, sometimes at the extra cost of genetic control of the maturation process (sterile monosex triploids), have lead to the "creneau" of large red flesh salmonids, driven by the salmon image. Thus, the interactions between these emerging new products – especially large size red flesh trout – produced either in freshwater or seawater environments became more acute. The rapidly declining prices of salmon, associated with the spectacular evolution of its production, made this interference and competition even more active.

Salmon vs. marine fishery catch?

From a situation of a product rarely available in a fresh form – thus very expensive and with only limited interaction with other fishery products – the Atlantic salmon underwent a huge production increase, and has become a major product in the range of products distributed fresh, and more recently even in the frozen fish commodity markets. Thus, salmon took a major place among the fishery products, and its wide availability as well as its cheap price affects necessarily the consumer choice against other products of the same range.

Nile perch vs. tropical seabass?

We have seen earlier that tropical seabass (*Lattes calcarifer*) production is increasing in Asia/Oceania, mainly for the satisfaction of local markets, especially the live fish segment for restaurants. But questions frequently arise on the export potential of this interesting product to more distant markets, especially the European ones. Due to the similarity and resemblance to its freshwater cousin the Nile perch (*Lates niloticus*), extensively fished from the waters of Lake Victoria in Eastern Africa, and whose landings have been consistently increasing over the last years, doubts are expressed about the capacity of the aquaculture fish to compete in price and characteristics with the large wild fish, available in large quantities, under very clean and guaranteed forms to the European market.

Cheap white fish fillets from aquaculture origin vs. marine fishery catch?

Moreover, *Nile perch* sales have been gaining share of the retail market for fresh fillets, where it is often presented together with other white fish fillets from marine catch origin, with which it competes efficiently in the range of medium price products. In the same way, the growing supply of *Tilapia* fillets tends to complete this panel of white fish fillets, extending the possible choice of the consumer towards cheap or medium price fillets as an alternative.

The mirage of export market captive niches

The motivation for new aquaculture speculations is often triggered by the very attractive prices offered for some specialized products, given a situation of shortage in specific domestic markets, especially that of Japan: abalone, sea urchin, *Fugu* fish or *tuna* are common examples of new productions initiated in different countries and all aiming at the Tsukigi market of Tokyo or that of other large Japanese cities. Some of these choices may well be pertinent, but the existence of high market prices at a given time, for a certain type of specialized product, should not be considered as a unique determining factor.

First, these extremely high prices are conditioned by the situation of high demand or even shortage on highly specialized markets, and are generally associated with strict quality reference criteria, and apply to a limited amount of products. If the initiatives multiply around the world and all focus on the same objective, there is no doubt that not everyone will succeed if the proposed quantity was approaching the capacity of the target market. Moreover, for export products regulated by world trade constraints, currency fluctuations may result in extremely profitable periods, as well as very difficult ones; as illustrated by the evolution of the value of the Japanese Yen against the Dollar over the last years.

A similar attitude was observed in the first years of the development of Mediterranean aquaculture (1988-1994), where all producers developing seabass farming were aiming at the Milan market in Italy, due to its extremely high prices, often forgetting that these prices were operating for a demand of 1500 tonnes per year, with seasonal fluctuations. As a result, the rapidly expanding production had to face a very rapid erosion of market prices due to the saturation of the target market. Thus, competition between producers became more drastic.

Species transfers and introductions

The choice of species for aquaculture development must address the alternative between the farming of local or introduced species. Historically, one has to admit that many valuable productions arose from the introduction of non-indigenous species to European waters (oysters, rainbow trout, Siberian sturgeon, Manilla clam) or of European species to other areas (Atlantic and Pacific salmons in Chile, several species of scallops or marine fish). In certain cases, the introduction of a non-indigenous species, the Japanese cupped oyster (*Crassostrea gigas*), in France has been the only solution to maintain an oyster farming production in the light of the collapse of "local" Portuguese oyster (*Crassostrea angulata*) stocks due to a viral disease. A strong and justified concern exists now for further introductions, due to the emergence of the concept of biodiversity protection and of the "precaution principle". Thus, some questions remain.

The hazards of species introductions

In many cases, the ecological impact does not appear to have been important or measurable (admitting however that it may be very difficult to assess properly), especially when considering marine fish species. But other cases of transfer (freshwater fish, invertebrates, plants) resulted in unexpected effects on the ecosystem, the new species colonizing new ecological niches and competing with existing ones. In some cases, such as that of the introduction of the Manilla clam in European waters, this led to the explosion of self-reproducing populations, impossible to control, which in turn generated new economic activities for their exploitation.

The major risks associated with species transfers, relates to the accidental introductions of unexpected pests or commensals, which have occurred in many documented cases (fish, shrimps, etc.). This risk can be minimized by imposing adequate quarantine procedures, but probably not totally avoided.

Multiplication of research attempts with local species?

A general trend in favour of the development of aquaculture activities with *"local species only"* is now widely established. In some cases, these species may appear to be less adapted to farming in captivity (stress and disease resistance) than non-indigenous ones already domesticated elsewhere and chosen for their *"domesticability".* This is the case of salmon farming in British Columbia, where the introduced Atlantic salmon appeared much more appropriate for farming in Pacific waters than the local Pacific species (*Chinook* and *Coho* salmons). It is thus probable that if the BC salmon industry had restricted its developments to the endemic *Oncorhynchus*, it might not have been able to survive against the competition of imports from countries with a different choice: Chilean salmon (both Atlantic and coho salmon), for instance.

It has to be noted that the establishment of rearing procedures for a new species *always* requires several years of research and R&D before the first commercial productions become profitable. Even when considering species closely related to others whose domestication is already effective. Thus the question has to be raised before spending time and money in the possibly infinite multiplication of potential species for "domestication", compared to the alternative of a limited number of species, well adapted to farming in captivity, and whose genetic "progress", in terms of farming performance, will give them strategic competitive advantages. The scientific and industry communities are still discussing about this long-term issue, and answers may not be very clear.

The question may be raised about a few species, whose exceptional aptitude to farming should require some attention. In the case of *sciaenid* fish for instance, the extremely rapid development of red drum aquaculture (*Sciaenops ocellatus*) in several places of the world out of its own range – such as China and probably the Indian Ocean – will undoubtedly lead to massive exports towards the European markets. This will stimulate new demands from the consumer, opening new market segments for species which are at present in a situation for niche products. Thus, the opportunity to investigate the aquaculture potential of closely related candidate species (in this specific case: meagre – *Sciaena aquila*, corb – *Umbrina cirrhosa* or *U. canariensis*) compared to that of the alien candidate is clearly raised, in order to bring some strategically important answers to the proposals for introduction, especially for rearing in closed recirculated systems thus avoiding any accidental release to the environment.

Impact of farmed populations on natural stocks?

But even when restricted to local endemic species and with strong policies against any introductions, when the development of aquaculture is very successful and stimulates the multiplication of cage sites, the possible impact of farmed fish on local populations will be raised. This is, of course, the case in Norway and Scotland, where the density of farms, the number of fish raised and the amount of escapees, finally result in the presence of large amounts of escaped farmed Atlantic salmon on spawning grounds, possibly breeding with natural stocks. Knowing that the domesticated populations will progressively differ more and more from their wild ancestors, due to selective breeding plans, the impact on the wild stocks will be a reality. However, some geneticists consider that this effect may not be drastically detrimental to the wild stocks.

The same situation may well occur in the case of seabass and seabream in the Mediterranean where the magnitude of the farmed population is now 20 times larger than that of the wild stocks. If considering that 5% of the fish escape during the rearing period and that 50% of them survive up to the reproduction stage, aquaculture will represent a reproductive potential (in number of fish) corresponding to 50% of that of the wild population. Then just like in Norway, the frequency of farmed fish on spawning grounds may become extremely high in some intensively developed aquaculture zones.

The ultimate question: to farm or not to farm?

The development of the two previous alternatives within the emotional discussion about the choice of species for developing new productions – required by demanding consumers – shows that the question is not simple: (i) choosing introduced species presents a double risk: ecological and pathological; and (ii) choosing to farm local species leads, when successful, to significant impacts on the wild stocks.

Aquaculture – which is expected to be the only solution to maintain the contribution of aquatic products to human protein consumption – cannot be neutral and have zero impact on the ecosystem or the wild populations. So if it is irrationally considered that no impact at all should result from aquaculture practices – while any other primary production activity has, including fishing of wild stocks – then there is no aquaculture possible. So the question becomes clear: *to farm or not to farm aquatic environments?*

The development of food production will undoubtedly bring some changes in the existing ecosystem, just like all other human activities which contribute to the anthropization of the environment, including fishery exploitation of wild aquatic stocks.

Conclusions

Aquaculture products represent today between 15% and 35% of aquatic products consumed in southern European countries (one third for the French market). This share will continue to grow, regardless of the conflicts for development, with an increasing diversity of aquaculture products on the market. These products, which will provide strategically sound arguments like freshness and traceability, will have to proudly claim their "farmed" origin and demonstrate that the responsible practices for their production are environmentally friendly.

Thus, diversification in aquaculture is obviously an obligatory path of reflexion. But it should not lead to the conclusion that everyone will be able to benefit in a sustainable way from this evolution: diversification provides additional strategic opportunities for aquaculture but it should not be considered as the ultimate and immediate solution to restore profitability in a production system facing declining prices. Competitiveness will remain the main challenge, and prospects for sustainability have to include mid- or long-term evolution trends, and consider their competitiveness. Because only the strongest and best-performing will win in this long-distance race.

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