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Planning for aquaculture diversification: the importance of climate change and other drivers

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Planning for aquaculture diversification: the importance of climate change and other drivers

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Edited by

Brian Harvey
President
Fugu Fisheries Ltd.
Nanaimo, Canada

Doris Soto
Senior Scientist, INCAR, the Republic of Chile
Former Senior Aquaculture Officer, FAO, Rome
Puerto Montt, the Republic of Chile

Joachim Carolsfeld
Executive Director
World Fisheries Trust
Victoria, British Columbia, Canada

Malcolm Beveridge
Acting Branch Head, FIAA
FAO Fisheries and Aquaculture Department
Rome, Italy

and

Devin M. Bartley
Senior Research Associate
World Fisheries Trust
Rome, Italy

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This publication is the proceedings of the Food and Agriculture Organization of the United Nations expert technical workshop on Planning for aquaculture diversification: the importance of climate change and other drivers, which was held in Rome, Italy, 23–25 June, 2016 and organized by the Aquaculture Branch of the Fisheries and Aquaculture Department and World Fisheries Trust (Canada). The workshop was attended by 16 internationally renowned experts from nine countries representing the private sector, industry, academia, government and research organizations, and five staff members from FAO. The workshop was financed by the Government of the Kingdom of Norway whose support is gratefully acknowledged.

Abstract

Aquaculture is the world's most diverse farming system in terms of number of species, methods and the environments where the farms are located. Member countries are increasingly requesting guidance from FAO regarding diversification of aquaculture as wild fisheries reach their limits, human population grows and the demand for aquatic plants and animals for food and other uses increases. In response to these requests, FAO and World Fisheries Trust (Canada) convened the workshop *Planning for aquaculture diversification: the importance of climate change and other drivers*. Although there is an ever-increasing number of species being farmed in aquaculture and diversification is high in some cases, further diversification is constrained by limitations in technology, profitability, regulations, sustainability and enabling environments that include community acceptance. However, the natural diversity and diminishing stocks of capture fisheries provide an ongoing incentive to diversify and farm new animals and plants.

The workshop identified three main strategies for aquaculture diversification: 1) increase the number of species being farmed; 2) increase the evenness of farmed species; and 3) increase the diversity within currently farmed species by developing new strains. The workshop identified some primary drivers of diversification: market demand (including export opportunities), funding opportunities, competition and climate change, as well as other environmental and social factors.

Diversification of species and culture systems and a more even distribution of production could provide resilience in the face of a changing climate and other external drivers and add economic, social and ecological insurance to aquaculture systems. However, diversification is not without risks and may not always be a viable means to increase fish production. In addition to purely economic costs there will be associated development costs, including evaluation and mitigation of environmental and social impacts and establishment of species-specific biosecurity frameworks. The workshop identified general principles that can help guide diversification in aquaculture.

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Contents

Tambaqui Colossoma macropomum *broodstock in Tocantins state, northern Brazil*

PHOTO CREDIT: JEFFERSON CHRISTOFOLETTI

Abbreviations and acronyms

AAC	Aquaculture Association of Canada
ABCC	Brazilian Association of Shrimp Farmers
AGIFISH	An Giang Fisheries Import-Export Join Stock Company
APFIC	Asia-Pacific Fishery Commission
ASC	Aquaculture Stewardship Council
ASFA	Aquatic Sciences And Fisheries Abstracts
ASFIS	Aquatic Sciences And Fisheries Information System
BAP	Best Aquaculture Practices
BCSGA	British Columbia Shellfish Growers' Association
BMLP	Brazilian Mariculture Linkages Project
BMP	best management practice
BNDES	Brazilian National Development and Social Bank
CAPES	Coordination for the improvement of Higher Level Personnel of the Ministry of Education, the Federative Republic of Brazil
CBD	Convention on Biological Diversity
CCRF	Code of Conduct for Responsible Fisheries
CEPTA	Aquaculture Research and Training Center
CERLA	Latin American Regional Aquaculture Centre
CGIAR	Consortium of International Agricultural Research Centers
CIDA	Canadian International Development Agency
CIRAD	Agricultural Research for Development
CITES	Convention on International Trade in Endangered Species of Wild Fauna and Flora
CODEVASF	Irrigation Development Agency for the São Francisco River
COFI	FAO Committee on Fisheries
CP	Charoen Pokphand Group
CSA	climate-smart agriculture
DEFRA	British Department for Food and Rural Affairs
DNA	deoxyribonucleic acid
DNOCS	National Department of Works Against Drought
EMBRAPA	Brazilian Agricultural Research Corporation
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FI	FAO Fisheries and Aquaculture Department
FLUPSYS	floating upwelling systems
GAA	Global Aquaculture Alliance
GAP	good aquaculture practices
GDP	gross domestic product
GIFT	Genetically Improved Farmed Tilapia
GMO	genetically modified organisms

GMT	genetically male tilapia
HACCP	hazard analysis and critical control point
HHI	Herfindal-Hirschman Index
IBGE	Brazilian Institute for Geography and Statistics
IMNV	infectious myonecrosis virus
IMTA	integrated multitrophic aquaculture
IMTA/SEA	integrated multitrophic aquaculture/sustainable ecological aquaculture
IPqM	Marine Research Institute, Federative Republic of Brazil
IRD	Research Institute for Development France
ISO	International Organization for Standardization
IUCN	International Union for Conservation of Nature
LMP	large market products
MAGRAMA	Spanish Ministry of Agriculture, Food and the Environment
MARM	Spanish Ministry of the Environment and Rural and Marine Affairs
MPA	Ministry of Fisheries and Aquaculture
MSC	Marine Stewardship Council
NACA	Network of Aquaculture Centres in Asia-Pacific
NAP	National Adaptation Planning
NGO	non-governmental organization
NMFS	National Marine Fisheries Service
NMP	niche market products
NOAA	National Oceanic and Atmospheric Administration
NOK	Norwegian krone
OECD	Organisation for Economic Co-operation and Development
pCO2	partial pressure of carbon dioxide
PEIXEBR	Brazilian Fish Farming Association
pH	potential of hydrogen
PLs	post-larvae
PLDM	local plans for mariculture development
RAS	recirculating aquaculture systems
R&D	research and development
SA	South America
SEAfood	Sustainable Ecological Aquaculture
SoW AqGR	State of the World's Aquatic Genetic Resources
SPC	The Pacific Community
STECF	Scientific, Technical and Economic Committee for Fisheries
SQF	safe quality food
SWOT	strengths, weaknesses opportunities, threats
TPA	tonnes per annum
UNCLOS	United Nations Convention on the Law of the Sea
UNESP	State University of São Paulo
USDA	United States Department of Agriculture
UNIDO	United Nations Industrial Development Organization
WFC	World Fisheries Congress
WFT	World Fisheries Trust

Genesis of the workshop

BACKGROUND

Member countries are increasingly requesting guidance from FAO regarding diversification of aquaculture as wild fisheries reach their limits, human population grows and the demand for aquatic plants and animals for food and other uses increases. Currently aquaculture is the world's fastest growing food sector as well as the world's most diverse farming system in terms of number of species farmed, the methods used and the environments where the farms are located. Primary drivers of the diversification of aquaculture include market demand, funding opportunities, competition for resources, landscape opportunities and shortages as well as other environmental and social factors. Climate change and extreme climatic events are likely to play increasingly important roles in determining the success or failure of aquaculture enterprises. Diversification of species and culture systems could provide resilience in the face of this and other external drivers. At the farm and local community scale, diversification can add economic, social and ecological insurance to aquaculture systems, particularly for small-scale and family-based enterprises. However, there are costs, challenges and risks associated with diversification.

Although an ever-increasing number of species is used in aquaculture, diversification continues to be constrained by limitations in the technology for effective husbandry of aquatic species, its profitability, and appropriate enabling factors. On the other hand, the diminishing stocks of the thousands of non-farmed aquatic species being harvested from the world's oceans, seas, estuaries, lakes, rivers, rice paddies and other wetlands are creating market opportunities for increased production of a wider diversity of farmed aquatic animals and plants. Some regions, such as Latin America and the Caribbean, have been requesting specific assistance to diversify aquaculture.

In terrestrial agriculture, diversification of farmed products is usually at the level of breed, variety or cultivar, with a few species accounting for the majority of production. Those species have been domesticated over millennia and are now represented by thousands of distinct livestock breeds and plant varieties. In aquaculture, development of domesticated strains of a few farmed species within some of the main commodity groups (carp, catfish, oysters, salmon, tilapia and trout) is also taking place, but progress is slow and may not provide the resilience to expected wide-scale climatic changes. A strategy of farming more species using established technologies, combined with continued domestication of more species of freshwater fish, tuna, eels, deep sea species, and algae – including more native species – is likely to generate more options for farmers facing changing climatic conditions, unexpected major climatic or socio-economic impacts and emerging markets. A more diversified sector is also expected to provide alternative pro-poor livelihood options, such as seaweed or shellfish farming.

Diversification will have associated research and development costs, especially for species that are not yet commercially viable. These costs include evaluation and mitigation of environmental and social considerations and establishing species-specific biosecurity frameworks to deal with potential diseases. Currently there are two main strategies for diversification: 1) increase the number of species being farmed, e.g. begin development of farming marine species that have an established market, such as lobsters or tunas, or 2) increase the diversity within existing species being farmed by developing strains and varieties that meet specific needs, e.g. salt-water tolerant tilapia. Each option will have strengths and weaknesses, and they may not be mutually exclusive.

OBJECTIVES

The main objectives of the workshop were: i) to provide an assessment of the current status and trends of aquaculture diversification (species and strains) at a global level, ii) to review and assess the many drivers, constraints and incentives for the diversification of aquaculture, iii) to provide guidance on the options for diversification and on socio-economic strategies to promote their implementation and iv) to determine how more diversification in the aquaculture sector could provide more resilience to climate change and other external forcing factors.

The workshop (see Agenda in Annex 1) brought together global experts (Participants List Annex 2) and information, including background documents, on aquaculture diversification in order to guide FAO in the development of policy recommendations regarding aquaculture diversification as one means of facing climate change and other external forcing factors.

DELIBERATIONS OF THE WORKSHOP

Presentations at the workshop covered a range of topics and regional reviews concerning species diversification in aquaculture (Annex 3 – technical presentations). Discussions centered on the concept of diversification, the importance of accurate and detailed aquaculture data in the assessment and monitoring of diversification, the drivers of diversification and the advantages and risks of diversification. Climate change informed some of the discussion at the workshop, although most of the issues discussed would be relevant even without considering the world's changing climate. The workshop developed general guidance on diversification that should be adapted to specific areas and conditions. These main issues are presented below.

AQUACULTURE DATA

The benefits and costs of diversification can only be accurately assessed when good information is available. FAO collects data from member countries through a standardized questionnaire that follows conventions and nomenclature of the Aquatic Sciences and Fisheries Information System (ASFIS). ASFIS keeps track primarily of species and higher taxa, but tracks very few hybrids and does not categorize sub-species, different strains of a species or other genetically altered farmed types. The lack of data on distinct strains alone is a major deficiency when so much diversification can be at the strain level. As countries file their reports for the first State of the World's Aquatic Genetic Resources (SoW AqGR)[1], it is becoming clear that the number of species grown is often higher than that officially reported to FAO. If diversification involving more species, more strains and more hybrids is to proceed with any degree of planning and control, an improved information system that considers both farmed and wild species and their derivatives would seem highly desirable[2].

CONCEPT OF DIVERSIFICATION IN AQUACULTURE

Participants recognized that a clear concept of diversification was needed to facilitate discussions. Aquaculture can diversify in terms of:

- Species
- Technologies
- Geography and environment
- Markets
- Governance.

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[1] www.fao.org/fi/static-media/MeetingDocuments/AqGenRes2016/Inf2e.pdf

[2] FAO. 2016. Report of the expert workshop on incorporating genetic diversity and indicators into statistics and monitoring of farmed aquatic species and their wild relatives, Rome, Italy, 4–6 April 2016. FAO Fisheries and Aquaculture Report No. 1173. Rome, Italy.

Although all these aspects are interrelated, species remains the prime mover and it was on species that the workshop concentrated.

Species diversification has two components: 1) richness, i.e. the number of species and 2) evenness. According to ecological theory, these two components can represent different adaptation opportunities. In an aquaculture context, diversification generally refers to culturing more species across different scales.

For millennia the agriculture sector has diversified domesticated species into thousands of livestock breeds and plant varieties.[3] Diversification can play fundamentally the same role in aquaculture. It is a strategy that decreases risk, capitalizes on opportunities and provides resilience. An analogy could be made to the practice of reducing risk in a financial portfolio by holding stocks of many different companies. But because diversification in aquaculture often means substituting one species, strain or other farmed type for another, resilience is more likely to come not from adding more stocks (as in the analogy above) but from replacing a worrisome stock with a winner.

In terms of the number of species grown and systems used, aquaculture is significantly more diversified than agriculture and livestock farming; this diversification has been a feature of aquaculture's growth since the 1980s. The inherent diversity in aquaculture stems primarily from the number of farmable aquatic species, which include microorganisms, seaweeds, freshwater aquatic macrophytes, rotifers, molluscs, crustaceans, echinoderms, fish, amphibians and reptiles. Diversity stems also from the many aquatic environments available for culture, from the wide range of culture systems used, and from the different degrees of culture intensity and technological and managerial sophistication.

In terms of breeds and strains, however, aquaculture (excluding ornamental species such as gold fish) is much *less* diversified than the other sectors, with only a fraction of the number of domesticated breeds/strains. With the exception of a few species e.g. common carp, channel catfish, Nile tilapia and rainbow trout and Atlantic salmon), aquaculture has nothing comparable to the distinctive and stable livestock and plant breeds; those few that do exist in the aquatic sector are poorly documented. Although the diversity in terms of number of species is high in aquaculture the contribution of each species to overall production (also called evenness) is highly skewed; 30 aquatic species provide about 90 percent of aquaculture production – far fewer than the close to two thousand species that contribute to capture fisheries.

Aquaculture can diversify at different spatial levels (local, district, country, region) and in a number of different ways. New strains or new species can be farmed; the number of species already farmed can be increased; familiar species can be farmed in a novel location (such as old shrimp ponds that are no longer used); the original species can be farmed using a new or repurposed system or technology; polyculture and integrated multitrophic aquaculture (IMTA) can combine species in a farming system to take advantage of different feeding strategies and aquaculture products can be diversified post production. The focus of the workshop was on diversification of species rather than on the farming system or post production processes (Table 1), although it was recognized that these elements are inter-related.

Diversification can also be increased by making production of the currently farmed species more even. This would entail increasing the production of those species that are currently farmed in small quantities, or reducing the production of those that contribute most to production. The latter strategy would be problematic in most circumstances as it would involve changing resource allocation from a productive species/strain to a less productive one.

[3] For livestock, see: www.fao.org/nr/cgrfa/cthemes/animals/en/ and for plants: www.fao.org/nr/cgrfa/cthemes/plants/en/

TABLE 1
Species diversification in aquaculture

Method	Example
Increase the evenness of currently farmed species	Salmonids in Chile*
Introduce new species or strains from other areas	Salmon in Chile, tilapia in Asia
Polyculture and IMTA	Chinese carp culture; seaweed/shrimp culture
Create hybrids from existing strains/species	Thai catfish; pacu hybrids in Brazil
Genetically alter existing species/strains, e.g. selective breeding, polyploids, sex reversal	Monosex tilapia; GIFT** or GIFT-derived fish; triploid oysters

* In Chile in 1990 salmon farming consisted of more or less even production of rainbow trout, coho salmon and Atlantic salmon. After 2000, production was dominated by Atlantic salmon (>90 percent). In 2006 a catastrophic disease affecting this species almost wiped out the salmon industry in Chile. Trout and coho salmon production increased in response, inadvertently, providing some resilience to the sector.

** Genetically Improved Farmed Tilapia

DRIVERS OF DIVERSIFICATION

Important drivers of aquaculture diversification include market forces, opportunities, reduced availability of a species in the wild, location or resource availability, diseases, government policies, social pressure and climate change (Table 2). Drivers act at different levels, some operate in cascades (for example, lack of wild stocks can be due to poor policies and fisheries management), and others work in combination.

Participants acknowledged the role of diversification in increasing profitability and resilience in aquaculture, but also identified significant risks. For example, the Kingdom of Norway attempted to diversify its aquaculture industry by adding halibut and Atlantic cod, but both species were out-competed by their respective wild fisheries; in this case, the market, not technology, was the driver. In some areas it is government and academia that are driving diversification, whereas the private industry prefers to continue farming existing species. A significant amount of time, in the order of 10–15 years, may be required to introduce some new species or strains to aquaculture and develop the necessary technologies; this is too long and/or costly for most private industry. Governments that are driving diversification might choose to subsidize these efforts and indeed government has a role to play, especially in a nascent industry and in governance.

Most of the presentations at the workshop identified “market demand” as a main driver of diversification in aquaculture; some even noted that markets can drive diversification in reverse, i.e. lead to less diversification. In reality, though, the market is better thought of as the medium through which primary drivers or “forcing factors” stimulate diversification in aquaculture.

Climate change is a good example of a primary driver: if a species of fish grows poorly under warming conditions but the market still wants fish, then climate change is “forcing” a farmer to diversify into a species that grows better under the changed conditions. The market is simply the mechanism through which climate change acts to cause diversification. So too with social pressures for responsible aquaculture, most commonly in Europe and North America. If consumers demand a fish grown with fewer environmental consequences, growers will find themselves responding directly to consumers, or to government regulations that reflect consumer concerns. Again, “the market” is the main mechanism.

Competition was identified as another relevant driver, although not universally so. In the Kingdom of Norway, for example, competition in the dominant salmon culture business is one of the most important drivers, but this has not lead to diversification. In this case, the best return on investment may come from increased efficiencies and better performance of currently farmed species rather than from diversification.

TABLE 2
Main drivers of diversification

Driver	Mechanism
Market demand	As the world becomes more populated, urbanized and rich, more people will want, and be able to afford more fish and fish products
Climate change	Changing environments will necessitate new species/strains, or the movement of established species into new areas
Desire for increased resilience	Aquaculture will need to supply consistent products in spite of external impacts
Consumer demand	Consumers will want to continue to eat fish that they are accustomed to eating and at affordable prices; tastes may change in response to new trends or the introduction of new species
Environmental concerns	Governments and consumers will want to promote and eat fish that are efficiently grown in an environmentally friendly manner.
Profit	Aquaculturists will strive for species, breeds and systems that are efficient and meet market/consumer demands
Competitive advantage	Developing new species, breeds or farming systems often gives the innovator an initial competitive advantage

CONSTRAINTS TO DIVERSIFICATION

The participants stressed that although diversification can have advantages and can help increase resilience in aquaculture, there are challenges that can constrain diversification. Just as the market can promote diversification, it can also be a constraint, for example where consumers have narrow tastes in seafood.

The cost of developing new species for culture and the time required to bring a species to market are further constraints. Resources and research may need to be spent on culture design, marketing, regulatory modifications and post processing modifications.

Regulations and biodiversity concerns can be further limitations. Restrictions on species introductions and exports, permitted genetic technologies and areas available for farming may limit diversification. When diversification involves the introduction of new species or farmed types, escapes from aquaculture facilities can impact native genetic resources. Wild genetic resources can also be impacted when seed or early life history stages are collected from the wild for grow-out or for culture-based fisheries. Wild genetic resources underpin both capture and culture fisheries; such impacts could become negative feedback on aquaculture development.

REGIONAL PATTERNS OF DIVERSIFICATION

The background papers regarding diversification revealed that the regions are not homogenous. That is, there are significant differences within a region with regard to the development of the aquaculture industry, governance and regulatory frameworks, the role of capture fisheries and the drivers of, opportunities for and threats to diversification. There are, however, some region-specific characteristics (see Appendix 3 for full papers). Asian aquaculture is the most diversified (Davy and Zhou, 2016); North America is diversifying production practices that promote responsible aquaculture (Cross *et al.*, 2016); African aquaculture farms a few species that are adaptable to a wide variety of farming systems (Brummett, 2016); European aquaculture is dominated by a few countries that have very different levels of diversification (Polanco and Bjorndal, in Appendix 3). Asia also displays another trend that is common elsewhere: a rise in diversification followed by a leveling off (Davy and Zhou, 2016). Many indigenous species in Africa and Latin America, both of which have exceptionally high native freshwater genetic diversity, merit screening for aquaculture diversification.

The Republic of Chile presents a case where importation of technologies and species has resulted in an export-oriented aquaculture economy in which small-scale farmers and native species have not been much involved. Future plans for diversification promoted by government and academia will concentrate on native species and small to medium scale production in geographic areas that have not been involved in the country's aquaculture growth to date (Wurmann and Routledge, 2016).

In areas with an established export-oriented aquaculture industry like the Kingdom of Norway's, there may be little interest in diversification of species, apart from some small local efforts (e.g. kelp and char culture in the Kingdom of Norway). Aquaculturists in North America and Europe choose instead to concentrate on efficiency, system improvement, adding value and building corporate responsibility that relates less to "what" is farmed and more to "how" it's farmed ("healthy, sustainable food"). In Asia, a large number of small operations, responding to demand from a population with broad gastronomic tastes and often catalyzed by the appearance of enabling infrastructure like roads and electricity, help diversify the sector. In Africa, capture fisheries are still a more important source of food fish and related livelihoods and income than is aquaculture. Nonetheless, government interest in supporting aquaculture and introducing new species and technologies is substantial and non-native species and strains are being considered in many regions to diversify and improve production.

KEY ISSUES

Several key issues were raised during the workshop. A main discussion point was how to decide whether it is better to increase the number of species being farmed, i.e. increase species diversity, or to focus on improving the culture of existing species or strains. Under a changing climate it may be safer to continue with a species with an established market, technology, genetic management etc. than to domesticate or introduce new species. Increasing the number of species being farmed and or spreading their production may not be the answer under all conditions.

Means of diversification

Broad diversification could lead to more research and development that would benefit the development of the aquaculture sector in general. The workshop acknowledged two general schools of thought with regard to how that research and development should proceed (Bjørn Myrseth, personal communication):

1. Invest in existing aquaculture species by diversifying strains, areas and growing systems; be cautious with new species and introduction of already-farmed species into new areas.
2. Work on new species and/or strains to accommodate or even stimulate shifts in consumer preferences.

Although diversification can involve adding species, it may be wise to concentrate on a small number of "new" species for diversification rather than to spread research funds over many candidate species, new farming or processing systems and new marketing strategies. In general, private industry was not seen to support diversification of species; these efforts are largely driven by research and development groups, academia and governments. Therefore the government has important roles to play in supporting research, developing public/private partnerships, creating an enabling environment that considers communities and native resources, and promoting promising species (Zhou 2016, personal communication).

Choosing species for diversification

There are strategies that can help make wise decisions on diversification. Project Diversify has recommended several species for expansion of aquaculture in the European Union (Member Organization) based on fast growth, size and economic potential.[4] The workshop identified further attributes to consider when thinking about

[4] www.eufic.org/article/en/show/eu-initiatives/rid/diversify/

diversifying by adding new species, hybrids, strains and other farmed types. The new candidates should:

- have reliable seed supply and survival to harvest;
- be euryhaline and/or eurythermal;
- tolerate low oxygen and pollution;
- come from lower trophic levels;
- have cost-effective feed conversion;
- have short production cycles;
- comply with biosafety requirements; and
- be culturally acceptable and reflect evolving consumer preferences.

The above list provides general guidance and some of the characteristics may be more important than others in some areas. For example in the Federative Republic of Brazil consumer preference created a demand for marine fish that came from higher trophic levels.

Choosing culture systems for diversification

Diversification of culture systems, e.g. recirculating aquaculture systems (RAS), integrated multitrophic aquaculture (IMTA) and offshore aquaculture, will provide additional opportunities for using new species or strains in aquaculture. Introducing a RAS to an area with low input extensive aquaculture could help ensure biosafety in the culture of exotic species, eliminate seasonality, be located close to markets, reduce water use and allow effluent treatment. There is scope for further diversification in culture systems, particularly in urban and offshore areas, and in irrigation systems. Multicomponent systems, e.g. IMTA, can be difficult to manage, as has been seen even in seemingly simple integrated systems such as rice-fish systems (Brummett, 2016, in Appendix 3).

Diversification using native or introduced species

The importation of non-native species that are farmed elsewhere would seem like an easy means to diversify aquaculture. However, countries often have legislation that prevents introduction of a non-native species, primarily to protect biodiversity. Furthermore, species may not perform as well or be socially acceptable in their new environment.

While native species may require investment in new technologies, their use could lessen the need for introductions and transfers of alien species. Culturing a local species is not without environmental risk: escapes of an already-adapted species that has similar diseases to wild stocks may have more serious ecosystem implications than escapes of an introduced species. Native species that are farmed are often genetically different from their wild relatives and may also pose risks to wild stocks.

Diversification through culturing species that have been fished unsustainably

Farming a species caught in an existing fishery can promote diversification – particularly if the wild-caught species products are in short supply, seasonally limited or expensive. Adding a species that consumers are already familiar with is easier than trying to promote a new species. The strategy can, however, backfire, as with the collapse of Norwegian Northern cod farming, whose relatively high cost made it difficult to compete with recovering wild stocks (Polanco and Bjorndal, in Appendix 3).

Diversification as a specific response to climate change

Much attention has been paid to the projected decline in capture fisheries as a result of climate-related changes in productivity, pH and temperature; this decline only places more pressure on aquaculture to provide aquatic animals and plants for food. Farmed types and culture systems in some areas will face extreme temperatures, droughts, floods, storms and saline intrusions. Africa is especially vulnerable to climate change.

While large, multinational companies will be affected by climate change, their global presence and resource base provide opportunities for mitigation and adaptation. For smaller operations, diversification of species and culture systems can help in meeting these challenges.

There are still very few examples of aquaculture diversification specifically in response to climate change-induced challenges or opportunities; they include use of salinity-resistant catfish in Viet Nam, temperature-tolerant salmon and pH resistant mollusc larvae. A high-level panel of experts recommended developing and farming more salt-tolerant species in coastal aquaculture to adapt to rising sea levels[5].

The workshop did, however, identify scenarios where diversification can help mitigate or adapt to climate change. Saline intrusions and storm surges will favour the farming of brackish water and euryhaline species; high water temperatures and turbidity will favour species that tolerate low dissolved oxygen levels and air-breathing fish. In general, deep, marine waters will be less vulnerable than shallow freshwaters; hatcheries will be a more reliable source of seed than wild seed collection; short culture cycles will be better than long ones and species with broad-based feeding strategies may be less vulnerable than those with a narrow diet.

ADVICE TO MEMBER COUNTRIES

It is clear that aquaculture production will continue to grow; more species are being farmed now than ever before and globalization is making connections to markets, species and information easier. Member countries will need to consider carefully how best to participate in the expanding aquaculture sector. Diversification will play a role, but must follow the principles in the FAO Code of Conduct for Responsible Fisheries (CCRF), Art. 9 and other international instruments such as the Convention on Biological Diversity. When considering the use of non-native species, the guidelines of the International Council for the Exploration of the Sea[6] and FAO Technical Guidelines for Responsible Fisheries[7] should be followed. Special consideration should also be given to the potential social, economic and environmental impacts of new technologies, and socio-economic implications of geographic diversification.

Aquaculture follows very different patterns in different countries and regions. So does its diversification, so it is hard to generalize about advice. Plans to diversify species should follow science-based appraisals regarding ecosystem health, biosafety and biosecurity, as well as thorough economic and social studies. Such measures *should* be carried out everywhere, but they are only *likely* to be done in places where society can afford them. Nevertheless, national governments have a responsibility to go as far as they can in providing technical advice to farmers. The list of principles that follows sets general standards that need ultimately to be met to ensure sustainable aquaculture and that could guide any diversification process, especially under climate change.

The approach outlined below states that the risk of adverse impacts should be assessed at each step, and the outcome should be sustainable. Diversification should also be equitable. Good governability is critical at every link in the production chain, and may involve the enforcement of previously unenforced laws or the creation of new ones.

PRINCIPLES FOR AQUACULTURE DIVERSIFICATION

The following principles (Pullin, 1991, in Appendix 3) represent a useful starting point for a more definitive listing; each will have varying relevance for different aquaculture types and facilities, and regions:

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[5] www.fao.org/fileadmin/user_upload/hlpe/hlpe_documents/HLPE_Reports/HLPE-Report-3-Food_security_and_climate_change-June_2012.pdf

[6] www.nobanis.org/globalassets/ices-code-of-practice.pdf

[7] www.fao.org/3/a-w3592e/index.html; www.fao.org/3/a-i0283e/index.html

1. Diversification demands information. Identify knowledge gaps and seek expert advice.
2. Diversification should anticipate, adapt to and mitigate the effects of climate change.
3. Diversification should be compatible with local ecosystems and not reduce aquatic biodiversity.
4. Diversification should be compatible with other responsible food producing sectors.
5. Diversification should comply with national and international codes of conduct, conventions and laws.
6. Diversification should be planned in consultation with all stakeholders and be attractive to farmers.
7. Diversification should minimize risks from pathogens and predators.
8. Diversification should be profitable in domestic and/or export markets, taking account of the risks of market shifts.

Carp culture in Bolivia helps diversify livelihoods but can also cause environmental problems

PHOTO CREDIT: DELPHINE LARROUSE

APPENDIX 1

AGENDA OF THE WORKSHOP ON AQUACULTURE DIVERSIFICATION AS AN ADAPTATION APPROACH TO CLIMATE CHANGE AND OTHER EXTERNAL FORCING FACTORS

FAO Experts Workshop, Rome 23–25 June 2016

THURSDAY, 23 JUNE	
Session 1: Moderator – M. Beveridge	
09:00	Welcome by FAO – ADG of the Fisheries and Aquaculture Department, Mr. Árni M Mathiesen
09:20	Introductions
09:30	Clarifying aims and process; climate change challenges to aquaculture – Soto and Beveridge
10:00	Current status of global diversification – Soto
10:30	Coffee
11:00	Summary of SoW AqGR draft – Garcia Gomez
11:30	Diversification in aquaculture – Pullin
12:00	Discussion
12:30	Lunch
Session 2: Moderator – D. Bartley	
14:00	Europe diversification – Norway and Spain: Polanco and Bjorndal
14:30	South America diversification – Chile: Wurmann
15:00	South America diversification – Brazil: Routledge
1530	Coffee
16:00	North America diversification – Canada, the United States of America: Cross
16:30	Summary discussion on the day – diversification and barriers
17:00	closing
FRIDAY 24 JUNE	
Session 3: Moderator – D. Soto	
09:00	Asia diversification – Davy
09:30	Africa diversification – Brummett
10:00	Coffee
10:30	Europe Industry perspective – Myrseth
11:00	North America Industry perspective – Dean
11:30	Enabling diversification and costs – Faria
12:00	Discussion: diversification accessibility at different scales
12:30	Lunch
Session 4: Moderator – J. Carolsfeld	
14:00	AQ species diversification: selected cases in Asia – Xhou
14:30	OECD-FAO model aquaculture forecasting – Bjorndal
15:00	Coffee
15:30	Recommendations
17:00	Closing
SATURDAY, 25 JUNE	
Session 5: Moderator – M. Beveridge	
09:00	General discussion and Synthesis Report development
10:30	Coffee
11:30	Wrap-up

Genetic diversification: collecting milt from broodstock salmon in British Columbia
PHOTO CREDIT: BRIAN HARVEY

APPENDIX 2

List of participants

Devin Bartley Scientist, World Fisheries Trust E-mail: devin.bartley@fao.org	**Matthias Halwart** Senior Aquaculture Officer, SP2, FAO E-mail: matthias.halwart@fao.org
Malcolm Beveridge Acting Branch Head, FIAA, FAO E-mail: malcolm.beveridge@fao.org	**Brian Harvey** Consultant, Fugu Fisheries Ltd., Canada E-mail: brian.harvey@shaw.ca
Trond Bjorndal Senior Researcher, CEMARE, University of Portsmouth, United Kingdom E-mail: trond.bjorndal@snf.no	**Audun Lem** Deputy Director, FIAX, FAO E-mail: Audun.lem@fao.org
Randy Brummett Senior Aquaculture Specialist, World Bank E-mail: rbrummett@worldbank.org	**Bjorn Myrseth** Vitamar A.S., the Kingdom of Norway E-mail: bjorn.myrseth@vitamar.no
Junning Cai Aquaculture officer, FIAA, FAO E-mail: junning.cai@fao.org	**José Fernandez Polanco** Faculty of Economics and Business, University of Cantabria, the Kingdom of Spain E-mail: Jm.fernandez@unican.es
Joachim Carolsfeld Executive Director, World Fisheries Trust, Canada E-mail: yogi@worldfish.org	**Roger Pullin** Consultant, Philippines E-mail: pullin.roger@gmail.com
Steve Cross Department of Geography, University of Victoria, Canada E-mail: sfcross@mail.geog.uvic.ca; Stephen.Cross@nic.bc.ca; sfcross@seavisiongroup.ca	**Eric Routledge** Research and Development Head EMBRAPA Fisheries and Aquaculture, Brazil E-mail: eric.routledge@embrapa.br
Brian Davy Research Associate, World Fisheries Trust, Canada E-mail: fbdavy@gmail.com	**Doris Soto** Scientist, World Fisheries Trust E-mail: Dorisst07@gmail.com
Guy Dean Vice President, Albion Fisheries Ltd., Canada E-mail: guy.dean@albion.ca	**Amalie Tusvik** Research Assistant, CEMARE, University of Portsmouth, United Kingdom E-mail: amalie.tusvik@outlook.com
Maria Faría Project Manager, World Fisheries Trust, Canada E-mail: maria@worldfish.org	**Carlos Wurmann** Executive Director, AWARD Ltd., Chile. E-mail: carwur@gtdmail.com; awardchile@gmail.com
Simon Funge-Smith Senior Fisheries Resources Officer, FIAF, FAO E-mail: simon.fungesmith@fao.org	**Xiaowei Zhou** Fishery Statistician, FIAS, FAO E-mail: Xiaowei.zhou@fao.org
Ruth Garcia Gomez* Aquaculture Officer, FIAA, FAO	

* Aquatic Biosecurity Specialist, Aquaculture Branch, Fisheries, Aquaculture and Marine Ecosystems Division, The Pacific Community (SPC) (ruthgg@spc.int).

Reef fish for sale in Suva, Fiji. Are any of these species candidates for aquaculture diversification?

PHOTO CREDIT: PETER EDWARDS

APPENDIX 3

Technical Presentations

PAPER 1

DIVERSIFICATION IN AQUACULTURE: SPECIES, FARMED TYPES AND CULTURE SYSTEMS

Prepared by
Roger S.V. Pullin
Consultant to FAO
E-mail: pullin.roger@gmail.com

ABSTRACT

The richness of aquatic biodiversity is summarized and compared with that in current use for aquaculture. The case is made for further diversification, followed by summaries of the main issues for choosing what to farm and which culture systems to use, taking a whole ecosystem perspective. Prospects for failure or success are discussed and 10 principles are suggested for a responsible path to diversification. Examples are given of the use of biological and economic criteria and quantitative indices for evaluating candidate species. Based on the author's perspectives and experience, 10 fish species are suggested as possible candidates for new or wider use in aquaculture and a further 10 are suggested specifically for inland aquaculture in Africa. This review affirms diversified aquaculture as an increasing contributor to world food production in the face of rapid change.

1. INTRODUCTION

1.1 Context

Humans depend upon ecosystems for essential ecological goods and services, including water, food, and waste processing. The same applies to all forms of aquaculture. Aquaculture has positive and negative impacts on its supportive ecosystems, all of which are shared to various extents with other sectors. This is the context for exploring diversification in aquaculture – choosing responsibly what to farm and where and how to farm it.

The future vision of FAO includes the goal of "*ecosystem well-being*", such that "*aquatic ecosystems are utilized in an optimal way that maintains social, economic, food and ecosystem service benefits* (FAO, 2012a). Achieving that goal and overcoming country-specific constraints require the sustainable use and conservation of aquatic ecosystems and biota, making the best of all available options, in rapidly changing circumstances. The Commission of the European Communities (2002) called for research on new species for aquaculture and development of new culture systems, especially recirculating and offshore systems. The same approach is likely to be needed in all regions for the development of sustainable aquaculture.

1.2 Definitions

FAO definitions of terms (FAO, 2014a) are followed here, unless otherwise stated. Responsible aquaculture means the farming of aquatic organisms, following the FAO Code of Conduct for Responsible Fisheries (FAO, 1995). Diversification in aquaculture means the adoption or wider use, in research and development (R&D) and/or production, of new species, farmed types and culture systems. Farmed types in aquaculture are all aquatic organisms bred in captivity, including strains, hybrids, varieties and products of applied biotechnology, such as triploid and genetically monosex populations).

Culture systems include all natural and artificial aquatic ecosystems used for aquaculture R&D and/or production, together with all necessary structures, equipment, procedures, and treatment of wastes. In aquaculture, all hatchery, nursery and grow-out systems are aquatic ecosystems.

1.3 Sources

This main sources used for this review were FAO statistics (FAO, 2014b), other FAO publications, aquaculture journals, and conference proceedings, notably Expert Panel Reviews from the 2010 Global Conference on Aquaculture (FAO/NACA, 2012). AlgaeBase[8], SeaLifeBase[9] and FishBase[10] were also major sources. FishBase was used to suggest some fish species for possible new or wider use, based on the author's perspectives and experience. The overall trend towards diversification in the farming of native and alien aquatic species was summarized from 40 Country Reports, submitted in 2016 to the FAO Commission on Genetic Resources for Food and Agriculture as information for compiling the first State of the World Report on Aquatic Genetic Resources for Food and Agriculture.

2. AQUATIC BIODIVERSITY

2.1 Species diversity

The diversity of aquatic species is very high but imperfectly documented, especially for aquatic microorganisms. The aquatic microorganisms that have been described represent only a small fraction of total aquatic microbial diversity. For the macroalgae, AlgaeBase (Guiry and Guiry, 2016) numbers 10 500 species of seaweeds. The diversity of aquatic animal species is also very high.

The taxonomy of aquatic species is often revised, especially through the use of genetic techniques, such as the Barcode of Life[11]. Marine invertebrates that stay within particular coastal localities are sometimes separate species that have yet to be recognized as such (Thorpe, Solé-Cava and Watts, 2000). However, there is also much phenotypic variation; for example, in oysters (Newkirk, 1983).

Feral populations of aquatic plants and animals, derived from introductions of alien species, are also highly diverse. Some are centuries old; for example, some common carp introductions to European waters (Jeney and Jian, 2009). Wild and feral populations of aquatic species and hybrids are free-living genetic resources for aquaculture. All can be categorized as the wild relatives of farmed types – potentially useful for R&D, including use in breeding programmes, and therefore meriting *in situ* and *ex situ* conservation.

2.2 Intraspecific diversity

For many aquatic species, some populations are sufficiently genetically distinct to be named as subspecies, strains and varieties This applies particularly to island, riverine and lacustrine wild and feral populations and to populations near the borders of their geographical ranges.

The task of documenting so-called farmed strains and varieties and the extents to which they are being used in aquaculture is best limited to highly distinctive and stable

8 www.algaebase.org
9 www.sealifebase.org
10 www.fishbase.org
11 www.barcodeoflife.org

ones; for example, the many farmed strains of the common carp (*Cyprinus carpio*) (e.g. FAO, 2001; Jeney and Jian, 2009) and the hundreds of so-called varieties of ornamental fish; for example, goldfish (*Carassius auratus*) (Zhen Li, 1988).

Beyond these examples and arguably a few others among farmed tilapias and salmonids, aquaculture has nothing comparable to the multiplicity of highly distinctive and stable livestock and pet breeds. Nevertheless, the captive populations of farmed aquatic species comprise hundreds of what can be legitimately called strains and varieties, as well as many hybrids (see below).

Genetic manipulation to produce triploid populations of farmed aquatic animals is also well established and likely to be developed for an increasing number of species (Tiwary, Kirubagran and Ray, 2004). Moreover, brood-stocks can be manipulated genetically to produce monosex progeny; for example, genetically male tilapia (GMT) (Mair *et al.*, 1995). This wide intraspecific diversity of captive populations used for aquaculture R&D and production, together with the non-standard use of descriptors such as breeds, strains, stocks and varieties, makes the case for using the collective term farmed types for all of the above, as well as for all hybrids.

2.3 Hybrids

Hybrids are produced by crosses between species, sometimes from different genera, and within species, and between different farmed types. Hybrids differ significantly in commercial traits depending on the choice of female and male parents.

Some farmed and potentially farmable aquatic species hybridize readily. For example, Wohlfarth and Hulata (1983) listed 25 well-documented interspecific and intergeneric tilapia hybrids and Selvaraj and Kumar (2004) listed five interspecific hybrids from four *Labeo* species and nine intergeneric hybrids from crosses among *Labeo* species, *Catla catla* and *Cirrhinus mrigala.*

Bartley, Rana and Immink (2001) reviewed the use of interspecific hybrids in aquaculture, including carps, catfish, groupers, salmonids, sturgeons and tilapias. FAO (2014b) listed five farmed hybrids. The contributions of hybrids to aquaculture production require fuller coverage.

3. AQUATIC BIODIVERSITY USED IN AQUACULTURE

3.1 Aquatic microorganisms

Microorganisms (bacteria, cyanobacteria, fungi, microalgae and protozoans) are ubiquitous in aquatic ecosystems and are at the base of all aquatic food chains. Aquatic microorganisms provide some or all of the following for all farmed aquatic animals: oxygen, food, waste treatment and disease control.

Detrital food webs (Moriarty and Pullin, 1987) and green water (Neori, 2013) account for most production of farmed microphagous molluscs, crustaceans and fish. The provision of periphyton substrates such as bamboo stakes in culture systems can improve fish survival and production in pond systems (e.g. Keshanavath and Wahab, 2001; Azim, Wahab and Asaeda, 2004).

Some aquatic microorganisms – for example, marine yeasts (Kutty and Philip, 2008) – are cultured industrially to produce enzymes and other chemicals. The production of fermented aquatic food products and the ensilage of discarded fish catches and post-harvest wastes also depend on bacteria. The genetic resources of aquatic microorganisms cultured as food or for use in food products merit inclusion with coverage of the genetic resources of terrestrial microorganisms for food and agriculture.

3.1.1 Microalgae as live foods

Most hatchery-based production of seed for aquaculture relies on the mass culture of microalgae for feeding the larvae of target species directly and/or feeding their live food organisms, mostly rotifers and small crustaceans. FAO (1996a) listed 24 genera cultured in hatcheries to feed molluscan and crustacean larvae and to produce their live foods (rotifers, *Artemia*, marine copepods and freshwater zooplankton). Further diversification is expected as more wild populations are sampled and assessed (e.g. Iba and Rice, 2015).

3.1.2 Microalgae and cyanobacteria as target species

Few aquatic microorganisms have been cultured as target species and marketed as such. Borowitzka (1999) reviewed the commercial culture of Chlorella and Spirulina as health foods, as well as *Dunaliella salina* for production of β-carotene and *Haematococcus pluvialis* for astaxanthin.

FAO aquaculture statistics (FAO, 2014b) listed only four species not elsewhere identified. There is scope for culturing more microalgal and cyanobacterial species and varieties, especially as health foods and food additives.

3.1.3 Microorganisms as probiotics

Probiotic bacteria, mostly *Bacillus* and *Lactobacillus* species have been tried as additives to culture environments and as feed ingredients for penaeid shrimp and fish; the goal is to boost growth and feed conversion efficiency and to reduce the use of antibiotics for disease control (Anthony and Philip, 2008). The major successes have been in shrimp farming (e.g. Decamp and Moriarty, 2006).

3.1.4 Bioflocs

Bioflocs are macroaggregates of bacteria, fungi, algae, protozoans and meiofauna that can provide protein- and micronutrient-rich food for microphagous and filter feeding species, such as penaeid shrimp and tilapia, improve culture environments and reduce disease, and to treat wastewater from aquaculture (e.g. Avnimelech, 2014; Taw, 2014).

3.2 Macroalgae (seaweeds)

FAO (2014b) listed 21 named species of farmed seaweeds. The number would increase if more farmed populations were identified to species level and reported as such. Further diversification is expected in the farming of edible macroalgae, for local availability as marine vegetables, which are also health foods. For example, Yarish *et al.* (1998) proposed the domestication process of indigenous Northeast American nori species. Further genetic improvement is expected for some farmed macroalgae, especially those farmed for industrial phycocolloids.

3.3 Freshwater macrophytes

Edwards (1980) noted over 40 species of freshwater macrophytes used as human food, livestock and fish feeds, and fertilizers. Some are very important in human nutrition; for example, water spinach (*Ipomoea aquatica*) and water mimosa (*Neptunia oleracea)* produced from peri-urban aquaculture in Southeast Asia (PAPUSSA, 2006).

The aquatic fern *Azolla*, which has at least seven species and multiple strains, contains the symbiotic nitrogen-fixing cyanobacterium *Trichormus azollae* and is used as a crop fertilizer and an ingredient of poultry and pig feeds (FAO, 1989). FAO (2009a) reviewed the use of freshwater macrophytes as feed in small-scale aquaculture. Yong *et al.* (2010) catalogued over 300 species of freshwater macrophytes that can be cultivated to improve the appearance and/or quality of urban waters.

The potential for farming additional species of freshwater macrophytes as human food appears to be low, but there is scope for wider use of presently farmed species and for assessing new species and varieties as ornamentals and for improving the health of aquatic ecosystems.

3.4 Rotifers

Rotifers of the sibling species complex *Brachionus* are used widely in hatcheries for feeding fish larvae. Rotifer types are chosen to match larval mouth sizes and are fed with particular microalgae or yeasts to suit larval nutritional requirements.

3.5 Molluscs

FAO (2014b) listed 68 named species of mollusc and seven additional families or genera not represented by any of those species. The total numbers of farmed molluscan species are likely to be substantially higher than this statistic suggests, especially for the bivalves. For example, Angell (1986) listed seven named species of the oyster genus *Saccostrea* in experimental and/or commercial aquaculture and a further two species for which information was lacking. FAO (2014b) listed only *Saccostrea cucullata* and *Saccostrea commercialis*.

The identification of oysters farmed in the tropics can be difficult because of phenotypic variations among local populations. Further checks using genetic data and up to date nomenclature are needed in order to improve statistics. The same applies to wild and farmed populations of mussels, especially *Mytilus edulis* and *Mytilus galloprovincialis.*

The scope for diversification in farmed molluscan species is probably highest for bivalves, especially tropical oysters and clams. Wider use of some farmed and farmable species is planned; for example, *Crassostrea lugubris* in Viet Nam (Cao Van Nguyen *et al.*, 2014). SealifeBase lists *Lunarca ovalis* in experimental aquaculture and *Tagelus plebeius* and *Donax serra* as having likely future use. Some new gastropods are also likely to be farmed to supply particular products for niche markets; for example, the giant Hawaiian limpet *Cellana talcosa* (Hua and Ako, 2012).

3.6 Crustaceans

The total number of farmed crustacean species is not known, but certainly exceeds the 44 named species in FAO statistics (FAO, 2014b). Pullin, Williams and Preston (1998) concluded that around 60 species of crustaceans had been farmed experimentally or commercially; they listed 21 ornamental species.

The identification of some farmed crustaceans and the nomenclature used in production statistics require updating at local and national and international levels. For example, the farming of four mud crab species of the genus *Scylla* is not yet fully reflected in aquaculture statistics.

Crustaceans are used widely as live food organisms in hatcheries. The most important are nauplii of the brine shrimp Artemia (*Artemia salina*) (FAO, 1996b; Sorgeloos, Dent and Condreva, 2001). Artemia strains are adapted to various ranges of temperatures and salinities. Cladocerans, especially *Daphnia* and *Moina* species, are used widely for feeding freshwater fish larvae (FAO, 1996c) and marine copepods, such as *Acartia, Tigriopus* and *Tisbe* species, for feeding marine fish larvae (FAO, 1996d; Sumares, Noguiera and Cunha, 2013).

There is scope for further diversification in the farming of crustacean species, especially more *Macrobrachium* and penaeid shrimp species. SealifeBase lists 10 penaeid species from four genera in experimental aquaculture. Many more copepods and cladocerans could be assessed for use as live foods.

3.7 Echinoderms

3.7.1 Sea cucumbers

Dried sea cucumber and sea urchin gonads are highly valuable food products and overfishing has greatly reduced the wild populations of many species. Aquaculture has great potential to increase and sustain supplies, but R&D is still at an early stage for all but a few species.

An FAO compilation on sea cucumber farming R&D (FAO, 2004a) included work on *Isostichopus fuscus* in the Republic of Ecuador and *Actinopyga mauritiana* in the Arab Republic of Egypt. FAO aquaculture statistics (FAO, 2014b) listed only two named species, *Holothuria scabra* and *Stichopus japonicus* (synonymous with *Apostichopus japonicus*).

FAO (2012b) catalogued over 60 commercially important sea cucumber species. This wide diversity and the high demand for dried sea cucumber suggest that sea cucumber farming will diversify in the number of farmed species and the number of countries involved. For example, the California sea cucumber (*Parastichopus californicus*) has been suggested as a new candidate for aquaculture (Azad *et al.*, 2014).

3.7.2 Sea urchins

FAO statistics (FAO, 2014b) listed only one named sea urchin species, *Paracentrotus lividus*, plus *Strongylocentrotus* spp. Lawrence *et al.* (2001) mentioned three additional genera and nine additional species under R&D for aquaculture. Small sea urchins can be gathered as wild seed for grow-out, as described by Juinio-Mendez, Malay and Bangi (2001) for *Tripneustes gratilla*. Further diversification in farmed sea urchin species is likely because of the demand for sea urchin gonads as a high value food product and the limited supplies available from capture fisheries.

3.7.3 Other invertebrates

The ascidians *Halocynthia roretzi* and *Styela clava*, the echiuran *Urechis unicinctus*, and a few cnidarians (jellyfish), named in FAO statistics as *Rhopilema* spp., are farmed for human consumption. There is some limited potential for the farming of additional edible species in these phyla.

3.8 Fish (Pisces)

FAO (2014b) listed 273 named species of fish, five hybrids, and about 15 additional genera or families not represented by those species. The numbers of named freshwater/diadromous, and marine species were as follows:

Freshwater/diadromous

carps, barbels and other cyprinids, 41
tilapias and other cichlids, 16
other freshwater, 83
sturgeons and paddlefish, 8
river eels, 4
salmons, trouts and smelts, 17
shads, 2
miscellaneous diadromous, 4

Marine

flounders, halibuts and soles, 7
cods, hakes and haddocks, 3
miscellaneous coastal, 68
miscellaneous demersal, 4
miscellaneous pelagic, 12
tunas, bonitos and billfishes, 4

FAO statistics are based on official government reports. In contrast, FishBase compiles its information from individually referenced scientific publications. FishBase lists 261 freshwater and 167 marine fish species used in commercial aquaculture, with a further 61 freshwater and 40 marine species as being in experimental use or for likely future use. At local and national levels, accurate identification of farmed fish species and comprehensive reporting are crucial for compiling better production statistics. This need will increase with further diversification.

R&D efforts are continuing towards farming new fish species, for example Atlantic croaker (*Micropogonias undulatus*) (Sink and Lochmann, 2011), cubera snapper (*Lutjanus cyanopterus*) (Sanches *et al.*, 2012), black sea bass (*Centropristis striata*) and southern flounder (*Paralichthys lethostigmata*) (Alam *et al.*, 2015).

More ornamental fish species will likely be farmed in the future in order to guarantee supplies from sources other than wild populations. Clownfish culture is widely established; for example, Gopi *et al.* (2014) reported successful culture of four *Amphiprion* spp. and *Premnas biaculeatus* in the Lakshadweep Islands, India.

3.9 Amphibians and aquatic reptiles

FAO aquaculture statistics (FAO, 2014b) list only two farmed frogs (*Rana ridibunda* and *Rana catesbiana*) and one farmed freshwater turtle (*Trionyx sinensis*), plus aggregate listings for the farming of other *Rana* spp. and river and lake turtles not elsewhere identified. This incomplete picture can be remedied only by more complete reporting at local and national levels.

4. DRIVERS AND TRENDS FOR DIVERSIFICATION IN AQUACULTURE

Ecological change and economic change are the main drivers of diversification in all food production systems. In aquaculture, as in agriculture and forestry, monocultures are at risk from new challenges by pathogens, parasites and pests, and environmental change. Climate change will have increasing impacts on aquaculture (e.g. FAO, 2009b; Pörtner and Peck, 2010; FAO, 2011a, 2015a). Farmed types and culture systems will face extreme temperatures, droughts, floods, storms and saline intrusions. Diversification can help in meeting these challenges.

Following trends in the total numbers of farmed aquatic species is difficult because some production is reported by commodity group, family or genus, or as "not elsewhere identified". FAO (2014c) estimated that aquaculture uses about 600 species, including the following fully named ones: 37 algae, 102 molluscs; 59 crustaceans; 354 fish, with five fish hybrids; and six amphibians and reptiles.

Over 90 percent of aquaculture production is generated from much smaller numbers of species, estimated by Benzie *et al.* (2012) as 29, comprising two macroalgae, seven molluscs, four crustaceans and 16 fish. However, hundreds of farmed aquatic species are vital for local and national food security and livelihoods and many more are likely to have culture potential. Moreover, organic aquaculture has a bright future (Prein *et al.*, 2012) and will probably develop a wide diversity of species, farmed types and products.

The early growth of aquaculture from its small beginnings in the 1950s involved substantial diversification in farmed aquatic species and culture systems and diversification continues to spur aquaculture expansion, especially in developing regions. For example, the recent growth of aquaculture in the Federative Republic of Brazil has involved the farming of at least 64 species and hybrids, with more in R&D (Roubach *et al.*, 2003).

Developing a new species for aquaculture need not entail huge costs from the outset. Aquaculture R&D for new candidate species can begin with simple, inexpensive trials in which wild seed are fattened in captivity. Further investment in R&D for hatchery technology and genetic improvement can follow if initial grow-out and marketing trials succeed. Captive breeding and hatchery seed production are always desirable for farmed aquatic species, but wild seed provide for the profitable farming some bivalve molluscs, all anguillid eels, and a wide variety of other fish (FAO, 2004b).

Aquaculture has a much shorter history of domestication and genetic improvement than agriculture and sometimes makes great progress simply by switching from a problematic species to a new one. Tilapia farming took off with the replacement of *Oreochromis mossambicus* by *Oreochromis niloticus* Penaeid shrimp farming in Asia was saved largely by switching from disease-prone species to the white-legged shrimp (*Litopenaeus vannamei*).

In both these cases of diversification, the new species were farmed as alien species in most countries, targeting domestic and global markets. Much of aquaculture mirrors the heavy reliance on alien species seen in agriculture and forestry. The adoption of new native species for aquaculture could lessen the need for introductions and transfers of alien species. Nevertheless, farmers will always seek to farm the most profitable species available, native or alien, with or without following codes of conduct and complying with regulations.

FAO (2007, 2008a) recommended the twinning of aquaculture, using native or alien species, with effective measures for the conservation of wild aquatic biodiversity at sites beyond the influences of farmed aquatic organisms and farm waters. The World Conservation Union has provided further guidance on aquaculture of alien species (Hewitt, Campbell and Gollasch, 2006).

The global trend towards further diversification is indicated in Country Reports received by FAO in 2016 for compiling the first State of the World Report on Aquatic Genetic Resources. Forty such Country Reports contain plans for culturing the following numbers of new aquatic species, designated as native (N), alien (A) and origin unknown (U): Africa – 9 countries, 2–24 N, 1–4 A; Asia – 10 countries, 2–25 N, 1–2 A, 1 U; Europe – 5 countries, 1–9 N, 1–2 A; Latin America – 13 countries, 1–72 N, 1–2 A; Oceania – 3 countries, 1–6 N.

5. CHOOSING WHAT TO FARM

Farmed aquatic organisms must have the following attributes within the range of environmental conditions to be expected: adequate survival and reproductive success; fast growth and good feed conversion; resistance to pathogens, parasites and predators; and high product quality, profitability and competitiveness. Because of the risks of unpredictable weather and extreme climatic events, farmers will prefer species and farmed types that can be grown to marketable size quickly, preferably in less than 12 months. Their choice of species will also be influenced by the proximity of markets – the shorter the distance between production and consumption the better.

Saline intrusions and storm surges will favour the farming of brackish water and euryhaline species in some inland and coastal areas. High water temperatures and turbidity will favour the farming of air-breathing fish. Lefevre *et al.* (2014) listed 18 families of air-breathing fish already used to some extent in aquaculture and gave oxygen consumption and critical dissolved oxygen data for 40 species. The less that an air-breathing fish depends on dissolved oxygen, the more likely it is to be a candidate for successful aquaculture.

In fed aquaculture, the availability and cost of feeds and their efficiency of conversion to harvestable products are usually the main determinants of profitability. The FAO Committee on Fisheries (COFI) has recommended that the production of non-fed aquatic species be substantially increased, with production of fed species focused on herbivores and omnivores (FAO, 2012a).

Costa-Pierce (2012) provided evidence that non-fed aquaculture is one of the world's most efficient systems for production of microbial, plant and animal proteins. Culturing herbivores is cheaper than culturing carnivores and is more earth-friendly and ecologically sustainable. The best choices for fed aquaculture are species that are naturally herbivorous or that can accept feeds containing plant or microbial ingredients.

Gerking (1994) listed 14 freshwater and 21 brackish water and marine fish families with largely herbivorous species. Horn (1989) reviewed 56 species from 14 families, tabulating their feeding habits (browsers, grazers, or both) and relative gut lengths (gastrointestinal length/standard body length). Higher relative gut lengths indicate more dependence on herbivory. The following families could provide new herbivorous candidates for marine and coastal aquaculture: *Acanthuridae, Mugilidae*, *Scaridae, Siganidae*, and *Sparidae*.

However, some success stories in aquaculture would not have been predicted on the criteria mentioned above. For example, the Atlantic salmon (*Salmo salar*) is naturally carnivorous and takes at least two years to bring to market, yet it has become one of world's most important farmed fishes. Its capacity to tolerate higher temperatures than some other farmed salmonids (Elliot and Elliot, 2010) will be important as coastal waters become warmer.

6. CHOOSING CULTURE SYSTEMS

All culture systems must be good fits with their supportive ecosystems and must establish harmonious relationships and where possible synergy with other sectors, including agriculture, forestry, water resources management and capture fisheries (e.g. Pullin and Prein, 1995; FAO, 2008b; Soto *et al.*, 2012). A good fit means the integration of aquaculture with human activities in general (Edwards, 1998); in other words, as ecological aquaculture (Costa-Pierce, 2002, 2010). It is important to assess the capacities of aquatic ecosystems for supporting aquaculture (e.g. Hecht and Heasman, 1999; Byron *et al.*, 2011).

Ecological integration is essential throughout aquaculture, including the harvesting of wild seed for capture-based aquaculture (FAO, 2004b), all brood-stock, hatchery and nursery operations, and all grow-out systems. Edwards (2015) reviewed aquaculture-environment interactions in traditional and modern aquaculture, the decline of integrated agriculture-aquaculture and wastewater-fed systems, and new systems from which future contributions to aquaculture production are still uncertain, including recirculation aquaculture and aquaponics, offshore ocean aquaculture and integrated multi-trophic aquaculture (IMTA).

The term IMTA has been used to describe a wide range of multi-component systems. For example, Fang and Zhang (2015) described IMTA as subtidal sea ranching, involving macroalgae, abalone, clams, scallops, sea urchins and sea cucumbers, and as combinations of caged and fed carnivorous fish with the culture of macroalgae, bivalves and sea urchins.

The wide diversity of culture systems seems set to continue, with the balance of use between the main ones, such as cages and ponds, changing to fit ecological and economic circumstances. There is scope for further diversification in culture systems, particularly in urban aquaculture, offshore aquaculture, and aquaculture in irrigation systems. Multicomponent systems can be difficult to manage, as has been seen even in seemingly simple ones, such as rice-fish integration.

7. PROSPECTS FOR FAILURE OR SUCCESSES

Poorly planned diversification in aquaculture usually fails, sometimes with adverse ecological impacts and legacies; for example, attempts to farm the golden snail (*Pomacea* sp.) in the Philippines (Acosta and Pullin, 1991) and red claw (*Cherax quadricarinatus*) in the Republic of Ecuador (Romero, 2002).

The reasons for failure usually include one or more of the following: over-estimation of future markets; over-capitalization of start-ups; over-estimation by farmers of expected production and under-estimation of costs; over-promotion by administrators and parties with vested interests; and inadequate science-based appraisals.

Even with good planning, however, many attempts at diversification fail to progress from R&D to commercial production because of unforeseen biological, ecological and economic factors. Some idea of the rates of failure and success can be gleaned by comparing publications that proposed new candidates with listings in FAO aquaculture statistics and country reports.

For example, Abellan and Basurco (1999) reviewed 25 Mediterranean marine fish, which seemed to have potential for new or wider use in aquaculture. Eight were subsequently farmed. New (2003) suggested four crustaceans and nine marine fish for new or wider use in aquaculture. Three of the crustaceans and seven of the marine fish were subsequently farmed. This can be taken as a high rate of success.

8. THE RESPONSIBLE PATH TO DIVERSIFICATION

Diversification in aquaculture begins with creative brainstorming. New ideas can come from many sources: farmers, scientists, business people, consumers, and even children. It sometimes takes a non-expert to say – why not try this?

Thorough desk studies and preliminary fieldwork must then precede any costly R&D and pilot farming, and must always be undertaken before any transfers of genetic material and/or modifications to ecosystems. There must be science-based appraisals regarding ecosystem health, biosafety and biosecurity, as well as thorough economic and social studies.

The ensuing R&D must cover biological, ecological and socioeconomic issues, rather than focusing only on narrow technical goals such as induced spawning and polyploidy. The following 10 principles are suggested as a responsible path to diversification in aquaculture.

8.1 Ten Principles for Pursuing Diversification in Aquaculture

8.1.1 Gather information, identify knowledge gaps and seek expert advice

Knowledge is the key to success in aquaculture (Davy *et al.*, 2012). In addition to seeking biological and economic information, ecological forecasts (Clark *et al.*, 2001) should be sought for aquaculture sites.

Expert advice helps in finding important information, which is often scattered in published and unpublished sources, sometimes in diverse languages. Local experts often know most about the true status of and trends in the aquatic ecosystems and biota on which they depend.

Major sources of information include aquaculture journals and magazines; FAO[12]; national, regional and international institutes and networks, such as the World Aquaculture Society[13] and the Network of Aquaculture Centers in Asia-Pacific[14]; and databases, particularly AlgaeBase[15], FishBase[16] and SealifeBase[17].

Aquamaps[18] provide the native ranges, suitable habitats and expected suitable habitats in 2100 for marine and coastal species, based on current data and IPCC forecasts of bottom depth, temperature, salinity, primary production, sea ice concentration and distance to land. Further development is planned for freshwater species, basins and sub-basins in order to assist inland aquaculture and fisheries, especially in Africa.

8.1.2 Adopt the Precautionary Principle; assess risks of adverse impacts

Bodansky (1991) summarized the history of the Precautionary Principle and its wide use. FAO (1996e) applied it to species introductions. It should be applied to all proposed diversification in aquaculture. The risks of adverse impacts to be considered include the following: damage to aquatic and terrestrial biodiversity; escapes from farms, especially of alien and potentially invasive organisms; and the possible spread of aquatic diseases. The FAO Code of Conduct for Responsible Fisheries (FAO, 1995), its Technical Guidelines and other technical publications (e.g. FAO, 2004c) provide guidance on all of the above. The Global Invasive Species Database[19] provides guidance on invasive species.

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12 www.fao.org
13 www.was.org
14 www.enaca.org
15 www.algabase.org
16 www.fishbase.org
17 www.sealifebase.org
18 www.aquamaps.org
19 www.iucngisd.org

8.1.3 Assess contributions to coping with and reducing climate change

The pros and cons of any proposed diversification in aquaculture should be assessed in terms of adaptation, mitigation, resilience and vulnerability to climate change. The National Adaptation Planning (NAP) Process established by the United Nations Framework Convention on Climate Change provides guidance[20].

8.1.4 Assess contributions to goals for conservation and use of biodiversity

Discuss possible contributions to the Sustainable Development Goals[21], the Strategic Plan for Biodiversity and the Aichi Targets[22].

8.1.5 Assess compliance with codes of conduct, certification schemes, market standards, conventions and laws

Comply with the FAO Code of Conduct for Responsible Fisheries and follow its Technical Guidelines that apply to aquaculture, including those for taking an ecosystem approach. Comply with all obligations under relevant international conventions, including, *inter alia*: the Convention on Biological Diversity (CBD)[23]; the Ramsar Convention[24] and the United Nations Convention on the Law of the Sea (UNCLOS)[25]. Comply also with national legislation on biosafety, biosecurity, and the conservation and use of biodiversity and natural resources, including land and water.

Consult the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES)[26] and the IUCN Red List[27] for information on trade restrictions whether species under consideration for aquaculture are listed as threatened. Endangered and vulnerable species are not necessarily excluded from use in aquaculture, as long as the necessary permissions are obtained and trade restrictions are complied with. Farming such species can sometimes contribute to their conservation, through responsible use.

Review options for acquiring certification for Best Aquaculture Practices and for products that meet market standards and food safety requirements, especially those of the Hazard Analysis and Critical Control Point (HACCP) System (FAO, 1997). FAO (2011c) and Ababouch (2012) provide guidance on aquaculture certification.

Certification is issued by numerous organizations, including, inter alia: the Aquaculture Stewardship Council[28]; the Global Aquaculture Alliance[29]; Ornamental Fish International[30]; the Marine Aquarium Council[31]; and the Ornamental Aquatic Trade Association[32].

8.1.6 Assess acceptability and profitability in domestic and export markets

Ensure that there are no taboos, image and reputational problems for the proposed farmed aquatic products. Assessing profitability requires making a detailed business plan, including realistic appraisals of the following: availability and cost of sites and systems; variable production costs, especially feed and seed; best, worst and most probable ranges of expected prices; competitiveness with other products; harvesting

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[20] www.unfccc.int
[21] www.un.org/sustainabledevelopment/sustainable-development-goals/
[22] www.cbd.int/sp/
[23] www.cbd.int
[24] www.ramsar.org
[25] www.un.org/depts/los/convention
[26] www.cites.org
[27] www.iucnredlist.org
[28] www.asc-aqua.org
[29] www.gaalliance.org/bap
[30] www.ofish.org
[31] www.marineaquarium.org
[32] www.ornamentalfish.org

cycles; seasonality; and accessibility of markets. Trade associations provide guidance for the marketing of many farmed aquatic products.

8.1.7 Assess risks from pathogens, parasites and predators

Ensure that there are no insurmountable health, survival and product quality risks from existing and expected pathogens, parasites and predators. Extensive advice on the diseases of farmed aquatic organisms, quarantine requirements and countermeasures is available from FAO publications (e.g. FAO, 2004c) and from the Office Internationale des Epizooties[33], which provides an International Aquatic Animal Health Code and guidance for diagnosis of aquatic diseases.

8.1.8 Assess likely adoption by farmers

Estimate the likely numbers of existing farmers and/or new entrants who would adopt the diversification, and the extension and training needs.

8.1.9 Assess governability and sustainability

Assess governability issues along aquaculture produce chains, from ecosystems to consumers, with the goal of improving governability where possible (Pullin, 2013).

Assess also the likely sustainability of any aquaculture enterprise using biological, ecological and intersectoral indicators (e.g. Pullin, Froese and Pauly, 2007) as well as economic and social ones (e.g. Valenti et al., 2011).

Take a realistic, time-bound perspective on sustainability. For example, part-time, small-scale tilapia hatchery operators in the Philippines, who formerly farmed only rice, were able to build better houses, buy domestic appliances, pay school fees and repay debts over a 10-year period, until land tenure problems and competition from large hatcheries closed them down (Gaite *et al.*, 1983).

8.1.10 Assess insurability

Explore the possibilities for insurance against losses and/or third party claims. For guidance, see FAO (2006) and Tisdell *et al.* (2012).

9. EXAMPLES OF THE USE OF CRITERIA AND INDICES FOR CHOOSING NEW SPECIES

Mathews and Samuel (1992) proposed a simple bioeconomic culture index, CI', for ranking new candidate species for aquaculture:

$$CI' = \emptyset' . P$$

Where:
- Ø' (lower case phi prime) is Pauly's growth performance index;
- $\emptyset' = \log10 K + 2 \log10 L\infty$;
- K and L∞ are parameters of the von Bertalanffy growth equation;
- P is the mean annual price for the fish species being considered.
- Ø' values are given in FishBase and SealifeBase for many farmed and potentially farmable fish and aquatic invertebrates.

Mathews and Samuel (1992) calculated CI' values for seven fish and three penaeid shrimps as new candidates for aquaculture in Kuwait. The CI' values for the fish ranged from 4.92 for *Lutjanus malabaricus* to 20.50 for *Acanthopagrus cuvieri*. Only the second ranked fish, *Acanthopagrus latus*) and the top ranked shrimp, *Penaeus semisulcatus* appear to have been farmed commercially in the same region. However,

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33 www.oie.int/

desk studies using such indices can be useful pointers to culture potential and to prioritizing species for culture trials.

Pauly, Moreau and Prein (1988) used 150 data sets to compare the Ø's for wild (N) and cultured (A) populations of seven farmed tilapia species. *Oreochromis niloticus* had the highest mean Ø's but the difference between them was smaller than that for *Oreochromis aureus*. This suggests that the farmed populations of *Oreochromis niloticus* were less domesticated than the *Oreochromis aureus* ones. By comparison, *Tilapia rendalli* populations had low mean Ø's and a low ΔØ' suggesting slow growth and little progress towards domestication.

Lal and Pickering (2012) appraised 59 indigenous fish species from 20 families as potential candidates for small-scale inland aquaculture in Pacific island nations. They gave scores for economic considerations (farm size, fish size and marketability), biological/ecological considerations (ease of producing seed in hatcheries, trophic level, growth rate, feeds, disease tolerance and environmental tolerance limits, amenability to captivity) and environmental considerations (suitability of culture habitat, consequences of escapes, and impacts of culture practices such as using chemicals and drugs).

An overall score was calculated for each species.

The top 10 species and scores were as follows: river mullets (*Cestraeus goldei*, *Cestraeus oxyrhynchus* and *Cestraeus plicatilis*), 38; other mullets (*Crenimugil heterocheilos*, *Liza melinoptera*, *Liza subviridis* and *Mugil cephalus*) and rock flagtail (*Kuhlia rupestris*), 36; and spotted scat (*Scatophagus argus*) and jarbua terapon (*Terapon jarbua*), 35. From these species, FishBase lists only *Mugil cephalus, Scatophagus argus* and *Terapon jarbua* as cultured commercially and *Cestraeus plicatilis* for likely future use. FAO aquaculture statistics list only *Mugil cephalus* and *Scatophagus* spp.

10. CANDIDATES FOR NEW OR WIDER USE IN AQUACULTURE

Based on rapid appraisals and the present author's perspectives and experience, 10 fish families were chosen as possible sources of new species for aquaculture. Ten species from these families are suggested as possible candidates for new or wider use in aquaculture (Table 1).

TABLE 1

Ten fish families, the numbers of species therein currently farmed experimentally (E), for likely future use (L) and farmed commercially (C) and suggestions for 10 species with possible potentials for diversification (i.e. new or wider use in aquaculture), based on: total length, growth (Ø'), trophic level, waters, temperatures. Main source, FishBase. N/A, not available

Family: nos. of species farmed experimentally (E), for likely future use (L), commercially (C); suggested species	Max. total length (cm); mean Ø'; indicative trophic level	Waters: fresh (F); brackish (B); marine (M); diadromous (D); temperatures (°C)	Comments (references)
Acanthuridae: E, L and C, 0 ***Acanthurus lineatus*** (Lined surgeonfish)	38; 2.57; 2.0	M; 24–30	Indo-Pacific; herbivore; start with wild seed; potential unknown, for this and all acanthurids
Arapaimidae: E and L, 0; C, 2 ***Arapaima gigas*** (Arapaima)	450; 4.17; 4.5	F; 25–29	Amazon; carnivore; air breather; farmed; potential high
Cichlidae (euryhaline only): E and L, 0; C, 1; ***Etroplus suratensis*** (Pearlspot)	40; N/A; 2.0	F, B, M; tropical	S. Asia; herbivore; farmed; potential high (De Silva, Maitipe and Cumaranatunge, 1984)
Clariidae: E and L, 0; C, 6; ***Clarias batrachus*** (Philippine catfish)	47; 3.34; 3.4	F, B; 10–28	Asia; omnivore; air breather; prized for taste; potential moderate
Cyprinidae: E, 6; L, 2; C, 36 ***Labeo dussumieri*** (Hiri kanaya, Sri Lanka)	50; 3.26; 2.0	F; tropical	S. Asia; herbivore; farmed; low priced potential unknown

TABLE 1 (CONTINUED)

Family: nos. of species farmed experimentally (E), for likely future use (L), commercially (C); suggested species	Max. total length (cm); mean Ø'; indicative trophic level	Waters: fresh (F); brackish (B); marine (M); diadromous (D); temperatures (˚C)	Comments (references)
Eleotridae: E and L, 0; C, 3 ***Dormitator latifrons*** (Pacific fat sleeper)	41; 2.98; 2.03	F, B, M; 25–33	E. Pacific, California to Peru; detritivore; farmed; potential unknown
Kuhliidae: E, L and C, 0 ***Kuhlia rupestris*** (Rock flagtail)	45; N/A; N/A	F, B, M; 20–26	Indo-Pacific; carnivore; start with wild seed; potential unknown
Lutjanidae: E, 1; L, N/A; C, 8 ***Lutjanus argentimaculatus*** (Mangrove red snapper)	150; 3.31; 3.58	B, M; 16–30	Indo- W. Pacific; carnivore; farmed; potential high, for this and other lutjanids
Mugilidae (only river mullets): E, 0; L, 1; C, 0 ***Cestraeus plicatilis*** (Lobed river mullet)	32.5; N/A; N/A	D; tropical	S.E. Asia – S. Pacific; herbivore; likely future use; can be very highly priced; start with wild seed; potentials unknown for all *Cestraeus* spp.
Salmonidae: E, 2; C, 19 ***Hucho taimen*** (Taimen)	200; 3.20; 4.5	F, B; temperate	Eurasia; carnivore; farmed experimentally; wild stocks vulnerable; potential unknown
Scaridae: E, L and C, 0 ***Bolbometopon muricatum*** (bumphead parrotfish)	130; 3.05; N/A	M; tropical	Indo-Pacific; eats algae/corals; start with wild seed; wild stocks vulnerable; potential unknown
Scatophagidae: E and L, 0; C, 1 ***Scatophagus argus*** (spotted scat)	38; 2,88; N/A	F, B, M; 20–28	Indo-Pacific; omnivore; farmed; potential high, including use of low quality waters
Siganidae: E, 1; L, 1; C, 4 ***Siganus guttatus*** (goldlined spinefoot; rabbitfish)	42; N/A; N/A	M, tropical	E. Indian Ocean – W. Pacific; herbivore; start with wild seed; potential high, for this and other siganids (Duray, 1998; Pastor *et al*., 2002, Ayson *et al*. 2014)
Soleidae: E, 1; L, 0; C, 3 ***Solea senegalensis*** (Senegalese sole)	60; 2.73; 3.1	M, subtropical	E. Atlantic coasts, S. Europe to N.W Africa; carnivore; potential high.
Terapontidae: E and L, 0; C, 3 ***Terapon jarbua*** (Jarbua terapon)	36; 2.48; 3.93	D, tropical	Indo-Pacific; eats zooplankton and nekton; potential unknown

11. DIVERSIFICATION IN AFRICAN AQUACULTURE

Africa is especially vulnerable to the impacts of climate change, especially droughts and floods. African aquaculture has the potential to contribute much more to food security and livelihoods, but diversification must be approached with caution, especially concerning introductions and transfers of alien species or of indigenous species to new ecosystems.

Indigenous species often have advantages over alien species, having established markets and theoretically less likely to have adverse environmental impacts. Many indigenous species in Africa merit screening for their aquaculture potential. This process is ongoing; for example, a mangrove oyster (*Crassostrea tulipa*) and a blood clam (*Senilia senilis*) in the Gambia (Rice *et al.*, 2012). There is also scope for farming indigenous macroalgae, molluscs (abalone, mussels, oysters and clams), crustaceans (penaeid shrimps, crabs and *Macrobrachium* spp.) and fish.

African marine fish species have been little used in commercial aquaculture, apart from some mullets (notably, *Mugil cephalus*), sea bream (notably, *Sparus aurata*) and sea bass (*Dicentrachus labrax*) in North Africa. The following emphasis on fish for inland aquaculture, mostly in sub-Saharan freshwaters, is justified by their high importance for African food security.

Teugels and Gourène (1998) reviewed eight African freshwater catfish families. From the *Clariidae*, which comprise 12 genera and 74 African species, the following four African species are used in commercial aquaculture, but only the first is widely farmed: *Clarias gareipinus*; *Clarias anguillaris*; *Heterobranchus longifilis*; *Heterobranchus isopterus*; and *Heterobranchus bidorsalis*. From the *Clareotidae*, which comprise 13 genera and 88 species, one species, *Chrysichthys nigrodigitatus*, has been farmed to a limited extent.

Pullin, Casal and Brummett (2001) emphasized the high diversity of African freshwater fish (ca. 2 650 species); for example, there are about 120 *Labeo* spp. The same authors listed the following 15 farmed species: *Anguilla anguilla*; *Chrysichthys nigrodigitatus*; *Clarias anguillaris*; *Clarias gariepinus*; *Heterotis niloticus*; *Lates niloticus*; six *Oreochromis* spp. (*O. andersonii, O. aureus, O. macrochir, O. mossambicus*, *O. niloticus* and *O. shiranus*); *Sarotherodon melanotheron*; *Tilapia rendalli*; and *Tilapia zillii.*

It is important to keep a broad perspective when considering new species for African aquaculture. The tilapias could have been discounted based on the uncontrollable reproduction and poor performance of the species first chosen for culture, *Oreochromis mossambicus*. Families that might provide some new candidates include the following, *inter alia*: *Bagridae*; *Cyprinidae*; *Citharinidae*; *Mochokidae*; *Mormyridae*; and *Schilbeidae.*

However, at this early stage in the development of African aquaculture, the best strategy for diversification is probably to attempt wider use of some species that are already farmed, while assessing a limited number of entirely new ones. Based on the present author's perspectives and experience, 10 fish species are suggested for new or wider use in African inland aquaculture (Table 2).

TABLE 2
Ten fish species with possible potentials for diversification (i.e. new or wider use) in African inland aquaculture, based on: total length, growth (Ø'), trophic level, salinity, temperature. Main source, FishBase. N/A, not available

Family Possible new species	Max. total length (cm); mean Ø'; indicative trophic level	Salinities (ppt); temperatures (˚C)	Comments (references)
Arapaimidae ***Heterotis niloticus*** (African bonytongue)	100; 3.40; 2.7	N/A; 25–30	Widespread; carnivore; air-breather; farmed; potential high
Bagridae ***Bagrus docmak*** (Semutundu)	127; 3.40; N/A	N/A; 21–25	Widespread; carnivore; not yet farmed; fast growing; tolerates low oxygen; potential unknown
Cichlidae (only tilapias) ***Tilapia rendalli*** (Redbreast tilapia)	45; 2.56; 2.2	Up to 19; 11–41	Widespread; herbivore; farmed; some wild relatives grow faster; e.g., an Okavango population (Ø'=3.20; Mosepele and Nengu, 2003); potential high (Pullin, 1986)
Sarotherodon melanotheron (Blackchin tilapia)	28; 2.62; 2.0	Prefers 10–15, survives to 45; tropical	West Africa; detritivore; farmed; some wild relatives grow faster; e.g., some sourced from Dakar grew to 200g in six months (Gilles, Amon-Kothias and Agnèse, 1998)
Oreochromis aureus (Blue tilapia)	45.7; 2.31; 2.1	N/A; 8–30	Widespread; herbivore; farmed; like *Oreochromis niloticus* in most culture attributes and more cold-tolerant; potential high, alone and as the female parent of hybrids
Oreochromis andersonii (Three spotted tilapia)	61; 2.56; 2.1	Up to 20; 18–33	Southern, incl. Kafue and Zambezi; herbivore; farmed; prized for taste; an alternative to *Oreochromis niloticus*; potential high

TABLE 2 (CONTINUED)

Family Possible new species	Max. total length (cm); mean Ø′; indicative trophic level	Salinities (ppt); temperatures (°C)	Comments (references)
Clareotidae ***Chrysichthys nigrodigitatus*** (Bagrid catfish)	65; 3.10; 2.7	Low; 22–28	West Africa; omnivore; farmed; potential high for this and possibly other *Chrysichthys* spp.
Clariidae ***Heterobranchus longifilis*** (Sampa)	150; 3.17; N/A	N/A; tropical	Sub-Saharan large rivers; carnivore; farmed; air-breather; grows fast; potential high
Cyprinidae: ***Labeo coubie*** (African carp)	75; 3.05; 2.0	N/A; tropical	Widespread; low trophic level; farmed (Baijot, Moreau and Bouda, 1994); potential unknown for this and other African labeos
Gymnarchidae: ***Gymnarchus niloticus*** (Aba)	167; 3.74; N/A	N/A; 23–28	Widespread; carnivore; farmed; air-breather; fingerlings stocked as predators in tilapia ponds grew to about 4kg in 18 months (Pullin, 1986; unpublished trip report, Ghana); potential high

12. CONCLUSIONS

Further diversification in aquaculture will be essential to maximize its contributions to world food production and economic growth, in concert with those of other sectors that share the same supportive ecosystems.

The availability and quality of lands and waters for aquaculture will continue to change because of their increasing use by humans, extreme climatic events and long-term climate change. In these challenging circumstances, the success of aquaculture can continue only by using species, farmed types and culture systems that are chosen and developed as good fits with the prevailing environmental and economic realities.

Aquatic biodiversity is amply sufficient for these purposes, provided that diversification follows a responsible path, with aquaculture development and biodiversity conservation at all levels (genetic, species, and ecosystem) pursued together. The contributions of aquaculture to world food production and livelihoods will then increase, coming from an increasing diversity of species and farmed types and increasingly ecologically integrated culture systems, supporting a wider diversity of aquaculture enterprises and yielding a wider variety of farmed aquatic products.

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PAPER 2

AQUACULTURE DIVERSIFICATION IN EUROPE: THE KINGDOM OF SPAIN AND THE KINGDOM OF NORWAY

Prepared by
José Fernández Polanco, PhD
Department of Business Management
University of Cantabria
Santander, the Kingdom of Spain
E-mail: jm.fernandez@unican.es

and

Trond Bjorndal, PhD
Professor, NTNU Norwegian University of Science and Technology, and
Senior Researcher, SNF Centre for Applied Research at NHH
Bergen, the Kingdom of Norway
E-mail: Trond.Bjorndal@snf.no

ABSTRACT

This paper illustrates the most relevant examples of aquaculture diversification in Europe by focusing on the cases of the Kingdom of Spain and the Kingdom of Norway, two well-differentiated large producers. Norwegian aquaculture is almost totally dominated by salmon farming. In the Kingdom of Spain, mussels are the dominant species in quantities but the number of other farmed species produced at commercial scale, which includes other molluscs and fish, is comparatively higher. In contrast, Norwegian aquaculture is export-oriented, resulting in a higher diversification in terms of markets and products.

1. INTRODUCTION

Although different forms of aquaculture have been present in several European countries since ancient times, it is in the second half of the 20th century when the European industry emerges. Starting with mussels and trout, today's main farmed species reached commercial volumes of production by the end of the 1980s. In the following decades production grew rapidly and prices fell, compromising the profitability of producers and leading to a period of turbulence in markets. At the turn of the century the European aquaculture industry faced important challenges including globalisation of markets (Asche and Bjørndal, 2011) and acceptability of aquaculture products (Lappo *et al.*, 2016).

European countries are strongly dependent on imports in order to satisfy their seafood demand. The growth of industrial aquaculture in developing countries increased competition for European producers in the domestic markets even though markets were expanding. On the other side, the increase in supply, added to concerns and misconceptions about production methods and the quality of farmed species, led the industry into keen price competition (Fernandez-Polanco and Luna, 2010; 2012). European aquaculture needs to improve its efficiency in order to remain profitable in such a competitive environment. Research, innovation and diversification have been identified as key elements to improve the competitiveness of the European industry.

European aquaculture is diversified in different ways. Diversification of species is the result of the efforts in different countries and under different production and environmental conditions. Attention is being focused on developing new species for commercial purposes and several public funded projects are ongoing. Diversification at the system level is also occurring. Different species require different production systems, and these technologies result in different product attributes. New developments in this field may overcome the growth limitations, mainly spatial, of European aquaculture (Bjørndal and Øiestad, 2010). Finally, aquaculture in Europe is also diversified in terms of products and targeted markets. This paper illustrates current diversification in the industry, with special reference to the Kingdom of Spain and the Kingdom of Norway.

2. AQUACULTURE INDUSTRIES IN EUROPE

This section describes the production figures of the European aquaculture and the key directions for diversification. The European Union (Member Organization) has great impact on primary industries in Europe, since all the Member States are committed to the same common goals, strategies and policies. Aquaculture diversification is not an exception. Non European Union (Member Organization) members include relevant fishing nations like the Republic of Iceland, the Kingdom of Norway and the Russian Federation, but almost all aquaculture production is located in the Kingdom of Norway.

2.1 Historical background

As in other continents, the origins of European aquaculture can be tracked to ancient times (Nash, 2011). Archaeological and written sources locate the origin of Mediterranean aquaculture in the Arab Republic of Egypt. However, it is in the Roman Empire that aquaculture is described as an economic activity and the first technical writings on how to adequately grow aquatic organisms appear. The works of Varro (*Rerum Rusticarum*), Pliny the Elder (*Historia Naturalis*) and Columella (*Res Rustica*) introduce aquaculture as a complementary source of income in farms containing or located near water resources. Roman aquaculture was a well diversified industry covering different species of shellfish, marine and freshwater fish and trying to satisfy the large demand for seafood products. From the examples provided by Roman writers, economic profit was the main goal for producers in a market-driven industry, resulting in several examples of success and failure.

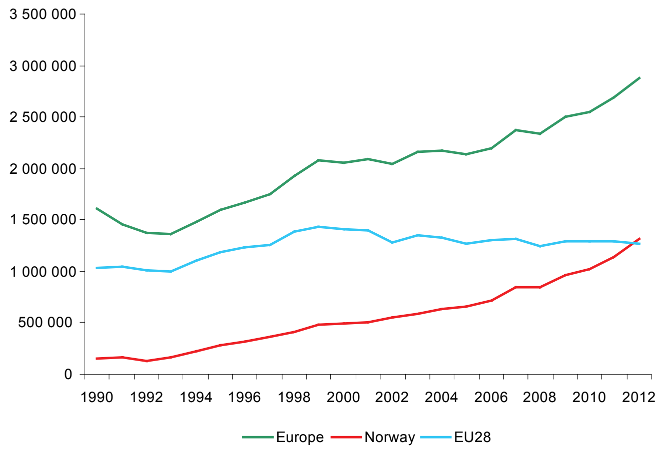
Following the fall of Rome, the remaining knowledge of the ancient society was kept and preserved in the Christian monasteries. It was in these monasteries, especially in Central Europe, where carp aquaculture, introduced in Europe during the Late Empire, became a regular source of protein for the monks and the surrounding communities. This activity was of special interest in landlocked areas, securing the supply of fish for special occasions when meat consumption was forbidden for Roman Christians (Easter) and contributing to a more diversified diet. Aquaculture persisted as an assurance of food security for several centuries.

The development of natural sciences after the Enlightenment resulted in a renewed interest in aquaculture and in alternative usages beyond food supply. In 1763 and 1765, Stephen Ludwig Jacobi published his results on trout and salmon breeding with the focus on restocking and conservation of natural populations. Beyond food supply, restocking became the main driver of aquaculture development in Europe and North America until the twentieth century (Nash, 2011). However, the success of new technologies and the scientific progresses in different species made business opportunities appear. By 1980, stimulated by the idea of a gap in demand due to stagnation of wild stocks, aquaculture production increased in some European countries to an industrial scale. Today, beyond some experimental and conservation programmes, the main focus of European aquaculture is to profitably satisfy market demand, like any other business.

2.2 European aquaculture: production and performance

With a total output of 2.883 million tonnes in 2012, the production of European aquaculture has increased 78.8 percent in the last two decades. About 90 percent of the total European aquaculture production is in the Kingdom of Norway and a few European Union (Member Organization) countries, in particular the Kingdom of Spain, the United Kingdom of Great Britain and Northern Ireland, the French Republic, the Republic of Italy and the Hellenic Republic. According to FishStat (FAO, 2015), the Kingdom of Norway produced 1.3 million tonnes of farmed species in 2012, which represented 45 percent of the total European production. Another 44 percent of the European aquaculture was concentrated in the European Union (Member Organization), mainly in the above-mentioned countries, with a total production of 1.2 million tonnes in 2012. Norwegian production increased since 1990 at a much higher rate than in the European Union (Member Organization) countries, becoming the main engine of the recent growth of aquaculture in the continent (Figure 1) with a larger production than the European Union (Member Organization) combined.

FIGURE 1
Evolution of European aquaculture production (in tonnes)



Source: FAO (2015).

The various species produced in the European Union (Member Organization), which exhibit cases of growth and contraction, result in a less pronounced growth trend when the aggregated production is considered. In contrast, Norwegian aquaculture is dominated by Atlantic salmon (Table 1), which counts for 93 percent of the national production in quantities and value in 2012. Other species produced in the country during the same year accounted for 89 024 tonnes, where 85 percent were trout and chars and other 11 percent was farmed cod.

TABLE 1
Norwegian aquaculture by main species in 2012, quantities and value

	Quantities (tonnes)	Value in 1000 US$
Atlantic salmon	1 232 094.90	4 808 358.00
Trouts and chars	74 977.00	294 490.62
Atlantic cod	10 032.70	36 099.21
Other	4 014.60	27 902.51
TOTAL	1 321 119.20	5 166 850.34

Source: FAO (2015).

Within the European Union (Member Organization), the Kingdom of Spain, the United Kingdom of Great Britain and Northern Ireland, the French Republic and the Hellenic Republic are the dominant aquaculture producers, representing 71 percent of total EU28 aquaculture production. The most important aquaculture industry in the European Union (Member Organization) in terms of quantities produced in 2012 was shellfish farming, accounting for 48 percent of total aquaculture production. Marine fish farming represented 31 percent and freshwater aquaculture the remaining 21 percent. The distribution in terms of value shows a different picture (Table 2). The higher value of marine fish like salmon and the low ex-farm price of mussels change the ranks and percentages. In terms of value, marine fish accounted for 53 percent, shellfish for 28 percent and freshwater fish for 19 percent (STECF, 2014).

TABLE 2
European Union (Member Organization) aquaculture by main groups in 2012, quantities and value

	Quantities (tonnes)	Value in 1000 US$
Shellfish	602 021.38	1 334 568.93
Marine fish	399 320.27	2 551 892.84
Freshwater fish	262 520.90	910 298.91
TOTAL	1 263 862.55	4 796 760.68

Source: FAO (2015).

In contrast with the Kingdom of Norway, the European Union (Member Organization) aquaculture industry is well diversified by species, as a consequence of specialisation by the different member states. This sort of specialisation reflects environmental conditions. The main farmed species are Mediterranean mussel (26 percent), Atlantic salmon (14 percent), rainbow trout and Pacific oyster (around 11 percent each). These four species account for 62 percent of the total European Union (Member Organization) aquaculture output in volume. Mediterranean mussels are mainly farmed in the Kingdom of Spain, representing 62 percent of the European Union (Member Organization) production, followed by the Republic of Italy (26 percent). Atlantic salmon was mostly produced in the the United Kingdom of Great Britain and Northern Ireland, with more than 92 percent of the total production. Pacific oysters are mostly produced in the French Republic (93 percent). Finally, rainbow trout[34] is less geographically concentrated, with Denmark (31 percent), the French Republic (24 percent), the Kingdom of Spain (13 percent) and the United Kingdom of Great Britain and Northern Ireland (11 percent) as the main producers (STECF, 2014). As above, the distribution in terms of value differs from the composition by main species and their relative importance. Atlantic salmon is the most important species in terms of value (20 percent), followed by Pacific oyster (16 percent), European seabass (11 percent), Gilthead seabream (11 percent) and rainbow trout (10 percent).

Business characteristics and performance significantly differ across main groups and species. Mussels and the shellfish industry are based on small scale business. In many cases they are family owned, with an important social impact on the surrounding communities in terms of employment and income. Despite differences in the profits returned by species, shellfish farming reported positive net profits in all species and countries in 2012 (STECF, 2014). Marine finfish farming appears as the most profitable segment in European aquaculture, mostly due to the market success of salmon. Other species such as seabass and seabream are much less profitable and have reported losses in several years. Marine fish producers are usually organised in medium and large size companies. Freshwater aquaculture reported losses in 2012.

Two different segments can be identified in European freshwater aquaculture. Extensive farming is a traditional, community based, industry, mainly located in Central Europe and directly connected with the ancient farming activities of the monasteries. On the other hand, the majority of trout is being farmed in countries all over Europe under intensive systems, by small and medium sized companies (STECF, 2014).

2.3 Diversification in European aquaculture

The history of European aquaculture is itself an example of alternative uses and diversification. From an initially market driven source of income for landlords in Roman times, aquaculture played a role in food security and became an instrument of

[34] Rainbow trout is small freshwater fish while trout farmed in Norway is seatrout which in size is similar to that of Atlantic salmon.

environment preservation in the 18th and 19th centuries. It is possible to assume that all the three orientations – market driven, food security and environmental preservation – coexisted in time with more or less predominance, until aquaculture became again a mainly market driven industry in the second half of the 20^{th} century. Officially, food security is no longer an issue in European countries. Today, the remaining orientations in aquaculture production are restocking and the supply of food or other products to the market.

Restocking of indigenous species is still widely practiced in Europe in all aquatic environments. These efforts are commonly funded by public programmes. Restocking policies in Europe can have two main drivers. On one side, there is an environmental driver focused on preserving the indigenous stocks. On the other side, the effort of restocking is to sustain the activity of existing fisheries such as salmon, eel or clams. The relevance in quantity and value of these programmes at the European level may be marginal compared with industrial, market-driven aquaculture. However, it is extremely important from a social and environmental perspective at the regional level, in the areas where these actions are being implemented (Nielsen and Prouzet, 2008).

Diversification has been proposed as a potential tool for the economic success of some aquaculture industries in Europe at the national and European Union (Member Organization) levels. The efforts in diversification of the European aquaculture industry have been focused on diversification of species, production systems and products.

To improve the efficiency and profitability of the European Union (Member Organization) industry by means of diversification in species and production systems, the project DIVERSIFY (Mylonas and Robles, 2014), funded by the European Commission for the period 2014–19, has identified six species from different environments and production systems with potential for significant expansion of European Union (Member Organization) aquaculture. The species under study for warm water cage culture are meagre (*Argyrosomus regius*) and greater amberjack (*Seriola dumerili*). Wreckfish (*Polyprion americanus*) was proposed both for warm and cool water cage culture and Atlantic halibut (*Hippoglossus hippoglossus*) for cool water. Two species are under study for freshwater aquaculture under two different production systems: grey mullet (*Mugil cephalus*) in pond culture and pikeperch (*Sander lucioperca*) in recirculation. The species were selected based on previous national initiatives in the Kingdom of Spain, the Hellenic Republic, the United Kingdom of Great Britain and Northern Ireland and Hungary with the aim of overcoming previously identified bottlenecks. The main bottlenecks not only involve biological and technical aspects such as availability of broodstock, larval survival and fish health, but also market and economic factors such as price elasticity of fish, cost of production and perceptions regarding aquaculture products.

While some exotic species like Pacific oyster and rainbow trout have been successfully introduced in the past and have become major aquaculture commodities in Europe, it has become almost impossible today given the restrictions now in place to avoid negative environmental impact from invasive alien species. Exotic species can only be farmed in close circuit facilities, increasing the costs and constraining the volumes of production. African catfish, tilapia and olive flounder are some of the species grown under these conditions.

Research on new species is not only expensive and time consuming; even if the technical constrains are overcome, the final product needs to be marketed profitably, which require a strong effort in market development. The emergence of new products will also put pressure on the prices of already established products. In addition to the technical difficulties there is the risk of competition across products of the same company, which implies that these new species may grow at the cost of already existing aquaculture species and industries. Beside these examples, most of the new seafood species introduced or developed in the European Union (Member

Organization) markets remain as niche markets and their growth is constrained by the lack of economies of scale due to small volumes of production both for technical and market reasons. From an economic point of view, it may be more efficient to focus on improving the performance of already existing species. These improvements may come from costs optimization, market enhancement and product diversification (STECF, 2014).

Diversification of aquaculture products varies across species. While some species have succeeded as processed products, others are still sold almost exclusively as a whole fresh fish. Salmon, trout and shellfish in general are sold as a wide range of processed products with an optimal demand size, including smoked, frozen, fresh, portion sized, canned or precooked. In other cases like seabass, seabream or carps, even though various new product development projects have been undertaken, processed products are much less common in the markets.

Different factors may affect the success of new food products in the markets. Among these factors, cost and optimal scale are technical constrains from the industry side, while social acceptability, demand size and willingness to pay are market constrains (Stewart-Knox and Mitchell, 2003).

3. AQUACULTURE DIVERSIFICATION IN THE KINGDOM OF SPAIN

The Kingdom of Spain has a long tradition of fishing and aquaculture. The geography of the country allows harvesting cold-water species in the Atlantic coast and warm-water in the Mediterranean. This is an opportunity for species diversification which also results in differentiation in terms of production systems, markets and products. Modern aquaculture started in the second half of the 19th century, with a main focus on restocking continental salmonids. Mussel and trout, along with European flat oyster, remained the only three species farmed at commercial level until the 1980s. Mussel production reached 150 000 tonnes in 1970. Trout farming reached 10 000 tonnes in 1979. Gilthead seabream, European seabass and turbot started being farmed in the mid 1980s and became consolidated industries in the 1990s.

Because the Kingdom of Spain is one of the main markets for seafood in Europe, internal demand is strong. The market is, therefore, the main driver for the development of aquaculture in the country and, despite some export activity, domestic demand is the main destination of Spanish aquaculture production. Beyond market drivers, there is still a significant effort in restocking, whether for conservation or for supporting the yield of some shellfish fisheries.

3.1 Diversification of species

As stated in the multiannual strategic plan for Spanish aquaculture (MAGRAMA, 2015b), diversification of species is officially identified as one of the main strategies for improving the economic sustainability of Spanish aquaculture. Several studies on new potential marine fish species are under way with the support of public institutions through national and regional aquaculture plans. Actually, Spanish aquaculture is quite diversified in terms of species, producing a large number of bivalve molluscs, several marine finfish and a few freshwater fish at commercial scale.

The Spanish Ministry of Agriculture, Food and Environment reported a total production of 305 735 tonnes of aquaculture products ready for consumption in 2014, from 47 different species including fish, molluscs, crustaceans, algae and other invertebrates. Almost 79 percent of this production was Mediterranean mussels, and the rest is mainly concentrated in other four main fish species (MAGRAMA, 2015a). Gilthead seabream, European seabass and turbot are the dominant species in marine fish farming and rainbow trout in the freshwater environment (Table 3).

These figures may suggest that the performance of Spanish aquaculture is totally dependant on mussel farming, but the picture changes when value is considered.

TABLE 3
Spanish aquaculture production by groups and species in 2014 (in tonnes)

Groups	Species	Quantities in tonnes
Marine fish	Seabass	16 319.82
	Seabream	16 068.38
	Turbot	7 891.41
	Bluefin tuna	3 966.33
	Meagre	1 114.77
	Sole	757.74
	Black spotted bream	184.18
	Other marine fish	181.96
Freshwater fish	Rainbow trout	14 009.38
	Eels	395.83
	Sturgeons	77.72
	Tench	17.55
	Tilapia	12.00
	Other freshwater fish	5.16
Mollucs	Mussel	241 478.74
	Clams	1 726.22
	Oyster	1 066.31
	Other molluscs	293.13
Crustaceans	Shrimp and prawn	163.46
	Other crustaceans	0.65
Seaweds and algae		3.44
Other marine invertebrates		0.46
TOTAL		305 734.69

Source: MAGRAMA (2015a).

Mussels represented only 26 percent of total value in 2012 (FAO, 2015), which reveals the importance of fish farming when the economic yield of Spanish aquaculture is considered. The three most important species of marine fish contributed 54 percent, and rainbow trout 10 percent; in terms of quantities, the three representative species in marine fish farming represented only 14.7 percent and rainbow trout 6.2 percent (Table 4). However, despite its low proportionate value, mussel farming is a profitable activity, while the bass and bream industry continuously faces financial and economic crisis and constraints (STECF, 2014; MAGRAMA, 2015c).

Among the minor species (in terms of quantities) there are some high value fish and shellfish such as bluefin tuna and oysters, contributing to the relative important weight in value. Other species of commercial interest which have been long researched and are now providing results are meagre and sole. However, technical limitations keep the volumes of production at very low levels. Domestic production of marine crustaceans declined over the last decade and has now almost disappeared.

TABLE 4
Spanish aquaculture by main species in 2012, quantities and value

	Quantity in tonnes	Value in EUR	EUR per tonne
Mussel	241 478.74	106 063 206.63	439.22
Seabass	16 319.82	91 406 506.30	5 600.95
Seabream	16 068.38	73 234 961.96	4 557.71
Turbot	7 891.41	50 381 793.13	6 384.38
Bluefin tuna	3 966.33	41 184 318.00	10 383.49
Rainbow trout	14 009.38	16 050 513.32	1 145.70

Source: FAO (2015).

Beyond commercial aquaculture, the Kingdom of Spain makes an intensive effort in restocking activities undertaken by public institutions. Restocking has both conservation and economic purposes. On the conservation side, production of indigenous species of trout and other freshwater species is being used in restocking inland waters. In 2014 the production of freshwater juveniles for restocking was 487 tonnes, and trout represented 97 percent of the total production. On the economic side, restocking is the main engine for hatchery-based capture fisheries of clams and other bivalves. 4.5 million clam seeds were produced in 2014 with this purpose. The seeds are released on the beaches where harvest takes place, assuring stability in the reproduction of the stock.

As in other countries, the impact of climate change on the performance of the farmed species is still under assessment. Some species are more sensitive to changes in the environment than other. In the case of the shellfish industry in the Northwest, floods and red tides negatively affect productivity. Some of these issues have increased in recent years. However, the connection between global climate change and the occurrence of these climate phenomena is still a matter of controversy among stakeholders.

3.2 Production allocation and systems

The diversity of species farmed in the Kingdom of Spain has a lot to do with the geography of the country. The north and west coast is confined by the Atlantic Ocean, while East and South coast is the Mediterranean Sea. Even in the Atlantic, the waters in the Canary Islands are suitable for farming warm water Mediterranean species. Thus the Kingdom of Spain has access to cold and warm marine water resources which allows optimal conditions for farming a wide variety of species under different production systems (MARM, 2011).

The vast majority of the cold-water aquaculture, including shellfish, is located in the estuaries of the northwestern region of Galicia. Mussels, clams and turbot are the three main marine species farmed in this region. Mussels are farmed in floating rafts, in a vertical system of hanging ropes where the mussels are fixed for the fattening period. Mussel juveniles are harvested from the wild and transferred to the rafts until they reach commercial size. Clams are seeded in the beach, whether for common or private exploitation. Most of the harvest is managed as a common resource by the fishermen's cooperatives, but some areas are exploited under concession. This is mainly a hatchery-based fishery.

Turbot is farmed in ponds, in land facilities with water exchange with the estuaries. Aquaculture in Galicia is restricted to the estuaries since they provide a protected environment from frequent adverse climatic conditions in the open sea. Developments in land-based technology (Bjørndal and Øiestad, 2010) and offshore aquaculture appear as key factors for potential increases in production and the extension of aquaculture to other regions of the northern coast.

Mediterranean aquaculture is mainly focused on marine finfish such as seabream, seabass and meagre. These species are fattened in cages, where the juveniles are transferred from nurseries and kept until they reach commercial size. These species can also be harvested in semi-extensive and multitrophic systems in protected areas, which result in products with better acceptability and higher prices. However, these production systems represent a very small proportion of the total production mainly due to limitations in available space for farming. Freshwater species can be farmed in intensive or extensive systems. Trout is farmed in intensive farms located at the side of the rivers. Other species with much lower volumes of production such as tench, carps or barbs, are farmed in extensive cultivation in lagoons.

3.3 Diversification of markets and products

With some exceptions, of which bluefin tuna is the best example, the majority of the production of Spanish aquaculture targets the domestic markets. Seafood processing is, therefore, driven by traditional consumer preferences, and dominated by well-established domestic industries such as salting and canning (Fernández-Polanco *et al.*, 2012). Product diversification of aquaculture species strongly depends on their linkages with these traditional industries and consumption preferences. New product concepts are hard to introduce in societies with strong culinary traditions. In this sense, farmed species adapted to processing according to the already-existing consumer preferences.

Mussels and other shellfish have been traditionally associated with the canning industry, and a large range of different processed products have been present in the market for many years. These efforts in product diversification were usually undertaken by the processing industry. However, in recent years mussel farmers' cooperatives have begun to integrate processing into their operations, with new forms of preservation different from canning pushing for a share of the market.

Finfish aquaculture is less developed in this sense. While several different new product concepts have been tested both in freshwater and marine fish, the bulk of supply still consists of fresh whole fish. Fish fillets are the most evolved processed product so far. Recently, more attention is being paid to modified atmosphere as a way to extend the shelf life of the fresh fish (MARM, 2011). The advantages of aquaculture products include the speed with which they can be put on the market and regularity of supply. Modified atmospheres have proved to be a very useful technology in increasing shelf life, which can lead to improving the competitiveness of the products. This sort of packaging is much more frequent in supermarkets than in traditional stores, and it is frequently produced by the retail chains, packing part of their purchases of fresh fish. In general terms, fresh and whole fish remains the dominant product at the ex-farm level.

4. AQUACULTURE DIVERSIFICATION IN THE KINGDOM OF NORWAY

Norwegian farmers set up the first floating cages for growing salmon and trout in fjords in the 1960s. The technology was developed over time and by the early 1980s the industry started to take off. The industry was regulated by the government from early on. Initially the policy was to achieve an owner-operated industry and to promote employment in outlying areas. A government licence was required to establish a farm. Moreover, the size of farms was regulated, and ownership was restricted to the operators of the farms. The success of these first experiences extended salmon farming to other countries in Europe and other continents.

Table 5 depicts sale of slaughtered fish in 2014. Total sale of salmonids represented 1 327 342 tonnes at a value of NOK 44.1 billion with Atlantic salmon representing about 95 percent. Total sales of other marine species represented only 3 140 tonnes of which 94.4 percent was based on produced juveniles and the remained based on wild caught fish. The main species are turbot, halibut and angler-fish, although a detailed breakdown is not available. Some additional information can be gleaned from export statistics. In 2014, exports of farmed halibut were 688 tonnes while 158 tonnes of farmed turbot were exported[35]. In 2012, cod was the most important component of "other marine species"; by 2014, cod farming had collapsed. Recently (2016), it has been announced that Marine Harvest, the largest halibut farmer in the Kingdom of Norway, will close its halibut operations[36]. It is too soon to say whether their operations will be closed down permanently or taken over by a different company.

The rapid rise in production combined with very substantial increases in landings of wild salmon led to market saturation in the late 1980s, with consequent price falls.

[35] Source: Capia/Statistics, the Kingdom of Norway.

[36] http://sysla.no/2016/02/05/havbruk/kveite-ansatte-vi-har-ikke-gitt-opp_76349/

TABLE 5

Norwegian aquaculture production 2014 weight and value

Sale of slaugthered fish. Weight in tonnes round weight	**2014**			
	Atlantic salmon	Rainbow trout	Trout	Total
Total	1 258 356	68 910	76	1 327 342

Value of slaughtered fish.

Value of slaugthered fish. Value in 1000 NOK	**2014**			
	Atlantic salmon	Rainbow trout	Trout	Total
Total	41 822 501	2 298 985	6 145	44 127 630

Total sale of other marine species specified on whether the production is based on produced juvenile or wild caught fish. Weight in tonnes.	**2014**		
	Produced1)	Wild2)	Total
Total	2 967	173	3 140
Total sale of other marine species. Weight in tonnes	**2014**		
	Produced1)	Wild2)	Total
Total	2 967	173	3 140

1) Production based on produced juveniles
2) Production based on wild caught fish

As the industry collapsed due to a substantial price reduction, ownership regulations were abolished (Asche and Bjørndal, 2011). This crisis resulted in a major restructuring of the sector. As a consequence, there has been a tendency towards horizontal and vertical integration and greater concentration in production. There are, however, still some restrictions on ownership. A single firm cannot control more than 10 percent of total licensed capacity although exceptions can be given up to 22 percent. The largest company, Marine Harvest, had 207 licenses which represents about 20 percent of capacity while the second largest, Leroy, has about 13 percent of capacity. The Herfindal-Hirschman Index (HHI), which is a commonly used concentration measure in anti-trust cases, is estimated at 0.091 for salmon farming in the Kingdom of Norway in 2009, based on the largest 50 firms in the industry (Asche *et al.*, 2013). This indicates that despite substantial consolidation in recent decades, industry concentration is still modest.

Over time, farmers have gained much greater control of the production process. Vaccines and better husbandry have contributed to reduced mortality and improved growth. The expansion in salmon farming benefitted greatly from developments in logistics, in particular, air transport of fish – in fact, this was developed due to the advent of farmed salmon. This meant that fresh salmon could be supplied all over the world. It is also advantageous that both fresh and frozen salmon can be used for smoking.

The main challenges facing the industry today are environmental, in particular sea lice and the consequences of escapees that mix with wild salmon. According to Iversen *et al.* (2015), in 2014 the total costs for the Norwegian aquaculture industry related to salmon lice, including prevention and treatment amounted, to NOK 3–4 billon. Results presented by Jay, Asche and Wilen (2016) suggest that 3.62 – 16.55 percent of total biomass growth is lost due to infestation despite control. An average infestation over a typical release cycle in central the Kingdom of Norway generates damages of US$0.46/kg of harvested biomass, equivalent to 9 percent of farm revenues. Thus the costs to the industry of sea lice infestation are substantial. Moreover, the situation leads to concern by consumers and the public in general. Thus, both industry and society at large, including the government, are very concerned about the situation. A number of measures to improve this situation, including new technologies, are being investigated.

Salmon and trout are totally export-oriented (Table 6). For salmon, quantity showed little increase from 2013–15, however, value increased by almost 20 percent over the period, indicating higher unit price. For trout, quantity declined, but a small increase in price can also be inferred. The domestic market is insignificant. In order to succeed in the global market, Norwegian farmers had to adapt to a range of different consumer preferences, quality requirements and product presentations and preparations. Norwegian salmon products can be found in the market under many different levels of processing and preservation including fresh, frozen and smoked.

TABLE 6
Norwegian exports of farmed fish 2013–2015

		2013	2014	2015
Atlantic Salmon	Tonnes wfe	1 106 287	1 156 165	1 193 950
	Value NOK (bn)	40.0	44.0	47.8
Large trout	Tonnes wfe	66 872	61 430	64 430
	Value NOK (bn)	2.4	2.4	2.3

wfe = whole fish equivalent.
Source: Kontali AS.

Attempts have been made to farm several other non-salmonid species including cod, turbot (using hot water from power plans or other industry), halibut and Arctic char. Cod farming, which attracted substantial attention and investment, basically collapsed. Reasons for this are to be found on both the demand side and the supply side. Large quantities of wild cod have reduced the price. At the same time, farmers were not able to control the production process, experiencing high mortality rates and consequently high cost of production (Skuseth, 2010). Quantities of other species have remained modest (Table 1). For cod, these developments can be explained by reference both to market side, where huge quantities of wild product are available and production costs are high because high mortalities, low growth and other factors. Research and cultivation efforts of Atlantic halibut started in the 1980s. Significant research effort was undertaken but the complicated life cycle made aquaculture progress slow and less interesting for investment.

The impact of climate change on fish farming is still under uncertain. Salmon is farmed more or less along the entire coastline of the Kingdom of Norway, from south to north. An increase in sea temperatures may make farming further north more attractive, which may lead to a geographical shift in the location of the industry. Nevertheless it is too early to say if and to what extent this may be happening.

5. SUMMARY AND CONCLUSIONS

Diversification in European aquaculture can be classified into three broad categories: diversification of species, production systems and markets. The cases presented in this paper illustrate two different scenarios. Despite incipient experiences in farming other coldwater species, Norwegian aquaculture remains almost totally focused on salmon. On the contrary, Spanish aquaculture is a good example of species diversification. Spanish aquaculture is mainly targeting the domestic markets, while Norwegian salmon is an export-oriented industry. As a consequence of globalisation, salmon is more diversified in terms of markets and products than any of the Spanish finfish farming industries and probably more so than any other farmed species for that matter.

Diversification of species could be understood as a direct consequence of the different environments in which aquaculture is done. This fact would explain in part why Spanish aquaculture is more diversified than Norwegian. However, the aims behind the European efforts in domesticating new species go beyond adaptation to the environment and point to a competitive advantage. The two cases described in this paper also differ in this sense. Diversification of species is a key strategic element for the Spanish aquaculture industry, while it does not go beyond publicly funded experimental projects in the Kingdom of Norway. The environment, in particular its northern location, constrains Norwegian aquaculture to cold-water species, and any alternative would require developments in recirculation systems as well as high energy requirements to allow optimal production, which result in much higher costs than for international competitors.

The growth of Spanish aquaculture has been driven by the domestic seafood market. On the contrary, domestic demand would never support the growth of the Norwegian salmon industry. The result is a more diversified supply of salmon products in contrast with the Spanish marine finfish industry which, fitting with domestic consumer demands, is concentrated in fresh products with minimum processing. This is not the case of mussel farming, which has been traditionally associated with specific processing industries.

Diversification is presented as a way to improve business performance of aquaculture in the European Union (Member Organization) member states. However, the examples presented in this paper raise some questions about the effectiveness of this solution. Norwegian aquaculture is a profitable industry. The same can be said about the Spanish shellfish industry. These two industries are not much diversified in terms of species, but they are well diversified in terms of products and markets. In contrast, marine finfish aquaculture is quite diversified in the Kingdom of Spain in terms of species, and efforts in developing new species are ongoing. However, product diversification is still a pending issue for the Spanish finfish farming industry.

There are several necessary conditions to ensure sustainable development of aquaculture. First, control with the production process in terms of fish growth and mortality is required. Second, as production takes place in water, and often in the sea, environmental sustainability is necessary. Third, economic sustainability is requited, in the sense that production is profitable in the long run. These conditions have been met to varying degrees by the species discussed in this paper.

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Macroalgae Kappaphycus alvarezii *farmed in Santa Catarina, southern Brazil*

PHOTO CREDIT: LEILA HAYASHI

PAPER 3

AQUACULTURE DIVERSIFICATION IN SOUTH AMERICA: GENERAL VIEWS AND FACTS AND CASE STUDIES OF THE REPUBLIC OF CHILE AND THE FEDERATIVE REPUBLIC OF BRAZIL

Prepared by

Carlos Wurmann G.
M.Sc. Economy, Ing. Civil Industrial
Executive Director, AWARD Ltd
International Consultants, Aquaculture and Fisheries
Santiago – the Republic of Chile
E-mail: carwur@gtdmail.com

and

Eric Arthur Bastos Routledge
M.Sc. Aquaculture, Biologist.
Research and Development Head
Embrapa Fisheries and Aquaculture
Palmas – the Federative Republic of Brazil
E-mail: eric.routledge@embrapa.br

1. AQUACULTURE AND AQUACULTURE DIVERSIFICATION IN SOUTH AMERICA

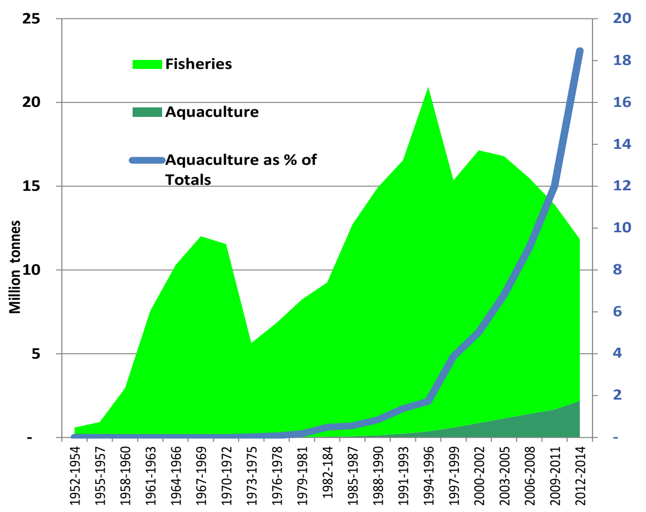
1.1 Facts and figures

South America (SA) is one of the main fishing areas of the world (third economic region, after Eastern and Southeastern Asia, according to the FAO). South America has relatively poor domestic consumption of fish (about 10 kilos per caput in recent years), with wild landings of 9.7 million tonnes per year in 2012–2014, which depend a lot on the pelagic fisheries off the Republic of Chile and the Republic of Peru, whose products are mainly used to produce fishmeal and oil. Wild landings have experienced a serious regression since 1994–1996, when they reached a peak of 20.5 million tonnes.

In contrast, and as a response to fairly open world market opportunities arising from the levelling of marine capture fisheries since the mid-1990s and new technological developments, regional aquaculture has been able to grow, from negligible amounts in the early 1950s, to 2.4 million tonnes in 2014, currently accounting for 18.5 percent of total regional landings and for 3.1 percent of world farmed outputs (average for 2012–2014; Figure 1).

Aquaculture in SA is still a fairly young industry in most countries, and currently (2014) three of them, the Republic of Chile (50.7 percent), the Federative Republic of Brazil (23.4 percent) and the Republic of

FIGURE 1
South America: Wild and aquaculture production, 1952–2014



Source: Basic figures from FAO, FISHSTAT, 2016.

Ecuador (15.4 percent) account for 89.5 percent of production. Of the remaining eleven countries or territories, the Republic of Peru (4.8 percent) and the Republic of Colombia (3.8 percent) also stand out (Table 1).

TABLE 1
South America: Aquaculture production, 1982–2014. Average annual crops, thousand tonnes

Country	1982-1984	1985-1987	1988-1990	1991-1993	1994-1996	1997-1999	2000-2002	2003-2005	2006-2008	2009-2011	2012-2014
Argentine	0.1	0.3	0.3	0.5	1.2	1.2	1.5	1.9	2.7	2.8	3.6
Bolivia		0.0	0.3	0.4	0.5	0.4	0.4	0.4	0.6	0.9	1.2
Brazil	9.2	11.7	18.1	27.9	51.6	110.7	208.6	266.9	297.3	403.7	506.3
Chile	1.6	4.0	19.0	67.5	164.3	279.9	501.1	655.7	805.7	816.3	1 106.4
Colombia	0.6	1.2	6.5	20.1	30.8	47.5	58.9	60.7	68.3	81.6	90.4
Ecuador	30.8	48.4	74.9	103.9	101.4	135.6	65.5	114.2	171.2	267.1	340.9
French Guyana	0.0	0.0	0.1	0.0		0.0	0.0	0.0	0.0	0.0	0.0
Guyana	0.0	0.1	0.0	0.1	0.2	0.4	0.6	0.6	0.5	0.4	0.3
Malvinas/Falkland Is.								0.0	0.0		
Paraguay		0.0	0.1	0.1	0.2	0.2	0.6	1.8	2.4	3.5	6.5
Peru	2.3	4.9	5.0	5.7	6.4	7.9	8.6	20.6	37.0	75.2	104.4
Surinam				0.0	0.0	0.1	0.4	0.3	0.1	0.1	0.1
Uruguay		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2
Venezuela	0.5	0.6	0.7	2.0	5.7	9.8	16.0	19.6	20.7	19.0	27.9
Totals	**45.1**	**71.2**	**124.9**	**228.1**	**362.4**	**593.7**	**862.1**	**1 142.7**	**1 406.6**	**1 670.5**	**2 188,0**

Source: Basic figures: FAO FISHSTAT, 2016.

Production is highly concentrated in terms of species farmed. Salmon and trout contribute with 41 percent to SA's crops in 2012–2014, while shrimp, particularly *P. vannamei*, add another 19 percent to totals, tilapias an extra 13 percent and mussels 11 percent of aquaculture production in this subcontinent. It is also interesting to note that the 'production structure' of SA's aquaculture has varied a lot over the years (Table I–2). In the 1950s, this subcontinent produced only molluscs, particularly oysters and mussels. In the early 1960s salmonid production starts, followed by shrimp late in that decade. Only in the 1970s SA does start producing tilapias and other freshwater fishes. Shrimp dominate local aquaculture until the early 1990s, when salmonid production explodes, leading regional crops until now. SA farms 'negligible' amounts of marine fishes, even though several countries have been working for years with introduced species such as turbot, and with native plaices, robalos and the like in warmer waters.

Development and diversification efforts have always been present in SA's aquaculture since its earlier stages of commercial interest. In fact, aquaculture production growth rates in the subcontinent have surpassed world averages for the last six decades, and have reached very high levels, particularly between the 1970s and 1980s (43.2 percent per year, as seen in Table I–3). However since the 1980s, regional growth rates, even if positive and attractive, have started to diminish, to the point that in the last ten years (see Table I–3) these figures tend to approximate world averages.

The situation is much more variable with wild fisheries. Here, growth rates are very dissimilar in different decades, with negative figures for the last 20 years ending in 2014. In the case of world wild fisheries, though, growth rates have been steadily declining since the 1950s, and have been very close to zero during the last two decades ending in 2014. This difference between SA's and world's growth rates have permitted regional aquaculture to increase its global relevance, to a still modest 3.1 percent of totals (2012–2014).

TABLE 2
South America: Species farmed by group of species and environment, 1982–2014 (thousand tonnes)

ISSCAAP Group	1982-1984	1985-1987	1988-1990	1991-1993	1994-1996	1997-1999	2000-2002	2003-2005	2006-2008	2009-2011	2012-2014
Salmons, trouts, smelts	1.7	3.7	18.5	66.2	156.1	257.4	456.2	569.6	642.0	600.7	893.8
Shrimps, prawns	31.5	50.5	81.7	115.6	118.4	159.2	119.5	213.7	266.5	330.7	421.9
Tilapias and other cichlids	0.2	0.5	1.6	9.8	25.4	45.7	77.1	113.3	143.4	248.2	278.4
Mussels	1.1	1.6	2.5	3.4	8.3	20.9	45.1	86.6	169.5	242.5	263.4
Miscellaneous fresh water fishes	8.8	11.1	17.4	27.8	27.2	45.3	75.6	76.9	105.7	161.1	248.0
Scallops, pectens	0.6	2.1	1.1	2.9	10.2	17.9	22.1	28.4	34.4	54.4	54.2
Carps, barbels and other cyprinids	0.0	0.0	0.1	0.2	13.8	40.1	55.8	47.1	39.8	28.4	23.1
Oysters	0.1	0.3	0.4	0.7	1.7	5.0	7.3	5.4	3.6	2.4	3.0
Abalones, winkles, conchs					0.0	0.0	0.1	0.2	0.4	0.8	1.0
Frogs and other amphibians		0.0	0.0	0.1	0.3	0.6	0.7	0.6	0.6	0.6	0.4
Sturgeons, paddle fishes					0.0	0.0	0.0	0.0	0.0	0.1	0.2
Flounders, halibuts, soles				0.0	0.1	0.3	0.3	0.3	0.3	0.3	0.2
Miscellaneous pelagic fishes										0.1	0.1
Freshwater crustaceans	0.9	1.2	1.6	1.3	0.7	0.4	0.5	0.5	0.3	0.2	0.1
Miscellaneous coastal fishes						0.8	1.9	0.0	0.0	0.1	0.0
Cods, hakes, haddocks											0.0
Marine fishes not identified		0.0				0.0	0.0	0.0	0.0	0.0	0.0
Turtles									0.0	0.0	0.0
Miscellaneous marine crustaceans						0.0	0.0				
Miscellaneous marine molluscs	0.1	0.1	0.1	0.2	0.1		0.0	0.0	0.0	0.0	
Total	**45.1**	**71.2**	**124.9**	**228.1**	**362.4**	**593.7**	**862.1**	**1 142.7**	**1 406.6**	**1 670.5**	**2 188.0**
ISSCAAP Divisions											
Aquatic animals,various		0.0	0.0	0.1	0.3	0.6	0.7	0.6	0.6	0.6	0.4
Crustaceans	32.5	51.7	83.3	116.9	119.1	159.6	120.0	214.2	266.8	330.9	422.0
Molluscs	1.9	4.2	4.0	7.2	20.3	43.8	74.5	120.7	207.9	300.1	321.6
Fresh water fish	9.0	11.6	19.1	37.7	66.4	131.2	208.5	237.3	288.9	437.7	549.5
Diadromous fish	1.7	3.7	18.5	66.2	156.1	257.4	456.2	569.6	642.1	600.7	894.0
Marine fish		0.0		0.0	0.1	1.1	2.2	0.3	0.3	0.4	0.4
Totals	**45.1**	**71.2**	**124.9**	**228.1**	**362.4**	**593.7**	**862.1**	**1 142.7**	**1 406.6**	**1 670.5**	**2 188.0**
Environment											
Fresh Water	11.5	15.3	26.2	47.9	78.1	148.6	224.1	256.4	310.1	500.3	646.2
Brackish	30.3	47.7	73.8	101.8	104.2	138.3	64.6	114.7	168.9	235.3	329.4
Marine	3.3	8.2	25.0	78.3	180.1	306.9	573.4	771.7	927.5	935.0	1 212.4
Total	**45.1**	**71.2**	**124.9**	**228.1**	**362.4**	**593.7**	**862.1**	**1 142.7**	**1 406.6**	**1 670.5**	**2 188.0**

Source: Basic figures: FAO FISHSTAT, 2016.

TABLE 3
Growth rates in South American and World aquaculture, 1952–2014 (Mean average cumulative annual rates of variation, percent)

From	To	Aquaculture	Fisheries	Total
		South America		
1952-54	1962-64	8.2	31.5	28.3
1962-64	1972-74	28.3	-4.2	-3.8
1972-74	1982-84	43.2	4.4	4.1
1982-84	1992-94	18.8	7.4	6.8
1992-94	2002-04	15.3	-2.0	-1.3
2002-04	2012-14	7.6	-4.6	-2.9
		World		
1952-54	1962-64	6.1	6.1	5.5
1962-64	1972-74	6.0	3.3	3.1
1972-74	1982-84	7.3	2.0	2.1
1982-84	1992-94	11.1	1.9	2.7
1992-94	2002-04	8.1	0.3	1.9
2002-04	2012-14	6.0	0.2	2.1

Source: Basic figures: FAO FISHSTAT, 2016.

TABLE 4
South America's and World's aquaculture and wild fisheries production, 1952–2014 (thousand tonnes and percentages)

Region	1952-1954	1962-1964	1972-1974	1982-1984	1992-1994	2002-2004	2012-2014
South America							
Aquaculture	0.0	0.1	1.2	45.1	253.5	1 052.5	2 188.0
Fisheries	589.2	9 144.0	5 960.5	9 206.4	18 767.9	15 403.7	9 652.2
Totals	**589.2**	**9 144.1**	**5 961.7**	**9 251.5**	**19 021.3**	**16 456.2**	**11 840.2**
World							
Aquaculture	958.3	1 729.2	3 097.6	6 279.9	18 016.4	39 202.7	70 170.0
Fisheries	23 912.7	43 262.6	60 040.1	72 955.6	87 967.6	90 743.9	92 475.1
Totals	**24 871.0**	**44 991.8**	**63 137.8**	**79 235.5**	**105 983.9**	**129 946.6**	**162 645.1**
South America as % of Totals							
Aquaculture	0.0	0.0	0.0	0.7	1.4	2.7	3.1
Fisheries	2.5	21.1	9.9	12.6	21.3	17.0	10.4
Totals	**2.4**	**20.3**	**9.4**	**11.7**	**17.9**	**12.7**	**7.3**

Source: Basic figures: FAO FISHSTAT, 2016.

1.2 Diversification of aquaculture in South America: a few figures and concepts

A total of 70 different species are currently farmed in SA (2012–2014), down from a maximum of 79 in 2009–2011[37]. Before the 1970s, only between two and six species were farmed in this subcontinent. In 2012–2014, 54 species farmed (77 percent of totals) were produced in quantities of less than 10 000 tonnes per year, thus they represented only 2 percent of the overall production, with an annual average crop per species of just over 1 400 tonnes throughout SA.

Production structures have also changed over the years, with salmonids accounting for nearly 41 percent of SA's farmed production in 2014, the most important aquaculture category in the subcontinent. Only 30 years ago, those species represented only 3.7 percent of farmed production, while farmed production was headed by

[37] As per FAO's FISHSTAT, 2016.

crustaceans (72 percent of aquaculture production). Only the environmental origin of fish farming has remained relatively stable along the years, as in 1982–1984 about 26 percent the crops were associated with fresh water operations, while currently (2012–2014) almost 30 percent is produced in this environment.

Fourteen SA countries and territories currently report their aquaculture statistics to the FAO. By 1952–1954, only one nation, the Republic of Chile, was farming two marine species, i.e., oysters and mussels, totaling 47 tonnes. Twenty years later (1982–1984), there were nine countries farming 34 species totaling 45 116 tonnes, and by 2012–2014, thirteen nations cultivated 139 species[38], totaling 2.188 million tonnes per year.

However impressive this development process might seem, most of it is mainly related to the same small number of species and countries highlighted before. So, even though the number of countries/territories and species farmed in SA have increased along the years, most of them have yet to show their impact in production volumes and values.

Most of SA's aquaculture production until the present is of introduced or non-native species, such as salmon, trout, turbot and abalones in the Republic of Chile; trout in many other countries; tilapia all over the subcontinent; white shrimp in the Federative Republic of Brazil, the Republic of Colombia, the Bolivarian Republic of Venezuela and the Republic of Peru; carps and catfishes in different countries, etc. This has been because, with few exceptions, there were no technologies available to readily farm native species. However, this trend is changing, as most expansion and diversification efforts in current years refer to the development of new technologies to farm native species.

The Federative Republic of Brazil, with 25 species[39], has the more diversified production in SA during 2012–2014, 18 of which surpass the 1 000 tonnes per year. However, the number of species farmed there has diminished from a maximum of 35 in 2009–2011. Argentina follows, with 19 species farmed, but with fairly insignificant average crop per species (189 tonnes per year) and only 2 of them exceeding 1 000 tonnes per year. Then comes the Republic of Chile, with 18 species, 11 of them exceeding 1 000 tonnes per year, and an average per species of about 61 500 tonnes per year, the highest value for the subcontinent in this last triennium. In all, only 35 percent of the species farmed by each country in SA show mean annual crops of over 1 000 tonnes, with only three countries – the Republic of Chile, the Republic of Ecuador and the Federative Republic of Brazil – surpassing farmed productions of ten thousand tonnes per species and year.

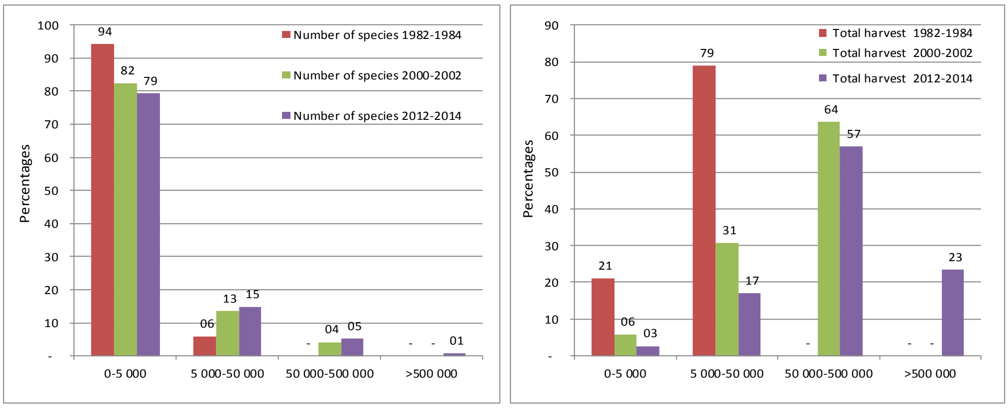
Therefore, it is evident again that, even though aquaculture production is advancing in SA for a limited number of countries and species, this subcontinent is in a very early stage of development of its aquaculture industry. Aquaculture output in SA is highly dependent on a very limited number of species farmed in high volumes. A high number of species is now being considered for aquaculture diversification in SA, but it is clear that a good number of them can hardly be expected to progress significantly in the near future or even in the mid-term.

Present diversification efforts are based on several factors, among which the following are of particular relevance: (1) Governmental desire to create more job

[38] These are mean annual averages calculated over triennial periods. Therefore, decimal values are here acceptable, and are used as such when dealing with other calculations, such as those for the values of mean annual crop per species. Of course, some species farmed in one country are also farmed in another, so that this number does not reflect the actual number of 'different' species farmed in SA. That number is smaller, and equivalent to 70, as stated on previous paragraph.

[39] Here, the number of species is calculated adding species farmed in fresh water to those in marine/brackish environments. As some species are cultivated in both types of environment, the actual number of 'different' species is somewhat smaller than the resulting figure, if one does not take into account this division among environments.

FIGURE 2
Distribution of the number of species farmed (left) and their harvest volumes (right), per harvest interval (expressed in tonnes), 1982–2014 (Percentages of the total number of species farmed and of total volumes harvested, percent)



alternatives and improve food security, replace food-fish imports, etc.; (2) Scientific drive and ingenuity, to move the frontiers of 'what can be learnt and done'; (3) Private sector moves, to explore new business alternatives.

Many species targeted for aquaculture diversification and development in SA will probably not succeed in becoming commercially viable targets in the coming 10–15 years, because the resources needed to complete the R&D efforts and related subjects, the time required, and the need for technical personnel and proper development programs are limiting almost everywhere in this subcontinent. As a consequence, more concentrated efforts, referred to a more limited number of species would be much more convenient for SA, if results of commercial interest are wanted in reasonable periods of time. Practically non-existent country- to- country cooperative efforts and the challenges associated with the marketing of 'new' aquaculture products make the whole diversification process risky, if not unfeasible in many countries and/or with several species.

Therefore, in the authors' minds, a more creative, realistic and result-oriented SA strategy has to be devised for future action. Here, some basic premises become apparent, such as the need to look at the diversification process from a more holistic perspective. The most significant efforts until now have been devoted to basic biologic and technologic studies, and those studies did not achieve the critical 'mass' necessary to produce results; in parallel, other 'dimensions' of aquaculture development, such as governance, markets and marketing, logistics, social and environmental impacts, human capital, financial backing and the like have been neglected, becoming at some point the weak link that prevented the achievement of results of any significance. If these realities are ignored, aquaculture diversification in SA will consume scarce economic, social and human resources to no avail.

Paiche/pirarucu technology has been developed in the Federative Republic of Brazil, the Republic of Peru and the Plurinational State of Bolivia for well over a decade without producing significant commercial results; cobia has been and is being tried in the Republic of Ecuador, the Republic of Colombia, the Federative Republic of Brazil, the Republic of Panama, the Republic of Chile, the United Mexican States and other places without much commercial success; mussel, salmon, silversides and plaice production have been tried for many years in Argentina, while the Republic of Chile has invested in merluza austral (southern hake), sea urchins, halibut, Atlantic cod, hirame, red abalone, the European scallop and many other species without much achievement, while the Republic of Panama works with yellowfin tuna, the United Mexican States and the Republic of Chile with yellowtail kingfish, etc.

Facts and figures also show that for most part, this subcontinent's production seems to concentrate more on continental (101) than on marine (38) species. Fresh water aquaculture seems to pose relatively fewer demands, and is more readily applicable in small scale, while marine species require more extended R&D, need more financial resources and technical personnel not available in many parts of this subcontinent. Marine aquaculture initiatives could probably be tackled more efficiently by associating local countries, and also including 'foreign' partners to produce results in reasonable periods of time. Whatever the case, efforts should be devoted to deal with issues beyond technology, availability of which is still insufficient to provoke sustainable additional harvest on its own. Countries (and groups of countries as well) need a 'renewed' approach to aquaculture diversification, with fresh, more realistic and cost and socially effective long-term strategies based on well-conceived ideas.

Many SA countries do not have government personnel or scientists/technologists with the abilities and/or knowledge to lead these processes; aquaculture is fairly new to them, and they need support to achieve better results in their farming developments. As well, a more integrated 'subcontinental approach' to diversification, with joint planning and work, can enhance results in the medium term. All these actions require political will, well-conceived ideas and programs, and the concerted efforts of the SA's scientific, governmental and social communities.

TABLE 5

South America: Countries with aquaculture activity, volumes and species farmed, and various coefficients, by type of environment, 1952–2014 (figures are mean annual values for each period)

Country/Territory	1952-1954	1982-1984	1991-1993	1997-1999	2000-2002	2003-2005	2006-2008	2009-2011	2012-2014
Number of species farmed by country									
Argentina	-	1	3	8	9	9	10	18	19
Bolivia	-	-	4	3	5	5	5	5	5
Brazil	-	4	6	26	29	30	30	35	25
Chile	2	7	14	14	15	17	17	17	18
Colombia	-	8	7	14	13	11	8	16	13
Ecuador	-	3	9	7	6	5	8	9	7
Falkland/Malvinas Isl.	-	-	-	-	-	2	2	-	-
French Guiana	-	1	1	2	5	3	3	3	3
Guyana	-	2	2	7	6	6	6	10	9
Paraguay	-	-	3	6	6	5	5	9	5
Peru	-	5	11	11	15	15	17	15	15
Suriname	-	-	1	2	2	1	2	4	3
Uruguay	-	-	3	4	5	7	5	5	9
Venezuela	-	3	6	6	7	5	8	10	8
Total	**2**	**34**	**70**	**110**	**123**	**121**	**126**	**156**	**139**
Number of species farmed									
Fresh water	-	18	45	69	83	82	87	114	101
Marine/brackish waters	2	16	25	41	40	39	39	42	38
Total	**2**	**34**	**70**	**110**	**123**	**121**	**126**	**156**	**139**
Number of species farmed with over 1 000 tonnes per year									
Fresh water	-	1	8	20	23	24	27	30	33
Marine/brackish waters	-	3	11	14	16	16	16	14	15
Total	**-**	**4**	**19**	**34**	**39**	**40**	**43**	**44**	**48**
Percentage of species farmed above 1 000 tonnes per year, %									
Fresh water	-	25	42	59	59	60	63	68	69
Marine/brackish waters	-	75	58	41	41	40	37	32	31
Total	**-**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

TABLE 5 (CONTINUED)

Country/Territory	1952-1954	1982-1984	1991-1993	1997-1999	2000-2002	2003-2005	2006-2008	2009-2011	2012-2014
Number of countries with aquaculture production									
Fresh water	-	8	12	12	12	12	12	13	13
Marine/brackish waters	1	7	8	9	9	10	10	9	9
Total	**1**	**9**	**13**	**13**	**13**	**14**	**14**	**13**	**13**
Aquaculture production, tonnes									
Fresh water	-	11 513	47 924	148 569	224 082	256 367	310 133	500 257	646 151
Marine/brackish waters	47	33 603	180 144	445 175	638 036	886 324	1 096 443	1 170 257	1 541 863
Total	**47**	**45 116**	**228 068**	**593 744**	**862 118**	**1 142 691**	**1 406 576**	**1 670 514**	**2 188 014**
Average annual harvest per species, tonnes									
Fresh water	-	640	1 065	2 153	2 700	3 126	3 565	4 388	6 398
Marine/brackish waters	23	2 100	7 206	10 858	15 951	22 726	28 114	27 863	40 575
Total	**23**	**1 327**	**3 258**	**5 398**	**7 009**	**9 444**	**11 163**	**10 708**	**15 741**
Average annual harvest per country, tonnes									
Fresh water	-	1 439	3 994	12 381	18 673	21 364	25 844	38 481	49 704
Marine/brackish waters	47	4 800	22 518	49 464	70 893	88 632	109 644	130 029	171 318
Total	**47**	**5 013**	**17 544**	**45 673**	**66 317**	**81 621**	**100 470**	**128 501**	**168 309**

Source: Basic figures: FAO FISHSTAT, 2016.

In recent decades much has been gained in scientific/technological knowledge aimed at farming different native species, or in adaptation of foreign technologies to local circumstances. However, more and complementary work is needed to make new production feasible and lasting. Moreover, aquaculture diversification efforts do not necessarily pay sufficient attention to 'production models'. Here, even if technologies and other aspects can be dealt with reasonably well, 'new' species might not be produced competitively enough, because of inadequate production scales, bad selection of sites, excessive restrictions, etc. In these cases, sales prices are higher than desirable, inhibiting domestic consumption and/or favouring imports. These situations mainly occur as a result of pressures exercised by local communities which want to have more access to work, or from poorly evaluated governmental or scientists' acts, resulting in unsustainable and short-lived activities, and severe social frustration.

Climate change also poses new questions to aquaculture development and diversification. Here, the subcontinent is facing (and has faced) extended periods of drought in some areas; floods in others; desertification of some coastal zones; variable catches in oceanic waters; algae blooms in several countries and regions and other so far unpredictable events that will challenge aquaculture and its future. Even though some efforts have been made within the FAO, other international organizations and in several countries to predict and evaluate the possible outcomes of climate change over this subcontinent, little is known beyond the fact that Governments and producers, together with the scientific communities, have to keep these long term and accentuated effects in mind, paying more attention to R&D in this field, and on their prospective effects in production, employment, community life and environmental change. This variable, scarcely considered until very recently in South American aquaculture, will have to be addressed by planners, governments and other players; more financial resources will be required.

TABLE 6

South America: Distribution of the number of species farmed and of harvest per species, in different harvest intervals, 1952–2014 (intervals are in tonnes. Figures are mean annual values for each period)

Harvest intervals	1952-1954	1982-1984	1991-1993	1997-1999	2000-2002	2003-2005	2006-2008	2009-2011	2012-2014
Number of species in different harvest intervals expressed in tonnes									
<=100 tonnes	2	14	32	50	55	51	54	75	61
100-500	-	12	14	18	20	20	19	21	18
500-1 000	-	4	5	6	6	7	8	15	11
1 000- 5000	-	2	10	13	17	17	18	17	17
5 000-10 000	-	1	3	9	4	7	3	2	7
10 000-50 000	-	1	4	7	12	8	14	14	13
50 000-100 000	-	-	1	2	2	5	2	2	1
100 000-250 000	-	-	-	2	3	1	4	6	5
250 000-500 000	-	-	-	-	-	1	1	-	1
>500 000	-	-	-	-	-	-	-	-	1
Total, species	**2**	**34**	**69**	**107**	**119**	**117**	**123**	**152**	**135**
Percentage of species in each harvest interval, %									
<=100 tonnes	100.0	41.2	46.4	46.7	46.2	43.6	43.9	49.3	45.2
100-500	-	35.3	20.3	16.8	16.8	17.1	15.4	13.8	13.3
500-1 000	-	11.8	7.2	5.6	5.0	6.0	6.5	9.9	8.1
1 000-5000	-	5.9	14.5	12.1	14.3	14.5	14.6	11.2	12.6
5 000-10 000	-	2.9	4.3	8.4	3.4	6.0	2.4	1.3	5.2
10 000-50 000	-	2.9	5.8	6.5	10.1	6.8	11.4	9.2	9.6
50 000-100 000	-	-	1.4	1.9	1.7	4.3	1.6	1.3	0.7
100 000-250 000	-	-	-	1.9	2.5	0.9	3.3	3.9	3.7
250 000-500 000	-	-	-	-	-	0.9	0.8	-	0.7
>500 000	-	-	-	-	-	-	-	-	0.7
Totals	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**
Volumes harvested per species, in different harvest intervals									
<=100 tonnes	47	375	843	915	892	903	1.079	1.977	1.539
100-500	-	2 405	3 891	5 463	5 720	4 524	4 132	5 385	4 587
500-1 000	-	2 563	3 736	4 254	4 856	5 005	5 759	11 138	8 236
1 000-5000	-	4 177	21 918	27 050	38 497	38 003	38 909	44 185	43 561
5 000-10 000	-	8 500	22 758	60 327	28 056	56 044	23 089	13 453	44 443
10 000-50 000	-	27 096	83 929	131 388	236 305	170 421	243 211	294 828	328 257
50 000-100 000	-	-	90 994	143 106	107 651	408 049	159 247	128 097	68 229
100 000-250 000	-	-	-	221 241	440 142	121 389	565 696	1 171 450	868 640
250 000-500 000	-	-	-	-	-	338 354	365 455	-	308 367
>500 000	-	-	-	-	-	-	-	-	512 155
Totals	**47**	**45 116**	**228 068**	**593 744**	**862 118**	**1 142 691**	**1 406 576**	**1 670 514**	**2 188 014**
Percentages of harvests per species in different harvest intervals, %									
<=100 tonnes	100.0	0.8	0.4	0.2	0.1	0.1	0.1	0.1	0.1
100-500	-	5.3	1.7	0.9	0.7	0.4	0.3	0.3	0.2
500-1 000	-	5.7	1.6	0.7	0.6	0.4	0.4	0.7	0.4
1 000- 5000	-	9.3	9.6	4.6	4.5	3.3	2.8	2.6	2.0
5 000-10 000	-	18.8	10.0	10.2	3.3	4.9	1.6	0.8	2.0
10 000-50 000	-	60.1	36.8	22.1	27.4	14.9	17.3	17.6	15.0
50 000-100 000	-	-	39.9	24.1	12.5	35.7	11.3	7.7	3.1
100 000-250 000	-	-	-	37.3	51.1	10.6	40.2	70.1	39.7
250 000-500 000	-	-	-	-	-	29.6	26.0	-	14.1
>500 000	-	-	-	-	-	-	-	-	23.4
Totals	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Source: Basic figures: FAO FISHSTAT, 2016.

Note: Here the number of species is somewhat smaller than in the former table, as in this case species farmed both in fresh and marine environments are counted only as one and not as two.

2 AQUACULTURE AND AQUACULTURE DIVERSIFICATION IN THE REPUBLIC OF CHILE

2.1 Current situation, production models and strategies

The Republic of Chile is an outstanding world aquaculture producer, currently ranked among the ten most important countries in this field, with the Kingdom of Norway as the only other Western nation in this category. This fact is basically associated with the production of salmon/trout and mussels, which together represented over 98 percent of Chilean aquatic farmed production in 2014. The Republic of Chile ranks second only to the Kingdom of Norway in salmon and trout farming, and is the second largest mussel grower in the world, after the People's Republic of China.

It was not easy to introduce commercial aquaculture in the Republic of Chile, which for decades was mainly concerned with abundant capture fisheries developed since the 1960s with governmental support. Fish farming was not considered to be an important sectoral 'addition' for some time, a view that led to certain degree of complacency both at private and governmental levels. Whatever the reason, the Republic of Chile has evolved to become a leading aquaculture nation whose story is linked to extraordinary natural and environmental conditions, to the opening of the Chilean economy in the late 1970s, and to the drive of many entrepreneurs who, with limited help from government at the outset, led the way in conjunction with institutions such as Foundation Chile and several universities.

FIGURE 3
Chile and Its regions

Table 7 shows aquaculture production evolution since 1990 and the relative importance of the different species being cultivated. Even though growth since 1990 has been substantial (Table 8), the process is slowing down, indicating that the development 'model' used until now[40] has lost dynamism, and suggesting that there is a need for a new strategy in a country which still has ample room for aquaculture progress and diversification. The loss of vitality can be explained by several factors, i.e., lower export growth rates to the main destinations, growing complexities in the assignment of farming permits and other governance issues, disease outbreaks, questionable environmental situations and financial constraints.

Aquaculture development is a highly desirable proposition in many parts of the country not currently involved in this industry, and in others where further diversification is still attractive. The use of diversification, as an alternative for further growth, will be explored in more detail in the following paragraphs.

Up to now, and because of a restricted domestic demand, commercial aquaculture in the Republic of Chile is mostly export oriented, and it was targeted with that intention from its very beginnings. Thus, most farming enterprises related to salmon/trout production, processing and marketing are fairly sophisticated, of a large size and use state of the art technology to compete globally. Following this pattern, the Republic of Chile became the main supplier of imported salmon to the United States of America and Japan, and more recently, in the Federative Republic of Brazil.

[40] Chilean recent growth rates in production are inferior to those observed worldwide as an average.

TABLE 7
Chile: Aquaculture production, 1990–2014 (in thousand tonnes)

Year	1990-1994	1995-1999	2000-2004	2005	2006	2007	2008	2009	2010	2011	2012
Atlantic salmon	22.3	87.7	263.2	385.8	376.5	331.0	388.8	204.0	123.2	264.4	399.7
Coho salmon	22.6	67.5	103.0	102.5	118.2	105.5	92.3	120.0	122.7	159.6	162.8
Rainbow trout	16.9	60.0	108.5	123.0	150.6	162.4	149.4	149.6	220.2	224.5	262.8
Other salmonids	0.7	0.4	2.7	2.9	2.0	1.9	0.1	0.6	0.6	1.1	1.7
Other fish	0.0	0.2	0.3	0.3	0.3	0.4	0.3	0.3	0.3	0.3	0.3
Total fish	**62.6**	**215.8**	**477.6**	**614.4**	**647.6**	**601.2**	**630.9**	**474.5**	**467.2**	**649.7**	**827.2**
Mussels	3.0	9.7	47.0	87.7	127.0	153.4	187.1	175.7	221.5	288.6	257.8
Scallops	4.0	13.3	18.5	17.3	19.4	20.1	21.3	16.5	8.8	11.0	5.8
Abalones	0.0	0.0	0.1	0.3	0.4	0.4	0.5	0.9	0.8	0.8	0.9
Oysters	0.8	3.5	4.7	2.6	1.6	1.0	1.1	0.2	0.3	0.4	0.3
Other mollusks	0.3	0.6	1.3	1.4	1.5	1.7	2.3	2.0	2.5	4.5	2.6
Total mollusks	**8.0**	**27.1**	**71.7**	**109.4**	**149.9**	**176.6**	**212.2**	**195.3**	**233.9**	**305.3**	**267.4**
Gracilaria algae	51.6	71.4	46.2	15.5	33.6	23.7	21.7	88.1	12.2	14.5	10.6
Other algae	0.0	0.0	0.0	0.0	4.6	2.7	6.0	0.0	0.0	0.0	0.0
Total algae	**51.6**	**71.4**	**46.2**	**15.5**	**38.2**	**26.4**	**27.7**	**88.2**	**12.2**	**14.5**	**10.6**
Other species	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	**122.2**	**314.3**	**595.5**	**739.4**	**835.7**	**804.2**	**870.8**	**758.0**	**713.2**	**969.6**	**1105.2**
Index, 2005=100	**17**	**43**	**81**	**100**	**113**	**109**	**118**	**103**	**96**	**131**	**149**

Source: SERNAPESCA: National Fisheries Service, the Republic of Chile

TABLE 8
Chile: Average growth rates of commercial aquaculture, 1990–2014 (mean average cumulative rates, calculated between mean average crops of five-year periods)

Species	1990/94	1995/99	2000/04	2005/09
	1995/99	2000/04	2005/09	2010/14
Total fish	28.1	17.2	4.4	4.4
Total mollusks	27.5	21.5	18.7	9.3
Total algae	6.7	-8.3	-3.2	-20.4
Other species	–	14.9	-24.2	–
TOTAL	**20.8**	**13.6**	**6.1**	**4.8**

Source: SERNAPESCA: National Fisheries Service, the Republic of Chile.

Atlantic salmon (*Salmo salar*) is by far the main species produced, followed by Coho salmon (*Oncorhynchus kisutch*) and trout (Oncorhynchus mykiss), with 67 percent, 17 percent and 16 percent of salmonids' crops in 2014, respectively. Salmon farming takes place almost exclusively in Southern Chile, from the Araucanía to the Magellan Regions. In the former area, but also south of it, farming aims at producing smolts in fresh water for later transport to marine sites, to complete the production cycle in cages.

Cage farming at sea takes place in the Los Lagos (Lake), Aysén and Magellan Regions, where temperatures and other environmental conditions – such as sheltered sites on a very indented coastline – are optimal for these purposes. Lately, Aysén has surpassed the Lake Region as the main source of production. In Magellan, commercial farming started more recently, and so far accounts for about 5–6 percent of total crops. However, production there is advancing rapidly.

Mussel production was initiated as a low-scale family oriented undertaking in the 1960s and 1970s, and changed significantly when Spanish entrepreneurs started operations in the Lake Region late in the 1990s, bringing in new technologies and developing unexplored market opportunities abroad. There currently are many medium size mussel farmers, a few large scale ones, and just a handful of huge processing plants dominating the export trade, producing their own crops and/or buying from third parties. They have enormous capacities and use state of the art technology. This trade, again, is export oriented, highly technical and large scale in processing, and increasingly mechanized in primary production.

Mussel farming takes place almost exclusively in the Lake Region; production reached 290 000 tonnes in 2011(240 000 tonnes in 2014) and employment in this trade is estimated at 17 000 direct and indirect posts.

For both salmon and mussels, the main production drivers have been the excellent local environmental conditions plus technology brought from abroad. In the case of salmon/trout, production models were adapted mainly from the Kingdom of Norway, Japan and the United States of America, while farming technology from the Kingdom of Spain and New Zealand have shaped local methods to produce mussels. Producers, universities, and technologic institutes have successfully adapted and improved foreign systems. However, the Republic of Chile still lacks the scientific/technological capacities to produce world class equipment and to fully develop local solutions in several matters that need further attention. Even though efforts are being made, in several subjects the country will still have to rely on foreign technology and equipment for farming and processing in the years to come.

In sum, most Chilean aquaculture is highly sophisticated, increasingly technical, able to compete globally, but still highly dependent on two products only: salmon/trout and mussels. Large scale production dominates the domestic scene. Local producers of salmon currently number less than 25, but, there are about 1 200 enterprises that provide them with all sorts of services, being a part of a big 'cluster' in the Lake Region, around Puerto Montt and Castro (Chiloé Island)[41].

Most other farming enterprises are small or medium-size in terms of production, and are not always organized so as to be able to compete globally or with eventual imports.

Because salmon and mussel farming are well established and have their own dynamics, when talking about aquaculture diversification in the Republic of Chile, reference will be made mainly to other species farmed, mostly in southern Chile, and to other promising possibilities that might have the ability to 'open' new fish farming activities in other parts of the country where environmental conditions are different (for example, there are fewer sheltered marine sites, and less fresh water available).

Whatever the story of aquaculture development and diversification, it has to be said that sectoral governance in the Republic of Chile is the cause of many problems and limitations. For instance, small producers have not yet received sufficient attention; they face difficulties with farming authorizations and many other bureaucratic procedures; they badly need technical assistance and a proper statute to facilitate their incorporation in this industry, etc. Poor regulations about the carrying capacity of the different water bodies are behind disease outbreaks in salmon production; farms have been authorized and sited based on insufficient scientific knowledge; there is overcrowding in some areas; R&D activities are insufficient and poorly focused; suppliers of goods and services are not treated fairly by primary producers; there are short and mid-term financial shortages and difficulties, etc. Production cycles in mussel farming are longer than they used to be, demonstrating the existence of overcrowding and poor management in many areas. On a social level, aquaculture has not shown the capacity to properly interact with local people or to integrate in their communities, facts that also deserve further consideration.

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[41] Prospectus Consulting, 2016, Consultoría para Construir Hoja de Ruta de Programa Estratégico – Salmón Sustentable, Unpublished study carried out for the Salmon Strategic Program, CORFO, Santiago.

There are growing concerns that the Chilean industry might not be sustainable in the long term without corrective actions and the enhancement of the whole 'production model'. It is also true that the Republic of Chile has excellent and ample space for further aquaculture development, not only from a spatial standpoint but also in terms of market prospects, process sophistication, R&D or in many other aspects connected to 'diversification' and governance.

2.2 The aquaculture diversification process in the Republic of Chile: recent history and current status

2.2.1 More on salmon and mussels

Since the early years of the twentieth century, aquaculture activities changed dramatically in orientation, size, economic and environmental importance in the Republic of Chile.

Late in the nineteenth century, salmon and trout eggs were brought from the United States of America and Europe, aimed at producing juveniles to seed southern rivers and lakes and enhance sports fisheries. Governmental facilities were built to handle ova and produce juveniles that were released in lakes and rivers, and sometimes in the sea. This work was complemented in the 1960s by trials led by the Servicio Agrícola Ganadero (SAG) with assistance from JICA (Japanese International Cooperation Agency), to generate 'salmon runs' in the Aysén Region by producing and releasing pink and chum salmon[42]. This program was not at all successful despite a decade of costly efforts. Those exploratory moves were widened with activities led by American and Canadian experts during the 1970s and early 1980s, showing that cohos and chinooks were the species with higher probabilities to return to their sites of release. Juvenile releases were carried out in Chiloé (Curaco de Vélez, Lake Region), and were very successful. However, local fishermen started to catch those juveniles and the whole process was discontinued. These last trials were conducted by Foundation Chile, a remarkable technology transfer institution (50 percent ownership by the Chilean Government) that bought Curaco's farm and later started with intensive farming in that same area, while continuing with 'ranching' trials, this time in the more isolated but equally promising Magellan Region.

During the 1960s, as well, IFOP (Fisheries Development Institute), an institution created by the Chilean Government with technical support from FAO, started experimenting with Spanish and French technologies to produce mussels, other molluscs and Chilean oysters, to help providing local populations in the Lake Region with new work opportunities to improve their livelihoods. These activities were partially successful, but took 25 years to positively affect local communities, when Spanish mussel entrepreneurs started large-scale activities in Chiloé Island.

Commercial aquaculture in the Republic of Chile only 'took off' with trout and salmon intensive production late in the 1970s and the early 1980s in the Lake Region, after promising results from experimental work with cohos in Aysén. At this point, a few private entrepreneurs and Foundation Chile started farming operations in cages at sea[43]. Environmental conditions were considered optimal for these purposes, there were plenty of sites available, temperatures were ideal and an indented coastline permitted farmers to work with fairly cheap components (cages) in well-sheltered areas.

From the outset, salmon farming was seen as a large-scale and export oriented activity. It incorporated the best technology available and adopted very high production and sanitary standards to be able to access the most demanding world markets. Interestingly, the first local salmon farmers did not have a fisheries background. They came instead from agriculture, construction, trade, etc., bringing fresh energy and

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[42] Introduction into Aysén, Chile of Pacific salmon Program

[43] Several unpublished reports by Foundation Chile, where the author directed the Marine Resources Division for many years

drive, at a time when the Chilean economy was opening to the world, exports became attractive and foreign trade firms were looking for diversification options. In parallel, foreign capital brought technology and good management, and institutions such as Foundation Chile and some universities started to provide technical assistance and prepare staff to back these new salmon farming enterprises.

Crucial to these developments were showcase enterprises put in place by Foundation Chile, (Salmones Antártica, Salmones Huillinco and others), which demonstrated that salmon farming was feasible and attractive; that technology was locally available; that trained personnel could be found or formed, and that world markets were anxious to buy locally farmed salmonids. Foundation Chile also provided technical assistance, evaluated investment proposals, looked for sites and was able to supply smolts and feed. It also created a highly reputed fish health service, developed quality standards for this new industry, and encouraged the formation of the Association of Salmon Producers, an institution instrumental in the promotion of Chilean salmon in different markets and in discussions about governance issues. In parallel, it also approached insurance companies, shipping agencies, airlines and governmental institutions to inform them about salmon developments in the Republic of Chile, helping to avoid bottle-necks, and facilitating the inception and growth of many salmon farms owned by foreign investors.

As noted, at the beginnings of intensive salmon farming there already existed trained technicians to handle the fresh water stage of production. Cage farming technologies were brought from abroad; they have been well adapted locally, and have evolved substantially through the years. However, the country still relies mainly on foreign developments for these purposes, as local R&D efforts are still limited and/or financially frail.

2.2.2 Farming of other species

Work of some relevance with other species dates back to the 1960s, when IFOP experimented with the farming of mussels (*Mytilus chilensis*) and the native oyster (*Ostrea chilensis*). Results were was not very appealing in commercial terms, but helped training personnel and facilitated the starting of several small scale farms until the 1980s, when the Pacific oyster was introduced first in central Chile and later in the Lake Region. Native oyster and mussel production were mainly based on the collection of seeds from the wild[44]. Only Pacific oyster seeds were produced in hatcheries. That process continues, and supplies both Chilean and foreign farmers located in the United Mexican States, the Republic of South Africa, Canada and other countries.

Until the late 1990s, when 'industrial-size' mussel production started, native oysters and mussels were almost exclusively destined for local consumption, a fact that limited production and incentives to introduce more competitive technologies. On the contrary, the growing availability of Pacific oyster seed encouraged the formation of several on-growing farms, which introduced more modern production methods motivated by export prospects, which after several years of trials did not produce consistent results. Here, diseases and poor market performance have resulted in an almost complete stoppage of these export-oriented farming activities in more recent years.

In parallel, scallop farming (*Argopecten purpuratus*) aimed at exporting to the French Republic and other destinations started in Central Chile, following Japanese methods, and established an industry in Tongoy and Caldera. This new crop exceeded 20 000 tonnes in 2007 but has diminished considerably since then, as a result of competition with Peruvian farmers and wild scallops from that origin, proving that the Republic of Chile's production structure was neither competitive enough nor sustainable. Most local producers have very small farming capacities, and rely almost

[44] Even today, when Chile ranks among the most important mussel farmers of the world, local production is almost 100 percent based on wild seed, collected by many farmers, and thereafter sold to growers.

completely on wild seed, factors responsible for disruptions which prevented achieving a sustainable and competitive production pattern. Restructuring of production models, better technology and the opening of new markets could again attract the attention of investors. Local conditions to farm scallops in northern waters are excellent, and those improvements can help compete with the Republic of Peru.

Other local molluscs such as cholga (*Aulacomya ater*), choro zapato (*Choromytilus chorus*) and some clams are also farmed, mainly in small quantities, to satisfy local demand, supplement declining wild stocks and/or create future exports. Cholga are similar to New Zealand's green mussels, a species which can be used as an example on what 'creative marketing' can do to promote consumption in different markets. Local seed is again mainly collected from the wild[45], and at least with cholga, better technology and the opening of new foreign markets can dramatically enhance future farming prospects.

Farming technologies developed in the United States of America and Japan for red abalone from California (*Haliotis rufescens*) and green abalone (*Haliotis discus hannai*) were also fairly successful when those species started to be farmed during the 1980s. The former showed good success, while the latter yielded limited results only. Today, Chilean abalone farmers produce close to 1 200 tonnes per year (2014), almost all of them 'reds' exported to Asian markets. [46]

Accessing foreign technology also permitted farming turbot (*Scopthalmus maximus*) in the country in the early 1990s. This first effort to farm marine fish in the Republic of Chile with European technology was a 'technologic success', but it was almost completely discontinued in 2014 because of difficulties related to marketing that species abroad. Production never surpassed 400 tonnes per year, a level that scarcely justified sufficient marketing efforts and was not attractive to foreign buyers. Even if turbot farming did not succeed in establishing a new work alternative in sustainable commercial terms, it permitted training a number of technicians in marine fish farming, opening the gates to further developments with other introduced marine species like hirame (*Paralichthys olivaceus*), and several native ones such as the local plaice (lenguado, *Paralichtys adspersus*), merluza austral (*Merluccius australis*), bacalao de profundidad (the well known Chilean seabass, *Dissostichus eleginoides*) and more recently, palometa or dorado (yellowtail kingfish, *Seriola lalandi*), corvina (*Cilus gilberti*) and conger eels such as congrio dorado (golden kinkclip, *Genypterus blacodes*) and congrio colorado (red kingclip, *Genypterus chilensis*) among other species.

Currently, development work is evolving favorably with yellowtail kingfish, conger eels and corvina, leading many to believe that in the next 5–10 years these species will be farmed at commercial levels of some importance, again aiming at foreign destinations. In the case of the Chilean seabass expectations are also high, but practical results will not become available before 10 to 15 years. In other cases, such as that of hirame, prospects are also fair. Farming technology brought in from Hawaii and Asia in the early 1990s is well mastered, but there are no juveniles or brood stock locally available, as all remaining fish used to do experimental and pre-commercial work were unexplainably sacrificed. Local plaice, a species which does not grow very well after reaching one kilo, along with turbot, well mastered technically and a faster grower, need to be completely reevaluated in economic and market terms, if a second chance is ever going to be offered to these species by local entrepreneurs.

Yellowtail kingfish, available in the wild in very small quantities in Chilean waters, has been targeted for farming because of its market prospects in several countries and the evolution of recirculation farming technology. Most development work

[45] Reference should be made to the fact that even though seeds come from the wild, there is human intervention that facilitates seed fixation in artificial devises, which are thereafter cropped, to proceed with further on-growing on other locations and with different methods.

[46] All these references are based on the author's recollection of events.

undertaken in the Republic of Chile refers to this last technology, while experiments to on-grow *Seriola* in cages are also under way. Work is carried out in northern Chile, because higher temperatures are required. Here, cage farming takes place in more exposed sites, requiring more demanding offshore technologies. R&D activities with this species have created high expectations regarding the opening of new fish farming opportunities in the north of the country, to the point that some have branded it as 'the salmon of northern Chile'. In any case, the R&D work with *Seriola*, which already stretches for almost a decade and is carried out at pre-commercial scale, is undertaken by four different groups, at least two of which have governmental support. The most advanced R&D efforts in the coming 4–5 years will be concentrated on recirculation, but grow-out trials in cages will also take place, to gain a good understanding on which system works better. In parallel, the production capacity of juveniles will be enhanced, to be able to offer them in due course to prospective producers of this excellent fish.

Three additional introduced marine fish species are also farmed experimentally. Cobia (*Rachycentron canadum)* is produced in very limited quantities under recirculation, with eggs/juveniles originally brought from the Federative Republic of Brazil. This fish requires a much higher temperature than that naturally available in Northern Chile, and therefore production takes place using cooling waters from a huge thermoelectric power plant in Mejillones, close to Antofagasta. Halibut (*Hippoglossus hippoglossus*), originally brought from Europe, has been the subject of trials and technical assistance schemes since 1997, without scaling up to commercial production. The third species is the Atlantic Cod (*Gadus morhua).* There are no indications, though, that cod or halibut will ever be permitted to be grown in open ocean conditions, and if at all successful, those species might have to be farmed exclusively inland, most probably under recirculation.

Sturgeon farming in fresh water has also been tried for over 20 years, without practical results, because of a poor handling of this idea. Trials are being undertaken simultaneously with white sturgeon (*Acipencer transmontanus*) and Siberians (*Acipencer baerii*). Curiously enough, there are still interested parties willing to insist in these endeavors, with still unforeseeable prospects.

Other farming trials involve freshwater fish and aquaponics. In this case reference is made to tilapia (*Oreochromis spp)* and pirarucú/paiche (*Arapaima gigas*), species being tried in Arica, in Northern Chile, with imported juveniles. Both species are intended for human consumption. Other small-scale undertakings are also under way in that same region, with fresh water ornamental fish, whose juveniles are mostly brought in from the Republic of Peru or other origins, when brood stock are not available in the Republic of Chile. These fish are thereafter grown to commercial size, and sent to southern Chile to be marketed with other imported ornamentals, to be sold in the domestic market.

In the case of macro algae, where farmed volumes surpassed 105 000 tonnes in 1996, most local efforts have been devoted to produce pelillo (*Gracilaria spp*), a species with high but fluctuating demand and prices. Its farming has been adopted by hundreds (if not thousands) of small scale producers, mainly in the Lake Region but also north of Santiago in more limited quantities. The Republic of Chile is one of the world's most important producers of wild algae, so farmed production tends to fluctuate a lot with respect to market conditions. There also exist several commercially oriented operations to farm huiro (*Macrocystis spp*) and chascón o huiro negro (*Lessonia nigrescens*), either to be used as feed in abalone farming or to be sold as raw material, but local statistics are not accurate enough to capture these activities in adequate detail.

Other macro algae are also targeted for farming, as yet without results of commercial importance. Chances are, however, that this situation might change in the coming decade, if enough resources are allocated to these aims. For now, it is evident that the Republic of Chile will widen its supply of most of these species in the future. It is still uncertain if local capacities will lead to further processing of these species in this country (to prepare fillets, smoked products, and the like), or whether the Republic of Chile's role will be that of a supplier of raw materials, with limited value added.

The Republic of Chile has also produced micro algae for several years, but rather inconsistently. Today's farming efforts mainly refer to Spirulina (*Spirulina spp*.) and Haematocuccus (*Haematococcus pluvialis*). The former is used as a food supplement of commercial interest, and the second is aimed at producing the antioxidant astaxanthin, important in aquaculture feeds, human health and cosmetics. In both cases, but mostly with *H. Pluvialis*, production is still fluctuating, and takes place north of Santiago, in continental areas exposed to high radiation and with good temperature patterns. Again, the Republic of Chile has the potential to becoming an important producer and exporter of these species and several others. In any case, it is still unknown if the country ends up producing raw materials only or will further process these crops. The Chilean market for salmon feed can probably absorb most foreseeable supplies of locally produced astaxanthin, but producers will also target international destinations.

Over the years, farming experiments in the Republic of Chile have referred to well over 50 species, including Australian lobster, *P. vannamei*, puye (*Galaxias maculatus),* carps, octopus, razor clam (macha, *Mesodesma donacium*), loco (Chilean abalone, *Concholepas concholepas*), several clams, sea snails, sea urchin, sea cucumbers, the very valuable centolla (king crab, *Lithodes antarctica*), the locally demanded camarón de río del Norte (*Cryphiops caementarius*),several crabs, frogs, and many others, native or exotic, none of which have reached commercial production levels as yet. Almost always, trials with these species have been aimed at developing intensive production methods. Alternatively, in the case of sea urchins, loco, and even the local plaice (lenguado) the idea has been to produce seed or juveniles, to be released in the wild to enhance small scale fisheries.

2.2.3 Drivers

Different drivers are responsible for these diversification efforts, the majority of which have not led to results of commercial significance. However, they have certainly enhanced domestic research capabilities of several groups, which currently run laboratories, hatcheries and consolidated teams that can readily continue the work on diversification if required. Hopefully, future efforts will concentrate mainly on a reduced number of species, so that whatever resources are used have a better chance of succeeding and producing practical results.

Among these drivers, the most relevant ones are (1) Market opportunities, (2) The availability of farming techniques abroad, (3) Scientific curiosity and drive, (4) Governmental programs that back R&D in this field, (5) The drive of different institutions (such as Foundation Chile, etc.), (6) The lower availability of wild species, and the wish to replenish coastal areas, (7) Ample space available, (8) Trained personnel at all levels, (9) The idea of creating job opportunities in different parts of the country, of enhancing exports, etc.

In sum and this far, successful commercial aquaculture in the Republic of Chile has been based on introduced species, adapted foreign technologies and ample world market opportunities. As well, the country has tried to develop more commercial farming opportunities with native and exotic species. The ample availability of natural conditions and space, and a limited domestic market, have also helped direct this industry towards exports. For this reason salmon, trout and mussel farming enterprises are large scale, use state of the art technology, and are competitive worldwide. With the exception of abalones and perhaps gracilaria algae, no other species have reached this development stage, and many struggle to survive, with doubtful prospects.

By now, the state has also learnt that it makes poor sense to continue backing too many development projects at any one time. It has become evident that whatever money is available has to be concentrated on a limited number of programs (composed of many projects), confined to a small number of species, and conducted continuously for as many years as necessary. It is known that to develop commercially viable aquaculture production methods with 'new' marine species can take as long as 10–20 years, while 5–10 years might be necessary with fresh-water species.

2.3 Diversification and the role of government and private industry

2.3.1 The scope of diversification

Aquaculture diversification does not only refer to increasing the number of species farmed. In the Republic of Chile, this process is understood to encompass new production technologies and work in non-traditional geographic areas, and the opening of further opportunities to small-scale farmers, long forgotten in the current development process. The concept can also include the widening of commercial opportunities with new products, new destinations and/or different consumers abroad and/or domestically.

As noted before, up to now, Chilean commercial aquaculture has been mostly linked to the southernmost part of the Republic of Chile and to salmon and mussels. The remaining part of the country, with a more exposed coastline and other challenging geographic and environmental conditions, remains nearly untouched or under-developed, as do several other species. The center-north and northern parts of the Republic of Chile (north of Santiago) do not offer a wide range of work opportunities to local populations, so aquaculture would be most welcome there. The same applies to southern Chile, where additional aquaculture production, under sustainable patterns, would again be much appreciated.

It was shown (Table II–2) that during the last 25 years or so aquaculture growth rates in the Republic of Chile are continuously diminishing. Here, diversification is certainly an option, and a desirable one for the ample space available. Clearly, though, irrespective of whatever might be done regarding aquaculture diversification, and perhaps for several decades, Chilean aquaculture will remain highly dependent on salmon and mussel production, even if the first grow at diminishing rates in the future and mussel production stabilizes at current levels or grows only slowly. Past growth rates are unlikely to be repeated. With oyster and scallop crops in sharp declinev variable and cyclical algae yields and limited progress signs with other molluscs and fish species, it has become evident that the Republic of Chile has to change its strategy if further success and sustainable aquaculture development are desired.

2.3.2 Trends in species selection

So far, commercial aquaculture in the Republic of Chile has been focused on exotic[47] species, such as salmon and trout, turbot, abalone, Pacific oyster, sturgeon, hirame, halibut, etc. In several cases, complete environmental impact reports were prepared before introduction trials were permitted. The main motivations to work with these exotic species were the availability of farming technology and equipment from abroad, as well as market opportunities.

More recently, though, all over Latin America (LA) there is a clear trend to devote most R&D efforts to native species, because environmental concerns have made it difficult to introduce exotic species, even if they have proven farming technologies elsewhere.[48] This move towards native species will be far more challenging and farming them at commercial levels will certainly face inconveniences. For instance, R&D work to develop husbandry techniques and equipment to farm native marine species might be

[47] Salmon and trout cannot be fairly categorized as exotic species any longer, as their introduction efforts started in the second part of the XIXth century.

[48] Atlantic Cod is the only exotic, not yet commercially farmed in Chile, for which R&D efforts have been devoted in recent years. In previous ones, work to introduce the Atlantic scallop was also undertaken, but it was discontinued at some stage.

more costly and time consuming compared to salmon and mussels, where technology 'packages' were easily bought in different places. And while salmon and other species such as shrimp, tilapia, oysters etc. are generally well known in many countries, and production can target several markets, most native species will have to rely more on domestic demand before pursuing exports. These species are not normally known abroad, and their market introduction elsewhere requires financial resources and consistent work for several years. However, whatever has been learnt in the Republic of Chile in the past 30–40 years facilitates future R&D efforts, thus shortening the path to achieving commercially applicable results.

Other desired aspects of diversification include stretching production to the central and northern parts of the Republic of Chile, opening new production systems such as offshore farming, reseeding of coastal areas, additional production under recirculation, further use of aquaponics, a better use of desert areas (microalgae and the like), etc. Of course, widening market options and products are also wanted, as most Chilean aquaculture exports are highly concentrated on a limited number of destinations, and there are many unexplored commercial opportunities.

2.3.3 Diversification and its main actors

But for few notable examples, private firms do not normally invest in production diversification, nor it is expected that they change their attitude. Diversification is fairly expensive and risky, and technologic developments for little known native species might take a long time.

Therefore, to diversify aquaculture production with 'new' native species, governmental resources and leadership are required, at least in the early stages, where stakes are higher and costs can hardly be recovered through future income flows. However, to ascertain the desirability of the diversification process, private partners should be identified and their monetary contribution – however small – secured. Additionally, R&D institutions should also work in these endeavors. The difficult part is to secure a long-term financial commitment, eventually stretching for 8–10 years or more, particularly by governments that last for only four years. Additionally, experience has shown that the dynamics of R&D institutions can also be challenging, as scientists and technologists tend to give priority to publication rather than to obtaining results of practical interest. Therefore, governance for these programs should balance the interest of all participating partners, and ensure cost-effectiveness and speed.

International technical assistance through institutions such as the FAO will always be important, but increasingly, local scientists and technicians have gained confidence and expertise. In other Latin American countries, where aquaculture is less developed, institutional help on wider terms can still be highly appreciated. Horizontal cooperation among LA countries can also be envisaged, particularly with the Republic of Chile, the Federative Republic of Brazil, the Republic of Ecuador and the United Mexican States having good possibilities of offering technical assistance to sister nations.

2.4 Technology and expertise, markets, institutional facilities and governance as drivers and/or constraints to aquaculture diversification in the Republic of Chile

Market opportunities worldwide have shaped much of Chilean commercial aquaculture until now, and prospects are equally attractive for the future, both domestic and international. 'Static factors' such as environmental conditions are excellent and promising. The learning of farming techniques from elsewhere and work with exotic species have also been instrumental to achieving current standings and are an asset to be highly regarded.

Additional 'dynamic conditions' are now at the center of the decision making process leading to expand the frontiers of Chilean aquaculture. They include governance, legislation, fitness of governmental action, capacities to exercise adequate controls, conditions to give fair access to small scale producers, more economic resources and long term commitment to financing R&D, the formation of human capital, the abilities of the scientific/technical community and the capacity to appraise the cost-effectiveness of development strategies.

Many other factors influence diversification and development possibilities beyond salmon and mussels. They include infrastructure needs, conflicts with artisanal fishermen and various other users of the coastline, marine and fresh water environments, working conditions offered to employees, as well as a poor appreciation of aquaculture by local communities and public opinion in general. In all, there are a good number of drivers and constraints that will make aquaculture development and diversification more complex than in previous years. However, opportunities are so wide that they should be able to adequately offset challenges and invite private and state actors to become involved in widening current farming options through the introduction of 'new' species; the 'conquest' of new and untouched areas north and south of Santiago, in the Lake Region and further south; the development/adoption and/or streamlining of new technologies, etc.

Lessons learned to date suggest some basic criteria for producing results in reasonable periods of time:

a. To concentrate financial and other resources on a limited number of species, to be chosen very carefully; to develop all necessary knowledge in parallel, so as to avoid the situation where a neglected link might inhibit achieving practical results;
b. To make sure that whatever is done will guarantee sustainability from environmental, social, market and economic perspectives;
c. To work in a more holistic manner, considering that even if technical developments are crucial, other factors such as governance, market knowledge, production models and the like are also important to achieve meaningful results;
d. To promote cooperation and interaction between state and private actors, and between them and technical/university institutions;
e. To first validate objectives with local communities and with national public opinion; and
f. To make sure that plans and financial resources are subject to continuous evaluation of their economic, environmental and social cost-benefit; to ascertain that all other resources are wisely used and intermediate results are promising enough to continue working on any particular field.

2.5 The future of aquaculture diversification in the Republic of Chile

The Republic of Chile should benefit from aquaculture diversification because current growth rates in this field are poor. Future prospects are good; there is plenty of space available throughout the country; there are excellent environmental conditions and wide open market opportunities worldwide.

Future aquaculture development in the Republic of Chile will have to follow two basic principles: (1) Salmon and mussel production should continue to grow, ensuring sustainable development with these species, and (2) There is a need to incorporate 'new' native species in the production matrix.

In the first case, short term efforts will have to be devoted to reshaping current production structures and to regaining a lost and badly needed sustainability. After completing this process, there are good prospects for further growth in the foreseeable future, the Republic of Chile should remain second only to the Kingdom of Norway with world salmon production. Less conflictingly, mussel crops can also expand, and will certainly find market opportunities in different countries. Therefore, sustainable growth can also be expected in this field.

For native species, as there are no readily available technologies to farm most of them commercially in the short run, diversification with these species will take a long time, and will require financing, ingenuity and determination.

In addition to technical matters, the Republic of Chile will also have to face the need for renewed, modern and simpler governance, with better and firmer leadership from both government and private industry, as well as new models for coordination, arbitration and agreements among all stakeholders. A lot will have to be done to incorporate (and support) small scale farmers into the development and diversification processes, and to work with and integrate local communities where production will take place. All these changes are required so that aquaculture can gain wider social acceptance in the Republic of Chile and abroad.

The Republic of Chile has come a long way in the handling of technologies during the last 40 or so years. Universities have organized programs to prepare aquaculture scientists and technicians (and lately, for postgraduate studies); sophisticated laboratories and pilot plants have been built; private entrepreneurs and R&D institutions have bought technology and trained personnel abroad. Thus there is a lot of accumulated experience related to the development of salmon, trout and mussel farming to world class levels and with R&D with other species; whatever needs to be done in terms of further diversification can take advantage of all these gained abilities.

The next section will focus in more detail in opportunities and restraints faced by the aquaculture development and diversification processes in the Republic of Chile, specifically for species other than salmon/trout and mussels.

2.5.1 Opportunities

Basic opportunities for further diversification and aquaculture development in the Republic of Chile are based on the following aspects:

a. Open market opportunities worldwide and in local markets, for the decades to come. No restrictions are envisaged in this field, except for those that may arise from lack of competitiveness or in relation to product characteristics and/or quality;
b. Ample space and excellent environmental conditions to sustainably increase production levels with currently exploited species, and in the near future, with the introduction of native species to the farming matrix;
c. Good and experienced scientific and technological communities, with well-established labs and pilot facilities in most parts of the country (however, the Republic of Chile still needs to prepare human capital, to achieve the standards observed in more developed and competing nations);
d. A work force skilled in fresh-water and marine farming techniques, together with manufacturing and logistic processes at all stages of production and the value chain;
e. A large number of enterprises rendering specialized services to current aquaculture production, that could widen their activities to serve new farming initiatives; and
f. Governance experience that has already shown what should best be done to facilitate and consolidate future diversification and development actions.

2.5.2 Challenges

Several problems have to be addressed and solved, to foster sustainable and more diversified aquaculture development processes in the Republic of Chile. Here, the following aspects should be considered.

2.5.3 Planning needs an overall vision of the future

To progress and diversify, it is desirable to have a clear ‘vision’. Objectives and measurable goals have to be defined, and a good strategy (roadmap) is needed to guide the development process. This basic planning approach has not existed in the past. Consequently, efforts, financial, human resources and equity have probably been lost or mismanaged during an interesting but bumpy development process. Currently (2015–2016), new efforts are being made to devise roadmaps and direct future aquaculture activities along well established paths. Even if a 'fully integrated planning exercise' is not being carried out, proposals for further development regarding salmon and trout, mussels and aquaculture in general are being elaborated separately by different 'programs'. Each of these programs will have its own vision, objectives, goals and roadmap. Given their synthesis, Chilean aquaculture will shortly have access to a good proxy for a concerted vision of where to go, where to concentrate scarce financial and human resources, and above all where to focus governmental and private actions according to long term views and requirements.

Considering only the day to day needs of industry, as has normally been the case, results in erratic moves that confuse sectoral actors and even stop a healthy evolutionary process. Such consequences are well reflected in recent production statistics, in overcrowding of several water bodies, and in severe losses of competitiveness in salmon farming because of disease outbreaks, excess costs related to the use of vaccines and other therapeutics, more production controls, and the like.

2.5.4 R&D

Government should support R&D through different organizations, taking good care to coordinate their actions. It should also concentrate funds on a limited number of promising species, and finance whole 'programs' rather than 'isolated projects', as this last approach has shown poor results in the past. R&D programs should be financed for as long as required, without interruptions, and if so needed, for six, eight or even more years. Joint ventures by government, several private enterprises and R&D institutions should be favored. All R&D initiatives financed with government funds should be evaluated on their achievements on intermediate dates, with the option of cancelling those exhibiting poor results or mishandling. They should also be evaluated at the end, making as much information available to the community as practically possible[49]. Participating enterprises and/or R&D institutions that perform improperly should have to comply with much more stringent requirements in their next eventual bid for funds, or should be banned at all from bidding for public resources. Evaluation of project proposals should be as stringent and dedicated as possible, to ascertain that scarce public and private funds are duly used. Government should only call for project proposals on subjects that are relevant to the global development/diversification strategy[50]. There is a need for consistency on what should and should not be done, following the above-mentioned criteria.

2.5.5 Governance

Governance has been the most fragile of drivers in recent years and the cause of much frustration to industry, communities, workers, etc. Governance has to improve in many areas to address severe problems that jeopardize diversification and development efforts, some of which are outlined here:

- Effort should be made to devise regulations that guarantee aquaculture sustainability, from environmental, economic, financial, social and market perspectives;

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[49] Measure should be taken to safeguard proprietary information, resulting from these projects, particularly when private enterprises and/or R&D institutions co-finance these initiatives.

[50] There is no such thing as a detailed aquaculture development plan for the coming decades, but several studies with official funding are proposing strategies to further promote this trade sustainably, in what refers to salmonids, mussels, aquaculture diversification and others topics. These studies provide a good background on what is most desirable. However, they do not show priorities 'among' different options, a fact which should therefore receive detailed attention.

- Aquaculture authorizations should only be granted after assessing the carrying capacities of the different water bodies, whether in fresh water or marine environments. If studies take more time than is available, a precautionary approach should be used at the beginning. A trial-and-error approach can also be used, with certain limits;
- Appropriate ‘sanitary corridors’ should be devised to avoid as far as possible the dissemination of diseases. In parallel, rules to identify and control other disease vectors should be devised and put in place;
- Further attention has to be given to small scale production, incorporating a special statute applicable to small-scale farmers, to ‘level the ground’ with large scale aquaculture, and make small scale activities feasible and sustainable;
- Ensure that technical assistance is given to initiatives addressed to support small scale farming activities. The same should be applicable to small scale providers of services along the production chain;
- Evaluate on a regular basis the performance of this industry, addressing its impacts on all perspectives, and proposing corrective measures, when applicable, and development strategies, where needed;
- Support the collection and timely analysis of good quality environmental, production, economic, market and social data, and get it published as soon as practicable;
- To devise control procedures that work and that can be properly applied, establishing strong penalties to offenders
- Revise all current measures applicable to aquaculture production and control, suppressing or modifying all restrictions and procedures that are not essential to safeguard the long term sustainability of this industry;
- Devise measures to further facilitate and promote investment in aquaculture development; and
- Safeguard animal welfare.

2.5.6 Communities, coordination, workforce

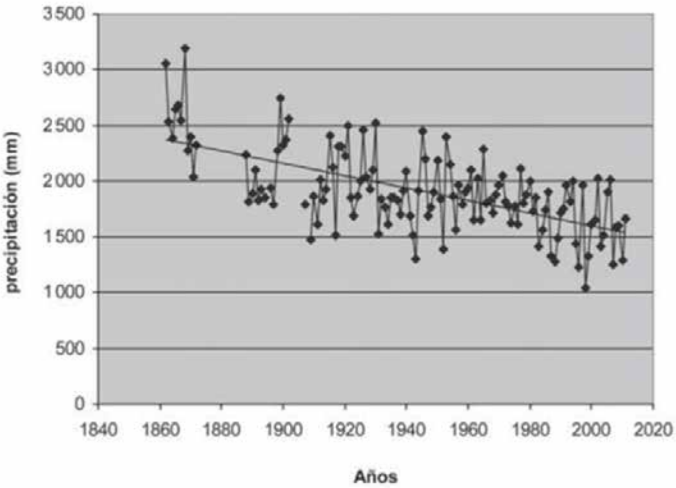
The aquaculture industry in the Republic of Chile has not been successful in relating properly to local communities. As well, labor relations in this industry should be improved. Moreover, the public image of aquaculture within the domestic population is also poor, and relations between primary producers and the enormous amount of firms that service them need to be upgraded. Efforts should be devoted to solve all of these problems, to gain social acceptance of aquaculture and the full development/diversification processes.

2.5.7 Climate change

The Republic of Chile is already affected by climate change. One of its results is the desertification of several coastal areas; others include changes in fish availability in coastal and oceanic waters and a marked change in rainfall levels in many parts of the country. In the first case, sand dunes are advancing in many areas, while in the case of fish availability, patterns are changing. Artisanal as well as industrial fishermen are feeling these effects, which in several cases mean diminishing fish landings and very fluctuating availability of pelagic species, some of which provide the raw material for fishmeal and oil that Chilean and world aquaculture require.

Declines in rainfall levels in many parts of the country is also accompanied by erratic behavior of rivers, and several flooding episodes have affected thousands of people in several occasions in recent years. Algae blooms, which recurrently but ‘unexpectedly’ hit some parts of the country, have also been present with noticeable strength, particularly during the early months of 2016 in southern Chile. They have distressed salmon production and prevented the extraction of wild bivalves affected by poisonous ‘red

FIGURE 4
Rainfall levels in Puerto Montt, Lake Region, the Republic of Chile, 1860–2010



Source: J.J. Sanz Donaire, 2012. Estudios Geográficos Vol. LXXIII, 273, 'Las series anuales de precipitación anual más largas de Chile: estudios y enseñanzas'. Extracted from a power point presentation by Rodrigo Torrijos, April 2016, 'Nuevas Tendencias en la Producción de Agua Dulce y sus desafíos para el sector en la Araucanía'.

tides' in locations where these events were not ordinarily present. Clearly some of these events should happen more or less periodically, linked to 'El Niño' events, but others are bound to become established in the long run as a net effect of climate change.

As an example of diminishing rainfall levels, the city of Puerto Montt, at the heart of the Lake Region, and Valdivia, the capital city for the River Region north of it, have seen diminished precipitations for a very long time (see Figure 3 for P.Montt figures). The availability of fresh water has affected animal and agriculture production at large, and could also have effects on the long term availability of fresh water resources for the production of salmon smolts, trout, etc., and in oceanic conditions in neighboring areas.

Other effects, such as higher temperatures between one and three (moderate scenario) or two and four degrees Celsius (severe scenario) by the end of the century could also be expected[51], with further changes in rainfall patterns, glaciers and snow storage capacity in mountain areas. These changes can result in still unpredictable but meaningful effects on the regional capacities to continue farming hydro biologic species, as used now.

However important these events might be, the truth is that little can still be predicted on the precise effects of climate change on the future of aquaculture in the Republic of Chile. In any case, though, as these changes take some time to occur and to get established, there might be chances for adequate responses, or in the worst scenarios, to apply whatever mitigation measures are possible. The warming of the oceans can certainly affect fish aquaculture production in many different manners, for instance, limiting salmon production and/or production densities in some southern areas, but encouraging the farming of species such as yellowtail kingfish in the northern seas, as a result of higher and 'more favorable' temperatures.

In all, because of the many worries and uncertainties attached to climate change, there is no doubt that the Republic of Chile will have to invest much more on R&D dealing with this subject, as the only means to learn on how to predict, solve and/or mitigate the several unwanted effects that could be forthcoming. As well, aquaculture stakeholders will also have to learn on how to make the best of any positive effect related to climate change.

2.5.8 New species and other options for diversification

Concerning species, the diversification process should start by considering which species currently farmed commercially with poor technology and/or in reduced volumes and/or facing other difficulties should receive further help. Among these, the following should be assessed:

[51] Peter Muck, 2012 Chile: National Adaptation Plans to Climate Change, Climate Change Office at the Ministry of Environment, Chile. P.point presentation available at: www.oecd.org/env/cc/50426634.pdf

1. Red and green abalone: Further R&D efforts should mainly come from private actors, and could be supported by eventual R&D funds from different governmental sources.
2. Native and Pacific oysters: Subject to market considerations, could receive eventual support from Government and private firms.
3. Cholga and Choro zapato: With eventual support from Government.
4. Spirulina algae: To be supported mainly with private sector efforts.
5. *H. Pluvialis:* Still requiring governmental and private-sector support to scale up and stabilize farming and processing technologies.

Here, efforts should concentrate in the coming years only, and if any or all of them do not show adequate results, support should be discontinued.

With reference to species whose technologies are still fragile and/or under development, a recent study of 2015[52], financed by CORFO, suggests the following for diversification, implying that this selection will be heavily backed with long-term financing from governmental sources. Marine fish targeted for intensive farming are:

1. Bacalao de profundidad or Chilean seabass	*Dissostichus eleginoides*
2. Congrio dorado or golden kingclip	*Genypterus blacodes*
3. Congrio Colorado or red kingclip	*Genypterus chilensis*

Chilean seabass aquaculture is just starting in the Republic of Chile and in a few other locations, but it certainly is the most promising venture in projected commercial terms. If practical aquaculture solutions are devised after a prudent period of time – say 10–15 years – this industry will have 'found a 'new salmon', with wide market possibilities for high end customers.

Congrio dorado is also an excellent species with promising market prospects abroad, although at a smaller scale, while congrio colorado could be directed mainly to a domestic market which has been facing decreasing supplies of wild species for several decades. Two more species are to be added to the former three:

4. Palometa o dorado or yellowtail kingfish	*Seriola lalandi*
5. Corvina or croaker	*Cilus gilberti*

Work with these species is already under way, but will be reinforced in the coming years with further financing, to finalize their development processe with adequate and highly efficient farming techniques.

This same study selects as well the following species for diversification purposes, but this time in the production of juveniles/seeds, to be further released and grown in the wild:

1. Erizo rojo or red sea urchin	*Loxechinus albus*
2. Loco or Chilean abalone	*Concholepas concholepas*
3. Almeja venus (clam)	*Venus antiqua*
4. Almeja taquilla (clam)	*Mulinia edulis*
5. Almeja culengue' (clam)	*Gari solida*
6. Macha or razor clam	*Mesodesma donacium*

This novel line of action for the Republic of Chile will not have much future unless formulas to permanently finance these efforts are devised and applied. Otherwise, whatever investments are made to improve seed/juvenile production techniques and/or further farming facilities will be completely lost. Here, government should probably subsidize seed/juvenile production for a number of years. Thereafter, fishermen that

[52] Cooperación y Desarrollo Limitada. May 2015, Informe Final Consultoría de actualización de ranking de especies prioritarias para la diversificación acuícola, CORFO, Gerencia de Capacidades Tecnológicas, Santiago.

take advantage of these seeding efforts should pay an agreedupon fee, so as to finance the costs involved in producing and seeding these juveniles.

Additionally, it is this author's opinion that further attention should be given to the full development of intensive farming techniques for king crab (centolla) and red sea urchin. The latter is a valuable species that could enhance aquaculture prospects in the Magellan Region and further north, and for which seed production is fairly well handled by now, while intensive growing methods are being developed in the Kingdom of Norway, Australia and in other countries. Those advances can very well be applicable in the Republic of Chile. In the case of king crab, local scientists have already closed the production cycle in captivity, but there still remain a good number of aspects to be researched until commercially viable methods are devised, most likely during the coming 10–15 years.

New farming technologies should be incorporated in future years, or some currently at use should be improved to open new avenues to innovations and to working not only in southern Chile, but as well in central and northern continental or marine areas. Here, there is a need to further develop 'open ocean' aquaculture techniques and equipment, as the Republic of Chile will need to compete with foreign countries that will certainly move towards high-energy areas in the near future, with projects that will challenge local salmon/trout exports[53]. These techniques and equipment are also required to incorporate new areas for salmon and new species production in the Republic of Chile. In the case of salmon, this is particularly promising as it might help redeploying some heavily seeded production sites, diminishing biomass there and lessening prospects of disease outbreaks and dissemination, and of environmental damage. The same applies to recirculation, a technology that, if improved and made more accessible, will help eliminate smolt production in southern lakes, and will contribute substantially to enhancing small and medium-scale marine aquaculture production along the country's coastline, and in fresh water projects as well.

Finally, diversification of markets is also a must, to diminish dependency on just a few major destinations for Chilean exports. It is also needed to respond to a change in commercial paradigms, as a good part of future demand will be associated with developing countries, a fact that needs further preparation of local market and marketing people, new products, new commercial practices and the like. All these factors will also challenge customary practices with new requirements that will have to be met by the aquaculture industry.

In sum, the Republic of Chile has enormous growth and diversification possibilities for aquaculture in the coming decades, including the introduction of 'new' species (mostly native ones), technologies, markets and/or new production areas. The basis for diversification is strong, and even if there are problems to be addressed, chances are that if adequate resources are devoted to these aims, aquaculture diversification efforts could evolve reasonably well in coming years. However, even if a selection process has been undertaken by official sources as recently as in 2014–2015, their results plus other priorities will most probably require financial and human resources that are not readily available in the Republic of Chile or, alternatively, cannot be sustained for the required number of years to produce meaningful results. Therefore it is evident that ***a new prioritization effort will be needed to narrow the diversification focus****, as otherwise, the handling of this ample set of options will not produce the required outcomes and will again frustrate the wishes and expectations of many.*

In the foreseeable future, local aquaculture production will still be concentrated on very sophisticated and massive production units, supplemented by a number of small

[53] Reference is made to probable salmon production in oceanic waters in front of the US coastline; in Europe; in Australia, New Zealand, China, etc., which at some future date will challenge Chilean salmon exports to the US, Europe, Asia, etc.

and medium size enterprises that until now were mostly nonexistent in the country. However important diversification efforts might be, it will still be true that local productions and exports for at least the coming 15 years or more will still be highly reliant on salmon, trout and mussel farming.

A final point on the much-wanted incorporation of the small-scale farmer to Chilean aquaculture. Here, as in several other countries, it should be understood that, particularly in the case of many marine species, neither the production techniques nor the capital required to produce seed or juveniles or handle brood stock are easily accessible to small-scale farmers. If the Republic of Chile wants to incorporate them to aquaculture production, chances are that juvenile/seed production and/or availability might become critical or limiting, and a formal solution to this restriction has to be devised. On top of this, a proper statute to govern small-scale production will also be required, as will adequate financial schemes and technical assistance.

3. AQUACULTURE AND AQUACULTURE DIVERSIFICATION IN THE FEDERATIVE REPUBLIC OF BRAZIL

3.1 Current situation and main species farmed

3.1.1 Current situation

Brazilian aquaculture offers many opportunities for future diversification. There are options in freshwater and marine ecosystems with different production systems, from small to large scale. A continuous improvement of technology and the domestication of a few native species, focusing on market demands, can have lasting benefits for the development of Brazilian aquaculture.

Considering FAO data, Brazilian aquaculture grew 58.9 percent in terms of volume from 2008 to 2014, reaching over 561 803 tonnes (FAO, 2016). Aquaculture in the Federative Republic of Brazil is mostly inland, despite the enormous potential for marine production using the long coast (more than 7 000 km) and estuarine areas (2.5 million ha) (Table 9). Introduced species such as tilapia (*Oreochromis niloticus*) and the white legged shrimp (*Litopenaeus vannamei*) are the most important species produced inland and in mariculture, respectively.

TABLE 9
Brazilian aquaculture production 2008 till 2014 (metric tonnes)

Aquaculture production	2008	2010	2012	2014
Inland	247 876	325 989	381 648	474 693
Marine	83 357	85 058	98 502	87 110
Total	331 233	411 047	480 150	561 803

Source: FAO, 2016 (excluding aquatic plants and miscellaneous aquatic animals products).

Beyond growth in recent years and government actions for the development of this activity in the Federative Republic of Brazil, there is considerable potential to increase aquaculture production and diversification, due to the large quantity of water resources and the huge biodiversity in the country. This diversity is illustrated by the Brazilian Institute for Geography and Statistics (IBGE, 2015), which listed 28 different species and five different hybrids farmed in 2014 in the official national production statistics. Possibilities for increasing farmed production are diverse, and recently much attention was given to hydroelectric reservoirs and estuarine areas, where aquaculture parks regulated by the Brazilian government are used by local producers. As an example, there are 219 hydroelectric reservoirs distributed in 22 states throughout the country, comprising a total area of 3.14 million hectares of surface waters. Moreover, and according to estimates of the Brazilian Agricultural Research Corporation (EMBRAPA), the 37 largest reservoirs have an annual aquaculture production potential of approximately five million tonnes of fish (Table 10), a figure representing over ten times the production levels reached in 2010.

TABLE 10
Annual freshwater fish production potential in the 37 largest Brazilian reservoirs, 2015

Region	Production (tonnes)
Northeast	1 934 100
Southeast	1 569 660
North	872 025
Midwest	429 435
South	173 750
Total	4 978 970

Source: Pedroza, M., personal communication. 2015.

However, even considering recent growth in production and its potential, the Brazilian aquaculture industry still has many structural problems. For instance, this country has many different ecosystems and its size makes it difficult to provide the needed infrastructure and logistics, a special challenge for product distribution.

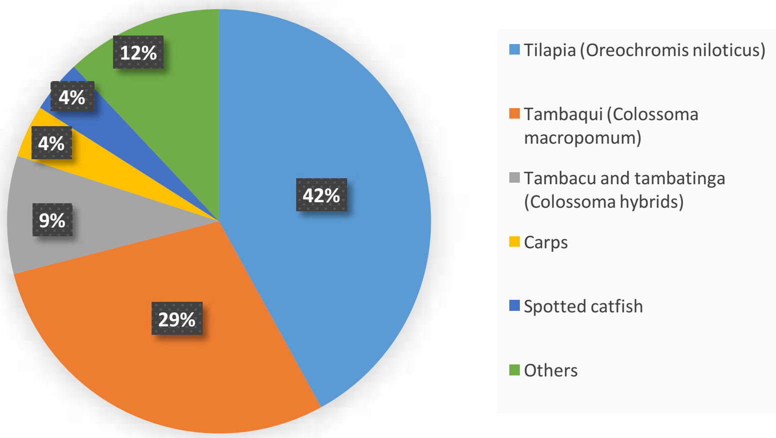
Rabobank (2013) identified this situation as being of importance for Brazilian aquaculture development, as many farms are located in isolated areas and do not necessarily have access to proper roads, nearby ports, feed producers and/or big consumption markets; challenging logistics affect the economic feasibility of those enterprises. The Federative Republic of Brazil is also affected by climate change, experiencing extreme conditions and generating unforeseen impacts in all sectors, including aquaculture. Longer dry seasons with irregular rainfall are causing negative impacts on the water levels of reservoirs and on grain production for aquaculture feeds. Climate changes may force changes in production profile and business strategies in the near future. Fortunately, native species, naturally adapted to different climate conditions, could make diversification a key strategy for sustainable aquaculture in a time of climate change.

3.1.2 Main species

According to the IBGE, freshwater fish account for about 82 percent of Brazilian aquaculture production volumes in 2014. Shrimp is the second most important category, representing nearly 14 percent of total production (IBGE, 2015). Shrimp farming began in the Federative Republic of Brazil during the 1970s; after 1995, the reintroduction of *Litopenaeus vannamei* accompanied by more advanced technology made industry experience a period of continuous development.

About 28 different species of freshwater fish have been farmed in the Federative Republic of Brazil in recent years, with the Nile tilapia (*Oreochromis niloticus*) and tambaqui (*Colossoma macropomum*) being the most important so far. These two species combined accounted for nearly 71 percent of fish farming production in 2014. Tilapia farming has had one of the fastest growth rates in Brazilian aquaculture at a compounded rate of eight percent per year from 2008 to 2014.

FIGURE 5
Fish farming production in the Federative Republic of Brazil by species in 2012

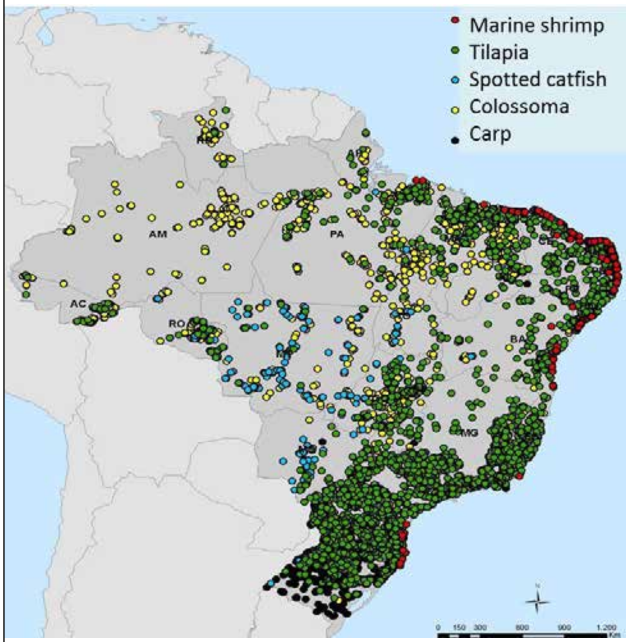


Source: IBGE (2014).

The expansion of tambaqui farming (*Colossoma macropomum*) has also caught the Federative Republic of Brazil's attention in recent years. This omnivorous Amazonian fish has become increasingly popular among local consumers, given its low fat content and characteristic flavor. Here, besides being largely available in most Brazilian supermarkets, a small amount was exported in recent years.

In terms of geographical distribution, Brazilian aquaculture is spread throughout the country (Figure 6). Nile tilapia is produced almost everywhere, but it is more important in the northeast, southeast and south regions, where production is carried out in net cages in large reservoirs and on earthen ponds. The great adaptability of this species to different climate conditions, low-cost feed and intensive culture systems allows for this wide distribution.

FIGURE 6
Geographical distribution of Brazilian aquaculture by main species in 2008



Source: Data adapted from MPA (2013).

Production of tambaqui (*Colossoma macropomum*), pirapitinga (*Piaractus brachypomus*), pacu (*Piaractus mesopotamicus*) and its hybrids is mostly located in the northern and midwestern regions, because of this species' preference for warmer waters. Local market demand also justifies the interest in tambaqui farming in these regions. The production of tambaqui is mostly carried out in earthen pond system, but in recent years farming in cages has also started, with limited success.

Due to environmental restrictions on tilapia production in northern Brazil, tambaqui and other species of *Colossoma* spp. and, *Piaractus* spp. and their hybrids are increasingly becoming an alternative to explore the great potential of the large reservoirs, and also an option to recover degraded forest areas of that region.

3.2 Recent history and current status of aquaculture diversification: Main drivers, constraints and species

3.2.1 Tilapia

Tilapia was introduced in the Federative Republic of Brazil in the 1950s, *Tilapia rendalli* being the species chosen by São Paulo state agencies for fisheries restocking. In the 1970s, the National Department of Works against Droughts (DNOCS) introduced Nile tilapia, *Oreochomis niloticus* and Zanzibar tilapia, *Oreochromis urolepis hornorum* in Ceará State reservoirs, located in the northeast region, to increase local fisheries output. In the 1980s, fee-fishing private farms made tilapia more popular near potential big markets such as those in São Paulo State and also helped raising other native species known by the local market. However, and due to lack of adequate technical knowledge, tilapia off-flavor became a strong deterrent that affected consumption in Brazilian main cities in those years.

Kubitza (2011) summarized the main drivers for tilapia development in the Federative Republic of Brazil as:

- Improvement in seed quality through the adoption of sex reversal technology in the early 1990s and the Genetically Improved Farmed Tilapia (GIFT strain), introduced by World Fish Center in 2005. These genetic advances shortened the grow-out phase, increased productivity and allowed for the production of large

size tilapia, adding value to the cultured products as compared to reservoir wild-caught tilapia;
- Intensive culture using small volume/high density cage technology, which allowed production to expand rapidly in the southeast (São Paulo and Minas Gerais States) and northeast (notably in Ceará, Bahia and Pernambuco States);
- Brazilian animal feed industry enabling the production of feeds for tilapia and other fish species; and
- A large domestic market, which so far has absorbed most part of production.

Tilapia products became more widely available in the domestic market around 2005 as the United States of America dollar devaluation against the Brazilian real made exports of tilapia fillets less competitive in the United States market. This industry's productive chain is professionally run and can be considered as being the basis for further diversification of freshwater fish aquaculture. In fact, Brazilian tilapia culture became a basic "platform" for diversification of aquaculture in the Federative Republic of Brazil, as most technological advancements obtained by the tilapia industry are helping to establish protocols to further develop technology for other species, and also by providing well trained personnel that can be employed in new and more professionally run developments.

3.2.2 Tambaqui and other native fishes and hybrids

In the 1980s, Governmental agencies including DNOCS, the Irrigation Development Agency for the São Francisco River (CODEVASF), the State University of São Paulo (UNESP) in Jaboticabal and the Aquaculture Research and Training Center in Pirassununga in São Paulo State (currently called CEPTA), were the key players responsible for most fish farming developments in the Federative Republic of Brazil. These government institutions played an important role in understanding the biology and reproduction of different fish indigenous to the Federative Republic of Brazil. Here, development of techniques for fingerling mass production of different fish species was the first big step towards Brazilian aquaculture diversification (Kubitza, Ono and Campos, 2007).

For the Brazilian Fish Farming Association (PEIXEBR), the private sector played an important role at the beginning of commercial production of native fish species in the 1980s, mainly in Mato Grosso and Mato Grosso do Sul States. At that time, the main fish farmed was pacu (*Piaractus mesopotamicus*) based on a strong regional demand and the ease of producing fingerlings. However, the non-availability of adequate feed was a main constraint that limited production. There was no information regarding the digestibility of different ingredients used in feeds, such as corn, cassava and fruits. Moreover, consortia that dealt with other animals, such as swine, devised and offered unbalanced feeds for farmed fish. Most of the time, cultured fish presented off-flavor, and compared poorly with the taste of fish coming from natural stocks. Initially, growth rates observed with farmed pacu were low. To solve these limitations, farmers started to bring in tambaqui (*Colossoma macropomum*) fingerlings from northern states and different basins. However, tambaqui has low resistance to low temperature, and high mortality peaks were experienced in winter (Ferrari, Lucas and Gaspar, 1991).

CEPTA started to diversity scientific experiments, testing crosses of different fish species, and creating the 'tambacu' hybrid, resulting from the crossbreeding of ♀ *Colossoma macropomum* (tambaqui) and ♂ *Piaractus mesopotamicus* (pacu) (Bernardino *et al.*, 1986). This hybrid became a great success among farmers in the midwest region and also in São Paulo State, due to the combination of tambaqui's fast growth performance and pacu's resistance to lower temperatures.

During the 1990s, the private sector introduced commercial production of tambaqui in Rondonia State, taking advantage of suitable temperatures that favored growth, survival and yields in earthen ponds. Improvements in the grow-out technologies and best management practices (BMPs) also helped to increase productivity. Some years later, the state government started to provide technical assistance and helped with simple procedures to get environmental licenses for those who wanted to start businesses by diversifying animal production, going from cattle to fish. Good quality ingredients locally available also contributed to produce better feeds. The main market was – and still is – Manaus, where tambaqui from wild stocks have been declining since then. Today, a 2kg fish is also sold in the domestic market in other Brazilian states.

Also in the 1990s, the fish farm "Projeto Pacu" started the production of another hybrid in Mato Grosso do Sul State. The new hybrid was a cross of two native catfishes, 'pintado' (*Pseudoplatystoma corruscans*) and 'cachara' (*Pseudoplatystoma reticulatum).* The hybrid advantage was based mainly on the availability of mature females of 'cachara' for longer periods throughout the year and the fact that 'pintado' was already well known by local consumers (Campos, 2013). Some public funding helped to build more modern hatcheries and proper ponds. However, commercial production faced problems, including the lack of fingerlings all year round and their high cost, the need to lower feed costs for carnivorous fish, and competition in the market with wild fish. Today, it is possible to find this catfish hybrid in a few farms of Mato Grosso do Sul State only. Frozen fillets are exported to Europe, but most production is targeted for the domestic market.

Another important hybrid introduction took place at the beginning of the year 2000, in Mato Grosso state, with 'tambatinga', a cross of 'tambaqui' ♂ (*Colossoma macropomum*) with 'pirapitinga' ♀ (*Piaractus brachypomus*). This hybrid became very popular for its faster growth and better carcass yield and started to replace 'tambacu' in farms. Today, even Rondonia farmers are raising this hybrid. Recently, the hybrid 'pintado-da-amazônia' or 'jundiara', a crossbreed of two different catfishes (*Pseudoplatystoma punctifer*) and 'jundia-da-amazônia' (*Leiarius marmoratus*) showed a performance similar to that of 'tambatinga'.

Today, most Brazilian fish farmers prefer to grow hybrids because they generally result in higher productivity, accelerated growth, disease resistance and better meat quality (Porto-Foresti *et al.*, 2013). In spite of higher performance and profitability, there are many concerns about fish hybridization and its production. Hybrid sterility is an important characteristic that can reduce the possible impacts of aquaculture escapes, but released in nature, hybrids can compete for habitat and feed with wild stocks. There are few studies regarding possible risks of hybridization of Brazilian fishes. Almeida-Toledo *et al.* (1996) found that a production. Hybrid sterility is an important characteristic that can reduce the possible impacts of aquaculture escapes, but released in nature, hybrids can compete for habitat and feed with wild stocks. There are few studies regardin stage, when they are usually sold to farmers. This can be seen as a market issue, because consumers do not know which fish species they are buying and, from an environmental standpoint, fish farms represent the main source of hybrid escapes (Porto-Foresti *et al.*, 2013).

3.2.3 Carps

Carp culture became popular in the 1980s with its introduction into different regions of the Federative Republic of Brazil. However, after the reproduction success of other fish species, carp farming is now mainly restricted to southern Brazil, where polyculture and extensive farming methods still prevail. Lately, this small scale system was improved and farmers adopted aeration along with commercial feed in the last three months of the grow-out period, reducing the farming cycle to ten months, with a higher productivity of up to 1.4 tonne/ha/year. Carp markets are concentrated in small cities in western Santa Catarina and Rio Grande do Sul states, where there is a strong tradition of buying live fish and eating carps (Casaca, Tomazelli and Warken, 2005; Borghetti and Silva, 2008).

3.2.4 Shrimp

This sector started with its first operations during the 1970s with a government – run Project "Projeto Camarão" in Rio Grande do Norte in northeastern Brazil. Several different species were tested, including the Kuruma shrimp *Marsupenaeus japonicus,* the native southern brown shrimp *Farfantepenaeus subtilis* and the white legged shrimp *Litopenaeus vannamei*. Production systems were extensive, with very low stocking densities and little technology applied. Much government funding flowed into the activity, but productivity was not good. It was only around 1995 that commercial culture really took off, when industrially formulated aqua-feeds and hatchery-produced postlarvae of *Litopenaeus vannamei* became available (Nunes and Rocha, 2015). Brazilians brought in expertise from the Republic of Ecuador and other countries, where shrimp farming was based on *Litopenaeus vannamei*.

From 1989 to the 1990s, public universities started several developments in southern Brazil. There were a few experimental grow-out trials with native species, such as pink shrimp (*Farfantepenaeus paulensis*) and white shrimp (*Litopenaeus schmitti*), but survival and productivity were not attractive. Commercial farms started to run, but by the end of the 1990s they had all adopted the exotic *Litopenaeus vannamei*. Most production from small and large farms was exported to Europe and the the United States of America. Around 2004, the white spot virus hit almost all commercial farms, closing down the activity in southern Brazil. In the same period, an endemic virus, the Infectious Myonecrosis Virus – IMNV appeared in the State of Piauí in the Federative Republic of Brazil's northeast. Before that event, industry was obtaining high productivities, reaching 6 000 kg/ha/yr seeding up to 100 shrimp/m^2. Today shrimp stocking densities can range from 30 to as many as 70 post-larvae (PLs)/m^2 but can be 15 PLs/m^2 or less in ponds without artificial aeration (Nunes and Rocha, 2015). The United Stated dollar devaluation against the Brazilian real changed dramatically production destination from exports to the domestic market, helping local industry to keep going. In 2011, the Brazilian Association of Shrimp Farmers (ABCC) carried out a survey and estimated there were 1 222 farms in operation. The study found out that on 89 percent of the farms, stocking densities during grow-out were below 30 shrimp/m^2 (ABCC, 2013).

3.2.5 Bivalve molluscs

The first farm trials with the native brown mussel (*Perna perna*) and the Japanese oyster (*Crassostrea gigas*) in Rio de Janeiro were recorded in the 1970s by the Marine Research Institute – IPqM, managed by the Brazilian Navy, under the project "Cabo Frio". It was only in the early 1990s that commercial culture started to develop in the southern State of Santa Catarina. Production systems were low-cost and enabled fishermen to get an extra income in sheltered and very shallow bays. After 20 years, Santa Catarina is the leading state in brown mussel production, with around 20 000 tonnes per year. Here, there are several constraints for further development, such as the lack of enough wild mussel seed and that almost all the oyster industry relies on a single public hatchery for its seed. Additionally, complex legislation for becoming legally established as a farmer in federal waters and scarce public funds for water quality monitoring also increase challenges faced by farmers.

3.3 The role of government, private industry and international organizations in aquaculture diversification

Government and the private sector have shared the responsibility for developing Brazilian aquaculture since the beginning of the process. Most introductions of exotic species were promoted and funded by governmental institutions. In the 1970s and 1980s, there were not many concerns regarding the risks of importing diseases or negative environmental impacts, related to the introduction of exotic species.

Most actions undertaken in those days were aimed at recovering fish stocks in water reservoirs, to facilitate wild fisheries.

Nowadays, government policies still prioritize production growth, whether the process refers to established exotic species, such as tilapia or white-legged shrimp, or to new ones (MPA, 2015). The Federative Republic of Brazil presents high aquatic biodiversity whose aquaculture potential still has to be investigated. However, federal and state government elections every 4 years combined with the lack of long-term policies have inhibited long term investments, necessary to develop complete technology packages required to introduce and/or improve new farming alternatives. This fact is more evident in the case of native species such as tambaqui and the mangrove oyster. Additionally, legislation is complex and can change from time to time; and environmental agencies exercise pressures that inhibit/restrict production. Thus the lack of a continuous sustainable aquaculture policy in recent decades has meant that aquaculture diversification of any significance has been driven mainly by the private sector.

This legal and political scenario makes the Federative Republic of Brazil a country that should look into better governance and institutional stability to offer solid investment conditions to develop any further its aquaculture industry. A good example of the frailty of governmental support to aquaculture is the absence of a good breeding program for target species, where good results demand a long-term approach. Without a program like this, the private sector is always forced to look for alternative methods and technology to reduce production costs and gain productivity.

When it comes to international players, some interest is starting to be shown by foreign investors, and the experience with tilapia and shrimp in the Federative Republic of Brazil is enabling aquaculture diversification and attraction of new investors; farmed production of those species has led to specialized production of aqua-feeds, the availability of imported vaccines, and more and better hatcheries and trained technicians and personnel. Furthermore, the Federative Republic of Brazil is a huge market for aquatic food, and domestic demand surpasses by far local capabilities to produce the necessary supplies, a fact that has meant that recently the Federative Republic of Brazil has been importing seafood products for values in excess of US$1.4 billion per year, a record figure for a Latin American country, where consumption per caput is fairly low.

Several international organizations have had a long experience in aquaculture cooperation and diversification efforts in the Federative Republic of Brazil. The FAO has worked for the past 40 years at federal level, regarding aquaculture development and diversification. The Project (FAO/UNDP/RLA/76/010) established the Latin American Regional Aquaculture Centre (CERLA) aiming at: (a) undertaking applied research, (b) providing training in aquaculture for high-level staff and (c) establishing an aquaculture information system. The project's most significant achievements in the field of applied research include the development of commercial modules for the production of pacu and tambaqui (Commission for Inland Fisheries of Latin America, FAO, 1987). In 2001, the Brazilian Government started an FAO Technical Cooperation Project (TCP/BRA/0065) for the development of seaweed farming for coastal communities of the northeast region (Ceará, Rio Grande do Norte and Paraíba). As a follow-up, the project entitled "Coastal Communities Development (UTF/BRA/066/BRA)" started in 2006 with the following objectives: a) consolidation of the *Gracilaria sp.* seaweed culture; b) diversification of mariculture; c) development of pilot projects on co-management of marine resource and d) establishment and organization of inter-institutional committees. This project opened new options for aquaculture diversification with a clam, *Anomalocardia brasiliana* and the mangrove oyster, *Crassostrea gasar,* however, with limited success, so much so that it was discontinued in 2012. In its turn, the Canadian International Development Agency

(CIDA) funded the project Brazilian Mariculture Linkages (Project BMLP) from 1993 to 2002. Its activities involved cooperation between Canadians and Brazilian universities for capacity-building, technology transfer, and community economic development aimed at promoting sustainable mariculture in the impoverished coastal regions of north and eastern Brazil.

These last two projects helped the Federative Republic of Brazil to develop technologies for oysters, mussels, clams and seaweed culture. Small scale farms are still working on these subjects in northeast states, but community organization, cost of production and restricted local demand still constrain production development. In Santa Catarina, bivalve mollusc culture became an organized production chain, well recognized by society, but local government did not succeed in establishing a national reference mariculture center, through which it was expected to replicate and disseminate technology to other regions.

3.4 Technology and expertise, markets and institutional facilities as drivers and constraints

The Brazilian aquaculture diversification process has been influenced by government, private sector and international organizations. Government hatcheries built through international cooperation projects made knowledge available for fingerling production of several species. Capacity building and training also drove diversification. As aquaculture became important, the number of higher education courses increased. Thus, and according to data from the Coordination for the Improvement of Higher Level Personnel (CAPES) of the Ministry of Education, the Federative Republic of Brazil has 18 graduate courses specifically related to aquaculture. Most of those courses are concentrated at public universities in southern and northeast states with a few institutions in northern and midwestern regions, exactly where outstanding aquaculture growth has taken place in recent years (Figure 7). Moreover, the majority of the students are mainly trained to become scientists, in some cases without enough hands-on experience or not well prepared to face and solve real industry problems.

One of the main challenges of R&D in Brazilian aquaculture relates to establishing priorities, considering the large number of potential native species for aquaculture diversification and development purposes, and their corresponding high demand for technology improvements and developments, together with very scarce human, private and governmental resources split among too many objectives.

To partly address these problems, and in order to raise more funds and respond to scientific and industry demands for more and better aquaculture technology, the Ministry of Fisheries and Aquaculture (MPA) jointly with the Ministry of Science and Technology has called nine times for project proposals between 2003 and 2010. These calls always considered potential native species for diversification and have enabled funding for around 210 projects, focusing on different species, through

FIGURE 7
Geographical distribution of Brazilian graduate courses in aquaculture

Source: Data adapted from CAPES (2016).

grants, scholarships and research facilities worth around BRL[54]60 million (Routledge *et al.*, 2012). Around 74 potential species were considered in those projects, with the top seven species studied representing 46 percent of the projects (Table 11). In more recent calls, government stressed the need to work on applied research through professional networks, and thus, interesting advances have been possible with a few species.

TABLE 11
Aquaculture R&D projects funded by Brazilian agencies, by species studied, 2003 to 2010

Species	Common name	Projects
Oreochromis niloticus	Tilapia	31
Litopenaeus vannamei	White legged shrimp	14
Rhamdia quelen	Jundia – Southern native catfish	14
Arapaima gigas	Pirarucu	12
Colossoma macropomum	Tambaqui	11
Piaractus mesopotamicus	Pacu	8
Centropomus paralellus	Robalo – Brazilian snook	7

Source: Routledge, personal communication (2016).

It is generally believed that these funds helped the Brazilian institutions to upgrade equipment and redesign experimental hatcheries and pilot farms, to be better prepared to develop applied technology and reduce aquaculture costs within industry.

The situation described by Ostrensky, Borguetti, and Soto (2008) regarding the Brazilian aquaculture industry still applies. There are many well-established providers of services, equipment and supplies, and an increasing number of hatcheries for the most commonly cultivated species. These hatcheries are being modernized with water treatment and biosecurity systems. There is still plenty of space for improvements and automation, as qualified workforce is becoming more expensive in rural areas. Processing facilities and other links within the aquaculture industry also need to move fast to apply more and modern technology in order to back whatever is being done with diversification of aquaculture products.

Feed availability and production systems are improving, but feed conversion rates for tambaqui and hybrids cannot still compare to those observed with tilapia farmed in earthen ponds and cages. Good genetic material and specific feed makes tilapia production systems more efficient. There are also several groups of people that want to intensify further work with native species. Amazonian small farmers are culturing tambaqui with aerators up to 10 Hp/ha in earthen ponds and medium-scale farmers in Mato Grosso have started testing hybrids of tambaqui, pacu and pirapitinga at commercial scales in large volume cages, with promising results.

On the market side, the appreciation of the Brazilian Real against the United States of America dollar and the global economic crisis in 2008 reduced the competitiveness of Brazilian seafood exports and consequently the domestic market became more attractive. Indeed, in that period, and after the implementation of social policies aimed at improving living standards of poor populations, average per capita income grew significantly. As a result, Brazilian consumers have increased their demand for fish products. That demand has been satisfied by a growing domestic production, but also through increasing imports, mainly from the Republic of Chile, the People's Republic of China and the Kingdom of Norway. Farmed salmon from the Republic of Chile is one of the main aquaculture imports. This fact is reflected in Brazil's international trade accounts, which show increasing levels of fish imports. Here and in 2014, a negative trade balance of more than US$1.3 billion dollars was mainly due to the increase in

[54] 1 USD = 3.123 Brazilian Real (BRL).

imports (Kubtiza, 2015). Despite the appreciation of dollar and the internal economic crisis since 2015, imports of seafood remain very high in the Federative Republic of Brazil.

In 2016, the domestic political and economic crisis may affect shrimp and tilapia exports. Production of freshwater native species is still not large enough to support exports and compete with other producing countries like the People's Republic of China. However, in the domestic market, several native fish species are increasing their share, not only at traditional markets in northern and midwestern regions, but also in big cities such as those in São Paulo and Rio de Janeiro States, where consumers are becoming freshwater fish eaters.

3.5 The future of aquaculture diversification: Main concerns, opportunities, restrictions, main species to consider

There is no doubt that the Federative Republic of Brazil is a strong player when it comes to aquaculture diversification. Native freshwater species production has been rising based on government investments, international institutional projects and private sector initiatives over the last 40 years. However, the Federative Republic of Brazil presents options for diversification based on both native and exotic species.

The main constraints faced by aquaculture diversification are: (1) the legal framework concerning the use of water for aquaculture, (2) the long process needed to get an environmental license, and, (3) insufficient fish processing plants constraining value-adding and market access. There are considerable bureaucratic procedures needed to obtain all of the permits/licenses required to start an aquaculture operation. The pioneering work with the Santa Catarina mollusc industry is an example of the benefits of working together with all stakeholders, and considering an 'ecosystem approach' for aquaculture planning and legislation. Aspects of coastal zone characterization were considered in the elaboration of Local Plans for Mariculture Development (PLDM), including environmental, legal, socio-economic and possible impacts of mariculture. This experience has high potential to be adaptable to other Brazilian states wanting to develop mollusc farming (Suplicy *et al*., 2015).

Bivalve mollusc farming offers a wide range of opportunities for aquaculture in the Federative Republic of Brazil. Because molluscs are filter feeders, the cost to raise and run a small farm is usually small compared to other species (based on lower feed costs). Normally, production systems are simple and family based. The native lion´s paw scallop (*Nodipecten nodosus*) and the mangrove oyster (*Crassostrea gasar*) are considered the best options for further diversification in southern and northern regions, respectively. However, there are still constraints regarding the availability of seed. Scallop seed is only produced through hatchery work, and mangrove oyster seed source is based on natural spat collection on artificial collectors. This system can also result in a mix with another mangrove oyster (*Crassostrea rhizophorae*), which does not reach commercial standards. However, both mangrove oyster species are salinity tolerant and offer opportunities for social development at traditional communities based on simple production systems for grow-out.

Plenty of suitable areas for marine fish farming can be found along the Brazilian coast. Brazilian universities already have considerable experience with experimental production of potential species. The main ones are the common and fat snook (*Centropomus sp.*), flounder (*Paralichthys orbignyanus*), snappers (*Lutjanus sp.*) and cobia (*Rachycentron canadum*). The first commercial farm experience in the Federative Republic of Brazil focused on cobia off the coast of Pernambuco State. Growth rates observed (up to 5 kg in 15 months) were very attractive. However, after only a few years in operation, this offshore cage farm closed down for several reasons, among which lack of a specific feed for this carnivorous species was particularly relevant. Today small private hatcheries and farms are raising cobia in relatively large cages, but in small quantities, in the north of São Paulo State and south of Rio de Janeiro State. A partnership with a local feed company that produced a specific feed is still not showing good results, with survival and growth rates up to 3kg in 12 months (Kubitza, 2014). Current limited production is sold to restaurants specializing in oriental cuisine, mainly in São Paulo. As production scales up, cobia could become an option for local fishermen to become fish farmers, if they obtain environmental licenses. Shrimp farmers could also drive further marine fish farming developments, focused on estuarine species in deactivated earthen ponds. The accumulated knowledge concerning fingerling production and grow-out could also open opportunities for diversification with other native species.

Concerning freshwater native species, pirarucu, also known as paiche (*Arapaima gigas*) is always going to be a potential fish for aquaculture in the Amazon and other countries outside its natural distribution (Hill and Lawson, 2015). This carnivorous fish, which can reach 10 kg in a year, is attractive to any fish farmer. The main challenge here is the limited availability and high prices of fingerlings, which represents around 25 percent of production costs, with fingerling price around US$3.00 (Pedroza Filho *et al.*, 2016). To date, fingerling production relies on natural spawning, as artificial reproduction is not controlled yet. This fact also puts pressure on the natural stocks, as the use of fingerlings from the wild for farming purposes is difficult to control, and for several reasons, this species is already considered as 'threatened' by CITES.

Problems with the reproduction of *Arapaima gigas* in captivity start with the lack of reliable techniques for sex identification. Recent technologic advances for sex identification have yielded a portable kit for this purpose (Chu-Koo *et al.*, 2009). Today, this technology is helping farmers to increase the quantity of fingerling produced as establishing fish couples into earthen ponds seems to enable reproduction in the rainy season (Núñez *et al.*, 2011). A current project in the Federative Republic of Brazil leaded by Embrapa is dealing with a range of problems related to the reproduction of *Arapaima gigas*, such as tools for assessment of maturation, protocols for hormonal treatment and also the genetic variability of captive broodstock in the Federative Republic of Brazil. Despite the many technological unsolved issues, pirarucu production is growing from year to year and official data indicate that over 11 000 tonnes were produced in 2014, mainly in the northern state of Rondonia.

Nowadays, the introduction of a new exotic species for aquaculture must follow different procedures. First, a potential farmer or institution must apply for a specific environment license that involves a lengthy risk-assessment study. Normally, Brazilian environmental institutions are precautionaryprecautionary on aquaculture licensing. Even species introduced decades ago and established as an important industry in the Federative Republic of Brazil (tilapia, white legged shrimp and Japanese oyster) are subject to environment license revisions which can restrict their development. Furthermore, in Brazilian scientific circles, the subject is controversial and the argument that the Federative Republic of Brazil has many potential native species for aquaculture usually prevails. Industry, however, cannot wait for a fully developed technologic package produced locally, and from time to time, considers new introductions. Recently, the exotic catfish (*Pangasius sp.*) and barramundi (*Lates calcarifer*) were considered for feasibility studies, but the idea did not prevail due to license constraints.

Hybrids in Brazilian aquaculture are a reality. It is difficult to imagine today's industry without hybrids. Concerns about hybrid escapes and possible interaction with wild populations could affect the future of Brazilian aquaculture. Assessment studies, hatchery monitoring procedures and breeding programs for species such as tambaqui and pirarucu should be considered as strategic governmental actions to secure sustainable aquaculture.

Currently, domestication efforts with target native fish for cage production are taking place, with interesting results, and could finally help diversifying production while relieving pressures on the farming of tilapia in northern Amazonian states, where legislation constraints regarding exotic species are higher. Good examples of cage fish farming are under evaluation in Mato Grosso state, considering tambaqui and pacu hybrids in big cages from 100 m^3 to 1 400 m^3 (F. Medeiros, personal communication, 2016).

3.5.1 Climate change

The effects of climate change on Brazilian aquaculture is becoming a general concern in different regions. The industry started to worry about its effects on farming systems due to the economic impacts caused by production losses. It is difficult to find official data regarding these impacts. However, more frequently, extreme weather events (such as flooding, water scarcity and storms) probably increased the frequency of diseases, fish and shrimp escapes and toxic algal blooms events on different production systems around the country.

The shellfish industry in Santa Catarina has faced climate change events recently. Algae blooms are becoming more frequent, preventing commercialization and pushing local government to establish an insurance policy to cover periods without sales. Future studies regarding the impact of sea acidification on the main mollusc species should also be encouraged. Brazilians are not avid consumers of bivalves, and to further promote consumption, specific campaigns need to be considered to open new market opportunities.

For the last five years, several reservoirs used for tilapia farming are facing lower mean annual rainfall levels. As the main purpose of the majority of these reservoirs is to generate electricity, fish farming is considered a secondary activity only and reservoir levels tend to be adjusted, affecting fish farming, and thus increasing the negative effects of lower reservoir volumes. In Ceará State, long dry periods affected several reservoirs. This scenario has been changing the geography of both production and trade, once farmers move from one reservoir to another searching for better environmental conditions and industries from southern states take advantage of the market gaps in the affected regions. To avoid losses, farms reduce stocking densities and feeding rates and move cages to deeper waters or other reservoirs in other states, whenever possible. All these procedures can maintain water quality and control mortality, but fish production has fallen in the main reservoirs used for fish farming in Ceará.

The Brazilian government is establishing measures that will help to deal with climate change effects on aquaculture following De Silva and Soto's (2009) overview on climate change impacts on aquaculture. Thus, during this last decade, the former Ministry of Fisheries and Aquaculture (MPA) funded several carrying capacity studies to support aquaculture planning, which in turn are seen by the same authors as insurance to improve resilience against climate change, as environmental limits should be respected as the main criterion to define space to be leased for aquaculture use.

An Aquaculture National Monitoring Program is also being planned by government. The plan is to provide real time data on physical and chemical conditions for aquatic environments, in order to manage inland cage culture farming. The program is waiting for funds in order to be implemented.

De Silva and Soto (2009) considered that the spread of pests and diseases is a major threat under climate change scenarios, and that this issue must become a priority for aquaculture, considering relevant biosecurity measures. A few years ago, the National Network of Laboratories of the Ministry of Fisheries and Aquaculture (Renaqua) was created, and became responsible for monitoring, analysis and the provision of official data regarding fish health. These laboratories also provide training and define strategies to prevent disease outbreaks in this industry.

3.5.2 Conclusions

The Federative Republic of Brazil is well known for its aquatic biodiversity and favorable climate for aquaculture development. These characteristics could convert the country into a strategic player among world aquaculture producers. Moreover, different authors already consider that there is a clear tendency to diversify farmed species, technologies and production systems. In evolutionary terms, it is commonly understood that diversity provides the ground for natural selection and for adaptation, and therefore, it can also be proposed that culturing more species provides a form of insurance and offers better adaptation possibilities under different climate change scenarios, especially when unexpected events such as diseases occur (De Silva and Soto, 2009).

Brazilian aquaculture presents a production model based mainly on small farmers with poor technology. This scenario is changing and today it is possible to find a few vertically integrated farms. However, most farmers are still small scale and family based. Under these conditions, production growth becomes more challenging and products show low diversification and high prices, factors that affect competitiveness of Brazilian farmed products with imports, challenging the sustainability of Brazilian aquaculture.

Imports can also be seen as an opportunity for the Brazilian industry to become more competitive, as local farmers, needing to sell their products try to improve their management practices and biosafety procedures, and there are more and growing initiatives for new equipment developments such as for automatic feeders and graders, to promote productivity and further aquaculture development.

Sidonio *et al.* (2012) from the Brazilian National Development and Social Bank (BNDES) pointed out several options to modernize this industry. Among governmental measures, they suggest stimulating the installation of more structured industries (leading companies), which could accelerate the introduction of technologies adapted to Brazilian conditions and species. Additionally, they state that technology transfer and partnerships could make small and medium farms more competitive and would foster production growth and develop products for export, which would help in replacing part of current imports. The Brazilian government could encourage a research and technology network program (research institutions and industry) focusing on applied research to face challenges and bottlenecks. Credit lines could encourage international investment and technology transfer for aquaculture diversification (species, production systems and products).

The Brazilian government should also consider the effects of climate change on aquaculture and translate these concerns into formal policies. As well, further actions to implement a more competitive framework to enable private sector investments are also needed to better explore the Federative Republic of Brazil's aquaculture potential and biodiversity.

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Diversification through integrated multitrophic aquaculture: kelp is one of the species cultivated in this operation in Canada

PHOTO CREDIT: ALLISON BYRNE

PAPER 4

DIVERSIFICATION OF AQUACULTURE IN NORTH AMERICA

Prepared by
Stephen F. Cross
University of Victoria, Geography Department, Canada
North Island College, Center for Applied Research Technology and Innovation, Canada
Global Aquafood Development Corp., Canada
E-mail: stephen.cross@nic.bc.ca

Mark Flaherty
University of Victoria, Geography Department, Canada

and

Allison Byrne
North Island College, Center for Applied Research Technology and Innovation, Canada

1. OVERVIEW

This chapter provides a Case Study for North America, using regional aquaculture diversification examples from this large geographic area. Our attention is confined to the area within which most aquaculture activity currently occurs and therefore includes the land and coastal areas between the Tropic of Cancer (23.5º N) and the Arctic Circle (66.6º N).

Motivation for the diversification of aquaculture in North America continues to evolve, and in essence is becoming more complex over time. The decisions to introduce new aquaculture species, develop and apply new production technologies or systems, and to advance/improve farm operational protocols have typically and historically been driven by industry in response to market opportunities and/or to reduce cost of production – each with the goal of increasing the bottom line (profitability).

Economic drivers of aquaculture species diversification remain very much market related. In western North America, for example, increased access to Asia-Pacific markets brings with it a consumer demand for products that may not typically be part of the local market, and thus represent new and profitable business opportunities. Species such as sea cucumber, sea urchin, seaweeds/kelps, and rockfish are all in short supply and hence in high demand, making the product of high value and supporting a business case for entering the supply chain for such species. These opportunities will also require new forms of production infrastructure and capital investment, including investment in diversification of species and systems.

But what makes a good species or production system a candidate for diversification? Industry (established businesses) will not typically move from one species or production system approach to something entirely new, but may consider a transition or investment in a multiple species/system approach that can be justified through a defensible business case. In short, industry will want to thoroughly assess risk (technical, financial) and be satisfied that a decision to diversify is justified in terms of overall cost of production, long term market demand, product pricing, differentiation, segmentation, and competition – and that any such decision will result in an adequate (or better) return on investment.

For entirely new approaches such as IMTA/SEA or RAS, a simple transition in product diversification model is not quite as simple. These innovative approaches to diversify or 'improve' seafood production very much represent a new industry sector, and are often introduced through government-funded demonstration and proof-of-concept projects before attracting commercial investment. Commercial success in establishing new system approaches will also be determined by the business criteria used to direct how aquaculture species diversification would be considered.

The above are the key *economic* (business) drivers of aquaculture diversification, but today these are also becoming increasingly influenced by both environmental and social drivers. In North America, *social license* has a strong influence on producers, and how you farm is as important to the consumer as what you farm. System innovations that improve farm operations (e.g., reduced use of antibiotics or chemicals) or selection of native species over introduced ones are all viewed (or perceived) as being better for the environment and/or safer to eat. Satisfying social criteria can represent a costly aspect of farm operations, and system innovation, species diversification, and adaptive operational protocols can meet the challenges of achieving social license.

While many of the environmental drivers that stimulate species and/or system diversification are related to the demands of social license, there is also an increased reality that changing climate and ocean conditions will have a negative and potentially devastating impact on coastal aquaculture production. In the Pacific Northwest, impacts of ocean acidification have already impacted the shellfish sector; water quality (pCO_2, pH) within hatchery facilities have been adjusted to increase survival of larvae and production of seed for farm operations. Land-based operations (hatcheries, RAS production) have the advantage of being able to control water quality and adapt to changes in ocean conditions – but can this form of technology alone be cost effective in terms of the global seafood demand?

Species diversification is an important adaptive response to climate and ocean change by industry. A move to multiple species within individual farm operations tends to reduce risk, especially if operations select species with differing environmental tolerances (e.g., salinity, temperature ranges). The integration of broodstock selection programs has developed in finfish aquaculture, and is now recognized as an important component for other sectors – shellfish, echinoderms, seaweeds.

In conclusion, diversification of aquaculture in North America is driven largely by economic factors, although social and environmental drivers are increasingly influencing the structure of this industry sector. Diversification of species and of production systems is seen as an important and critical adaptive response to changing climate and ocean conditions.

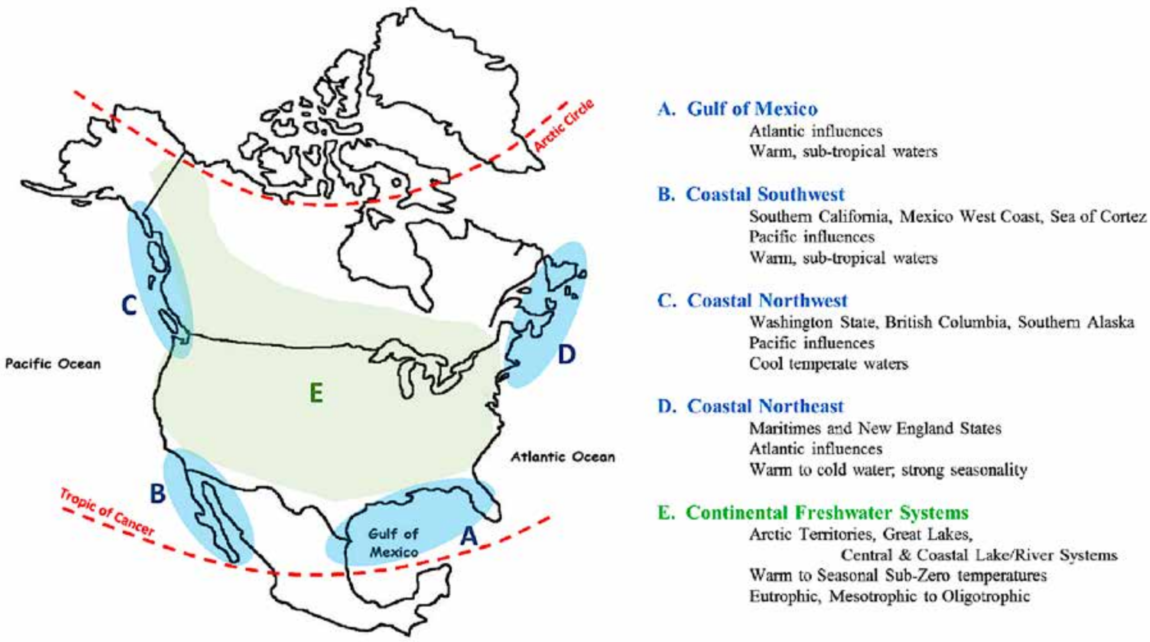
2. CHANGING AQUACULTURE PRODUCTION – REGIONAL DRIVERS

North America is represented by an extremely diverse suite of aquatic environments and hence by its current aquaculture production and its diversification opportunities – both in terms of species cultured and production system approaches. With a geographical range that encompasses warm subtropical latitudes in the south to the cold temperate latitudes in the north, the continent provides coastal access to the Pacific and Atlantic Oceans and to the Gulf of Mexico and the Sea of Cortez in the south. Figure 1 illustrates the boundaries of our study area defined for this evaluation, as well as five key North American sub-regions that support the majority of the current aquaculture production and diversification.

As in many regions of the world, North American aquaculture has evolved in the wake of declining and/or threatened regional fisheries and generally as a way to offset loss in target harvest volumes, in associated coastal community livelihoods, and in economic opportunities. As such, aquaculture has typically followed established fisheries with little historical effort placed on developing new production species and methods, but rather in increasing supply of established products as market demand increased.

While increasing global demand for seafood has universally stimulated growth in aquaculture, North America has been influenced by a variety of drivers that have

FIGURE 1
North America aquaculture production regions used for this evaluation



directed its regional growth and supported an increasing diversification in aquaculture production. In general, a trend towards increased diversification and production innovation has been stimulated by three general drivers: (i) economic and livelihood opportunities; (ii) social license and eco-ethical consumer demands; and (iii) as an adaptive response to changing environmental conditions. But aquaculture in North America lags behind the rapid expansion seen elsewhere, largely due to governance burden (red tape) and widespread environmental activism.

The following sections provide three specific, regional examples of the aquaculture diversification activities in North America – the Pacific Northwest, the Northeastern Seaboard, and the subtropical waters of the southeastern States and northern Mexico (Gulf of Mexico and Baja Peninsula).

3. EXAMPLE 1: PACIFIC NORTHWEST

Aquaculture in the Pacific Northwest occurs along the coasts of Washington State, British Columbia, and Alaska. The major aquaculture production in this region, in terms of species diversity and harvest volumes, is centered in British Columbia, Canada – and it is this coastal area that provides the most varied and complicated motivation for aquaculture diversification and innovation. The following discussion is therefore based on coastal British Columbia, although similar such diversification interest and development activities also occur in Washington State. Wild ocean fisheries remain dominant in southern Alaska, where aquaculture is largely associated with ocean ranching of salmon with an additional albeit small (developing) shellfish production sector (Pring-Ham and Politano, 2015).

3.1 Diversification and innovation in aquaculture production

The diversification of aquaculture in the Pacific Northwest region of North America has been stimulated by social, economic, and environmental drivers. The movement towards a more diverse seafood production sector is reflected in the variety of species cultured as well as the innovations associated with production system improvements and new system research and development. Examples of aquaculture diversification, including species and systems, are provided in the following sections.

3.1.1 Aquaculture species

Aquaculture in this coastal region is generally classified as: (i) marine plants (seaweeds/kelp); (ii) finfish; and (iii) shellfish – the latter including all invertebrate species. This classification is the basis for coastal zone management (farm siting) and the aquaculture industry operational regulations. Each of these sectors has considerable diversification potential, and research and development in support of new candidate species began approximately 15–20 years ago and has increased considerably over the past 5–10 years.

3.1.1.1 Shellfish – bivalves and echinoderms

Oysters: Pacific oyster (*Crassostrea gigas*) production is a well-established aquaculture species on the west coast. Yet it is one that has experienced significant diversification over the past 100 years in terms of production methods – from beach culture to suspended longline culture to raft culture. These changes have also resulted in a commensurate transition from bulk production of a shucked product (beach and longline) to the higher valued single oyster (raft produced), which generates small, fresh half-shell (cocktail) product for the restaurant market. The pursuit of higher farm-gate prices for half-shell oysters has most recently been associated with product branding, and various system innovations (e.g. automated grading, tumbling protocols, packaging), to physically and aesthetically differentiate oyster products (AAC, 2011).

In addition to ongoing production improvements and associated product differentiation for the Pacific oyster, there has also been recent interest in looking at new oyster species to further support the growing market demand. In particular, introduction of the native west coast oyster (*Ostrea lurida*) as a culture candidate would support production of the coast's only native oyster, a species that was almost harvested to extinction a century ago (Gillespie, 2009). It has been classified as a species of Special Concern since 2001 (COSEWIC, 2011); industry views this as an opportunity not only to re-establish an endangered native species, but also to capitalize on a species that has *marketability* given its history on the west coast.

Drivers: Economic – added value and diversification within oyster product line
Social – supporting enhancement of an endangered, native species

Clams: The primary clam produced through aquaculture on the west coast is the introduced Manila species, *Venerupis philippinarum*. This species has established itself along most of the Washington and the southern and central British Columbia coast, but occurs higher within the intertidal zone and hence does not compete with many of the native clam species which occur at lower elevations (Gillespie *et al.*, 2012).

Diversification in clam production is occurring as a result of interest from the shellfish sector itself, and has been stimulated by increasing demand, by product value, and by opportunities to supplement and increase existing farm-level production with additional species (co-culture). For the beach production areas, the addition of geoduck (*Panopea generosa*) to the lower intertidal and shallow subtidal regions (Liu, Pearce and Dovey, 2015) is seen as a high-valued option that would complement Manila clam operations. In deepwater farms, where rafts are typically used to support oyster production, a unique opportunity to add native cockle (*Clinocardium nuttallii*) is under consideration – this is the only clam species that shows the potential of being able to be cultured in suspended trays and in the absence of beach substrate (Gurney-Smith *et al.*, 2009).

Driver: Economic – both of these new bivalve species, and geoduck in particular, represent high value products with low and/or declining supply.

Scallops: Introduction of the Japanese scallop (*Patinopecten yessoensis*) to the west coast took place in the mid-1990s (Gillespie *et al*., 2012). This species demonstrated a much faster growth than the indigenous weathervane scallop (*P. caurinus*), but over time revealed some issues with meat yield and susceptibility to local parasite populations and possible indirect effects of changing ocean water chemistry (Blackbourn, Bower and Meyer, 1998; Bourne, 2000). Production diversification of this shellfish group has occurred in two ways: (i) genetic crossing of the two *Patinopecten* species (Guo, 2009); and (ii) introduction of the native rock scallop (*Crassadoma giganteum*) as an additional production candidate.

Drivers: Economic – diversification of products, increased meat yield
Environmental – adapting to changing ocean conditions

Urchins: The subtidal (dive) harvest of green sea urchins (*Strongylocentrottus droebachiensis*) has resulted in significant fluctuations (Parry, Zhang and Harbo, 2002) in wild populations (and thus interest in development of a farming approach to supply the growing demand for the species roe ("uni", popular in Japan). Seed for this echinoderm is relatively easy to produce in hatcheries, and suspended culture methods, as opposed to bottom seeding and subsequent dive harvests, are currently being explored (Pearce and Robinson, 2010). Their co-culture with oysters or scallops as an extractive species within an IMTA/SEA system configuration provides biofouling control (Lodeiros and García, 2004; Ross, Thorpe and Brand, 2004; Switzer *et al*., 2011) as well as farm diversification and the inherent environmental benefits associated with a multi-species, ecological system design.

Drivers: Economic – new species with stable market value; potential co-culture within shellfish farms; resulting regional diversification with associated jobs and revenues.
Environmental – use of the species within an IMTA/SEA system, representing one of the extractive species candidates for intercepting, extracting and converting the organic wastes released by the fed finfish species.
Social – public support, social license associated with "natural", multi-species (ecological) system designs.

Sea Cucumbers: An extremely high-value delicacy in the People's Republic of China, the demand for sea cucumber has increased dramatically over the past 10 years as China's middle class has grown and the global supply has failed to meet the demand (Anderson *et al*., 2011). As an epibenthic detritivore, the sea cucumber has the potential as a co-culture species with shellfish (Paltzat *et al*., 2008) and with finfish, within an IMTA/SEA multi-species system configuration, as an organic waste extractive species (Hannah, Pearce and Cross, 2013; Van Dam-Bates *et al*., 2016). Regional challenges with this species include cost of production if containment is required, and the present regulatory restrictions that prevent an ocean ranching approach if proposed. Current industry-government research is addressing each of these development constraints.

Drivers: Economic – new species of very high value; potential co-culture within shellfish and finfish farms; regional diversification with associated jobs and revenues.
Environmental – use of the species within an IMTA/SEA system, representing one of the extractive species candidates for intercepting, extracting and converting the organic wastes released by the fed finfish species.

Social – public support, social license associated with "natural", multi-species (ecological) system designs.

3.1.1.2 Finfish

Sablefish: Dominated by Atlantic salmon production, with an associated but small volume of Pacific salmon, the west coast has only recently explored new finfish species as commercial aquaculture candidates. Sablefish (*Anoplopoma fimbria*), which is also known as Alaskan Black Cod and butterfish, is a native marine finfish species that has an established fishery. The age structure (lifespan >90 years [Munk, 2001]) of the wild sablefish population brings into question the long-term viability and sustainability of the fishery, given the increasing demand for this very high valued species, and has thus suggested a role for aquaculture. Following years of research on hatchery methods and juvenile rearing, this species is now under early stage commercial production with four licensed and operating farms on the coast. The methods developed for this species will provide the groundwork for new marine species with similarly complex early life cycle stages.

Drivers: Economic – new species of very high value; regional finfish diversification with associated direct and indirect jobs and revenues.
Social – diversification of fish farming, using indigenous not exotic species

Wolf eel: The wolf eel (*Anarrhichthys ocellatus*) is a marine finfish that has recently been evaluated as a potential commercial aquaculture candidate. This fish (not an eel) has a number of characteristics that have suggested its suitability for culture. First, the juveniles that are released from the eggs can be introduced directly to formulated feed (Moksness and Pavlov, 1996), and do not require the preparation of live feeds as with sablefish culture. Furthermore, the animals reveal a high survival through the production cycle with reasonable growth rates and feed conversion ratios. The animals also perform better under higher stocking densities (> 40 kg/m^3) and thus could support profitable production levels at the culture unit level (AAC, 2013).

Drivers: Economic – new species with potential within the white fish market; regional diversification with associated jobs and revenues.
Social – development of aquaculture methods for wolf eel and other marine species (rockfish) as a conservation approach (work conducted by the Vancouver Public Aquarium.)

3.1.1.3 Marine Plants – Seaweeds and Kelp

Marine plants represent higher aquaculture production by weight than all of the globally farmed marine animal species combined (FAO, 2015). Despite the significant production in Asia-Pacific countries, North America produces very little in comparison with fish and invertebrates (shellfish). Nevertheless, the nutrient-rich temperate waters of the Pacific Northwest offers a diversity of seaweed and kelp species and hence significant opportunities for development of a diverse marine plant aquaculture sector in the future.

Sugar kelp: Although a small commercial harvest of natural kelp (brown macrophyte) beds has historically been conducted along the Pacific Northwest coast, there has been little in the way of commercial kelp production. Three small companies are currently active in this area, although production levels have yet to achieve a level to warrant development of commercial processing facilities. Each company is exploring the product opportunities offered through sugar kelp (*Saccharina lattissima*) production, although each is also exploring smaller volume R&D of other related kelp species and valued seaweeds. As an effective nutrient extraction species, sugar kelp is also being assessed as one of the species of an IMTA/SEA system design, offering a component that would intercept and extract the inorganic nutrient wastes generated form the fish component (Neori *et al*., 2004; Cross, 2012; Wang *et al*., 2014). Sugar kelp has a variety of products and uses (alginates, nutraceuticals, sea vegetables) some of which will depend upon volume of production, e.g. bioethanol.

Drivers: Economic – new west coast species; multi-product development potential; new farming sector of co-culture potential; regional diversification with associated jobs and revenues.
Environmental – use of the species within an IMTA/SEA system, representing one of the extractive species candidates for intercepting, extracting and converting the inorganic dissolved nutrient wastes released by the fed finfish species.
Social – public support, social license associated with "natural", multi-species (ecological) system designs; development of aquaculture that has regional water quality improvement capacity.

3.1.2 Ocean-based systems

The Pacific Northwest region also provides examples of aquaculture diversification and ocean-based infrastructure innovation that facilitates improvements in production efficiency as well as entirely new production systems or approaches that support new species or species combinations.

3.1.2.1 Shellfish juvenile rearing systems

Shellfish seed produced in hatcheries are typically transported directly to farms and grown out to market size following numerous grading exercises, changing the size and mesh or the culture nets and trays as the product grows. Ongoing improvements in juvenile rearing systems have realized a significant increase in seed survival and in the initial growth rate of seed introduced into the ocean. Juvenile rearing using these Floating Upwelling Systems (FLUPSYS) will save farmers substantially, both in seed purchases (volume required) and in production planning given the decrease in overall growout period (BCSGA, 2013).

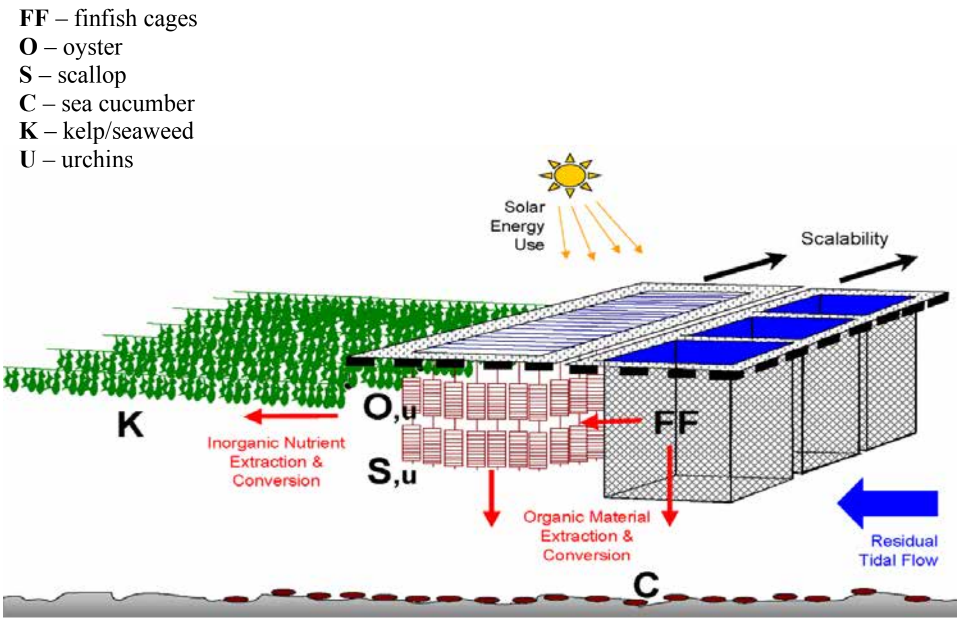
Driver: Economic – increasing production efficiencies through juvenile shellfish growth rates and early stage survival

3.1.2.2 Integrated Multi-Trophic Aquaculture (IMTA) and Sustainable Ecological Aquaculture (SEAfood) systems

The development and commercial-scale testing of designed multi-species production systems began in Canada in 2004 when the term 'Integrated Multi-Trophic Aquaculture' (IMTA) was proposed in favor of 'polyculture'. IMTA was considered a more accurate descriptor for a system that was purposely designed to intercept, remove, and convert the various organic and inorganic waste components generated and released from a fed aquaculture species (typically a fish), by a suite of complementary, and strategically placed extractive species (Chopin *et al.*, 2012, 2013; Cross, 2012).

In the Pacific Northwest, only one ocean-based multi-species license has been issued. To address the nutrient and organic wastes loading from fish culture, the company uses an ecological (IMTA) design for its multiple species production (sablefish, scallops, native cockle, green urchins, sea cucumbers, and sugar kelp). However, this system development also addresses the potential chemical and antibiotic residue release by adopting the National Certified Organic Standards for aquaculture, and integration of alternative energy components to reduce its overall operational carbon foot-print. The combination of IMTA nutrient sequestration, carbon foot-print reduction, and organic operational protocols within a single farm facility has been termed Sustainable Ecological Aquaculture (SEAfood) production (Cross, 2012; www.SEAvisiongroup.ca).

FIGURE 2
Sustainable Ecological Aquaculture (SEAfood) System Configuration



Source: Diagram from Cross, 2012; www.SEAvisiongroup.ca.

Drivers: Economic – multi-product development potential; use of new species; new farming sector of co-culture potential; regional diversification with associated jobs and revenues.
Environmental – use of multiple species within an IMTA/SEA system, with species candidates selected for intercepting, extracting and converting the inorganic dissolved nutrient wastes released by the fed finfish species. SEAfood Systems also eliminate chemical discharges and reduces operational carbon foot-print.
Social – public support, social license associated with "natural", multi-species (ecological) system designs; development of aquaculture that has environmental quality improvement capacity; a green approach.

3.1.3 Land-based saltwater systems

Some aspects of coastal marine aquaculture are routinely conducted in land-based systems, while a number of new saltwater production systems have been designed exclusively for terrestrial environments and add to the diversification of aquaculture production in the region. Innovation in these systems is further supporting diversification in aquaculture production and in some cases increasing operational efficiencies.

3.1.3.1 Seed production facilities – hatcheries

All aquaculture species produced in the Pacific Northwest rely upon hatcheries to produce the requisite seed for the various farm operations. Hatchery operations have developed into large facilities that generate substantial quantities of seed, and in the case of the shellfish sector have become suppliers for entire industry sectors (small-medium sized farm operations). However, and as exemplified in the finfish (e.g. salmon farm) sector, larger vertically integrated companies (e.g. Marine Harvest Canada, Cermaq Canada, Grieg Seafood BC Ltd.) build and operate their own seed production facilities to maintain control of the entire production cycle – volume, timing, and quality/biosecurity associated with juvenile production.

In the shellfish sector, hatcheries have become increasingly susceptible to changing ocean conditions (ocean acidification) and given that these large independent facilities often supply seed for many small to medium-sized companies, there is a growing industry-wide seed supply risk associated with issues that may negatively impact these facilities. Two companies in the region are looking at new hatchery models for the shellfish sector, each designing smaller seed production facilities that are situated directly among the farming tenures – floating, barge-based operations. With recent advancement in larval feed (phytoplankton) production systems, which is a significant component of all hatchery facilities, the scale of these facilities can be reduced and the concept being explored by these companies is to develop a greater number of smaller facilities that thereby spread out the operational risks.

Drivers: Economic – development of vertical integration in sectors currently relying upon third-party seed supply; increased control and reduced cost of production

Environmental – address the risks of changing ocean conditions by spreading hatchery operational risk among a greater number of seed production facilities.

3.1.3.2 Recirculated Aquaculture Systems (RAS)

Interest in the development of land-based fish production system has evolved from system innovations that have occurred with fish hatcheries (e.g., water treatment and recirculation technologies). Recirculated Aquaculture Systems (RAS) have gone from concept to initial commercial production in the last decade, although production levels remain small and profitability is still questioned. Kuterra[55] has built a new RAS facility on the north end of Vancouver Island, and is working in partnership with a local First Nation community that has expressed concern over salmon production approaches used along the British Columbia coast. Development of this new facility has been support by government, environmental NGOs and the local First Nation community. The company is now producing limited quantities of salmon for market and is exploring methods for using dissolved inorganic and particulate organic wastes.

Drivers: Social – development of a production system that eliminates the perceived risks associated with traditional coastal fish production systems, and although currently focused on salmon it may represent an opportunity that has greatest potential with other, less energetic species

Environmental – control over water quality and other open water factors that impact cage production (e.g., pathogens, Harmful Algal Blooms).

3.2 Socio-economic impacts of aquaculture diversification

Diversification of aquaculture production in the Pacific Northwest region of North America has been stimulated by social, economic and environmental drivers. The long history of environmental controversy over open net-cage salmon farming has been largely responsible for the various system innovations that have developed in recent

[55] www.kuterra.com

years – many suggesting that they represent the '*solution*' to the perceived and real issues associated with fish farm production.

In a region where wild salmon populations have been central to coastal community livelihoods and the foundation of a historically productive and valuable fisheries, the development of salmon aquaculture (from its start) has been viewed as a threat to wild salmon – a controversy that has grown among fishers, indigenous peoples (First Nations), and the general public, and one that continues to be stimulated by activists and media. Acquiring and sustaining social license for aquaculture has therefore become a primary motivation or driver for most of the system improvement and diversification in this region.

Integrated Multi-Trophic Aquaculture (IMTA) and the aforementioned Sustainable Ecological Aquaculture (SEAfood) System approaches both provide multi-species designs that were conceptualized to mitigate the organic and inorganic wastes released from fed aquaculture systems, with the latter system eliminating all of the introduced chemicals and animal welfare compounds (e.g. antibiotics). With the increasing demands for "*sustainable seafood*" by a growing eco-ethical consumer base, operational protocols within industry have changed to meet the criteria of corporate and/or third-party management and/or consumer standards such as ISO14000/9000, Monterey Bay Seafood Watch, Marine Stewardship Council (MSC), and the Aquaculture Stewardship Council (ASC).

4. EXAMPLE 2: NORTHEASTERN SEABOARD

Aquaculture operations have been established along the Northeastern Seaboard in the four Atlantic Canadian provinces (Newfoundland and Labrador, New Brunswick, Nova Scotia and Prince Edward Island) and in six New England states (Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island and Vermont) for over four decades. Records of Eastern oyster culture dating back over 150 years. The aquaculture sector currently provides more than 7000 jobs (direct and indirect) in these provinces and states, most of which are in rural coastal communities with long histories of commercial fishing. From Newfoundland and Labrador south to Connecticut, the Atlantic Ocean transitions from subpolar influences of the Labrador Current and sea ice melt to an increasing influence of the subtropical Gulf Stream, resulting in favorable conditions for cultivating a host of temperate-water marine species.

The mariculture of Atlantic salmon (*Salmo salar*), Eastern oyster (*Crassostrea virginica*), and blue mussel (*Mytilus edulis*) accounts for more than 95 percent of the aquaculture production value in Atlantic Canada (Statistics Canada, 2015). Atlantic salmon and Eastern oysters are also the dominant finfish and shellfish aquaculture species, respectively, in New England. Atlantic salmon is farmed using circular sea cages in Atlantic Canada and off the coast of Maine; oysters and mussels are farmed throughout the Atlantic provinces and New England states using longline, bottom, bag (suspended or floating), and tray culture technologies. Diversification of the aquaculture industry, as well as the regional environmental and socio-economic drivers of diversification, are discussed in the following sections.

4.1 Diversification of aquaculture species and production systems in Atlantic Canada and New England

Climate change will continue to impact ocean conditions and is an important incentive for fostering the development of a diversified, adaptable aquaculture industry. Sea surface temperature, which directly affects the growth, food conversion, reproduction, pathogen presence, etc. of marine aquaculture crops, has increased dramatically in some areas of the North Atlantic, e.g. 0.38±0.07°C/decade from 1981–2010 in the Labrador Sea (Han, Ma and Bao, 2013). Sea surface salinity has increased by 26 percent over the last 150 years, with most of this increase in the last several decades (Doney *et al.*, 2012). Seasonal and long-term changes in sea level have been observed in Atlantic Canada with rising rates of 31.1±2.2, 31.6±1.8, and 23.6±5.6 cm/century observed at stations in Charlottetown (Prince Edward Island), Halifax (Nova Scotia) and St. John's (Newfoundland and Labrador), respectively (Xu, Lefaivre and Beaulieu, 2013).

Primary production is predicted to decrease in the North Atlantic owing to climate change-induced reduction in Atlantic meridional overturning circulation (Schmittner, 2005). An overall increase in storm events is expected throughout most regions and is a concern for aquaculture operations that, along the Northeastern Seaboard, are typically either in the ocean or in close proximity to the coast and prone to costly infrastructure damage. Though much uncertainty exists regarding how these changing ocean conditions will impact aquaculture operations, as with all regions a diversified aquaculture industry will be better-equipped to adapt production in response to climate change impacts.

Efforts to diversify farmed fish, invertebrates, and seaweeds/kelps are well underway in Atlantic Canada and New England. Progression beyond the traditional salmon and shellfish mariculture is motivated in part by the aforementioned overarching climate change drivers, though more immediate environmental, social and economic concerns/opportunities are largely what drive change in the industry. The rationale behind many of the alternative species echoes that of Pacific Canada (Section 2.0).

4.1.1 Fishes

A small fraction of the aquaculture market in Atlantic Canada and New England encompasses "other" fish species cultured by only one or a handful of companies. Specialized land-based recirculating aquaculture systems (RAS) have been commercially developed for sturgeon (*Acipenser oxyrhynchus* and *Acipenser brevirostrum)*, for meat and caviar production in New Brunswick, Atlantic halibut (*Hippoglossus hippoglossus),* European seabass (*Dicentrarchus labrax*) and sea bream (*Sparus aurata*). Arctic char (*Salvelinus alpinus*) and rainbow/steelhead trout (*Oncorhynchus mykiss*) are cultured in RAS and sea cages with ongoing research and development efforts to help expand production. Atlantic cod (*Gadus morhua*) is a high priority species for commercialization. Harvests of farmed Atlantic cod have already occurred in New Brunswick, Newfoundland and Maine but production challenges remain and large-scale aquaculture operations have not been established. The spotted and Atlantic wolfish and American eel are under development for land-based culture. Innovations and investment in alternative fish production systems have been primarily focused on the development of land-based systems (freshwater and saltwater) in all provinces and states, and Atlantic salmon integrated multi-trophic aquaculture (IMTA, see 2.1.2.2) in New Brunswick and Maine.

Drivers: Environmental: Innovations in RAS and IMTA to reduce marine pollution and fish health concerns associated with sea cage culture.

Socio-economic: Negativity towards Atlantic salmon farming (sea lice and other fish health concerns, benthic pollution and habitat degradation, use of fish meal/fish oil); reliance on Atlantic salmon creates high-risk; sustainable production of culturally and economically valuable products whose wild fisheries have declined (e.g. Atlantic cod, Atlantic sturgeon caviar, halibut).

4.1.2 Invertebrates

Mussels and oysters dominate the shellfish aquaculture industry in Atlantic Canada and New England. Blue mussels have more recently been cultured in multi-trophic aquaculture systems (with Atlantic salmon and seaweed) in New Brunswick and Maine to filter-feed and recycle suspended nutrients (natural seston and fish-derived organics). Additional commercial species that are established (in some areas, with room for geographical expansion) are giant and Northern Bay scallops (*Placopecten magellanicus* and *Argopecten irradians irradians*), and softshell and hardshell clams (quahogs) in New England. Other species still in the R&D and/or early commercialization phase include green sea urchins (*Strongylocentrotus droebachiensis*) and razor clams (Atlantic jackknife, *Ensis directs*) in New England.

Drivers: Environmental: sustainable, low trophic-level sources of protein that do not require feed inputs; potential for suspension- and/or deposit-feeding species to be co-cultured with finfish to help recycle waste organic nutrients (IMTA).
Socio-economic: popular food items with existing international markets where supply is not meeting demand; opportunity to provide consistent supplies of shellfish that are not abundant and/or difficult to harvest in the wild; improved social license of finfish farms that include cultured invertebrate species.

4.1.3 Seaweeds/kelps

Farmed seaweeds and kelps constitute only a small percentage of current aquaculture production along the Northeastern Seaboard but have huge potential for expansion. Until relatively recently seaweed and kelp have been wild-harvested only. Irish moss (*Chondrus crispus*) is now cultured in land-based tanks in Nova Scotia, and brown seaweeds *Saccharina latissima* (sugar kelp) and *Alaria esculenta* (winged kelp) are have been cultured alongside Atlantic salmon and blue mussels at an IMTA system in New Brunswick, and at sea sites in Maine. Horsetail kelp (*Laminaria digitata*) is also cultured commercially in Maine. Research, development and early commercialization of dulse (*Palmaria palmata*) and nori (*Porphyra* spp.) is ongoing in Atlantic Canada and New England.

Drivers: Environmental: inclusion on finfish farm tenures to act as inorganic nutrient "scrubbers"; increased dissolved carbon dioxide in the oceans may promote photosynthesis and growth.
Socio-economic: potential for the region to contribute to the international seaweed market and provide local products for nearby businesses; myriad commercial applications (food, pharmaceuticals, cosmetics, aquaculture feed replacement, etc.); this inherently 'ecological' approach increases social license for aquaculture.

There is considerable interest from industry/entrepreneurs and government (at the federal and provincial/state levels) to expand production of alternative aquaculture species that are currently only being farmed in low quantities in select areas. The numerous fish, invertebrate and seaweed species in the R&D or early commercialization phase have the potential to further diversify aquaculture on the eastern coast of Canada and north eastern United States beyond salmon and shellfish mariculture to help fulfill economic opportunity, improve societal acceptance of aquaculture, and buffer the industry against climate change uncertainties and challenges.

5. EXAMPLE 3: GULF OF MEXICO

The Gulf of Mexico region includes Alabama, Louisiana, Mississippi, Texas, and West Florida. Coastal populations and ecosystems in the Gulf are threatened by sea level rise, more intense hurricanes, and storm surge (EPA, 2015). Rising sea levels are driven by both increased warming of oceans and ground subsidence.

5.1 Aquaculture production history

Overall, aquaculture production in the Gulf is highly diverse. This diversity, however, is not distributed across all states. Florida aquaculturists produce the greatest variety of aquatic species of any state in the United States, and is a highly diverse farming sector across species, production systems and geographic locations. There are an estimated 1 500 species or varieties of fish, plants, molluscs, crustaceans, and reptiles grown. Florida aquafarms culture products for food and non-food markets that include seafood (fish and shellfish), freshwater and marine aquarium hobbyists, high fashion leather, water gardening, bait, biological control, biofuels, or as "seed" for national and international aquaculturists (Aquaculture Review Council, 2015). Ornamental fish (freshwater and marine tropicals, koi, and goldfish) are the largest segment of Florida aquaculture with 155 farms reporting farm gate income in 2012 totaling US$35.5 million, whereas sales of aquaculture products for human consumption totaled US$24.1 (USDA, 2013).

TABLE 1
Value of aquaculture products sold

	TOTAL				Food Fish			
	2013		2005		2013		2005	
	Farms*	Sales ($1 000)	Farms	Sales ($1 000)	Farms	Sales ($1 000)	Farms	Sales ($1 000)
Alabama	156	111 215	215	102 796	147	109 169	201	99 458
Louisiana	500	90 639	873	101 314	8	(D)	14	(D)
Mississippi	224	203 579	403	249 704	216	202 808	393	248 355
Texas	98	69 770	95	35 359	72	58 441	63	17 917
Florida**	393	77 948	359	57 406	58	(D)	49	3 641
TOTAL	1 371	552 151	1 945	546 579	501		720	

* For the 2013 Census of Aquaculture, an aquaculture farm is defined as any place from which $1 000 or more of aquaculture products were produced and sold or distributed for conservation, enhancement or recreation during the census year. Aquaculture is defined as the farming of aquatic organisms, including: baitfish, crustaceans, food fish, mollusks, ornamental fish, sport or game fish and other aquaculture products.

** Data are for the entire state.

(D) Withheld to avoid disclosing data for individual farms.

Source: USDA, 2014. Census of Aquaculture.

Coastal communities in the Southeast are already experiencing warmer temperatures and the impacts of sea level rise, including seawater flooding. Higher temperatures and greater demand for water will strain water resources in the Southeast. Incidences of extreme weather, increased temperatures, and flooding will likely impact human health, infrastructure, and agriculture. Sea level rise is expected to contribute to increased hurricane activity and storm surge, and will increase the salinity of estuaries, coastal wetlands, tidal rivers, and swamps.

TABLE 2
Freshwater and saltwater acres used for aquaculture production

	Freshwater		Saltwater	
	2013	2005	2013	2005
	Acres	Acres	Acres	Acres
Alabama	20 596	25 351	121	(D)
Louisiana	97 904	104 645	103 159	215 770
Mississippi	47 475	102 898	–	(D)
Texas	6 855	4 651	1 365	2 432
Florida2	2 003	2 292	1 078	718
TOTAL	174 833	239 837	1 057 243	218 830

Source: USDA, 2014. Census of Aquaculture.

Harvest of oysters in the Gulf has declined owing to a variety of factors. On April 20, 2010 an explosion at the Deepwater Horizon drilling rig in the Gulf of Mexico resulted in a sea floor gusher. By the time the well was sealed 87 days later, over 757 million litlres[56] of oil had spilled into the Gulf resulting in the contamination of Gulf of Mexico waters, sediments, coastal wetlands and marine life. Many oyster growers and harvesters blame this incident for the sharp decline in oyster production (Digges, 2014).

Carmichael *et al.* (2012), however, found no evidence of assimilation of oil-derived C and N and, therefore, no evidence of an oyster-based conduit to higher trophic levels. Trace elements in shell were inconclusive in corroborating oil exposure. These findings are not an indication that oysters were not exposed to oil; rather they imply oysters either did not consume oil-derived materials or consumed too little to be detectable compared with a natural diet.

In many areas, 60 to 80 percent of the oysters were wiped out, not by oil, but by the massive infusion of freshwater diverted from the Mississippi River into wetlands by the State of Louisiana in an effort to keep oil from sensitive coastal areas. As a result, oysters were killed en masse by the reduced salinity. To make matters worse reefs were further depleted by a naturally occurring flood in 2011.

Camp *et al.* (2015) argue that the oyster collapse was not related to contamination from the oil spill, but rather to factors affecting oyster recruitment and survival, which may have been mediated by both human, e.g. fishing-related habitat alteration, and environmental, e.g. increased natural mortality from predators and disease, factors. High mortality in 2010 may be due to extended valve closing and resulting starvation or asphyxiation in response to the combination of low salinity during high temperatures (>25 °C).

Texas oyster production has taken a succession of hits, including sediment dumps from Hurricane Ike in 2008 and continually increasing water temperatures – along with hypersalinity caused by drought and thirsty inland cities with fast-growing populations (Brezosky, 2014). Heightened saltiness encourages the spread of parasites and disease. Continuing drought has also been an issue in Florida's Apalachicola Bay.

Interest is growing in the states along the Gulf of Mexico to increase shellfish farming and restoration. Drought conditions in some states, and freshwater diversions of the Mississippi River. States across the region are looking to once again jumpstart both commercial farming, using off-bottom and cage culture methods, restoration, building up hatchery production, traditional oyster beds and sanctuaries, and living shorelines (NOAA Fisheries, 2014).

5.2 Diversification in production

Over 90 percent of the seafood consumed in the United States is imported from other countries around the world. NOAA Fisheries data show, however, that a significant portion of this imported seafood is caught by American fishermen, exported overseas for processing, and then imported back to the United States (Seafood Health Facts, 2016). While the size of the gap between domestic production and demand is difficult to determine, it is large and the expansion of production from aquaculture is seen as one of the most important pathways for closing it. The opportunities for growth and diversification of aquaculture in the gulf are influenced by many factors. All of these opportunities need to be considered against the backdrop of climate change.

Anderson *et al.* (2013) provide a comprehensive assessment of the impact of climate change on aquaculture in the southeast of the United States of America. They note that hypoxic events are likely to increase as a result of increased run-off, droughts and increased temperature, which will affect immune responses and growth. While

[56] Over 200 million US gallons.

southern Florida and the Gulf coasts of Louisiana and Texas already experience frequent and intense hurricanes, some analysts (e.g. Emmanuel, 2005) are predicting stronger and more frequent storm events due to increases in ocean temperature. This could have a devastating effect on aquaculture infrastructure, including boats, docks, equipment, processing plants and distribution centres.

Warming water may lead to an increase in waterborne pathogens associated with shellfish harvest and consumption. The human-pathogenic marine bacteria *Vibrio vulnificus* and *V. parahaemolyticus* are strongly correlated with water temperature. In the face of likely changing *Vibrio* concentrations with impending climate change and warming estuarine and coastal waters, food-borne infections could increase. Historically, oysters have been grown on and harvested from reefs on the water bottom. Oyster suspension, however, can significantly reduce some populations of potentially pathogenic *Vibrio* spp., and could be a viable approach for pre-harvest treatment to reduce illness in consumers of raw oysters (Cole *et al.*, 2015). State fisheries experts in Louisiana are have promoting off-bottom cultivation as a way to diversify the oyster industry. Once productive oyster growing areas that are now too salty – and thus too friendly to an oyster's predators – can be prime spots for off-bottom cultivation (McNulty, 2015). Off-bottom techniques also can better protect oysters from hurricane storm surges.

5.2.1 Species

An annual Florida Aquaculture Plan is authorized by statute to communicate the research and economic development needs of Florida aquaculturists to state government and the public (Aquaculture Review Council, 2015). The goal for identifying these priorities is to support public funding to conduct applied research that will create new technologies, improve farm productivity, diversify production, increase farm income and employment, and provide other benefits to the state of Florida. The applied research priorities are directed at providing answers biological or technical challenges that benefit aquafarmers raising aquatic plants, clams and oysters, crustaceans, alligators and turtles, and fish for food, aquariums, pond stocking, and bait. Florida's aquaculturists are adapting to change by investigating new species (e.g. marine ornamentals, molluscs, and food fish), new markets (e.g. biofuel), and new, sustainable production systems (e.g. alternative energy).

Since the 1998 Marine Aquaculture Industry Development workshop evaluation of 35 candidate marine fish species, Florida's research and commercial community has focused their efforts on the development and evaluation of husbandry and system technologies for seven marine fish species or species groups. These species are targeted for food, stock enhancement and ornamental production and include: cobia, Florida pompano, black sea bass, southern flounder, mutton snapper, spotted sea trout, common snook, red drum, and marine ornamentals (Florida Oceans and Coastal Resources Council, 2007). Nevertheless, the expansion of Florida's aquaculture industry is challenged by the high cost and limited availability of coastal land and water resources, environmental impact concerns, high production costs, and lack of sufficient quality fish seed stock.

5.2.2 Systems

On 11 January 2016, the National Oceanic and Atmospheric Administration (NOAA) announced the publication of a final rule implementing the Fishery Management Plan for Aquaculture in Federal Waters of the Gulf of Mexico. The rule allows for large-scale fish farming in offshore, federal waters of the Gulf beyond state waters where United States aquaculture has historically been conducted. In the United States, federal waters begin where state jurisdiction ends and extend out to 200 miles offshore. In this case, federal waters begin three nautical miles off Louisiana, Mississippi, and Alabama and nine nautical miles off Texas and the west coast of Florida. The rule authorizes NOAA Fisheries to issue permits for an initial period of 10 years for growing species for native, non-genetically modified and non-transgenic species such as red drum, cobia, and almaco jack (NOAA, 2009).

Although the opening of federal waters to aquaculture has been well received by industry representatives, on 12 February 2016, a coalition of twelve organizations representing fishery interests and environmental and food safety groups filed suit in the United States District Court for the Eastern District of Louisiana challenging the final rule (Center for Food Safety, 2016). The complaint alleges that industrial aquaculture is sufficiently different from fishing that NMFS does not hold permitting authority over its regulation. Rather, the complainants believe that it should be regulated more akin to farming practices. Opponents' major concerns are that escapes from aquaculture pens could affect wild populations through genetic modification or disease, and that operations will adversely affect the environment through waste and chemical contamination.

Mexican regulators are more open to offshore aquaculture than in the United States of America and now there's a major effort by Mexican offshore fish farmers and government officials to make their country 'the place' for raising fish offshore in North America (Lueing, 2015).

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PAPER 5

AQUACULTURE DIVERSIFICATION IN ASIA

Prepared by
F.B. Davy
World Fisheries Trust
Victoria, B.C., Canada
E-mail: fbdavy@gmail.com

1. INTRODUCTION: CONCEPTUAL STARTING POINTS

This paper argues that as a region Asia is, and will likely continue to be a major global aquaculture region. Better understanding of what is happening in Asia, and why, will likely provide critically important guidance for aquaculture planning for much of the future of aquaculture. It is also timely to examine the issue of aquaculture diversification, and FAO is to be congratulated for initiating this review.

Overall there is limited material looking at the aquaculture diversification issue. This review has therefore sought initially to look more broadly at a variety of selected diversification thinking with a view to guiding future understanding of aquaculture diversification including its definition, components and their implications. We therefore begin by examining lessons from agriculture and then move to analyze key drivers, some related economics and what we have called the many faces of diversification. Overall the hope is that the workshop, of which this paper forms a part, will seek to look increasingly at aquaculture diversification via this kind of wider lens, not only across global regions, but also across disciplines and scales (and perhaps other subdivisions). This case study first considers briefly some lessons from agriculture, particularly related to the post-Green Revolution, market-led diversification thinking.

1.1 Some lessons from Asian agriculture

Agriculture, with its longer history of dealing with diversification, offers an increasing variety of related (and perhaps more developed) learning, and this seems particularly the case in Asia. Using a mini SWOT[57] like review in developing the approach, my thinking has focused particularly on larger scale lessons on the macroeconomic side, for instance examining and understanding issues such as emergence of the more significant (or perhaps larger scale) change processes. I note the usefulness of emergence thinking (Kuperberg, 2007) for instance in aggregating outcomes at higher levels. In a way, emergence thinking sums the various interactions of individual aquaculture activities and agents whose actions are not easily compiled into such outcome linked change processes (sometimes with surprising outcomes). I argue that examining such larger scale changes offers critically important potential starting points for aquaculture diversification. This is particularly true given the longer history of agriculture/agriculture economics, in examining, for instance, the various thinking around key drivers.

The case study now takes a brief look some of these concepts, then moves on to look at some learning from the market-linked diversification of rice-based farming systems. Note, as one key conceptual point from such agriculture thinking, that "diversification is the single most important source of poverty reduction for small farmers in South and Southeast Asia" (FAO and World Bank, 2001). Small scale farmers have been and are still one of the predominant stakeholders in Asian aquaculture and therefore

[57] https://en.wikipedia.org/wiki/SWOT_analysis

diversification linked to small farmer interests is one important underlying theme. This theme will come up again in various ways throughout this paper; one key aspect of the way forward for aquaculture diversification should be examination of continued small farmer benefits.

1.2 Economics, key drivers and change

One must be cautious about generalization but the Asian case suggests that diversification has a strong economics link. In fact some would argue that diversification is really more about economics and particularly concepts such as emergence and perhaps development change processes (including what is changing, better understanding where and why it is occurring, key trends, underlying thinking and broader longer term process issues)[58]. This thinking and its links need to fit more prominently into diversification discussions. Such change thinking (Krznaric, 2007) also links well to the wider push pull developing in various Asian contexts. There is also continued environmental controversy, institutional change (fish for feed, pollution, climate change, food safety...the list is long!). So the change argument is linked to this need to develop better understanding of key diversification drivers, desired directions/ outcomes, improved prediction and anticipation of constraints.

The rice farm level diversification experience, for instance river deltas in Viet Nam, is one key example of this thinking (Jirström and Rundquist, 2005). Panarchy and resilience (Berkes and Ross, 2016) provide useful cross scale thinking regarding changes originating at higher levels of organization, where increasingly key drivers of change such as global market forces, national policies and other such changes have been shown to lead to significant impacts on sustainability (particularly at local levels). Additionally, many of our institutions do not adequately keep up with the increasing speed of development change, for example in small scale fisheries and feed safety certification processes; this will likely be the case for climate change.

1.3 Drivers, particularly markets as one of the key drivers

Subasinghe, Soto and Jia (2009) provide another useful starting point, "Markets, trade and consumption preferences strongly influence the growth of the sector, with clear demands for the production of safe and quality products". A variety of authors in agriculture point to the importance of market-led diversification often linked to changing diets, particularly shifts away from staples such as rice to a more diversified mix of products (e.g. meat/dairy products with increasing vegetables and fruits), often with more location specificity via strong market links, leading to increased farmer productivity and income and reduced environmental impacts. Related constraints to such diversification include access to inputs, credit and market and related knowledge; future research is suggested on improving crop choice decisions, for instance how to shift among crops (Pingali, 2005; Hengsdijk *et al.*, 2005), and the issue of local vs international market governance implications (Marschke and Wilkings, 2014; Demand, 2016). This market driver is particularly strong in Asia. As a consequence, increasing emphasis is likely needed on enhanced enforcement of regulations and better governance of the sector; "good governance" thinking (e.g. Garcia and Charles, 2008) will figure increasingly in many of the future scenarios around this set of issues. Similar shifts are suggested to be taking place in aquaculture but diversification specifics are little studied.

Most reviews suggest that present demand for Asian aquaculture products is strong (Delgado *et al.*, 2003) and that this demand is one of the key continuing drivers under

[58] We suggest that this diversification issue (however we agree on framing it) is and will continue to be a longer term process that needs to be pursued and FAO and its partners should stimulate follow up actions guided by our deliberations.

most future Asian scenarios, especially in the more rapidly growing economies in Asia. This assessment also notes that a variety of "broader changes" are already underway, though more visible in some cases than in others. These changes include stronger influence by developing countries particularly those in Asia, increasing "South-south" trade driven by a rapidly emerging middle class, more imports by countries in the "North" (see for example the later *Pangasius* case study), trade wars/controversy/price increases (also *Pangasius* case) and fish value increase in relation to other meat/food sources. Other related trends include shifts in purchasing behaviour as buyer incomes increase, parallel to similar trends in rice demand "leveling off" changes (Toriyama, Heong and Hardy, 2005).

There is a need for more detailed examination of related parts of this thinking, for example the roles of key actors (Callon,1999) driving such demand, as well as those actors feeding it and the likely implications and/or impacts related to perceived opportunities by farmers and related entrepreneurs in such food chains. It is also suggested that these extremely strong economic drivers will likely intensify in the Asian region and follow difficult to predict paths under various scenarios of increasing complexity. FAO and other agencies have an important opportunity to examine this set of issues and it is hoped that this workshop will be a critical next step in furthering this process.

This review also includes a macroeconomics orientation to demand-driven opportunities and diversification. As mentioned above, this is suggested to include further consideration of the history and importance of emerging key issues as well as the broader thinking around the rapid growth of certain Asian economies as critical parts of the drivers scenario in Asia. This includes the Asian economic tigers[59] and tiger club economies as well as the particular role played by overseas Chinese[60], parts of which we will examine later as part of one evolving Asian case study. There is a rapidly evolving opportunity in lessons that can be learned about emergence in aquaculture (see for example the thinking of OECD, 2016, De Silva, 2012, and Nguyen *et al.*, 2009) and how it is playing out in an increasing variety of ways.

Perceived market opportunities including new species is one of the main drivers. Asia is often characterized as a very market-driven high fish demand region, as suggested above, emergent changes are increasing at higher/different system levels, for example at the production-market system level rather than at the species level. Improved understanding of key actor perceptions of opportunities/constraints, for instance as outlined in the *Pangasius* case in Viet Nam and mitten crab in the People's Republic of China, is critical. Both are suggested as market-led examples of such shifts in aquaculture (and we note that both are mainly undertaken by relatively small scale farmers). We draw attention to the challenges concerning limited understanding of such change processes and such diversification strategies more generally, particularly supported by appropriate case material with data (both socioeconomic as well as biological production based).

There exists a strong and increasing demand that could lead to a variety of unintended and undesirable impacts/crises. Market pull and perceived economic gain are, and will likely continue to be key drivers in the Asian scene. We will develop this line of thinking further with a focus on emergent species thinking. Where possible we include some suggested proposed outputs: building on the above plus evolution of strategies, lessons learned from agriculture and others.

In summary, in terms of fish/aquatic protein demand/supply now and in the future, especially in Asia, market influence is suggested as one of the main drivers particularly in combination with change opportunities. In much of the work to date, this set of drivers does not seem to be examined much in terms of aquaculture diversification.

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[59] https://en.wikipedia.org/wiki/Four_Asian_Tigers
[60] https://en.wikipedia.org/wiki/Tiger_Cub_Economies

1.4 Change and change processes

Examination of change process thinking (Adger, Brown and Hulme, 2005) provides an improved understanding of the role(s) of such key drivers[61] particularly as part of a broadly based approach of the causal factors in aquaculture diversification. We outline below some further parts of this thinking, with an initial focus on larger scale activities/ changes associated with such drivers. Asia can be a critically important window for analyzing such changes given its unique high demand-led change processes as outlined above. As well Asia offers a powerful wider contextual set of learning opportunities from other sectors of agriculture.

1.5 Climate change as an increasingly important change process

Change, and climate change, as a process, merits more detailed examination, initially on the more macro issues and perhaps along the lines of work by the small scale fisheries community[62] or related networks in agriculture and changing diet choices related to population and income changes (Ranganathan *et al.*, 2016). Adaptive capacity building to allow farmers to adapt and diversify their more market linked production systems to cope specifically with climate related changes could play a critical next stage of this process, including understanding how such stakeholders are already dealing with change.

There are of course a variety of related aspects that should be considered. It is said that change is a given but in recent years aquaculture seems driven by more rapid as well as more profound changes. These changes seem increasingly difficult to predict and all have a variety of implications for aquaculture's future planning, and particularly for our better understanding of diversification and its implications for aquaculture sustainability. The next section outlines examples from the history of rice agriculture and Green Revolution case histories in Asia, including the shifting diet choices in such future scenarios.

2. THE MANY FACES OF DIVERSIFICATION IN AGRICULTURE, LINKS TO AQUACULTURE IN ASIA

2.1 Agriculture diversification thinking and trends

"In the agricultural context, diversification can be regarded as the reallocation of some of a farm's productive resources, such as land, capital, farm equipment and spaces to other farmers and, particularly in richer countries, to non-farming activities such as restaurants and shops. Factors leading to decisions to diversify are many, and include reducing risk, responding to changing consumer demands or changing government policy, responding to external shocks and, more recently, as a consequence of climate change"[63]. For comparative purposes note also that, in finance, diversification is "the process of allocating capital in a way that reduces the exposure to any one particular asset or risk. A common path towards diversification is to reduce risk or volatility by investing in a variety of assets. If asset prices do not change in perfect synchrony, a diversified portfolio will have less variance than the weighted average variance of its constituent assets, and often less volatility than the least volatile of its constituents"[64].

[61] Drivers of Change is a way of understanding the political economy of change and poverty reduction in developing countries. It directs attention to the structural and institutional factors likely to 'drive' change in the medium term, and to the underlying interests and incentives that affect the environment for reform. www.gsdrc.org/topic-guides/political-economy-analysis/examples/drivers-of-change-country-studies/ and Mcloughlin, C. (2014). Political Economy Analysis: Topic Guide (2nd Ed.) Birmingham, the United Kingdom of Great Britain and Northern Ireland: GSDRC, University of Birmingham.

[62] For one example see thinking such as http://toobigtoignore.net/research-cluster/global-change-responses/

[63] https://en.wikipedia.org/wiki/Agricultural_diversification

[64] https://en.wikipedia.org/wiki/Diversification_(finance)

Agriculture diversification takes a variety of other forms, for instance, the shifting out of rice farming is an increasing trend in post green revolution Asia in recent years. Crop replacement can involve a wider variety of often new market (emergent) crops e.g. pulses, vegetables, fruits, oilseeds, fibers, fodder and grasses.

The British Department for Food and Rural Affairs (DEFRA) defines diversification as "the entrepreneurial use of farm resources for a non-agricultural purpose for commercial gain." Using this definition, DEFRA found that 56 percent of the United Kingdom of Great Britain and Northern Ireland farms had diversified in 2003. The great majority of diversification simply involved the renting out of farm buildings for non-farming use, but 9 per cent of farms had become involved with processing or retailing, 3 percent with provision of tourist accommodation or catering, and 7 percent with sport or recreational activities and similar non farming trends are increasingly likely in aquaculture.[65]

2.2 Drivers of agriculture diversification on small farms: are there lessons for aquaculture?

The small farm/farmer issue is critically important in Asian aquaculture. Note, for instance, that "agricultural diversification is an important mechanism for economic growth. It depends, however, on there being opportunities for diversification and on farmers' responsiveness to those opportunities. Agricultural diversification can be facilitated by technological breaks through, by changes in consumer demand, or in government policy or in trade arrangements, and by development of irrigation, roads, and other infrastructures. Conversely, it can be impeded by risks in markets and prices and in crop management practices, by degradation of natural resources, and by conflicting socioeconomic requirements, perhaps for employment generation, or for self-sufficiency or foreign exchange earning capacity in particular crops or livestock or fishery or forest products"[66].

Concerning the opportunities for economic growth when farmers pursue such strategies, note in particular the importance of emerging market opportunities (Vorley, Lundy and MacGregor, 2009). New technologies, changes in consumer demand, changes in government policy or new trade agreements all present similar options. Of course the reverse is also true. India provides a wealth of interesting and innovative case material related to agriculture diversification. Examples include experimentation with crop diversification vs crop specialization, the many forms of cropping (e.g. multiple, intercropping etc), and the development of a whole set of "new emerging" crops, many of which seem to have spread in certain geographical Indian states/regions but not in others. However, most of these trends in Indian agriculture seem not to have been transferred to aquaculture in India or elsewhere in this wider region; some explanations lie in the time and place market linked thinking cited above. The evolution of market-driven small farmer experiences offers an interesting set of learning for aquaculture (see for example Taylor, 2005).

Other data suggest that small-scale farm operations do practice diversified farming including some cases from aquaculture, but appropriate census/field data from aquaculture operations are difficult to locate, particularly comparative data that look at advantages and or disadvantages of various diversification options for farmers practicing aquaculture. This seems particularly true for data comparable to agricultural census data covering seasonal crops, fruits, and vegetables, dairy cattle, and poultry (for instance in terms of maximizing household labour and income).

Agricultural diversification can assist in food security and improved human nutrition as well as increased rural employment. It also has been shown to improve

[65] https://en.wikipedia.org/wiki/Agricultural_diversification
[66] https://en.wikipedia.org/wiki/Agricultural_diversification#Definitions_of_diversification

soil fertility and reduce the incidence of pests. India, as mentioned, would appear to be a leader in much of this agro-climatic regional planning and therefore it may offer an interesting entry point for further examination of small farmer climate-related aquaculture diversification. In addition, tools such as the Simpson index of diversity (Keylock, 2005) (and related agricultural indices) do not seem to have been applied very often to aquaculture diversification. There are likely other lessons to be learned regarding rapid economic and income growth, urbanization and globalization, which in many parts of Asia have led to dietary shifts away from staples towards livestock and dairy products, vegetables and fruit, fats and oils. The tendency for per capita rice consumption to decline with income growth and urbanization has been documented extensively in some of this literature (Toriyama, Heong and Hardy, 2005) and suggests another line of thinking that merits examination by the aquaculture community.

2.3 Changes in farming systems linked to changing consumption patterns in agriculture

I now examine some lessons from agriculture diversification with a focus on lessons from "Green Revolution" rice-based farming systems mainly driven by shifts/drops in rice consumption. FAO projections indicate that the per capita consumption of rice will level off by 2015 and start to decline by 2030 (Pingali, 2007). The rice sector in Asia has the dual challenge of sustaining high rates of growth in rice productivity while at the same time transforming itself from a subsistence-oriented monoculture system into a more modern diversified market-oriented system. Milk offers a similar agricultural diversification model (Henriksen, 2009) with India as a very interesting case. It is likely that aquaculture will continue to undergo similar market-linked changes around related diversification strategies but few studies are presently available.

The diversification of rice-based farming systems in the post-Green Revolution period offers important lessons for aquaculture and poverty reduction. The three most important systems are the tropical lowland rice system, the rice wheat system, and the rain-fed upland systems accounting for about 80 percent of the agricultural production from about one half of the total agricultural area in Asia.

The tropical lowland and rice wheat systems are the dominant sources of rice supply in Asia. It was these systems that exhibited the most rapid productivity growth during the Green Revolution and their productivity continued to be high in the post-Green Revolution period. Paradoxically, it is these same systems which now seem to be facing the greatest pressures to diversify out of rice, due mainly to low prices relative to alternatives such as vegetables and linked to changing consumer trends and market choices. While Japan has chosen to support artificially high rice prices, other regions like India have moved into diversifying into other crops with the better market prices and profitability often associated with new nearby market opportunities. It this type of thinking that aquaculture needs to examine, and its relation to better understanding, and perhaps later guiding, shifting farmer crop choice decision making.

Upland areas, however, often continue to shift between rice and other crops, partly to reduce additional investment. In most cases it is the access to markets and the relative prices of rice and other crops, particularly other high value local market crops, that seem to be key drivers of diversification. As well it has been discovered that although roads and markets are important, it is really the proximity to urban areas and their markets that are critical, especially for fresh produce. Other research in Thailand (Ahmad and Isvilanonda, 2005) identified a variety of similar trends in agricultural diversification at the farm level, including its effects on farm income and the constraints faced by farmers in different regions and under different production environments. The aquaculture cases that follow illustrate some of the early stages of some of the above, especially intensification, new and evolving market opportunities and their links to the overall economic development and changing consumer demand in many of these “Asian tigers”. Overall there seems to be a variety of related aquaculture diversification changes parallel to those that have already occurred in agriculture, featuring moves away from traditional food crops to more commercial, plantation or horticultural crops.

It seems likely that aquaculture will need to examine many of the same agriculture questions, especially as demand levels off. The Mekong *Pangasius* case would seem to be approaching such a leveling off point. Mitten crab culture in the People’s Republic of China provides another interesting illustration of this farmer crop choice decision-making; here farmers pursued a new, often local, market opportunity in which diversification often took place from the traditional Chinese carp culture, utilizing nearby freshwater bodies, to culture mitten crab, a new species with strong local market sales in various parts of central China.

3. ASIAN AQUACULTURE CASE STUDIES

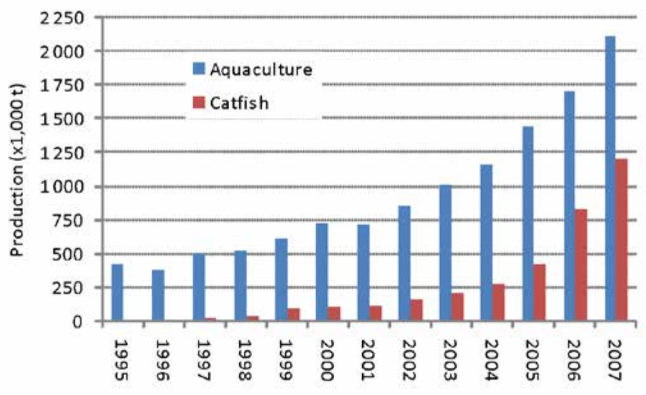
Pangasius catfish and mitten crab are examples having increasingly large scale impacts, strongly linked to perceived market opportunities. Each illustrates change processes in aquaculture that have and or are expected to lead to future larger scale changes. The *Pangasius* case, for example, concerns the export-led first species to reach the one million tonne milestone. The mitten crab case illustrates the more local fresh market shift from traditional Chinese carp culture, linked to the more profitable use of existing nearby water bodies. Both cases build on the thinking outlined in the earlier sections of this review.

3.1 *Pangasius* catfish aquaculture production in the Mekong River, Viet Nam

Pangasius (or just panga for short) is also called ca tra in Vietnamese, or the striped catfish or sutchi catfish, *Pangasianodon hypophthalmus* (De Silva and Phuong, 2011). Large numbers of Vietnamese farmers (and other value chain participants) diversified into this culture system; some switched from the former *Pangasius* cage/pen culture but the majority switched from other aquaculture and agriculture sectors (Phan *et al.*, 2009). It is difficult to find the desired diversification data on details of these shifts, but clearly the magnitude of the shift to *Pangasius* farming was well beyond that in any other aquaculture system to date. Perceived economic gain related to new, mainly export markets for a white fleshed fish, likely acting as the main driver. Better understanding of these drivers related to such change processes may offer important guidance in terms of aquaculture diversification, including guiding future responses to climate change. Sea level rise and saltwater intrusion are, for example, projected to occur in parts of the lower Mekong basin; however, major projected impacts on the Pangasius farming industry are unclear. A variety of studies are underway and genetics research on salt tolerant Pangasius strains are also being initiated (Kam *et al.*, 2012).

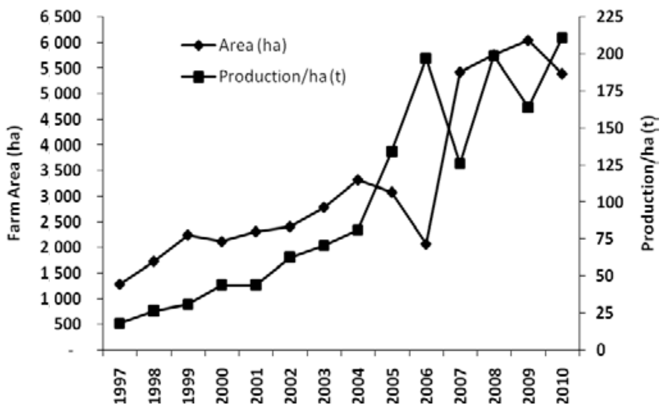
As mentioned, further analysis of the drivers associated with the shift to *Pangasius* farming is suggested (see Figures 1 and 2). Below are initial sample change process timeline data (Davy *et al.*, 2010; Phoung and Davy, unpublished manuscript) for the

FIGURE 1
Production of Pangasius striped catfish in comparison to total aquaculture production in Viet Nam



Source: courtesy of N.T. Phoung and S.S. De Silva.

FIGURE 2
Trends in the export volume of Pangasius catfish



Source: courtesy of N.T. Phoung and S.S. De Silva, based on data from VASEP, 2009, 2010.

crucial seed production and grow out components.

3.2 Mitten crab in freshwater bodies in the People's Republic of China; a new opportunity with upscale demand

Eriocheir japonica sinensis, the mitten crab, is an exotic species originally from Southeast Asia and introduced in various parts of the People's Republic of China. It is increasingly being stocked in cages and pens, typically in freshwater bodies formerly used for the culture of Chinese carp (Cheng et al., 2008). Chinese carp pond culture had been one of the long standing traditional fish culture

TABLE 1
Timeline of Pangasius catfish seed production development (a diversification change process example)

Date	Important Change Events
Prior to 2000	Striped catfish wild larval collection and nursery started in the 1940s. It became a key activity of a number of farmers after 1954. This activity provided seed stocks for home-pond culture until 2000, when hatchery-reared seed stock became available.
Late 1980s: initial research	Research on induced spawning of striped catfish was initiated in 1979. The first fingerlings were produced in 1979 by a joint effort of Long Dinh Vocational School, Nong Lam University. The initial successes could not be repeated and research activities were scaled down until 1995. The period of 1978–1980 could be considered as a starting point for research on induced spawning of striped catfish.
1995–1998: successful research	Research re-initiated in 1995 under European Commission of Can Tho University involving French Agricultural Research Centre (CIRAD), Research Institute for Development (IRD) France, Can Tho University and An Giang Fisheries Import-Export Join Stock Company (AGIFISH). The induced spawning technique was successful in 1995 with complete success in the following years.
2004-present: rapid growth	Striped catfish hatcheries, especially large-scale hatcheries from private companies were rapidly established. The hatchery operation technique was mainly transferred or consulted on by Can Tho University and Research Institute for Aquaculture No. 2. Striped catfish genetic improvement research was initiated in 2002 and the first batch of improved broodstock was obtained and introduced to some selected hatcheries. Recently, seed production of striped catfish can be done in most freshwater hatcheries in the Mekong Delta. The technique has also been introduced to other parts of Viet Nam.

TABLE 2
Timeline of Pangasius catfish grow-out development

Date	Important Change Events
1940–1950	Tra catfish culture in small-family ponds using wild fingerlings commenced in An Giang and Dong Thap provinces, up-stream of the Mekong river delta in Viet Nam.
1981 – 1982: trials of pond culture	First trials of tra catfish intensive culture in small ponds conducted by a farmer in Can Tho city using wild caught fingerlings.
1996 – 1999: expansion of pond culture and trials of cage culture	Tra catfish intensive culture in ponds expanded gradually to other provinces. First trials of tra catfish culture in cages (replacement of basa catfish) and pens were conducted as well. Both production systems used wild and hatchery-reared fingerlings.
2000–2004: rapid expansion of cage and pond culture	Tra catfish intensive culture in cages and ponds expanded rapidly. Hatchery-reared fingerlings met the demand for stocking. Productivity was significantly improved. Farmers gradually shifted from home-made feeds to commercial feeds.
2005-to present: high increase of productivity	Collapse of tra catfish cage and pen culture. There were significant improvements of pond culture techniques and remarkable increases in productivity. Introduction of sustainable production standards such as SQF-1000, AquaGAP, GlobalGAP and BMPs. The catfish farming sector (2009) supports 105 535 livelihood (full-time equivalents); an additional 116 000 people in the processing sector the bulk of which are rural women.

mainstays of aquaculture in the People's Republic of China as well as other parts of the Asian region. Mitten crab farming is a relatively recent aquaculture change process driven by the high demand for this species; yields have reached 3.4 × 105 tonnes (2002 data).

This case is chosen as one example of the high value market diversification shifts that have taken place over most of the People's Republic of China. The rapid growth of this culture system has led to a variety of water quality and related sustainability problems, leading to a reduction of yield and quality and subsequent profits (Wang *et al.*, 2006). Nevertheless this industry continues to expand into other freshwater bodies, particularly those close to large cities and related nearby markets, particularly for fresh product. There are few data available at present to allow a more detailed consideration of the diversification issue but it is suggested that this fast-growing species will offer a good test case for the future studies on these issues in Asia. Research related to understanding the tradeoffs and how and why farmers are choosing this species for culture may offer important insights related to earlier suggestions that the aquaculture sector needs to think about transforming itself from a subsistence-oriented monoculture system to a more market-oriented diversified system.

3.3 Future study: The CP agriculture/aquaculture business case

Future case studies could include an examination of the role of selected private sector actors – for example the often controversial case of CP[67] (Charoen Pokphand, or the CP Group) which is likely most responsible for the vertical integration of aquaculture (and agriculture) production, first in Thailand and subsequently elsewhere in this region. Diversification seems often driven by farmers increasingly pursuing emerging markets and the CP business model offers a variety of interesting angles to this driver thinking. Examples include country environmental response and organization (Hall, 2004) and links to overseas Chinese (Weidenbaum and Hughes, 1996)). Goss, Burch and Rickson (2000), and Lebel *et al.* (2002) outline various additional consequences that agri-food restructuring and the intensification of aquaculture may have, including the participatory control of such resources. A variety of personal field visits and key actor consultations confirm the strong emergence of the CP model. Farmer adoption of this business model seems to be increasing as well as spreading for various agriculture and aquaculture systems through much of South and Southeast Asia but few data are available, particularly around diversification questions.

4. PRELIMINARY CONCLUSIONS, AND A WAY FORWARD

There are many faces of aquaculture diversification. Next steps should focus on agreeing on appropriate definitions and priority ways forward. As noted in the opening section, diversification has been shown to be critical to poverty reduction and the Asian cases suggest this should be a stronger element of the aquaculture diversification next steps, for instance, in terms of enhancement of resilience (Troell *et al.*, 2014). Additionally, a focus on key emerging trends such as the macro change events (e.g. the next *Pangasius* case) offer important potential case material, particularly via wider socio-economic views (Degnbol *et al.*, 2006).

Future work is suggested around anticipating and coping with change, for example farmer diversification into much more market-oriented aquaculture systems. I have tried to capture other sector learning and outline links to a conceptual base built initially on a wider set of lessons from agriculture (with its longer history of diversification). I also suggest that more such crossover learning may be very useful in our continued aquaculture planning. The intent is to put some of these key issues on the table for discussion and use some of the larger-scale emergent cases that are now underway to

[67] www.cpgroupglobal.com/en

develop guidelines for future diversification strategies. For instance, examination of what kind of diversification futures might be of importance and interest to small scale famers concerned about climate change and adaption in various target areas.

Overall it is suggested that workshop outputs include documented discussion, and hopefully agreement, on key issues for follow-up and focus, perhaps including some sort of framework for next steps, including future targets, rough costs and if possible suggested funding sources. It is also suggested that an initial list of key future actors and actions for follow-up be developed. These might include FAO and some of the sources cited above plus a mix of other agriculture diversification experts, the Commission on Genetic Resources for Food and Agriculture, Bioversity International[68] selected private sector groups, as well as other key partners (e.g. WFC/other CGIAR centers, key regional organizations e.g. NACA, etc.), selected government departments as noted at various points above.

5. DIVERSIFICATION AND CLIMATE CHANGE: FARMER CROP CHOICE AND GUIDANCE MECHANISMS

This paper has focused more on the larger scale emerging changes and on understanding their often more pronounced economic drivers in the Asian socio economic context (including for instance learning from the potential lessons learned from other sectors such as agriculture). A variety of reviews have pointed out how climate change has and will continue to change agriculture production systems in difficult-to-predict ways, most of which are likely to present higher risks for small scale farmers in aquaculture.

A parallel for aquaculture may be found in climate-smart agriculture (CSA), an integrative approach to address these interlinked challenges of food security and climate change that explicitly aims for three objectives:

- Sustainably increasing agricultural productivity, to support equitable increases in farm incomes, food security and development;
- Adapting and building resilience of agricultural and food security systems to climate change at multiple levels; and
- Reducing greenhouse gas emissions from agriculture (including crops, livestock and fisheries)’.

6. ACKNOWLEDGEMENTS

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PAPER 6

ADAPTATION OF AQUACULTURE TO CLIMATE AND EXTERNAL FORCING IN AFRICA

Prepared by
R.E. Brummett
Senior Aquaculture Specialist
The World Bank
E-mail: rbrummett@worldbank.org

ABSTRACT

Aquaculture is highly flexible and adaptable to a wide range of environments, markets and investment levels from small ponds that produce a few kg of fish for home consumption up to high density raceways or cages that can carry hundreds of kg per m^3 destined for international markets. Ponds and reservoirs used in aquaculture are built for water storage, animal watering, flood control, irrigation and hydropower. Support for aquaculture development in Africa has varied from a donor-driven focus on very small scale operations for water harvesting and family food security to foreign private investment capital aimed at revenue generation from export. In the absence of a single, dominant motivation for undertaking aquaculture, Africa has exploited the adaptability of the aquaculture bundle of technologies to evolve a wide range of production systems that represent a microcosm of aquaculture globally and make the industry resilient in the face of change and other external perturbations.

1. TRADE-OFFS IN BASIC PRODUCTION SYSTEMS

1.1 Ponds

Ponds are the cheapest and simplest systems to build, the main problem being that they must be sited in areas where the soil is heavy enough to hold water and the topography has enough slope to permit complete draining without the use of expensive pumping[69]. Ponds also take up a lot of space as their carrying capacity seldom reaches 1 kg per m^2, being limited by the ability of the natural ecosystem to produce oxygen and absorb metabolic wastes. On the other hand, ponds make more efficient use of feeds and fertilizers and the more or less natural environment of ponds ensures healthy fish which can resist disease and grow efficiently on a combination of low-value inputs and natural foods (Figure 1).

Over 90 percent of current African fish culture is based on one or a few earthen ponds of generally less than 500 m^2 in surface area, constructed and operated with family labour (Satia, 1989; King, 1993). These ponds produce between 300–1000 kg/ha (15–50 kg per crop), on an annual harvest cycle usually corresponding to fingerling availability, water supply or local demand. About half of the output from these systems is consumed by the family and half sold or bartered to neighbours. Little of the crop is sold for cash, either due to lack of access to wealthier markets or out of a need to meet more local food security priorities (Brummett, 2000). In these systems, the fishpond plays a role similar to that of the chickens, pigs, fruit trees, herb gardens and other micro-enterprises undertaken by smallholders to generate small amount of cash for emergencies, school fees, etc. (Satia, Satia and Amin, 1992).

[69] Depending upon land value and/or water supply it can be cost-effective to use plastic liners in areas where pond construction would otherwise be impossible.

FIGURE 1
In 2005, the ponds of Kafue Fisheries near Lusaka, Zambia produced 10-12 tons of tilapia per month, primarily on inputs of pig manure

PHOTO: RE BRUMMETT

1.2 Raceways

Raceways (Figure 2) are round or elongated, usually built of cement, with water flowed through to bring in oxygen and remove metabolic wastes. Raceways take up less space than ponds, are easy to harvest and can carry as much as 100 kg/m^3 of *O. niloticus* (Losordo, Masser and Rakocy, 2001) or 400 kg per m^3 of *C. gariepinus* (Hecht, 1997). However, they are expensive to build and may involve pumping. They usually require a lot of water, although most of the outfall is of good quality and can be used for other purposes. Because there are no natural foods in raceways, the fish must be fed a complete diet. In addition, the artificial environment creates the potential for disease and mechanical damage to fish living in cramped quarters.

Recirculating systems are normally based on raceway technology with a filtration system installed to remove nitrogenous wastes, add oxygen and cycle the water back to the fish. These systems are very popular in areas close to big cities and/or where land and water are scarce and expensive. They are, however, complicated and expensive to build and operate and even short electricity failures can result in disaster. Also, being unnatural environments, the fish face the same constraints as in raceways, including the need for a complete diet. Raceways, recirculating or not, are expensive to build and thus of most interest to wealthier investors operating close to higher-end markets where they can recover their heavy investment and operating costs. The fact that they are relatively compact and self-contained, however, reduces their vulnerability to social conflict and other externalities.

FIGURE 2
Flowing water raceways such as these in A. Volta Lake, Ghana and, B. Bingerville, Côte d'Ivoire can hold more fish per m^3 than ponds, but require a ready source of high-quality water

PHOTO: RE BRUMMETT

FIGURE 3
The cages of Lake Harvest, Ltd. in Lake Kariba, Zimbabwe (left) and Tropo Farms, Ltd, in Volta Lake, Ghana

PHOTOS: RE BRUMMETT

1.3 Cages

Cages (Figure 3) come in many shapes and sizes depending upon the availability of materials, the type of waterbody into which they are installed and the amount of money available to invest. The number of cages that can be installed in any given waterbody depends upon depth, water current and wind velocity, all of which contribute to the circulation of water through the cage. Fish in cages lack access to most natural foods, so production depends upon the provision of a complete pelleted diet. Cages are easy to harvest and are modular so that cage systems can be scaled up as the farmer gains experience and the market grows.

In smaller waterbodies, cages have a big advantage over capture fisheries in terms of resource utilization. Instead of having a mixed flock of different species and ages, caged fish are all in one place so they can be easily fed and managed. The highest natural productivity of small waterbodies is no more than 300 kg/ha. The same waterbody used for fed cages would be at least 3 tonnes per hectare.

With thousands of small and large reservoirs and lakes in Africa, cage aquaculture has seen rapid growth in recent years. The cage industry in Ghana's Volta Lake has grown from virtually nothing in 2000 to nearly 10 000 tonnes in 2015.

Because they generally occupy open access waterbodies, cages are prone to vandalism and theft and often come into conflict with other resource users. A good deal of energy has gone into site selection and zoning of cages in other regions, lessons that would be wisely learned as Africa continues to expand the aquaculture sector.

1.4 Culture-Based Fisheries

In addition to forms of aquaculture where all aspects of production are controlled by a farmer, natural waterbodies can be stocked and/or fed to improve production. In Benin, traditional *whedoes* (Figure 4) are holes dug in floodplains that hold water and fish through at least part of the dry season. All over the continent, rural communities utilize natural small waterbodies, either temporary or permanent, for fish production. Often this simply involves the

FIGURE 4
A whedo in northern Benin. Whedoes, or fish-holes, hold residual water on floodplains through the dry season where fish shelter until captured

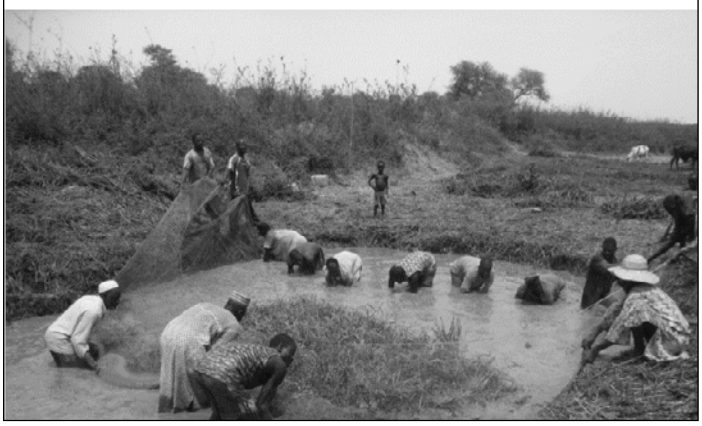


PHOTO: M. HAUBER

periodic capture of wild fish, but increasingly, productivity is being enhanced through the use of stocking or other aquaculture practices. In the Guinea rainforests, for example, controlled stocking of small dams (2 000 – 10 000 m^2) with or without fertilization is being used to increase typical background productivity of normally no more than 100 kg/ha up to between 600 and 2 500 kg/ha/yr (Oswald and Pouomogne, 2000). In the Lower Shire River valley of Malawi local communities stock otherwise fishless temporary waterbodies, locally known as *thamandas*, with fingerling tilapias and catfishes, producing an average of 600 kg/ha (range 300 – 1 575 kg/ha) in a 2–3 month growing season (Chikafumbwa *et al*., 1998).

In Niger and Burkina Faso, traditional reservoir management systems have evolved in the direction of restocking after annual drying with fingerlings of *O. niloticus, Labeo coubie* and/or *C. gariepinus* produced through artificial reproduction of adults captured at harvest and held over the dry season (Baijot, Moreau and Bouda, 1994), increasing productivity from 50–100 kg/ha/y up to over 600 kg/ha/yr.

These types of decentralized fish production systems could have broad applicability across Africa's vast dry savannah area, including all or parts of virtually every African country. While such extensive aquaculture may not be the most productive in terms of fish output, the additional benefits of water table replenishment, flooding and erosion control and possibilities for multiple uses such as livestock watering, emergency irrigation and capture fisheries could return substantial benefits to local communities and help in the fight against desertification (Roggeri, 1995).

2. SPECIES

In addition to flexible production systems, the species that dominate African aquaculture are themselves highly adaptable and resistant to poor feeds and water quality. The most widely cultured of these are the tilapias, mostly *Oreochromis niloticus*, and the clariid catfishes, mostly *Clarias gariepinus*.

The tilapias are famous for being tough. They can withstand long periods of low dissolved oxygen, low pH and high CO_2 without large negative impacts on growth rate. Under normal pond culture, they do not need aeration, although most commercial farming systems that stock more than 1–2 fish per m^2 have installed paddlewheels as dissolved oxygen of less than 2.0 mg/l can reduce economic performance, even if the fish do not die. Tilapias can withstand temperatures of up to 40° C, but are vulnerable to temperatures of less than 15° at which point they become highly susceptible to bacterial and virus diseases.

There are nearly 100 species of tilapia in Africa, many of which have been tested in aquaculture and a few of which have proven potential including *Oreochromis mossambicus and Oreochromis urolepis* from the Lower Zambezi and environs; *Oreochromis macrochir* in the South-Central and S-Western parts of the continent; *Sarotherodon galilaeus* in the Center and West; *Oreochromis andersonii* in the upper Zambezi and Kafue Rivers; *Oreochromis aureus* in the Nilo-Sudan zone; *Tilapia guineensis* and *Sarotherodon melanotheron* in the coastal regions of West Africa; *Tilapia rendalli* in South-Central; and *Tilapia zillii* in Northern and Western Africa; and *O. spilurus* along the Eastern coast (Figure 5). Many of these possess important culture traits for aquaculture: *O. andersonii* is a more placid and easily handled fish than *O. niloticus*; *O. aureus* is the most cold-tolerant of the tilapias and, when crossed to *O. niloticus,* produces all male hybrids that can be used in organic fish production; *T. guineensis* and *S. melanotheron* are tolerant of brackish water and the latter tends to mature at a later age than other species, potentially reducing the problems with precocious spawning mentioned above. *T. zillii* and *T. rendalli* are herbivores that can help control weeds in ponds.

Tilapias generally feed low on the food chain, targeting plankton, aufwuchs and benthic detritus. Their feeding behaviour is often disruptive to sediments and rooted plants, which can undermine water clarity and lead to pond bank erosion or even allow them to chew through cages and escape.

Nile tilapia are particularly territorial and thus tend to rapidly form distinct sub-populations, a characteristic that if reinforced by long-term geographical separation has led to a certain amount of genetic divergence (Nyingi 2007). Trewavas (1983) recognized seven subspecies of Nile tilapia in their natural ranges: *O. niloticus niloticus,* the largest group representing populations in West Africa and the Nile River valley; *O. n. eduardianus* in Lakes Edward, Kivu, Albert, and Tanganyika; *O. n. cancelatus* in Ethiopia; *O. n. barengoensis* in Lake Baringo; *O. n. vulcani* in Lake Turkana; *O. n. sugutae* in the Sugutu River of Kenya; and *O. n. filoa* in a hot spring in the Awash River basin of Ethiopia. An eighth subspecies was proposed by Seyoum and Kornfield (1992) from Lake Tana and, based on micro-satellite and mitochondrial DNA analyses, Nyingi (2007) proposed a ninth subspecies found in a warm water spring in the Loboi Swamp near Lake Bogoria in the Republic of Kenya. Overall, heterozygosity and gene polymorphism are relatively low in Nile tilapia compared to some other fish species. Nile tilapia easily hybridize with other *oreochromiines* both in the wild and in captivity, although some of these crosses produce sterile offspring or skewed sex ratios (Wohlfarth and Hulata 1983; Agnèse, Adépo-Gourène and Pouyaud, 1998).

If anything, clariids are even tougher than tilapia. The synapomorphic characteristic of the family Clariidae is the suprabranchial organ (Teugels, 2003), formed by folds of the second and fourth branchial arches. With this organ, which functions like a lung, *Clarias* species are able to practice aerial respiration and can thus tolerate very low dissolved oxygen and even survive long periods out of water, provided their suprabranchial organ remains moist. Even under conditions of dissolved oxygen saturation, Clariids rely on atmospheric oxygen for about 50 percent of their needs, increasing to 80–90 percent under low dissolved oxygen conditions (Moreau, 1988).

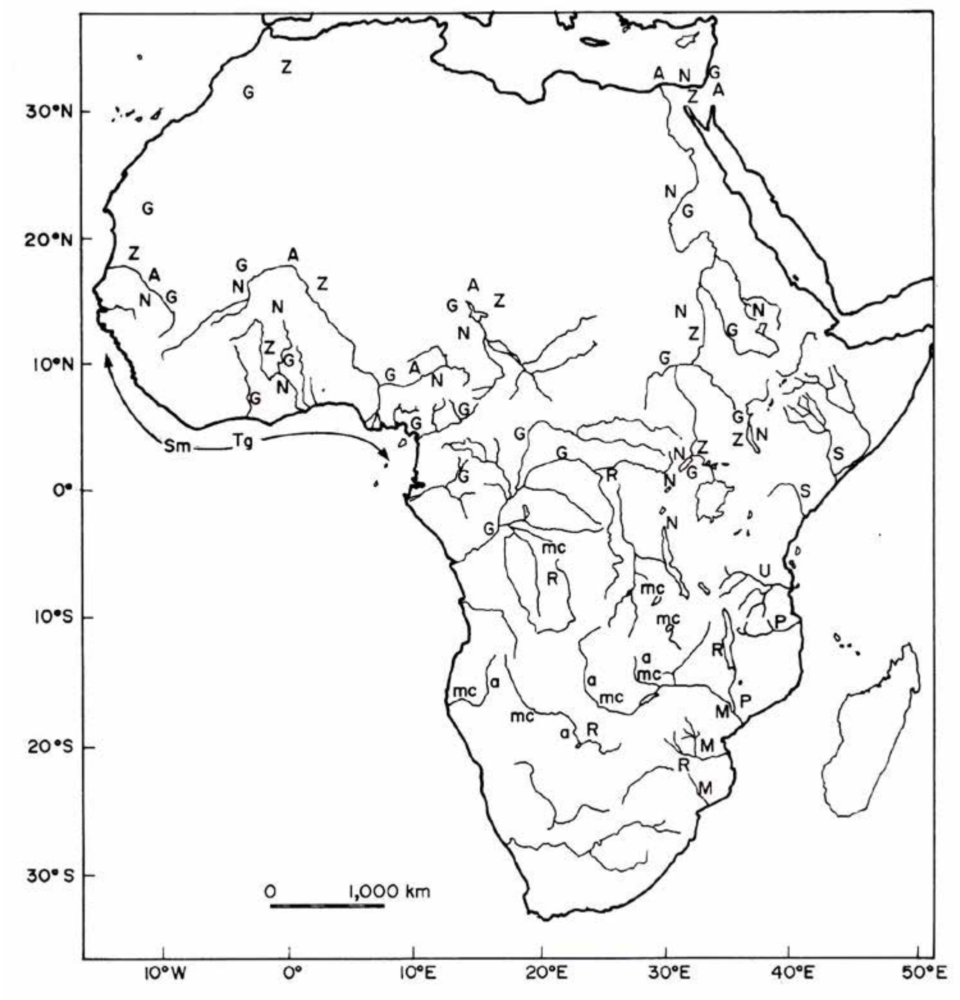
The main culture species in Africa are *C. gariepinus* (by far the most widely cultured) and to a lesser degree *C. anguillaris. C. anguillaris* and *C. gariepinus,* are very similar (Volckaert, Galbusera and Guyomard, 1995; Rognon *et al.*, 1998; Teugels, 1998; Teugels, 2003). Agnèse *et al.* (1997) found some evidence that *C. anguillaris* and *C. gariepinus* in the Senegal River hybridize naturally under certain conditions. Reaching over 1 m in length and 55 kg in weight (Skelton, 1993), the non-*Clarias* Clariid that has received the most attention by fishfarmers and is actually produced in a number of African countries, is *Heterobranchus longifilis*. Of particular interest has been the hybrid between *H. longifilis* ♀ and *C. gariepinus* ♂ first produced in the Republic of South Africa and commonly known as the "heteroclarias".

Clarias species occupy a wide range of habitats from cascading mountain streams and deep lakes to swampy holes. However, they are especially fond of slow-flowing lowland streams, shallow lakes, swamps, ponds, ditches, rice paddies and pools left in low spots after rivers have been in flood. Many species seem to prefer stagnant, muddy water, where their suprabranchial organ gives them a competitive advantage over species requiring higher concentrations of dissolved oxygen (Jackson, Marshall and Paugy, 1988). In larger waterbodies, *Clarias* seem to prefer marginal weedy areas (Daget, 1988; Welcomme and de Merona, 1988).

The ability to breathe atmospheric oxygen, the elongated body form and strong pectoral spines are used by *Clarias* species to wriggle over land and, coupled with the ability to leap considerable vertical distances, invade new waterbodies or escape from stressful conditions. Most such movement occurs at night.

Members of the genus *Clarias* are omnivores and are highly opportunistic feeders, taking almost anything they can fit into their mouths (Lauzanne, 1988). *C. gariepinus*, one of the more successful *Clarias* species based on extent of its native range, exhibits a variety of feeding strategies including sucking the surface for terrestrial insects and plant fragments washed into the water by heavy rains and pack-hunting of small

FIGURE 5
Natural distribution of tilapias used in aquaculture. M = *O. mossambicus*, U = *O. urolepis*, mc = *O. macrochir*, G = S. galilaeus a = *O. andersonii* A =*O. aureus*, Sm = *S. melanotheron*, *T. rendalli*, *T. guineensis*, Z = *T. zillii*, S = *O. spilurus*



Source: from Pullin, 1988.

cichlids (Bruton, 1979). Stomach contents of *Clarias* species typically include insects (adults and larvae), worms, gastropods, crustaceans, small fish, aquatic plants and debris, but terrestrial seeds and berries, and even birds and small mammals, have also been observed. Larvae are almost exclusively dependent on zooplankton for the first week of exogenous feeding (Hecht, 1996). Although generally omnivorous, *Clarias* spp. are relatively better at digesting high-protein diets than carbohydrates (Wilson and Moreau, 1996).

3. ECOSYSTEMS FOR AQUACULTURE

Vulnerability to externalities depends to a large extent on the ecosystem in which aquaculture is being conducted. Communal waterbodies are inherently vulnerable to risk from alternative uses, particularly during droughts when smaller lakes may disappear entirely, concentrating usage on fewer, larger lakes. Fresh water generally is in short supply in many parts of Africa and may become more so with climate change. Marine ecosystems are vulnerable to rising sea levels and increasingly violent storms predicted by climate change models.

3.1 Fresh water

All food production systems require water. Conflicts over access to increasingly scarce resources occur in almost all African countries. Fish production, being conducted entirely underwater, would seem to be potentially one of the greater consumers. However, consumptive use of water by aquaculture is, in theory, negligible. Also, aquaculture has the advantage over rainfed plant crops of being somewhat disconnected from rainfall periodicity. Through the use of recirculation technology and/or integration of cage aquaculture into other water use schemes, consumptive use of water can be reduced even further to the amount lost to evaporation and leakage, which, in water-stressed areas are often controlled with the use of plastic liners and/or greenhouse-like covers.

Overall, commercial freshwater aquaculture probably uses something on the order of 5 000 l of water per kg of fish produced (Table 1), although most of this use is non-consumptive, being either directly usable for other purposes or indirectly usable following settling or biofiltration to remove excessive nutrients and/or suspended solids.

TABLE 1
Water requirements for some aquaculture systems of relevance to Africa

Species	System	Production (mt/ha)	Water Requirement (m^3/mt)
Clarias batrachus	Intensive, static ponds	100–200	50–200
Oreochromis niloticus	Extensive, static ponds	0.05–0.3	3 000 – 5 000
O. niloticus	Sewage, minimal exchange ponds	6.8	1 500–2 000
O. niloticus	Intensive, aerated ponds	17.4	21 000
C. carpio/O. niloticus	Conventional ponds	3	12 000
C. carpio/O. niloticus	Semi-intensive ponds	9	5 000
C. carpio/O. niloticus	Intensive ponds	20	2 250
C. carpio	Intensive raceways	1 443	740 000
Ictalurus punctatus	Intensive ponds	3	6 470

Source: Phillips, Beveridge and Clarke, 1991.

3.2 Mariculture

Aquaculture in marine or brackish water ecosystems can avoid conflicts with other sectors over use of freshwater, but good coastal sites for mariculture are scarce in Africa. Offshore cages of the type used in salmon farming could be deployed, particularly in the relatively calm Gulf of Guinea, but this expensive technology will only be available to the largest scale of producer and would be, for the foreseeable future, dominated by foreign investors who already have the know-how, capital and markets necessary for success. Also, piracy is rampant along both the eastern and western coasts of Africa and offshore floating cage installations are hard to hide.

In addition to a general lack of good sites, larval rearing is a major problem for most marine species. As the eggs and fry of marine fishes tend to be very small, they are difficult to feed and protect from predators, requiring sophisticated, usually land-based, hatchery facilities with attendant high land values and expensive pumping costs. Also, the majority of marine fish culture candidates are carnivorous, requiring high quality (i.e., high protein with a large fishmeal component) feed. Not only is such feed expensive but, in a continent with chronic food insecurity, the decision to feed forage fish (in the form of fishmeal) to carnivores destined for high-end, usually export markets will be politically difficult to justify.

Globally, one of the most successful types of mariculture is the production of penaeid shrimps in coastal ponds, often carved out of mangrove forests. The Federal

Republic of Nigeria, the Republic of Kenya, the Republic of Senegal and the Republic of South Africa have all experimented with shrimp culture. Expansion of shrimp culture in the Republic of Mozambique has taken advantage of existing processing infrastructure and market development investments made by the large, but now generally defunct (due to over-fishing) shrimp fishing fleet. Several large farms currently operate along both sides of the Mozambique Channel.

Seaweeds benefit from natural fertility to produce valuable export products using relatively simple technology to the benefit of the local population. In the United Republic of Tanzania, especially Zanzibar, 7000 tonnes of *Eucheuma* seaweeds are cultured by an estimated 20 000 small-scale growers in satellite production schemes. Production technology is relatively simple, being based on algae seedlings attached to a network of wooden stakes and monofilament anchored onto tidal flats. Producers can earn about twice the average income of an entry-level civil servant. With global trade on the order of 250 000 tonnes per annuum (TPA) (and rising) and an average wholesale price of about US$900 per tonne, African producers could be competitive, but good sites are scarce. The Republic of Namibia, the Republic of South Africa, the Republic of Senegal, the Republic of Mozambique and the Republic of Madagascar have all piloted seaweed production of various types, but their total annual production does not exceed 200 tonnes, combined (FAO, 2007). Although the lack of suitable sites is a major constraint to the expansion of seaweed farming, seaweeds can be effectively grown in relatively polluted waters where they have been shown to remove up to 90 percent of excess nitrogen, serving as an effective biofilter (Troell *et al.*, 2005). With some modifications of the current production system, seaweed culture could be adapted for use in such areas as the heavily polluted West African lagoons.

Another group of marine organisms amenable to relatively low-tech culture techniques is the filter-feeding bivalves including, mussels, clams and oysters. African bivalve culture is dominated by the Republic of South Africa, which produces about 2 500 TPA of mostly Mediterranean mussel (*Mytilus galloprovincialis*). The Republic of Namibia, the Republic of Senegal and the Republic of Mauritius have pilot bivalve farming projects, but together produce less than 150 TPA. As bivalves feed on and accumulate particulate matter, including pathogenic bacteria and viruses, they must be reared in sites protected from contamination by human or animal wastes. Bacteria can be effectively removed through depuration in clean running water for 48 hours. Viruses and vibrios, particularly Hepatitis A, cannot be effectively removed through depuration (Pivirotto, 1993). As with other types of mariculture in Africa, the main constraint to the expansion of bivalve mariculture is the shortage of suitable sites, especially protected bays away from sources of human pollution.

4. ADAPTING TO FUTURE CHANGE

Unlike other regions where a single production system has evolved over large areas in response to markets or other incentives, African aquaculture has grown in response to highly variable signals from markets and governments. There has been little to no consistent government support for aquaculture, which is perceived as a low priority compared to public health, schools, agriculture (of staples), etc. Aquaculture has either been left to local people to undertake as they see fit, or to international donors preoccupied with food security for the “poorest of the poor” or other humanitarian priorities. In both cases, aquaculture has diversified over space and time to take advantage of local and sometimes temporal opportunities.

While this diversity has made it difficult for African researchers and extension personnel to provide simple messages to farmers, arguably one key reasons why aquaculture has failed to keep up with the sector elsewhere (Brummett, 1994), it has also built into the African aquaculture sector a natural adaptability and, among farmers, a basic understanding of the principles of aquaculture that might be less obvious to

FIGURE 6
Recirculating pond aquaculture system in Vilanculos, the Republic of Mozambique

farmers who have been able to make money farming fish by following a tested formula.

As climate change accelerates, this ability to match production system design to prevailing conditions might protect the industry in Africa, while it struggles to adapt elsewhere. Copying technology from places where aquaculture has a longer history and greater overall productivity has been a major feature of African aquaculture in the past, and could well play an important role in the future.

Such innovations as the use of plastic greenhouses (Figure 6) is spreading in the Republic of South Africa and other areas where temperatures are seasonally too low for optimum production. Combined with relatively simple recirculating technology, these enclosed greenhouses can also serve to conserve water in dryer areas.

Many of the small family ponds that currently serve as a buffer against short term famine might in future play a more important role in long-term survival, especially for poorer, more isolated communities. Few of the inputs for artisanal aquaculture are purchased, productivity being based almost entirely on composts, manures and other organic materials found on the farm and recycled through the pond. The best fish productivity in such systems is about 1500 kg/ha/yr, mostly of small tilapias (Brummett and Noble, 1995). These “farmponds” are generally integrated into other food production systems such as vegetable gardens where they serve as sources of emergency irrigation water and as bio-processors for by-products and wastes, turning low quality materials into valuable fish at minimal cost. In Malawi, farms with integrated fishponds produce almost six times the cash generated by the typical smallholder (Brummett and Noble, 1995). Similar systems exist throughout the continent, producing thousands of tonnes of fish annually for rural families.

Diversifying a smallholding by integrating aquaculture can also affect the ecological sustainability and economic durability of small farms. In Malawi, a serious drought from 1991 through 1995 had a major negative impact on smallholding agriculture. Yet in all cases studied, even though staple crops failed and farmers lost money, the integrated fishpond sustained the farm. By retaining water on the land, ponds enabled farms to continue food production and balance economic losses on seasonal cropland. For example, in the 1993/94 season, when only 60 percent of normal rain fell, average net cash income to integrated farms was 18 percent higher than to non-integrated farms (Brummett and Chikafumbwa, 1995).

In areas with high population pressure, integrated aquaculture systems can help keep people alive and on the land, producing food for themselves and their communities. However, because they generate minimal cash revenues and therefore no liquid capital for reinvestment and expansion, especially the purchase of inputs, they create little or no economic growth (Delgado, Hopkins and Kelly, 1998).

Having said that, for most farmers and communities, the best insurance against any external perturbation is money in the bank. One of the main drivers of the recent surge in African aquaculture is the profitability of systems based on local species, technology and markets. The dramatic growth of the sector in the Republic of Ghana, the Federal Republic of Nigeria and the Arab Republic of Egypt is evidence that farmers searching for credible investment alternatives will adopt aquaculture if it can be proven to work under local conditions. As African aquaculture continues to grow, it will continue to exhibit the characteristics that have so far made it unique: high variability and adaptability in the face of a lack of quality extension, weak research and low quality inputs. With these skills the African aquaculture sector can be expected to continue to grow despite climate change and other externalities.

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Native mangrove oyster culture diversifies livelihoods in Northeastern Brazil

PHOTO CREDIT: WORLD FISHERIES TRUST

PAPER 7

PATHWAYS FOR AQUACULTURE DIVERSIFICATION

Prepared by
Joachim Carolsfeld
Executive Director
World Fisheries Trust
E-mail: yogi@worldfish.org

María-Alejandra Faría
Project Manager, World Fisheries Trust
E-mail: maria@worldfish.org

and

Guy Dean
VP/CSO Albion Farms and Fisheries Ltd.
E-mail: guy.dean@albion.ca

1. INTRODUCTION

The fast-growing contribution of aquaculture to food supply for an increasing population and increasing appetite for fish and shellfish is well known. Aquaculture has been promoted as a means to relieve the fishing pressure on wild stocks, introduce new items to the global palate, produce pharmaceuticals and biodiesel, and provide livelihoods. In this fashion, it is both an ancient art and a "*futurist*" activity in the food, economic, and development sectors, and is diversified in a variety of ways. Challenges faced by aquaculture and its growth are similar to those of agriculture and include biological idiosyncrasies of aquatic organisms, expectations of sustainable environmental and social practices, as well as the risks and opportunities of climate and social change.

An objective for the FAO is to promote and provide guidelines for sustainable aquaculture development so that farmers and communities prosper and people are healthier. The worldwide aquaculture sector, including small and large scale producers and all the links in their value chains, often refer to FAO guidelines, statistics, trend reports and recommendations that inform policies and legal frameworks in many countries.

Climate change is increasingly recognized as likely to generate serious risk to human survival, including the expectation of impacts on aquaculture that are still largely unclear. Greater diversification has been proposed as a strategy to increase preparedness for such impacts, reducing associated risks – also referred to in the climate change literature as adaptation. Assessing the current status of diversification in aquaculture, and its potential to address risks such as climate change, is the purpose of this workshop. Drawing on comparisons of diversification in other fields of human endeavor and ecological systems, our chapter examines the triggers, enabling factors and drivers for the different types of diversification in aquaculture, including consideration of what is needed to foster its expansion.

1.1 Current levels of Aquaculture Diversification

There are about 567 aquatic species currently farmed in the world (FAO, 2016). Aquaculture is practiced by the poorest farmers as well as affluent multinational companies, in rivers, lakes, dams, coastal areas, open oceanic areas, and in closed and semi-closed systems. Diversity in various forms is thus already a reality in aquaculture, providing options that improve the ability to meet demands of diverse markets, producers and economies and thus a key component of its evolution.

Specialization, on the other hand, focuses on some of these options and provides comparative advantages that consolidate opportunities. This is also an essential ingredient of development (Rodrik, 2005 in Kaulich, 2012). Diversification and specialization, and their interplay, build economic and social profitability as well as resilience to economic, social, and environmental volatility.

MARM-Spain (2011) and Moehl (2013) suggest that aquaculture diversification contributes both to growth and resilience through:

- distribution of risk,
- access to new market opportunities,
- occupation of a wider geographic area or hydrological region,
- different opportunities to complement an existing supply,
- expansion through new economically viable species,
- increased productivity with diversified technologies,
- attraction of funds for Research and Development (R&D),
- contribution to the development and strengthening of the scientific and technological management, logistics and management of aquaculture.

Nevertheless, adoption of new species or technologies in aquaculture is often a considerable challenge, even once technological stumbling blocks have been overcome and scientific analysis has predicted suitability for culture. Understanding this challenge is a key component of promoting diversification. We feel that examination of how diversification fares in other spheres of human endeavor is illuminating in this regard.

2. DIVERSIFICATION IN DIFFERENT SPHERES

2.1 Financial, business and macro-economics

The word diversification is widely used in the financial sector to define a risk-management technique that mixes a wide variety of investments within a portfolio in order to minimize overall volatility.

Many kinds of businesses have applied this concept of diversification to either expansion or scale-up. For example, spatial or geographical diversification of production is a common risk-management tool used by companies. According to Oglend and Tveteras (2009), this tool seems especially relevant for companies who value risk reduction to such a degree that they are willing to give up some potential returns. The returns from diversification come in the form of a reduction of profit risk primarily through reduced output risk. However, diversification may also reduce the probability of high profits of a successful, more focused specialization. On average, diversification generally comes at the cost of reducing expected short-term profits.

Oglend and Tveteras (2009) suggest that diversifying production can lead to over-investment in businesses with poor investment opportunities (Stultz, 1990; Rajan, Servaes and Zingales, 2000) in addition to increased costs of information sharing in divisional *vs* central management. In a study of diversification in the United States during the period of 1986–91, Berger and Ofek (1995) found that diversification reduced the average value of a company by 13–15 percent. Langemeier and Rodney (2000) found that amongst Kansas farms during the period 1982–2000, specialization increased the mean return on equity, but also increased the variability of returns. There is, however, also evidence that diversification has a positive effect on a company's value. Claims have been made that highly diversified companies have benefits from multiplan economies (Beckenstein, 1975), reduced incentive to drop on-going projects, larger debt capacity, lower taxes and benefits from managerial economies of scale and internal capital markets (Chandler, 1977). Further, one might argue that firms operating in markets where stability and predictability of supply are highly valued will be rewarded with a higher chance of survival. Pope and Prescott (1980) examined the connection between farm size and specialization. By using four measures of diversification, they found that larger farms are more diversified, and that wealthier and less experienced farmers are more specialized. This strengthens the claim that diversification comes at an economic cost but provides a higher survival rate for companies in the long run.

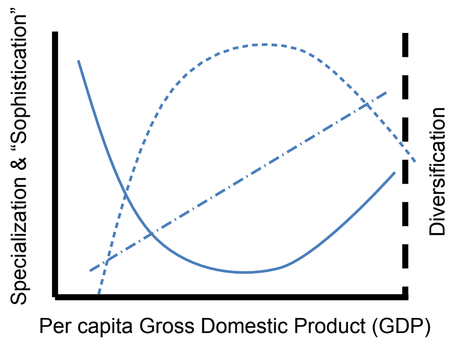
From a macroeconomic perspective, according to Kaulich (2012), the most straightforward argument for diversification is that diversified economies are less vulnerable to economic shocks. Osakwe (2007, p. 1) argues "Although there are good theoretical arguments for specialization to build comparative advantage, in practice policymakers in developing countries are interested in diversifying their production and export structure to reduce vulnerability to external shocks." Moreover, more diversified economies are less volatile in terms of outputs, and lower output volatility is associated with higher economic growth (Ramey and Ramey, 1995).

UNIDO (2009) and Kaulich (2012) summarize research by Cadot, Carrere and Strauss-Kahn (2009) on the relationships between per capita Gross Domestic Product (GDP) and diversity, "sophistication"[70], and specialization in export products of 159 countries between 1988 and 2004. Diversity and specialization show inverse "U-shaped" curves, while "sophistication" rises throughout (Figure 1). The authors interpret this as meaning low-income, slow-growing countries export few and less sophisticated products, but grow by expanding their diversity. At a per capita GDP of approximately US$22 500, countries then start to specialize in fewer products produced with greater sophistication, and high income countries tend to have a limited set of specialized, highly sophisticated products (UNIDO, 2009). The implication for low-income countries, in particular, is that they can overcome economic marginalization through the acquisition of skills and knowledge necessary to diversify their economic portfolio rather than focusing only on "what they do best", while high-income countries benefit more through specialization – presumably having settled into a market niche that best suits the country's production conditions. This empirical evidence indicates that while policies of low- to middle-income countries, particularly those with natural resource endowments, may strive for diversification of the economy to hedge against volatility (de Ferranti *et al.*, 2002), higher income countries are more specialized and potentially more susceptible to destabilizing impacts. "Sophistication," in this report, is considered as a PRODY index, calculated as the average income level of countries producing a particular product. By definition, an average linear rise with GDP is expected, as shown in Fig. 1.

Could we expect the same trend in aquaculture development at a macroeconomic level or at local levels? Is a country's aquaculture production initially of low diversity, then, as the income becomes better it diversifies and then re-specializes as income keeps growing? How does this relate to the decisions of individual farmers or companies and policy development?

Both similarities and anomalies appear evident. Results of the present workshop suggest that diversification trends are primarily market-driven, though early stages in developing countries may be skewed by international development projects. For example, the Kingdom of Spain, a country with a per capita GDP 3.5 times lower than the one estimated for

FIGURE 1
Relationship between per capita GDP and diversification (dotted line), specialization (solid line), and sophistication (dash-dotted line) of export products



Source: adapted from UNIDO, 2009.

[70] PRODY index describes "sophistication" of a product as a function of the average income level of producing countries.

the Kingdom of Norway (World Bank, 2013), is more diversified in its aquaculture production. Much of the diverse aquaculture in this country serves an internal market, while exported products are relatively few and specialized (Polanco and Bjorndal, this volume). Decisions by individual farmers and companies in a mature marketplace no doubt are driven most by the perceived market opportunities, both domestic and export, modulated to some extent by policy-based funding opportunities. The importance of policy-driven diversification, supported by funding, is likely greater in less mature markets that are "experimenting" with potential products. In this sense, aquaculture development probably also follows the "U" development curve, modulated by the richness of domestic markets.

"Sophistication" of the UNIDO report is particularly interesting when low GDP countries are producing products that are more characteristically produced in high income countries. In aquaculture, specialized technology packages, as in salmon culture or intensive tilapia culture, are interesting examples of this, representing economic diversification for low-income countries, geographical diversification for international companies, and technological specialization with respect to species and technology. Social and environmental aspects of this approach to aquaculture development remain equivocal.

2.2 Ecological and social systems

The diversification concept also has parallels in ecology. Species diversity is thought to be the key for resilient ecosystems in the face of disturbance (Peterson, Allen and Holling, 1998; Cleland, 2011). Notably, this concept does not suggest improved survival of individual species, but resilience of ecosystem functionality despite the loss of some species.

The development community promotes social diversification of livelihoods as a pathway to resilience and poverty alleviation, including in small-scale fisheries (APFIC, 2009). However, the effectiveness of a diversification approach to building resilience at a household level has been questioned, with Van Kien (2011) finding no benefit from diversified livelihoods in recovery from flooding in Vietnamese villages of the Mekong Delta; Liao, Barrett and Kassam (2014) found no benefit from diversification to the welfare of pastoral people in the People's Republic of China. Start and Johnson (2004) suggest that diversified livelihoods are most appropriate for unstable or transitional economies. Livelihood diversity, plotted against a scale of developing economies, may also show a "U-shaped" relationship as seen in Figure 1.

Ecological models have been used in the design of aquaculture systems, for example polyculture, to make more complete use of a culture system and/or to decrease environmental impact of a culture system, though Brummet (this workshop) warns that the actual costs of complex polyculture or multi-purpose aquaculture systems make them impractical for low-income applications and unattractive for industrial farmers. New technologies may also make use of other nature-inspired designs (Edwards, 2015). However, these are rarely considered in the sense of diversification for increased individual resilience, rather for improved efficiency, productivity, or social licence. No studies are available assessing the resilience of country-level aquaculture due to diversity in its aquaculture portfolio.

Aquaculture continues to be promoted in developing countries as a diversification option for small-scale farmers or, in the case of landless poor, as an opportunity for communal subsistence or income generation. As described below, the effectiveness of this approach is equivocal and depends on appropriate socio-economic and cultural environments. Similarly, diversification of the aquaculture of existing farmers and farming companies (*vs* specialization/intensification) appears to depend on market opportunities, and rarely on consideration of resilience (Myrseth, this volume).

2.3 Agriculture

In the agricultural sector, diversification has been used to reduce risk and to respond to changing environments due to government policies, market fluctuation and climate; the concept also includes diversification of income and activities of the farmers (DEFRA, 2012).

According to Culas and Mahendrarajah (2005), farm diversification has been considered as a way to spread the risk that farmers might confront. The same authors find that farm diversification can be a way to attain certain policy objectives other than to spread risk (ie: alternative income sources and income stability, employment opportunity, efficiency in agriculture, environmental and natural resources management, rural peri-urban development). The same principles are likely applicable to aquaculture farms and development.

According to the FAO (2003), agricultural diversification is an important mechanism for economic growth in developing countries. It depends, however, on there being opportunities for diversification and responsiveness by farmers to these opportunities. Agricultural diversification (and expansion) can be facilitated by technological breakthroughs, changes in consumer demand, government policy or trade arrangements, and by development of irrigation, roads, and other infrastructure. Conversely, it can be impeded by reluctance to change in the face of risks of markets and prices and conflicting socio-economic factors – cultural norms, income generation, self-sufficiency or export of existing products supported by the status quo.

Adoption of aquaculture as part of agricultural diversification is a common proposal for international development promoting improved livelihoods, food security, and poverty alleviation. Bene *et al.* (2016) identified two forms of this aquaculture development: "immanent" systems, whereby aquaculture emerges in response to demand, and "interventionist" systems, in which external agencies support the promotion of predominantly small-scale subsistence aquaculture systems (Brummett, *et al.*, 2011; Little *et al.*, 2010; Belton and Little, 2011). His review suggested that these two forms do not necessarily make the same contributions to economic growth and poverty alleviation. Only a few critical studies have challenged the established view that donor support to small-scale subsistence aquaculture alleviates poverty in Sub-Saharan Africa (Muir, 1999), or even in countries such as Bangladesh, where smallholder aquaculture is widely practiced (Belton, Haque and Little, 2012). Nevertheless, small-scale aquaculture can be a good complementary option to improve the income and productivity of poor and medium income farmers (Brummett *et al.,* 2011), and potentially their resilience. Diversification of this aquaculture, once adopted, is discussed below.

3. WHAT ARE THE REQUIREMENTS, COSTS AND BENEFITS OF AQUACULTURE DIVERSIFICATION?

Wilson and Archer (2010) suggest that diversification could be used as a tool to look at risk management for aquaculture businesses at any scale. Driver and constraint type and how these may or may not influence the outcome will depend on the scale of the aquaculture farm or development, though these authors feel that the drivers are inadequately understood. Diversification in addition to production could be a key factor to increase income, profitability, and sustainability for a small-scale aquaculture business. For example, small-scale aquaculture could be making money from aquaculture-related businesses (diversification), not just from growing fish (specialization). In fact, fee-fishing, restaurants, and value-added processing are common elements developed by entrepreneurial small-scale fish farmers throughout the world (Brummet, this workshop).

At the individual level, aquaculture development as a business generally takes the form of sequential adaptation to reduce immediate risk and/or optimize returns (e.g.

Moehl, 2013). Cumulatively, however, it represents an increased, diversified, portfolio of aquaculture skills and options. In this sense, diversification at the farm level may be an adaptation process, looking very much like specialization. This could be analogous to the diversity in natural ecosystems, where overall system resilience over the long term is afforded by a diverse set of specialized components. Individual resilience may be compromised in this view, unless offset by a capacity to switch to other specialized modes.

Gonsalves *et al.* (2015) suggested aquaculture diversification as one of the strategies for adaptation to climate change in Asia, as well as to reduce carbon emissions by farming species lower in the food chain. This appears to be an example of responsive research rhetoric more than a demonstrable practical approach, but highlights the importance of marketing drivers at all levels of the diversification movement.

We see diversification affecting small-scale aquaculture, largely in developing countries, differently from its effect on larger scale aquaculture, mostly based in developed countries.

3.1 Small scale aquaculture

There is great perceived potential to alleviate poverty and improve food insecurity of small scale farmers through the addition of aquaculture income or protein. Integration with other farm activities through the use of farm byproducts, irrigation ponds, and otherwise marginal areas is generally part of this proposal. Likewise, culture-based fisheries or cage culture in public water bodies is promoted as an option to provide opportunities for landless poor. These small-scale aquaculture initiatives are considerably diverse at a global level, though based on a relatively limited technical tool-kit. Most diversify and supplement agricultural or other income and (i) integrate into an existing farming system or family livelihood (i.e. stocking of water storage ponds, integration with rice or small livestock); (ii) are dedicated, small-scale, low investment systems (ie: small fish cages in water bodies, seated lines, staked culture of oysters and mussels, small fish ponds); and (iii) are highly adaptive (ie: fitted to families' resources and time).

In practice, the success of these approaches in alleviating poverty is equivocal, except in traditional fish-farming and fish-eating cultures. Introduction of aquaculture as a new practice faces the same challenges of any technology adoption to move from pilot projects of early adopters to more general use (Rogers, 1962). In the case of Philippine farmers diversifying into aquaculture, for example, such advances are inaccessible to the poor without financial and technical assistance (Hartmann, Jahnke and Peters, 2006). In other areas, such as Africa, where fish farming has less of a history, adoption of such advances also faces cultural barriers (Moehl, 2013). Allison (2011) describes how diversification into aquaculture may be more appropriate for small and medium enterprises, rather than for the very poor.

3.1.1 What could convince small scale farmers or entrepreneurs to become aquaculturists, or adopt new technology or species?

Adoption of new technologies, including starting with aquaculture or changing existing aquaculture practice, can be described by Roger's (1962) technology adoption bell curve, starting with innovators and early adopters, then facing a "Chasm" of hesitation (Moore, 1991), before moving on to gradually engage a majority (if successful). The literature identifies several enabling factors for small-scale producers contemplating aquaculture, including:

- the recognition of aquaculture as a viable economic activity and source of livelihood (Tacon *et al.*, 2010; Moehl, 2013),
- the provision of an enabling legislative framework for conducting the activity (Tacon *et al.*, 2010),

- access to subsidies and/or credit for initial infrastructure and start-up costs (Moehl, 2013),
- low-technology type production systems accompanied by training and on-going extension services (Funge-Smith, 2014),
- good fit with existing farming system/livelihood activities (Funge-Smith, 2014),
- gradual introduction with step by step approaches (Funge-Smith, 2014),
- simple, robust/resilient innovations (Funge-Smith, 2014),
- ready access to established (local) markets (Funge-Smith, 2014),
- access to key inputs such as feed and fingerlings (Brummett *et al.*, 2011; Karim *et al.*, 2011; Moehl, 2013; Saguin, 2014),
- simple market requirements (ie: product quality/freshness/characteristics easy to meet) (Funge-Smith, 2014),
- adequate training and extension services (Moehl, 2013),
- social acceptability of the practice – likely to become a growing constraint with multiple land-use conflicts (Tisdell *et al*., 2010).

International development experience clearly shows that a listing of benefits, such as the above, even if supported by substantial foreign aid, rarely leads to sustainable adoption of new practices (Bene *et al.*, 2016). Moehl (2013) feels that existence of associations ("clusters"), demonstrated profit potential, and consumer demand are key triggers to stimulate aquaculture adoption in Africa. However, participative processes, peer-peer learning, action research, co-management, and other processes that help to ensure that new technologies or approaches respond to local needs, are identified by farmers themselves, and are locally tested are also increasingly emphasized as essential to their successful adoption and scaling up (e.g. Davy *et al.*, 2012). In addition, Bene *et al.*, (2016) found that, despite narratives that highlight the potential contributions of capture fisheries and aquaculture to improved food security and poverty reduction, little has been done to rigorously evaluate the evidence for the actual contribution of the two sectors. It is also unlikely that beneficiaries that adopt aquaculture or other technology view the benefits in the terms as international funders.

On the other hand, the rhetoric of the above benefits, as well as food insecurity, poverty alleviation, climate change, and resilience, are effective in raising money for development and research, as well as for influencing governmental policies, which in turn are key inputs to the technology development and adoption curve.

3.1.2 Organization to improve small-scale access to diversification opportunities

Organization amongst small-scale growers, both in developing and developed countries, is often seen as a pathway to increasing access of individual farmers to financing, materials, technical expertise, markets, political and social lobbies, and peer support. This has been quite successful in some cases as in India (de Silva and Davy, 2010), but can face substantial social challenges and cost.

3.1.2.1 Aquaculture cooperatives and associations

Cooperatives and associations have been long promoted as appropriate pathways to improve affordable participation of small-scale farmers in the local or export markets, but are challenging endeavors (e.g. FAO, 1990; Derr, 2013). Community empowerment, training, recognition of local social environment, good definition of a group-inducing collaborative objective(s), support of association costs, and recognition of local needs are some of the elements that are important for their success (FAO, 1990; Kasabov, 2015; Tregear and Cooper, 2016).

In both the Bolivarian Republic of Venezuela and the Plurinational State of Bolivia, as an example, public subsidies have only been available to official associations or collaboratives rather than individuals, and much of the international funding has focused on communal ownership for poverty alleviation. At least some of the social organizations appear to have evolved opportunistically to access this funding, rather than out of interest for the communally driven activity. Moehl (2013) also reports on low sustainability of communally owned aquaculture initiatives in Africa. Promising initiatives for aquaculture often have not survived beyond the subsidies and funding, though it is still unclear if the investments have long-term outcomes through the latent training and experience with social organization. Associations, with a looser collaborative structure than cooperatives, can still provide many of the benefits of technology-sharing, lobbying, marketing and certification, and bulk purchasing of supplies also ascribed to cluster organization (see below). Nevertheless, these are also sensitive to social challenges and long-term costs of organization and maintenance, which can be overlooked in their planning.

3.1.2.2 Aquaculture clusters

Aquaculture "clusters" were a version of association innovated in India to respond to the challenges of wide spread white-spot disease in small-scale shrimp farms. The approach initially focused on technical advice and adoption of Better Aquaculture Practices through collaborative access and peer-peer learning, with substantial success. Subsequently, the collaborative structure facilitated access to quality feed, other supplies, funding, markets, and interaction with larger farms and corporations–as well as continuing knowledge sharing. Benefits of organizing small-scale farmers summarized by these authors, Kassam, Subasinghe and Phillips (2011) and NACA (2011) include:

- legal recognition;
- improved technical and financial sustainability;
- improved knowledge exchange and sharing experiences;
- middlemen/agents are eliminated at all levels;
- societies provide a workable model for small-scale farmers to meet market requirements;
- increased stakeholder interaction and involvement;
- increased awareness and social responsibility;
- economies of scale for buying supplies, marketing and certification;
- self-propagating nature of the model (spontaneous scale up); and
- reduced irresponsible culture practices (e.g. use of banned antibiotics, release of water from disease-affected ponds) due to peer pressure.

These reviews stress that cluster management uses a participatory approach in order to address common risk factors and accomplish a common goal. Above all, cluster farming fosters social harmony in a community, fundamental to the progress of society. The peer-to-peer relationship can also trigger spontaneous scale up, thus bringing more champions to the cluster or organized group.

"Clusters" are also described in the economic development literature as concentrations of related businesses and resources for a particular product theme (e.g. UNIDO, 2009). Likewise, "innovation platforms" have been promoted in Africa (van Roonen and Homann, nd) and the Plurinational State of Bolivia (www.pecespara lavida.org) as a development strategy that recruits related local businesses of a value chain in support of scaling up a particular technical or social innovation.

3.1.2.3 Organizational contribution to diversification

Promotion of some form of organizational enhancement is generally part of the sustainability planning for international development projects that provide technical or social innovations for poverty alleviation/food security/enhanced sustainable livelihoods. This includes proposals for both diversification and enhancement (specialization) of small-scale aquaculture, and would no doubt be part of future proposals for diversification in the face of climate change. Recent evidence suggests, however, that process-oriented aspects, such as appreciative inquiry, participative research, peer-peer learning, community-led priorization, etc., in addition to securing markets and ensuring local appropriateness of an endeavour, are particularly important to the effective and sustainable adoption of such innovations.

3.2 Large scale aquaculture

Most large aquaculture businesses supply an export market with global "commodity" products, like salmon, mussels or shrimp. Operations and markets in developed countries, where many of these companies are based, tend to be more sensitive to social license and concepts such as organic, fair trade, social and/or environmental responsibility – particularly in western countries. These companies tend to be driven towards spatial diversification, either because of lack of space where they originally were based or as a way to take advantage of less restrictive legislative frameworks for the industry and/or to use cheaper labor. However, this geographic spread is generally based on proven species and technological specialization. Diversification into other species is constrained by these high investments in specialization and market links (Myrseth, this workshop). New market opportunities and incentives or partnership ventures with government seem the most likely stimuli for diversification of species or strains for this sector, though the increasing threat of impacts from climate change may also start to provide new incentive.

4. ENABLING ENVIRONMENT FOR SUSTAINABLE DIVERSIFICATION IN AQUACULTURE

FAO (2016) notes the following trends in aquaculture diversification:

- a continuous exploration of new species options, particularly high species value in regions where aquaculture is well established,
- expansion to marine areas as areas for freshwater aquaculture become limited,
- a continuing diversification of production systems and practices to afford greater economies,
- polyculture or integrated culture (particularly in marine systems) offers a means for diversifying products from a system, improving efficiency of resource use and reducing negative environmental impacts,
- new markets are continuing to develop and domestic demands are increasing,
- processing and product diversification are developing in response to better market information,
- increased 'eco-labeling', driving a diversification towards this type of market,
- improved governance in aquaculture development and management, with more integrated land use planning and registration of farms for aquaculture.

These trends reflect globally averaged enabling spaces, triggers and drivers for aquaculture diversification as defined in the literature on theory of change and technological scaling up. The enabling spaces are demonstrated in New Zealand's aquaculture strategy and summarized in Hartmann and Linn (2008) as:

Fiscal/financial space. Receptive markets are key elements to providing incentive for diversification. In addition, fiscal and financial resources need to be mobilized to support the diversification process and/or the costs of the interventions need to adapt the aquaculture diversification components to fit into the available fiscal/financial space. Examples include incentives for R&D for private and public research institutes, better options or rates for insurance of diversified aquaculture entrepreneurs, science and technology taxes to cover for R&D or/and social components costs, etc. Harache (2002) and Muir and Young (1998) noted that the establishment or rearing procedures for new species always require several years of research and R&D before commercial production becomes profitable.

Natural resource/environmental space. Aquaculture and its diversification depends on physical space, feed sources, brood stock, and sometimes seed. These needs are increasingly recognized as needing to be sustainable, with minimal deleterious impact on other natural resources and the environment. In some instances, aquaculture can have positive environmental influences, as in the enhancement of aquatic environments in degraded agricultural land.

Policy space. The policy (and legal) framework has to allow for needs to be adapted to support the diversification. A good example is the plan for aquaculture and aquaculture diversification in New Zealand (Government of New Zealand, 2012).

Institutional/organizational/staff capacity space. Institutional and organizational capacity has to be created to carry the diversification process forward, in both small-scale farmers and large-scale industries, as well as in the markets (local and global).

Political space. Important stakeholders, both those in support of and those against aquaculture diversification need to be attended to through outreach and suitable safeguards to ensure political support for the diversification process.

Cultural space. Possible cultural obstacles or support mechanisms need to be identified and the intervention suitably adapted to allow diversification in a culturally diverse environment (for example the use of traditional or indigenous aquaculture practices, social license of the sector and/or industries, and peer-peer and participative processes).

Partnership space. Partners need to be mobilized to join aquaculture diversification. A mix of clusters, large-scale producers, contracted farmers, participative and collaborative value chains should be promoted.

Learning space. Knowledge about what works and doesn't work in aquaculture diversification needs to be harnessed through monitoring and evaluation, knowledge sharing and training in a manner that is effective for the participants.

These enabling spaces interact differentially with local situations to produce distinctive technical development and adoption curves that are a combination of diversification and specialization processes. Diversification is an essential part of technical development, where developers look for groundbreaking innovations that might have commercial advantages of monopolized supply and/or patents, or, on a more altruistic basis, allow improved aquaculture for the poor (or some combination of the two). Subsequent adoption and scaling up of the new technology or the culture it enables generally depends on cultural propensity to take risks– modulated by marketing of the ideas and perceived market potential of product sales.

Dobrinsky (2008) and Kaulich, (2012) make general recommendations on stimuli for diversification from a macro-economic point of view. Some of these may apply to the case of aquaculture development and diversification, but compared with triggers and drivers identified by Moehl (2013) as necessary for profitable African aquaculture indicate some interesting gaps (Table 1).

The triggers, drivers and enabling environments of such innovations and their scale-up processes are likely the ones to focus on when thinking about pathways for aquaculture diversification.

Harache (2002) cautions that not everyone will be able to benefit or access changes in a sustainable way. Diversification provides additional strategic opportunities for aquaculture, but it should not be considered as the ultimate and immediate solution to restoring individual profitability in a production system facing declining prices, and this author warns that not every farm will survive.

TABLE 1
Comparison of macroeconomic and aquaculture triggers and drivers

Macroeconomic Diversification Dobrinsky (2008) and Kaulich (2012)	Triggers and drivers for profitable aquaculture in Africa Moehl, 2013	Gap Analysis
Competition fosters diversification through the hunt for distinctive products with a marketing edge.		Trigger for innovators and early adopters; may be fostered by external funding and rhetoric
Market failures need to be selectively evaluated and addressed, as knowledge-specific or systemic failures; in aquaculture this could be of particular interest, as the market integrates social and economic aspects of production, value chains and the market.	Products in the market (trigger); Demonstrable profits (trigger)	Market-driven development
Collaboration and connectivity between market agents and other stakeholders to achieve mutually agreed goals is important. In the case of aquaculture diversification this could be seen as the organization of communities and stakeholders in clusters, platforms or roundtables that address power differentials.	Successful cluster of producers, service providers (trigger); Functional producer organizations; Supportive partnerships	Importance of peer support and approval
Jointly established acceptable "rule(s) of the game" are beneficial, if they can be established and followed. In aquaculture, demonstrated best practices could be considered as basic "rules of the game" for growers and can be policed by peers, while rules of the game in the market are always challenging.	Successful cluster of producers, service providers (trigger); Functional producer organizations; Supportive partnerships	Requirements for government policy or local rules supported by collaborative organization
Knowledge of the nature and size of externalities and related remedies is important – essentially the map of enabling spaces, drivers, and challenges described above.	Supporting production and market information driver – public marketing; Effective outreach	Prior evaluation of local socio-environmental potential for aquaculture or diversification, including through maps, essential, but easily overlooked in face of funding opportunities
Creation of an enabling environment for desired changes in the behavior of market agents is important, though possibly challenging.	Supporting production and market information driver – public marketing; Effective outreach	Reliable market opportunity important; Mechanisms for equitable value chains desirable
Risk-sharing among agents and stakeholders is advisable. In the aquaculture sector the risk for the producers is high, while ideally the risk should be shared more evenly amongst the stakeholders.		Risk-sharing may be a by-product of adequate cluster organization
	Credit availability – convincing lending agencies that aquaculture is bankable	Essential components of scaling up innovations, including diversification
	Affordable quality feed and seed	
	Adequate capacity, training, practical gap-filling knowledge	

4.1 Case study: A North American market perspective on aquaculture diversification

Aquaculture markets in North America are closely tied to those of fisheries. The 2016 FAO biannual oceans assessment "State of World Fisheries and Aquaculture" concludes that 90 percent of wild fisheries are harvested either at or above their sustainable limits (FAO, 2016). Moreover, global warming is influencing distribution and migration patterns of fish, further impacting reliability of seafood supply from wild fisheries. At the same time, the North American middle class continues to grow, and with this expanding wealth comes a desire for diversity at the dinner table, including fish. As global seafood[71] consumption continues to increase and wild capture stocks are either

[71] "Seafood" for the purposes of this study includes freshwater fish and crustaceans.

diminishing or remaining static, a greater contribution by aquaculture is critical to address seafood demand.

In the North American marketplace, experience has shown that it is much more difficult to introduce completely new items from aquaculture to the market than to build on established markets for wild fishery commodities. Aquaculture's value proposition is primarily to fill the need of established markets for wild fisheries products with the same or similar species from culture environments (Table 2).

TABLE 2
North American aquaculture products and corresponding wild fishery product and status

Aquaculture product	Wild fishery product and status
Farmed Atlantic salmon	Wild sockeye salmon – seasonally limited
Farmed prawns	Wild Gulf of Mexico prawns
Farmed Atlantic halibut	Wild Pacific halibut – seasonally limited
Farmed tilapia/Pangasius	Wild rockfish – limited fishery
Farmed trout	Small wild fishery
Farmed steelhead	Commercial fishery ended
Arctic char	Limited wild fishery
Sturgeon	No commercial fishery
Sablefish	Limited fishery
Sea bass	Limited fishery
Sea bream	Limited fishery
Oysters/clams/mussels	Limited wild fishery

Aside from augmenting fisheries products, aquaculture's major advantage is in providing a more consistent product with improved supply, sizing, fat content, quality, taste and stable pricing. For both food service (restaurants, institutions, etc.) and retail (supermarkets, grocery stores, fish markets) markets, aquaculture products have become increasingly accepted due to the consistency outlined above. From a chef's perspective, consistent year round supply and size grades available with most aquaculture products ensures portion and plate costs remain constant. This provides peace of mind when putting seafood on menus on an annual basis, and reduces waste.

For the retail market, consistent supply and stable pricing allows supermarkets time to promote and advertise products in their stores and on their flyers. Wild fisheries tend to a less guaranteed supply and more volatile pricing, increasingly so as fish distributions are affected by increased ocean temperatures. For example, albacore tuna arrive in West coast Canadian waters and migrate` away much earlier than in the past. In 2015, tuna availability was one month earlier and one month shorter than in 2014. Sockeye salmon returns are occurring later and later every year with peak returns trending over a week later over the past three years, in addition to being considerably reduced in some years. Ocean acidification is greatly affecting wild harvest of shellfish in Pacific waters. Aquaculture production has the capacity to reduce these impacts and provide more consistency. In the case of shellfish aquaculture, for example, technology can mitigate acidification in hatcheries, improving the reliability of production.

Surveys indicate that the primary considerations for North American retail seafood consumers are quality and taste, with price coming a close third. Beyond these three main attributes, other concepts that contribute to consumer selection and price differential include: locally produced, organic, non GMO, environmentally sustainable, socially responsible, reduced carbon foot print, drug free and traceability. Aquaculture has the ability to differentiate products with these specific additional attributes through diversified production systems and technologies, further expanding the market reach for aquaculture products. Increased stability of price differentials associated with these attributes has resulted from their ongoing use and marketing. For example, Oceanwise, an established Vancouver Aquarium eco-ranking program that follows the Seafood Watch criteria and has been marketed for over a decade, highlights farmed Arctic char from the Yukon. After gaining Oceanwise approval for sustainability, based on production protocols, producers of this product took advantage of increased demand and subsequently collected a 20 percent price premium.

Beyond affording marketing advantages, technological diversification for similar products can reduce the risk associated with the farming and increase areas available for aquaculture. For example, land-based closed system technology for salmon, while currently more expensive than traditional netcage farming, provides reduced risk, greater product control, and the option to set up in diverse terrestrial locations closer to markets, compared with open net pen farming. In addition, the production system affords attributes of environmental sustainability that provide access to market niches and price differentials. This further expands market demand while protecting the investments by the farm. Similarly, closed system intensive biofloc production of shrimp and prawns allows this aquaculture to be moved from the environmentally polemic coastal pond system (Hargreaves, 2013).

In North America, most major retail chains, multi-unit food service chains and institutional buying groups have developed Corporate Social Responsibility policies for ethical and environmental sourcing. Eco rankings (Monterey Bay Aquarium's Seafood Watch program, Vancouver Aquarium's Oceanwise program, Seachoice) and sustainability certifications (Aquaculture Stewardship Council (ASC), Global Aquaculture Alliance's Best Aquaculture Programs (BAP)) all play a role in providing positive solutions to address "sustainability" concerns that North American consumers express. Unlike many certifications for wild capture fisheries, aquaculture certifications also contain assessment criteria on human rights and social issues, which have become increasingly important in the food industry.

Consumer demand for certified and eco-ranked products has increased substantially over the past 5 years in North America, providing a higher financial return to the farms adopting these practices. This increased demand is important for both small-scale and large-scale aquaculture projects. Locally-based small-scale aquaculture projects tap into a growing consumer demand for local products. These regionally specific small-scale businesses provide social stability in the communities they are located in, in some cases reinforcing reduced fisheries-based economies of coastal communities.

Large-scale aquaculture businesses have an economy of scale that allows them to access a diverse institutional customer base with a broad geographic reach, providing predictably consistent high quality product to many consumers. In 2014, large-scale farmed Atlantic salmon producers in British Columbia exported in excess of US$255 million of farmed salmon – primarily to the the United States of America (a 10 percent increase over 2013). Marketing to this diverse market, both institutionally and geographically, provides good resilience to market volatility.

Many North American seafood markets have thus embraced aquaculture products, but overwhelmingly to satisfy demand for fisheries-like products. Farmed species are selected from global and local supply that approximate these familiar products, with appropriate quality, taste, and price. Technical and market diversification broaden the reach of aquaculture products, increasing options for aquaculture, increasing seafood consumption, and addressing societal production-related concerns.

So far, the North American aquaculture market appears to be resilient to climate change challenges, based on its technical and geographical diversity. In fact, market opportunities are being created by climate change impacts on wild fisheries. Species diversification has not been a significant response to market challenges, and is likely to continue to be primarily useful for securing supply of established products rather than for introduction of new ones. Nevertheless, several examples of opportunistic diversification in established infrastructure are notable:

- Lumpfish, a recent aquaculture species in the Kingdom of Norway for use as lice control on salmon farms, are now also being grown and marketed in Atlantic Canada for roe for human consumption (Vargas, 2015).
- Multi-trophic aquaculture on both Canadian coasts is proposing to market algae, shellfish, and sea cucumbers as additional products from fish net pen infrastructures (Chopin *et al*., 2012).

5. AQUACULTURE DIVERSIFICATION – NEW SPECIES INNOVATOR PERSPECTIVE

Identification and development of new species for aquaculture is an ongoing process, driven by perceived market opportunities or other evaluation of need or opportunity. This may include potential for food production, potential for production of other products for human use, revitalization of threatened wild populations, use in the ornamental trade or scientific research, or individual interest.

For Rodrik (2005), diversification implies “discovery” of an economy’s underlying cost structure, i.e. whether new products will be profitable. Entrepreneurs undertaking to produce non-traditional products discover what it actually costs to produce the product when producing it. The main problem is that private costs in this process may exceed gains. If the entrepreneur fails, he/she bears the full cost of the failure; if they are successful, others can follow their example and share the gains at a lower cost. Dissemination of entrepreneurial knowledge through “knowledge spillover” may thus decrease its value, though this spillover also is a significant driver of new growth (UNIDO, 2009) and increased protectionism may hinder effective innovation. In the absence of governmental intervention to protect or fund such innovation, there is limited entrepreneurial activity in diversification.

Harache (2002) recognizes two types of development, based on their anticipated position on the market: “niche market products” (NMP = small quantities, high price) and “large market products” (LMP = moderate to cheap prices). While this duality may exist as endpoints of a species culture development, it also describes the development process – generally, production progresses through a high-priced “honeymoon” period that drives innovation, followed by a predictable reduction in price as production scales up and novelty dissipates (Muir and Young, 1998). For example, Atlantic salmon were rare and expensive in the French Republic in 1970, with about 1000 tonnes annual import, but by 1999 had become a cheaper commodity, with annual imports of 90 000 tonnes (Harache, 2002).

In general, development of culture technology for a species can be a long process, including private and public research and significant investment in its various aspects. For example, Le François *et al*. (2010) review advances for a large number of finfish species. Suquet *et al.* (2002) and Quemener *et al.* (2002) present a multi-criteria analysis tool for screening finfish candidates, including biological, fisheries and economic aspects such as growth rate, selling price, availability of breeders, biological knowledge (number of publications in ASFA database), rearing potential (selling price/age at 3 kg), body section, presence of bones, presentation methods, flesh taste, reputation and geographic distribution. Their top new candidate for French aquaculture at the time was the Atlantic cod. However, despite substantial investment in cod aquaculture technology, it has not yet become fully established, and in Europe cannot compete with a recovered cod fishery. Nevertheless, such frameworks may help to guide investments in aquaculture diversification.

6. WHO ASSUMES THE COSTS OF AQUACULTURE DIVERSIFICATION?

Costs of aquaculture diversification are significant, and may be very long term. Who assumes these costs? In some cases, enterprises or innovators that see clear potential benefits will assume such costs themselves, generally with the expectation of protecting or controlling the technology generated to maximize profits – at least for some time. Alternatively, there is the expectation of public support of development costs. In practice, there is often a mix of the two approaches. For example, the Kingdom of Norway mandates that a proportion of private aquaculture profits is invested in research and development, as well as investing substantial public funds (Myrseth, this volume). Approximately 40 percent of research and development in the Kingdom of Norway is thus public monies, while 50 percent is private funding and 10 percent is from other sources (Valvåg, 2005). This author indicates that the funding profile is comparable to that of other developed countries, though the thematic distribution and investment priorities may vary.

Small and large-scale aquaculture may have different environments for diversification costs, as do developed and developing countries. Different opinions on the objectives and functions of diversification create different funding priorities. For example, there are many species whose "promising aquaculture potential" is promoted by respective champions, but different opinions on which should receive funding. In the Republic of Chile and the Federative Republic of Brazil, for example, there is a development focus on native species; in the case of the Federative Republic of Brazil this has evolved into a very productive diversified freshwater fish aquaculture industry for domestic markets, building on the success of non-native tilapia culture, while in the Republic of Chile it remains incipient and seen as competition for funding of more lucrative export-oriented aquaculture (Moroni *et al.*, 2015, Wurmann and Routledge, this volume). On the other hand, substantial analysis for appropriate priority setting of research in northern countries has resulted in decades of substantial investment in halibut and cod culture, but with a continuing incipient industry (Myrseth, this volume). In the case of developing countries with aquaculture development supported by foreign aid, priorities may be set by unrelated factors.

7. CONCLUSION

Aquaculture development is an interplay of diversification and specialization. How these processes interact is locally distinct, subject to history, socioeconomic conditions and markets. Overall resilience of the sector at a country or global level is no doubt afforded by the cumulative toolkit of species and technologies. However, individual farmers and businesses are more likely to optimize their operation through specialization – including adaptations to changing conditions. Diversification is most natural at times of evolving or unstable markets which provide new entrepreneurial opportunities, showing similarity to the macroeconomic "U-curves" of economic development. However, effective new markets are most likely to emulate existing fisheries or aquaculture commodities, rather than create absolutely new products. There is little evidence of diversification currently being used to respond to climate change challenges. Instead, increased specialization affords established aquaculture practices increased resilience to change and capacity to capitalize on climate- induced deficits in fisheries production.

Diversification is a policy objective for aquaculture development of many countries, both domestically and in foreign aid. This may aim for improved resilience, ecological balance and diversification of markets in developed countries, at the same time providing more accessible technologies or socio-technological development processes for farmers in developing countries. The scale and nature of aquaculture producers, as well as their objectives, are diverse, as are their appropriate paths for diversification.

Currently, aquaculture diversification is primarily pursued in search of new economic opportunities, but increasingly it is considered a hedge against impacts such as climate change. A significant technical repertoire of aquaculture opportunities is thus being created, but individual capacity of farmers or companies to tap into this unaided, in the case of major shocks, is limited.

Recommendations for countries promoting diversification, along with sources of investment, are:

1. a multi-factorial evaluation of potential species, technologies and markets, including elements of contributions to food security, where appropriate, and socio-environmental sustainability (governmental investment);
2. risk/potential mapping for the proposed aquaculture innovations, including multi-user conflicting interests and appropriate application of precautionary principles with respect to potential impacts such as escapees and invasive species (governmental and private investment);
3. technical research and development, including socio-environmental considerations (government, private, and external investment; management of knowledge ownership; access to global experience);
4. social research and development, focused on cultural aspects of production, marketing and technology adoption (government and private/external – particularly relevant to aquaculture diversification/adoption in developing countries; includes certification for developed country markets);
5. governance and policy development, including access to natural resources and conflict management among stakeholders and interest groups to build social license for operation (governmental investment; participative process);
6. support for association and multi-lateral platform building (particularly for small-scale aquaculture in developing countries; governmental and external investment);
7. market research and development appropriate to the aquaculture endeavor, both local and global (may include food security, sustainability and social license considerations; governmental and private investments; external support in developing countries); and
8. appropriate long-term fiscal plans to aid innovation adopters, particularly small-scale farmers, including effective knowledge sharing and development of pro-active planning for activity shifts if major impacts, such as climate calamities, require these.

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Aquaculture is the world's most diverse farming system in terms of number of species, methods and the environments where the farms are located. These proceedings report the results of a workshop convened by FAO and World Fisheries Trust (Canada) to summarize diversification successes and opportunities in North America, South America, Asia-Pacific, Europe and Africa, and to identify general principles that can help guide diversification in aquaculture.The document includes an assessment of main strategies and future steps for aquaculture diversification, not only in terms of purely economic costs but also in development costs, including evaluation and mitigation of environmental and social impacts and establishment of species-specific biosecurity frameworks.

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