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Impacts of climate variability and change on fishery-based livelihoods

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ABSTRACT

There is increasing concern over the consequences of global warming for the food security and livelihoods of the world's 36 million fisherfolk and the nearly 1.5 billion consumers who rely on fish for more than 20% of their dietary animal protein. With mounting evidence of the impacts of climate variability and change on aquatic ecosystems, the resulting impacts on fisheries livelihoods are likely to be significant, but remain a neglected area in climate adaptation policy. Drawing upon our research and the available literature, and using a livelihoods framework, this paper synthesizes the pathways through which climate variability and change impact fisherfolk livelihoods at the household and community level. We identify current and potential adaptation strategies and explore the wider implications for local livelihoods, fisheries management and climate policies. Responses to climate change can be anticipatory or reactive and should include: (1) management approaches and policies that build the livelihood asset base, reducing vulnerability to multiple stressors, including climate change; (2) an understanding of current response mechanisms to climate variability and other shocks in order to inform planned adaptation; (3) a recognition of the opportunities that climate change could bring to the sector; (4) adaptive strategies designed with a multi-sector perspective; and (5) a recognition of fisheries potential contribution to mitigation efforts.

1. Introduction

Fisherfolk depend for a major part of their livelihood on natural resources whose distribution and productivity are known to be influenced by climate dynamics [1]. Evidence of the impact of recent global climatic changes on fisheries resources has already been observed, with reduced productivity in African lakes attributed to elevated late 20th century atmospheric temperatures [2,3], and increases in the frequency and severity of coral bleaching with rising sea surface temperatures in tropical and sub-tropical coastal zones [4]. The impacts of coral bleaching on fish communities include changes in their diversity, size and composition [5,6]. Fish species distribution has also been altered in the North Sea due to recent increases in sea surface temperatures [7], and model projections show that climate change may lead to numerous local extinctions in the sub-polar regions, the tropics and semi-enclosed seas [8].

Anthropogenic climate change is thus already affecting aquatic ecosystems and the human societies that depend on them [9]. However, most research on climate variability, change and fisheries has in the past focused on documenting trends and fluctuations in fish abundance and distribution (see seminal work by Cushing and Glantz [10,11]), particularly in relation to oceanic regime changes and the major pelagic fish stocks of upwelling zones that are the target of large-scale industrial fisheries [12–14]. There are a number of studies that investigate the vulnerability and adaptive capacity of the fisheries sector and dependent communities to climate change [15,16]. Nevertheless, until recently there has been little directed analysis at the local scale of how climate variability and change is affecting the lives and livelihoods of the "tropical majority" of small-scale fisherfolk, who make up more than 90% of the worlds' fishers and fish traders.

There are compelling security reasons—both economic and nutritional—for investing in research to guide adaptation planning in fisheries. Worldwide, fish products provide at least 20% of the protein intake of 1.5 billion people and support the livelihoods of approximately 520 million people [17]. Fishery products are

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one of the most highly traded food and feed commodities, with an export value of 86 billion dollars in 2006 [17], contributing significantly to both total gross domestic product (GDP) and agricultural GDP as well as food security. The sector is also an important source of livelihood for women: it is estimated that in countries such as India, Cambodia and Ghana they represent on average half of the fisheries workforce (including post-harvesting activities) [18]. Additionally, many fisheries worldwide have declined sharply in recent decades due to overfishing [19], and many major fishing grounds are concentrated in zones threatened by pollution, mismanagement of freshwater and habitat, and coastal zone modifications.

Here, we first identify the pathways through which climate variability and change are impacting, or are likely to impact, upon fishing-dependent communities. We then focus on the capital assets component of the sustainable livelihoods framework [20,21] to identify the nature and, where possible, the costs of those impacts at household, community or sectoral level. The use of the livelihoods framework also facilitates the identification of suitable entry points for adaptation planning, which is the focus of the final section of the paper. We make the case for a major win–win, in that much adaptation response can be built on fisherfolks' existing strategies to cope with climate variability, and that investment in reducing vulnerability to climate change is, for the most part, that which was already needed to protect the economy and to reduce the poverty and vulnerability of people engaged in small-scale fisheries.

2. Potential impacts of climate change on the fisheries sector: multiple pathways

Climate change can impact fisheries through multiple pathways (Fig. 1). Changes in water temperature, precipitation and oceanographic variables, such as wind velocity, wave action and sea level rise, can bring about significant ecological and biological changes to marine and freshwater ecosystems and their resident fish populations [8,22,23], directly impacting peoples whose livelihoods depend on those ecosystems. Extreme weather events may also disrupt fishing operations and land-based infrastructure [24] while fluctuations of fishery production and other natural resources can have an impact on livelihoods strategies and outcomes of fishing communities [25–27].

Indirect impacts arising from adaptive strategies pursued by different sectors may also be significant and compound the effects of direct climate impacts on fish production and dependent livelihoods. These potential interactions make impact predictions difficult to make and more uncertain. For example, changing patterns of precipitation and increasing frequency of extreme flooding events in river basins may prompt adaptive strategies by the agriculture sector that focus upon the construction of more flood control, drainage and irrigation schemes. These structures are likely, however, to further exacerbate the direct adverse impacts of climate change on fisheries. Studies suggest that fish production can be 50% lower inside flood control schemes compared to outside due largely to diminished recruitment of high-value migratory whitefish species [28,29]. Crop diversification or replacement, in favor of high-yielding varieties that sometimes require more irrigation and flood control compared to traditional varieties, could exacerbate these impacts. These extra "water needs", which are likely to be withdrawn from rivers, other surface water bodies or aquifers, will affect hydrological and ecological regimes, including floodplain-river fisheries (Fig. 2). In Malawi's Lake Chilwa, it is the combination of a series of droughts and the conversion of fringing wetlands for rice cultivation that are putting severe pressures on water resources and fisheries [30].

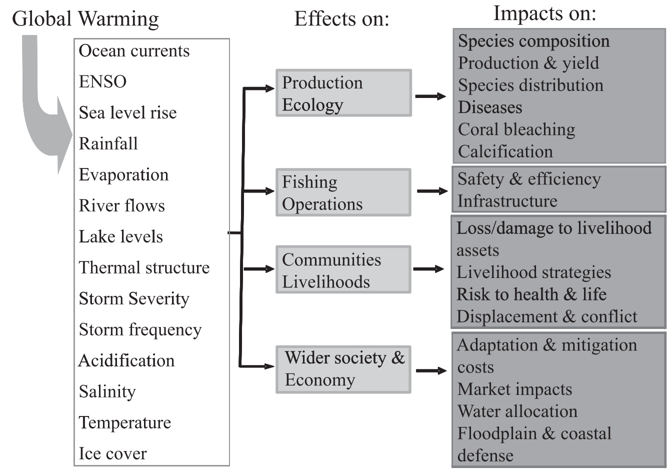

Fig. 1. Global warming and capture fisheries: impact pathways. (This figure is not intended to be comprehensive but to give examples of potential impact pathways.)

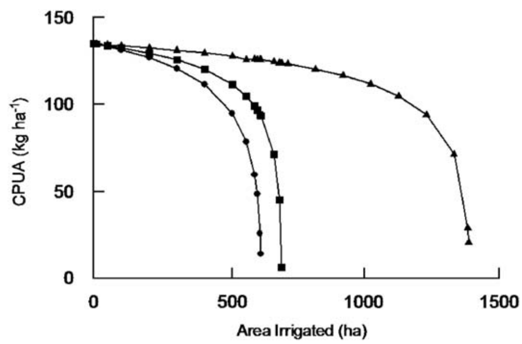

Fig. 2. Predicted response of annual catch per unit area (CPUA) to changes in the area of land irrigated for dry season Boro rice cultivation for low (▲); intermediate (■); and high (●) irrigation schedules in part of the Pabna flood control and irrigation compartment, North-West Bangladesh. *Source*: Shankar et al. [31].

The "direct" effect of climate change on hydrological regimes and ecosystems may therefore be enhanced in these situations.

In coastal zones, potential declines in mangrove forest habitat resulting from sea level rise, changes in sediment and pollutant loading from river and lake basins combined with land reclamation for agriculture or overexploitation could also impact on fisheries by reducing or degrading critical coastal habitats. Mangrove forest loss for instance can negatively affect the diversity of benthic invertebrates such as tiger prawns or mud crabs, which are exploited or managed for profits exceeding US $4 billion per year [32]. Faced with declining yields, income and food security, fishers may seek alternative livelihoods, placing pressures on other sectors or resources. For example, in West Africa, when coastal fisheries resources are scarce, fisherfolk adopt alternative livelihood strategies including hunting for bushmeat [33].

Climate change is thus likely to have multiple impacts across sectors, and interactions with other socio-economic and environmental drivers [34,35]. Most studies so far have looked at climate-driven changes in ocean productivity and its impact on fish distribution and production, and have not considered indirect effects such as those discussed above, especially in freshwater systems where the downscaling of global circulation models is more tedious. These are only some examples of the ways in which changing climate may impact fisheries; the relative importance of these different impact pathways is not yet known. The potentially far-reaching effects of ocean acidification, in particular, are almost completely unknown. Rising atmospheric carbon dioxide (CO_2) concentrations over the past two centuries have led to greater CO_2

uptake by the oceans, altering the seawater chemistry of the world's oceans [36,37]. While marine ecosystems have experienced warm conditions in the past they have never experienced acidification conditions as high as present [38]. This limited state of knowledge about the impact of increased CO_2 exposures on marine organisms and ecosystems poses new challenges for scientists as well as fisheries managers and their constituencies [39].

3. Using a livelihoods perspective to understand impacts of climate variability and change on households and communities

At the household and community level, the concept of the sustainable livelihoods approach (SLA) can be helpful in translating the likely impacts of climate change on fishery production systems into potential impacts on the economic and social viability of fishery-dependent households and communities. The SLA, developed in the 1980s from a combination of farming systems analysis, micro-economic and institutional analysis and the theory and practice of development economics, has been widely adopted in development policy research to achieve a more accurate understanding of natural resource management systems [40]. In the climate variability and change literature the concept of livelihoods is employed to understand the vulnerability context of communities [41–44] as well as impacts and livelihood responses [45,46]. Work on fisheries has focused on climate variability and disasters, and fluctuating stocks [25,47–49].

A livelihood can be defined as the capabilities, assets and activities required for means of living [20]. The concept of sustainable livelihoods seeks to bring together the critical factors, assets and activities, that affect the vulnerability or strength of household strategies [21,50]. People can access, build and draw upon capital assets, often categorized as: human, natural, financial, social and physical. The way in which people combine and transform those assets and how, through relationships with other actors, markets, and society, they attempt to maintain or expand their asset base, is a characteristic of livelihood inquiry [51]. Markets and other institutions such as laws, social relations and formal organizations (NGOs, government agencies, private sector firms) and related policies are understood as policies, institutions or processes (PIPs). PIPs can mediate access to assets while actors can change or transform the rules that govern access, distribution and transformation of assets [51]. They differ from the vulnerability context by being endogenous to the norms and rules of the society under study [52]. For instance exogenous disturbances such as climatic stress, whether seasonal or on a decadal scale, are considered within the vulnerability context [53]. Livelihood strategies are the range and combination of activities and choices that people make in order to achieve livelihoods outcomes. Livelihoods therefore are about how actors can mobilize their capital and capabilities to achieve well-being, building on the seminal work by Amartya Sen on entitlements, development, and capabilities [54,55].

Climate-induced changes to resource flows can fundamentally affect the viability of the livelihoods of the poor [56]. More specifically, the impacts of climate variability and change can be linked to the various elements of the livelihood framework such as impact on assets and changes in livelihood strategies and outcomes [57,58]. This is the use to which we put the framework in this paper.

3.1. Impacts of climate variability and change on livelihoods assets

3.1.1. Changes in natural capital

A review of the literature on possible impacts of climate change and climate variability on fisherfolk reveals that most of the research is centered on changes in fish stock distribution and abundance. Changes in the availability of fish products (natural capital) can affect total revenues and harvesting costs (net revenues), resulting in greater costs in managing and accessing natural capital. Reductions to net revenue arising from declines in stock abundance and subsequently catches is commonly cited as a consequence of climate variability and change [59–64]. For example, it is estimated that coral cover and complexity in the Caribbean basin has declined by 80% since the 1970s due to climate-related disease outbreaks, more frequent and severe hurricanes and elevates sea surface temperatures [65,66]. Coral cover is a major factor affecting fish abundance and diversity. Further reductions in coral cover in the region arising from climate change effects are predicted to diminish annual fish production by 30–40% by 2015, equivalent to a net revenue loss of between US$95 million and US$140 million for more than 100 000 fishers [67].

Landings of mackerels by Taiwan and Chile fell by nearly 50% and 70%, respectively, following the 1997/1998 El Niño due to changes in sea surface temperatures [68,69]. In Peru, fisheries for other pelagic species, including anchovy and sardine, were also particularly affected with reductions to landings in the order of 55% compared to the previous year equivalent to lost revenues of more than $26m [70]. During these events, prices of substitute products such as Baltic sprat typically peak [66]. La Niña events, which are associated with cooling sea surface temperatures around Peru and Chile conversely benefit these fisheries [71].

Climate change may favor certain species over others [72,73] and thereby change the biogeography of fish stocks and their relative abundance [8,74]. These responses are likely to require changes to harvest strategies and processing techniques [62,75] and may affect fishing costs through changes in travel time and associated fuel and ice consumption [59]. In Peru, the El Niño event of 1997–1998 benefited both the recruitment and growth of the scallop (*Argopecten purpuratus*). Fisherfolk responded quickly to the "scallop boom" migrating to the fishery from all over Peru, and/or switching from nets to diving methods resulting in a record harvest [76,77]. Fisherfolk, following an opportunistic behavior, dramatically increased their profits with the "scallop boom" and the exploitation of more tropical species not normally found in these waters, such as mahi–mahi and shark was initially highly profitable for the artisanal fisheries sector [75,78]. However, several factors prevented fishers from realizing the benefits of these species introductions including changes in demand, oversupply and inadequate gear [75].

Other natural resources upon which fishing communities depend may also be impacted by climate change. Freshwater, for example, limits life on small islands. Sea level rise and extreme events like storm surges can lower the availability and quality of freshwater sources to fishing communities [79] in addition to disrupting fishing operations.

3.1.2. Damage to physical capital, reduced financial capital

Climate variability and change through sea-level rise and storm and flood frequency can impact on the physical capital of households or of entire communities, leading not only to decreased harvesting capacity but also to the disruption of public infrastructure and services that support livelihoods.

More specifically storm and severe weather events can destroy or severely damage productive assets and infrastructure such as landing sites, boats and gear [80]. For instance during Hurricane Gilbert in 1998, Jamaican fisherfolk lost 90% of their traps resulting in a loss of revenue and high cost of repairs, as well as the ability to resume fishing activities promptly [81]. In Belize, the loss of fishing tackle and associated infrastructure as a consequence of Hurricane Mitch (1998) was estimated to have cost

US$1.2 million [82]. The impacts of climatic events outside the normal range (from El Niño to natural disasters) on post-harvesting infrastructure as well as damages to transportation and marketing systems have also been well documented [26,83]. In Peru, during the El Niño of 1997–1998, rural fishing villages in the northern part of the country were damaged by heavy rains and were unable to transport their products to markets due to washed out roads and bridges [70,75]. In fishing communities around the world women are mainly engaged in post-harvesting activities [84], a disruption of marketing systems and infrastructure having thus particular gender implications and affecting productive activities of men and women differently.

Damage to fisherfolks' non-productive physical assets such as housing and community infrastructure (hospitals, schools, sewage system etc.) are also important consequences of extreme climatic events [24]. In Northern Peru, damage to or loss of houses was perceived by fisherfolk has one of the most important impact of El Niño [85]. Poor housing conditions, loss of dwellings and community infrastructure can result in resettlement and displacement, and more broadly disruption of livelihoods.

The loss of physical capital compounded with a deteriorating financial asset base can also have significant effects on livelihoods. In Peru, at the time of the 1997–1998 El Niño, a percentage of the catch value was put into a recently privatized social security and health organization for industrial fisherfolk [75]. As a result of decreasing catches the agency's coffer quickly ran dry [75, p. 15]. This left fisherfolk without a safety net and access to financial resources to cope with the difficult economic situation.

During climatic events disrupting livelihoods, *ad hoc* government and international emergency aid are the main sources of financial relief [86]. The most-affected people are unable to raise formal bank loans due to lack of collateral (often lost during the event) and do not have insurance [49]. Additionally, as observed in many fishing communities, informal sources of credit are often the only ones available to fisherfolk, typically with high rates of interest, and unfavorable terms and conditions [87]. These disadvantageous financial terms could be exacerbated in the context of climatic disturbances. More broadly, the lack of financial assistance to fisherfolk during fisheries crisis is a pivotal problem in developing countries, while in countries like Canada and Norway, social safety nets and public programs can provide important support [88].

3.1.3. Impacts on human capital and social capital

The different dimensions of human capital, ranging from safety-at-sea to food security, are also affected by climate variability and change. The loss of lives can be the most dramatic impact of extreme climatic events on human capital, affecting not only surviving household members but also potentially disrupting economic and social activities and systems outside the immediate family [24, p. 18]. The Asian Tsunami provides an illustration of the gender gap between the vulnerability of females and males to being killed by extreme events. In some locations the likelihood of death was twice as great for women [89]. This is attributed to the fact that female household members were more exposed due to their traditional role of carrying out activities around the house and, in many cases, their inability to swim [89, p. 89].

Safety at sea and injuries are often associated with natural disasters linked to climatic stresses such as floods and hurricanes, reducing the physical capabilities of fisherfolk to pursue their livelihoods. Changes in safety while pursuing fishing activities because of changes in weather and storm events or, in the case of arctic communities, reduced stability and safety of ice and snow are significant operational challenges for fisherfolk [83,90]. Additionally, loss of revenues can be the result of closures or reduction of fisheries activities during weather anomalies [63,91,92].

In terms of health effects, it has been shown that the El Niño cycle in certain areas is associated with changes in the risk of diseases transmitted by mosquitoes, such as malaria and dengue fever [93]. The risk of malaria is highly sensitive to El Niño in South America, Central Asia, and Africa, areas where the majority of small-scale fisherfolk are located [15,94]. Red tides of toxic algal can be triggered by marine phytoplankton blooms, often associated with increased in SSTs. These toxic algal cause diarrheal and paralytic diseases linked to shellfish poisoning [95,96]. This increased exposure to health hazards can be combined with a health sector deficiency, jeopardizing the ability of fisherfolk to recover from health impacts and pursue their livelihoods. Indeed small coastal and riparian rural communities often lack of an adequate health systems, potable water, sewage and drainage that increase their vulnerability [26,97].

Changes in food availability and in food affordability due to climatic disturbances also add an additional health burden to households and communities. In a scenario of decreased catches due to climate change events, the risk of malnutrition and undernutrition for communities highly dependent on fish for a source of protein [98], combined with changes in diet (reduction of protein from a fisheries source), are some of the possible effects. This is of particular relevance for Asian and sub-Saharan African countries where nutritional reliance on fish as a source of animal protein is greatest [15]. Reductions in fishery-dependent incomes can also reduce the ability to purchase store-bought food during periods of natural resource scarcity [61]. Similarly, infrastructure damages due to extreme events or flooding can diminish access to local markets, reducing the availability of food products as well as increasing their prices [86,99].

Climate variability and change can also alter the local institutions that form the basis of resource management, specifically property rights. At the local scale, it could be argued that changes in abundance patterns and displacement of fisheries stock could lead to conflicts over property rights and resource access. For instance Peruvian "scallop booms" in Pisco trigger a flow of opportunistic migrants from all over the country wanting to share the bonanza of the El Niño event [76,100]. However, since the last El Niño event, artisanal fisherfolk in Pisco have been forming small associations to qualify for marine tenure to develop scallop aquaculture [100]. Under restricted access conditions and greater climate variability conflicts between migrant fisherfolk and scallop farmers are likely to increase [76].

In Southern Africa, increasing frequencies of droughts are forecast, leading to greater variability in lake levels and river flows, affecting lakeshore and river floodplain livelihoods that incorporate fishing [101]. Faced with greater spatial and temporal variability in landings, fishers may have to become more mobile and responsive to fishing opportunities. Such opportunistic behavior increases levels of displacement and migration and can put a strain on communal-level management and resource access systems, while decreasing commitment to stable settlement affects investment in community level institutions and services.

3.2. Current and potential adaptation strategies: responses to climate variability and change

3.2.1. Enhancing the livelihood platform

It has been shown that together with social, economic and gender inequities, low levels of technological development enhance the vulnerability of largely illiterate, unskilled, and resource-poor rural populations to current climate risks [102]. Enhancing fisherfolk's livelihood platform, that is the access and utilization of the five capital assets, through different adaptation strategies and policies may help to reduce this vulnerability. This enhancement can be achieved by public institutions or private individuals in anticipation of future effects or in response to impacts once they occur [103].

The capacity to quickly adapt to changing natural capital through new harvesting techniques and tools will be a significant factor determining the outcome of future fishery-dependent livelihoods. In Peru, during El Niño event of 1997–1998, boats previously equipped with gill nets and pure seine nets were rapidly modified to utilize trawl nets to exploit the new shrimp resource that appeared in the northern part of the country [104]. Re-tooling, and more broadly, changes in productive assets might require additional investments and adoption of new technologies. The physical exposure to climate variability and change can be reduced through disaster risk-reduction initiatives. In coastal areas, mangrove conservation can be promoted to create natural barriers against sea level rise and extreme events, and integrated coastal management and urban planning can be combined to promote the building or relocation to housing areas that are not at risk from flooding. These initiatives can contribute to sectoral mitigation efforts with the conservation of mangroves as carbon sinks.

Private or public insurance schemes could be put into place to avoid livelihood disruption arising from limited access to credit and loans to re-build the asset base in the aftermath of climatic disturbances. Whilst such schemes are already in development for the agricultural sector to help small farm holders face climate-related risk [105], little attention has been paid to the development of analogous schemes for the fisheries sector [106,107] and more broadly safety nets as tools to reduce the vulnerability of fisherfolk.

Education and skills upgrading are powerful adaptive strategies for individuals, families and communities [88]. Higher educational attainment may enable fisherfolk to make a broader series of choices, ranging from engaging in safe construction practices to assessing potential risk that result in fewer deaths when an extreme event strikes [108]. As an anticipatory adaptive measure, increasing access to climate information and forecasting with early warning systems would also reduce the vulnerability of the fishing sector [78,109,110]. Recognizing and utilizing traditional knowledge for developing adaptation strategies is also a key determinant for communities' ability to respond to climate variability and change impacts, for instance through the provision of additional forecasting abilities and observation on local environmental changes [90,111].

During extreme events, the lack of social cohesion and community ties, and disaster awareness can lead to loss and damage of material assets such as boats and dwellings [26]. Investing in social relationships and communities for support during difficult times, and building social relations and networks to increase cooperation, and the sharing of ideas and technological innovation can increase the adaptive capacity of fisherfolks' households [88,112]. Adaptation is embedded in complex social and cultural contexts. A case study in south India points out that the inability of some households to adapt their traditional methods for managing their fisheries ("padu system") to environmental change is rooted in a particular religious (caste) and cultural ("way of life") landscape [25]. This highlights the fact that apart from access to material assets, understanding how social capital shapes the adaptive capacity of fisherfolk is warranted to design appropriate adaptation strategies.

3.2.2. *Diverse and flexible livelihood systems*

It has been argued that more diverse fisheries livelihood systems can better adapt to change, including climatic disturbances [16,30,113]. Diversification includes occupational multiplicity (several income generating activities), occupational mobility and diversification outside fisheries (entering or exiting the fishery sector), geographical mobility (migration) and diversification within-in the fisheries sector (species, multiple gears) [21,114,115]. For example, prey-switching and migration are strategies adopted by fisherfolk in Peru in response to natural resource variability. In the North of the country during El Niño events, the increased river run-off in Sechura Bay leads to a higher mortality of benthic invertebrates such as scallops. Fisherfolk respond by targeting other species that increase in abundance due to appearance of brackish waters (mullet) or more tropical waters (shrimps) [86]. In the south, the scallop fishery experiences an opposite fluctuation in yields, leading to an increase in temporary and permanent migration [76].

Occupational mobility in response to climate variability is also a common practice in fishing communities. In Lake Chad fishing families diversify into farming [27] while droughts affecting agriculture in Africa may encourage more fishing activity [101]. During extreme events and natural disasters, the destruction of one sector infrastructure (e.g. agriculture, tourism, and manufacturing) could lead to the displacement of the labor force into the fishing sector if the latter was not significantly affected, leading to conflicts over scarce labor opportunities. In Antigua and Barbuda, during Hurricane Luis in 1995, the destruction and damage to tourist infrastructures resulted in the transfer of workers from this sector into fishing for short-term employment, adding pressure to fishing stocks and labor supply [59].

Diversification through occupational multiplicity is also a primary means by which many individuals reduce risk and cope with future uncertainty [50,116,117]. There is some evidence that the inability of fishing households to adapt to environmental change is not only linked to the level of poverty, but also to the "specialization trap" where fisherfolk rely mostly on one species or activity [25,118].

Enhancing the resilience of fisherfolk by supporting existing livelihood strategies and enabling diverse and flexible fisheries not only will address the impacts of climate variability and change [30], but will also support poverty reduction initiatives and sustainable fisheries management [114]. However, as noted by Brugère (2008), diversification must not be promoted at all costs if it implies not taking into account the social, cultural and economic landscape where livelihoods unfold [114]. In addition, diverse and flexible livelihoods require diverse and adaptable institutions and policies. For instance policies that support geographical mobility will require specific institutional arrangements regarding property rights.

3.2.3. *Policies and institutions: flexible and adaptable*

The management of trans-boundary fish resources is constrained by political and geographical delimitations [119] and the "fit" between institutions and ecosystems. Overcoming these constraints is likely to be more challenging in the context of increased climate variability and change. For example, projected temperature changes in the Pacific Islands could lead to a spatial redistribution of tuna resources to higher latitudes within the Pacific Ocean [120]. Distant water fishing fleets are expected to be able to adapt to changes in tuna distribution compared to domestic fleets which are restricted to exclusive economic zone [120] potentially leading to conflict between the two fleets. Similarly, Miller [121] observed that changes in sea surface temperatures and circulation patterns experienced in the North Pacific has led to divergent trends in Pacific salmon abundance in northern and southern parts of their range [122]. This directly affected the abundance-based management agreement between the US and Canada (Pacific Salmon Treaty) and led to conflicts in the management of the stock. Furthermore, climatic variations may destabilize efforts to cooperatively manage resources that are shared among multiple jurisdictions [121,123,124]. Munoz [125] also highlighted the importance of international cooperation when referring to El Niño impacts on pelagic fishery management in the Eastern Pacific. It has been argued that establishing property rights to fish is more complicated than establishing property rights to land for resources on and underneath land due to their migratory nature [126]. Defining boundaries and access rights for fisheries resources is thus a particular issue of aquatic resources, and climate variability and change pose new challenges to institutional design.

Additionally, the resilience of fisheries system depends on the ability of institutions to build and adopt knowledge in order to self-organize and transform in the face of climate variability and change [76]. Lebel et al. [127] hypothesize that the ability to detect thresholds in a timely manner, and the capacity to build knowledge about ecological processes into institutions should improve the fit between rules and ecosystems, and allow societies to take measures to prevent ecosystems from crossing thresholds. Knowledge building and institutional learning are essential facets of good governance and necessary for ;institutions to design adaptive management strategies. Adaptive management deals with the unpredictable interactions between people and ecosystems, emphasizing the importance of feedbacks from the environment in shaping policy [128, p. 10] and of the ability to learn, experiment and be flexible. Coping more effectively with climate change and variability requires governance systems and policies that not only foster flexibility [129–131] but consider it as a management goal, part of an adaptive management strategy, and instrumental to responses to climate change [132].

Finally, supporting policies that reduce fishing effort, overcapacity and promote the sustainability of the sector will also make fisheries and aquaculture-based livelihoods more resilient, and policies aimed at increasing the fuel-efficiency of the sector will contribute to global climate change mitigation efforts. It has been shown that the fishery sector accounts for about 1.2% of global oil consumption, an amount equivalent to that burned by the Netherlands, and that the energy content of the fuel burned by global fisheries is 12.5 times greater than the edible protein energy content of the resulting catch [133]. While it has been argued that fisheries are not a suitable focus for mitigation as this sector emits a small fraction of anthropogenic CO_2 output [134], the data presented above show that from an efficiency perspective there are opportunities to reduce the sources of emissions, which combined with the enhancement of carbon sinks such as mangroves, could make the contribution of the sector to mitigation efforts significant. Using payment of ecosystem services like carbon credits for mangrove conservation could have the advantage of diversifying fisherfolk ;livelihoods and ;promoting restoration and conservation of ecosystems.

4. Discussion

Fisheries managers and fisherfolk have historically had to adapt to the vagaries of weather and climate (see for instance [47,135–139]). Uncertainty is inherent to fisheries management, so there is an expectation of change and a stock of knowledge and experience of coping with it and adapting to it [140]. However, current rates of change are historically unprecedented [141, 142]. Furthermore, multiple stressors like overexploitation and anthropogenic-driven degradation of marine habitats are already threatening fisheries around the world and eroding their capacity to adapt to change in general, while sustaining both livelihoods and fishery resources. Effects of climate change will occur in activities that are already considered to be characterized by mismanagement and conflicts, and the capacity of conventional management systems to adapt to climate change effects has been considered low [134,143]. It can then be argued that climate change effects will reveal the fragility or resilience of certain management and livelihood systems. Responses to climate change impacts will vary across scales (local, regional, national, global), by sector of activity (aquaculture, fisheries, agriculture) or by actors (individuals, communities, private sector, governments). They can be anticipatory or reactive [144] and should include: (1) management approaches and policies that build the livelihood asset base, reducing vulnerability to multiple stressors, including climate change; (2) an understanding of current response mechanisms to climate variability and other shocks in order to inform planned adaptation; (3) a recognition of the opportunities that climate change could bring to the sector; (4) adaptive strategies designed with a multi-sector perspective; and (5) recognition of fisheries potential contribution to mitigation efforts. The last two aspects call for a greater inclusion of fisheries in on-going climate policy discussions [145].

4.1. Reducing fisherfolk vulnerability: a "no-regret" strategy

Reducing vulnerability to multiple stressors and helping build resilient livelihoods is how institutions can foster socio-ecological systems which provide building blocks for the maintenance of livelihoods in the face of critical and pervasive threats, and resilient fisheries that can absorb disturbances and reorganize themselves following perturbation while still delivering benefits for poverty reduction. While some specific investment will be needed (i.e. risk reduction and transfer initiatives such as early warning systems, storm-shelters, managed retreat and insurance), adapting to climate change becomes a matter of addressing the fundamental problems of fisheries management and the underlying factors that cause vulnerability.

4.2. Understanding livelihood strategies to inform planned adaptation

Understanding autonomous adaptation to past and current stresses such as extreme events can aid designing measures that reduce the adverse impacts of future climate change and the implementation of inadequate measures ("mal-adaptation"). For instance current patterns of livelihood diversification in response to environmental changes, including geographical mobility, require specific policy and institutional changes that can inform planned adaptation.

4.3. Harnessing opportunities brought by climate change

Negative impacts are extensively presented in the literature while positive impacts of climate variability and change on the fisheries sector are not duly highlighted. The impacts of climate change will not be distributed equally. There will be relative "winners" and "losers", some communities may suffer significant losses due to physical damages or changes in fish distribution, while other will be less affected—or may even benefit with for instance positive changes in abundance of certain species. Successful identification of policies that enhance adaptation will only occur if the opportunities brought by climate change are identified.

4.4. Addressing conflicts and synergies between adaptation strategies

Indirect impacts of climate change arising from adaptive strategies pursued by different sectors will require a more holistic planning perspective to ensure that adaptive strategies are designed with a multi-sector perspective to minimize net impacts. Pressure from other resources (e.g. water, agriculture coastal defense) might restrict the ability of the fishery sector to adapt to climate change in some cases, and enhance it in others (mangroves and reefs for coastal defense—enhances coastal fisheries; irrigation and flood control—disrupt inland fisheries).

4.5. Contributing to mitigation

The mitigation potential of the fisheries sector, whether through emission reductions or carbon sequestration, should be explored. The design of financial mechanisms to implement mitigation (e.g. UN program Reducing Emissions from Degradation and Deforestation, for which mangrove conservation is eligible) needs to take into consideration all sectors, including fisheries. The scientific, technical and socio-economic aspects of mitigation options such as carbon sequestration by aquatic ecosystems and energy efficiency need to be addressed by researchers and policy-makers alike.

Climate change will bring about new challenges to fisheries-based livelihoods in the coming decades. To tackle them, a diverse portfolio of responses is needed, where poverty and vulnerability reduction, fisheries governance and climate policies agenda are reconciled. The additional investment needed for local communities to adapt to climate change, if well targeted, can yield direct and ancillary benefits in the short and long-term, resulting in positive returns on investment and "win–win" situations.

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