

AQUACULTURE: PRINCIPLES AND PROSPECTS

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Summary

The aquaculture of animal organisms has yielded 30.8 millions tons of fish, crustaceans, and mollusks in 1998 for a value of \$US 47 billion; this is 30% in weight of the total landing by capture fisheries (86.3 million tons). There is a continuum of aquaculture systems going from farming in open water (in association with fishing activities) to extensive production in fishponds, industrial farming releasing wastes in the environment and entirely recycled water systems. Most of the fish are sold round or gutted, and mollusks shelled but more and more products are processed, and consumers are looking for good quality products. The culture in cage and raceways will have to reduce the amount of wastes released and produce, maybe in a less intensive way, products of improved quality. There is probably some future for two main production systems: 1) the pond fish culture and intensive systems both with entirely recycled water completely independent of the environment. 2) Systems in open water: the culture of mollusks, which must continue as it is a guaranty of a safe environment, and the ranching approach, which requires technical improvement for rearing juveniles and clarification of its status (especially the ownership of the released and captured fish).

1. Introduction

This topic on aquaculture follows the one on fisheries and should be understood as the exploitation of living aquatic resources in a continuity of systems from capture to culture. Then the principle and prospects of aquaculture will be analyzed in relation with fisheries and agriculture. Aquaculture has permanently taken advantage of the concepts, approaches and technologies all well established in the culture of terrestrial plants and animals. Fisheries, aquaculture and agriculture yield eventually final products, which come in competition or in complements and which use the same technologies for processing, conservation or marketing and require the same kind of research. This introduction proposes a definition of aquaculture and describes the originalities of the art and the general principles, which will be detailed in specific articles later.

A definition of aquaculture and a comparison with fisheries was proposed by FAO (1989): “Aquaculture is the farming of aquatic organisms, including fish, mollusks, crustaceans, and aquatic plants. Farming implies some form of intervention in the rearing process to enhance production such as regular stocking, feeding, and protection from predators etc. Farming also implies individual or corporate ownership of the stock being cultivated. For statistical purposes, aquatic organisms, which are harvested by an individual or corporate body, which have owned them throughout their rearing period contribute to aquaculture, while aquatic organisms, which are exploitable by the public as a common property resource with or without appropriate license, are the harvest of fisheries”. There is in fact a continuum in the exploitation of aquatic living resources, from traditional hunting–gathering to sophisticated intensive rearing in entirely recycled water systems. A good example is given by ranching with production of juveniles in hatcheries sometimes under elaborate technologies to support the fisheries stocks but FAO exclude from aquaculture statistics those hatcheries sustained stocks.

Compared to agriculture the aquaculture presents some originality. The major difference is that the aqua farmer does not own or has limited right on the substrate and sometimes the space in which the production takes place as the water is an open access resource and in the sea the production sites are not permanently allocated. As domesticated and wild forms of a same species co-exist at the same time and the same water-body, the risks of genetic alteration of the wild forms exist. Another peculiarity of aquaculture is that most of the animal reared are cold blooded and in temperate zone the true growing period is restricted to 100–150 days⁻¹ year for instance for cyprinids. But, as they live in sustentation in water, aquatic animals spent less energy for locomotion than Tetrapods, and this results in a better feed-conversion rate. The farmed aquatic animals are often carnivorous; while many land farm animals are herbivores or granivores.

The process of domestication of terrestrial plants and animals began during the Neolithic in agriculture and it is just starting now for aquatic species (aquaculture). This late occurring mutation is due to the difficulty of access to waters especially in the sea, to establish properties, to see the animals. More recently the demand for farmed products increased due to the decline of capture fisheries. Aquaculture in open water is exposed to a large variety of risks: climatic variation, water pollution, changes in the environment such as bloom of toxic algae, and predators (poachers, and birds). At the same time some aquaculture activities, oyster farming for example, are witnesses of good quality water. Aquaculture starts to develop at a time of an increasing use of the environmental resources by an increasing number of users, and has to deal with problems of protection and conservation of common (non-appropriated) natural resources (water, wild species, and ecosystems).

2. Historical Perspective

A bas-relief of fish in Egypt Ancient is believed to show tilapia rose in a pond. In China most historical reports keep saying that fish culture started more than 3000 years ago. A monograph entitled *Treatise On Pisciculture* by Van Li dates back to 473 BC. The Chinese authorities have published a few pages translation in several languages of at least some parts of this document. It is not really a treatise giving recipes but rather general notes on the ways to get profit from the culture of fish in ponds. Historical reviews also report that during the Tang Dynasty 618–907 the catching, selling and eating of the common carp *Cyprinus carpio* was prohibited because its name Li sounded the same as the surname of the Emperor. Then the farmers turned to other species such as the famous phytophagous “Chinese carps” and elaborated the polyculture system at that time. It is hard to admit that these species have been cultivated for more than one millennium and being still wild without marked signs of domestication. A reason may be that the reproduction was controlled only 40 years ago and before, the juveniles were exclusively captured in the rivers (the phytophagous carps do not reproduce spontaneously on ponds as the common carp). However a note from 1872 mentioned that the Chinese fish farmers recognized few domestic fish (including the silver carp *Hypophthalmichthys*, and various *Cyprinus*, and *Leuciscus* spp. Other written material on fish culture dates from the Song Dynasty 960–1279 (description of the transportation of fry taken from the river), and from the Ming Dynasty (1368–1644), (complete *Agriculture Art* by Xu Guanggi and *Treatise On Fish Culture* by Huang Shencken, giving details on how to collect fry from rivers, and how to rear them in ponds).

The Chinese technology was traditionally based on the growing in ponds of eggs, larvae and juveniles fish captured in the wild. A large variety of devices exist for the capture of larvae or embryonated eggs (floating or attached to various supports such as grass, straw, branch, and Spanish moss). This has lasted until the 1960s when the technologies for artificial propagation in hatcheries started at a large-scale in China. An original feature of the Chinese technology is polyculture, which associates several species in the same body of water (see § 3.2.1) and was probably elaborated over the ages (see *Freshwater Aquaculture and Polyculture*). The stocking of two species in small pond with organic fertilization and distribution of grass is reported in a text from 1872. Another peculiarity of the Chinese technology is that it is based on field experience and know-how accumulated by generations of fish farmers. Research on fish culture in China started only recently (middle of the twentieth century) and there was no consistent written material before.

Indigenous systems have existed for centuries in Southeast Asia, India, Indo-China, and Cambodia. The major Indian carp catla *Catla catla*, rohu *Labeo rohita*, mrigal *Cirrhina mrigala*, and calbasu *Labeo calbasu* have been cultured for centuries in the northeastern States of India probably in polyculture systems but it was, as in China, simply the growing on of young fish caught in nature (and it still is in India). The fact that there was no control of reproduction and consequently no selective breeding (not even massal selection) explains that, as in China, there was no domestication, and that the fish culture is still based on non-domesticated animals after one millennium's practice.

In Europe fish culture started in monastic ponds in the Middle Ages with some cyprinids especially the common carp introduced earlier by the Romans. Fish had a religious significance (to be consumed once a week at least by monks) but had also a social importance (it was eaten in special occasion as for example Christmas); only freshwater fish including those cultured in pond were available inland. May be written text book were more common in Europe than in China. *Treatise Of Fish Culture* was available as soon as 1547 in central Europe (Dubravius), and fish culture chapters were available in treatises of agriculture (Olivier de Serres 1600) or fisheries (Duhamel du Monceau 1769–1782).

The history of salmonid culture in freshwater is entirely different than the culture of cyprinids. Salmonid culture started once the artificial reproduction was controlled in the first part of the nineteenth century. Probably before there was capture of wild trout or salmon and growth in small fishponds or fish “stews” fed with kitchen residues but the scale was limited. It is often reported that Dom Pinchon of the abbey of Reome in France first discovered the art of artificial reproduction (about 1420). It was (again) discovered by Jacobi (in 1778) in Germany on brown trout *Salmo trutta fario*, and Shaw (1836), and Young (1848) in Scotland on Atlantic salmon *Salmo salar*, but none of these discoveries had resulted in development of culture. In 1841 two Frenchmen (Remy and Gehin) (one being a fisherman) started works on artificial fertilization of brown trout, and eventually set up a technique of artificial propagation including gamete collection, fertilization, and incubation in metal boxes. Their work was well advertised and recognized by the French Academy of Science in 1849. This resulted in the initiation of an intensive program of stocking trout, which continued throughout the twentieth century. At the end of the nineteenth century hatcheries were also established

for rainbow trout *Oncorhynchus mykiss* for the growing of fish in raceways in commercial fish farm in Europe, Northern America, and Japan.

In marine water it is reported that the Romans have excavated ponds or tanks to fatten fish but it was probably more a simple storage, supplying fish when fishermen could not go at sea, rather than a true aquaculture activity. It was also a way to exhibit fish combining gastronomy and aquariophily. A first form of marine aquaculture was probably the oyster culture by the Romans, Greeks, and Japanese starting 2000 years ago. Another form was the stocking and cropping Valli (Comacchio Italy, seventeenth century), reservoirs (Arcachon France, nineteenth century), and tam baks (in Southeast Asia-Java, fifteenth century). These systems are still in use, especially the tam baks.

The idea of stocking fish in the sea also occurred. As soon as 1866 brood fish cod were reared in Norway in hatcheries and produced larvae for stocking. The technologies became efficient and in 1896, 327 millions cod fry were released. In the early 1900, other hatcheries were set up in North America, Scotland, Denmark, and Norway for the rearing of juvenile flatfish and cod, and their release. Due to the difficulty to establish a reliable return rate of the released fish and assess their economic feasibility these hatcheries progressively disappeared. The following development was the transplantation of plaice *Pleuronectes platessa* from 1892 to 1957 in the Limfjord on the west coast of Jutland (DK). It consisted to take the larvae from the nursery ground where they were in excess and to transfer them to the under occupy Limfjord. It was first considered as a success but at the end it was economically not justified and the operation was stopped. Other transplantation experiments carried out from 1900–1930 consisted to transplant overcrowded and slow growing plaice from the coastal banks to the Dogger Bank, which is their great feeding ground. In 1904–1905 the average recapture rate was 8%, and in 1924 it was 27% the first year, and 4% the second year. The project was found uneconomical and was stopped.

Another approach to enhance the growth of the natural stocks was the mineral fertilization of sea locks carried out in 1943 in Scotland. The plankton production was increased but no conclusion could be drawn on the benefit for the fish as they left the fertilized zone before they reached the marketable size. Other trials to fertilize feeding zones were carried out later in Canada. It is clear that a lot of activities more or less related with fish farming and manipulation of populations and ecosystems took place over the last two centuries.

A first form of ocean ranching started in Japan early in the eighteenth century when a river was divided into spawning channel in order to increase the surface of spawning beds available for the local run of chum salmon *Oncorhynchus keta*. The artificial reproduction of salmon in hatcheries and the production of juveniles to be released in the wild started in Japan in the end of the nineteenth century.

| | Production | |
|------------------------------------|------------|--------------|
| | In tons | US \$ × 1000 |
| Total Aquaculture (algae excluded) | 30 863 067 | 47 081 126 |
| Inland/brackish waters | 20 055 906 | 22 027 303 |

| | | |
|--|------------|------------|
| Marine waters | 10 807 161 | 15 053 824 |
| Fish | | |
| Carps and cyprinids | 14 142 298 | 15 054 849 |
| Tilapias | 972 773 | 1 253 974 |
| Miscellaneous freshwater fish | 2 240 182 | 3 427 777 |
| Sturgeons, eels, salmon, and other diadromous | 1 909 047 | 5 906 723 |
| Marine fish: flatfish, gadids, redfish, mullets, and tunas | 781 066 | 3 395 510 |
| Crustaceans (marine mostly shrimps and prawns) | 1 564 047 | 9 233 732 |
| Mollusks | | |
| Oysters | 3 537 830 | 3 362 116 |
| Mussels | 1 377 830 | 506 999 |
| Scallops, pectin | 874 225 | 1 263 668 |
| Clams | 2 226 025 | 2 750 407 |
| Miscellaneous (marine and continental waters) | 1 196 023 | 487 436 |

(1) FAO Fish. Stat. Aquaculture Production **86/2**, 1998, 170 pp.

Table 1. Production statistics of aquaculture (fish, crustaceans, and mollusks) in the world in 1998.

3. Aquaculture Production and the Number of Cultivated Species

The aquaculture production of fish, crustaceans, and mollusks has reached in 1998, 30.8 million tons (MT) for a value of \$US 47 billion (see Table 1). Aquaculture is mainly the production of animals restricted to 3 groups: fish (Ostariophysi, Perciforms, and some Acipenseriformes) mollusks, and crustacean (shrimp, prawn). Plants are cultivated to a lesser extent (8.6 MT in 1998), micro algae are produced as food for juveniles in hatcheries (fish, mollusks), and growing on fish (in pond culture); macro algae are also cultivated such as Nori in Japan. The weight of algae is expressed in wet weight and the production data of animal and plants are given separately in the FAO statistics. The capture in 1998 was 86.3 MT by fisheries, less than the previous year (93.6 MT) (see *World Yields of Marine Organisms*).

There was a regular increase (up to 8% year⁻¹) of aquaculture production over the past 10 years (see Figure 1) while the capture by fisheries remained stable. Aquaculture now reaches 30% in weight of the total aquatic production. The world total production of aquatic living resources is half of the meat produced by domestic animals in the world (which amounts to 170 million tons). Over the past few years the production of fish increased more rapidly compared to livestock meat production. Fish represented 63% of the world aquaculture production, mollusks: 29%, crustacean: 4.3%. The major contribution by fish comes from cyprinids (14 MT), followed by salmonids with 1.3 MT, and tilapias nearly 1 MT. A group of species shows production included in a range of 100 to 800 000 tons: milkfish, yellowtail, channel catfish, and eels (see Figure. 1).

One characteristic is that fish are mostly produced in continental waters, and mollusks and crustaceans in marine waters. The production is concentrated in a limited number of countries. China is by far the leading country with 20.8 MT, 70% of the total world production. The production reaches 1.7 MT in India and around 1 MT in a group of Asiatic countries (Japan, Korea Rep., Philippines, and Indonesia). A dozen countries show production in the range of 100–400 000 tons. Asia appears the main producer with 80% of the total production, Europe has 16%, N. America 3.3%, S. America 0.8%, and Africa 0.3%. Another expression is the production per capita per year; it is 2248 g. in Asia, 1566 g. in Europe, 749 g. in N. America, 208 g. in S. America, and 34 g. in Africa. A few countries produce more: 70 kg. $\text{capita}^{-1} \text{ year}^{-1}$ in Norway or 10 kg in Ecuador but it is exported. Aquaculture produces mostly food for human consumption and some non-food products (fish for angling, bait fish, ornamental fish, compounds for cosmetology, and fish skin). The human consumption of aquatic products is in the range of 10–18 kg. $\text{Capita}^{-1} \text{ year}^{-1}$ in the different continents but the coverage by aquaculture is variable: 14% in Asia, 9% in Europe, and less than 5% elsewhere.

The aquaculture activities are carried out in a large variety of water bodies: in the wild (seas, lakes, rivers, in cages, enclosures, and sluice) or inland in ponds, tanks, and raceways. With some exception the structure of the farms is small (often on a family scale basis). It is very often integrated to other activities in the coastal zone or in the rural area. The prospects of aquaculture in tropical countries is promising as conflicts of interest are less critical and the climatic condition more favorable than in temperate zones (see *Fish Farming in The Tropics*).

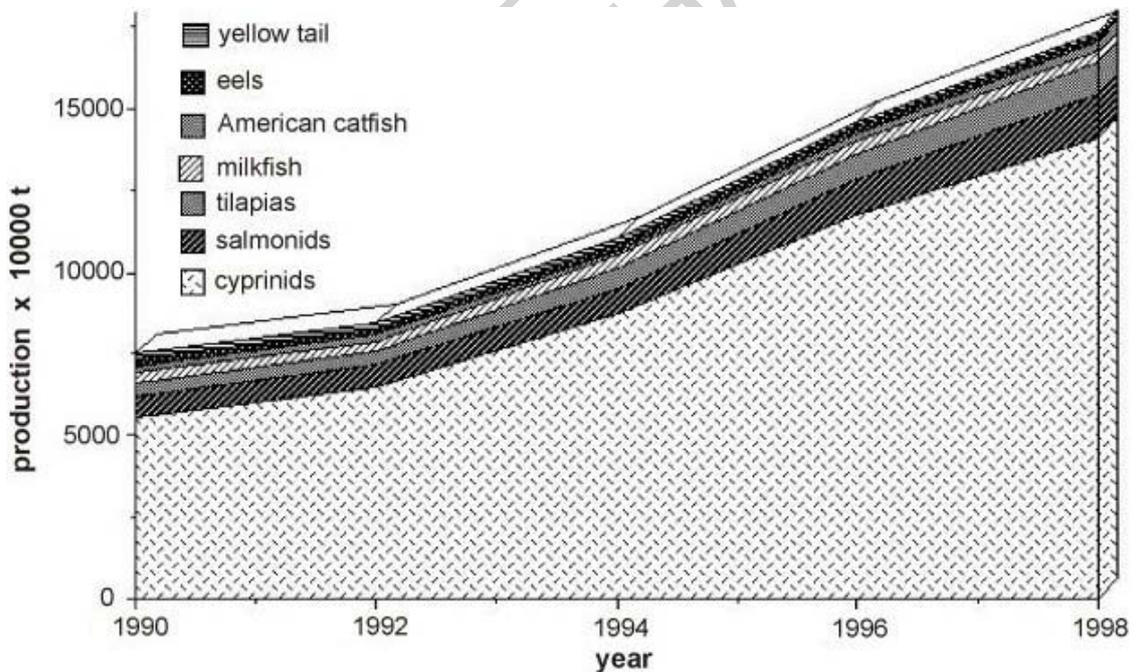


Figure 1. Changes in the aquaculture production by species in recent years (FAO Statistics 1998).

More than 200 species showing significant production ($> 10\,000 \text{ t. year}^{-1}$) are cultivated: more than 100 species of fish (60 in freshwater, 15 in brackish water, and 30 in the sea);

50 of mollusks, 25 of crustacean, 10 of algae but most of the world aquaculture production is due to a limited number of species (for only 20 species the production per taxa exceeds 500 000 t.). Fish (such as cyprinids, salmonids) and oysters have been widely introduced in many countries for aquaculture purposes; several other exotic species recently introduced in Europe have already yielded some commercial production such as the crawfish *Procambanus clarki*, several sturgeon species, and the clam *Ruditapes philippinarum*. Goldfish *Carassius auratus* and brown trout *Salmo trutta fario* are well domesticated, and several races/varieties have been created. Domestication of the other cultivated fish is more recent. The process of domestication was relatively fast, about 25 years for prawn *Peneus japonicus*, 15–20 years for Atlantic salmon, sea bass *Dicentrarchus labrax*, sea bream *Sparus auratus*, and red sea bream *Pagrus major*, channel catfish *Ictalurus punctatus*, and tilapias, especially the Nile tilapia *Oreochromis niloticus*. The process of domestication was strongly accelerated by research programs, and was realized by the combined efforts of fish farmers and scientists. The first step of rearing often starts in laboratories, for example sea bream, groupers *Epinephelus aeneus*. In most of these species domestication resulted from the reproduction in hatcheries of specific stocks isolated from wild populations with still a low number of brood fish and generations; this approach may result rapidly in loss of genetic variability. Genetics changes have been observed as well as changes in behavior.

Introduction, now, of new species is highly restricted in most Western European countries but it is still possible legally in countries from the South. A code of practice has been established by EIFAC. The concept of introduction may be extended and regulation adapted. A form of introduction is the transfer of species from one river basin to another one, inside a same country. For instance due to its interest for aquaculture and angling the European catfish, which was first located in the Rhine and Saone basin in France, is now nearly distributed over the whole country. Another form of introduction is the inter-river basin transfer of local populations.

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Bibliography

Bardach J. E., ed. (1997). *Sustainable Aquaculture*, 251 pp. John Wiley and Sons, Inc. New York [This book is mostly dealing with problems of aquaculture and specific related questions raised by sustainable aquaculture and food security in the developing world: economic decision making, modeling in management and planning, role of biotechnologies integration to coastal management, planning regulation and administration as well as pollution and impact on biodiversity, prospect of offshore farming.]

Barnabé G. (Coord.) (1989). *Aquaculture, English Edition, Technique Et Documentation Lavoisier*, 2

vol., 1308 pp. Paris, [Overview of aquaculture practices.]

Boyd C. E. (1979). *Water Quality In Warm Water Fish Ponds*, 359 pp. Auburn, Alabama, Auburn University Agriculture Experiment Station. [The bible of the pond farm managers.]

Elsevier (1976–1999). *Developments In Aquaculture And Fisheries Sciences*. [Series started in 1976 with 28 volumes published in 1998. Several volumes are devoted to the culture of a species or a group of species (Seaweeds, oysters, mussels, clam, scallops, shrimps marine fishes, and shrimps, catfish salmonids) to the aquaculture in a country (North America, Japan, and China) or to technologies (reuse systems, water quality in ponds, bio-economics, disease, design, and operating seawater systems).]

Huet M. (1986). *Textbook Of Fish Culture*, 2nd ed. 438 pp. Farnham, Fishing News Books, [A classic book on aquaculture.]

Kirpichnikov S. (1999) *Genetics And Breeding Of The Common Carp*. INRA Paris. [A posthumous book of the well-known Russian fish geneticist.]

Miur J. F. and Roberts R. J., eds. (1985). *Recent Advances In Aquaculture*, Vol. 2, 282 pp. Beckenham, Croom Helm. [Five volumes have been published in this series giving pertinent review on a given aquacultural topic.]

McLarney W. (1984). *The Freshwater Aquaculture Book*. 583 pp. Hartley and Marks Washington, Vancouver [Another classic book on aquaculture.]

Moriarty D. J. and Pullin R. S. V., eds. (1987). *Detritus And Microbial Ecology In Aquaculture: Proceedings Of The Conference On Detrital Systems For Aquaculture*. ICLARM Conference Proceedings: No. 14, 420 pp. 26–31 August 1985, Bellagio, Como, Italy. Manila, International Center for Living Aquatic Resources Management.

Nash C. E. and Novotny A. J., eds. (1995). *Production Of Aquatic Animals, Fishes*, 405 pp. [This book reviews the problems of biology and farming of fish. Each chapter is devoted to one species or group of fish: carps, catfishes, sturgeons, eels, tilapias, colossomids, basses, salmonids, milkfish, mullets, sea bass, sea breams, groupers, drums, flatfishes, rabbit fishes, and cod. Some oceanic pelagic fishes and the production of live food for fishes are also treated.]

Pennell W. and Barton B.A., eds (1996). *Principle Of Salmonid Culture*, 1039 pp. [Book of the Elsevier series gives a complete view of the principles and technologies on all aspect of the commodity chains of the main cultivated salmonids: History (Laird), biology (Barton), life history (Groot), brood stock (Pepper/Crim), gamete (Billard/Jenssen), early rearing (Pinnell/McLean), growth (Iwama), smolt production (Clarke et al.), rearing (Novotny/Pennell), nutrition (Halver), breeding and genetics (Jorstad/Naevdal), transports (Wedemeyer), disease (Bruno/Ellis), ranching (Heard), marketing (Shaw/Egan), environmental impacts (Weston et al.), and biotechnologies (Donaldson/Devlin).]

Pillay T. (1990). *Aquaculture: Principles And Practices*, 576 pp. Oxford: Fishing News Books. [A well illustrated book on aquaculture].

Stickney R. R., ed. (1986). *Culture Of Non-Salmonid Fishes*, 201 pp. Boca Raton, FL: CRC Press.

Tucker C. S., ed. (1985). *Channel Catfish Culture*, Volume 15, 657 pp. Elsevier [Fifteen authors give information on all aspects of the production, processing, and economics on a successful fish commodity chain in the USA.]

Biographical Sketch

Roland Billard was born in 1934 in France, graduated from Lyon University in 1965. He received his Doctorat d'Etat at the Paris P & M. Curie University. He has worked as Assistant and Director of research at the National Institute of Agronomic Research (INRA) and was Director of the Fish Physiology Laboratory in this institute from 1970 to 1984. Since 1986 he is Professor at the Muséum National d'Histoire Naturelle in Paris and Director of the Laboratory of General and Applied Ichthyology. His main research interest is fish reproduction, spermatogenesis (structural and quantitative aspects, endocrine regulation), and physiology of spermatozoa with application to the control of reproduction and spawning, gamete preservation, and artificial insemination. He also showed interest on the production systems in

aquaculture. He has published more than 300 scientific articles and 200 technical papers, and published or edited a dozen books. He is a member of the French Academy of Agriculture, foreign member of the Romanian Academy of Agriculture, and a member of the Academia Georgofilli (Italy).

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