Food and Agriculture
Organization of the
United Nations

FAO
FISHERIES AND
AQUACULTURE
TECHNICAL
PAPER

627

ISSN 2070-7010

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Synthesis of current knowledge, adaptation and mitigation options

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FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 2018

ISBN 978-92-5-130607-9

Chapter 20: Effects of climate change on aquaculture: drivers, impacts and policies

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KEY MESSAGES

- Growth of aquatic food supplies to meet demand will come mainly from aquaculture for the foreseeable future; it is therefore essential that we understand the effects of climate change on the sector from the broad to the finest spatial scales.
- Countries considering aquaculture in their Nationally Determined Contributions are mostly located in the developing countries, especially in Africa.
- Direct and indirect climate change drivers may result in favourable, unfavourable or neutral changes in aquaculture, in the short- or long-term and at different spatial scales. Unfavourable changes are likely to predominate in the developing countries, adversely affecting investment and sector growth.
- Several adaptation measures are already available to mitigate impacts of negative changes or increase resilience. They must be considered in accordance with multi-sector National Adaptation Strategies.
- Knowledge gaps in science, institutional and socio-economic change and policies hamper more effective adaptation of aquaculture, especially in the developing countries.

20.1 INTRODUCTION

Although capture fisheries continue to play a major role in the livelihood, food security and nutrition of millions around the world (FAO, 2016c), most global aquatic products now come from aquaculture (Chapter 3). By supplying an increasing amount of fish, crustaceans and molluscs, the sector not only contributes to meet growing demand for the foreseeable future, but also helps dampen price rises (Béné *et al*., 2016). It is thus paramount that we understand the likely interactions between climate change and aquaculture – for both mitigation (Chapter 27) and adaptation – and help to build resilience and adaptation, especially among the many small-scale practitioners who still account for most of the production by the sector.

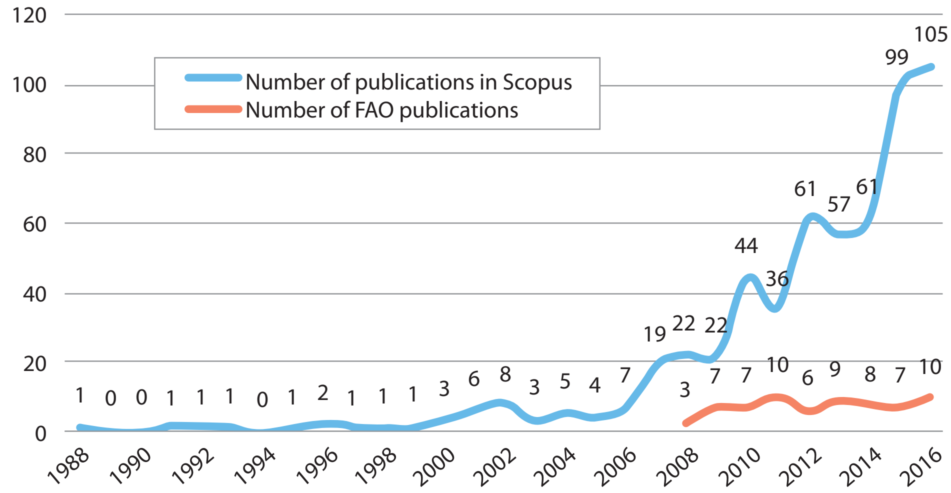
Despite its long history (Beveridge and Little, 2002), for the most part aquaculture must be considered a modern industry – indeed, in 1950 aquaculture accounted for only 3 percent of global aquatic products supplies (Fishstat, FAO[1]). The difficulties of farming

[1] http://www.fao.org/fishery/statistics/en

aquatic environments, exposed as they are to the vagaries of waves, storms and flooding, are argued to have been a major disincentive to the wide-scale uptake of aquaculture, at least until recently when modern materials and designs became available.

The first mention of research on climate change and aquaculture in the scientific literature was at the end of the 1980s[2] but it took more than 15 years after that for researchers to invest significant effort on the topic (Figure 20.1). The uncertainties related to climate change – aquaculture interactions are likely one of the reasons why it was not prioritized earlier. To date, the climate-related issues considered in research have included global and marine/fishery models, impacts on fish and shellfish biology, disease, habitat changes (temperature, acidity and salinity) as well as livelihoods, resilience and sustainability assessment.

FIGURE 20.1
Numbers of published scientific papers per year dealing with aquaculture and climate change in Scopus and FAO databases, as a proxy of interest in the issue



The terms aquaculture and climate change were searched for in the title and/or abstract. The Scopus database includes peer-reviewed papers published in scientific journals, books and conference proceedings. The FAO database includes all publications released by the organization.

The Intergovernmental Panel on Climate Change also highlighted a number of potential impacts of climate change on aquaculture as early as 1990 (Tegart, Sheldon and Griffiths, 1990), but it was only in 1995 that for the first time the sector merited a dedicated chapter (Watson, Zinyowera and Moss, 1995). After the Fourth Assessment Report, released in 2007, the issue became truly mainstreamed in global discussions (Parry *et al*., 2007).

During the twenty-seventh session of its Committee on Fisheries in March 2007, FAO was requested to undertake a scoping study to identify the key issues, to initiate a discussion on adaptation, and to take a lead in informing stakeholders and policy-makers. As a result, in 2008, the FAO Fisheries and Aquaculture Department held an Expert Workshop to provide the FAO Conference with a comprehensive overview of the fisheries and aquaculture climate change issues. This resulted in the publication of the FAO Fisheries Report No. 870 (FAO, 2008), followed by the release of an overview of the scientific knowledge (Cochrane *et al*., 2009).

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[2] The oldest paper in the Scopus database is **Sherwood, J.E.** 1988. The likely impact of climate change on south-west Victorian estuaries. *In* G.I. Pearman, ed. *Greenhouse: planning for climate change*. CSIRO, Melbourne, Australia. pp. 456–472.

20.2 IMPACTS OF CLIMATE CHANGE DRIVERS ON AQUACULTURE

Direct and indirect climate change drivers can be responsible for changes in aquaculture, whether in the short- or long-term. Examples of short-term impacts include loss of production or infrastructure due to extreme events, diseases, toxic algae and parasites; and decreased productivity due to suboptimal farming conditions. Long-term examples include scarcity of wild seed, limited access to freshwater for farming, limited access to feeds from marine and terrestrial sources, decreased productivity due to suboptimal farming conditions, eutrophication and other perturbations. These are well described by De Silva and Soto (2009), Santos *et al*. (2016) and FAO (2017a). Tables 20.1 and 20.2 list some of the likely impacts at different scales, from modification of the metabolism of aquatic organisms to those operating at global scales. Note that there may also be location-specific positive effects, potential complex interactions between drivers (e.g. mutual cancellation or amplification), or new drivers emerging from adaptive strategies, which are not considered here.

TABLE 20.1

Direct climate change drivers, possible overall impacts on aquaculture and adaptations at different scales. For a given scale: green = overall favourable impact, yellow = potentially both positive and/or negative, red = overall unfavourable change

Drivers		Aquatic organisms	People	Farming system	Land-Seascape/AMA[3]	Country	Global
Warming	Potential impacts	• Increased metabolism and growth rate	• Increased production, improved feed conversion and shorter production cycles should translate into a more profitable sector and higher income	• Increased farm production • Improved feed conversion efficiency for species with higher thermal tolerance • Shift to shorter production cycle aquaculture; intensified production	• Need for informed spatial planning, which, among others, would also reduce potential conflicts with other sectors and contribute to the effective management of aquaculture zones.	• New areas become favourable to aquaculture (higher altitude), while others become unfavourable • Increased monitoring of environmental variables	• New areas favourable to aquaculture (higher latitude), others become unfavourable • The most resilient species may develop on a large scale
		• Increased plankton respiration and proliferation • Changes in mollusc spatfall • Changes in reproduction and sex ratios • Increased/decreased transmission of some diseases	• Relocation of some farming facilities (e.g. seaweed, finfish, shellfish) to cooler/deeper areas in the sea may create new safety risks • Moving facilities may affect livelihoods and increase production cost	• HABs may force farm movement/closure or installation of depuration facilities • Effects of increased jellyfish blooms on marine farms • Lower feed conversion efficiency for species subjected to increased stress	• Increased stratification in lentic systems • Changes in nutrient circulation		
		• Species with a narrow thermal range may no longer be farmed • Increased sensitivity to other drivers (e.g. acidification, pathogens) • Increased Harmful Algal Blooms (HABs)			• Some areas may become unfavourable to farming • Changes in the performance of the supply of ecological services to aquaculture • Increased local eutrophication		
	Adaptation measures	• Farm species and/or strains with higher thermal tolerance • Move farming facilities to cooler/deeper offshore or inland areas	• Adopt guidelines on decent work in aquaculture (e.g. FAO, 2016b)	• Selective breeding for thermal tolerance • Adjustment in farming calendar/practices • Change of farmed species • Climate-smart facilities (e.g. deeper ponds, etc.)	• Closure and relocation of production sites • Spatial planning for determining new favourable and unfavourable areas • Risk-based siting	• Closure and relocation of production sites • Spatial planning to determine new favourable and unfavourable areas	• Spatial planning to determine new favourable and unfavourable areas

Drivers		Aquatic organisms	People	Farming system	Land-Seascape/AMA[3]	Country	Global
Acidification	Potential impacts	• Seaweed sequestering excess dissolved CO_2 may benefit, possibly also contributing locally to some impact mitigation • Changes in bivalve reproduction • Slower growth rates in shell-bearing organisms and corals • Weakened $CaCO_3$ shells and skeletons • Changes in pearl formation in oysters • Impaired growth in some marine finfish, especially embryonic and larval stages • Eutrophication exacerbates ocean acidification	• Some shellfish farming may have to be discontinued or moved to more favourable sites, creating new safety risks • Moving facilities may affect livelihoods	• Spat may have to be bought from new sources • Selective breeding for acidity tolerance • Shellfish hatcheries relying on natural marine water may have to move to more favourable areas	• Reduced spat availability in some areas • Changes in the ecosystem supplying ecological services to aquaculture • Fish production relevant for aquafeeds may be negatively impacted	• Lower shellfish production • Mass die-offs of oyster larvae in hatcheries • Pearl culture in deeper waters/ new sites	• Seaweed farming may develop
	Adaptation measures	• Shift in farmed species or strains, especially of shell-bearing organisms and corals • Move farming facilities to new areas offshore or inland	• Follow guidelines on decent work in aquaculture (e.g. FAO, 2016b)	• Move farming facilities to new areas offshore or inland	• Move farming facilities to new areas offshore or inland	• Closure and relocation of production sites	• Mainstream spatial planning
Hypoxia	Potential impacts	• Species and/or strains with higher tolerance should be less affected • Increased mortality • Reduced growth • Higher sensitivity to other drivers (e.g. pathogens)	• Relocation of some farming facilities to better oxygenated areas may create new safety risks • Moving facilities may affect livelihoods and add to costs	• Lower carrying capacity of ecosystems • Increased aeration costs • Reduction in the number of annual crops when hypoxia is seasonal (e.g. stratification cycles in lakes)	• Lower carrying capacity of ecosystems • Some aquaculture areas may become unfavourable • Changes in ecological services to aquaculture	• Lower production resulting from lower carrying capacity	• New areas become favourable to aquaculture, others become unfavourable
	Adaptation measures	• Shift to more tolerant farmed species or strains	• Follow guidelines on decent work in aquaculture (e.g. FAO, 2016c)	• Relocate farming facilities to new areas offshore or inland	• Move farming facilities to new areas offshore or inland • Mainstream spatial planning and ecosystem approach	• Mainstream spatial planning and ecosystem approach	• Mainstream spatial planning and ecosystem approach

[3] Aquaculture management areas (Aguilar-Manjarrez, Soto and Brummett, 2017).

Drivers		Aquatic organisms	People	Farming system	Land-Seascape/AMA[3]	Country	Global
Distribut-ional shifts	Potential impacts	• Changes in plankton distribution may affect production of filter feeders • Poor growth of stock if natural feed availability is reduced	• Changes in labour availability due to climate-driven migrations • Relocation of some farming facilities to more favourable areas may create new safety risks	• Changes in plankton distribution may change production of filter feeders • Reduced availability of natural seed	• Lower productive capacity for filter feeders of the ecosystems in areas where plankton abundance decreases • Changes in ecosystem services	• Drop in national production if ecosystem integrity is compromised and productivity is decreased	• Changes in production of fish oil and fishmeal and consequences on markets
	Adaptation measures	• Move farming facilities to new areas	• Follow guidelines on decent work in aquaculture (e.g. FAO, 2016b)	• Shift to commercial feed formulation for carnivorous species currently using low-value fish directly as feed • Farmed stocks adjusted to the new productive capacity	• Move farming facilities to new areas • Spatial planning	• Move farming facilities to new areas • Spatial planning	

Sea level rise	Potential impacts	• Higher salinity in affected areas may induce:
		  • lower growth
		  • higher mortality
		  • greater sensitivity to other drivers
			• Damage to properties
			• Complex socio-economic effects (e.g. changes in access/ownership rights and rights to use of ecosystem services)
				• More marine and brackish water aquaculture
				• Less freshwater aquaculture
				• Loss of areas providing physical protection
				• Increased exposure of infrastructure and impacts on value chains
				• Increased exposure to disasters (e.g. tidal surge)
					• New opportunities for aquaculture in coastal areas
					• Loss of intertidal area for freshwater aquaculture
					• Coastal erosion
					• Flooding of coastal rivers
					• Saline intrusion upstream of river systems
						• New opportunities for aquaculture in coastal areas
						• Loss of coastal areas
						• Disruptive shift in activities to upstream or inland
						• High adaptation costs
						• Complex socio-economic effects (e.g. integration of farms in the overall agriculture landscape etc.)
							• New opportunities for aqua-culture in coastal areas globally
							• Increased pressures on coastal aquaculture by other sectors

	Adaptation measures	• Shift toward natural or selected saline-tolerant freshwater species or strains • Shift toward euryhaline (e.g. estuarine) or marine species	• Mainstream ecosystem approach to aquaculture (FAO, 2010) • Support the development of local governance and conflict resolution schemes, in which aquaculture stakeholders are involved	• Investment in protection infrastructure		• Investments in new infrastructure (dams, dikes etc.) to reduce salinity intrusions • Mainstream spatial planning and ecosystem approach	

Drivers		Aquatic organisms	People	Farming system	Land-Seascape/AMA[3]	Country	Global
Water currents, circulation & winds	Potential impacts	• Sudden changes in stratification may induce mass mortality, reduced growth and/or higher sensitivity to other drivers, but can also result in beneficial flow of oxygen rich waters	• Land-based farming systems (e.g. recirculation systems) should develop, reducing hazards to workers currently operating in the sea • Increased hazards to workers with more frequent storms and bigger waves for farming systems sited offshore	• Changes in stratification may affect aquaculture in floating cages (through upwelling of low dissolved oxygen waters or the release of toxic gases such as H_2S) • Increased exposure to tidal surges and waves	• Changes in the direction and strength of circulation and winds may alter transport/retention of contaminants and nutrients for seaweeds and filter-feeders • Increased risk of fish escapees	• Mainstreaming of spatial planning and management • Development of contingency plans	• Changes in dispersal of eggs/larvae
	Adaptation measures	• Shift toward species with wider water quality tolerance	• Follow guidelines on decent work in aquaculture (e.g. FAO, 2016b)	• Greater investments in stronger cage and mooring systems and in other equipment			

Drivers		Aquatic organisms	People	Farming system	Land-Seascape/AMA[3]	Country	Global
Extreme events (e.g. droughts, floods	Potential impacts	• Changes in reproductive cycle for rain-dependent species in capture-based aquaculture systems • Drought may induce low water quality, mass mortality, reduced growth and/or higher sensitivity to other drivers	• Increased hazards to workers from sudden extreme events • Increased damage/ destruction to properties • Loss or disruption of livelihoods	• Supply of inputs such as wild seed or plant-based feed ingredients may be disrupted • Stock losses to floods/ sea storms/extreme temperatures • Higher adaptation costs	• Increased risk of fish escapes as a result of flooding, overspills and facility destruction • Eutrophication of water bodies • Pollution of freshwater resources by heavy rainfall runoff • Erosion and/or silting-up of mollusc-growing areas	• Increased competition for, and potential conflicts over, freshwater	• Short or long disruption of aquaculture value chains (supply, production, post-harvest, markets, supporting services)
	Adaptation measures	• Shift to species with higher tolerance to poor water quality	• Follow guidelines on decent work in aquaculture (e.g. FAO, 2016b)	• Shift to shorter production cycles • Shift to indoor or Recirculating Aquaculture Systems (RAS) • Invest in water efficient technologies • Invest in stronger facilities • Relocate farms to less exposed areas (e.g. upstream, protected bays)		• Certification by countries of the design, construction and environmental standards of farming facilities allows the industry to operate with stronger equipment, more resilient to extreme events (Chapter 21) • Increased investments in mitigation measures, such as mainstreaming of spatial planning and management, contingency plans, emergency/ disaster responses	
Disease & harmful algal blooms (HABs)	Potential impacts	• Accumulation of residues and toxins affecting flesh quality (off-flavour) product safety, growth and survival, especially of filter feeding species • Increased mortality • Lower market value (off-flavour)	• Increased risks to human health • Increased use of anti-microbial drugs • Increased risk of anti-microbial resistance	• Increased cost to protect stock • Higher production cost arising from depuration • Increased occurrence of diseases • Impact of HABs on caged stocks may be particularly deleterious	• May prompt closure of growing sites and relocation of cages	• Will require higher investments in biosecurity frameworks at national level and contingency plans	
	Adaptation measures	• Increase environmental, food safety and quality monitoring	• Mainstreaming at farm level of methods such as Hazard Analysis and Critical Control Points (HACCP)	• Investment in depuration facilities and controlled environments production systems (RAS, ponds, etc.)	• Increased surveillance and monitoring costs	• Increased surveillance and monitoring costs	

TABLE 20.2

Other climate change-related drivers leading to possible impacts and adaptation measures at different levels/scales of impact. For a given level: green = overall favourable impact, yellow = both positive and negative, red = overall unfavourable change, white = no foreseen impact

Drivers		Aquatic organisms	People	Farm	Land-Seascape /AMA	Country	Global
Gaps in knowledge and uncertain-ties on specific climate change impacts	Potential impacts	• The variability of the future environment may differ from the spectrum of tolerances of species available	• People make ill-informed aquaculture choices, increasing the risk of maladaptation and further livelihood losses, especially for the most vulnerable	• Farm facilities may not be adapted to the average or range of variability of the future environment • Higher cost of adaptation if maladaptation options are chosen first	• Individual maladaptation may have a cumulative impact on the local aquaculture or economy	• Higher risk of national maladaptation strategies	• Small- and medium-scale farmers have limited resources and access to technical assistance to cope with uncertainties • Increased cost of risk management/ increased insurance premiums
	Adaptation measures	• Selecting species with a wide spectrum of tolerance (e.g. euryhaline, eurythermal) to cope with a wide range of uncertain environmental variations • Diversifying farmed species and systems to cope with a wide range of uncertainties	• Social protection strategies • Development of new tools for coping with uncertainties (e.g. complex adaptive systems, etc.) • Need for building increased resilience • Need for increasing local knowledge	• Modified insurance schemes • Facility designs that can be adapted to a certain range of conditions	• Better monitoring and early warning systems • Diversified production • Development of new tools for coping with uncertainties (e.g. complex adaptive systems, companion modelling etc.)	• Better monitoring and early warning systems • Focus research to fill the gaps and reduce uncertainties • Diversified production	• Focus research to address complex uncertainties (e.g. overlap and synergies amongst different drivers)
Water shortage	Potential impacts	• Farmed aquatic products contaminated by polluted water • Water stress may induce low water quality-mass mortality, reduced growth and/or higher sensitivity to other drivers	• Water stress • Aquaculture may not be prioritized for water use	• Reduce production efficiency	• Competition for water resources • Reduce production efficiency	• Water stress • Competition for water resources	• Some territories with limited freshwater such as the small island developing states may invest in marine aquaculture
	Adaptation measures	• Promotion of new species tolerant to low water quality	• Include multisectoral adaptation priorities into aquaculture adaptation plans (e.g. choose between local food production vs. export, etc.) • New governance schemes that ensure equitable access to water, especially during water shortage periods	• Promotion of new water-saving practices (no water renewal, water recirculation, etc.) • Building of climate-smart facilities for water storage • Promotion of climate-smart agriculture, including aquaculture	• Aquaculture may benefit from integrated farming • Aquaculture may benefit from collective water storage • Aquaculture may benefit from multiple use of water schemes • Aquaculture must be included in collective water management schemes • Need for spatial planning	• Need for National Adaptation Plans (see below)	• Promote mariculture where possible

Drivers		Aquatic organisms	People	Farm	Land-Seascape /AMA	Country	Global
Climate change impacts on fisheries[4]	Potential impacts	• Change in the availability of fish oil and fishmeal for feed • Survival and growth of some species, especially marine, may be affected by fishmeal/ oil-free feed • Fishmeal/oil-free feed impact flesh composition and may reduce nutritional value, in particular with regards to n-3 polyunsaturated fatty acids (PUFAs)	• Reduced profitability if feed cost increases	• Additional restrictions on feedstuffs and seeds for capture-based aquaculture may create new constraints where commercial feeds are not available • Higher feed cost if resource becomes scarce	• Increased cost of feed	• Increased aquaculture potential as alternative provider of food and livelihood • Reduced aquaculture investment interest	• Aquaculture market development and demand likely to be positively driven by stagnation of fisheries • Aquaculture development could be negatively driven by stagnation of capture fisheries, feed shortage and higher costs
	Adaptation measures	• Use of species more efficient at using feed, especially at lower trophic levels • Selective breeding for strains efficient in using plant feed, especially for species at higher trophic levels • Focus research to reduce negative side effects of terrestrial feedstuffs • Develop new feeds	• Need for capacity building on efficient feed use • Farmers may look for alternative livelihoods	• Better on-farm feeding practices and performance	• Cluster approach to access better feed • Cluster approach to improved feed management	• Increase incentive to consume and farm non-fed species • Increase research investment on better feeds and feeding	• Increase incentive to consume and farm non-fed species • Increase research investment on better feeds and feeding • Increase research on feed-efficient species
Climate change impacts on agriculture	Potential impacts	• Increased competition for freshwater may result in lower water quality and subsequent impacts on survival, growth and/or sensitivity to other drivers or flesh contamination	• Adaptive measures, e.g. integrated/agro-ecological aquaculture will mitigate impacts of risks on the farming system • But they may also create new burdens for farmers (such as increased workload, restrictions on pest/disease treatments etc.)	• Decreased availability and higher cost of terrestrial ingredients for fish feed • Limited availability of land for new farms	• New constraints on the availability of land and water resources inland and in coastal areas. • Increased competition for freshwater • Increased competition for land and water use	• Adaptation in agriculture such as creation of water reservoirs may open an opportunity for cage farming (e.g. Brazil) • Reduced space and water availability for aquaculture growth	• Spatial competition between crops used for human food security and for producing aquaculture feed
	Adaptation measures	• Selective breeding for species more efficient in using feed • Need for species adapted to integrated farming and/or agro-ecological farming	• Integrated/agro-ecological aquaculture to cope with freshwater and land use competition may create benefit to people, e.g. higher income, higher productivity of rice crops etc.	• Better feed management practices • Integrated farming, aquaponics	• Integrated aquaculture-agriculture (e.g. irrigation-aquaculture, rice-fish farming, aquaponics etc.) • Building of irrigation facilities as an adaptive answer to climate change may create new opportunities for aquaculture	• Appropriated freshwater use governance schemes • Spatial planning and management	• Promote integrated water and land uses considering aquaculture potential to provide opportunities for the sector

[4] Reduced catches of marine fish will restrict availability of fishmeal and fish oil even further.

Drivers		Aquatic organisms	People	Farm	Land-Seascape /AMA	Country	Global
Distal drivers[5]	Potential impacts	• New diseases and algal blooms (Table 20.1) • New invasive species may create new risk for farmed species	• Competition for space and resources in some regions such as coastal or peri-urban areas, making them inappropriate for aquaculture • Aquaculture may provide employment and livelihoods • Need for more stringent collective action for multi-users of common resources	• Higher cost of energy, resources, feed etc. may lower farm profitability • Urban aquaculture systems (e.g. aquaponics) may develop	• Recycling of food by-products/organic wastes through aquaculture in support of a circular economy • Aquaculture land may usefully serve other purposes, including by hosting solar panels, in addition to aquatic production • Extractive aquaculture may contribute towards removing nutrients and organic loads in some areas	• Need for increased monitoring for water quality, disease outbreaks, etc. • Demography and demand for aquatic products drive aquaculture development • New information and communication technology tools allow for upscaling aquaculture development	• Aquaculture development driven by demography and growing demand for aquatic products • Globalization and inter-regional trade may help to cope with regional imbalance in fish availability • Growing pressures will require planning of aquaculture development as part of integrated multi-sectoral planning • Several distal drivers will make aquaculture impossible or non-profitable in some areas with high human or environmental pressures
	Adaptation measures	• Conduct vulnerability assessments • Spatial and integrated multi-sectoral planning • Local, regional and national adaptation strategies must consider other changes that have the potential to modify the drivers of climate change					
National Adaption Plans (NAP)	Potential impacts	• New farmed species promoted by NAPs	• Creation of new opportunities for aquaculture within the NAPs	• Aquaculture may have to overcome additional constraints to meet the priorities set for other sectors in the NAP	• Aquaculture may have to overcome additional constraints to meet the priorities set for other sectors in the NAP	• Aquaculture may have to comply with additional constraints to cope with the priorities set for other sectors in the NAP	• International cooperation on NAPs
	Adaptation measures	• Mainstream spatial planning and management • Ensure aquaculture is included in NAPs • Ensure aquaculture is included in multisectoral approaches (e.g. Blue Growth (FAO, 2017b) etc.)					

20.3 OVERVIEW OF SOME CLIMATE CHANGE ADAPTATION POLICIES: NAPAS, NAPS, NDCS

Established in 2001 by the Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC), the National Adaptation Programmes of Action (NAPAs)[5] are intended for least developed countries (LDCs) to coordinate and communicate priority actions that allow access to adaptation funding mechanisms (Vadacchino, De Young and Brown, 2011). By June 2017, 51 NAPAs had been received by the Secretariat, of which 21 include actions in relation to aquaculture. Six countries have also prioritized projects directly addressing aquaculture. These focus on developing small-scale farming (Cambodia, Myanmar), rehabilitating aquaculture sites (Mali), increasing fish production and preservation of fish (the Gambia), adaptation to new climate-induced environments, including increased salinity (Bangladesh), and spatial planning of land use practices (Zambia).

Ten years after the launch of the NAPAs, the National Adaptation Plans (NAPs) from developing countries[6] were established by the Parties to the UNFCCC (FAO, 2017d). Unlike NAPAs, NAPs are not explicitly linked to a funding source; moreover, all developing countries, not only LDCs, are encouraged to develop NAPs. Of the seven NAPs from developing countries available on the UNFCC website in June 2017, six include measures relating to aquaculture. Priority areas include the vulnerability of aquaculture (Brazil, Cameroon), implementation of best practices (Burkina Faso), upscaling of aquaculture (Kenya), adaptation to salinity and wastewater reuse (Sri Lanka) and building resilience (Sudan).

The Paris Agreement entered into force on 4 November 2016 (FAO, 2016a). It stipulates that each party shall prepare, communicate and maintain successive Nationally Determined Contributions (NDCs) to the global response to climate change[7] that it intends to achieve. In June 2017, of the 197 Parties to the Convention, 142 had already submitted their first NDCs, and 19 make reference to aquaculture or fish farming, of which nine focus on adapting aquaculture to climate change (Cambodia, Cameroon, Chile, Madagascar, Mexico, Nigeria, Peru, Sri Lanka, Viet Nam) while a further ten propose agro-ecological or conventional aquaculture development as an adaptation and/or mitigation measure (Belize, Central African Republic, Chad, Congo, Côte d'Ivoire, Equatorial Guinea, Gambia, Mauritania, Morocco, Zambia).

20.4 KNOWLEDGE AND POLICY GAPS AND THEIR IMPLICATIONS

The impacts of a warmer, less predictable and more extreme climate are not evenly distributed across the globe. Some regions will experience potentially detrimental changes, such as increased drought or flooding, while others may find that conditions for aquaculture improve (De Silva and Soto, 2009; FAO, 2017a, 2017c; Chapters 1 and 21). Increased scientific knowledge may contribute to a reduction in uncertainties and improve the adaptive capacity of poor and small-scale aquaculture producers and value chain actors. In order for aquaculture to adapt to climate change, relevant research is required and regions and countries need to work on common issues.

Research gaps include:

- knowledge of synergistic interactions between stressors (e.g. acidification and increased water temperature);
- understanding of bioclimatic envelopes of species tolerance to extreme weather events, or a combination of stressors;

[5] http://unfccc.int/adaptation/workstreams/national_adaptation_programmes_of_action/items/4583.php
[6] http://www4.unfccc.int/nap/Pages/national-adaptation-plans.aspx
[7] http://www4.unfccc.int/ndcregistry/Pages/Home.aspx

- realistic scenarios for aquafeed resulting from the increasing diversion of crop-based feedstuffs for the production of biofuels and/or to other animal husbandry sectors (Troell *et al*., 2014, 2017a; Troell, Jonell and Henriksson, 2017b);
- better feeds and feeding practices; further reduction in use of fishmeal and fish oil; disease susceptibility, new diseases and preventive treatments; evidence of the impacts of climate change on the post-production food chain;
- understanding of the relationship between species and habitat based on optimal thermal limits and salinity levels; the impacts of climate change on public health risks for consumers of farmed fish (e.g. HABs);
- the consequences of combined climate change impacts on resources, physical assets, livelihoods and health; and
- understanding of how climate change impacts on food systems in general and economics may lead to changes in demand and in market prices.

Research to enhance the adaptation to climate change of farming households, farming communities and industry includes: analyses of the social and economic consequences of climate change; reporting on adaptation strategies at all levels of the value chain; and developing and strengthening integrated monitoring systems to provide information on environmental variables and diseases that fish farmers can use to make decisions.

Information gaps and capacity building requirements must be identified and addressed through networks of research, training and academic institutions. Research to inform policy includes:

- the recommendations of physical assets, social and institutional options to enhance the sustainability of livelihoods and the resilience of poor people to multiple climate change impacts;
- improved assessment of the interactive effects of different climate variables (for example, the identification and improved understanding of pathways between climate effects and aquaculture impacts at various scales i.e. including effects on other food systems and human development) so as to better inform strategies that aim to mitigate adverse impacts and encourage adaptation to change; and
- improved understanding of the gender dimensions of adopting climate-smart smallholder aquaculture innovations (Morgan *et al*., 2015).

Regional adaptation plans are also needed for transboundary water bodies (e.g. Mediterranean Sea and Mekong, Lake Victoria and Amazon basins).

Potential adaptation measures could be built on a sustainable livelihoods framework and the ecosystems approach to aquaculture, supported by risk assessment and management along the value chain, and guided by a feasibility assessment.

20.5 ACKNOWLEDGEMENTS

Dr Max Troell from The Beijer Institute of Ecological Economics, University of Stockholm provided thorough and helpful comments on an early version of this manuscript.

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