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Chapter 6: Impact of Climate Change on Inland and Ocean Fisheries and Aquaculture

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Chapter Abstract

Fisheries and aquaculture produce highly nutritious foods that are generally of high value, and often targeted at export markets. Slow to recognise the threats from climate change, research by sectoral experts and greater attention to aquatic systems (freshwater and marine) by the IPCC rapidly improved understanding of likely productivity changes from climate change. Diverse approaches to adaptation are revealed by reviews of today’s adaptation practices, the most prominent pathways promised by technological fixes and emerging more comprehensive socio-technical systems approaches. The major challenges brought by climate change are going to exacerbate the ongoing dilemmas of how adaptation will affect small-scale fisheries and aquaculture and the large-scale enterprises, and which people will be advantaged or displaced in the adaptation processes.

Introduction

Fish and other aquatic products such as seaweeds, molluscs, crustaceans, and echinoderms are recognised as important and growing components of the world food system, vital traded commodities in the economies of many countries, and providing livelihoods and businesses for millions of people (Table 1).

Since World War II, the global growth in fisheries and aquaculture production has been dramatic, increasing by nine times while human populations tripled. These relative growth figures explain the large increase in per capita fish consumption (Table 1). Over the same period, fish also maintained its value, according to the FAO trade-based Fish Price Index Williams and Syddall (2022, p. 4). In the mid-1980s, the production of fisheries and aquaculture in developing countries (countries of the global South) began to outstrip that of countries in the global North. Northern countries shifted to stronger management of their depleting fisheries resources and satisfied their needs for fish by importing more from countries of the South. Governments supported increasing fish production, especially through aquaculture, to garner trade benefits such as foreign exchange income. The high economic value of fish and other aquatic foods may create tensions between the drive to export, mediated through well-off firms, and the role of aquatic foods in nutrition and food security for the poor and less well-off people. Reconciling the tensions requires economic policies that also address social justice and sustainability (Gephart et al., 2020). Increased production of higher value aquatic animal products tends to be directed towards international trade. The poor may benefit is they work in the sector, and/or government revenue from the sector is redistributed fairly. They are unlikely to directly consume the additional production. Indeed, based on a rigorous meta-analysis of peer-reviewed literature, the links between poverty alleviation and fisheries and aquaculture were found to be complex, although often explained by simple cause and effect narratives (Béné et al., 2016, p. 187).

Table 1. Global importance of fish and other aquatic products, and fisheries and aquaculture sectors.

Production of fish and other aquatic organisms, 2020, (FAO, 2022, pp. 3,26)

- Capture fisheries: 90.3 million tonnes
- Aquaculture (animal species excluding aquatic mammals, crocodiles, alligators and caimans): 97.5 million tonnes
- Algae (aquaculture and fisheries): 35.1 million tonnes

Fish as aquatic food

- Global per capita consumption: 20.5 kg.capita^{-1}.year^{-1}; up from 9.0 in 1961 (FAO, 2022, p. 1)
- Aquatic food as share of total food: Protein: 7% of protein, 17% of animal protein
- Other nutrients: essential fatty acids and micronutrients, e.g., iron, zinc, calcium, iodine and vitamins A, B12 and D. (FAO, 2022, pp. 85-88)

Labor force participation and people who depend on aquatic food resources

- Capture fisheries: 120 million people in the value chains for small and large scale capture fisheries (FAO et al., 2023, p. 105); 94% of the workers are engaged in small-scale fisheries value chains; 492 million people engaged in subsistence fishing and, small-scale fishing or live in households depending on these
- Aquaculture: 21 million people in fish farming node of value chain (FAO, 2022, p. 68). No estimates for whole of value chains and dependent people

International trade

- 59.8 million tonnes, USD151 billion (FAO, 2022, pp. 91,93) (excluding algae)
- Aquatic animal products represented 49% of global value of all internationally traded animal meat products (bovine meat 19%, pig meat 18%, chicken meat 11%, other meat 3%: (FAO, 2022, p. 92)

Source: Author, based on references cited in Table.

As a source of animal meat, animal-based aquaculture has had the fastest growth rate of all aquatic and terrestrial forms of animal meat. However, production of edible terrestrial meat (beef, pork, chicken, and other meats) is three times that of the combined total production of aquatic animal meat (i.e., minus shells and bones and excluding seaweeds and other plants) (Edwards et al., 2019). The higher value of many aquatic animal products is reflected in strong international trade, in which aquatic products account for nearly half the value of all animal products traded (Table 1).

Whereas most countries produce at least some aquatic products, the bulk of fisheries and aquaculture production is highly concentrated. In 2018, the top 25 countries produced 83% of world production (excluding aquatic plants) (Table 2). Seventeen of the top 25 countries are from the global

South. Looking at the top producing countries from a dry-lands perspective, a notable number are also countries often categorised broadly as dry-land countries, e.g., China, India, Peru, Chile, Mexico, Egypt. In the case of major capture fisheries producers, fishing vessels from these countries may fish widely across the globe, e.g., China, or have access within their own Exclusive Economic Zones to biologically productive upwellings that support many of the largest fisheries, e.g., the Peruvian anchoveta (*Engraulis ringens*) fishery. Where aquaculture contributes a large share of aquatic production, freshwater and land-based production is often overlooked in current estimates and in future projections that focus on the potential of marine aquaculture (mariculture) (Zhang et al., 2022). In countries such as Egypt, for example, fish farming, predominantly of tilapia, including Nile tilapia (*Oreochromis niloticus*) is carried out in ponds in the highly productive Nile River delta (Nasr-Allah et al., 2021).

Table 2: Capture and aquaculture fisheries production of top 25 countries (2018). OECD member countries are considered to be in the Global North. Data source. FAO FishStatJ.

Country	**2018 Production (MT)**	**1=Global S 2=Global N**
China	62,206,893	1
Indonesia	12,642,158	1
India	12,386,253	1
Peru	7,273,403	1
Russian Federation	5,308,359	1
United States of America	5,212,603	2
Bangladesh	4,276,641	1
Norway	3,843,920	2
Japan	3,773,779	2
Chile	3,388,485	2
Myanmar	3,163,460	1
Philippines	2,875,632	1
Thailand	2,598,000	1
Mexico	1,939,237	2
Egypt	1,934,742	1
Korea, Republic of	1,904,636	2
Malaysia	1,675,515	1
Morocco	1,372,853	1
Brazil	1,319,292	1
Iceland	1,278,478	2
Spain	1,273,347	2
Nigeria	1,169,478	1
Ecuador	1,138,557	1
Taiwan Province of China	1,098,112	1
Canada	1,019,050	2
United Kingdom	897,845	2
Denmark	825,725	2
South Africa	565,917	1

█	>10 m MT
▓	> 5 m and < 10 m MT
▒	>2 m and <5 m MT
░	>1 m and <2 m MT
□	<1 m MT

Production of top 25 countries as % 2018 world total	83	
Grand Total	178,528,817	

Compared to other sectors such as agriculture, fisheries and aquaculture were slow to recognise the challenges of climate change (Brugère & De Young, 2015), but now climate change is reckoned to be one of the most important sources of uncertainty in fish production over the next decade (OECD & FAO, 2023, p. 222). Part of the slow realisation of the importance to the sectors was due to the lag in including marine and freshwater data series by the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports (AR). In The 4th AR (2007), for example, only 85 marine and freshwater time series were used in examining impacts, compared to 28,586 time series from terrestrial system (IPCC, 2007, pp. 4, Figure SPM.2). Nevertheless, AR4 did engender a greater interest in climate change among fisheries and aquaculture experts (Cochrane et al., 2009). Since 2016, the aquatic sectors literature has grown exponentially (FAO et al., 2023, p. 74). In the 2023 IPCC Assessment Report (AR7), projections for marine fisheries yields were highlighted in the main synthesis report (IPCC, 2023, p. 16), and oceans and dependent sectors were given detailed treatment in the report of Working Group II on Impacts, Adaptation and Vulnerability (IPCC, 2022)

From around the time of the IPCC AR4, small-scale fisheries and aquaculture experts were already considering pathways through which small-scale fishers and fish farmers would experience vulnerabilities to climate change (Allison et al., 2009), being particularly vulnerable because of where they live and their poverty levels (Barange et al., 2018, p. 612).

The present chapter provides an overview of the impacts of climate change on marine and inland fisheries and aquaculture, and of the aquatic production sectors on climate change, drawing on available syntheses, and highlights the fundamental factors of climate change impacts, especially from biophysical perspectives as socio-economic studies are less developed. A brief review is given of current knowledge on greenhouse gas emissions from fisheries and aquaculture. The chapter will focus on adaptation pathways and deal little with mitigation, although the production of certain aquatic foods and the technological directions of the global aquatic food system contributes to greenhouse gas emissions, certain species more than others (Gephart et al., 2021). Adaptation pathways are grouped into three categories: adaptation of today's practices, pathways relying on major technology developments, and pathways that take a sociotechnical systems (STS) approach to change. In each category, selected examples are presented, illustrating the range and complexities of situations.

Impacts of climate change on inland and marine fisheries and aquaculture

For more than 150 years, fisheries scientists have struggled to understand the distribution, abundance, and fluctuations in stocks of harvested aquatic species (Smith (1994(2007)). For many fish stocks, the scientists' endeavours have brought success, depending upon the biology and ecosystem complexities of the harvested species and ecosystems, and the data available for assessments. Where the advice from the assessments has been followed by sound fisheries management, fish stocks are improving and are sustainably managed. For marine fisheries, however, this situation applies only to about half of the catch (Hilborn et al., 2020), leaving many fish stocks poorly understood and poorly managed. In the case of inland fisheries, answers – typically for the declines of catches - were sought from understanding the decline in water quality from competing uses (Welcomme, 2016) .

Climate has long been recognised as a factor in fish stock fluctuations. Often, climate variability must be distinguished from the impacts of fishing on the stocks. Whether in marine, brackish or freshwater, climate change, rather than climate variation over time around a stable long-term pattern, raises further challenges. The major En Nino event of 1997-1998 was one of the first alerts to scientists such as Guerrero (1999) who estimated substantial production losses in the Philippines of nearly 300,000 tonnes, and some minor gains, from an annual expected production of about 2.3 million tonnes. Clearly the impacts of such severe events indicated the scale of possible impacts on aquatic production of the changing climate should the frequency and intensity of such events change.

As the IPCC periodic assessments became more inclusive, fisheries researchers began collaborating with climate modellers to better understand the challenges of integrating fisheries impact studies into climate projections (Stock et al., 2011). Studies on local, national and regional changes in fisheries resources due to climate were undertaken, e.g., southeast Australia (Last et al., 2011), West Africa (Lam et al., 2012), tropical Pacific fisheries and aquaculture (Bell et al., 2011). Among other actions, FAO summarised the relevant parts of IPCC Assessment Report 5 for fisheries and aquaculture (Seggel & De Young, 2016).

The upswing in climate change and fisheries assessments for a variety of geographies enabled globally coordinated assessments, notably through FAO whose mandate necessitated a focus on the impacts on people engaged in fisheries and aquaculture and consumers reliant on aquatic foods. Following preparatory desk and field studies that focused on vulnerability assessment approaches (Brugère & De Young, 2015), in 2017 FAO embarked on a full expert consultation process leading to a global synthesis (Barange et al., 2018). The synthesis by Barange et al. (2018) concluded that climate change would cause considerable changes in harvestable aquatic resources, affecting availability, trade and having economic impacts, especially in countries most dependent on the resources. The synthesis used experts' studies of major marine regions, inland systems, and aquaculture, complemented, in the case of marine fisheries, by model projections of potential impacts, based on two IPCC scenarios (Cheung et al., 2018).

Barange et al. (2018) summarized the overall impacts of climate change on aquatic products from marine ecosystems, inland waters and aquaculture as follows. Climate change will impact aquaculture and fisheries in ways that are short and long-term, occurring at multiple scales. Key biophysical factors are changes in temperature, precipitation, ocean pH – typically acidification that is dangerous for organisms including plankton with calcareous skeletons, increasing hypoxic areas and sea level changes. Changes may be Food safety may be affected, by increased growth of pathogenic bacteria, and aquatic organisms will suffer psychological stresses from temperature regimes. Vulnerabilities, resilience and adaptation options for people, communities and economies engaged in or consuming the products from aquatic systems vary with specific local and geographic conditions.

For marine regions by 2050 the synthesis concluded that the catch potential in the world's exclusive economic zones (EEZ) would decline by between 2.8 and 5.3% under greenhouse gas emission scenario RCP2.6, and between 7.0 and 12.1% under greenhouse gas emission scenario RCP8.5. Regional variation is high and therefore many projected regional impacts are much greater than these global projections imply. The biggest decreases are projected for the tropics, especially in the South Pacific whereas harvestable stocks may increase in some high latitude countries or show less decrease.

For inland fisheries systems, the largest threats are expected to come from competition for scarce water by other powerful sectors such as those responsible for municipal water use, energy production and agriculture. Pakistan, Iraq, Morocco, and Spain are facing high inland water stresses, and these are projected to become more severe under climate change. Some areas will receive higher precipitation but to capture the benefits of this from an inland fisheries perspective will require additional investments, technologies, and management developments advantageous to fisheries within inland water systems.

In the short-term, production may decrease, and infrastructure suffer damages from extreme temperatures and events such as floods and droughts. Diseases, parasites, and harmful algal blooms may increase in frequency under changing climate conditions. Long-term impacts may arise from reduced water availability and/or more competition for available water, and, for some cultured species, less wild seed.

In freshwater aquaculture, in Asia, China, Bangladesh, Lao People's Democratic Republic, and Vietnam were projected to be the most vulnerable countries. In the Americas, the most vulnerable are Belize, Costa Rica, Ecuador, and Honduras. In Africa, Egypt, Nigeria, and Uganda are particularly vulnerable.

In brackish water aquaculture production, Egypt, Thailand, and Viet Nam Thailand were projected to be highly vulnerable. For marine aquaculture, Chile and Norway were the most vulnerable, due to their high production that focuses on a limited selection of species, with the more diversified countries of China, Madagascar, the Philippines, and Viet Nam also highly vulnerable.

In reviewing the evidence for projecting the likely impacts of climate change on capture fisheries, the dominant focus has been on biophysical changes, whereas, in aquaculture, relatively greater emphasis has been given to economic and social impacts.

In biophysical terms, the fundamental factors that underlie the impacts of climate change are many, complex, and frequently related. The four key factors are: (1) water, its availability and chemistry; (2) temperature, which has a particularly direct effect on utilised aquatic animals which are all poikilotherms that do not regulate body temperature; (3) the occurrence of extreme events such as storms, floods, droughts; and (4) the conditions of supporting ecosystems that may be subject to effects such as sea level changes, and changes in their extent from inundation and other water depth changes, pollution, and deliberate destruction such as for land reclamation. How these come together in specific regions, fisheries, aquaculture setting has been explored in detailed expert studies and reviews, e.g., see Phillips and Pérez-Ramírez (2018) and Barange et al. (2018).

Phillips and Pérez-Ramírez (2018, pp. 959-961) concluded that the productivity of harvestable aquatic organisms may be changed by biodiversity of the target and supporting species, e.g., through shifts to higher latitudes and deeper cooler waters. Larvae and juveniles may be affected by ocean current changes, as demonstrated by the major impacts of periodic ocean changes such as the El Nino Southern Oscillation, the southern Oscillation Index, the Pacific Decadal Oscillation, and the Indian Ocean Dipole. Acidification resulting from the uptake of greenhouse gases in the oceans is affecting calcification rates in marine organisms such as corals, molluscs, and crustaceans. The distribution and abundance of small (e.g., herrings, anchovies, sardines) and large (e.g., tuna and mackerels) pelagic fish species that live their lives the water columns are affected by changing currents and temperatures and access to nutrients for food and reproduction. Spatial shifts are already being recorded. Each of the major oceans is exhibiting different types, complexities, and magnitudes of climate change, e.g., the Pacific and Atlantic oceans show different types and magnitudes of climate change.

In the intersection of marine and freshwater ecologies, estuaries are often critical feeding and breeding space for many species, including offshore species, but their biological productivity is disrupted when freshwater flow patterns change (Gillanders et al., 2011), and estuaries warm and acidify (Scanes et al., 2020).

In aquaculture, Galappaththi et al. (2020) surveyed the literature on climate change adaptation. In 44 studies that met their selection criteria for cases, the authors found a focus on extreme events such as floods, droughts and cyclones that affect the aquaculture enterprises, and multiple and general impacts. More than half the studies used integrated approaches. Reflecting the less ecological focus of aquaculture research, the cases reviewed tended to look at impacts that were simultaneous such as heatwaves and extreme weather events or interrelated such as disease outbreaks and economic impacts to supply chains, or geographically specific such as particular storms (Galappaththi et al., 2020).

Greenhouse Emissions from Fisheries and Aquaculture

Aquaculture and fisheries are not only impacted by climate change but their operations throughout the value chains also contribute to greenhouse gas emissions and environmental changes. These industries have boomed partly because many of the enterprises have mechanised, scaled up, intensified, digitalised, and the products have been traded over long distances, all which factors have progressively increased energy needs and therefore carbon footprint. This increasing trend is recognised by experts in the fish sectors, but often addressed in a defensive way by comparing the carbon footprints of different aquatic production with those from terrestrial animal products, e.g., Parker and Tyedmers (2015, p. Figure 2 showing median expected greenhouse gas emissions from fuel use in different fisheries, aquaculture, pork and chicken).

In marine fisheries, trawl fisheries have often been the target of conservation campaigns because of their operations. In these fisheries, fishing trawlers pull ropes or chains across the seafloor, herding fish and other mobile organisms into large nets that are then hauled up onto the vessel(s). These fisheries land 26% of global marine fisheries catches. Hilborn et al. (2023) conducted a comprehensive study of the environmental impacts of trawl fisheries, comparing them to other fishing methods with respect to impacts on sustainability of target species, impacts on the seafloor, bycatch and discards and carbon footprint. Carbon footprint was standardised on kilograms (kg) of CO_2 produced per kg of processed product from life cycle analyses for foods ranging from corn (lowest at 0.10) to beef (19.2) (Hilborn et al., 2023, p. Table 3). The bottom trawl fisheries average was 4.65, compared to 5.50 for Atlantic salmon. The trawl fisheries average carbon footprint is higher than those for chicken (2.28), pork (2.92), and a plant -based meat alternative called Impossible Burger (3.50).

In aquaculture, MacLeod et al. (2020) estimated the global total greenhouse gas emissions for aquaculture, based on the production node rather than a life cycle analysis, and compared emissions across aquatic (fisheries, aquaculture) and terrestrial anima protein types. For 2018, global aquaculture emissions (aquatic animals only) were estimated at approximately 0.49% of anthropogenic emissions. The authors noted that aquaculture occurs across a wide range of intensities of energy use. Compared to terrestrial livestock, particularly cattle, sheep and goats, aquaculture emissions are low because the cultured organisms do not emit enteric methane, have high fertility rates, and, as poikilotherms supported in water, have low feed conversion ratios.

Diverse adaptation pathways

The types of adaptation pathways that aquaculture and fisheries may still in their early stages of development. This section uses examples to illustrate possibilities, some taken from work directed to climate change adaptation, and others from adaptations to major environmental change from natural and anthropogenic causes. The examples are organised into three categories. The first comprises those pathways that are adaptations of current practices. As such, these pathways incrementally push the envelope available for today's practices, stretching out the time for which people may still conduct their enterprises. The second category is for bolder technological fixes, trying to establish fundamentally different options for production. The third category takes a more inclusive and nuanced approach by proposing sociotechnical changes that aim to create solutions that are more sensitive to people.

1. Adaptation of today's practices

Many of the articles on adaptation are written from current perspective that confront short term realities and options. Transformative changes are major and therefore not achievable in the short term. Vulnerable people must survive the near term without recourse to radical options, other than out-migration. In the aquaculture literature, Galappaththi et al. (2020) identified three adaptation pathways: coping mechanisms, adaptive strategies and management approaches. The adaptation measures found in the literature review ranged from near term 'no regrets" coping strategies to far reaching and much more complex adaptative measures.

Studies on coping mechanisms were mainly focused on marine and coastal aquaculture, including shrimp farming. Other studies were on inland aquaculture. The mechanisms, depending on the aquaculture operations of interest, relied on knowledge of adaptation strategies that is mediated by access to extension, consultants, workshops and conferences, farmers' access to early-warning information, and access to credit facilities. Adaptive strategies were all derived from studies carried out on aquaculture in the global South, many initiated by researchers from the global North. In the national natural resource management plans of Fiji, Solomon Islands, Timor Leste and Vietnam, aquaculture is named as a marine strategy for adapting to climate change (Galappaththi et al., 2020, p. 2166). The third adaptation pathway was management plans, which varied from expert led climate adaptation planning, to bottom-up community-based adaptation, iterative planning, through to top-down government-provided support.

Based on the findings of this literature review, four main areas of focus for aquaculture emerge (Table 3). The dominant area for action is managing water and farm infrastructure at all scales - pond, farm, ecosystem, catchment and national. The second area is the need for climate and weather information and warning systems at local levels. The third area for adaptation action concerns better, more affordable farm inputs (seed, breeds, disease management) to meet the climate challenges. Finally, cost-cutting and income securing measures for the farmers are needed for enterprises to survive, including insurance and financial support.

Embedded within all types of adaptation suggestions are some that appear logical and straightforward yet, due to historical issues and matters of the balance of power, are proving immensely difficult. The adaptive strategy "integrated water resource management recognizing aquaculture stake," for example, throws up a challenge to existing water users in countries such as Egypt where, under law, aquaculture is only permitted in brackish and marine waters and infertile lands not suitable for agriculture. Irrigation water (freshwater) cannot be used for aquaculture (Cai et al., 2017, p. 39).

Table 3. Adaptive strategies mentioned in the aquaculture literature, paraphrased and reorganised from the measures presented in the literature review by Galappaththi et al. (2020, Table 3)

1. COPING STRATEGIES

No regrets	Supplementary pond aeration
	Harvesting fish early to reduce pending losses
	Monitoring water conditions and fish behaviour frequently
	Actively adjusting pond water levels during rains
	Reducing disease risk by better pond and feed management
	Sharing knowledge in fish farming groups and networks
Low regret	Shift stocking dates and adjust stocking density to conditions
	Buy fingerlings nearby to reduce heat stress during transport
	Use groundwater to refill ponds
	Adjust stocking tanks to regulate pond water supply
	Shade hatchery tanks/cages; grow aquatic weeds in ponds for shelter
	Strengthen cages to lessen risks of damage in extreme events
	Stock and harvest multiple fish species to reduce risk or switch species
	Dip ice bags in pond/hatchery to reduce water temperature
	Exchange pond water frequently
	Plant fruit trees on pond dikes and vegetation on pond slopes
	Seek compensation assistance following disaster-related losses
	Enter contract farming arrangements, e.g., leases
2. ADAPTIVE STRATEGIES	
Future benefit strategies	Early-warning systems informing about floods, droughts and heatwaves
	Research and development to improve climate risk information systems and accessibility
	New farm-level technology to improve water productivity
	Rainwater harvesting tanks to use rainwater for fish culture and pond-dike cropping
	Protect and restore ecosystems for flood protection, water storage and water quality services
	Community-based watershed management
	Zone production so that aquaculture has sufficient water (volume/quality)
	Integrated water resource management recognizing aquaculture stake
	Reuse waste and integrate resources into the farm to reduce input costs and dependencies on input suppliers
	Broad range of higher thermal tolerance breeds
	Diversify into other business/income sources to subsidise risk reduction investments
	On-farm value-added processing
	Increase savings to buffer household from losses and still make risk reduction investments
Upfront strategies	Water treatment equipment in storage ponds with recirculating technology
	Protective flood dike around aquaculture ponds
	Large-scale water storage and infrastructure development to consider aquaculture uses of water
	Standards to improve climate- and water-related risk management
	Avoid risk prone areas and shift production site to a lower-risk location
	Seek opportunities for floodplain aquaculture
	Develop new export markets and strengthen existing markets for farmed fish products, to create higher farm prices
	Establish mutual or weather-indexed insurance for aquaculture
3. MANAGEMENT APPROACHES	
	Climate adaptation planning for aquaculture based on expert knowledge
	Community-based adaptation using bottom-up approach

	Adaptive management using iterative approach
	Government support involving active governmental provisioning of resources, such as technical trainings or financial subsidies for individuals or communities

Geographic and farmer surveys of aquaculture vulnerability may help guide decision-makers on climate change adaptation. Islam et al. (2019) applied 21 climatic, environmental, and socio-economic indicators in all 64 districts of Bangladesh, finding that aquaculture was highly vulnerable in 8 inland and 4 coastal districts. In India, Adhikari et al. (2018) surveyed farmers in five major freshwater aquaculture states. The farmers reported on the impacts of extreme flooding, cyclone and hot and cold weather events leading to loss of fish or fingerlings and ponds and increases in pollution and fish diseases. Measures to cope with the risks echoes many mentioned in Table 3.

In fisheries, recent expert assessment of best practice in climate-adaptative management such as that led by FAO (Bahri et al., 2021) has reinforced mainstream fisheries management practices applied to addressing the climate change impacts. The FAO assessment drew from the evidence of 13 case studies of fisheries management under climate change conditions and supported 15 measures. The case studies are drawn from all continents and cover a wide range of fished species. The measures address one or more of the significant climate change impacts on fished species, namely: distributional change, productivity change, and species composition change. Each measure was required to meet three essential criteria for good practice: explicitly addresses climate change impacts, sufficient evidence to ensure/infer its effectiveness, and return a win-win (costs and benefits) or lose-win outcome. In addition, two beneficial criteria were also considered: flexible/responsive, socially acceptable. A literature review by Galappaththi et al. (2022) found many of these measures also, and several additional suggestions, with particular relevance to the conduct of fishing operations. The two sets are merged in Table 4.

Table 4. Climate-adaptative fisheries management good practice measures recommended in Bahri et al. (2021, p. 25, Table 5) and those by Galappaththi et al. (2022, p. 11, Table 2) from a literature review of coping responses and common adaptive strategies. The measures have been ordered into six categories from monitoring and early warning through to market and financial measures. Some have been paraphrased.

	1. Monitoring and early warning
•	Enhance monitoring programs through community-based approaches
•	Update with weather information before fishing trips
•	Establish early warning systems for extreme events
•	Adjust spatial scale of monitoring to be responsive to shifting stocks
	2. Fisheries assessments
•	Incorporate environmental variables and risk into fisheries assessment and management advice
•	Using multiple knowledge systems, e.g., Indigenous, local and Western science
•	Using new technology for collaboration, e.g., location- aware mobile devices, cloud-based computing, and visualization and query of geographical data over the web to capture, visualize and share logbook data
	3. Practical fisheries management and fishing measures
•	Flexible and adaptable fishing seasons
•	Tradable fishing rights/allocations to allow flexibility in response to stocks shifting across international borders
•	Close fishery during climate-driven events to support resilience and recovery

• In-season management systems that are responsive to rapid climate-driven stock changes
• Conserve keystone species complexes to avoid ecological tipping points and related changes in target species abundance
• Develop new fishery opportunities to capitalise on distribution shifts or enhances productivity (including for ‘new’ species)
• Increasing fishing gear diversity or using a different technology, including revival of traditional fishing techniques and
• Improving vessel fuel efficiency
• Capacity building to inform/train fishers (e.g., workshops, education, research)
4. Manipulating the resources
• Relocate fishery species to more productive areas to compensate for changes in productivity
• Tree planting to reduce river temperature
5. Household and community measures
• Collaborating with fellow fishers and sharing food
• Building community resilience by increasing social capital (social cohesion, local fundraising, maintaining cultural identities); strengthening local institutions and establishing new institutions
• Using family members as labour
• Taking out small loans of pawning gold jewellery
• Temporarily migrating (low regrets); permanently migrating (upfront strategy)
• Livelihood diversification inside and outside fisheries, including quitting fisheries altogether
6. Market, economic support and infrastructure measures
• Relocate landing and processing practices
• Source more diverse supplies of seafood for processing facilities
• Develop new products and markets to maximise fishery value as catches decline
• Making the sale price of fish more responsive to fuel price fluctuations
• Develop insurance schemes that protect fishers against loss and damage after climate events or due to ‘forced’ practice changes or exit from the industry

Some of the adaptative management measures would be more appropriate for fisheries with advanced fisheries management capacity, e.g., tradeable quotas. Small-scale fisheries (SSF) often present additional challenges because they are often data-poor and have limited financial and management resources. More work is needed to develop short term no-regrets or low regrets policies suitable for SSF (Gutierrez et al., 2023, p. 79).

Regional studies have addressed climate change adaptation for specific water bodies and regions.

For the Central and Western Pacific. Bell et al. (2011) examined the climate change outlook for industrial and small-scale coastal fisheries and aquaculture noting that the projected changes in the distribution and abundance of tuna required industry and country flexibility. Some more eastern countries such as Kiribati, Nauru, Tuvalu and Tokelau may benefit from more tuna. The more westerly countries with major tuna fisheries were also large and more diverse economies and considered more capable of handling changes. Aquaculture of freshwater fish may benefit from greater rainfall predicted in some countries that typically suffer water scarcity. Nearshore coastal fisheries including reef lagoons where women, men and children spend considerable time gleaning for subsistence, will suffer from coastal erosion, rising sea-levels and heating reefs. Those people will need to consider making more use of nearshore pelagic fishes, including skipjack and yellowfin tuna, through establishing local anchored fish aggregating devices. Despite efforts in some countries, such as

Solomon Islands, to engage women in fishing from boats around these anchored devices, their involvement has been minimal, tends to deepen gender inequalities within the household and can lead to conflicts (Labuinao, 2019).

For Africa, Kolding et al. (2016) reviewed the long term climate-linked patterns of water availability and fisheries production – "fish come with the rains" - in rivers and lakes in African dryland regions. The results of quantitative studies from such water bodies as Lakes Chad, Malawi, Malombe, Victoria, and Turkana, and River Niger showed how irregular rainfall was the most critical driver of fisheries in the drylands through its impacts on surface water availability. The dryland water bodies are unstable ecosystems fed by pulses of unpredictable rainfall. Their fish biota tends to be productive, comprising small-sized, opportunistic, resilient fish species that have "boom and bust" abundance patterns. People living in the arid and semi-arid areas and using fish from these water bodies will be subject to increasing variability in these already erratic climate patterns. However, with greater recognition of the benefits of fish when available, Kolding et al. (2016) stressed that such fish may still provide some greater productivity, but the people using them would need to adopt diversified livelihood strategies to match the irregular production.

Lubembe et al. (2022) reviewed the African literature for fisheries and aquaculture, concluding the confluence of overfishing and climate stresses in the case of capture fisheries, and climate factors such as rising sea levels, rising water temperatures, rising water salinity, ocean acidification, changes in precipitation patterns, disease, and algal blooms, Fish and fishing communities have both adapted to the changes, but often to the detriment of sustainability, such as fishing more intensively on already depleted or shifting fish stocks. Some mitigation and adaptation are possible such as through mangrove replanting and coral reef restoration, methods for which are being tested in over 50 countries. Despite the challenges, many adaptative measures rest with the local fishers and their collective understanding of climate change measures and adaptive management options. Unfortunately, support to local adaptative management is through a patchwork of ministerial arrangements such wildlife, water and fisheries agencies, and rarely becomes part of National Adaptation Plans (Lubembe et al., 2022, p. 67).

2. The technological fix pathways

As the foregoing section outlines, experts including fishers, farmers, researchers, and policy makers have begun to incorporate climate change impacts into their work considerations. In parallel, the stresses on current operations, and the emerging and pending stresses of climate change have pushed better endowed fishing and farming enterprises, research and development institutes and entrepreneurs to push for more cutting-edge technological fixes. Some of these were hinted at in Tables 3 and 4. In aquaculture, the technological fixes either address current bottlenecks such as the supply and cost of feeds in aquaculture, and/or the desire for much greater control over the aquaculture process. In fact, most of the technology pathways are not being designed as fixes for climate change but as growth pathways for production. They are, however, happening in an era of greater sensitivity to climate and environmental challenges and frequently promote their superiority in these regards (Ahmed & Turchini, 2021). In fisheries, the fixes are more likely to be concerned with manipulating the ecosystem or improving knowledge for fishers, firms, and managers. In marine fisheries, fisheries management and fish stock assessment technologies are paramount. In inland fisheries, technology pathways are more likely to be concerned with how fish and fishers can cope with major waterway changes, such as from dams and competition with urban and irrigation water use.

Aquaculture

Aquaculture is particularly focused on technology options and performance. As a major growth area, aquaculture is subject to the entry of many new adoptees on steep learning curves, as well as established actors expanding their operations and restlessly seeking new technology options to give them a competitive edge. With respect to technologies, each of the items in Table 5 merits deeper treatment that is beyond the scope of the present chapter, but three items are singled out for mention in the present chapter, because each is receiving public attention beyond fisheries and aquaculture. These areas are recirculating aquaculture systems (RAS), seaweed farming, and the application of genetic technologies to aquaculture. They illustrate the challenges and opportunities indicative of those facing aquaculture more generally.

Table 5. Innovative aquaculture technology systems and core strategic technologies under development and implementation, with a focus on those with the potential to cope with or reduce climate change impact. The Table draws on Yuan (2021). Descriptions are taken, where possible, from the FAO Aquaculture Glossary (https://www.fao.org/faoterm/collection/aquaculture/en/), and supplemented with information from Yuan (2021).

Aquaculture system	**Description**
Recirculating aquaculture systems (RAS)	A closed or partially closed system employed in aquaculture production where the effluent water from the system is treated to enable its reuse. Highly capital intensive.
Shipping container-based fish culture	The fish are intensively raised in steel tanks modified from shipping containers. RAS models have been designed for use in shipping containers.
Pond-based recirculation systems	Reservoir for water storage, pond(s) for water supply, and culture ponds. Tend to use large areas for water treatment, often using biological methods (bivalves, plants, and filter-feeding fish).
In-pond raceway aquaculture	Based on water structure, usually above ground, with a long, linear configuration; high water turnover rate; highly controlled environment; often terraced with water reuse. In-pond systems integrate traditional pond culture and intensive raceway culture.
Aquaculture and photo-voltaic integration (API)	In China, water beneath photo-voltaic panels is stocked with fish that are raised in intensive ways, such as using raceways.
Off-shore cage culture	Large-scale cage, and even ship-based culture is being tested, mainly in China. Highly capital and technology intensive, often combined with tourism for multiple income streams and targeted at higher value species.
Polyculture	Rearing of two or more non-competitive species in the same culture unit, e.g., shrimp-fish, shrimp-plants. Rice-fish and rice-shrimp is another form of polyculture in which land use may rotate between rice and aquaculture or may carry out the two simultaneously.
Integrated multi-trophic aquaculture	Species from different trophic levels are raised in proximity to one another and the co-products (organic and inorganic wastes) of one cultured species are recycled to serve as nutritional inputs for others.

	(Knowler et al., 2020). Attractive environmentally, but knowledge intensive and not widely practiced.
Aquaponics	Bio-integrated system that links recirculating aquaculture with hydroponic vegetable, flower, and/or herb production.
Seaweed culture	Seaweed is often touted as a major solution to carbon sequestration
Strategic Technologies	**Description**
Genetics	Whole genome sequences done for 52 aquaculture animal species, large-scale SNP genotyping including constructing genetic linkage maps, QTL mapping, genome-wide association study and genomic selection for e.g., growth and body shape, stress, salinity tolerance, disease resistance (You et al., 2020); and genetically modified fish including using CRISPR (Yuan, 2021), (Okoli et al., 2022).
Feeds	Novel feed ingredients replacement for fish meal and fish oil, functional feed additives, improved on-farm feed management, dietary fortification for improving nutrient value of aquatic products, prebiotics, and probiotics to improve aquatic animal nutrition.
Information, digital and artificial (AI) technologies	Supports automation, process controls, trading, and communications.
Management technologies	Farm management technologies, often involving combinations of other strategic technologies are critical for aquaculture adaptation and mitigation measures.

RAS and other contained systems are receiving the greatest commercial attention; offshore cage installations are also in the news for some of the same reasons. These are driven by onshore constraints for suitable farming space and water and the need for greater water and nutrient recycling (circular) (Verdegem et al., 2023). RAS is attractive for its high productivity but it is also complex, highly capital intensive, requires low-emissions energy solutions, and is rarely considered a suitable option for community-based adoption, especially in developing countries (Ahmed & Turchini, 2021). Despite not arousing some of the same animosity shown to inshore aquaculture, RAS nevertheless competes for onshore space and resources, natural and human constructed. Proponents of RAS facilities have to build local legitimacy, credibility and trust, arising from concerns over its local sources of energy, competition for space, integration with local practices and culture, and potential animal health and welfare issues (Fudge et al., 2023).

Seaweed farming is receiving attention as creating large investment opportunities as a multi-purpose solution to environment, climate, and development. A typical statement is that recently given in a World Bank document:

> *With its ability to sink carbon, sustain marine biodiversity, employ women, and unlock value chains, seaweed farming demonstrates how development, climate, and nature work together to generate value and uplift communities.* (World Bank, 2023, p. XI)

The World Bank market report canvassed a range of market sectors and ecosystem services that seaweed production could serve (Table 6). It noted the current concentration of seaweed production in Asia, especially brown algae or kelps in the genera *Saccharina* and *Laminaria*, tropical red seaweeds comprising eucheumatoid seaweeds of the genus *Eucheuma* and *Kappaphycus*, and *Gracilaria* species, and the major growth in seaweed production of the last decade.

To the present, seaweed has been serving three major markets – direct human food (85%), aquaculture animal feeds, and the hydrocolloid markets (carrageenan, agar, alginates) (World Bank, 2023, p. 4). The hydrocolloids markets are dominated by about 10 major firms, located in China, Denmark, France, Philippines, and USA (Porse & Rudolph, 2017).

As the multiple benefits of seaweed production are promoted, e.g., see "*Seaweed Revolution: A Manifesto for a Sustainable Future*" (Anon, 2020), the distribution of benefits along the value chains are rarely analysed. In 2019, first sale prices of various species of seaweed varied from USD 0.21 to 0.89 kg^{-1} (wet weight) (Cai et al., 2021, p. 8). Most tropical seaweeds are sold dry, with the primary producers providing the labour for drying (Ramirez et al., 2020). Much of the value in seaweed production, therefore, is captured after the first point of sale, raising questions about the extent to which the expansion of seaweed production advantages human development.

Forward looking market reports project that existing complex, high value-added markets, and other emerging ones will become more important. The World Bank (2023) examined 10 emerging and potential market sectors: biostimulants, animal feed additives, pet food, methane-reducing feed supplements, nutraceuticals, alternative proteins, fabrics, bioplastics, pharmaceuticals and constructions materials. Predicting market size and time to maturity, nutraceuticals are judged the most promising market and construction the longest term bet (World Bank, 2023, Figure 32). The market and non-market potential and challenges for realising ecosystem services include blue carbon, seaweed bioremediation, methane reduction, seaweed for biodiversity and other ecosystem services.

Other experts express much more cautious views on the promises and consequences of simultaneously growing seaweed to feed the world, provide animal feeds promising lower livestock emissions, and mitigation through mass-scale automated farming of seaweed for ocean carbon sequestration. Considerable uncertainty surrounds the timescales of carbon cycling of seaweeds, the economics, ecological impacts and ethical considerations (Troell et al., 2023).

Genetic improvement of farmed crops and terrestrial livestock species have been at the core of agricultural progress for millennia. Widespread application of genetic technologies is more recent in aquatic animals, although fish culturists altered the genetic composition of farmed fish to suit their needs since the start of fish culture thousands of years ago (Dunham, 2023, Chapter 1). Despite significant progress in genetic improvement, the production of many commonly farmed aquatic animal and plant species is based on species and species groups that are little improved over wild types (Table 6). Many seaweeds are little genetically improved. An exception is the agar producing *Gracilaria* species that are favoured in the hydrocolloid industries (Porse & Rudolph, 2017).

Table 6: Extent of genetic improvement of the world's top 15 cultured aquatic species or species groups (plants and animals). The information in this table is summarised from Table 3 of Sonesson et al. (2023, Table 3).

Genetic Improvement Status	**Species or species groups**
Very High	Atlantic salmon – *Salmo salar*
	Whiteleg shrimp – *Penaeus vannamei*
High	Common carp -*Cyprinus carpio*
	Gracilaria seaweeds – *Gracilaria spp*
	Gold fish and crucian carps - *Carassius* spp

Moderate-High	Cupped (Pacific) oysters – *Magallana gigas*
Moderate	Nile tilapia - *Oreochromis niloticus*
	Rohu carp - *Labeo rohita*
Low	Japanese kelp – *Laminaria japonica*
	Silver carp -*Hypophthalmichthys molitrix*
	Manila clam/Japanese carpet -shell – *Ruditapes philippinarum*
	Bighead carp -*Hypophthalmichthys nobilis*
Very low	Eucheuma seaweeds - *Kappaphycus alvarezii*, *Eucheuma cottonii*, *Eucheuma denticulatum* and *Eucheuma* spp
	Grass carp – *Ctenopharyngodon idellus*
	Catla - *Catla catla*

From species selection through to genetically improved farmed varieties, aquaculture production faces the challenge of where to invest safely in genetic advances. A large number of aquatic species are farmed. Metian et al. (2020) noted 462 identified species and 145 groups not elsewhere included (nei) but often reported at the genus level, making for more than 600 farmed species. Aquatic animal production (by volume), however, comes mainly from about 20 species accounting for 70% of the global total. Of these, whole genomes are available for 52 species of aquaculture animals (You et al., 2020). The aquaculture industry has embraced high-throughput sequencing technologies, producing many genetic markers especially finding and applying single nucleotide polymorphisms (SNPs) to create genetic linkage maps, map quantitative trait loci (QTL), study genome-wide associations (GWAS), and perform genomic selection (GS).

QTLs identified in aquaculture species were mainly focused on growth and related factors, but climate-linked factors such as osmoregulation, temperature tolerance, and several types of disease resistance received significant attention (You et al., 2020, Table 7). GWAS focused on growth, but salinity, temperature, oxygen and disease factors also received some attention (You et al., 2020, Table 8). GS studies are focusing almost equally on growth and disease management factors, depending on the species used (You et al., 2020, Table 9). Current applications of genetic technologies to aquaculture species hold considerable promise that knowledge gained on a species may be transferrable to other species (You et al., 2020). The overall dominance of growth and associated factors, including disease management, does not create a strong pipeline of targeted work to food security species, i.e., those of lower market value, and climate adaptation characteristics. However, the rapid progress with genetic technologies do offer the possibilities that, with strategic planning and the right incentives, a pivot towards genetically improved aquatic species that could better adapt to climate change would be possible. Concomitant targeting of genetic solutions to food security needs is economically and policy-wise more complex.

Finally, in light of an expected upswing in applying genetic technologies, stakeholders of access and benefit sharing (ABS) arrangements and patents must comprehend the options available and haw these apply to aquatic genetic resource use, if they are to operate legally (Sonesson et al., 2023). As indicated by the relatively low level of genetically improved stocks used in aquatic farming, relative to crop and livestock farming, aquatic activities still rely considerably on native germplasm and biodiversity and ABS arrangements are less mature or well understood in aquaculture.

Fisheries

In considering adaptation in capture fisheries, the major focus has been on the technologies of fisheries management, i.e., the strategies, rules and regulations operating on the fishers, their operations, and the fish value chains, and fish stock assessment. Empirical studies verify that managed fisheries are more sustainable, yet many fisheries are not under the most effective management (Hilborn et al., 2020). Fish stock assessment is central to fisheries management, although the social and economic context of management is also germane to success (FAO, 2022, pp. 126-136). Fish stock assessment gauges the state and projected sustainable productivity of aquatic resources. If suitable data are available, stock assessment typically combines increasingly sophisticated mathematical modelling approaches, predicting the impacts of fishing on the stocks and disentangling the effects of weather, climate, and environmental variables including pollution and supporting habitat states. Stock assessment good practice has been codified by experts, e.g., see Punt (2023). Ideally, the results of fish stock assessments are heeded and used in making fisheries management decisions.

Fisheries management is considered critical to achieving key targets in SDG#14 (Life Below Water) and a Blue Transformation (see FAO (2022, pp. 126-136)), which is defined as a "*set of actions, policies and strategies aimed at sustainably expanding and enhancing aquatic food systems and increasing their contribution to affordable and accessible healthy diets, while fostering equitable growth.*" (FAO, 2022, p. 225). Fisheries management strategies for climate adaptation are also critical to the sector, as illustrated in the case studies reviewed by Bahri et al. (2021), and the resulting adaptation strategies included in Table 4, especially in parts 1-4 of the Table.

For many fisheries in the global South and the global North, however, data for stock assessment and management are limited. In many countries, the capacity for stock assessment and fisheries management is also limited. Data- and management capacity-limited fisheries are characterised by poor data collection, management arrangements that are not fit for local social and economic contexts, e.g., ignoring local knowledge, and poorly applied through having weak and ineffective monitoring, surveillance, and enforcement. Fortunately, long term capacity building support, often provided through regional fisheries management and technical agencies can provide cost-effective solutions (FAO, 2022, pp. 135-136). With respect to data for management, my own experience covers nearly 50 years of working in and keeping in touch with fisheries data arrangements at levels from small-scale local fisheries to international industrial scale (tuna) fisheries. It has shown that modern information technology – computing hardware, software and connectivity - has brought into reach real solutions. This was well illustrated in the recent newsletter of the Philippines National Fisheries Research and Development Institute that covered articles on capacity building in data enumeration, field fish taxonomy, stock assessment, and harvest strategies for management (FISEARCH, 2023)

Due to progress in decadal and seasonal climate predictions for the oceans, some of these are now at a scale usable to regional fish stock assessments for fisheries management, according to Tommasi et al. (2017) who also recommend practices for assessing forecast needs, developing the forecast and delivering the results. The authors concluded that although a start has been made on integrating fisheries and climate forecasts, further institution building is needed to achieve a mutual understanding of needs between climate and fisheries scientists, develop shared understanding of prediction uncertainties, and means for coping, *post hoc,* with failures in predictions. Practitioners will also have to cope with what is realistic in terms of management reform, but noting that climate-adaptive fisheries management, according to modelling by g., Free et al. (2020), is more profitable than business as usual.

Practices for integrating fisheries and climate assessment for many small-scale fisheries face the challenges of having schemes that are relevant to their geographic scales, much as terrestrial farmers are linking with the most local of weather, climate and climate change forecasts available.

Mainstream fish stock assessment is mainly the domain of marine fisheries scientists, whereas adaptation technology pathways for inland fisheries are more likely to be concerned with the major disruptions to water bodies caused by other uses of water as well as by climate change. To cope with these disruptions, and the creation of new water bodies, technologies such as stock enhancement (stocking reservoirs, dams, rivers and lakes with fry or more advanced specimens of desirable species), fish migration systems to overcome barriers in waterways, and other water engineering structure. The case of the Aral Sea in Central Asia presents a case in which catastrophic degradation from human interventions was ameliorated in one part of the ecosystem by remedial technology pathways.

The plight of the drying Aral Sea has captured world attention for its loss of fisheries and fisheries livelihoods in the decades since the 1960 (Aladin et al., 2018; Micklin et al., 2020). The Aral Sea, in Kazakhstan and Uzbekistan, is major brackish water lake in the Central Asian desert, formed in a closed basin fed by the rivers Amu Darya (feeding the southern part of the Sea) and Syr Darya (feeding the northern part). Excessive draining of the rivers for agricultural irrigation during the Soviet Union caused, from the 1960s, progressive desiccation and salinisation of the Aral Sea and severe toxic salt and dust storms. When the Aral separated into a small northern (Small Aral) and larger southern (Large Aral) part in 1987-89, an earthen dike was constructed in 1992 to prevent backflow of water from the Small Aral. After the temporary dike was breached in 1999, a more permanent structure was constructed in the early 2000s, deepening the Small Aral and greatly improving its ecology and fisheries. The Large Aral has been desiccated and salinized to the extent that even the remaining water cannot support fish but only some introduced brine shrimp that are harvested for their eggs, whereas the engineered hydrological solution has helped the Small Aral achieve a 1960s-like ecosystem and fisheries (Aladin et al., 2018). Furthermore, Aladin et al. (2018) believe that with further engineering structure, a partial recovery of the Large Aral may be possible. An international coalition of multi-disciplinary, multi-sectoral actors including researchers, artists, policy makers and industry representatives have formed to promote the possibilities for finding solutions and raising awareness of the issues and options, as the declaration from the 2019 conference on the Aral Sea problems reports (https://www.zin.ru/conferences/Aral2019/index.html). Among the headline statements coming from the conference were that "*reports of the death of the Aral Sea are premature*" and that "*scientists, artists and cultural experts all have important roles in the preservation and rehabilitation of the Aral Sea and its region*." In specific terms, cooperative management of the flow of the Amu Darya and Syr Darya rivers was essential, but (heroic) engineering solutions such as redirecting major rivers (from outside the catchment) is not feasible for solving the problems. The role of cross-cultural communication and its emotional content have been recognised (Dumetz & Aladin, 2021).

3. Sociotechnical systems approaches:

The technology fix pathways discussed in the previous section were mainly based on the idea that a single technology would be critical to adaptation. Many of these examples, however, soon reached implementation challenges that caused them to invoke the need for new institutions, networks, legal instruments, and other contextual elements to succeed. Early in their development, climate mitigation and adaptation solutions have increasingly been acknowledged as requiring development, testing and dispersion in highly complex systems, named socio-technical systems (STS).

(Geels, 2002, 2004) developed methodology to encompass interactions among actors, levels and institutions in STSs, concerned across the spectrum from creation, production, and distribution to use of technologies. Of particular interest in this work was understanding the longer-term forces acting as technologies and society jointly changed, often with one STS changing into a new one.

Geels (2004); (Geels, 2019) recognized not only the material technology but the multi-layered systems within which STSs operate. The layers are (a) the niches in which innovations are tested and developed, (b) the legal, management, and social regimes that form the current systems, and (c) the higher-level landscape that constructs the regimes and over which the lower layers have little influence. In a political economy sense, this is the set of organising institutions of the political economy.

A major field of interest for social scientists working with STSs is the issue of how they transition from one regime to another. In this regard, the study of transitions in climate change mitigating technologies is a major theme among STS studies (Hess & Sovacool, 2020). STS approaches have been rarely used yet in fisheries and aquaculture, but they are nevertheless drawing attention from an emerging rank of inter-disciplinary social scientists and holds promise for a providing insights and pointers to action in more inclusive and positively directed STS transitions (Williams & Syddall, 2022). Rather than full STS approaches, other researchers are modelling complex fisheries scenarios under climate change using such methodologies as game theory (strategic interactions approaches), e.g., Vogel et al. (2023) in examining options for managing fisheries conflicts arising from climate change impacts on transboundary fish stocks. Multi-disciplinary and transdisciplinary capacity in research into complex systems is recognised as fundamental, although research tends to focus on socio-ecological systems (Cooke et al., 2023), rather than socio-technical systems.

Our exploration of the possibilities of applying STS transitions approaches to improve the inclusion of women's interests and gender equality in fisheries/aquaculture technology transitions indicated that *post hoc* and anticipatory sociotechnical systems transition research could both be useful (Williams & Syddall, 2022). The same applies in the case of social inclusion more generally under technology transitions in fisheries/aquaculture affected by climate change. *Post hoc* studies illuminate the current situation with respect to who benefits, i.e., are the benefits reaching or bypassing the poor and why; anticipatory research may guide researchers and policy-makers on how to achieve a more inclusive political economy outcome.

Many of the technological fix pathways outlined in the previous section do not take an expansive systems approach, but will, if successful, diffuse and transform industries and enterprises (Table 7). These are the types of technological fixes that need research and monitoring so that their transition impacts can be understood and adjustments made to help achieve justice in access to the benefits, and in mitigating any negative impacts.

Table 7. Technology fix pathways, selected from examples in the preceding section, which, if successfully developed and widely dispersed, will lead to socio-technical systems transitions, some of which may have unintended consequences, creating winners and losers.

Recirculating aquaculture systems (RAS)
Seaweed culture as blue carbon solution
Genetic aquaculture technologies
New aquaculture feeds
Information, digital and artificial (AI) technologies in aquaculture
New aquaculture management technologies
Improved marine fish stock assessment and management of data- and management capacity-limited fisheries
Improved fisheries and climate oceanography projections to support fisheries management
Engineering and biological enhancement solutions in inland fisheries

Source: Author, based on references cited in the current Chapter.

Conclusions

In this chapter, I have attempted to provide a snapshot of fisheries and aquaculture research and strategy development in the face of climate change. Relevant research has mainly been conducted in the last decade, coinciding with tangible evidence that resource changes and challenges due to climate change are already strongly affecting fisheries and aquaculture, plus IPCCs increasing efforts to include the oceans, freshwater and aquatic production systems in their Assessment Reports. The impacts of climate change are specific to each geographic area and the aquatic systems in which fish are produced naturally or in culture. Projections of future impacts are available for a few aquatic systems, but more modelling of aquatic resources and climate changes are needed, especially at locally meaningful scales.

Reviews of how fisheries and aquaculture are adapting to climate change show a wide set of strategies being applied by key actors (Tables 3 and 4). The fish sectors are choosing technology fix pathways as the main adaptation approach. Fisheries, which has already faced three decades of total production limits, has been more accommodating of the need to factor in climate change in stock assessment and management than has aquaculture. The aquaculture sector tends to be still concerned with maintaining its rapid growth rate but also recognises climate change as a rising challenge. Both sectors will benefit from emerging collaborations with climate oceanography. Many of the technology fixes being sought are leading to appreciation of the complexities of major technology transitions, whether driven by sectoral growth or climate change. Little work is yet being done using socio-technical transitions approaches.

The major challenges brought by climate change are going to exacerbate the ongoing dilemmas of whether adaptation will affect small-scale fisheries and aquaculture more than the large-scale enterprises, and which people will be displaced in the adaptation processes. People in dry areas will certainly struggle more than those in areas with greater water availability, but disasters such as extreme weather (storms, floods, droughts, fires) appears to be affecting those in even the most well-endowed areas. Climate adaptation options, technical fix pathways and the pathways of transitions occurring in systems that are complex in socio-technical and ecologically senses will all be called on for fisheries and aquaculture to continue to help feed the world.

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