Chapter 2
Genetic Resources: What Are Genetic Resources and Their Importance for Food Production?

2.1 About Biological Diversity

The biological diversity present on planet Earth is the result of dynamic evolutionary processes that began approximately 4.5 billion years ago (Ward and Kirschvink 2015). **Stromatolites** – sedimentary strata formed in coastal regions on which microbial biofilms rich in Cyanobacteria are found – likely were the first complex life forms, more than 3.4 billion years ago (Lowe 1980). Life based on information stored as RNA (ribonucleic acid) and later as DNA (deoxyribonucleic acid) (Orgel 1994) found on Earth conditions driving diversification and expansion (Ward and Kirschvink 2015). This biological diversity, or **biodiversity**, can be defined as the "variety of species and ecosystems, and the ecological processes of which they are part and which comprises two components: diversity of species and of ecosystems", or as "the variety of life on Earth in all its levels, from genes to ecosystems, and the ecological and evolutionary processes that perpetuate them" (Gaston 1996). According to the Convention on Biological Diversity (CBD 1992), "biological diversity means the variability of living organisms from all sources, including, among others, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; understanding yet the diversity within species, between species and of ecosystems". Climatic changes experienced by Earth, including transitions from glacial to interglacial periods, have driven five major and several minor waves of extinction, followed by more favorable conditions driving the evolutionary diversification of species (Ward and Kirschvink 2015).

As man the hunter/gatherer developed the first agricultural production methods and achieved animal domestication starting about 10,000 years ago (Sauer 1952; Higgs and Jarman 1969), he assumed a pivotal role in the environmental changes that would come to impact biological diversity on Earth (Ponting 1993). The Industrial Revolution was a milestone in the transition from the feudal mode of agricultural production to a production system based on exploitation of natural resources. An anthropogenically driven decline in abundance and the extinction of many wild species is documented

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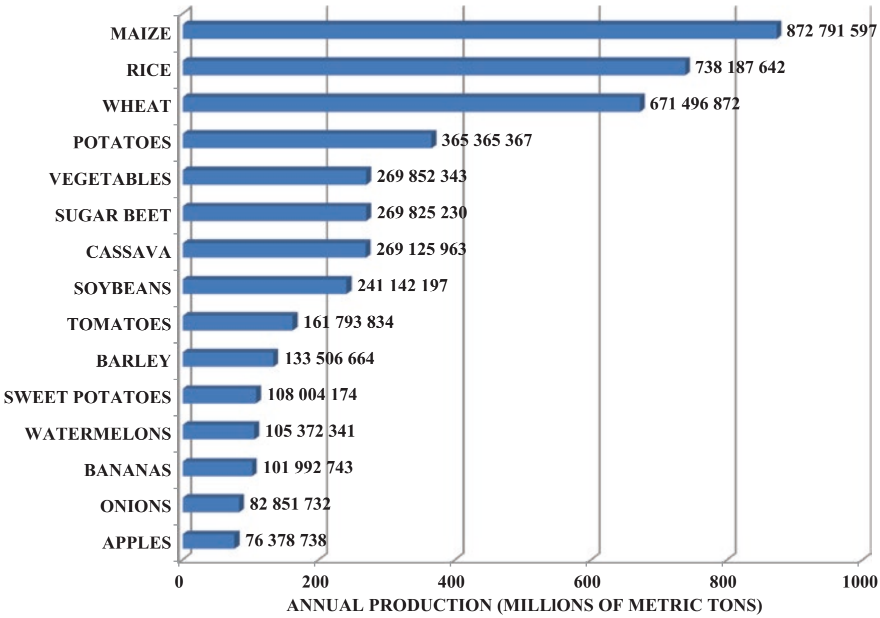

Fig. 2.1 Total world production of the 16 top crop commodities (FAO (2012) – http://faostat.fao.org/site/339/default.aspx)

from this period on (Vitousek et al. 1997). The hunter/gatherer mode of feeding was based on exploiting a wide range of plants and animals. In the beginning of agriculture and animal domestication, however, the first settlers restricted their nourishment to a few of the more productive plants and animals that are docile by nature or otherwise suited for domestication (Diamond 1999). As a result, most of the human diet is currently based on just 16 major crops. Four of them – wheat, rice, corn and potato – yield more than all the others put together (Fig. 2.1).

Centers of origin of the main vegetable crops cultivated by man were first recognized by the Russian geneticist Nikolai Ivanovich Vavilov (1887–1943). Vavilov traveled in the first half of the twentieth century over five continents, where he collected wild seeds of cultivated plants and stored them in collections at the Scientific Research Institute Leningrad, currently St. Petersburg, in the former USSR, where he was director between 1916 and 1936. His main work – *Origin and Geography of Cultivated Plants* was originally published in 1926 in Russian (with the last English version published as Vavilov 1926, 2009). In this book, Vavilov and collaborators introduced the concept of Centers of Origin, which describes the distribution patterns of varieties of plants cultivated by man. The diversity of these plants is distributed unevenly over the planet. The most diverse areas are those in some way suitable by soil and weather conditions for the diversification of cultivars, and therefore are regarded as their location of origin. According to Vavilov, "the location of origin of a given cultivated plant species is to be found in an area in which contains the largest number of genetic varieties of this plant”.

The term Centre of Origin used by Vavilov is often mistaken for Center of Diversity; the first concept is an interpretation, and the second a biological fact. Vavilov proposed that the most-cultivated plants are derived from eight centers of origin, namely the: (I) Chinese; (II) Indian; (IIa) Indo-Malay; (III) Central Asian; (IV) Near East; (V) Mediterranean, to Abyssinia (present-day Ethiopia); (VI) Southern Mexican and Central American; (VIII) South-American; (VIIIa) Chiloé Island (south of the Chile archipelago); and (VIIIb) Paraguayan-Brazilian. Vavilov also acknowledged the existence of secondary centers of origin, in which varieties from the primary centers were developed. Genetic processes including mutation and natural hybridization may occur in secondary centers, allowing the appearance of new varieties, thereby increasing the genetic variability of the species.

The ideas expressed by Vavilov on centers of origin (diversity) in some ways were an interpretation of the ideas first proposed by John Christopher Willis (1868–1958), an English botanist who proposed what became known as the **age-and-area hypothesis** (Willis 1915). In this proposition, selective agents promoted by the environment operate similarly on a group of species at a given location. According to Willis, “The area occupied by any given species (of plants) at any given time in any given country in which there occur no well-marked barriers depends upon the age of that species in that country”. Thus, the older a given species, the wider is its range. In addition, this view includes the idea that the disappearance of a species occurs only rarely except as a result of drastic environmental changes. This idea led to the concept of **endemism**, the occurrence of a species only within a narrow range, a concept widely used in conservation and conservation genetics.

Terrestrial animal farming was made possible through the domestication of wild species by selecting individuals more adapted to interaction with humans. Wolves were domesticated at the end of the Pleistocene glacial period by hunter/foragers in Europe and Asia (Benecke 1987; Savolainen et al. 2002; Derr 2011). Crop and other animal domestication followed, starting profound changes of pristine *Homo sapiens*, who gradually transformed from the hunting and foraging culture into more complex social organizations that in turn led to the emergence of different civilizations, a process known as **Neolithisation** (Vigne 2011). Only a small part of animal diversity on the planet has been domesticated and used as food by most human populations. For example, the prehistoric aurochs (*Bos primigenius*), which became extinct in the seventeenth century, gave rise to the current *Bos taurus* (Helmer et al. 2005). The main ancestor of domesticated sheep is the urial (*Ovis orientalis*), with later additions from argali (*O. ammon*) and mouflon (*O. musimon,* Zeuner 1963). The main ancestor of the domestic goat is the bezoar (*Capra hircus*), with possible later contributions locally from markhor (*C. falconeri*) and Nubian ibex (*C. ibex,* Harris 1961).

2.2 What Are Biological Resources, Genetic Resources, and Genetic Heritage?

Throughout this century, mainly from the 1960s, there has been a growing perception of the importance of preserving the environment and the organisms living in it. This human perception, however, often imbues within itself the awareness of the survival and well-being of just one species – *Homo sapiens* (Chivian and Bernstein 2008). Different societal actions have brought environmental issues onto the agenda of national and international decision-making bodies only recently; such concern about environmental issues was unusual during the first half of the twentieth century. Unlike past geological times, in which mass extinctions occurred due to catastrophe or extreme weather changes, processes leading to current species extinctions largely have been the consequence of human activities, especially those giving rise to habitat loss (Tilman et al. 1994) and more recently to global climate change (Thomas et al. 2004).

Currently, various national and international bodies have proposed terminologies to establish legislative and treaty frameworks for the conservation and sustainable use of biodiversity. Allem (2000) examined the definition of concepts such as genetic resources and biological resources, and showed that such concepts often are used uncritically, leading to misinterpretations about the scientific basis of these terms. For example, in 1991, at the intergovernmental meeting in Nairobi organized by United Nations Environment Program, the term "**biological resources**" emerged, and was used by the Food and Agriculture Organization of the United Nations (FAO) for the first time (UNEP 1991). The working document of the Intergovernmental Negotiating Committee for the Convention on Biological Diversity, in its second and fourth rounds of negotiation in Nairobi, was the basis for coining terminology for Article Two (Terms) of the final version of the Convention on Biological Diversity (CBD 1992). In this article, the definitions used for **genetic resources** and biological resources (genetic material) were very similar.

The concept of genetic resources also was used during the Leipzig conference promoted by FAO in 1996. This utilitarian concept at its core emphasizes the human use of living resources, and refers to genetic resources as an asset, from which some sort of wealth can be produced. However, the continued existence of such resources depends on the survival of other resources not directly useful to humans. Against this background, in Table 2.1 we present a summary of concepts of biological and genetic resources set forth by various international organizations. A close view of all definitions shows that the concepts of biological and genetic resources generally overlap, approaching the same goal, the utilization the genetic variability of organisms in order to yield useful products for human beings.

Table 2.1 Concepts of the terms: biological resources and genetic resources

Concept	Definition	Source
Biological resources	Term is used without a proper definition	UNEP (1991)
	"Includes genetic resources: organisms or parts thereof, populations, or any other biotic component of ecosystems that have potential usefulness for mankind"	CBD (1992)
	Biodiversity components of direct use, indirect or potential use by humanity(= biotic resources)	WRI (1996)
	"Forest resources, plant cultivation, aquatic and non-aquatic animals, which bring benefits today or which may bring in the future. Each resource category is subdivided into subcategories of arable and not cultivated"	OECD (2013)
Genetic resources	"Plant Material with potential value and gift for food, agriculture and forest"	Plant genetic resources – (Brockhaus and Oetmann 1996)
	"Germplasm of plants, animals or other organisms that contain useful characters of actual or potential value"	IBPGR (1991) (p. 74)
	"Plant genetic resources refer to economic, scientific and social values that contain inheritable materials within and between species	FAO (1989) (p. 19)
	"'Genetic Material' means any material of plant, animal, microbial or other containing functional units of heredity"	CBD (1992)
	"Genetic resources: genetic material of actual or potential value"	
	"The genetic material of plants, animals and microorganisms that have value for future generations of mankind"	OECD (2013)

2.3 Genetic Resources and Food Production

The growing welfare of the human population over the last century has increased life expectancy. The global expectancy for survival from birth is currently 71 years, 7 years longer than in 1990 (World Health Statistics 2015) and 24 years longer than for those born between 1950 and 1955 (Hosseinpoor et al. 2012). Projected human population growth for the next decades, however, is troublesome considering the increasing environmental disturbance and resource demands posed by the over seven billion *Homo sapiens* living currently (UNFPA 2011).

Currently, despite advances in the technologies for food production, living today are 852 million people without the minimum income suitable for their survival and well-being, especially in underdeveloped and developing countries, and 16 million malnourished children even in developed countries (FAO, WFP, IFAD 2012). In a utopian world, food must be produced and distributed to everyone without regard to population growth or differences in regional economic development; however, with less water, less arable land, and likely with less favorable environmental conditions, to produce food for everyone will be a pivotal challenge for the future.

The importance of the conservation of genetic resources in the context of food production (from now on, we will use the term genetic resources, or GR in accordance with CBD 1992) lies in the fact that much of the wealth produced by humans for their survival and well-being still has nature as its main source. Since man began producing his own food through agriculture, a quantum leap in food production led to the coining by then-Director of the United States Agency for International Development (USAID) William Gaud at a meeting of the Society for International Development in DC in 1968 of the term Green Revolution in 1968 (Patel, 2013). In his own words:

> *These and other developments in the field of agriculture contain the makings of a new revolution. It is not a violent Red Revolution like that of the Soviets, nor is it a White Revolution like that of the Shah of Iran. I call it the Green Revolution.*

The green revolution began with the studies of the American agronomist, humanitarian, and 1970 Nobel Peace Prize laureate, Norman Ernest Borlaug (1914–2009), who developed genetically improved plant varieties, such as the IR8 rice variety (Fig. 2.2). In his own words (quoted by Ortiz et al. 2007):

> *For more than half a century, I have worked with the production of more and better wheat for feeding the hungry people, but wheat is merely a catalyst, a part of the picture. I am interested in the total development of human beings. Only by attacking the whole problem*

Fig. 2.2 Dr. Norman Ernest Borlaug, called the "Father of the Green Revolution". Increase of rice yields followed Dr. Borlaug's work (Sources: AP photo and National Geographic graphic)

can we raise the standard of living for all people in all communities, so they will be able to live decent lives. This is something we want for all people on this planet.

The development of new plant varieties more productive than local varieties, in addition to the development of new techniques of soil management, pesticide use, distribution of genetically improved seeds, and agricultural mechanization, doubled or even tripled the productivity of major crops over a short period, mainly from the early 1960s (Vietmeyer 2011).

The advent of modern agricultural technologies and expansion of the use of improved plant varieties increased food productivity throughout the world. At the same time, the diversity of cultivated plant varieties developed by our ancestors, as a result of different cultivation conditions as well as local needs and preferences, was being replaced by genetically improved varieties of seeds (Frankel and Hawkes 1975; Keneni et al. 2012). Productivity growth also brought its own consequences; farming of vast areas with genetically uniform cultivars made them vulnerable to diseases and crop pests and therefore highly dependence on pesticides and other agrochemicals (Adams et al. 1971). The erosion of genetic resources, the basis for genetic improvement programs, raises the issue of how the genetic diversity of local races of plants should be protected from the inevitable advance of adoption of improved cultivars (Plucknett et al. 1983). Growing international concern with the loss of genetic resources relevant to food production, and the concomitant increased vulnerability of improved cultivars, led to the creation in 1974 of the International Board for Plant Genetic Resources (IBPGR). The IBPGR is an international organization under the auspices of the Consultative Group on International Agriculture Research (CGIAR), whose mission is the conservation and use of plant genetic resources for the benefit of present and future generations.

One of the aims of the IBPGR was to encourage the establishment of germplasm banks where seed representing genetic diversity of local varieties could be stored, catalogued, and its potential use evaluated (Frankel and Bennett 1970). Over the years, several ex-situ germplasm banks have been established by government initiatives. The FAO (2010) *Second Report on the State of the World's Plant Genetic Resources for Food and Agriculture* emphasized progress in expanding the number of plant varieties kept in national germplasm banks. Currently, an estimated 1,750 gene banks are established over the world that together retain about 7.4 million seed deposits, an increase of 20% since the last assessment in 1996. FAO pointed out several reasons for the conservation of genetic resources for food and agriculture. It is crucial to protect the adaptability of cultivars and wild populations in order to preserve genetic characters that ensure a sustainable food production. For this reason, plant and animal genetic resources – in our context, notably including aquatic resources – must be conserved both ex-situ and in-situ. These types of gene banks are defined by the FAO (2013) as follows:

Conservation in-situ Maintenance and recovery of viable wild populations of aquatic genetic resources (AqGR) in their natural environment where they have evolved their distinctive suites of traits. This approach is pivotal for the long-term survival of **fisheries genetic resources (FiGR)** as a repository of genetic variability for new species domestication and breeding programs. Therefore, environmental protection is a key issue for AqGR conservation. Common approaches undertaken to establish **in-situ conservation** plans delve into population genetic diversity of AqGR in order to optimize the costs and efforts toward establishment of reserves and protected rivers and other lacustrine areas. For example, the Brazilian Amazon has 27% of its territory protected in Conservation Units, which means 42 million hectares under federal or state protection. Promoting the long-term survival of viable AqGR within their natural ecosystems meets the expectation of the Convention on Biological Diversity (CDB 1992) under Article 8 – in situ conservation (Fig. 2.3).

Conservation ex-situ Includes the conservation of components of biological diversity outside their natural environments and held in locations outside their normal management. The main infrastructure for storage and for the establishment of techniques for such conservation is "gene banks" (or germplasm banks). In the case of **aquatic genetic resources (AqGR)**, **conservation ex-situ** means maintaining animals as live fish. Populations of AqGR can be held in commercial fish farms where strains are used in breeding programs and in aquaculture facilities where wild populations of AqGR are used as broodstock for purposes of stocking into the wild. Alternatively, populations may be held at public facilities dedicated in part or fully to conservation purposes. One leading example is the Southwestern Native Aquatic Resources & Recovery Center (formerly the Dexter National Fish Hatchery and Technology Center) in New Mexico in the United States, where populations of 15

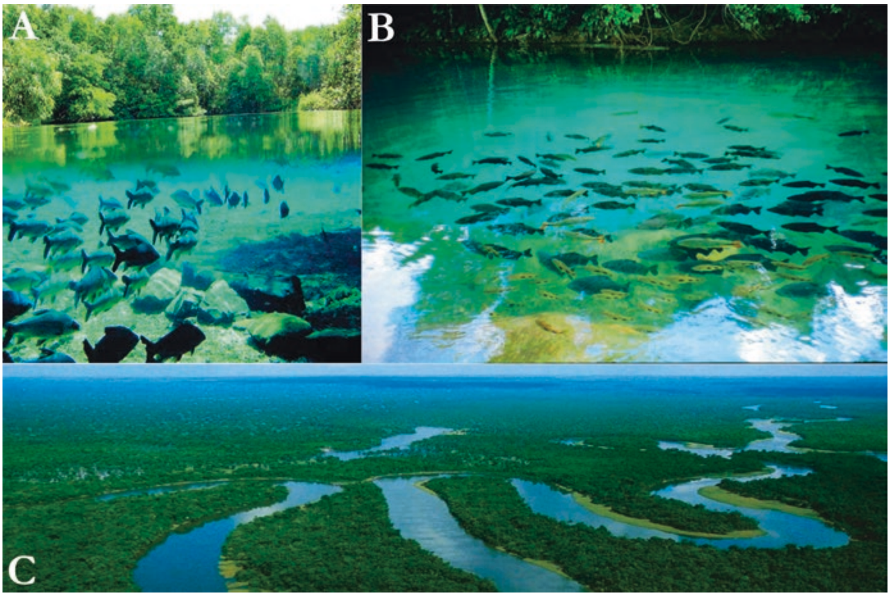

Fig. 2.3 Examples of in situ conservation of FiGR. (**a**, **b**) Municipality of Bonito, State of Mato Grosso do Sul, Brazil, protected aquatic ecosystems used for ecotourism. (**c**) Amazon basin and its mosaic of aquatic ecosystems

imperiled species are held (U.S. Fish and Wildlife Service 2016). Many U.S. federal or state hatcheries produce imperiled finfishes or shellfishes in addition to more conventional sportfishes. Inner Bay of Fundy Atlantic salmon are propagated for conservation purposes by the Department of Fisheries and Oceans Canada, and a Norwegian Atlantic salmon gene bank in central Norway is operated by the Directorate for Nature Management (O'Reilly and Doyle 2007). Non-governmental organizations (e.g., the Tennessee Aquarium Conservation Institute and Conservation Fisheries, Incorporated) also are contributing to ex-situ conservation of aquatic species.

Another strategy to conserve AqGR germplasm is **in vitro conservation**. This approach involves germplasm maintenance in artificial environments, including keeping sperm, oocytes, embryos, somatic cells, and tissues under cryopreservation, supporting the potential for reconstituting living organisms (Cloud and Thorgaard 1993; Fig. 2.4). For example, milt samples of 6,500 individuals from 169 prioritized Atlantic salmon populations are held under cryopreservation in Norway (O'Reilly and Doyle 2007).

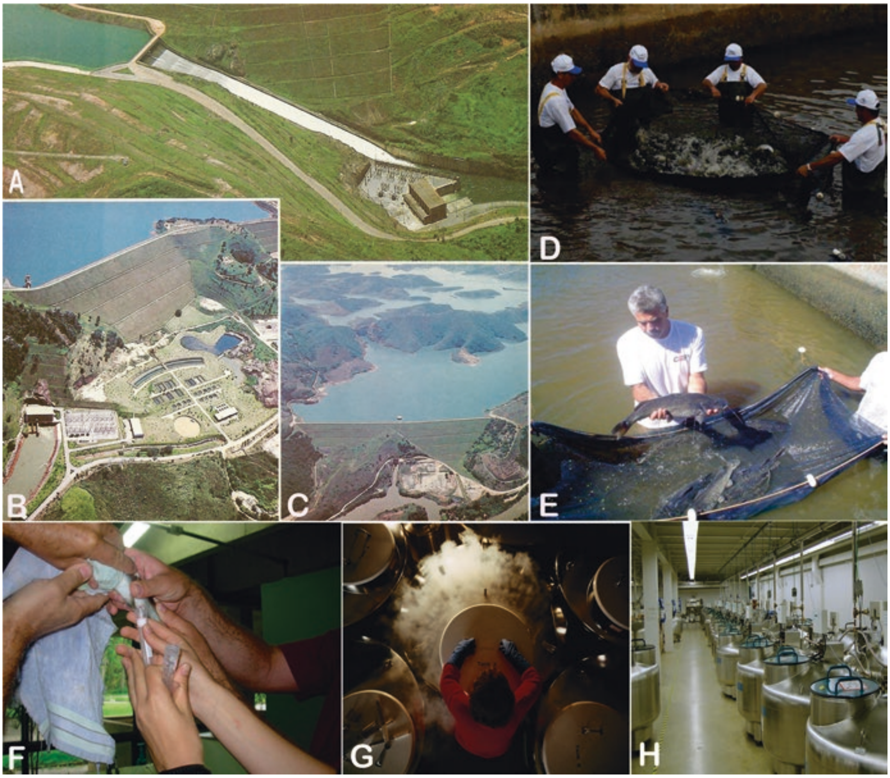

Fig. 2.4 Examples of ex situ conservation of FiGR. (**a**, **c**) Paraibuna hydroelectric power plant and dam; (**b**) hatchery facilities at Paraibuna Dam (São Paulo – Brazil); (**d**–**f**) Native FiGR in captivity for fingerling production and release; (**f**) Semen collection for cryopreservation; (**g**, **h**) cryopreservation facilities at the National Center for Genetic Resources Preservation, Fort Collins, Colorado, USA

The Convention on Biological Diversity states that in-situ conservation, the preservation of populations and species in their natural habitats, should receive priority over the ex-situ conservation in which populations, species, and gametes are kept outside their natural environment (in parks, zoos, aquariums, breeding or gene banks). Those who believe strongly in in-situ conservation are concerned that removal of individuals or gametes from their place of origin can lead to several problems. These include broodstock "mining", the unsustainable removal of reproducing individuals from wild populations. Other concerns regard interruption of the ongoing adaptive evolution of the species, increasing reliance on technological solutions to environmental problems, and especially the diversion of attention and investment from solving the root problems that threaten the species in their natural environments. However, it is not always possible to perform in situ conservation as quickly as would be desirable to save species or populations at risk of extinction. Proponents of ex-situ conservation argue that their collections are also important for research and reference, and that such a strategy can be more cost-effective.

2.4 Animal Genetic Resources

The need for conservation of animal genetic resources of interest to food production was first expressed in 1959, at a symposium on germplasm resources for plant and animal breeders (Simon 1984). Animal genetic resources contribute in many ways to the survival of man. About 30% of the current human food requirements originate from livestock, with the prospect of achieving 39% by 2030 (FAO 2007). The contribution of food and animal by-products is also very significant for about 70% of the rural population, mainly in low-income and lower-middle-income countries (Livestock in Development 1999).

According to the FAO (2016a), of the approximately 8,200 animal breeds, more than 2,500 are on the verge of extinction or already extinct. Thus, we are losing unique genetic make-up, which threatens long-term global food security by decreasing the genetic variability of animal breeds. Changes in the proportion of the world's breeds by risk status according to FAO (2007, 2015a) can be observed in Fig. 2.5. This on-going erosion of animal genetic resources is caused by, *inter-alia*: (i) the dissemination of genetically homogeneous breeds and intensive production; (ii) environmental pressure on natural resources, decreasing the area utilized for local-breed production; and (iii) lack of policies and strategies for ongoing management of local animal genetic resources adapted over time for production with low input.

2.5 Genetic Resources of Freshwater Fishes in the world

In earlier sections, we discussed the concepts developed by different international organizations on the importance of plant and animal genetic resources. Such concepts were based mainly on plants and animals of importance to terrestrial

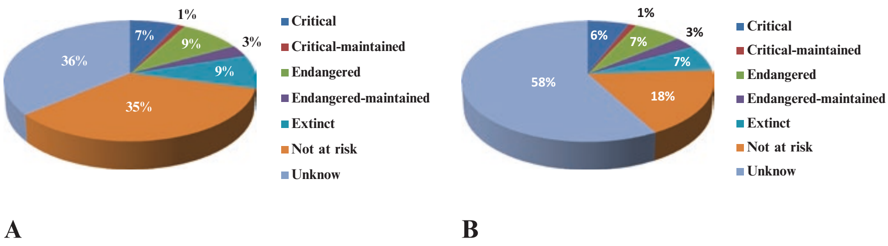

Fig. 2.5 Proportion of the world's livestock breeds by risk status category ((**a**) FAO 2007; (**b**) FAO 2015a)

agriculture. Unlike terrestrial animals, protein originating from aquatic animals is still obtained mostly through extractive activities such as fishing.

Bartley and Pullin (1999) raised an important issue regarding aquatic genetic resources (AqGR): "Everything that lives in an aquatic environment and has life and all genetic material (DNA) contained in these bodies have real or potential value". This statement raises important questions about the magnitude of biodiversity in oceans and freshwaters, and about gaps in our knowledge about aquatic biodiversity. In the case of direct and indirect interest in utilizing aquatic organisms for food, key issues include: (i) How does an aquatic ecosystem work towards maintaining sustainable fishery yield? (ii) What is the status of sustainability of fished stocks in the face of intense and constant environmental changes promoted by the man in the last century? (iii) What criteria should be used for choosing aquatic species for domestication? and (iv) How can these species be managed to sustain food production for human populations?

Due to its peculiarities, conceptualization of AqGR should cover various hierarchical levels, from genes, to varieties or "races", to populations, species and ecosystems. In the case of species of commercial value for fisheries or aquaculture, considering the extreme dependence of these species on the aquatic ecosystem and other species, how can we effectively characterize genetic resources? Should we consider only species targeted by fisheries as genetic resources, or should we include other species without commercial value, but which are key to the sustainability of target species? This issue was especially highlighted in the Executive Summary for Policy-Makers of Global Biodiversity Assessment (UNEP 1995):

The Earth is home to a diverse set of living organisms whose genetic diversity with their interrelationships, as well as their interaction with physical environment, constitute the biodiversity of our planet.

The aquatic environment on planet Earth always seemed an inexhaustible source of food and wealth for mankind (Huxley 1883). The development of industrial fishing, however, made clear that the assertion that fisheries are an inexhaustible source of food is a myth (McGoodwin 1991). While finite, fisheries resources can be effectively managed. The FAO Code of Conduct for Responsible Fisheries (2011) established ten clear objectives that must be followed to promote long-term sustainability of aquatic resources. Among them, are objectives to: (i) promote the contribution of fisheries for food quality and security, giving priority to the nutritional needs of local communities, and (ii) promote protection of living aquatic resources and their environments and coastal areas.

In this work, emphasis will be given to the AqGR of continental waters of the Neotropical region, especially fishes. The importance of such resources for the economy and food production in many countries is undeniable. Welcomme (2011) pointed out that fisheries production from continental waters on all continents is declining. Six main threats to fisheries sustainability in continental waters have been identified:

(i) Management which is bad or non-existent, including uncontrolled fishing with incorrect or illegal mesh size, and introduction of exotic and invasive species,
(ii) Water withdrawal: diversion of rivers to irrigation of agricultural crops,
(iii) Drainage of flooded areas: draining of swamps and floodplains to plant agricultural crops,
(iv) Construction of dams: the need for electric power for economic growth led to damming of many free-flowing rivers for hydroelectric power generation. River disruptions directly impact the life-cycle of many fish species, and thereby the long-term survival of fish species and communities,
(v) Pollution/eutrophication: human occupation of areas near riverine or lacustrine habitats without appropriate measures of sewage or wastewater treatment has deteriorated water quality through eutrophication, exposure of aquatic organisms to heavy metals, other toxins, and bioactive compounds, and
(vi) Climate change: climate change presents an ever-growing threat to aquatic organisms because it can rapidly alter aquatic environments and impact sensitive species.

Despite numerous environmental changes experienced globally by freshwater ecosystems, harvests in inland waters have increased, even taking into account that in many countries there are no records of harvest from small-scale fisheries. The contribution of inland fisheries to total world fishery and aquaculture production was 7.12% in 2014 (FAO 2016c). Inland fishery harvest has been maintained at a constant level over the last several years (Fig. 2.6). Even with the low contribution of freshwater fisheries to world production of fish, the catch in rivers, lakes and reservoirs is the sixth-largest supplier of animal protein for human populations (2.3%), behind pork (23.7%), marine fisheries (19.9%), poultry (17.8%), aquaculture (15.3%), and beef (13.8%) (Welcomme 2011). In addition, inland fisheries are a vital source of protein and income for the subsistence of people from the developed and developing world (Bartley et al. 2015).

The importance of genetic resources of freshwater fishes in terms of its contribution to human protein intake can be grasped when one considers that just 76 taxonomic groups of freshwater finfishes comprise 95% of total catch worldwide. Thirty fish families contribute an important part of the food supply, among which stand out the Cyprinidae, represented mainly by the Chinese and Indian carps with 22.2%, and Cichlidae, represented by the tilapias with 20.4% of total production (Welcomme 2011).

Aquaculture has become an important source of animal protein production. Although early Chinese and Egyptian records show fish cultivation under controlled

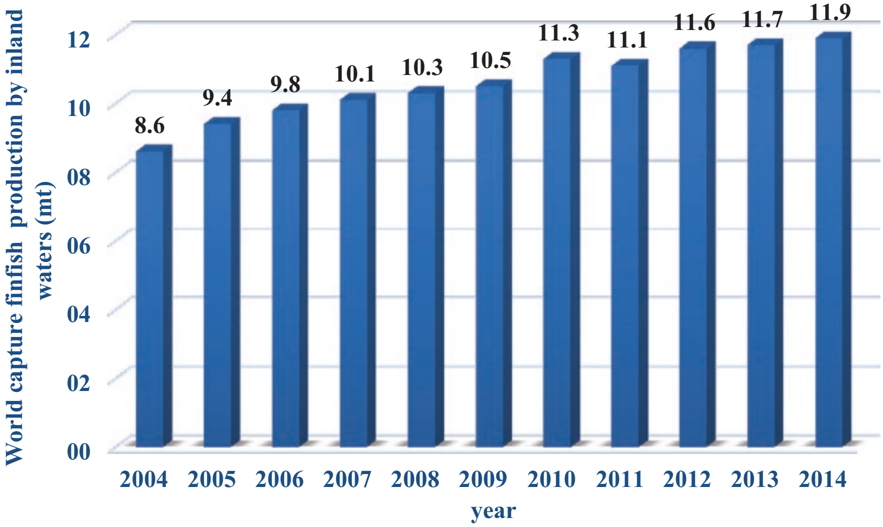

Fig. 2.6 World capture finfish production by inland waters (FAO 2008, 2010, 2016c)

conditions (Balon 1995), only in the last 50 years has this activity expanded significantly on a global scale. FAO world aquaculture production data (FAO 2014, 2015b) show expansion at an average annual rate of 7.5% in the period 2000–2013, from 35.5 to 70.1 mt. Inland aquaculture production comprises 63.7% of the total farmed production and 27.5% of the total world production of fish for food in 2013. A total of 136 million mt are used as food for mankind, providing an estimated 19.2 kg per capita of fish products, an increase of 2.6% relative to 2011, and of 93.9% relative to 1960. These data show the increasing importance of inland aquaculture to the world food supply over the last several decades (Fig. 2.7).

The data presented above clearly demonstrate that aquatic organisms, fishes in particular, are important sources of food for survival and for generation of wealth worldwide. Regarding FiGR of continental waters, such resources are still poorly evaluated. Unmanaged fisheries can directly impact wild populations, causing changes in the population age distribution, age of first reproduction, genetic structure and species composition (Boehlert 1996). For fish production from aquaculture, the sustainability of production systems depends on several variables specifically pertaining to the species. The maintenance of genetic variability and the integrity of populations are fundamental to the domestication of new species, and to continuing genetic improvement of the species cultivated. The use of fish genetic resources within a particular country for food production requires careful assessment in relation to the shared use of the benefits generated by the use of such resources (Bartley et al. 2009). As an example, tilapias currently are raised on almost all continents; yet, tilapia genetic resources are native to Africa and the Middle East (Pullin 1988; Eknath and Hulata 2009).

Fig. 2.7 World aquaculture production by inland waters (mt) (FAO 2008, 2010, 2016c)

2.6 Genetic Resources for Aquaculture Species

Against this background, a brief review of AqGR for key aquaculture species is in order. Analogous to crop and terrestrial livestock species, aquacultured fishes have centers of origin. Just like terrestrial farmers, aquaculturists have tended to domesticate species suited to aquaculture production using resource populations native to their region. Given, however, that domestication of aquacultured species occurs within the regions where valued wild populations exist, there are implications regarding in how genetic resources should best be managed. Eknath (1995) noted that management of aquatic genetic resources should involve a continuum of activities: documentation of genetic resources and the variety of ecosystems in which they are functional parts, including status of and potential threats to natural and farmed stocks; characterization of the genetic structure or distinctness and conservation value of the resource; evaluation of economic potential; and utilization of genetic resources in sustainable breeding schemes, including resolution of any issues regarding access to germplasm. The common theme among all these activities is conservation of genetic diversity. To illustrate that point, we consider leading sectors of global aquaculture and describe the centers of origin for the respective species, relating key points regarding management and conservation of FiGR in the Neotropical region. These case studies show how breeding and conservation considerations often affect one another.

Chinese carps Asia is an early seat of aquaculture, with origins in China reaching back some 4,000 years. A classical Chinese polyculture system involves production of combinations of silver (*Hypophthalmichthys molitrix*), bighead (*Aristichthys* *nobilis*), common (*Cyprinus carpio*), and grass (*Ctenopharyngodon idellus*) carps that respectively consume phytoplankton, zooplankton, invertebrates, and vascular plants, collectively converting most of the biological productivity of a pond into harvestable fish. This polyculture is practiced on a vast scale; production for 2014 was for silver carp 4.98 million metric tons (MMT), bighead carp 3.25 MMT, common carp 4.15 MMT, and grass carp 5.54 MMT (FAO 2016b). Despite the deep historical origin of the culture system, until recently Chinese aquaculturists went to the wild each generation to collect broodstock or seedstock; domestication of Chinese carps is relatively recent. There is some dispute as to the center of origin of the Chinese carps (Wolfarth 1995). Fossils of carps derive from the Pliocene in China (Committee for the Collection of Experiences on the Cultivation of Freshwater Fish Species in China 1981), and the greatest diversity of species in Subfamily Cypininae of Family Cyprinidae is in China. Hence, we regard the center of origin of aquacultured carps as China, likely in the Yangtze, Pearl, and Amur rivers for the respective species.

Indian carps Indian aquaculture also has a traditional polyculture system in which three Indian major carps – catla (*Catla catla*), rohu (*Labeo rohita*), and mrigal (*Cirrhinus mrigala*) respectively consume surface foods, algae and submerged vegetation, and detritus and decayed vegetation. The Indian polyculture system is practiced across India and has spread to Southeast Asia, often in combination with Chinese carps, tilapias and other species. Global production values in 2014 were for catla – 2.77 MMT, rohu 1.67 MMT, and mrigal 0.41 MMT (FAO 2016b). While widely cultured, all three species have their centers of origin in northern India. Catla is endemic to the rivers of northern India, the Indus plain, and adjoining regions of Pakistan, Bangladesh, Nepal and Myanmar. Rohu is an Indus-Ganges riverine species of northern and central India, and the rivers of Pakistan, Bangladesh and Myanmar. Mrigal is endemic to the Indus and Ganges river systems.

Salmonids Culture of Atlantic salmon has recent origins; systems for net-pen aquaculture were developed as recently as the late 1960s in Norway (Gjdrem et al. 1991). Atlantic salmon (*Salmo salar*) production subsequently spread from Norway to Scotland, the Faroe Islands, Canada, the United States, Chile and New Zealand. It has become a major sector of aquaculture, with 2014 production of 2.33 MMT (FAO 2016b). Selective breeding was initiated as early as 1971 (Gjedrem and Aulstad 1974). To assemble a broad genetic base for subsequent selective breeding, Atlantic salmon broodstock were sampled from 41 different rivers and localities, all but one from Norway; a few additional resource strains were added from 1975 to 1977. Matings were made both within and between strains (Gjedrem et al. 1991), selecting for rapid growth and low incidence of precocious male maturation. The Norwegian Atlantic salmon breeding program has proven highly successful, with gains in growth rate of 10.6–14.2% per generation (Gjedrem 2000).

Differentiation of allozyme and DNA markers showed that western Atlantic, eastern Atlantic, and Baltic Sea populations of Atlantic salmon differ at the molecular level (Stahl 1987; King et al. 2001, 2007). Further, **local adaptations** promoted by homing to spawning areas and strong selective pressures are known for Atlantic salmon populations throughout the world (Garcia de Leaniz et al. 2007). Hence, culture and escape of European-derived, selectively bred aquaculture stocks into North American waters and introgression with locally adapted North American populations poses risk of **outbreeding depression**, and hence a threat to conservation of native populations (NRC 2002). Such concerns provided the impetus for development of a North American strain of Atlantic salmon for use in regional aquaculture (National Cold Water Marine Aquaculture Center 2015). Hence, there are two centers of origin for cultured Atlantic salmon, one in Norway and one in eastern North America.

Several species of Pacific salmonids *Oncorhynchus* sp. have been domesticated and brought into aquaculture production. The most important among them is rainbow trout (*O. mykiss*). First domesticated in the late 1800s, production systems have evolved from simple ponds to raceways to floating marine netpens. Production or rainbow trout has expanded from western North America to Europe, Chile, Japan, and Australia, in 2014 totaling 813,000 MT (FAO 2016b). Among many strains of rainbow trout under production (Kincaid et al. 1997), particularly noteworthy are Shasta (derived from northern California), Kamloops (southern British Columbia) and Donaldson (Washington – Donaldson and Olson 1955; Hines 1976). Despite having a large range – from northwestern Mexico to the Amur River between Russia and China – the most important cultured strains of rainbow trout are from a rather narrow part of the range in western North America.

Tilapias Culture of tilapias (*Oreochromis* sp.) is one of the fastest-growing sectors of aquaculture, both within and outside their native range in Africa and the Middle East. Perhaps the key reasons that tilapias are so widely cultured are that they are hardy and easy to propagate. Tilapia are mouth brooders – after spawning, the females incubate eggs or fry in their mouths. Hence, tilapias are relatively easy to domesticate, and hence there may be multiple centers of origin for a given species. Foremost among several species widely produced is Nile tilapia (*Oreochromis niloticus*); 2014 production of Nile tilapia was 3.67 MMT (FAO 2016b). Many lines ranging from semi-wild unselected stocks to high-performance selectively bred stocks are produced. The tendency among breeders and producers to label their strains with the names of institutions, companies, or even individuals frustrates researchers and managers confronted with poorly characterized genetic material of largely unknown origins (Eknath 1995). Within this complicated background, tilapia breeding programs have been reviewed by Eknath (1995) and Eknath and Hulata (2009).

Among the many programs of selective breeding of tilapias, derivation from Nile River or other Egyptian stocks is common. The breeding program with the greatest international impact is the Genetically Improved Farmed Tilapia (GIFT) project, which was the result of collaboration between the Philippine Bureau of Fisheries and Aquatic Resources, two Philippine universities, AKVAFORSK of Norway, and the International Center for Living Aquatic Resources Management (now the World Fish Center). New germplasm was collected from Egypt, Ghana, Senegal, and Kenya, and four established farm stocks from the Philippines. A complete 8 × 8 diallel cross was made, and the 25 best-performing families were selected to produce a genetically mixed base population. A combined family and within-family selection strategy was adopted and implemented through nine generations as of

2009 (Ponzoni et al. 2011). Genetic gain for growth rate over nine generations was estimated at 64% relative to the founding population (Khaw et al. 2008). The outcome of the GIFT project generated interest from developing countries in Asia, the Pacific, and Africa, both in terms of developing their own aquaculture strains, and also in gaining access to the GIFT germplasm, and the GIFT strain has been disseminated to 11 countries in Asia (Gupta and Acosta 2004). The WorldFish Center decided not to introduce the GIFT strain into countries where *O. niloticus* is indigenous, concerned that interbreeding of the GIFT strain with locally-adapted native populations might compromise wild aquatic genetic diversity Following an expert consultation in 2002, the WorldFish Center, decided to help countries apply the GIFT methodology to the genetic improvement of indigenous tilapias in the 13 member countries of the International Network on Genetics in Aquaculture (Bangladesh, China, Cote d'Ivoire, Egypt, Fiji, Ghana, India, Indonesia, Malaysia, Malawi, Philippines, Thailand, and Vietnam; Gupta et al. undated).

2.7 Biogeography of Fishes Globally

Relating aquaculture production, management of fisheries, and FiGR on a global scale requires understanding of the natural distributions of cultured and fished species. To achieve such an understanding, we must have a working knowledge of the biogeography of fishes. That is, understanding patterns of fish distribution requires synthesis of knowledge among fields as diverse as geology, paleontology, systematics, ecology, and physiology. To be sure, our knowledge of these fields is incomplete, so any attempt to explain fish distributions, especially in understudied regions, will require some degree of uncertainty (Moyle and Cech 2001). To set the stage, plate tectonics is a unifying theory explaining the configuration of the Earth's surface and underlies much of our understanding of the historic distributions of aquatic and marine organisms (Berra 1981). In this section, we consider the biogeography of fishes globally. In the next section, we will consider biogeography within the Neotropical region, and in the following chapter, we will consider biogeography in yet greater detail, relating it to the distribution of genetic variation within Neotropical fish species.

Freshwater fishes can be divided into two zoogeographic types, **euryhaline marine fishes** and obligatory freshwater fishes. Euryhaline marine fishes have tolerance of wide variation in salinity; while they are primarily marine, they may enter freshwater for long periods of time, especially the lower reaches of coastal rivers. A regionally important example is bull shark *Carcharinhus leucas*. **Obligatory freshwater fishes** must spend at least part of the life cycle in freshwater. In the context of zoogeography, two types are distinguished. **Freshwater dispersants** are not capable of dispersing long distances through saltwater. Hence, the distributions must be explained by freshwater routes of dispersal or by plate tectonics. Regionally important examples include the cichlids and characids. Freshwater dispersants dominate the fresh waters of most of the world (Berra 1981; Moyle and Cech 2001). **Saltwater dispersants** are capable of dispersal through saltwater. Such taxa include both **diadromous fishes** (those that migrate between fresh and salt water to complete their life cycle) and freshwater representatives of mostly marine taxa. Diadromous species often give rise to non-diadromous species. Regionally important examples of saltwater dispersants include the galaxiids.

For global-scale study of zoogeography of fishes, the world can be divided into six **zoogeographic regions** (Darlington 1957): the African Region, the Neotropical Region (including South America and much of Central America), the Oriental Region (the Indian subcontinent, southeast Asia, most of Indonesia, and the Philippines), the Palearctic Region (Europe and Asia north of the Himalayas and the Yangtze River), the Nearctic region (North America to central Mexico), and the Australian Region (Australia, New Zealand, New Guinea and nearby islands). Each of these regions has distinctive elements of its fish fauna that reflect its historic isolation from other regions. Some faunal elements are shared even among continents because of past geographic connections; thus, because South American Africa and Australia were all once part of the southern supercontinent, Gondwanaland, they have derived members of certain shared ancestral evolutionary lineages – e.g., lungfishes, cichlids, characids, and galaxiids.

2.8 Biogeography of Fishes in the Neotropical Region

The dynamics of formation of the Neotropical region date to the Middle Cretaceous age, about 115–125 Mya, when South America became separated from the supercontinent Gondwanaland (Valencio and Vilas 1969). This long process of gradual geological and climatic changes, accompanied by the genesis and evolution of flora, fauna, and microorganisms, made the Neotropics by far the most species-rich ecozone on earth (Albert and Reis 2011). The importance of the Neotropical region to biodiversity was recognized by Alfred Russel Wallace (1876), a contemporary of Darwin, who wrote that:

> *The Neotropical Region . . . comprehending not only South America but Tropical North America and the Antilles . . . is distinguished from all the other great zoological divisions of the globe, by the small proportion of its surface occupied by deserts, by the large proportion of its lowlands, and by the altogether unequalled extent and luxuriance of its tropical forests. It further possesses a grand mountain range, rivaling the Himalayas in altitude and far surpassing them in extent, and which, being wholly situated within the region and running through eighty degrees of latitude, offers a variety of conditions and an extent of mountain slopes, of lofty plateaus and of deep valleys, which no other tropical region can approach.*

There is some debate about the origin of Neotropical mega-biodiversity. A leading hypothesis is that many or most Neotropical species emerged in glacial and interglacial periods during the Quaternary period or even during paleogeographic modifications during the late Tertiary period. Currently it is accepted that species in the Neotropical region appeared from the Eocene/early Oligocene (~39 Mya) to the Quaternary (~ 2 Mya) (Rull 2007). There is consensus that the Neotropics has a myriad of complex biogeographic patterns, interacting with each other and yielding an abundance of species distributed throughout Central to South America. Over the past

Table 2.2 Summary of hypotheses to explain the neotropical species richness (Hubert and Renno 2006)

Hypothesis	Main characteristics	References
The gradient hypothesis	Steep environmental gradient	Endler (1977, 1982)
The paleogeography hypothesis	Geological changes resulting from the Andean foreland dynamic during the Tertiary	Räsänen et al. (1990, 1992), Patton et al. (1994), Hoorn et al. (1995), and Patton and Da Silva (1998)
The river hypothesis	Fragmentation of terrestrial biota subsequent to the final establishment of the Amazon drainage during the late tertiary	Wallace (1852), Patton et al. (1994), Bates et al. (1998), and Hall and Harvey (2002)
The disturbance–vicariance hypothesis	Climatic cooling resulting in an ecologically unsuitable habitat	Colinvaux (1987, 1993) and Colinvaux et al. (1996)
The refuge hypothesis	Climatological fluctuations of the Pleistocene leading to alternative fragmentations and coalescences of the forestry ecosystem	Haffer (1969, 1997), Vanzolini and Williams (1981), Prance (1982), and Whitemore and Prance (1987)
The river-refuge hypothesis	Refuges enhancing allopatric differentiation across rivers	Ayres and Clutton-Brock (1992) and Haffer (1997)
The museum hypothesis	Species originating by allopatric differentiation in stable mountain forests during marine high stages and later accumulating by dispersal in the lowlands, which act as 'museums'	Fjeldsa (1994), Roy et al. (1997), and Nores (1999)

century, different hypotheses have been proposed to clarify how such species richness originated and evolved. Table 2.2 showcases a summary of the main hypotheses.

Freshwater fishes are among richest vertebrate faunas in the Neotropical region. The diversification of continental fish species found in rivers, creeks, or reservoirs is remarkable from the lowlands of Mexico through the southernmost tip of Argentina. The number of species found is uncertain. According to different authors, present estimates account for more than 7,000 species among the ~14,000 freshwater fish species formally described globally (Lundberg et al. 2000; Berra 2001; Reis et al. 2003a; Lévêque et al. 2005; Lévêque et al. 2008; Abell et al 2008; IUCN 2016). A database known as Fish-SPRICH, which covers more than 80% of the continental waters on earth, identified 4,321 fishes, including native, non-native, and endemic freshwater species (Brosse et al. 2013). We point out that this number may be underestimated since cryptic freshwater fish species are found more commonly than might be expected (Piggott et al. 2011). Taxonomic reviews of Neotropical ichthyology are set out very well by Malabarba et al. (1998) and Reis et al. (2003). Other aspects of the historical biogeography of Neotropical freshwater fishes can be found in Albert and Reis (2011), essential reading for those interested in the matter.

The vast diversity of the Neotropical ichthyofauna is within Class Actinopterygii, the ray-finned fishes. Fifteen orders of ray-finned fishes are found throughout the Neotropics (Table 2.3). These orders are roughly equal regarding their distribution

Table 2.3 Orders of ray-finned fishes found in continental waters of the Neotropics

Order	# families	# species	Examples of neotropical freshwater fish – some representative FiGR
Characiformes	15	868	*Brycon* spp., *Colossoma macropomum, Piaractus mesopotamicus, Piaractus brachypomum*
Siluriformes	13	788	*Pseudoplatystoma* spp., *Brachyplatystoma* spp., *Paulicea luetkeni, Pimelodus* spp., *Sorubim lima, Rhamdia quelen*
Perciformes	5	241	*Geophagus* spp., *Astronotus ocellatus, Plagioscion* spp., *Cichla* spp., *Crenicichla lenticulata, Plagioscion aquasissimus*
Cyprinodontiformes	4	114	*Poecilia* spp., *Heterandria* spp., *Profundulus* spp.,
Gymnotiformes	5	104	*Gymnotus* spp., *Magosternarchus* spp.
Clupeiformes	3	17	*Pellona castelnaeana, Triportheus* spp.
Atheriniformes	1	7	*Odontesthes* spp., *Chirostoma* spp.
Pleuronectiformes	1	7	*Potamotrygon* spp., *Hypoclinemus mentalis, Catathyridium jenynsii*
Synbranchiformes	1	4	*Synbranchus marmoratus*
Osteoglossiformes	2	3	*Arapima gigas, Osteoglossum bicirrhosum*
Batrachoidiformes	1	2	*Thalassophryne amazonica, Batrachoides goldmani*
Tetraodontiformes	1	2	*Colomesus asellus*
Anguilliformes	1	1	*Stictorhinus potamius*
Beloniformes	1	3	*Strongulura* spp., *Hyporhamphus mexicanus, Potamorrhaphis* spp.
Syngnathiformes	1	4	*Pseudophallus mindii, Microphis brachyurus lineatus*

Adapted from Albert et al. 2011

and number of species (Rosa and Lima 2008). Some orders, such as Characiformes (characids), Siluriformes (catfishes), Perciformes (perches), and Osteoglossiformes (bony tongues), comprise important species for fisheries and aquaculture, and others have representatives in the ornamental fish trade. Thus, among the thousands of native freshwater fishes of the Neotropics, many of them play an important part in the economies of countries as a source of animal protein for riverine communities or at a more industrial scale from fish farming, commercial fisheries, and recreational sport fishing. Further elaboration upon regional differentiation of fish faunas within the Neotropical region may be found in Chap. 3.

2.9 Fish Genetic Resources in the Neotropical Countries

The Neotropical region encompasses a myriad of freshwater habitats characterized by streams, rivers, floodplains, lakes, aquifers and reservoirs, which make this region the richest in volume and diversity of continental waters across the world. Despite the abundance and variety of freshwater bodies in countries and territories in Central America, the Caribbean and South America, inland fisheries and aquaculture show only a recent history as a source of food and income for regional economies. During the 1950s, the contribution of inland capture and fish farming production did not exceeded 154,000 tons (FAO 2016b). The contribution of farming and inland capture of fish in the Latin America and Caribbean region has increased over the last four decades. Aquaculture production surpassed inland capture in 1999, and since then freshwater fish farming corresponds to 56.7% of the total freshwater fish production, with rather high sustained fish farming production (Fig. 2.8, FAO 2016b).

The most striking feature of FiGR in most of the Neotropical countries is the predominance of non-native species in aquaculture operations (Table 2.4). This stands in stark contrast to the immense native fish species diversity present in Neotropical continental waters. For example, Mexican federal government hatcheries produced finfish fingerlings encompassing 19 species, 12 non-native (tilapias, carps and bluegill) and 7 native (*Oncorhynchus mykiss*- rainbow trout, *Cichlasoma trimaculatum and C. urophtalmus* trimac cichlid, *Micropterus salmoides* – largemouth bass – *Ictalurus punctatus* – channel catfish, – *Algansea lacustris* – pátzcuaro chub, *Atractosteus spatula* – alligator gar), between 2001 and 2009 (Ibáñez et al. 2011). There is some regional progress towards domestication and culture of native species. In Brazil, a wide diversity of native fish species has been cultivated in different production systems and regions, among them *Arapaima gigas* - pirarucu, *Brycon cephalus* - matrinxa, *Colossoma macropomum* - tambaqui, *Pseudoplatystoma corruscans* - pintado, and *Piaractus mesopotamicus* - pacu (IBGE 2015; Valladão et al. 2016). Although within the region there certainly are large-bodied species amenable for domestication and production on locally abundant foods and feedstuffs, efforts at domestication and development of culture of regional species have been strikingly few. We regard development of culture of native species as a sign of the emerging maturation of the regional aquaculture sector and a favorable development for conservation of native aquatic communities. Other native regional species likely will emerge from ongoing evaluations in the near term.

Among native freshwater fish species listed as economically important for aquaculture and fisheries are *Atractosteus tropicus, Chirostoma spp., Alloophorus robustus, Rhambdia sp., Petenia splendida, Astyanax mexicanus,* among others (CNA 2012; CNP 2012). Alvarado (2005) assessed the ichthyodiversity of Lake Izabal, Guatemala and its tributaries, reporting 48 freshwater species of different levels of economic importance for ornamental use, aquaculture, and fisheries, such as *Astyanax aeneu, Archocentrus* spp.*, Cichlasoma octofasciatum, Parachromis managuensis, Ictalurus furcatus, Rhamdia guatemalensis, Brycon guatemalensis,* among others. Kinh-Pineda et al. (2006) reported 17 fish species in continental waters narrowly endemic to Guatemala. Many native fish species are shared among countries from Mexico to Panamá.

In South America, the Amazon forest and its rivers are shared among adjoining countries, such as Bolivia, Brazil, Colombia, Ecuador, Guiana, Peru, Suriname, and Venezuela. All of these countries harbor a specific and common ichthyofauna in their watersheds (Carvajal-Vallejos and Zeballos Fernández 2011; Buckup et al. 2007; Bogotá-Gregory and Maldonado-Ocampo 2006; Barriga 2012; Vari and Ferraris 2009; Ortega et al. 2012; Mol et al. 2012; Lasso et al. 2004). To grasp the

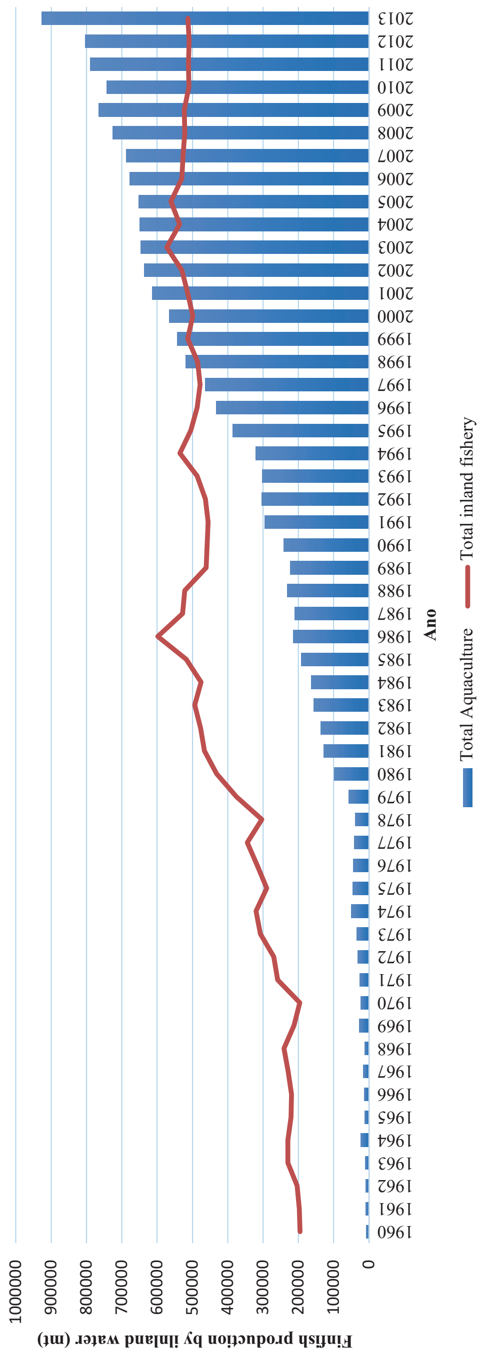

Fig. 2.8 Total inland aquaculture and fishery production in Neotropical countries from 1960 to 2013 (FAO 2016b)

Table 2.4 Major aquaculture species in selected Neotropical countries

Country	Species	native	Non-native
Cuba	Southern white shrimp, *Litopenaeus schmitti*	X	
	Whiteleg shrimp, *Litopenaeus vannamei*		X
	Giant freshwater prawn, *Macrobrachium rosenbergii*		X
	Common carp, *Cyprinus carpio*		X
	Silver carp, *Hypophthalmicthys molotrix*		X
	Bighead carp, *Aristichthys nobilis*		X
	Grass carp, *Ctenopharyngodon idellus*		X
	Channel catfish, *Ictalurus punctatus*		X
	Nile tilapia, *Oreochromis niloticus*		X
	Other tilapias, including hybrids		X
Mexico	Whiteleg shrimp	X	
	American cupped oyster, *Crassostrea virginica*	X	
	Pacific cupped oyster, *Crassostrea gigas*	X	
	Giant river prawn *Macrobrachium rosenbergii*		X
	Rainbow trout, *Onchorhynchus mykiss*		X
	Channel catfish	X	
	Silversides, *Chirostoma* sp.	X	
	Largemouth bass, *Micropterus salmoides*		X
	Nile tilapia		X
	Other tilapias, including hybrids		X
Panama	Whiteleg shrimp	X	
	Common carp		X
	Silver carp		X
	Rainbow trout		X
	Cachama, *Colossoma macropomum*		X
	Peacock cichlid, *Cichla ocellaris*		X
	Nile tilapia		X
Peru	Peruvian scallop, *Agropecten purpuratus*	X	
	Pacific cupped oyster		X
	Whiteleg shrimp	X	
	Rainbow trout		X
	Cachama	X	
	Pacu, *Piaractus mesopotamicus*		X
	Nile tilapia		X

(continued)

Table 2.4 (continued)

Country	Species	native	Non-native
Brazil	Brown mussel, *Perna perna*	X	
	Pacific cupped oyster		X
	Mangrove oyster, *Crassostrea rhizophorae*	X	
	Lion's paw scallop, *Nodipecten nodosus*	X	
	Giant river prawn		X
	Rainbow trout		X
	Common carp		X
	Bighead carp		X
	Silver carp		X
	Grass carp		X
	Cachara catfish, *Pseudoplatystoma fasciatum*	X	
	Pintado catfish, *Pseudoplatystoma coruscans*	X	
	Cachapinta (hybrid cachara x pintado)	X	
	Pacu	X	
	Tambaqui, *Colossoma macropomum*	X	
	Tambacu (hybrid pacu x tambaqui)	X	
	Nile tilapia		X
	Pirarucu, *Arapaima gigas*	X	
Chile	Chilean mussel, *Mytilus chilensis*	X	
	Pacific oyster	X	
	Atlantic salmon, *Salmo salar*		X
	Coho salmon, *Oncorhynchus kisutch*		X
	King salmon, *Oncorhynchus tschawytscha*		X
	Rainbow trout		X

Abstracted from data published by the Fisheries and Aquaculture Department, FAO (2016)

potential FiGR in just the Amazon basin, 100 economically important fish species are landed in the Manaus/Brazil fishing port on the Amazon River alone. Characiformes are the most diversified group with 46 species, followed by the Siluriformes with 28 species, and Characiformes with 22 species (Santos et al. 2006). About ten of these 100 species regularly caught in the Amazon River are used in different levels of farming systems in the Amazon region. Another important ecosystem shared by South American countries is the Pantanal, one of the largest wetlands worldwide, located mostly in central-western Brazil and spreading into Bolivia and Paraguay (Pott and Pott 2004; Silva and Girard 2004). In the large Pantanal floodplain, Britski et al. (2007) identified 269 fish species, encompassing 110 members of Order Characiformes, 105 Siluriformes, 15 Gymnotiformes, 17 Perciformes, 11 Cyprinodontiformes, and 11 other fish orders, a finding not surprising given the size of the region and lack of barriers to dispersal. Different fish species are economically important in this ecosystem, among them pacu (*Piaractus mesopotamicus*), pintado (*Pseudoplatystoma corruscans*), cachara (*Pseudoplatystoma fasciatum*), dourado (*Salminus brasiliensis*), jaú (*Paulicea luetkeni*), piavuçu (*Leporinus macrocephalus*), barbado (*Pinirampus pinirampu*), curimbatá

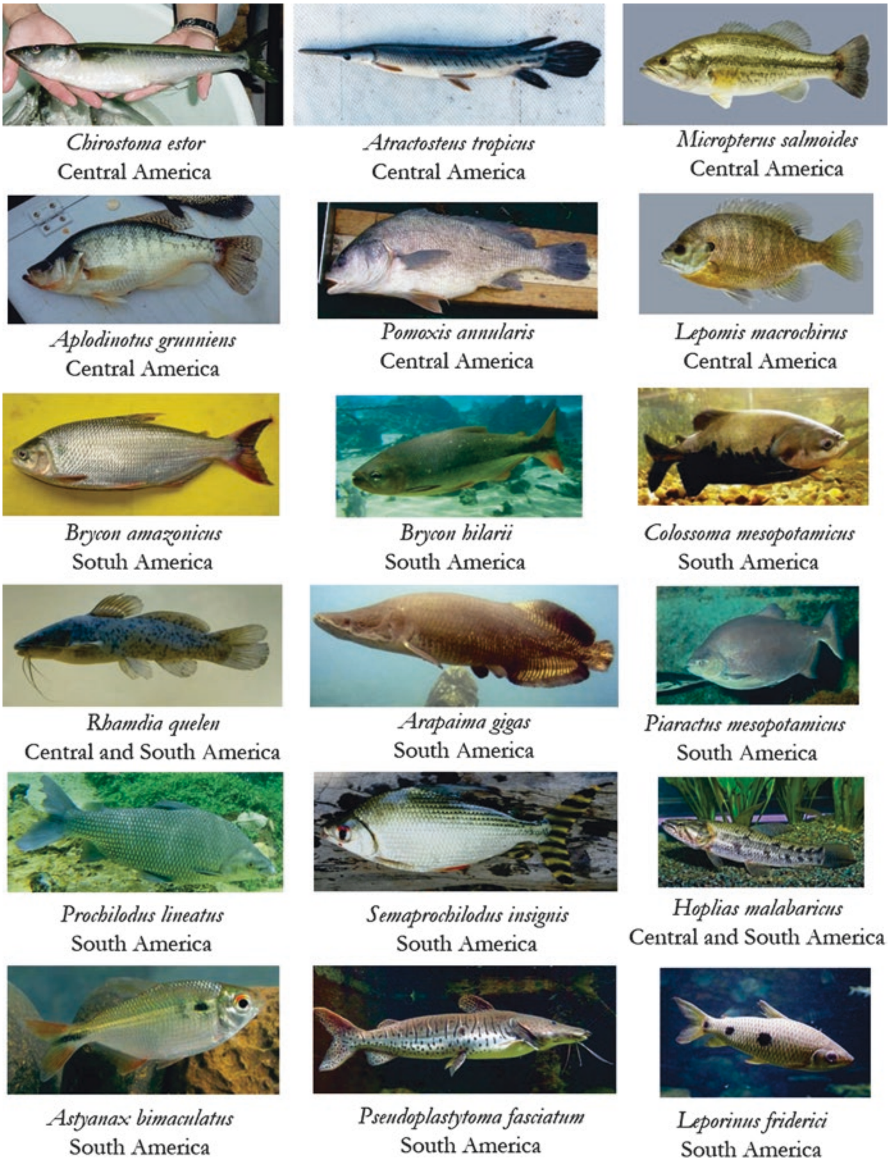

Fig. 2.9 Representative FiGR native to drainages of Central and South America of importance to fisheries and aquaculture

(*Prochilodus lineatus*), among others. Some representatives of the chief native fish species deemed FiGR in Neotropical region are showcased in Fig. 2.9.

Centers of genetic diversity for Neotropical fish species are mostly only now becoming recognized, as we note in detail in Chap. 3. In our context, a key point is that different genetic lineages within species may offer different aquacultural traits, and judicious choice of resource lines will have important bearing on the future success of selective breeding programs. Recognition that domestication of aquaculture stocks for Neotropical species is relatively recent, ongoing, or yet to begin emphasizes the importance of conserving wild FiGR. These genetic resources will provide the raw material for future foundation and genetic improvement of aquaculture stocks. The development of genetically improved stocks of Atlantic salmon and Nile tilapia provide case studies for how to systematically evaluate resource lines and purposefully make a diverse foundation stock upon which to practice selective breeding. Development of genetically improved lines of Neotropical species will contribute to development of the aquaculture sector in the Neotropical region. Similarly, recognition of patterns of population genetic differentiation will guide the recognition of biologically relevant units for management of capture fisheries.

2.10 Threats to FiGR

2.10.1 Damming

Freshwater ecosystems are of paramount importance not only for providing habitats for a remarkable diversity of life, but also for being crucial biotic resources for human survival through their history in this planet. Freshwater systems provide **ecological services** for human populations through water supply, energy generation, food production, and other benefits estimated to contribute US$1.7 trillion per year (Costanza et al. 1997). Freshwater fishes play an important part in generating ecosystem services through both ecological functions and direct human welfare (Holmlund and Hammer 1999). However, global conservation priorities have tended to overlook freshwater diversity. Abell et al. (2011), assessing data on about 13,300 freshwater fish species, identified ecozones of remarkable ichthyodiversity, overlapping regions of terrestrial importance, particularly in the tropics. Freshwater ecosystem services depend on the appropriate function and maintenance of all their biotic and abiotic components. Disturbance of this balance through elimination of species or populations will have a long-term impact on ecosystem services (Reis 2013; Alho et al. 2015).

Environmental disturbances in continental waters and their effects on the fish diversity and population depletion have been one of the main causes not only for the loss of ichthyodiversity in general, but also population size reduction, extirpation or even local species extinction. Revenga et al. (1998) mapped the situation of world's watersheds at the end of 1990s assessing the anthropogenic threatens that impacted continental waters and the life diversity they harbor. The authors listed the vulnerabilities and risks of the various human activities affecting freshwater ecosystems, which are described in Table 2.5.

Among all human disturbances on continental waters, damming is the most impacting due to the magnitude of freshwater ecosystem changes during and after dam construction (Baxter 1977; Nilsson et al. 2005; Liermann et al. 2012). Dams are primarily built for the benefit of human populations in order to irrigate crops, generate electric power for economy growth, prevent flooding, and provide a reliable

Table 2.5 Anthropic threats to freshwater ecosystems (From Revenga et al. 1998 and McAllister et al. 2001)

Sector	Measure of threat	Impacts (Add to each, biodiversity loss)
Agriculture	11% of land in crops, 26% in pasture. 3/4 of human water withdrawals, 250 million hectares under irrigation	Runoff of toxic pesticides (fish kills); fertilizers and manure (eutrophication); soil (turbidity and siltation). Overgrazing (loss plant cover, bank stability)
Deforestation	50% of world's forests lost; widespread clearcutting instead of selective harvesting	Soil erosion (turbidity and sedimentation. Rapid runoff. Loss stream food/habitat (leaves, wood, insects). Changed hydrological cycles
Dams	60% world's river flow regulated. 15% world's precipitation held in 500,000 km^2 of reservoirs. Blocking of movement of local- and long-distance migrations in neighborhood of dam	Fish migrations blocked; stocks lost. Seasonal flows changed; flows reduced. 25 million km river habitat modified. Flood plains and deltas lost. Lowered fish production. Sediment/turbidity/ nutrient changes. Running to still water
Industry and urban areas	Release toxic substances, hormone blockers, and untreated sewage. 1/4 of human water withdrawals	Fish kills and advisories. Impaired reproduction. Eutrophication. Reduced flows
Aquaculture and introductions	Escape of alien species. Pollution	Competition with and loss of native biota
		Spread alien pests and diseases. Loss of native habitats. Genetic pollution. Eutrophication
Channelisation and levee construction	Simplification of river structure. 500,000 km of river altered for shipping	Loss of habitats, flood plains and wetlands
Fishing	Over-harvesting. Gear damage	Reduced populations, loss of stocks, changed food webs, and habitat loss
Acid rain	Reduction of pH (increase in acidity) of lakes and streams down to 4.5 or lower in thousands of water bodies in North America and Europe	Reduction of populations or extirpation of species of mollusks, amphibians, fishes, etc. in water bodies. Development of skeletal abnormalities. Deposition of aluminum on fish gills
Human population and *per capita* consumption	Doubled to six billion since 1975. Per capita consumption doubled since 1950	Population/consumption rate increases magnify each sector impact above. Humans use 54% of geographically and temporally accessible water

source of drinking water. However, increasing population growth and economic development in recent years have demanded more water resources and driven the perceived need for dam construction in as many places as watershed geomorphology permits. Currently, around 60% of the world's rivers are somehow blocked by 37,000 large dams (higher than 15 m), among which more than 8,000 are built for hydroelectricity generation (International Commission on Large Dams 2011). Damming is a common practice across Neotropical countries from Mexico to Chile to form reservoirs for water supply and mainly to generate electric power. Brazil is deemed to be one of the most dammed countries in Latin America, with more than 75% of the energy stemming from hydropower generated by 706 power plant dams of different sizes (ANEEL 2008). Changes from lotic to lentic water because of damming impose both short- and long-term impacts, directly affecting the Neotropical fish fauna in different levels (Table 2.6).

The unprecedented boom in construction of hydropower dams seems to be a reality even for a sensitive ecosystem like the Amazon basin. According to Winemiller et al. (2016) "These projects address important energy needs, but advocates often overestimate economic benefits and underestimate far-reaching effects on biodiversity and critically important fisheries." The long-term impact on genetic diversity of an important genetic resource of the Amazon – *Colossoma macopomum* (cachama in Spanish and tambaqui in Portuguese) – was demonstrated by Farias et al. (2010), who showed that the Madeira River rapids are not a geographical barrier to genetic exchange of *C. macromum* between the Amazon basin and the Bolivian sub-basin. The authors suggested that the passive gene flow from the Bolivian basin into the Amazon basin is sufficient to avert independent demographic

Table 2.6 Impacts on fish fauna associated with damming (McAllister et al. 2001)

Impacts	Effects	Source
Preventing movement of migratory species up and down rivers,	Extirpation or extinction of genetically distinct populations or species	Neraas and Spruell (2001), and Agostinho et al. (2004a)
Changing turbidity/sediment levels	Affect species/ecosystems adapted to the rivers natural turbidity. Trapping silt in reservoirs deprives downstream deltas and estuaries of maintenance materials and nutrients that help make them productive ecosystems	Kondolf et al. (2014)
Changing conditions in rivers flooded by reservoirs	Running water becomes still, silt is deposited deep-water zones, temperature and oxygen conditions are created that are unsuitable for riverine species	Barrella and Petrere (2003), Poleto and Beier (2012), and Sabir et al. (2013)
Possibly fostering exotic species	Exotic species tend to displace indigenous biodiversity	Johnson et al. (2008)
Marginal lagoons provide vital habitat for the reproduction cycle of several neotropical fish species as nursery ground	Damming destroys marginal lagoons affecting directly fish recruitment because lack of feeding grounds for fingerlings	Gomes and Agostinho (1997), Pompeu and Godinho (2006), and Melo et al. (2013)
Changing the normal seasonal estuarine discharge and water quality	Can reduce the supply of entrained nutrients, impacting the food chains that sustain fisheries in inland and estuarine deltas	Jeong et al. (2014)
Modifying water quality and flow dynamics downstream	Affect hydrological features, altering the functioning of downstream ecosystems	Agostinho et al. (2004b)

histories of resident populations in the Bolivian and Brazilian components of the Amazon. Any attempt to construct dams along the Madeira River will disrupt the population dynamics not only of *C. macopomum*, but also of other endemic fish species. Another important fish species of the Amazon and its floodplain is *Arapaima gigas* (paiche in Spanish and pirarucu in Portuguese). This unique mammoth freshwater fish can reach over 200 kg, and is an important part of the diet and economy of the local dwellers (Saint-Paul 1986). Hrbek et al. (2005) carried out population genetic studies using mitochondrial DNA markers of *A. gigas* populations sampled along the Amazon River and its tributaries. The results showed low levels of population differentiation and high gene connectivity. The authors suggested that the Amazon basin acts as sources of emigrants within a **source-sink metapopulation model**, i.e., depleted populations can be recovered demographically by immigrating fish recruited from other conserved areas. Based on these outcomes, we can predict that isolation of *A. gigas* populations by damming can prevent the free movement and demographic rescue dynamics of the species, and can affect the geographic distribution of genetic variation in this species. We discuss other examples of population genetic structure of key regional species in Chap. 3.

River damming is inevitable in facing real-word development and human demands. The long-term fate of populations of Neotropical migratory fishes, which need upstream migration to complete their life cycles, may be to collapse or vanish in dammed rivers. Therefore, policy makers and power companies might be required to implement management actions, such as fish ladders, hatchery and stocking programs, and conservation of remaining river tributaries as refuges for critical components of the fish fauna. Agostinho et al. (2008) posited that in the Neotropical dammed freshwater ecosystem "Fishery/biodiversity management programs must incorporate a wide perspective of the system (environment, fishers and fish) and foresee a permanent ecosystem evaluation through monitoring and specific studies."

2.10.2 Fish Introductions and Hybridizations

The introduction of non-native species has been a common activity on all continents in order to boost local fishery potential, provide novel species choices for local aquaculture, promote sport fishing, for enjoyment as ornamental pets, to control unwanted organisms such as mosquitoes, and other uses (Welcomme 1988; Casal 2006). Approximately 17% of the world aquaculture production of fish originates from exotic species; this number shows the importance of the use of non-native species to the economy of many countries (De Silva et al. 2006, 2008). Chile is responsible for 27% of the total world production of salmon and this industry employs (directly, indirectly and induced) 53,000 people (Hishamunda et al., 2014). In Brazil, despite the impressive ichthyodiversity, the main aquaculture species is Nile tilapia, which amounts to 43.1% of Brazilian aquaculture production (IBGE 2015). As noted above, this same situation is found in other Neotropical countries (Table 2.4). Despite the importance of exotic species for the local economies, the uncontrolled introduction of non-native species is recognized as one of the principal causes of loss of species and local populations through habitat degradation (for example, common carp uprooting vegetation and disturbing sediment, thereby increasing turbidity), spread of diseases to native fish species, competition of introduced fishes with native species, and predation on native fish species (Fernando 1991; Ruesink 2005).

Another relevant issue concerning the conservation of FiGR is interspecific **hybridization**. The phenomenon was recognized by American ichthyologist Carl Leavitt Hubbs (1955), who pointed out the frequent occurrence of hybridization among freshwater fishes. More recent studies have reported hybrid zones, areas where different species meet and hybridize naturally (Barton and Hewitt 1985; Ribeiro 1985; Dowling and Secor 1997; Genovart 2009; Teixeira and Oliveira 2005; Montanari et al. 2012). Some features contribute to the more common incidence of natural hybridization among fishes than other vertebrates (Rahman et al. 2013), such as external fertilization, weak behavioral isolation mechanisms, unequal abundance of the two parental species, competition for spawning habitat, and decreased habitat complexity.

Aquaculture has increased the number of fish hybrids all over the world. The possibility of breeding fishes from different species of the same genus, or in some cases even a different genus, opens a window of opportunity to combine different genetic traits to produce new stocks offering desirable characteristics for aquaculture, such as better growth, low temperature tolerance, and flesh quality (Scribner et al. 2001; Bartley et al. 2001). Currently, interspecific hybridization has made a contribution to aquaculture in South America countries, including hybrids between species and even genera (Table 2.7). This genetic improvement methodology, however, can pose threats of backcrossing of fertile hybrids to elements of native FiGR (Hallerman and Kapuscinski 1995; Porto-Foresti et al. 2012). Wild populations would be vulnerable to introgressive hybridization driven by escapees into the freshwater ecosystem because some interspecific hybrids fishes are fertile and able to cross with the species from which they originated (Hashimoto et al. 2014). Figure 2.10 showcases three hybrids farmed in some South American countries. The cross between a *Colossoma macropomum* dam and a *Piaractus mesopotamicus* sire yielded the first hybrid produced in Brazilian aquaculture combining the meat quality and growth performance of *C. macropomum* with the low temperature tolerance of *P. mesopotamicus* (Almeida-Toledo et al. 1987; Calcagnotto et al. 1999). The hybrid is named tambacu (combining the dam's name – tambaqui – with the sire's name – pacu), and F_1 hybrids seem to be infertile (Santos et al. 2002). However, crosses between a *Pseudoplastystoma reticulatum* dam and a *P. corruscans* sire, which results in a robust hybrid for aquaculture, generate fertile progeny that currently are found in the wild (Prado et al. 2012; Vaini et al. 2014). Thus, continuing growth of hybrid production in aquaculture combined with the inevitable escapes pose risk to the genetic integrity of native populations. Introgressive hybridization poses outbreeding depression and loss of populations of the respective "pure" species. These outcomes could prove important for their impact on future domestication of potential aquaculture species, and on genetic resource material for breeding program of native species currently in the aquaculture industry (Fig. 2.11).

Table 2.7 Most common fish hybrids of Neotropical species in South America countries (Adapted from Hashimoto et al. 2012)

Dam species	Sire species	Reproduction viability		Aquaculture benefits	Hybrid countries producers	Level of FiGR risks
		Male	Female			
Colossoma macropomum	*Piaractus mesopotamicus*	Partially fertile	Unfertile	Faster growth, tolerant to low temperatures	Brazil (tambacu), México (tambacu)	Low
Colossoma macropomum	*Piaractus brachypomus*	Unknown	Fertile	Better growth than the parents	Brazil (tabatinga), Colombia (cachama hibrida), Peru (gamipaco), Venezuela (cachamoto), and México (tabatinga)	High
Piaractus mesopotamicus	*Piaractus brachypomus*	Unknown	Fertile	Fast growth and flesh quality	Southeast Brazil (patinga)	High
Pseudoplatystoma reticulatum	*Pseudoplatystoma corruscans*	Fertile	Fertile	Better growth performance	Brazil (cachapinta) and Argentina (surubí cachapinta)	High
Pseudoplatystoma reticulatum	*Leiarius marmoratus*	Unknown	Unknown	Omnivorous and fast growth	Brazil (cachandiá)	To be evaluated
Pseudoplatystoma reticulatum	*Phractocephalus hemioliopterus*	Unknown	Unknown	Used as ornamental and sporting fishing. Fast growth and flesh quality	Brazil (cachapira)	To be evaluated
Leporinus macrocephalus	*Leporinus enlongatus*	Unknown	Unknown		Brazil (piaupara)	Low

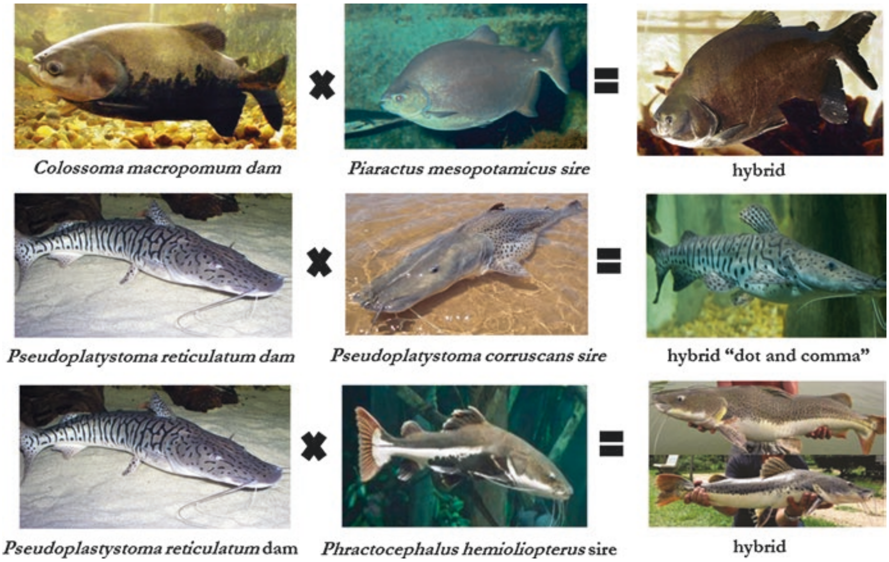

Fig. 2.10 Resource species and interspecific hybrids farmed in South American countries

Impacts of farm escapees on the wild populations of FiGR are more general than interspecific hybrids. The principal fish stocks used in the aquaculture industry are selectively bred strains, in which the genetic makeup can differ from conspecific populations. Gross (1998) reported that farmed Atlantic salmon (*Salmon salar*) encompass 94% of the total adult salmon, and wild populations are in continuous decline. The two distinct niches – wild and domestic – are currently so genetically unlike that there is a need to recognize a new biological entity of the domestic salmon, which he termed *Salmo domesticus*. The same prospectus concerns Nile tilapia (*Oreochromis nilotius*), the most cultivated tropical species worldwide, raised on all continents. The different strains used in farming operations, mainly the Genetically Improved Farmed Tilapia (GIFT) and other GIFT-derived strains, carry with them distinct allele and genotype frequencies yielded by several generations of selection. Therefore, conbcern is raised should these strains be produced within the natural geographic are of occurrence of wild Nile tilapia, as continuous escapes will likely erode the natural gene banks of this species, which may jeopardize the future of this important protein source for develop and developing countries (Eknath and Hulata 2009; Ansah et al. 2014).

Among the recommendations made by the Expert Consultation on the Conservation of Genetic Resources of Fish held in Rome, Italy in 1980 and The Workshop on Status and Trends in Aquatic Genetic Resources: a Basis for International Policy, convened in Victoria, Canada in 2006 (FAO/UNEP 1981; Bartley et al. 2007) to the audiences directly and indirectly involved in practical conservation of FiGR, two concerned the impacts of introduction and hybridization on FiGR:

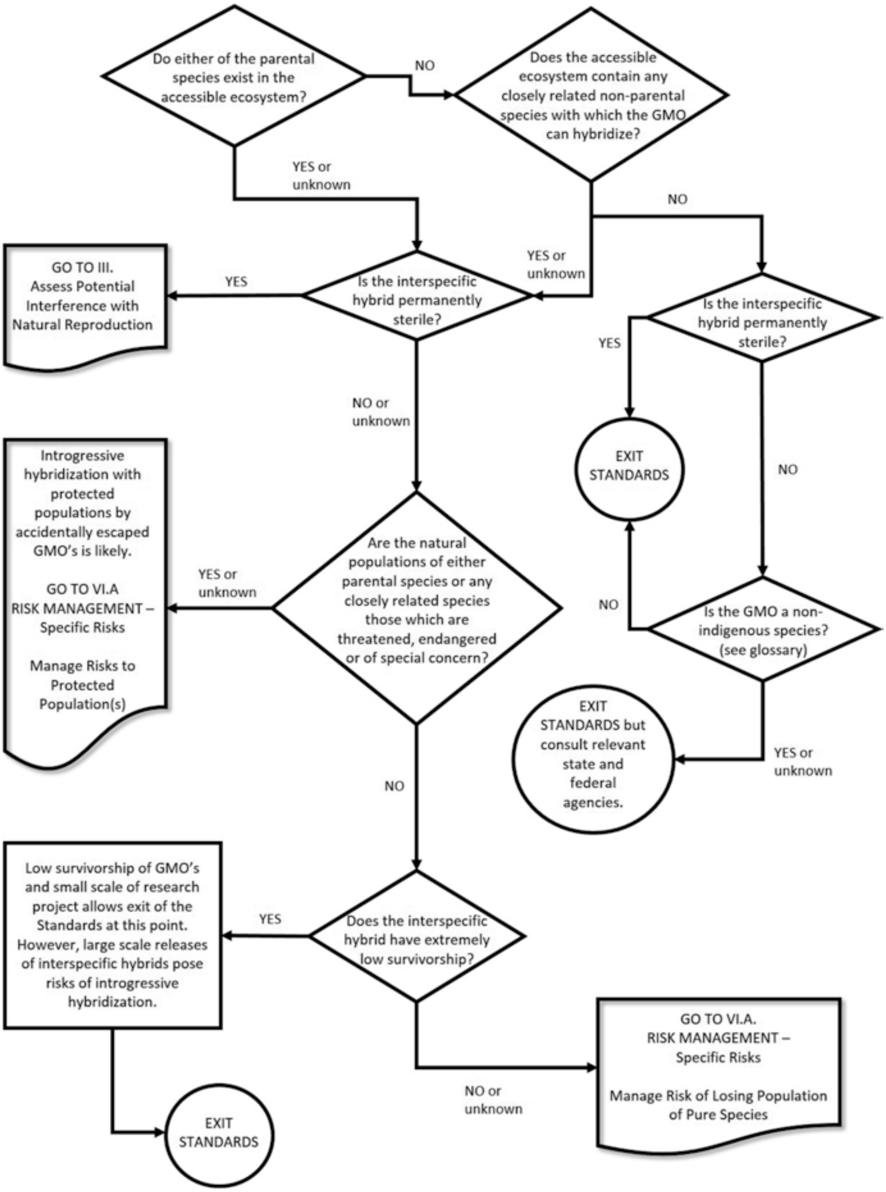

Fig. 2.11 Flowchart for assessing risks posed by production of interspecific hybrid aquatic organisms (ABRAC 1995)

Recommendation 7.2: To Governments (FAO/UNEP 1981)
"Introductions of new species into aquatic systems have often had serious consequences on existing resources. Governments which do not now have mechanisms to ensure that an objective analysis of risks precedes the introduction of an aquatic organism into national waters should take immediate steps to establish such mechanisms. Genetic, behavioural and ecological data, as well as potential for introduction of diseases, should be included in the risk analysis. In this connection, governments should be aware that the possibility of escape of cultivated aquatic species (even those kept only for research purposes) is so high that intend to confine imported aquatic animals does not obviate the need for such risk assessment."

Recommendations 7.5: Primarily for the Scientific Community (FAO/UNEP 1981)
"Research is needed on the controllability of sterile hybrids in relation to their impact on the ecosystem. It is particularly important to assess to possible genetic "leakiness" of "sterile" hybrid stocks and their possible impact on wild populations."

We observe that the recommendations made during the 1980s FAO meeting have not effectively changed the actions and precautions about fish introduction and hybridization by governments and producers across Neotropical countries. The 2006s workshop still pointed out that despite progress has been to protect FiGR further work is needed:

- to assess the status of FiGR in capture fisheries and aquaculture;
- to improve the capacities of scientists, technical persons, governments and industry;
- to improve facilities for characterizing FiGR;
- to develop genetically improved farmed types of aquatic species;
- to develop appropriate policy instruments on use and conservation of FiGR.
- to improve general awareness and levels of knowledge about FiGR; and.
- to prioritize species, geographic areas and production systems on which to expend resources for conservation and use of FiGr.

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