Chapter 6. Artisanal fisheries, climate change and scientific challenges for marine spatial planning

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Introduction

1 The direct effects of fishing on the distribution, demographics and stock structure of exploited species, combined with changes in productivity and community composition as a result of climate change, are likely to limit the ability of fisheries to function in their current form and to adapt to future changes (BRANDER, 2007; JOHNSON and WELCH, 2009). In this context, artisanal fisheries, which are defined in the United Nations Food and Agriculture Organization (FAO) glossary as "traditional fisheries involving fishing households (as opposed to commercial companies), using relatively small amounts of capital and energy, relatively small fishing vessels (if any), making short fishing trips, close to shore, and mainly for local consumption", appear to be very vulnerable, particularly in the intertropical zone. This area is more exposed to the consequences of climate change than the rest of the world, and the populations involved in artisanal fishing have a high level of dependence on the exploited resource and limited capacity to adapt due to a fragile socio-economic context. Despite this known vulnerability of artisanal fisheries, few studies at the local level have addressed how climate variability and change affect the lives and livelihoods of the "tropical majority" of small-scale fishers, who make up more than 90% of the world's fishers and fish traders (see BADJECK *et al.* 2010). Policy options to reduce the vulnerability of fisheries need to be considered at local, national and international scales, and to address short-, medium- and long-term risks (CINNER *et al.*, 2012). As a first step, reducing the vulnerability of artisanal fisheries requires a better understanding of the processes involved at these different scales in order to be able to assess their degree of exposure and their capacity to adapt

to the consequences of climate change. Improving knowledge of these processes and the dynamics of marine ecosystems should make it possible to implement marine spatial planning (MSP) that is consistent with all uses.

2 This chapter summarises the impacts of climate change on fisheries in general and then focuses on the vulnerability associated with the particular case of artisanal fisheries, presenting a case study of the shellfish fishery in the Sine-Saloum delta in Senegal. It also discusses the scientific challenges to be overcome to support the implementation of MSP adapted to the problems of artisanal fisheries.

Impacts of climate change on fisheries

3 The warming of the climate is unequivocal and has many consequences for the oceans (IPCC, 2019). These include:

- rising average temperatures and increasing frequency of extreme heatwaves
- acidification associated with the absorption of atmospheric CO_2 into the water column
- decreasing oxygen levels in the water and an increase in the number of hypoxic “dead zones”
- rising average sea levels and increased risk of coastal erosion
- modification of soil inputs to coastal waters by changes in the rainfall regime.

4 These consequences of climate change on the oceans have direct and indirect impacts on the distribution and productivity of natural resources. They directly modify the physiological performance and behaviour of species, affecting their growth, reproductive success, fitness and phenology (i.e. seasonality), disrupting their migrations and potentially impacting their survival by increasing their vulnerability to pathogens (BEAUGRAND and KIRBY, 2018; BURGE *et al.*, 2014; DONEY *et al.*, 2012). Climate change also acts indirectly, at the population and ecosystem levels, by generating habitat loss, altering food webs by changing the productivity of food sources, and modifying interactions between species by modulating the abundance of competitors, predators and pathogens (ALBOUY *et al.*, 2014; DONEY *et al.*, 2012).

5 The consequences of fisheries are multiple (Table 1). Variability in environmental conditions determines the distribution, migration, abundance and size of species caught. This redistributes catch potential on a global scale, modifies species composition locally and changes the average size of exploited species (BRANDER, 2007). In addition to the consequences for resources, fishing operations and infrastructure are also directly affected. Rising sea levels and increased occurrence of extreme weather events (storms, cyclones) are weakening port structures. Fishing effort is also impacted through the reduction of opportunities to go to sea and the need for fishermen to adapt their fishing strategies and gear.

6 However, the consequences of climate change are not homogeneous on a global scale. A projection of the redistribution of catch potential by 2050–60 in the RCP 8.5 “business as usual” scenario (CHEUNG *et al.*, 2009) explicitly shows that the intertropical zone will be much more affected than the rest of the world, with catch decreases of between 40% and 60%, while high-latitude regions could see their potential increase by 30% to 70% (fig. 1). This is fundamental to the concept of vulnerability, which, according to the third assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2001), is the extent to which climate change can damage or harm a system and depends

not only on the sensitivity of a system but on its ability to adapt to new climatic conditions. In the context of the artisanal fisheries studied here, this refers to a socio-ecological system, which is defined as "a system that comprises mutually interacting societal (human) and ecological (biophysical) subsystems" (GALLOPIN *et al.*, 1989). Considering the impacts of climate change on marine resources and the level of vulnerability of artisanal fisheries in developing countries in the tropics, the latter appear to be between a rock and a hard place, with higher exposure and lower adaptive capacity (ALLISON *et al.*, 2019).

Table 1. Examples of climate impact pathways on fisheries

Types of change	**Climatic variables**	**Impacts**	**Potential consequences for fisheries**
Physical environment	Ocean acidification	Effects on calcifying organisms, e.g. molluscs, crustaceans, corals, echinoderms and some phytoplankton	Potential decrease in the production of marine resources
	Warming of the surface layers	Cold water species replaced by warm-water species	Shift in the distribution of plankton, invertebrates, fish, birds, towards the North or South Poles, reduction in species diversity in tropical waters
		Modification of phytoplankton bloom periods	Potential mismatch between prey (plankton) and predators (fish populations) and decline in production and biodiversity
		Changes in zooplankton community composition	

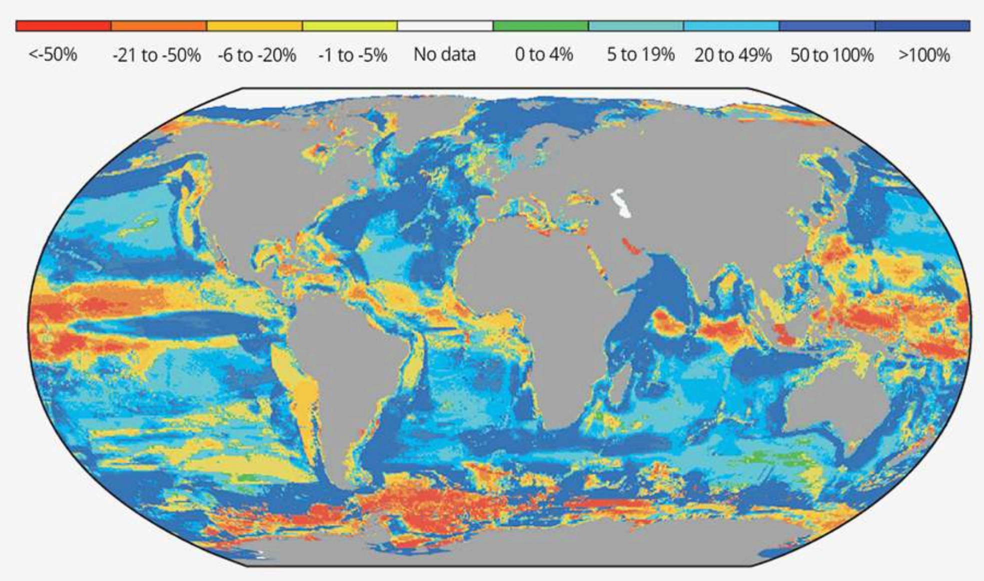
	Rising sea levels	Loss of habitats, e.g. nursery areas, mangroves, coral reefs	Reduction in inshore fisheries production
Stocks	Higher temperatures Changes in ocean currents	Changes in the sex ratio Changes in egg-laying periods Changes in migration periods Changes in peak abundance periods	Possible impacts on timing and productivity levels in marine and freshwater systems
		Increase in invasive species, diseases and toxic algal blooms	Reduced production of target species in marine and freshwater systems
		Reduction in recruitment success	Impact on the abundance of juvenile fish and therefore on marine and freshwater production
Ecosystems	Reduced flows and increased droughts	Changes in lake levels Change in low water periods	Reduced river productivity
	Increase in El Niño–Southern Oscillation (ENSO) events	Changes in the period and amplitude of upwellings Coral bleaching and loss	Changes in the distribution of pelagic fisheries Reduced productivity of coral reef fisheries

Coastal infrastructure and fishing operations	Rising water levels	Change in coastal profile, loss of harbours and settlements Increased exposure of coastal areas to storms	Adaptation costs make fishing less profitable, risk of storm damage increases insurance and/or reconstruction costs and increases vulnerability of coastal households
	Increased frequency of storms	More days at sea lost due to bad weather, increased risk of accidents	Increased risks to fishing and coastal fish farming, which become less viable livelihoods for the poor Declining profitability of large-scale enterprises Increase in insurance premiums
		Aquaculture facilities (coastal ponds, sea cages) more likely to be damaged or destroyed	
Inland fisheries operations and livelihoods	Change of precipitation level	Reduced opportunities for agriculture, fisheries and aquaculture	Reduced diversity of rural livelihoods Increased risks to agriculture Increased dependence on non-farm income
	More droughts and floods	Damage to productive assets (fish ponds, dams, rice fields, etc.) and housing	Increased vulnerability of riverside and floodplain communities and households

	Less predictable rainy/dry seasons	Decreased ability to plan livelihood activities e.g. seasonality of farming and fishing	

Source: FAO (2007b); see Allison *et al.* (2005) for a summary

Figure 1. Projection of the global redistribution of the maximum catch potential of about 1000 exploited species of marine fish and invertebrates



The projections compare decadal averages for 2001–2010 and 2051–2060 using ocean conditions based on a single climate model in a moderate to high warming scenario, without analysis of the potential impacts of overfishing or ocean acidification.
Source: Cheung *et al.* (2009); from IPCC (2014)

7 The impact of climate change must also be assessed in the context of other anthropogenic and/or natural pressures, which often have significant and more immediate effects (Brander, 2010). In particular, fish species will be more sensitive to the effects of climate change if their habitat is degraded. Destructive fishing practices that deplete stocks, reduce biodiversity through bycatch mortality and damage the structure of the seabed reduce habitat complexity and thus undermine the resilience of fisheries to climate change (Johnson and Welch, 2009). In addition, the decadal variability of regional climate conditions, characterised by climate indices such as the North Atlantic Oscillation (NAO), El Niño–Southern Oscillation (ENSO) or Pacific Decadal Oscillation (PDO), also puts pressure on fisheries resources related to, for example, wind conditions leading to variable intensity of coastal upwelling, or river run-off leading to contrasting coastal eutrophication, in combination with the effects of climate change (Lehodey *et al.*, 2006).

8 As a result, two major effects of climate change have been identified, which are likely to have a significant impact on fishing activity, and in particular on small-scale fisheries: a

decrease in species productivity and the geographic displacement of species. These are multifactorial processes that are governed by variables occurring on multiple temporal and spatial scales. To better assess the consequences of climate change on small-scale fisheries, it is necessary to specify the processes behind these effects. This should help guide the implementation of ecosystem observation systems and support the development of appropriate management measures.

Decrease in productivity

9 In ecology, productivity refers to the production of biomass in an ecosystem. In the case of a fisheries resource, this productivity depends on several processes:

- reproduction and recruitment, which determine the arrival of new individuals in a population
- individual development and growth, which increases the overall biomass of a population and allows animals to reach the reproductive adult stage
- mortality, which regulates the number of individuals, and can be associated with predation, disease, stress (thermal, hypoxia, pollution, etc.) or fishing
- migration, which can play a role in regulating local biomass when looking at a given geographical area.

10 There are many stressors associated with climate change that are involved in the decline in productivity of harvested species. These stressors occur at multiple spatial and temporal scales throughout the lifecycle of organisms.

11 Warming is one of the main stressors associated with climate change. Temperature is involved in the majority of metabolic processes and seasonal behaviour. It regulates the rate of processes associated with growth, reproduction and survival (PÖRTNER *et al.*, 2017). The implications for fisheries can be very significant. LYNE *et al.* (2003) estimate a 35% reduction in economic revenue from fisheries in Australia by 2070 as a result of climate change. Rising temperatures can also have indirect effects by degrading the habitats of species of interest. Coral bleaching associated with warmer water is a prime example (FRIELER *et al.*, 2013), with adverse consequences for artisanal fisheries in reef ecosystems (CINNER *et al.*, 2012). Temperature is likely to be associated with other stressors. In particular, it increases the risk of mortality, as in the case of the North Atlantic oyster. The susceptibility of oysters to diseases is increased by warming in the winter, which favours the development of pathogens and reduces the biological rest period of the oyster by prolonging the period of high metabolic activity, resulting in greater fragility (FLEURY *et al.*, 2020; THOMAS *et al.*, 2018). Finally, the modification of the seasonal temperature cycle is likely to cause a shift in the species' reproductive season (phenology), leading to a desynchronisation between the recruitment of predators and the presence of prey, what is known as a "trophic mismatch", which can penalise the productivity of the exploited species (EDWARDS and RICHARDSON, 2004; RÉGNIER *et al.*, 2019).

12 Changes in the physicochemical properties of the water body, such as water acidification due to the accumulation of atmospheric CO_2 or deoxygenation due to coastal eutrophication, also have an impact on marine resources by degrading the quality of marine habitats. There has been a marked increase in hypoxic "dead zones" in coastal areas as a result of climate change due to increased stratification, warming and greater nutrient discharges to coastal ecosystems (DIAZ and ROSENBERG, 2008). This deoxygenation affects the physiological performance of species and is likely to reduce

their productivity (AGUIRRE-VELARDE *et al.,* 2018; LAVAUD *et al.*, 2019; THOMAS *et al.*, 2019). Ocean acidification also strongly impacts species productivity, reducing the survival of larval calcifying organisms such as shellfish and lowering their recruitment potential (ANDERSEN *et al.*, 2013; BYRNE, 2012). Effects on fisheries resources may also be indirect, through changes in trophic interactions associated with reduced productivity of food sources (i.e. phytoplankton and zooplankton), leading to lower nutrient inputs for consumer growth and reproduction (BRANDER, 2010). All of these constraints are combined with anthropogenic pollution, the sources of which are multiplying, and among which plastic pollution is a major threat to marine resources of all species (WILCOX *et al.,* 2015). It has been shown that microplastic pollution can reduce by 40% the reproductive capacity of the cupped oyster (*Crassostrea gigas*), the main shellfish species exploited for aquaculture worldwide (SUSSARELLU *et al.*, 2016).

Geographic displacement of species

13 Different processes are responsible for the displacement of species: loss of habitat, modification of migration, or changes in the connectivity between habitats, in particular at the time of recruitment. This can lead to the displacement, contraction or extension of the species' distribution area. Each species has an ecological niche defined by (1) the range of physicochemical parameters in which it can develop and (2) the biotic interactions of the species (i.e. prey, predators, etc.). If these optimal conditions are altered in a habitat, the species may not be able to maintain itself, in which case it will become locally displaced or extinct, thus changing its distribution.

14 The thermal limits of a species are one of the main variables determining its geographic distribution (PÖRTNER, 2002). CHEUNG *et al.* (2009) used modelling to forecast the future of 1066 species of marine fish and invertebrates exploited under a global warming scenario (A1B "business as usual" scenario). They predicted many local extinctions in sub-polar regions, the tropics and semi-enclosed seas by 2050. Species tend to move to high latitudes and deep waters to maintain favourable thermal conditions. Thus, some fisheries located in high latitudes are likely to benefit from warmer water, to the detriment of temperate and tropical areas. This is, for example, the case for the cod fishery in the Northeast Atlantic (SCHRANK, 2007). Each species is likely to react differently to stress. Climate change will modify the structure of communities and the interactions between species, such as the prey/predator relationship, trophic competition or competition for space, leading to changes in local density (POLOCZANSKA *et al.*, 2008).

15 Furthermore, this geographic displacement of species subject to the constraints of climate change is compounded by the increase in international trade – in particular maritime transport – leading to a rise in the number and severity of invasions of non-native species on a global scale, with significant impacts on marine ecosystems, habitats and fisheries resources (RIUS *et al.*, 2014; RUIZ *et al.*, 1997). Ocean warming has been shown to facilitate these species invasions (STACHOWICZ *et al.*, 2002). This has been demonstrated, for example, with the introduction of the Pacific oyster in northern Europe in the 20th century: this species tends to increase its local productivity and expand its range northwards as a result of global warming (KING *et al.*, 2021; THOMAS *et al.*, 2016).

16 Many species, such as shellfish and crustaceans, have a lifecycle with a pelagic larval phase. Recruitment thus depends on the dispersion of larvae by the current and the swimming behaviour of the larvae. This relies on connectivity (COWEN *et al.,* 2007), which defines the probability that an individual born in habitat A will be recruited in habitat B, which is more or less distant. Climate-related disturbances not only alter larval dispersal pathways by reducing export from affected areas and altering hydrodynamics, they can also lead to changes in several processes involved in connectivity (see, for example, COWEN and SPONAUGLE, 2009) such as:

- the phenology of reproduction (earlier laying by adults)
- larval transport (shorter duration of the pelagic larval phase)
- larval mortality (exposure to lethal temperatures and shorter larval lifespan)
- behaviour (increased swimming speed of the larvae).

17 Population connectivity plays a key role in population and community dynamics, genetic diversity and the resilience of marine populations to human exploitation (FOGARTY and BOTSFORD, 2007). In this context and for marine-use planning purposes, knowledge of dispersal patterns and their variability is particularly important. This information can help guide the establishment of marine protected areas, in order to optimise recruitment potential (KRUECK *et al.*, 2017; MAGRIS *et al.*, 2014).

18 Changes in the range of exploited species associated with climate change are already being observed throughout the oceans (JOHNSON and WELCH, 2009). The consequences for fisheries are manifold and will alter catch potential on a global scale. In particular, a shift in stocks may raise governance issues, involving transboundary management of fisheries. According to PINSKY *et al.* (2018), almost all of the world's exclusive economic zones will be affected by this issue by 2100 if no measures to reduce CO_2 emissions are taken.

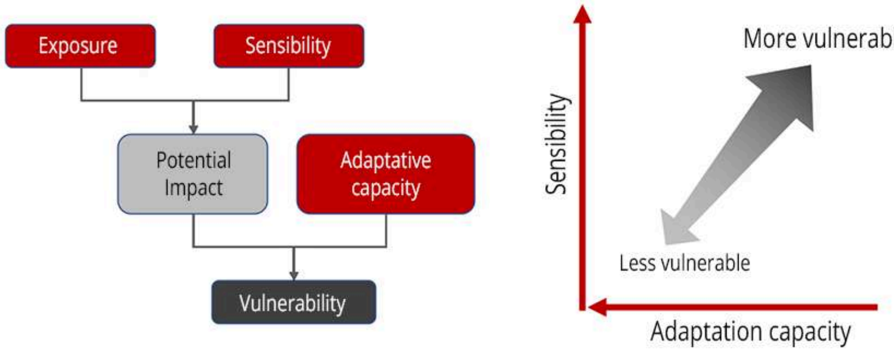
Vulnerability of artisanal fisheries

19 Vulnerability is generally considered to be the degree of change that a system is likely to experience as a result of the adverse effects of a chronic or stochastic disturbance and that it will not be able to cope with (ADGER, 2006). Several research frameworks have been developed to examine the vulnerability of societies to environmental change. This research generally measures three key dimensions of vulnerability (ADGER, 2006; CINNER *et al.*, 2012; fig. 2a):

- **Exposure** refers to the magnitude, frequency and duration to which a system is exposed to a climatic or environmental disturbance.
- **Sensitivity** is the degree to which a system is modified or affected by disturbance. Sensitivity can be strongly influenced by the degree of dependence on a resource that may be disturbed (e.g. a fish stock).
- **Adaptive capacity** is the ability of a system to adapt to changing risks or conditions, and to expand the range of variability it can cope with.

20 The more sensitive a process, activity or community, the lower its adaptive capacity and the more vulnerable it is (fig. 2). This vulnerability is exacerbated by a high level of exposure.

Figure 2. Representation of the vulnerability of coastal communities according to their exposure, sensitivity and adaptive capacity



Source: CINNER *et al.* (2012)

21 As JOHNSON and WELCH (2009) argue, “the marine fisheries most at risk from climate change are those whose fish stocks will experience the greatest ecological impacts due to their high exposure and sensitivity to changes in ocean climate, whose resilience is compromised by other pressures (such as overexploitation), and whose adaptive capacity is limited by resource dependence and weak economies”. In this context, “resilience” is understood as the capacity of the socio-ecological system to absorb shocks while maintaining its function, and to reorganise itself after a disturbance (WALKER *et al.*, 2004). On a global scale, the vulnerability of fisheries to climate change is very heterogeneous (ALLISON *et al.*, 2009). It is clear that the poorest countries are the most vulnerable, particularly in the intertropical zone. These countries have high exposure to climate change, high dependence on fisheries resources and low adaptive capacity. African nations are particularly vulnerable and have a high level of sensitivity, due to (1) their nutritional dependence on fisheries resources: fisheries provide employment for 10 million people and are a vital source of protein for 200 million people in Africa, (2) their semi-arid climate, which increases their exposure to warming, precipitation and coastal flooding, and (3) their low capacity to adapt to change due to low economic and development indices (FAO, 2007a; JOHNSON and WELCH, 2009; LAM *et al.*, 2012).

22 This vulnerability is exacerbated in the case of artisanal fisheries (BELHABIB *et al.*, 2016). This activity is practised intensively in tropical geographical areas that are highly exposed to climate change (CHEUNG *et al.*, 2009; IPCC, 2019) and are also highly dependent on the resource. Artisanal fisheries are worth US$5–7 billion per year and employ more than 12 million people globally, compared to US$25–27 billion and 0.5 million jobs for industrial fisheries (JACQUET and PAULY, 2008). The sensitivity of artisanal fisheries to climate change is significant, particularly because of the low capital available, which does not allow for large fluctuations in income. The capacity to adapt is limited by the small scale of the activity, as fishing grounds are often located close to residential areas due to small-scale equipment (boats, engines). Artisanal fisheries are also threatened by the fact that they are focused on a limited number of species, with few alternative opportunities for reasons linked to culture, food habits and available markets (BELHABIB *et al.*, 2016; COULTHARD, 2008). This phenomenon, which encourages fishermen to “follow the fish”, is likely to increase the vulnerability of the

activity by forcing them to increase their fishing effort and expand their fishing area, or even migrate to other, more productive areas (BELHABIB *et al.*, 2016).

23 Climate change thus represents an additional burden for artisanal fisheries in countries with unfavourable socio-economic conditions, particularly in the intertropical zone. These constraints are combined with other sources of vulnerability related to climate risks (e.g. submersion, salinisation, flooding, drought), which will undermine food security, reduce alternative livelihoods and increase health risks for the poorest populations (ALLISON *et al.*, 2009).

The artisanal shellfish fishery in Senegal: a case in point

24 The exploitation of shellfish by humans in coastal ecosystems dates back several tens of thousands of years (KLEIN and BIRD, 2016). This is particularly the case in West Africa, where shell middens dating back thousands of years as a result of accumulation from exploitation are found on the coast (HARDY *et al.*, 2016; KLEIN and BIRD, 2016).

25 The Sine-Saloum delta, located in the centre of the west coast of Senegal, 150 km south of Dakar, is home to a large artisanal shellfish fishing activity. The delta has been classified as a biosphere reserve (Saloum Delta Biosphere Reserve, SDBR) since 1981, and has been listed as a UN World Heritage Site since 2011, which allows the development of conservation measures, development actions and logistical support for the populations. The Sine-Saloum delta is a mosaic of terrestrial, lacustrine and palustrine wetland environments that are open to the ocean. From an ecological point of view, this interface zone contains various geomorphological units: mangrove mudflats, tidal flats, sandy strips and shellfish beds.

26 The delta is the centre of human activity developed around fishing and agriculture. The exploitation of shellfish, in particular the bloody cockle *Senilia senilis*, is very old (nearly 5000 years, HARDY *et al.*, 2016), and is an integral part of local culture and traditions, especially those of women's communities, as women typically carry out shellfish harvesting, processing and marketing (fig. 3). This artisanal fishery is highly vulnerable to climate change, in all three key dimensions of vulnerability.

27 It has **high exposure** to the impacts of climate change. The area has been subject to significant aridification over the past few decades (DESCROIX *et al.*, 2020); freshwater inflows into the delta have reduced and the hydro-biological properties of the water have been modified. The Sine-Saloum delta is a natural inverse estuary, which only receives freshwater during the monsoon season and contains hyperhaline water the rest of the year due to evaporation. As the delta is located north of the West African monsoon development zone, this ecosystem is very sensitive to the monsoon regime associated with the dynamics of the Intertropical Convergence Zone (ITCZ) and associated rainfall maxima (SULTAN and JANICOT, 2003). In conjunction with this, sea level rise is causing marked coastal erosion, which led to the development of a rift in the 1980s and significantly altered the morphology of the delta (DIEYE *et al.*, 2013). Agricultural land is becoming salinised as a result of sea level rise, reducing agricultural production and requiring the diversification of activities.

28 The area has **high sensitivity** to disturbance: a large majority of women in coastal villages are involved in shellfish collection and are directly dependent on this activity

for their subsistence and that of their families. Furthermore, a shift from food to commercial activity has led to the overexploitation of stocks, which are therefore more sensitive to the effects of climate change. The number of species exploited is also limited, and tonnages are mainly linked to a single species, which increases the degree of dependence.

29 There is **limited adaptive capacity**. The surface area of the available fishing grounds (sandbanks that are uncovered at low tide) is limited, as is the women's ability to travel: many women go to the fishing grounds on foot. Scientific lack of knowledge regarding the functioning of the ecosystem and the biology of the species exploited (e.g. ecological niche, biological cycle, population dynamics) also weakens the ability to support management measures in a context of environmental stress.

30 Measures to increase the adaptive capacity of local women's communities have been put in place. The women are supported by various partners at national and international levels, seeking to promote their traditional know-how and to modernise the processing cycle to improve the quality of the products. This positions them as a model of artisanal fishing in the West African region. In partnership with researchers and managers, the women have also implemented management practices to combat the overexploitation of resources, such as allowing a period of biological rest during the winter season, rotation of exploited sites, and the establishment of a minimum size for shellfish harvesting (DIOUF *et al.*, 2014; DIOUF and SARR, 2014). Actions to restock mudflats and mangrove reforestation have also made it possible to increase the availability of stocks and improve catches, contributing to the long-term food security for the women and their families by providing them with resources while improving their income. The women supplement artisanal shellfish harvesting with many other activities, such as the processing of natural resources like fish, shrimp, forest fruits or cereals. This diversification offers women many levers for action, enabling them to manage marine resources sustainably and thus limit their vulnerability.

31 Despite the significant involvement of local communities, in particular of women shellfish collectors, knowledge about ecosystem functioning and the response of marine species to stressors remains limited. Supporting the sustainable development of fisheries will require a better understanding of the response of populations of exploited species to biotic and abiotic factors in the environment. This would enable the anticipation, implementation and evaluation of appropriate management measures. These approaches must involve stakeholders, particularly in order to establish an observation system capable of providing information on ecosystem dynamics. The implementation of participatory and outreach approaches contributes to raising awareness of environmental issues among local communities as well as strengthening their capacity to adapt to climate change.

Figure 3. Artisanal shellfish harvesting by women in the Sine-Saloum delta (Senegal)

A. Collection of *Senilia senilis* clams at low tide
B. Collection of clams
C. Shell cluster from the village of Falia, made up of clam shells that may date back several thousand years
© IRD/Y. Thomas

Challenges for MSP involving artisanal fisheries

32 To best guide management measures, it is imperative that policymakers, researchers and stakeholders jointly consider the pressures associated with fishing and climate change in order to support fishing communities and increase their adaptive capacity. As proposed by CINNER *et al.* (2018), pathways for improving the adaptive capacity of artisanal fishing communities to climate change can be identified in five highly interconnected areas (*sensu* CINNER *et al.*, 2018):

- *assets*: the resources available to people, such as financial resources (e.g. savings or credit), technology (e.g. fishing gear) and services (e.g. healthcare)
- *flexibility*: the ability to grasp the diverse potential adaptation options available (e.g. changing fishing strategy, fishing location or even occupational sector)
- *social organisation*: the formal and informal relationships between individuals, communities and organisations, which provide social support and access to knowledge and resources (e.g. strengthening networks, creating arenas for interaction)
- *learning*: the ability to generate, appropriate and process new information about climate change, adaptation options and ways of living with and managing uncertainty (e.g. knowing about new fishing grounds, new gear, new weather patterns, new technologies, new species)

- *action*: the ability of people – individually or collectively – to have free choice to respond to environmental change (e.g. taking into account local knowledge, local skills and local management in both science and policy and increasing participatory processes).

33 Given this conceptual framework and the multiple pathways through which climate change impacts artisanal fisheries, reducing vulnerability begins with reducing exposure to climate change-related stress. The main – and perhaps only – lever for communities is to avoid overfishing, which leads to species fragility and increases the consequences of environmental stress (BRANDER, 2007; PERRY *et al.*, 2010). Such a pathway requires increased knowledge to better assess species production at local, regional and global scales. Improving our ability to model local-scale processes by integrating interannual, decadal (regional) variability and global climate change will be essential to provide relevant information for fisheries management and adaptive planning. This will involve improving observational capacity to provide information on current status and short- and medium-term trends. This is fundamental to assessing progress towards management objectives (WEIGEL *et al.*, 2018). Observational systems also provide measures to validate and assess the sensitivity of predictive models and to adjust the structure of existing models. Strengthening these observational systems should be considered from the perspective of community ownership and knowledge sharing. In this context, open science and low-cost development approaches are fundamental elements in constructing these dynamics.

34 To better understand the interactions between ecological processes and uses, it is also essential to take an interdisciplinary approach, combining natural and human sciences. This requires the integration of local Indigenous knowledge and the involvement of stakeholders in the development and implementation of monitoring and management plans. Communities that show a strong capacity for self-organisation reduce their vulnerability to climate change, as is the case in some villages in the Sine-Saloum delta through modernisation, diversification of activities and resource management; this has also been shown in other examples of artisanal fisheries around the world (KALIKOSKI *et al.*, 2010). However, this self-organisation seems difficult to generalise due to the specificities of local communities.

35 A key element in reducing the vulnerability of artisanal fisheries is the establishment of public policy and institutions for resource governance to enhance adaptive capacity (KALIKOSKI *et al.*, 2010). Management measures, as well as research in support of such management, need to be adapted to the diverse spatial and temporal scales at which the combined effects of climate change and natural resource exploitation occur. The impacts of climate change are likely to exacerbate existing variability in weather conditions, both in terms of frequency and magnitude, and thus increase uncertainty, which will require greater flexibility in management measures to support fisheries. Finally, vulnerability analysis needs to move from a global to a more local scale, incorporating the range of income and/or poverty levels of national populations in order to propose appropriate adaptive planning at national and local scales (ALLISON *et al.*, 2009). In the face of the challenges posed by climate change, added to the challenges of marine-use planning, it is essential that artisanal fisheries are properly taken into account in MSP in their diversity and in their specificities (COHEN *et al.*, 2019).

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