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ADAPTATION STRATEGIES OF THE AQUACULTURE SECTOR TO THE IMPACTS OF CLIMATE CHANGE

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ADAPTATION STRATEGIES OF THE AQUACULTURE SECTOR TO THE IMPACTS OF CLIMATE CHANGE

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PREPARATION OF THIS DOCUMENT

This document was one of the keynote papers presented at the Global Conference on Climate Change Adaptation for Fisheries and Aquaculture “FishAdapt”, organized by the Food and Agriculture Organization of the United Nations (FAO) on 8–10 August 2016 in Bangkok. An extended summary is included in the conference proceedings. The paper was presented by Dr Doris Soto. The feedback from the presentation was considered in the drafting of this final version.

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ABSTRACT

The need for adaptation in the fisheries and aquaculture sector and the associated challenges are expected to increase with climate change. This has been stated with a very high degree of confidence by the Intergovernmental Panel on Climate Change in its Fifth Assessment Report (IPCC AR5). The Report also refers to the complexity of adaptation in the description of nine constraining factors, and laying down ten overlapping approaches for managing the risks of climate change through adaptation. This document reviews the numerous options for aquaculture described in sector literature; it identifies key research areas that would improve the sector's capacity to adapt to climate change impacts and inform policy on adaptation. The document ends with a set of suggestions for assessing potential adaptation measures and implementing them. These are built around two pillars: a sustainable livelihood framework, and an ecosystems approach to aquaculture management, supported by risk assessment and management along the value chain and a feasibility assessment. The capacity of the main stakeholders to apply these concepts-sustainable livelihoods analysis, risk assessment and management, feasibility assessments (including cost-benefit analysis), and an ecosystem approach to aquaculture management should be developed or strengthened.

Key words: *adaptation, vulnerability, sustainable livelihoods, ecosystems approach to management, risk management, feasibility assessment*.

CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

LIST OF BOXES

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An important portion of the information on gaps in the science and the research needed for adaptation was provided in a draft review (requested by the Aquaculture Branch of the FAO Fisheries and Aquaculture Department) made by a team of faculty members, researchers and graduate students of the School of Marine and Environment Affairs of the University of Washington, Seattle, Washington, the United States of America. The team was led by Dr Edward H. Allison. The literature review was the basis of a larger work to describe and analyse published literature on the vulnerability and adaptation of aquaculture to climate change.

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ABBREVIATIONS AND ACRONYMS

AFSPAN	Aquaculture for Food Security, Poverty Alleviation and Nutrition
AHPND	Acute Hepato-pancreatic Necrosis Disease
AMA	Aquaculture management area
AR	Assessment report
BMP	Better management practices
CC	Climate change
CCRF	Code of Conduct for Responsible Fisheries
CO2	Carbon dioxide
EAA	Ecosystems approach to aquaculture
EAAM	Ecosystems approach to aquaculture management
EMS	Eosinophilia–myalgia syndrome
ENSO	El Niño-Southern Oscillation
FAO	Food and Agriculture Organization of the United Nations
FCR	Feed conversion ratio
GAR	Global assessment report
GDP	Gross domestic production
GEF	Global Environment Facility
GIS	Geographic Information System
HABs	harmful algal blooms
IDDRI	Institute for Sustainable Development and International Relations
IFAD	International Fund for Agricultural Development
IPCC	Intergovernmental Panel on Climate Change
ISA	Infectious salmon anaemia
NACA	Network of Aquaculture Centres in Asia-Pacific
NAPA	National action plans for adaptation
OECD	Organisation for Economic Co-operation and Development
PICTs	Pacific Island Countries and Territories
R&D	Research and development
SIDS	Small Island Developing States
SLA	Sustainable livelihood approach
SOFIA	State of World Fisheries and Aquaculture
SPC	Secretariat of the Pacific Community
SST	Sea surface temperature changes
UNISDR	United Nations International Strategy for Disaster Reduction
WSSV	White spot syndrome virus

KEY MESSAGES FROM THIS REVIEW

There is an increasing number and variety of adaptation options suggested in sector literature. These range from those that can be reliably applied to specific impacts, to those that might broadly apply to a variety of impacts; those that are easy and inexpensive, to those that are complex and need a significant amount of resources to implement.

There is as yet no robust guide to select or design suitable adaptation measures for impacts that are the cumulative result of a mix of risks, nor is there enough knowledge and a reliable tool to differentiate and understand the interactions of impacts from climate change and human action.

These two shortcomings present several potentially costly drawbacks: the choice of adaptation measure could be the result of addressing the wrong hazard or risk, or inadvertently avoiding accountability by attributing a man-induced hazard or risk to "climate change".

Given these current inadequacies, the choice and application of an adaptation option or strategy would benefit from the application of two strategic approaches: (i) sustainable livelihood approach (SLA); and (ii) ecosystems approach to aquaculture management (EAAM). Both strategies are supported by two essential tools: (a) risk assessment and management along the value chain; and (b) feasibility assessment (biological, technical, economic and social), which should be justified by a cost-benefit analysis of major adaptation measures, such as building structures, relocation or a mix of options.

The outcomes of their use and their synergy would be:

The selection or design of adaptation measures that engage the participation of the main stakeholders: the measures selected would be compatible with the livelihood objectives, strategies and assets of the stakeholders; the resources and actions needed to strengthen capacities for access and use of assets are widely agreed on and clear; options are not rigidly imposed, so it is reasonable to expect that participation in their implementation is sustained. This imparts effectiveness, efficiency and legitimacy.

EAAM offers the mechanism to integrate the economic, environmental, social and political components of the adaptation measure. The core of the ecosystems approach to aquaculture (EAA) process is that it fosters synergy in the governance of the aquaculture sector and of the other sectors; it helps avoid the maladaptation that results from, among others, competition over resources and lack of cross-sectoral governance; and it provides the opportunity to incorporate policy that reduces the adverse impacts of aquaculture. This imparts efficiency, equity and legitimacy.

Value chain-oriented risk assessment and management results in a holistic rather than a piecemeal adaptation measure. As such, it could easily be integrated into a sustainable aquaculture development plan. This imparts effectiveness and efficiency.

Feasibility assessments supported by cost-benefit analyses provide the basis for transparent decision-making, showing who bears the cost and who reaps the benefits, and how benefits could be shared equitably. This avoids maladaptation and imparts equity and efficiency.

Overall, these tools and strategic approaches would foster coherent and mutually strengthening adaptation measures among various economic sectors and most probably promote a resilient and highly adaptive social system.

1. INTRODUCTION: WHAT IS AT STAKE?

The rapid growth of- and the gains from- aquaculture, still a relatively young industry, could stall and dissipate from the effects of climate change. From an estimated 6.1 million tonnes produced in 1976 (the year the Kyoto Declaration on Aquaculture was adopted at the first FAO Technical Conference on Aquaculture), in 2014 the global output of farmed food fish, molluscs, crustaceans and other aquatic animals had reached almost 74 million tonnes, while cultured seaweed and other aquatic plants provided a further 27.3 million tonnes, valued at 160.2 and 5.6 billion dollars (US$) respectively. Fish provides essential nutrition for 3 billion people, as well as at least 50 percent of animal protein and essential minerals for 400 million people, mainly in the world's poorest countries. Farmed fish is gradually providing a higher proportion of humanity's fish consumption; in 2014 it surpassed wild fish as the source of food fish for the first time. Almost all fish originating from aquaculture ends up on the dinner table. The average consumption per capita worldwide was 19.7 kg in 2014, compared to 9.9 kg in 1960 and 14.4 kg in the 1990s. The share of farmed fish to fish intake has increased from 7 percent in 1974 to 26 percent in 1994, 39 percent in 2004 and, even if the People's Republic of China were excluded, 33 percent in 2013 (FAO, 2016).

Employment growth in the aquaculture sector was the fastest among food production industries, although it has stabilized recently. Fish farming employs 18 million people directly worldwide: 94 percent are in Asia, 1.9 percent in Latin America and the Caribbean, and 1.4 percent in Africa (FAO, 2016). An FAO study in 2010 had estimated that 117 million people were dependent on aquaculture through its multiplier effects of generating indirect employment and support to household members (Valderrama, Hishamunda and Zhou, 2010).

Global trade in fishery products was valued at US$148 billion in 2014 (compared to US$8 billion in 1976); the share of aquaculture products in this value is placed at 33–35 percent, a large part of it from developing countries (FAO, 2016). Demand is fuelled by a growing global population, aggravated by a stronger purchasing power, especially from urban dwellers and a raised awareness of the health benefits of fish in the diet. At a global level therefore, the following elements are generally at stake: food and nutrition security, poverty alleviation and livelihood security, and economic development.

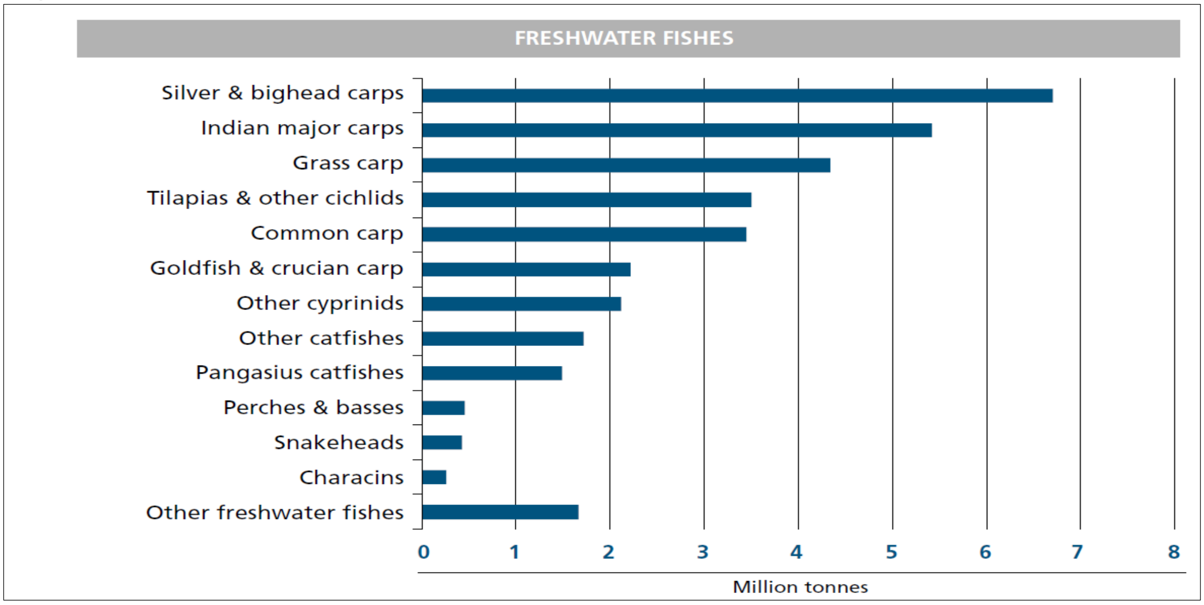
However, the stakes could be higher yet in the largely developing countries of the Asia-Pacific for the following reasons: (i) they produce almost 90 percent of the world's output; (ii) their farmers generally have less access to livelihood capital or less capacity to use the capital productively, or both (more than 80 percent of the fish farmers in Asia are small-scale and many are resource-poor); and (iii) they have a high per capita intake of fish, and therefore a high dependence on fish for food security and nutrition. The stakes are just as high in sub-Saharan Africa, because of the region's rapidly growing population and its need to raise the per capita consumption of fish which, unlike in all other regions, has stagnated at a comparatively low level. The region has also recently shown the fastest increase in the employment of people in fisheries and fish farming. A similar situation is to be observed in the aquaculture sector of Latin America and the Caribbean, where growth has also been accelerating, as indeed in most developed countries, which depend on imports from developing countries to meet their demand for fish products: this amounted to 23 kg/per capita in 2014 in all developed countries, a sizeable share of which comes from imports (FAO, 2016).

The toll could be particularly heavy on the Small Island Developing States (SIDS), which depend a great deal on capture fisheries for national income and/or protein-rich food, even as their agricultural base is narrow and weak (Tompkins *et al.*, 2005; Bell and Taylor, 2015).

Finally, a double threat looms over the source of food fish for nearly 3 billion people and the livelihoods of the millions of farmers producing freshwater species: on the one hand the scarcity and pollution of freshwater sources for fish farming – enhanced by climate change – and on the other the generally high vulnerability of the countries which farm the most common varieties of cultured freshwater fishes. As shown in Figure 1 (FAO, 2012), these include the People's Republic of

Bangladesh, the People's Republic of China, the Arab Republic of Egypt, the Republic of India, the Republic of Indonesia, the Republic of the Philippines, the Kingdom of Thailand, the Socialist Republic of Viet Nam and others.

Figure 1. Production of freshwater finfish species, 2010



Source: FAO, 2012.

1.1 Risks to aquaculture from climate change[1]

Hazard identification and characterization feed into risk assessment – in itself a major element of vulnerability assessment – which is the first step in the process of adaptation. Climate change has spawned three broad types of hazard: physical, chemical and biological. Most of the chemical and all of the biological hazards are an offshoot of the physical. According to the latest IPCC technical report, AR5, the relevant climate change implications for aquatic systems, especially oceans, coastal systems and low-lying areas should be expected. However, the scarcity of long time series data, the uncertainty of biological responses to change, and the cumulative impacts of climate and human drivers means that there is limited information on the “combined effects” of the chemical and physical drivers of climate change on aquatic environments. Consequently, “regional and subregional predictions” of climate change effects are difficult to make with certainty (FAO, 2016).

The main risks to aquaculture have been identified by De Silva and Soto (2009), but the AR5 and recent literature confirm their importance by ecosystem and region, as well as the increasing role of some hazards, such as ocean acidification, to various forms of mariculture.

1.1.1 Physical hazards

Temperature anomalies: higher air temperatures and an increased frequency of hot days and nights; heatwaves and abnormally cold events are more likely. Stock performance and therefore productivity is affected by surface air temperature anomalies, but the effect could be positive for some aquaculture species. Coral bleaching became widespread during the latest El Niño-Southern Oscillation (ENSO) episode that raised sea surface temperatures, affecting the habitat and breeding grounds of reef fish; much of the seed for the lucrative live reef fish trade is still sourced from the wild. Instances of extreme cold in the Republic of Tajikistan in 2007–8 and the People’s Republic of China in 2010 (FAO, 2013) caused widespread damage to fish stocks and facilities. In Tajikistan, the country’s carp brood stock was nearly wiped out. In the People’s Republic of China, particularly in the central and

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[1] Howes *et al.*, 2015.

southern provinces, stocks of warm water species such as tilapia and cobia were killed. However, even in the northern provinces, stocks suffered heavy mortality when hatcheries and indoor culture operations were rendered inoperable from power disruption because heavy snowfall snapped power lines and buckled power poles.

Sea surface temperature changes (SST): each species is adapted to a particular temperature range. In mariculture, a change in SST may put some production systems at risk if the increase or decrease in temperatures exceeds the optimal range for survival or growth.

Precipitation anomalies: likely increases in the frequency and intensity of heavy rainfall events on one hand, and a prolonged absence of precipitation on the other; aquaculture productivity is adversely affected by change, especially from erratic precipitation patterns.

Rising sea levels: sea levels are expected to increase more than the current IPCC projections, and the penetration of saline water inland could render some freshwater production systems unsuitable for the culture of freshwater species. Wave surges and inundations are also going to alter the habitats of aquaculture species, eroding coastal strips or submerging coastal areas.

Floods: flooding triggered by abnormally heavy rainfall – but often exacerbated by poor planning or the absence of coordinated action by different agencies – may become more severe as a result of global warming, rendering aquaculture systems, input sources such as wild seed, and plant-based feed more vulnerable.

Drought: possibly more intense, or of longer duration, or both. The risks associated with drought are not well understood compared to those associated with floods or cyclones. The impact of drought can only be partly attributed to deficient or erratic rainfall, as drought risk appears to build up over time as a result of a range of drivers. These include: poverty and rural vulnerability; increasing water demand due to urbanization, industrialization and the growth of agribusiness; poor soil and water management; weak or ineffective governance; and climate variability and change (UNISDR, 2011).

Cyclones: the growing intensity of tropical cyclones (although there is no consensus over whether they are becoming more frequent) can cause the widespread destruction of infrastructure and the disruption of services that affect aquaculture production; they can delay the resumption of farming activities, and disrupt activities along the other segments of the value chain (seed and feed production and supply, post-harvest, transport and marketing). Cyclones also cause the silting-up of mollusc-growing areas.

1.1.2 Chemical hazards

Lower pH values (acidification): a number of studies have shown that these affect the development of mollusc shells, and corals.

Salinity changes: may increase or decrease depending on changes in precipitation and evaporation; in coastal waters this arises by virtue of the heavy influx of floodwaters from rivers and estuaries; in rivers, changes are caused by the intrusion of seawater.

Low oxygen levels in culture waters: an increased impact of upwelling of anoxic water; plankton respiration intensified as a result of higher temperatures; eutrophication.

1.1.3 Biological hazards

These are driven by physical and chemical factors:

Eutrophication: rising temperature levels are likely to cause wide fluctuations in the thermal dynamics of freshwater bodies, including increasing stratification and nutrient circulation, with implications for primary production and hence higher trophic levels. More intense eutrophication and algal blooms will have implications for local aquatic ecosystems and for aquaculture, especially in static water bodies like lakes and reservoirs.

Harmful algal blooms: increasing temperatures, the increasing frequency and extent of algal blooms, as well as changes in the diversity of zooplankton and the 'tropicalization' of fauna have been observed in semi-enclosed seas such as the Mediterranean. Salmon and mussel farms in the Republic of Chile have also been severely affected recently (this incidentally raised crop insurance premiums: a financial risk as an offshoot of a biological hazard).

Pathogens and parasites: increase in prevalence, a shift in the distribution of pathogens and parasites, enhanced growth and reproduction of microbes.

Pollution: increase in pollution toxicity, including the dilution of microplastic as a result of rising water temperatures.

2. DIRECT AND INDIRECT IMPACTS ON THE SECTOR

The main climate change related drivers – warming of water bodies, rising sea levels, acidification of the seas, changes in weather patterns and extreme weather events – have direct and/or indirect impacts on aquaculture, and the evidence of such impacts has been well documented (FAO, 2009). IPCC AR5 offers evidence of the certainty of global warming and the fact that oceans, coastal and inland water bodies are being affected. There is high confidence that coastal systems and low-lying areas will be increasingly exposed to submergence, coastal flooding, coastal erosion, and saltwater intrusion. (IPCC, 2014).

The links between each driver and its impacts on aquaculture have been broadly – and, in a few cases, specifically – established by numerous studies, with varying degrees of confidence. For example, the predicted rise in seawater CO_2 partial pressure (and consequent acidification) will affect the physiology of bivalves both in terms of growth and reproduction, and may affect the quality of shells. On the other hand, warming can also increase spatfall and growth rates, as well as extend the latitudinal range of farming, which are positive effects. There had been reports of mass die-offs of oyster larvae in hatcheries in Maine, the United States of America, attributed by farmers and researchers to water acidity (Portland Press Herald, 29 October 2015); the impacts of acidification on marine finfish require greater study, but it seems that embryos and larvae are more sensitive to elevated CO_2 levels than juveniles and adults, and there could be sublethal effects such as impaired growth rates (Heuer and Grosell, 2014).

Links have been demonstrated between climate-induced temperature variability and growth rates, disease susceptibility, timing of spawning, mortality at certain life-cycle stages, as well as economic impacts related to direct impacts on the productivity and disruption of the culture process. Physiological impacts are linked to extreme weather events through changes in salinity and temperature on metabolic response and some extended physiological changes. There are a variety of socio-economic impacts, including loss of stock and damage to infrastructure and other assets, as well as the closure and relocation of production sites.

Indirect effects of climate change include: changes in circulation patterns and productivity in the sea (Brochier *et al.*, 2013) that will affect the production of fishmeal/oil; physical impacts affecting the production of terrestrial fish feeds; and physical impacts and adaptation in other sectors that negatively affect aquaculture, e.g. priority water use for agriculture under climate change.

AR5 recognizes the increased threat of disease to aquaculture under climate change, and many studies have examined the indirect effect of climate change on the spread and occurrence of disease in farmed aquatic organisms, in addition to shifts in the distribution of parasites and pathogens. Vibriosis, for instance, is one of the diseases that may be profoundly affected by climate change since Vibrios grow preferentially in warm waters (> 15^{o}C) and at low salinity (< 25 ppm). Vibrio outbreaks in molluscs have been linked to warming patterns in temperate and cold regions (Rowley *et al.*, 2014). Given that the culture environment for fish and shellfish can be modified to some extent – especially in ponds or recirculating systems – one can mitigate climate-related risks through controlled environments, albeit at an additional cost. However, global aquaculture is largely conducted by small- and medium-scale farmers who have limited resources and access to technical assistance.

A summary of the impacts[2]:

a. Biological: an increased prevalence and virulence of pathogens as a result of higher levels of stress on cultured organisms; a shift in the distribution of pathogens and parasites; harmful algal blooms; the disruption of shell formation in molluscs and crustaceans; a disruption in reproductive patterns; shortage of fish meal and fish oil; reduced availability of natural seed; but also faster growth, higher feed conversion efficiency and higher yield from a higher temperature (as long as it does not exceed the species' range of tolerance).

b. Environmental: the loss or alteration of habitat, eutrophication, harmful algal blooms, severe damage to corals, salinity intrusion – but also an expansion of the range of cultivation of some species.

c. Social and economic: the loss of arable land and culture areas from salinity intrusion, coastal erosion and floods; the loss or disruption of livelihoods from the biological and environmental impacts, and from the loss of stock and destruction of physical structures; physical dislocation; increased public health problems. The elevated risk to production systems also increases the cost of risk management e.g. increased insurance premiums, for instance, as in the Republic of Chile.

d. Gaps: four gaps in research are highlighted, two technical and two strategic (Section 5 provides more details):

- After temperature, the effect of acidification is the most studied hazard, yet its impact on seaweed and fish growth are not well understood (although higher CO_2 concentration might increase sea grass and seaweed biomass).
- Temperature and acidification impacts are mostly linked to the physiology of the species, and rarely to the consequent social and economic impacts.
- A third gap is the identification and understanding of the cumulative and combined impacts of multiple stress factors on species, habitat and communities.
- The fourth is the complicated and fraught task of differentiating the risk impacts from anthropogenic sources and climate change hazards, and understanding how they interact.

The impacts can also be categorized into short- and long-term (see examples below), which can provide a basis for the programming of responses and resource allocation. This might also be a useful guide when developing a strategy that prescribes actions tackling the short-term impacts, on which subsequent actions are built to address the longer-term ones.

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[2] A summary of the various findings on impacts of climate change to fisheries and aquaculture can be found in IFAD (2014); and the impacts of climate change in the Pacific region are described in Bell and Taylor (2015).

BOX 1. Impacts categorized into short- and long-term

Short term	Long term
• loss of production and infrastructure due to extreme events; and • loss of production due to diseases, toxic algae and parasites.	• scarcity of wild seed; • limited access to water for farming; • limited access to feeds (from marine and terrestrial sources); • decreased productivity due to suboptimal farming conditions, eutrophication and other perturbations.

3. SECTOR VULNERABILITIES

The consensus in risk management literature is that level of economic development and strength of governance are the basic determinants of vulnerability. The economic loss resulted from CC-induced risks continues to increase across all regions and seriously threatens low-income countries. Extensive disaster risk mirrors economic development pathways (UNISDR, 2011) and Small Island Developing States are always physically, economically and socially vulnerable (Tompkins *et al.*, 2005). Communities that rely on especially small-scale fisheries and aquaculture are often located in areas that are susceptible to climate change impacts (IFAD, 2014). In addition, there are the inherent features and attributes of the aquaculture sector that influence its vulnerability: whether predominantly small-scale ventures run by resource-poor farmers in the People's Republic of Bangladesh; commercial but still relatively small-scale – such as the shrimp farms in the Kingdom of Thailand and the Pangasius farms in the Socialist Republic of Viet Nam; or large, highly capitalized industrial farms employing large amounts of workers, as in the Republic of Chile, the Republic of Turkey or the Kingdom of Norway.

3.1 Culture environment

Many aquaculture systems are highly vulnerable to natural hazards. Sites are usually located in: low-lying areas; on marginal lands that are fragile and ecologically sensitive and prone to saline intrusion; in lakes or reservoirs which may not hold sufficient water for floating cages or pens over a prolonged drought, and therefore become eutrophic; along rivers and estuaries that could dry up or be inundated with little warning. Coastal areas, and even enclosed or protected bays, are invariably exposed to tidal surges and cyclones. Pond systems, whether brackish or freshwater, are susceptible to the effects of high temperature, erosion and siltation. Freshwater pond systems are usually of low priority in the allocation of surface water. Mariculture would be highly exposed to harmful algal blooms (HABs) and oxygen depletion from the upwelling of anoxic water.

3.2 Species and systems

Several approaches to assessing the vulnerability of species and systems are possible when devising institutional and structural adaptation strategies for farmers and at a local level. However, the most practical approach would probably be to categorise aquaculture units by geography – such as inland, coastal and arid – tropical – and then by farm density and production intensity. Within the same location and with the same farmed species, the combination of technology, farm management practice and area management could reduce the vulnerability of an aquaculture system.

As to a people's dependence on a species, one of the most vulnerable on a national basis is probably Pangasius aquaculture in the Mekong Delta. Apart from the vulnerability to several climate change hazards affecting the Delta where it is mostly farmed, the economy's dependency on this one species is high: over 50 percent of the aquaculture production of the Socialist Republic of Viet Nam is dedicated to this species, it is a major export commodity, and many jobs and livelihood opportunities are at risk along its value chain.

With respect to a specific impact on a specific species, molluscs in coastal aquaculture are probably the most vulnerable to acidification. Daiju, Rehdanz and Tol (2012) estimate that the economic cost to the world of the adverse effect of ocean acidification on molluscs “would be US$100 billion towards 2100, under certain assumptions” (Daiju, Rehdanz and Tol, 2012).

Pearl culture in the Pacific is the biggest export earner for the region; in 2007, pearl, giant clams and shrimp made up most of the US$211 million total export value of aquaculture commodities from the Pacific region (Bueno, 2014). A rise in sea temperature and an increased acidification of the ocean would stress pearl oysters and could affect pearl formation. Pacific cyclones have time and again destroyed onshore and nearshore installations and growing facilities.

Farmed trout, of which 22 percent is based on improved stocks, and farmed Atlantic salmon, 95 percent of which derives from genetically improved stocks (Gjedrem and Baranski, 2009), would be vulnerable to direct impacts (i.e. temperature rise beyond a tolerable range) and the indirect impact of reduced availability of plant- and fish-based raw materials for feed (Troell *et al.*, 2014). A study in the Kingdom of Norway, though, has shown better productivity of Atlantic salmon with warmer seawater: on average, a percentage increase in SST increases the production level by about 9 percent relative to no change in the sea temperature level; but the increase diminishes with increasing SST level (the effect is positive but diminishes as temperature rises). Furthermore, a higher temperature increases the bacterial density in the water and the frequency of algal blooms. Mortality rate will increase for all age groups. If the amplitude and/or average temperature increase to the level where the physiology of the fish is compromised, the probability of mortality rises. Global warming is counterproductive for the industry if the sea temperature increases too much (Lorentzen, 2008).

Tilapias would have a high resilience on a regional basis in subtropical and tropical climes. Several fast-growing strains, including saline-tolerant ones, have been bred. The hatchery technology is relatively easy and inexpensive, and now widespread. Tilapias are known to be highly adaptable to a range of environmental parameters, and notorious for their ability to adapt to and compete with other species over a wide range of ecological conditions. Tilapias are among the most widely bred species for commercial production; they are farmed in 140 countries and territories, and account for nearly 7 percent of world production of farmed aquatic animals, and more than 10 percent of farmed finfish (FAO, 2016).

As a species group, Cyprinids should also have a high resilience: comprising several species, it is grown over a wide climatic range, is artificially bred and the brood stock and hatchery technology is widely adopted. Two species, bighead and silver, are largely non-fed. Carps are versatile and can flourish in a wide variety of habitats including those which are highly degraded. They can tolerate a wide range of temperatures and environmental conditions. They have a higher tolerance to low oxygen levels, pollutants and turbidity than most native fish, and are often associated with degraded habitats, including stagnant waters. Changes to water flows, declining water quality and other changes to river habitats over the past few decades have negatively affected many native fish while favouring carp. Furthermore, in the major producers such as the People's Republic of Bangladesh, the People’s Republic of China and the Republic of India, the predominant culture practice is a polyculture of more than two species of carps, or of carps and other finfish species such as tilapia, Pangasius and Clarias catfish; it is a highly diversified culture system, one generally recognized as resilient.

The high dependence of several developing countries on marine shrimp for export earnings and the high exposure of – mostly coastal – brackish water culture areas to many climate change hazards – coastal storms and tidal surges, flooding, erratic rainfall, and temperature anomalies – make marine shrimp culture highly vulnerable. This being said, in practically all the penaeid shrimp farming countries in Asia and Latin America a large proportion of the recurring and heavy losses have been from disease.

3.3 Farmers: poor and small-scale stakeholders

They are less advantageously placed to avail themselves of opportunities and adapt to threats than larger-scale commercial actors. A strong focus should therefore be placed on building general adaptive capacity that supports poor and small-scale aquaculture producers and value chain actors, in order to make the most of new opportunities and cope with the challenges related to climate change (Phillips *et al.*, 2015).

3.4 Industrial aquaculture: employment

A general situation in commercial and industrial-scale aquaculture operations, including hatcheries, is that about 30 percent of the variable cost is labour, an indication of their sensitivity to risks. For example, a vertically integrated farm in the southern Philippines, ALSONS, whose main product is milkfish (Chanos chanos) and has an annual domestic and export sales of around US$19 million, employs 690 regular workers and usually 1000 contract workers. The processing (deboning) section alone employs around 600 women (Bueno, 2010).

While high-tech operations and good management of large farming companies generally offers good risk prevention and mitigation capability against risks, they remain vulnerable to hazards such as cyclones, red tides and disease, as in the case of the Republic of Chile's salmon farms that suffered from infectious salmon anaemia ISA. In 2008 it was estimated that some 55 000 people were employed in salmon aquaculture in the Republic of Chile, 60 percent of whom were women in processing (Hishamunda *et al.*, 2014). The dependence of many workers along the value chain makes industrial-scale aquaculture sensitive to CC-induced risks. In 2015–2016 the world experienced one of the strongest El Niño episodes. In the fjords and channels of southern Chile where salmon farming takes place, air and sea temperatures were higher than usual and the lack of rain raised the salinity of coastal waters. As in previous El Niño events, more frequent and intense algal blooms occurred. Under these conditions[3], there are at least two species groups causing salmon mortality in the sea cages: Leptocylindrus danicus, a diatom which in high densities can cause local oxygen depletion and damage fish gills, and Chatonella sp., a rafidoficeaen that can produce toxins that affect fish. In less than a month the industry lost millions of fish worth some US$800 million. According to some government estimates and other unofficial reports, at least 12 000 direct jobs were lost in one of the salmon regions. Some estimates indicated up to 30 000 indirect jobs were lost. The impact of climatic phenomena could be even stronger in the future, since businesses and livelihoods in this salmon region (Region X) are strongly dependent on salmon farming. The situation was aggravated by the proliferation of a number of highly toxic species that affected most filter feeders, including bivalves, severely affecting small-scale fisheries of benthic resources. The island of Chiloe in the Republic of Chile, one of the most important aquaculture producing areas in the Americas, underwent such a considerable socio-economic crisis that the government had to provide emergency assistance to fishers and coastal communities. As in the case of ISA disease, a significant proportion of the jobs lost were women's, mostly in post-harvest and processing. The high sensitivity of Chilean aquaculture communities – and even larger cities – is worthy of note, because, whether directly or indirectly, income and livelihoods are heavily dependent on salmon aquaculture.

3.5 Regions

The AR5 (Pörtner *et al.*, 2014) projections indicate the higher vulnerability of tropical ecosystems to climate change, with negative impacts on the communities that depend upon these resources for food and economic security. Climate change will affect food security in Asia by the middle of the twenty-first century, with South Asia being the most severely affected; 89 percent of aquaculture production takes place in Asia, mostly in the tropics and subtropics.

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[3] Information courtesy from Alejandro Clements; Plancton Andino SA. www.plancton.cl

Utilizing a series of indicators of exposure, sensitivity and adaptive capacity in a GIS model, Handisyde, Telfer and Ross (2006) identified the People's Republic of Bangladesh, Cambodia, the People’s Republic of China, the Republic of India, the Republic of the Philippines and the Socialist Republic of Viet Nam as the most vulnerable countries worldwide. Repeating the exercise with better modelling and data, they found that most aquaculture countries in Asia are very vulnerable (Handyside, Telfer and Ross, 2016), with the Socialist Republic of Viet Nam, the People's Republic of Bangladesh, the People’s Republic of China and the Kingdom of Thailand among the most vulnerable considering all environments (freshwater, brackish and marine). In other regions, the Republic of Uganda, the Republic of Honduras and the Republic of Costa Rica appear among the 20 most vulnerable in freshwater aquaculture, the Republic of Ecuador and the Arab Republic of Egypt are very vulnerable in brackish water production, and the Kingdom of Norway and the Republic of Chile appear the most vulnerable in mariculture – El Niño’s latest impacts on Chilean mariculture provide clear evidence of this (see section 3.4 above). In these vulnerability models, sensitivity is estimated through aquaculture production and its contribution to per capita GDP, although by ignoring sensitivity authors can also provide comparative vulnerability estimates of those countries where aquaculture is only beginning but where there is a potential, such as in a number of countries in Africa. Climate change could therefore prevent aquaculture from being a good source of nutritious food and livelihoods.

4. ADAPTATION: DEFINITION, DIMENSIONS, OPTIONS

Adaptation, defined later in this section, essentially involves four basic concepts: vulnerability, resilience, adaptive capacity and sustainable livelihood.

4.1 Vulnerability

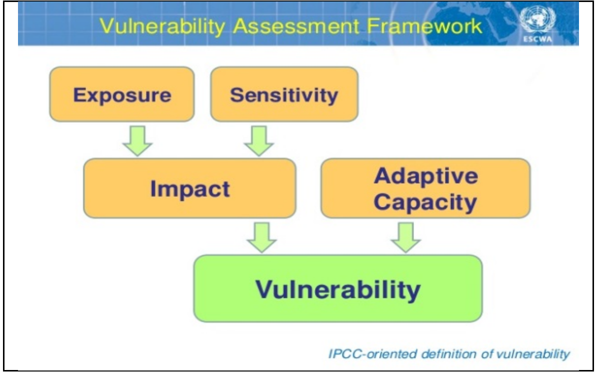
Vulnerability to climate change comprises a combination of exposure to climate change variables, sensitivity to those variables, and the capacity to adapt and build resilience to climate change. An assessment of vulnerability is usually seen as the first step in the adaptation process. A comprehensive discussion on Vulnerability Assessment is provided by Brugère and De Young (FAO, 2015).

- Exposure: the degree to which a system is susceptible to, or unable to cope with, the adverse effects of climate change, including climate variability and extremes.
- Sensitivity: the degree to which a system is affected adversely or positively by climatic stresses. Some use “dependency” as a measure of how serious the impact would be on each of the attributes that determine the overall well-being of the system.
- Adaptive capacity: the ability of a system to adjust to climate change, to mitigate potential damage, to take advantage of opportunities, or to cope with the consequences.

Adaptive capacity is context specific, as illustrated by aquaculture being located in fragile ecosystems in coastal, low-lying and highly exposed areas, and/or in a social context where farmers in an area have poor access to key services, or there is a lack of social cohesion, or where policies which aim to encourage investment in adaptation are absent or poorly designed. On the other hand, adaptive capacity has generic determinants (Yohe and Tol, 2002):

- the range of available technological options for adaptation;
- the availability of resources and their distribution;
- the structure of critical institutions;
- the stock of human and social capital;
- access to risk-spreading/risk-sharing mechanisms, i.e. insurance;
- the ability of decision-makers to manage risks and information; and
- the public’s perceived attribution of the source of stress and the significance of climate change exposure to its local manifestations.

Figure 2. A framework for understanding vulnerability



Source: IPCC, 2001

The IPCC's model of vulnerability (Figure 2) suggests that adaptation is founded on the reduction of vulnerability: adapting to climate change essentially involves: (a) reducing exposure, (b) decreasing sensitivity, and (c) strengthening adaptive capacity. Some practical examples, taken from various literature sources (FAO, IFAD, World Fish/SPC) are listed in Box 2.

One of the most important factors that shapes the adaptive capacity of individual farmers, farm households and farming communities is their access to, control over and ability to use natural, human, social, physical and financial resources productively, i.e. the livelihood capitals.

BOX 2. Purposes of an adaptation measure and examples of management measures

- Reduce exposure to climate hazards:
    - Conserve natural sea defences, i.e. mangrove;
    - Build/improve artificial river banks and sea defences (seawall, embankment);
    - Risk-based zoning (also considering longer-term changes) and site selection (for areas being developed for aquaculture);
    - Raise and fortify pond dikes; dig deeper ponds;
    - Implement safer, flexible and resistant cages, rafts and other holding systems;
    - Upgrade pumps and sluices;
    - Short cycle aquaculture techniques;
    - Closed aquaculture production system, i.e. recirculation aquaculture, aquaponics;
    - Shift production units to less exposed areas, relocate;
    - Minimize fish stress, ensuring plenty of oxygen;
    - Facilitate and enforce safety-at-sea measures.
- Reduce sensitivity:
    - Farm more tolerant species to the important stressors i.e. temperature, salinity, acidification;
    - Reduce dependence on wild-caught seeds;
    - Reduce dependence on fish meal and fish oil;
    - Reduce Feed Conversion ratios and improve feeding efficiency;
    - Diversify species or product range;
    - Diversify livelihoods;
    - Integrated farming systems.
- Increase adaptive capacity:
    - Better weather forecasting, water/environment monitoring, early warning systems;
    - Improved disease surveillance systems;
    - Insurance for crops and farm physical assets;
    - Durable and reliable access assets i.e. roads, power distribution system, water supply system, communications system;
    - Organize and professionalize farmers with the appropriate attention to gender, e.g. fostering women's associations;
    - Establish networks, societies, cooperatives; strengthen social capital;
    - Improve access to markets and fair trade;
    - Fair employment rules and enforcement;
    - Establish Aquaculture Management Areas;
    - Improve access to training and improved technology;
    - Promulgate clear and policies and regulations.

4.2 Resilience

The converse of vulnerability, resilience in the social-ecological context is the system's capacity to absorb recurrent disturbances in order to retain essential structures, processes and feedbacks (Adger *et al.*, 2005). Resilient social-ecological systems incorporate diverse mechanisms for living with and learning from change and unexpected shocks. Disaster management thus requires multilevel governance systems that can enhance the capacity to cope with uncertainty and surprise by mobilizing diverse sources of resilience.

4.3 Livelihood

Livelihood comprises the capabilities, assets and activities required for a means of living (Chambers and Conway, 1992). A livelihood is sustainable when: it can cope with and recover from stresses and shocks, and maintain or enhance its capabilities and assets both now and in the future, without undermining the natural resource base; when it provides sustainable livelihood opportunities for the next generation; and when it contributes net benefits to other livelihoods at the local and global levels.

Definition: On the above conceptual foundation, this review adopts this practical definition of adaptation, with one minor modification:

- A process that aims to develop resilience and capacity in vulnerable communities to enable them to prepare for and respond to potential shocks and trends with minimum costs, and responsibly and ethically take advantage of new opportunities (Daw *et al.*, 2009).

4.4 Options

Adaptation and mitigation responses are underpinned by common enabling factors. These include effective institutions and governance, innovation and investments in environmentally sound technologies and infrastructure, sustainable livelihoods, as well as behavioural and lifestyle choices (IPCC, 2014). These enablers are expanded into a list of ten options under three categories, namely: structural/physical, social and institutional (IPCC, 2014). The following list is an adaptation of the IPCC enablers:

- Structural/Physical:
  - Engineered and built environment (e.g. seawalls and coastal protection);
  - Technology (e.g. genetic diversification, new farming systems and technologies, early warning systems and technologies etc.).
- Social (including resource management):
  - Educational (e.g. integration of awareness-raising into education with the appropriate gender focus);
  - Informational (e.g. hazard and vulnerability mapping, early warning system, community-based adaptation planning, participatory scenario development);
  - Services (e.g. emergency services, social safety nets and social protection);
  - Behavioural (e.g. accommodation, retreat, migration, livelihood diversification, changing aquaculture practices);
  - Organizational (e.g. aquaculture area management under the Ecosystem approach to Aquaculture (EAA) (FAO and World Bank, 2015)).
- Institutional:
  - Economic (e.g. financial incentives including taxes and subsidies, payments for ecosystem services, insurance, microfinance);
  - Laws and regulations (e.g. building standards, defining property rights and land tenure, marine-protected areas, farming and fishing quotas, ethical employment, appropriate incentives);
  - Government policies and programmes (e.g. mainstreaming climate change into national and regional adaptation/development plans, integrated coastal zone management, fisheries

management, community-based adaptation, disaster planning and preparedness.

The ecosystem approach to aquaculture (EAA) is a crosscutting enabler – a strategy that can be implemented at different geographical and management scales – and considers climate change as a relevant external driver requiring adaptation measures. Such measures are included in the aquaculture management plans.

The following tables (1 and 2) provide two perspectives on adaptation options. The first gives examples of specific impacts and the mostly structural and social adaptation options to deal with the impacts. The second is a broader, strategic classification of impacts on ecological well-being, human welfare and sector governance, and describes adaptation options that are mostly institutional and social.

Table 1. Potential adaptation measures for the impacts of different climate change elements

Aquaculture system/culture environment	Impact +/-	Kind of impact	Adaptation
Driver: Temperature			
Cage, pond finfish in all environment	-	Temperature rises above optimal range of tolerance; temperature dips below optimal range of tolerance.	Breed for higher tolerance; short-cycle aquaculture; move production sites to lower altitudes/latitudes (in the northern and southern hemispheres according to temperature changes and trends); for pond systems, build deeper ponds.
All systems/all environments: finfish	+	Higher temperature could stimulate faster growth, higher yield.	Intensify production; increase feed input; improve management practice; tighter control of oxygen availability.
Freshwater: cage	-	Eutrophication and upwelling; mortality of stock.	Risk-based siting, monitoring of water quality.
Marine, brackish- and freshwater	-	Increase virulence of otherwise dormant pathogens; rampant growth of parasites; shift in their distribution.	Monitoring of environmental variables as well as diseases and pathogens; tighter biosecurity measures in general (including early warning and better dissemination of information); increase investment in vaccines and other environmentally friendly prevention methods.
Crustaceans and carnivorous finfish	-	Shortage of fish meal and fish oil	Fish meal and oil replacement; shift to non-carnivores; better feed management practice.
All fed fish	-	Shortage of terrestrial feed ingredients	Better feeds, better feed management practices; shift to non-fed species.
Capture-based aquaculture (e.g. bivalves and crustaceans)	-	Shortage of wild seed and spatfall	R and D in artificial breeding; hatchery production; incentives for more efficient access and use of available seed.
Reef fish culture based on wild seed	-	Destruction of coral habitats; loss of wild seed fishery of mostly high value reef fish species.	R&D in artificial breeding; hatchery production.
Drivers: Rising sea levels and floods			
All systems in coasts, river basins and deltas	+/-	Salinity intrusion	Shift upstream; switch to euryhaline species; however, pond culture of milkfish, seabass or saline tolerant tilapia in brackish water would, for example, have to be completely based on commercial feed as fertilization is ineffective in high salinity water. Research and explore new fertilization methods in saline systems.
	-/+	Erosion of topsoil and loss of land	Opportunity for alternative system i.e. from crop farming to aquaculture.
		Destruction of dikes and water channels, pond siltation.	Flood control dams; stronger and taller pond dikes, greenbelt establishment or conservation; better risk maps, improved siting, appropriate monitoring and early warning systems.
	-	Habitat changes or loss; less wild seed.	Switch to inland aquaculture; recirculation aquaculture system; aquaponics.

Aquaculture system/culture environment	Impact +/-	Kind of impact	Adaptation
Driver: Marine circulation and temperature changes			
Culture of carnivorous finfish	-	Reduced catch from artisanal fishing of low-value fish for feed; reduced availability of fishmeal and fish-oil.	Switch to commercial feed formulations (pellets); switch to terrestrial-based feeds and other by-products.
Mariculture: fish and mollusc	-	Increased fish stress due to suboptimal physiological conditions.	Contingency for emergency management, early harvest and/or relocation.
	-	Increase in harmful algal blooms.	Improved monitoring and early warning systems; physical barriers and other mitigation systems on site; Contingency for relocation of growing sites.
	-	Reduced spatfall.	R and D in artificial breeding; hatchery production; incentives for more efficient access and use of available seed.
	+	Warmer temperature increases spatfall and growth rates, extends latitudinal range for farming.	Mollusc farming offers an alternative to fish culture.
Driver: Acidification			
Most shelled molluscs, including species that produce pearl	-	Adverse effect on shell formation and deposition, probably on pearl development, too.	Move—if at all possible—to other production zones; switch to freshwater aquaculture; For pearls: culture in deeper waters, new sites; R&D for low pH tolerant strains.
Seaweed	-	Exploratory study shows macro-algae may tolerate long-term elevations in CO_2 levels but macroalgal habitats are altered significantly as pH drops.	
Finfish	-	Not well understood but could affect larval development	
Driver: Water stress from prolonged, intense drought			
Pond culture	-	Limits to water supply.	Conservation; efficient allocation and use of water; recirculation aquaculture systems, integration aquaculture-agriculture (e.g. aquaponics).
Culture-based fisheries	-	Water level drops very low in lakes, reservoirs, oxbow lakes, rivers.	Risk mapping to choose more suitable waterbodies; faster growing species; more efficient water-sharing with other users
	-	Decreased availability of wild seed.	Artificial breeding; hatchery produced seed.
Riverine, lacustrine, reservoir cage culture	-	– as above –	Risk mapping to choose more suitable bodies of water and sites. Faster growing, short-cycle species or strains; stock bigger fingerlings. Insurance.
Cage culture	-	Eutrophication and upwelling; algal bloom.	Appropriate monitoring of environmental variables and early warning, insurance, relocation.
	-	Shorter water retention period of lakes, reservoirs, oxbow lakes, rivers.	Faster growing species; more efficient water sharing with other users.
Drivers: Extreme events: tropical cyclones, heavy and prolonged rainfall causing floods			
All systems but especially coastal aquaculture	-	Destruction of structures, facilities; loss of stock; escape of cultured fish; Floods and the heavy run-off of freshwater into coastal aquaculture sites especially those for seaweed lowers salinity and stimulates growth of epiphytes that suffocate the seaweed.	Stronger structures; early warning systems; recirculation aquaculture system; aquaponics; greenbelt conservation; coastal embankment; insurance.

The perspective reflected in Table 2 categorizes impacts into those that affect ecological well-being, human welfare and the capacity for sector governance. The options are largely strategic in nature. The two tables are meant to provide examples rather than an exhaustive list of impacts and adaptation options.

Table 2. Adaptation strategies for impacts on Ecological and Social Well-being, and Sector Governance

Priority impact	Adaptation strategy	Level/scale of implementation
Ecological well-being		
1. Change in water quality parameters and alteration of habitats; increased risk from abiotic (physiological stress) and biotic factors (pathogens, parasites, HABS etc.)	Early warning system: monitoring, information analysis and dissemination	Farm, watershed, zone.
	Carrying capacity considerations (production, environmental and social), better management and biosecurity frameworks; aquaculture diversification, more resistant strains. Better management practices, i.e. better feed and feed management, water quality maintenance, use of higher quality seed.	Watershed/zone/aquaculture management area (AMA).
2. Extreme events leading to the destruction or degradation of natural resources and physical assets	Farmers are prepared to improve farming systems and deal with-avoid, mitigate or cope with-extreme events.	Watershed; zone; Management area.
	Scientific and local knowledge are synthesized; logistics to disseminate information.	Zone; management area
	Biosecurity frameworks are in place.	Zone/management area
	Appropriate environmental monitoring systems and reliable early warning system and a medium-term forecasting service; ensure access by farmers and the population in general.	National
Human well-being		
3. Food security	Integrated farming systems.	Farm
	R&D on new species, breeding for species tolerant to specific or a combination of stressors (disease, temperature, salinity, acidification).	National, Regional, International
	Diversification of aquaculture and of livelihoods in general, value addition, product form diversification.	National, regional International
	Better market access; new markets for new species and new product forms.	Zone; national; regional
	Better management practices, e.g. reducing FCRs, reducing fish stress, ensuring availability of adequate oxygen concentration etc.	Farm/National
4. Food safety	Standards and certification	National
	Safety assurance and control	National
	Information sharing	Regional
Sector Management		
1. Policies, regulations 2. Plans and programmes 3. Institutions	Improve information quality, access and training on climate change risks for the sector, for managers and users.	National, provincial, local
	Investments in R&D on aquaculture adaptation technologies.	National
	Incentives for aquaculture diversification according to risks and opportunities; incentives for diversification	National
	Organizing, strengthening farmers' and women's associations.	Management area National
	Development of national and local vulnerability maps and raising awareness of risks.	Subnational National
	Establishment of national and local (as appropriate) environmental monitoring and early warning systems, with the involvement of local stakeholders.	National to local
	Aquaculture insurance and other risk-sharing schemes.	National
	Spatial planning and management; strengthening cross-sectoral and institutional cooperation and coordination.	Zone National
	Promoting the diversification of livelihoods in more vulnerable areas.	National
	Country strategy and action plan: formulation, dissemination, support for implementation of national adaptation plans; sharing of lessons between countries.	National Regional International

4.5 Adverse impacts of aquaculture

Sector literature is replete with descriptions of the negative impacts of aquaculture on itself and the environment. The four widely covered impacts are: effluent discharge from farms, which pollutes local freshwater resources, marine environments and other fish farms; the escape of farmed fish, which can have detrimental effects on wild fish populations through competition and interbreeding;

the spread of parasites and disease between wild and farmed fish; and the conversion of mangroves into fish farms. Another impact is the use of fish for fish feed, either as ingredient of manufactured feed or as direct feed. An obvious effect of aquaculture on the vulnerability of an ecological system is mangrove clearing. The ecological effects of marine finfish aquaculture have been studied most thoroughly with salmon, but research on other carnivorous species is starting to emerge (Naylor and Burke, 2005). These are risks from aquaculture itself, and adaptation could provide the opportunity to mitigate the risks.

4.6 Aquaculture as an adaptation option for other sectors

The longstanding trend of aquaculture production catching up with that of capture fishery is a broad indication of aquaculture as an adaptation option, for the capture fishery sector at the very least. AR5 states that observed impacts of climatic drivers … and future projections allow for the assumption that a continuously growing global population will be confronted with a reduction of total biomass production from capture fisheries, and thus increasingly dependent on aquaculture production to cover the growing demand for fish (IPCC, 2014).

Reduced ocean productivity will reduce the energy available to higher trophic levels, such as those of pelagic fish. Fishery catches are projected to decrease in temperate and equatorial biomes, a large geographical area of distinctive plant and animal groups, which are adapted to that particular environment by 38 and 15 percent, respectively (IDDRI, 2015).

Climate change impacts that include the deterioration of aquatic ecosystems, increasingly erratic climatic patterns and weather changes are restraining production in all sectors, including aquaculture. On the other hand, aquaculture can itself be an adaptation option for other sectors for reasons including: its ability to respond to demand, improve efficiency of resource use, overcome disease shocks, and the high degree of control over its operation. To illustrate:

4.6.1 Livelihood

Reservoir cage culture in Brazil (AFSPAN, 2016). The introduction of cage culture tilapia in one of the largest reservoirs in Brazil provided displaced, resource-poor households with viable alternative livelihoods in a semi-arid region vulnerable to drought and erratic rainfall. It also reduced the widespread exodus of the labour force through the provision of employment opportunities.

The Republic of Chile has considered aquaculture as an alternative for fishers. The adaptation measure is to strengthen small-scale aquaculture and diversify livelihoods for the fisheries-dependent coastal communities, with due consideration given to different gender needs (Tang and Soto, 2016).

4.6.2 Food and nutrition security

Almost all Pacific Island Countries and Territories (PICTs) look to expansion in freshwater aquaculture – some opt for mariculture – to improve food security in light of the expected impacts of climate change on capture fishery (Johnson, Bell and De Young, 2013).

The most recent El Niño episode provided examples of how aquaculture can be a livelihood alternative for farmers whose crops have been destroyed by drought or, in the case of the Mekong Delta in the Socialist Republic of Viet Nam, both drought and salt intrusion. *The Economist* (2016) reports of a sugarcane farmer who was, “lucky to have a pond full of fish, which he shares with his neighbours”. The anecdote highlights the role of aquaculture as an adaptation option by being one of the enterprises in a farming system.

In a disaster-prone region in the People's Republic of Bangladesh, a study on the coping strategies of 401 aquaculture and non-aquaculture households two years after the destructive cyclone Sidr struck in November 2007 found that almost 80 percent of households were willing to reinvest in aquaculture despite the risk of stock losses and damage to facilities during recurrent disasters. A conclusion derived from the study is that aquaculture ponds are likely to provide a mechanism for coping after a disaster, in spite of the cost of repairing them. The study recommends that aquaculture development be promoted for income and food security for rural families. It cautions, however, that development should occur in areas where it will not compromise other ecosystem functions, such as mangroves. The study recommends the use of fast-growing fish to shorten the production cycle and allow early harvest (Karim *et al.*, 2014).

Opportunities from climate change impacts, i.e. expansion of area for fish farming, integrated systems, conversion of cropland to aquaculture

The rising adoption of polyculture practices opens opportunities for additional food production and income generation for farmers. Adaptive capacity is related to the level of diversity in the aquaculture species farmed in a given country. Farming a wider variety of species could provide more adaptation options to compensate for the uncertain intensity and timing of climate change effects. Based on ecology literature, risks to the ecosystem could be reduced and the prospects for a successful business improved through the diversification of species (Naylor and Burke, 2005; De Silva and Soto, 2009); adding new species would, in effect, increase diversity, or replace the current species with better adapted strains. Diversification in the ecological sense has two components: species richness and evenness. A more diversified community may have fewer species, but total abundance is similar. This is not often the case in aquaculture, and although there is a permanent increase in the number of species being farmed at the global level (up to 500 according to SOFIA, 2016) aquaculture continues to concentrate on a few species. If something goes wrong with one species there may be a global impact and limited options for replacement; this appears to be the case with shrimp aquaculture, which has suffered from waves of viruses and other diseases – such as the WSSV, Taura syndrome and the Acute Hepato-pancreatic Necrosis Disease or AHPND heretofore called early mortality syndrome or EMS.

By the same token, diversifying livelihood enterprises (farm and non-farm) increases coping ability (Karim *et al.*, 2014) and adaptive capacity to unforeseen and long-term changes.

In the coastal region of southwest Bangladesh, the increasing area of waterlogged croplands are now being redesigned and developed for crop-aquaculture systems. Shrimp or freshwater prawns are grown in the ponds, and vegetables and other field crops grown on the wide and raised embankments. In the northeast, where rainfall has become erratic and flooding of the haors has affected the fisheries, cage culture has been proposed as a means to produce fish during the dry season, when the floodwaters abate and the haors[4] become very shallow. (As seen directly or related by local stakeholders and national project staff to the authors during an FAO mission to the People's Republic of Bangladesh in November-December 2014 to develop a GEF-funded project on adaptation of aquaculture to climate change).

In the Socialist Republic of Viet Nam, in the low-lying terrain of many provinces, most rice farms can only produce one crop because of flooding. This often drives farmers to abandon the farmland. In 1999 the government passed a decree that allows farmers to convert inefficient low-lying rice paddies into aquaculture in order to alleviate poverty by increasing productivity. This new policy had a positive impact: a case study (under the AFSPAN project) found an increase in overall farm productivity, more jobs created and higher income for farm households (Phillips and Belton, 2014).

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[4] Haor is a wetland ecosystem in northeastern Bangladesh, which has the physical appearance of a bowl- or saucer-shaped shallow depression.

5. RESEARCH GAPS

A scan of 76 studies and reviews revealed that 94 percent of the reviewed literature focused on the impacts on fish production ecology-including physiology, phenology, and optimal habitat; 49 percent focused on other activities in the food system such as aquaculture operations and post-production.[5]

5.1 Gaps in the science[6]

Indirect impact of feed source disruption

Timmers (2012) highlights the need to reflect on the impacts climate change could have on crops for feed and how higher prices could alter the economic viability of farms.

5.1.1 Food chain

Vermeulen *et al.* (2012) indicate that evidence regarding the impacts of climate change on the postproduction food chain is scattered but it, “can affect volume, quality, safety and delivery of food in the postproduction stages”.

More work on species being cultured in developing countries.

Vermeulen *et al.* (2012) pointed out the apparent bias towards analysis of high-value species in industrialized countries. This may be related to the considerable work being done in the Northern hemisphere.

5.1.2 Impact on habitats

Somewhat absent from the literature reviewed is the very specific relationship between species and habitat depending on optimal thermal limits and salinity levels. Only 16 percent of studies focused on the impact of climate effects on habitat. Aquaculture facilities are largely fixed in space and, unlike the motorized fleets of capture fisheries, cannot readily move to a nearby location with more optimal conditions. Of the studies looking at habitat impacts, almost all of those reviewed hypothesized how optimal conditions would change, but did not conduct empirical research on the question. Few projected where optimal conditions would move for aquaculture species. Modelling exercises should be conducted on aquaculture systems at multiple scales in order to create models that could inform political decision-making and adaptive management.

5.1.3 Human health

Very few studies investigated the impacts of climate change on the public health of consumers of farmed fish. The relationship between toxic algae – particularly harmful algal blooms – and climate change has been heavily discussed as a topic, but how this translates into impacts on farmed species and human health is not well understood (Moore *et al.*, 2008). So far, improving the surveillance of blooms and shutting down aquaculture sites when toxins exceed regulatory limits have proven to be positive actions to prevent negative impacts on human health (James *et al.*, 2010).

5.1.4 Social and economic impacts

One study focused on the social and economic impacts of recent inundation in southwestern Bangladesh. Respondents reported that the flooding had a direct impact on aquaculture infrastructure;

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[5] Studies/reviews were screened from 1 106 documents relevant to climate change impacts on aquaculture and fisheries, published between 2000 and 2013, though it was not until 2007 that the surge in studies on climate change and aquaculture began.

[6] See “Acknowledgements”, page vii.

it also increased the prevalence of disease in people, leading to a deterioration in their health and sanitation conditions (Ali, 2006).

An FAO mission to formulate a GEF-funded project on aquaculture resilience and adaptation in the People's Republic of Bangladesh, joined by the authors (November-December 2014), highlighted two consequences of the combined CC impacts on resources, physical assets (owned and accessed), livelihood and health: social conflict and the erosion of self-reliance among households and communities.

5.2 Research to enhance adaptation by farming households, farming communities and industry

5.2.1 Socio-economic pathway

The reviewed literature indicated few well-studied pathways between climate change and aquaculture impacts; it focused largely on the physiological and economic dimensions of impacts on the aquaculture system. Furthermore, the research conducted concentrated on pathways linked to production ecology impacts more than those connected to socio-economic impacts. The impacts of physiology were studied in depth across all climate effects reviewed. On the other hand, economic dimensions – the second most commonly linked impact – were linked half as frequently across climate effects. It would therefore be useful for adaptation at levels above the farm (i.e. household, clusters and community) if research on temperature and acidification, for instance – both of which are generally well-studied and commonly linked to physiological impacts – were extended to research that describes and analyses their social and economic consequences.

5.2.2 Consideration of the value chain’s processing and marketing steps

Almost 80 percent of all studies report on adaptation at the production level; however, there are very few studies reporting on adaptation further down the value chain. Only one report (Timmers, 2012) proposes adaptation strategies at all levels of the value chain, for the adaptation of fish farming to climate change in the Republic of Uganda.

5.3 Research to inform policy

5.3.1 Multiple impacts

Research on the multiple, interactive impacts of climate change on aquaculture production areas, especially in vulnerable coastal regions, is understudied but has the potential to inform climate policy and benefit public health in local communities. A study on the impacts of multiple climate change variables (Nesar, Occhipinti-Ambrogi and Muir, 2012), including cyclones, rising sea levels, floods, drought, salinity fluctuation in brackish water environments, temperatures and rainfall patterns on the livelihoods and welfare of poor people dependent on gathering wild fry of freshwater prawn in a coastal area of the People's Republic of Bangladesh showed that:

- the alteration of the ecology of the coastal waters and brackish stretch of the river where prawn fry resources have been abundant was the key impact that gave rise to the other impacts, such as scattered distribution of the fry, change in reproductive pattern and abundance;
- while there were positive and negative effects on the fishery of freshwater prawn fry, the net effect is a growing scarcity of the resource;
- the welfare of fishers – especially the women – is adversely affected by extended exposure to the elements, as they spend more time looking for and catching fry even as their gear is occasionally destroyed by cyclones and flooding;
- people’s health is adversely affected by the decrease in income and therefore the ability to afford food and medical care;

- direct impacts, which include erosion or the inundation of habitations, have forced relocation;
- as can be expected, cyclones destroy assets.

In this case, adaptation to the multiple impacts would require a plural approach: a mix of physical, social and institutional options to enhance the sustainability of the community's livelihoods (the option of relocating to inland areas, while possible, is extremely difficult in a densely populated country).

5.3.2 The pathways of climate change impacts

Research on multiple climate effects with cumulative impacts on aquaculture systems is absent from the reviewed literature. The lack of scientific basis creates an uncertain environment for policy formulation and programme interventions. There is a need to better assess the interactive effects of different climate variables: identifying and understanding pathways between climate effects and aquaculture impacts would better inform strategies that aim to mitigate adverse impacts and encourage adaptation to change. The study cited earlier on a coastal area in the People's Republic of Bangladesh illustrates the need for this research focus.

From the workshop reports reviewed, only one report explicitly worked out options for integrating processing and commercialization into future adaptation measures, the case study conducted by the Network of Aquaculture Centres in Asia-Pacific (NACA) in the Republic of the Philippines (AquaClimate) (NACA/SEAFDEC, 2012).

6. MAINSTREAMING AQUACULTURE INTO NATIONAL ADAPTATION PLANS[7]

Incorporating the sector into national adaptation action plans requires an assessment of the weaknesses and gaps in governance and practices that reduce a country's capacity for adaptation. FAO has been monitoring the implementation of the 1995 FAO Code of Conduct for Responsible Fisheries (CCRF) with an aquaculture-specific questionnaire for Members. The most recent assessment, in 2014, shows there remain numerous institutional and governance weaknesses in addressing climate change, especially in regions where aquaculture is starting to develop. Government preparedness to mitigate climate change risks requires a good understanding of the sector's vulnerability at both the local and national level. This remains as a global gap and should be a priority in order to build preparedness and foster adaptation measures.

Another essential measure, aquaculture zoning, is weak globally, but particularly in regions where the sector is yet to grow. The inclusion of climate change and other risks into spatial planning and aquaculture zoning is urgently needed in areas and countries where aquaculture is beginning to develop. Where aquaculture has developed to such an extent that it is now difficult to relocate systems, the concept of risk-based area management becomes essential (FAO and World Bank, 2015).

Two other essential measures, government post-disaster assistance and farmers' access to insurance, are very limited. As fish disease is a frequent cause of significant loss in aquaculture, having adequate fish health management and biosecurity in place are essential to the sector's resilience. The global scoring is higher for these than other measures indicating higher implementation. However, with climate change intensifying the seriousness (frequency, severity and prevalence) of disease, a much better implementation is required, especially in Asia where aquaculture is more concentrated, with a very high density of farms.

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[7] This section draws much from the article, Aquaculture and Climate Change: from Vulnerability to Adaptation" contributed by the authors to *The State of World Fisheries and Aquaculture 2016* (FAO, 2016).

“Good to have” measures such as farmers’ access to institutional credit is scored very low; this may be a major obstacle for small farmers to improve farming conditions and invest in climate-resilient technologies such as more sturdy cages, deeper ponds, better water systems or improved seed.

The scoring indicates a limited integration of aquaculture into coastal zone and watershed management schemes. This undermines efforts to gain resilience; adaptation measures in other sectors (e.g. agriculture) could also be detrimental to aquaculture (e.g. water diversion, coastal walls and levies, and even roads).

Implementation and enforcement of ecosystem function considerations (such as mangrove coastal protection) and providing incentives for their restoration and rehabilitation receive a low and very low score, respectively. This emphasizes the need for a better understanding of threats and the importance of ecosystem services to the long-term success of aquaculture under climate change by the users and planners of the sector’s development.

Better management practices (BMP) to increase the resilience of farmed organisms and farming systems are also “good to have”, and had a slightly higher score, which is a good take-off point for increasing resilience. BMPs should be evaluated however, and climate change threats incorporated into the practices.

7. CAPACITY BUILDING MEASURES: SUSTAINABLE LIVELIHOOD APPROACH AND ECOSYSTEM APPROACH TO AQUACULTURE, SUPPORTED BY RISK ASSESSMENT AND MANAGEMENT ALONG THE VALUE CHAIN AND FEASIBILITY ASSESSMENT

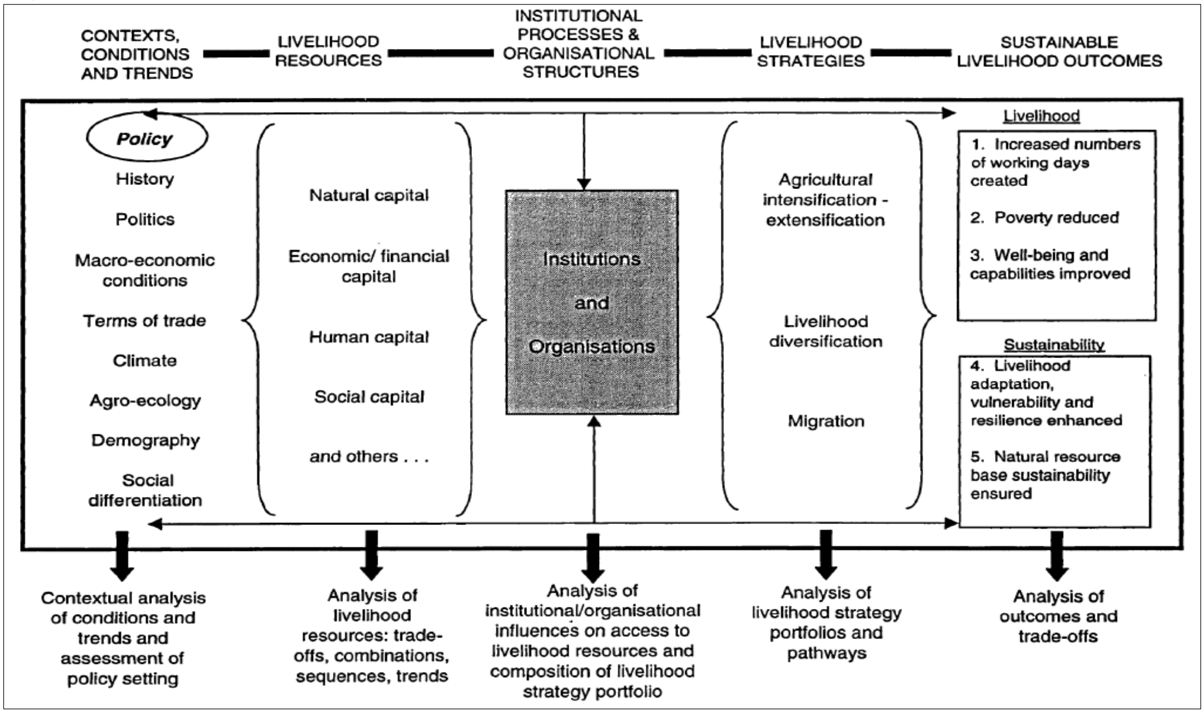
This section describes the capacity building measures designed to implement the strategic measures and technical options for adaptation described and recommended in sector literature effectively, numerous examples of which are described in earlier sections of this review.

The definition of sustainable livelihood comprises five elements (Scoones, 1998):

- creation of gainful employment (for subsistence, wage and/or status)
- poverty reduction
- well-being and capabilities
- adaptation, vulnerability and resilience
- natural resource base sustainability

The last two – adaptation, vulnerability and resilience and natural resource base sustainability – impart the sustainability dimension. The ability of a livelihood to cope with, and recover from, stresses and shocks is central to the definition of sustainable livelihoods. Such resilience in the face of stresses and shocks is key to both livelihood coping and adaptation. Those who cannot cope (temporary adjustments in the face of change) or adapt (longer-term shifts in livelihood or business strategies) are inevitably vulnerable and unlikely to achieve sustainable livelihoods. Most rural livelihoods are reliant on a natural resource base to some extent. Natural resource base sustainability refers to the ability of a system to maintain productivity when subject to disturbing forces, whether a ‘stress’ (a small, regular, predictable disturbance with a cumulative effect) or a ‘shock’ (a large infrequent, unpredictable disturbance with immediate impact). This implies avoiding the depletion of stocks of natural resources to a level that would result in a permanent decline in the rate at which the natural resource yields useful products or services (Scoones, 1998).

Figure 3. Sustainable Rural Livelihoods: a framework for analysis



Source: Scoones, 1998.

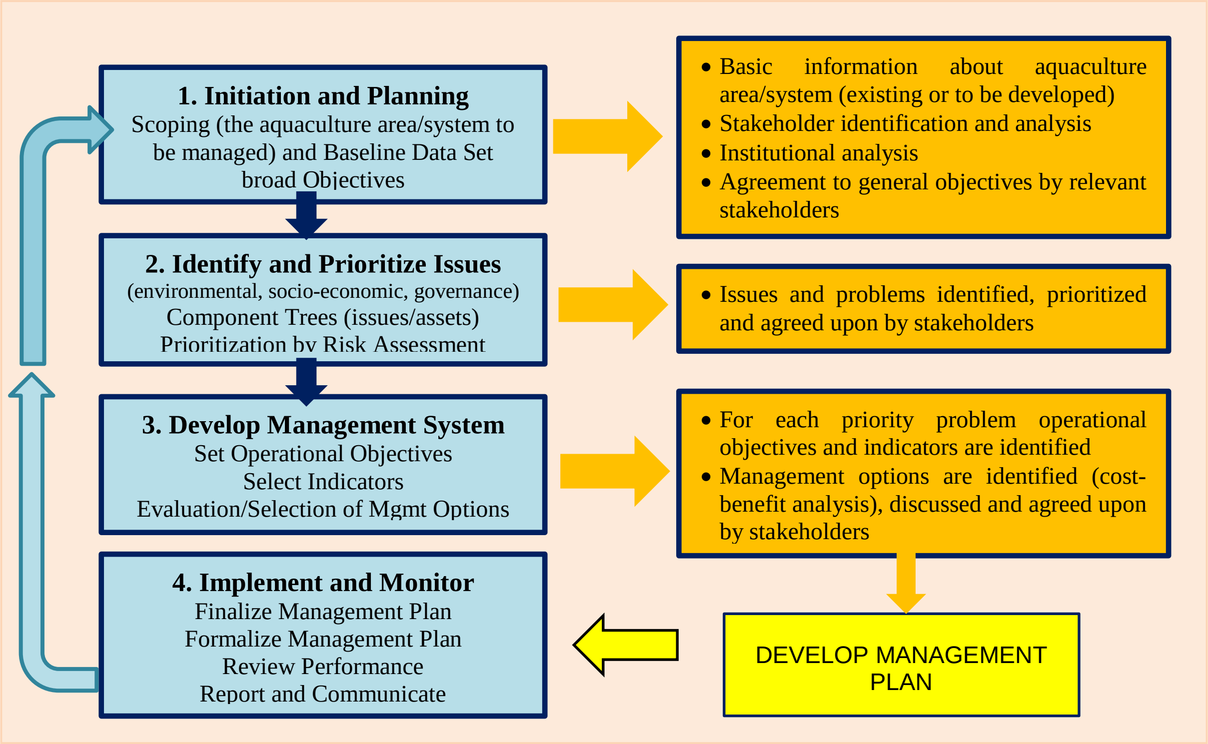
Figure 3 is suggested as a framework for the analysis of sustainable rural livelihoods. Central to the framework is the analysis of the range of formal and informal organizational and institutional factors that influence sustainable livelihood outcomes. The sustainable livelihoods approach (SLA) is thus a suitable framework for: (a) selecting the technical interventions that fit a community’s livelihood strategies and resource endowments; and (b) devising measures that strengthen adaptive capacity, reduce vulnerability and increase the resilience of a system – in short – building the capacity for adaptation. It can accommodate the IPCC’s three categories of adaptation options i.e. physical/structural, social and institutional. In this regard these capacity building strategies are suggested:

- General
  - SLA. Based on the preceding discussion, the priority recommendation is to promote livelihood analysis in aquaculture development planning and project formulation, and train planners and development workers on the concept and process of the sustainable livelihoods approach (SLA). This ensures that the choice of technical adaptation measures is compatible with the livelihood objectives and strategies, as well as the assets of the community or of certain groups within the community, especially women. Just as important is for the analysis to show: (a) which livelihood capitals need strengthening, (b) how to improve access to the assets, and (c) the roles in these (i.e. strengthening and access) of formal and informal institutions and the capacities they need to perform their roles effectively.
  - Risk analysis and management. The second general recommendation is to infuse all plans and projects with the concept and practice of risk analysis and strengthen the capacities of organizations and institutions – as well as increase the awareness of the farming communities – in risk analysis and management. Planning for and executing adaptation measures is essentially informed by hazard identification, characterization and risk assessment, followed by risk management. The risk impacts along the value chain need to be properly assessed, communicated and managed.
  - Lessons from applications. The experiences of states that have already begun implementing their respective national action plans for adaptation (NAPAs) could now be collated and analysed, in order to share and apply the lessons learned from their implementation.

- Structural/Physical
  - Plans for structural adaptation options such as coastal embankments and greenbelts should involve the stakeholders from the sectors that benefit from these structures, such as aquaculture, agriculture, tourism and even habitation. It would be preferable to design a project for public-private partnership. For any project that requires significant financial investment, and particularly for those involving built structures, a feasibility study should also be carried out; this can be an effective tool not only to justify investment, but also to gain broad support from stakeholders for its establishment and maintenance. It contributes to transparency in decision-making.
  - The development of a reliable early warning system would likewise include all the sectors benefitting from it, in addition to the public institutions and private organizations that form part of the chain of service providers, including the mass and social media.
  - A medium-term forecasting service should be provided to the production sector as a valuable guide for investment and planning (Bell and Taylor, 2015).
- Social
  - Livelihood analysis is integrated into adaptation planning. Livelihood diversification is one of the most recommended adaptation measures in fisheries and aquaculture (Weatherdon *et al.*, 2015). A livelihood analysis component would imbue an adaptation plan with a holistic perspective rather than a piecemeal and narrow approach: adaptation therefore becomes part of a sustainable aquaculture development plan. Additionally, it is hugely important for the livelihood analysis to identify what would be the most effective role of – and capacity building needs for – women and young people in livelihood diversification and adaptation in general.
  - Local environmental monitoring. Aquaculture is highly sensitive to sudden changes and long-term trends. However, there are very few cases of integrated monitoring systems providing information that fish farmers can use to make decisions. Simple data (e.g. water temperature, water transparency, water level, fish behaviour, salinity etc.) collected on a continuous basis and preferably institutionalized can provide a useful basis for decision-making, especially when changes can produce dramatic consequences. Locally collected and shared information can contribute to farmers' better understanding of biophysical processes; the information is worked into short-term coping measures, longer-term adaptation measures and early warnings, as well as investment decisions. To implement such monitoring systems, activities include the training of local stakeholders on the value of the monitoring and how to use the feedback for decision-making. A simple information system should be devised to receive, analyse and share the information, coordinate and connect with broader forecasts, and provide timely feedback to local stakeholders (FAO, 2016).
- Institutional
  - Governance. Strengthening governance – formal and informal institutions, policies and regulations – is always among the strategic recommendations in disaster risk management, as well as integrating the planning and management of climate change preparedness for the various economic sectors under one strong authority. At the sector level, the ecosystem approach to aquaculture (FAO, 2010) provides the concept and mechanism for coordinated management. Training in the concept and practical application of EAA should thus be provided to the country's disaster-risk-management personnel, and applied is in spatial management. The implementation of an EAA is more effective when applied to an aquaculture management area (see Spatial management bullet below) where the management plans in place to address the environmental, socio-economic and governance issues consider climate change as a crosscutting element to be addressed (see Figure 4). Developing a management plan implies identifying those priority issues that could be an obstacle to the achievement of agreed objectives, e.g. an expected level of production. Aquaculture is typically threatened by floods or drought; therefore, after the risks are assessed, specific management measures must be agreed and implemented (see Box 2 and Table 1). EAA management plans must also involve SLA and a livelihood analysis: specifically, potential diversification mechanisms that are not always considered an

adaptation mechanism within the realm of the aquaculture sector.

Figure 4. A typical EAA management plan development and implementation process which can include climate change-related issues.



- Spatial management (comprising zoning, site selection and area management). The physical location of aquaculture facilities is one of the most relevant determinants of exposure and therefore of vulnerability. For example, the location of fish cages in a coastal zone must consider their exposure to weather events, changes in currents, or to a sudden influx of freshwater from upstream, in addition to longer-term trends such as rising temperature and salinity and decreasing oxygen levels. Such information is essential in defining zones for aquaculture and deciding on the location of individual farm sites. The spatial distribution of inland and coastal ponds in many places around the world has responded more to land and water access opportunities than protection from external threats. The inclusion of climate change and other risks into spatial planning and aquaculture zoning is urgent in areas and countries where aquaculture is beginning to develop (FAO and World Bank, 2015).
- Where aquaculture has developed to an extent that it is now difficult to relocate systems, risk-based area management is needed (FAO and World Bank, 2015).
- Value chain. A failure in one segment of the chain invariably affects the entire chain. Various impacts on the aquaculture value chain should be assessed and an adaptation strategy developed for the entire chain.

7.1 The role of consumers

Consumers have an important role in the adaptation to climate change and the mitigation of its impacts. They need to understand the climate change-associated risks to food systems including aquaculture, and appreciate the role of market-based incentives in the reduction of risks. Better management practices, codes of practice, ecolabels, social labels, certifications and standards are ways by which the consumer – or more broadly, the market – can have a major influence on increasing the sector's capacity for adaptation. The market is a powerful governance mechanism and the use of market-based initiatives to make the sector environmentally and socially responsible also makes it resilient, less vulnerable, and adaptive.

8. CONCLUSION

Since 2014, farmed species have become the main source of fish for human consumption. By 2021 aquaculture is set to surpass total capture fisheries (including non-food uses) and is projected to reach 57 percent in 2025 (OECD/FAO, 2016). Aquaculture will need to continue to work efficiently in order to provide food, materials and services to a growing world population in the face of the uncertainties and risks posed by a changing climate. To do so it must adapt to the changes.

The key suggestion from this review rests on two pillars: (i) use the sustainable livelihood framework (NACA, 2012) to assess potential strategic and technical adaptation options and (ii) adopt the ecosystems approach to aquaculture management, in order to integrate the governance and implementation of the adaptation strategy. These are supported by risk assessment and risk management along the value chain and by the feasibility assessment of potential options.

To summarise:
- SLA fosters a wider participation of primary and other stakeholders in the process of searching for, designing, deciding on, adopting and executing adaptation options. It ensures the compatibility of the adaptation choices with the livelihood strategy, resource endowments and strengths of the target community; moreover, the options not being imposed by a rigid, top-down mechanism contributes to increasing adaptive capacity.
- As a strategic component of adaptation, the sustainable livelihoods approach requires the assessment of the influence of policies and institutions on livelihood options: it highlights the kind of policies needed to meet the people’s priority needs and the institutional capabilities to design, deliver and put into action policies and programmes.
- The ecosystems approach to aquaculture management allows for intersectoral integration and the coordination of adaptation plans and programmes: it ensures that any adaptation strategy for aquaculture does not undermine those of other sectors or groups within the sector; it can foster synergy with the management of the other sectors.
- The value chain perspective of risk assessment and management avoids fragmented and discrete adaptation measures along the chain.
- Feasibility assessments inform transparent decision-making over an investment; with a cost-benefit analysis, they show the distribution of the cost and benefits of an investment, and would suggest policy that enables an equitable sharing of benefits.
- This approach, based on the two pillars and the two support tools, also reduces the chance of maladaptation, defined by IPCC in its Third Assessment Report as an adaptation that does not decrease vulnerability but in fact increases it (more specifically, it is “action taken to avoid or reduce vulnerability to climate change that impacts adversely on, or increases the vulnerability of other systems, sectors or social groups”). The desired outcome, at the very least, is the absence of destructive competition or outright conflict; the ideal is a resilient ecological system and a cohesive, resilient and highly adaptive social system: the foundations of equitable and sustained economic development, in other words.

We conclude with the contention that subjecting an adaptation measure to these approaches and tools would endow it with the four elements of success as proposed by Adger, Arnell and Tompkins (2005), namely: effectiveness, efficiency, equity and legitimacy. Briefly, effectiveness relates to the capacity of an adaptation action to achieve its objectives: it can be gauged through reducing impacts and exposure to those impacts, or in terms of reducing risk and avoiding danger and promoting security. Economic efficiency relates to the cost of and benefits from adaptation; assessing economic efficiency also requires consideration of the distribution of costs and benefits of the action, the costs and benefits of changes in those goods that cannot be expressed in market values, and the timing of adaptation actions. Equity in outcome can be evaluated on the basis of who gains and who loses from the adaptation action, and who decides on taking it. Legitimacy is the extent to which decisions are acceptable to participants and non-participants who are affected by these decisions.

SLA would impart efficiency and legitimacy. EAAM would impart effectiveness, equity and legitimacy. Risk assessments of the value chain would impart efficiency and effectiveness, while feasibility assessments supported by cost-benefit analyses would impart equity, legitimacy and efficiency.

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