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Adaptation to Climate Change in Marine Capture Fisheries

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Abstract

This paper responds to the challenge of how and when to adapt marine capture fisheries to climate change by: (1) providing a set of fisheries policy options to climate change; (2) developing a risk and vulnerability assessment and management decision-making framework for adaptation; and (3) describing the possible strategies and tactics for *ex ante* and *ex post* climate adaptation in the marine environment. Its contributions include: (1) a discussion of how management objectives and instruments influence resilience and adaptation; (2) a decision-making process to assess vulnerabilities to climate change and to manage adaptation responses; (3) an inter-temporal framework to assist decision-makers when to adapt; (4) a risk and simulation approach to confront the uncertainties of the possible losses due to climate change and the net benefits of adaptation; (5) an explanation of how adaptive co-management can promote flexible adaptation responses and also strengthen adaptation capacity; and (6) a selection of possible 'win-win' management actions.

Keywords: climate adaptation, climate change, fisheries

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1. Introduction

In the coming decades climate change is expected to have substantial foreseen and also unexpected effects on the marine environment [1, 2]. Not all of these impacts will be negative, but the changes will almost certainly increase the degree of uncertainty [3] in terms of temporal and spatial variations of fish populations, habitat viability and stability, and ecosystem interactions and feedbacks [4]. Whether the ultimate effects of climate change are ‘mild’ or ‘severe’, prudent fisheries policy makers and managers should be precautionary and, at the very least, prepare a decision-making framework, strategies and tactics that, collectively, will assist fishers, their communities and stakeholders to adapt to the bio-physical, social and economic consequences of climate change.

This paper provides a guide to policy makers and fisheries managers about climate adaptation in marine capture fisheries. It stresses that any policy should be flexible and be able to adjust to unexpected impacts and policy outcomes and, whenever possible, encourage and assist fishers and their communities to autonomously adapt to climate change. It emphasizes that there are ‘win-win’ approaches in terms of best practice fisheries management that will be beneficial in both the present and the future, and that should be implemented regardless of possible climate change impacts.

2. Effects of Climate Change on Marine Capture Fisheries

The specific effects of climate change on particular marine ecosystems and fish populations are difficult to predict and quantify. However, on a global and regional basis there is sufficient research to indicate that many, but not all, of these impacts will be negative. The consequences of climate change include primary or direct effects due to sea-level rise, sea temperature change, lower ocean pH levels, changes in rainfall that will affect estuarine fisheries, and changes in ocean circulation. These primary effects will, in turn, alter habitats and change the distribution and mix of species that will have a profound impact on fisheries and marine ecosystems [1].

Climate change, at least in the short run, may only affect a relatively small proportion of fishes, but longer-run indirect effects are likely to have major implications on all marine ecosystems [5]. Not all of these impacts will be predictable or proportional to the bio-physical change. For instance, unexpected and non-linear effects of climate change [2], possibly exacerbated by fishing pressure, could result in shifts that favor lower-trophic species, such as jellyfish, at the expense of high-valued species, such as cod [4]. The fish populations and ecosystems most at risk with climate change will be those that are already: (1) near their physiological limits in terms of temperature, salinity and pH; (2) severely compromised in terms of their resilience due to existing anthropogenic factors, such as overfishing; and (3) are in locations most likely to suffer climate change impacts.

Some of the direct effects of climate change are predictable although many are not. For example, higher concentrations of CO_2 in the atmosphere will lower the pH level of the sea as it changes the carbonate-bicarbonate ion balance. This, in turn, is expected to have a negative impact on corals and calcifying invertebrates and some vertebrate species whose larvae are relatively sensitive to increased acidity [6]. Higher ocean temperatures are expected to shift fish populations to higher latitudes while migration of pathogens and parasites to new locations with climate change may cause population declines for species that may have had no prior exposure [7]. Sea-level rise, coupled with a higher incidence of intense storm activity, is expected to have negative impact on coastal breeding grounds of some key species, such as prawns. Changes in ocean circulation are also expected to reduce new primary productivity in key fishing areas [8], although some locations may benefit from these changes.

The consequences of climate change on fishing and coastal communities will be determined by: (1) their climate change exposure, as some locations will be more affected more than others; (2) the sensitivity of climate change in terms of targeted species and the ecosystem on which fishers and communities depend; and (3) on the fishers and their communities' ability to adapt to change. Artisanal fishers who are confined to harvesting in a very limited geographical area and who have few, if any, alternative sources of income are likely be the most vulnerable to climate change as they will have least ability to adapt. By contrast, more mobile fishers with an ability to catch different species using alternative gears over a wide geographical area, and with the capacity to borrow and access credit so as to manage climate variability, will be better able to adapt.

3. Promoting Sustainable Fisheries Management with Climate Change

To effectively adapt to climate change policy makers, fisheries managers, fishers and their communities must have clearly defined and quantifiable objectives. Different management goals generate different fisheries outcomes. For instance, if managers wish to maximize the sum of the discounted economic returns from fishing then low-levels of fishing effort and, ultimately, higher fish stocks are likely to be preferred [9]. If employment maximization is the goal then higher levels of fishing effort and lower fish stocks may be desirable.

The relevance in terms of adaptation to climate change is that goals that promote higher levels of fishing effort and lower stocks in the current state of the world may be less desirable in an environment subject to greater uncertainty due to climate change if it increases the risk of unsustainable harvesting. Conflicting goals are also problematic because if fish populations decline, possibly due to climate change, managers may seek to maintain current rates of employment even if it jeopardizes long-term sustainability [10].

3.1 Management Targets and Instruments

Sustainability in developed fisheries is often implemented through the use of target and limit-reference points, usually defined in terms of biomass, and implemented through a combination of effort restrictions and harvest strategies. Should climate change result in a more uncertain biomass, subject to greater shocks, these targets and limits should adapt to manage these risks.

The preferred management instruments with climate change will depend on the nature of the problem posed by climate change, the magnitude of the change, and the degree of uncertainty. In a risk assessment-based approach to adaptation, the likelihood of a given shock and its expected consequence or effect together helps to determine the preferred instrument(s). This is illustrated in Figure 1 with a probability-consequence risk trade-off in two states of the world. In a state of the world without climate change, given by risk trade-off curve R_1, low probability events but with a high consequence or negative impact may be viewed as equivalent to high probability events with a low consequence. The risk trade-off curve R_2 shows what might arise with climate change when the consequences of an event increase even if the probability of the event remains unchanged, or when the probability of an event increases but its consequence does not. Every point along a curve generates an equivalent level of risk, but all points on R_2 represent a higher level of risk than R_1.

A high probability event, but with a low consequence (P_H, C_L) under current management, such as 'high grading' of fish at sea, may be effectively managed in a no climate change state of the world (R_1) by incorporating the estimated this extra mortality in stock assessment models. However, with climate change the risk of high grading may be greater (R_2) even if the probability of high grading remains unchanged, as represented by (P_H, C_M), because of greater uncertainty in terms of the stock size. In this more risky state of the world with climate change additional management measures, such as improved monitoring at sea, may be required. Similarly, in the R_1 state of the world a low probability event with a high consequence (P_L, C_H), such as a recruitment failure due to higher ocean temperatures, may not be even be planned for because the likelihood of the event is too small. However, with climate change and an increase in the probability of the event, the risk becomes (P_M, C_H) with existing management measures. As a result, fisheries regulators may wish to establish additional management measures in response to a higher probability of recruitment failure.

3.2 Adaptive Management and Resilience

Adaptive management is a process whereby goals are quantified, strategies and tactics are developed to achieve these aims, and management actions adjust to new information and circumstances [11]. The greater is the uncertainty about the future and the less able are managers to predict the consequences of their actions, the more valuable is an adaptive approach to decision making. Its importance in terms of climate change adaptation is that not all impacts will be foreseen and fisheries managers will likely need to flexibly respond to large and unexpected shocks.

Adaptive management allows decision-makers to be more effective *ex-post* in an uncertain world. By contrast, resilience provides guidance about how to assist fish populations, ecosystems and people to *ex-ante* adapt to undesirable shocks. Resilience can be defined in various ways but it is essentially about how systems (bio-physical and socio-economic) are able to respond to change or shocks while maintaining their key characteristics or 'identity'. Two widely used resilience definitions are: (1) Holling-resilience that refers to how capable is a population or system to stay within a set of boundaries and maintain its 'identity' following a shock [12]; and (2) Pimm-resilience which refers to how quickly a system returns to within some neighborhood of its previous state following a shock [13].

The relevance of resilience in terms of climate change is that if a current state of the world is desirable, actions that allow systems to stay within a boundary of their desired state, or to return to it quickly if perturbed, are valuable. Consequently, management instruments that promote resilience, all else equal, are desirable. For example, it has been shown that even with optimal TAC setting appropriately designed marine reserves can increase both Holling and Pimm-resilience [14]. Thus, the establishment of appropriately sized and located marine reserves is a precautionary response that can promote resilience of marine ecosystems that may, in turn, assist in the adaptation to climate change.

Socio-economic resilience in terms of fishers and their communities refers to how they are able to maintain their livelihoods and desired ways of living, without outside assistance, following undesirable shocks. For instance, it would include their flexibility to substitute to more abundant fishery resources or to alternative economic activities to help offset declines in harvests from targeted fisheries. The greater proportion of a fishing community employed in a particular capture fishery, the fewer alternative employment activities available within the community, the greater the distance to other communities, and the more specialized the job skill set within fishing the less resilient will communities likely be to shocks associated with climate change.

4. Resilience and Adaptation to Climate Change

A heuristic for assessing the potential impacts of climate change that combines both bio-physical and social vulnerability measures is adapted from [15] and illustrated in Figure 2. At the top of the figure are the exposures to the bio-physical drivers of climate change and the sensitivities (bio-physical and socio-economic) that describe the degree to which the systems respond to climate change. The *potential* impacts are determined by the amount of exposure and the sensitivities that, together, determine the vulnerabilities — the potential for harm from climate change. The actual impacts, however, are determined by the capacity of bio-physical and socio-economic systems to adapt and the actual adaptive responses that are influenced by the adaptation planning processes described at the bottom of Figure 2. Thus, actual impacts of climate change can be reduced by: (1) promoting resilience so as to reduce system sensitivities; (2) increasing adaptation capacity and effectiveness of adaptation responses and (3) improving the adaptation-planning processes.

4.1 Promoting Resilience

Reducing bio-physical sensitivities of climate change is about promoting the resilience of marine ecosystems and fish populations. It is analogous to building walls or shelter before a storm ─ it does not prevent the storm from occurring, but reduces its impact. Desirable strategies to promote resilience must be developed at a fishery level because marine ecosystems, fish populations and communities are likely to have different structures and feedbacks. In all cases, however, the strategies should allow desired bio-physical and socio-economic systems to 'bounce back' and help maintain their 'identity' following undesirable shocks.

A useful way to develop strategies for resilience is to map the network structures within the bio-physical and socio-economic systems, and the connections between them. Some 'linkages' may need to be strengthened to help fish populations respond to shocks such as changing gear selectivity to ensure the targeted fish population has a wider distribution of aged cohorts. By contrast, undesirable linkages such as subsidies and other payments that keep fishers in particular locations and enterprises may need to be diminished or removed to allow them to effectively respond to environmental signals and avoid 'lock in' of undesirable and inflexible fishing behavior.

Strategies that could be helpful in promoting resilience in a bio-physical sense include: lower rates of fishing mortality; larger exploitable biomass of targeted species; and increased 'no take' areas that may provide a buffer stock in the face of unexpected shocks [14, 16]. A lowering of socio-economic sensitivities and increased socio-economic resilience could arise from economic and regional development and improved infrastructure (human and physical) that create a wider set of opportunities for residents of fishing communities.

4.2 Adaptation Capacity

The key to confronting climate change impacts is to ensure adequate adaptation capacity and effective adaptation responses. These responses exist at: (1) an ecosystem and fish population level; (2) an individual, community and stake-holder level; and (3) at a decision-maker, regulator or planning level. Adaptation capacity is about empowering socio-economic systems to respond to climate change and it differs to the actual adaptation response. For instance, poor countries are likely to have much lower adaptation capacity than rich countries [17]. Greater adaptation capacity of rich countries, however, does not necessarily mean that their adaptation responses will be more effective. For example, rich countries could use their greater financial resources to provide subsidies to assist fishers to stay fishing if incomes decline due to climate change. A subsidy approach that 'locks in' existing and unsustainable practices, however, is mal-adaptive and would likely increase climate change vulnerabilities.

Improved adaptation capacity can help overcome present and future constraints that may arise from inadequate financial resources, inappropriate governance structures [18], and a lack of information or knowledge in marine capture fisheries. A useful way to evaluate these constraints or barriers is to pose the following questions: (1) Who should adapt?; (2) What should be adapted?; and (3) How to adapt? These queries, collectively, form a 'triangular' adaptation process that is adapted from [19] and illustrated in Figure 3.

The 'Who' refers to those that undertake adaptation and includes: individuals; communities; and governments. Communities and governments have a comparative advantage in large-scale adaptation planning processes that require substantial resources over longer time periods. By contrast, individuals are better suited to adjusting to immediate short-run changes or shocks that are within their historical experience. The 'What' addresses the scale of adaptation (local, regional and national), and also the possible extent of adaptation in terms of bio-physical sensitivities and socio-economic sensitivities. The 'How' examines the resource or capital that is available (financial, human, natural) for adaptation and the approaches (bottom up or top-down) that can be used to respond to climate change.

4.3 Adaptation Processes

A priority in improving adaptation capacity is assistance to stakeholders in their planning processes. This is because although fishers may have a great deal of tacit knowledge, many lack the data, models and methods to assess the possible long-term effects of change. Such knowledge would typically reside with regulators and marine fisheries research agencies. Planned adaptation should, therefore, involve collaboration that mutually transfers knowledge to help fishers, communities, and also back to policy makers to improve the quality and scale of their own adaptation responses.

Climate adaptation can be both a 'top-down' and a 'bottom-up' process. Typically 'top-down' management is about mandating certain actions imposed by regulation so as to manage environmental and climatic variability. For example, restrictions on what fishing gear can be used, when and where provide limits on the effects of fishing mortality, especially at sensitive periods such as spawning times. They work best when there is a firm understanding of causes and effects developed from research, the tacit knowledge of fishers and stakeholders, and trial and error. Under rapid climate change, with unexpected effects, mandated approaches may not be adequate to promote effective adaptation, and may not respond quickly enough to negative shocks. For example, mandated vessel licensing provisions that prevent fishers from participating in a variety of fisheries make it difficult for fishers to adjust to variations in fish populations. By contrast, allowing fishers the flexibility to participate in many different fisheries, while maintaining desired levels of fishing mortality for each species, could reduce the socio-economic sensitivities of climate change.

Social adaptation is how communities and networks of fishers and stakeholders collaborate to respond to change. Such adaptation is important because it: (1) brings together and integrates different knowledge sets and experiences; (2) promotes sharing of risk across stakeholders; (3) assists in collective decision making about the delivery of common services and public goods enjoyed by stakeholders. Promotion of social adaptation may also contribute to socio-economic resilience as it provides additional governance arrangements to 'back stop' more formal management structures. By contrast, technical adaptation focuses on technological advances and innovations that will assist in reducing the consequences of climate change [20]. For instance, technical innovations that reduce by-catch and support biodiversity may increase the resilience of marine ecosystems. Both forms of adaption (social and technical) are important to effectively respond to climate change.

5. Vulnerability Assessment and Management for Adaptation Decision-making

A vulnerability assessment framework to assist with climate adaptation decision-making is provided in Figure 4. It consists of five inter-connected steps: (1) delineation of the adaptation context that includes management goals, description of the stakeholders and agents of change and the relevant climate change scenario; (2) a description of the exposures, impacts and vulnerabilities being evaluated; (3) a review and assessment of the current fisheries management strategies and tactics, and an assessment of current adaptation strategies in place to manage climate change variability and risks from climate change; (4) ranking of the possible exposures, impacts and vulnerabilities in terms of their significance; and (5) consideration of the adaptation options to manage the vulnerabilities and risks from climate change. Throughout these five steps there should be effective communication and consultation with stakeholders and explicit monitoring and review of actions that feeds back into the decision-making process.

5.1 Initial Vulnerability Assessment

To decide when, and also how, to adapt to climate change decision makers need to undertake a vulnerability assessment. If there are limited financial resources, personnel and information available as to the exposure and sensitivities to climate change, the decision making process may be abbreviated to an initial assessment. A key component of the initial adaptation assessment is to describe in detail the policy context and have this reviewed by key stakeholders. Following this feedback, and either as part of existing management planning processes with stakeholders or as an additional activity, fisheries managers and stakeholders would work together in collaborative 'vulnerability and adaptation' workshops. These workshops would be an important step in building and supporting adaptation capacity and would seek to: (1) identify key vulnerabilities; (2) analyze existing strategies and tactics to respond to potential climate change impacts; and (3) prioritize actions to help bio-physical and socio-economic systems respond to the most significant impacts, as identified in the planning process.

As part of the initial vulnerability and stakeholder workshop process, a prioritization of vulnerabilities would be required. A possible ranking of vulnerabilities to assess priorities could include: (1) Catastrophic vulnerabilities (key management objectives would not be achievable and there is little or no expectation of them being realized under current or alternative strategies); (2) Major vulnerabilities (key management objectives would not be achievable with existing strategies but alternative strategies offer potential pathways to realize these goals); (3) Moderate vulnerabilities (key management objectives would be placed at considerable risk without a change in strategies and/or tactics); (4) Minor vulnerabilities (key management objectives are achievable with existing strategies and only minor change in tactics is required); and (5) Insignificant vulnerabilities (key management objectives are achievable and no immediate action is required).

5.2 Inter-temporal Adaptation

A critical part of the adaptation decision-making process is when to adapt, before the effects are evident, or subsequent to their impacts. In many cases, adaptation involves a mix of *ex-ante* and *ex-post* responses. However, adaptation is not costless and deciding when to adapt involves trade-offs between the present and the future and consideration of the risk and returns of adaptation investments. A framework to help understand these trade-offs is presented in Figure 5 using a common metric that monetizes costs, benefits and also risks. On the horizontal axis is the monetary loss or gain in terms of the net present value from adaptation over the long-run that may involve a planning period of several decades. The vertical axis represents the monetary loss or gain in net present value terms from adaptation in the short-run, typically no more than three to five years. The four parts to the decision box represents the inter-temporal payoffs. The two squares to the left of the line that bisects the box vertically represent actions that, over time, will generate a negative net present value while to the right are actions that will generate a positive net present value. The two squares below the line that bisects the box horizontally are actions that generate a positive net present value in the short run while the two quadrants above this line generate a negative present value. In terms of the inter-temporal trade-offs, climate adaptation can be visualized as a process that tries to increase the payoffs in the future, possibly at the expense of increased costs and lower returns in the short run.

The four quadrants in Figure 5 represent the present and future payoffs of climate adaptation. The 'lose-lose' (L L) quadrant represents adaptation actions that generate losses both in the short and long run while the 'win-win' (W W) quadrant represent actions that generate positive net returns today and also into the future. The other two quadrants represent action space that may, or may not be, desirable depending on the qualitative benefits and costs that may be used in the adaptation planning process. The larger is the discount rate the greater will be the set of 'Win Lose' (W L) actions that generate positive payoffs in the short run, but net economic losses overall, and the smaller will be the set of 'Lose Win' (L W) actions that generate transitional costs or losses in the short-run, but positive net returns when evaluated over all time periods.

The inter-temporal trade-offs show that win-win actions should be implemented immediately while lose-lose actions should never be undertaken. Examples of win-win strategies are those that increase the net returns today, and also into the future, and would include appropriately designed dedicated catch shares that can reduce harvesting costs and increase revenues [21] or gear restrictions that increase yield per recruit. Lose-win actions such as stock rebuilding may initially generate short-run transitional costs, but result in an overall positive net present value that may be very large [22]. Examples of such actions would be harvest controls that reduce the current harvest to rebuild the overall biomass and that can promote bio-physical and socio-economic resilience. Larger fish stocks may also increase the net present value of returns from fishing [9], but are typically associated with short-run transitional costs. Win-lose actions provide positive short-run gains, but possibly at the expense unacceptably high or risky harvest levels and also result in an overall negative net present value in the long run. Examples of such actions would be deliberate recruitment overfishing to temporarily maintain higher employment levels in a fishery.

5.3 Risk and Simulation

The categorization of vulnerabilities should use a common and quantitative metric. A risk-adjusted monetary metric is one alternative that explicitly accounts for the likelihood of a climate change occurrence and the consequences or the costs of such an event. This can be implemented using a 'risk and simulation' approach that uses Monte Carlo simulations to construct a probability density function for: (1) the expected losses associated with specific climate change impacts; and (2) the expected net benefits of given adaptation responses or investments in adaptation capacity.

In almost all cases decision makers will not know the underlying distribution of potential costs associated with different climate change impacts, but may have some idea about the upper and lower bound of these costs. To account for this uncertainty, alternative distributions (uniform, triangular, normal, gamma, etc.) can be used to assess the payoffs of investments in adaptation capacity or in particular adaptation responses. For example, a decision maker may expect the costs of an increase in sea temperature on a given fishery to range from $0 to $10 million. If the decision maker assumes a triangular distribution for these costs then a 'most likely' value must also be estimated or determined by subjective judgment. If the most likely value is $2 million then the resulting probability density function is given in Figure 6, with a 90% confidence interval that ranges from $1 million to $8 million. Assuming a different 'most likely' value or a different distribution would generate a different probability density function. The value of the risk and simulation approach is in the hypothetical probability density function and confidence intervals it provides to decision makers. Different parameter values and bounds to assess potential climate change impacts would, ideally, be presented and refined with stakeholders in collaborative workshops.

The risk and simulation approach can also be used to assess the net benefits of adaptation strategies to mitigate vulnerabilities. In this case, decision makers need to also calculate the costs of adaptation and the expected benefits of adaptation. This approach should complement or be integrated with existing procedures to manage risk and uncertainty in fisheries that have been developed in the context of stock assessments and harvest control rules [23, 24]. Ideally, risk and simulation of climate adaptation responses should be part of a management strategy evaluation (MSE) that uses simulation-tests feedback-control management procedures [25] to adjust harvests and other management controls in response to shocks. The operating models within MSE would need to account for the possible effects of climate change, assess whether the management procedures are robust to climate change uncertainties, and consider 'whole of system' effects perhaps using ecosystem models [26]. Until such procedures are developed, it would be advisable to undertake initial assessments of climate change that utilize vulnerability assessments and a risk and simulation approach to identify robust adaptation responses.

5.4 Adaptive Management and Adaptation

Decision-making under uncertainty is an adaptive process whereby new information and circumstances feedback into goals, strategies and tactics that determine the adaptive responses. These responses can cover a wide variety of alternatives including: (1) risk sharing, whereby fishers mitigate shocks via co-operation and possibly revenue sharing; (2) avoidance, whereby fishers and their communities are provided with better forecasts to avoid negative impacts; (3) development of planning approaches that account for climate change and extend planning horizons that go beyond day-to-day operational management; and (4) bridging knowledge gaps in terms of forecast and predictions as well as sharing of information across stakeholders.

Stakeholder collaboration should not only be about knowledge sharing, but should also consider which actors or stakeholders (fishers, communities, non-governmental organizations, fisheries regulators, etc.) are best suited to what adaptation action. Polycentric or nested governance structures that involve multiple decision centers allows for greater flexibility and opportunity to experiment with alternative responses, and may also create 'redundancy' that promotes resilience in socio-economic systems [27, 28]. Different layers of management and complementary rules in fisheries governance also increase management options across scales: local; regional and national [29]. Such governance systems promote adaptation capacity and become increasingly important the greater is the uncertainty and the scale and scope of fisheries (species, geographic, stakeholders) to be managed. An adaptive co-management approach [30] also encourages autonomous adjustment by fishers and their communities, values different knowledge sets (tacit, traditional and scientific) and collaborative decision-making across key stakeholders.

The decision to respond and the choice of the response to climate change should, ultimately, be based on the risk that decision makers and stakeholders are prepared to accept and the expected net benefits. Monitoring and evaluation of actions should feed back to re-assess the value of the response as additional information becomes available. Thus when, what and how to adapt should be the outcomes of a decision-making process that uses a risk and simulation approach to (1) assess climate change impacts and (2) evaluate adaptive responses. The success of adaptation should be judged in terms of whether the planned strategies and adaptation actions ensure the identified vulnerabilities are limited to the levels projected in the planning processes.

6. Climate Adaptation and Fisheries Management Actions

Regulators have a wide range of strategies and tactics to manage fisheries that are summarized in Table 1. Output controls restrict the total harvest and can involve either a competitive TAC or the partitioning of the TAC into dedicated catch shares assigned to individuals or communities. Input controls restrict the fishing effort in particular ways, typically through licensing restrictions that limit the total number of vessels permitted in a fishery. In many fisheries, additional effort controls are also applied that try to constrain the amount of fish caught for a given level of effort. Technical and temporal measures control the type of catch for a given level of effort such as ensuring that only fish of a certain size are caught, or that the gear used avoids by-catch of protected or endangered species. Spatial controls constrain fishing and other use activities to particular locations and may also specify restrictions on where particular types of fishing or gear can be used. A combination of all four types of control may be applied to influence the harvest sector, the marine ecosystem and post-harvest, processing and consumption.

The availability of a suite of management tools is necessary, but not sufficient, to develop effective adaptation responses to climate change. These tools must be combined with processes that (1) promote resilient marine ecosystems and (2) model and confront uncertainty about the state of the world and the effect of adaptation actions. Using the criteria of accountability (with seven indicators), transparency (with three indicators), incentives (with four indicators), risk assessment and management (with four indicators) and adaptability (with four indicators) a method of benchmarking has been developed to evaluate fisheries governance using a five-point performance scale [18]. This approach can, and should, be extended to identify weaknesses in current governance, such as management controls that fail to prevent the 'race to fish' that result in overcapacity and other actions that detract from socio-economic/ecological resilience [31]. International case studies support a governance focused approach because where fishery governance systems are weaker it appears they are also less capable to adapt to climate change [32].

Many management tools currently in use were designed to ensure a given level of recruitment or fishing mortality, but not necessarily to promote resilience, or to provide robust management approaches to climate change. At best, they provide a degree of control over 'persistent vulnerabilities' or environmental shocks that are known and occur periodically. While ensuring populations remain above a minimum viable size is a useful strategy given a variable environment [33], this may not be sufficient with climate change, especially if measurement of fish populations and harvests is problematic. Moreover, even in the current state of the world management controls have frequently been applied ineffectively [34] because almost two-thirds of assessed fish stocks require rebuilding [35]. Many governments have also failed to fully deliver on their commitments to implement precautionary management [36]. Thus, confronting climate change in fisheries requires much more than precautionary TACs. It demands that fishers, stakeholders and managers develop approaches that provide a degree of leverage to known environmental surprises [37, 38] and also ‘emergent risks’ that are unexpected.

Management actions developed to confront uncertainty and promote resilience are likely to become more favored with climate change. For instance, appropriately designed ‘no take’ areas generate Pimm-resilience. This enables targeted fish populations to recover faster subsequent to a negative environmental shock [39] without necessarily requiring an adaptive management response. Importantly, this resilience effect generates positive payoffs that cannot be achieved with input or output controls alone, and in many cases there is no tradeoff between the economic payoff of fishers and ecological benefits if no take areas are established at equal to or less than their optimal size. Critical to generating ‘win-win’ outcomes is establishing no take zones in locations that are population sources.

Some types of fishing gear, such as line fishing, also help to maintain resilience better than other forms of harvesting, such as traps, because they help to reduce the catch of susceptible and recovering species in coral reef ecosystems [5]. Other types of gear reduce bycatch, such as turtle excluder devices on trawls and bird-scaring lines on longlines [40]. By reducing bycatch mortality and morbidity, these technical measures can help to maintain marine biodiversity, and promote resilience.

Experiences with existing management actions provide guidance about management controls that undermine resilience. For instance, the use of stand alone input controls or competitive TACs fail to resolve the ‘race to fish’ inherent in the exploitation of common-pool resources like fisheries. Consequently, fisheries managed by these approaches are frequently characterized by overcapacity that makes fishing a marginal activity for many harvesters. This, in turn, reduces the resilience of the socio-economic systems around fishing and their communities as even small shocks may generate large negative effects. By contrast, approaches that encourage to fishers to minimize costs for a given level of harvest and reduce the race to fish, such as incentive-based approaches to management [41], help promote a resilient fishing sector.

7. Concluding Remarks

Fisheries are inherently variable and subject to unexpected shocks. In response to such uncertainty fishers, their communities and regulators have developed ways to respond to change, but not always successfully. Climate change will increase uncertainty and accentuate the magnitude or incidence of shocks. Some changes may be positive for some areas and targeted populations, but the current state of knowledge suggests that for many fisheries the effects will be undesirable.

The dilemma for all fisheries stakeholders is when and how to adapt when confronted with the inherent uncertainties of marine ecosystems and the effects of climate change. Risk management that: (1) incorporates an assessment of current and future vulnerabilities; (2) engages stakeholders; and (3) models and simulates different states of the world and strategies, should be used to guide decision makers when responding to climate change. Precautionary fisheries management demands that vulnerability management planning framework be used today even if the actual planned adaptation from this process may not occur for several years to come. Without a precautionary decision-making process, current actions may increase vulnerabilities (mal-adaptation) or be inadequate (under-adaptation) to manage either the increased probability or greater magnitude of environmental shocks attributable to climate change.

The strategies and tactics to adapt to climate change will vary by fishery because exposures, sensitivities, vulnerabilities and adaptation capacity differ. Nevertheless, two broad approaches that are universally valuable are: (1) *ex-ante* measures that promote resilience in bio-physical and socio-economic systems where the current state is desirable; and (2) *ex-post* management that is actively adaptive and that ensures a speedy response to shocks. Strategies that are 'win-win' such that they increase net benefits in both the short-run and long-run, after accounting for all direct cost and risks, should be implemented immediately. For example, actions that rebuild depleted fisheries and increase the net present value of fishing promote bio-physical and socio-economic resilience. Similarly, appropriately designed and sized ‘no take’ areas can promote resilience and increase the discounted net returns from fishing. Barriers to implementation of win-win or lose-win actions can be mitigated if ‘losers’, such as fishers who may no longer have access to traditional fishing grounds, are compensated from the increased benefits that accrue to others via inter-temporal transfers.

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Captions for tables and illustrations

Table 1: Management Controls in Fisheries

Figure 1: Managing Climate Change Risks in Marine Capture Fisheries

Figure 2: Adaptation Capacity, Planning and Vulnerabilities to Climate Change
Adapted from Pecl et al. [15]

Figure 3: The 'Triangular' Adaptation Process
Adapted from Preston and Stafford-Smith [19]

Figure 4: Vulnerability Assessment and the Adaptation Decision-making Process

Figure 5: Inter-temporal Climate Adaptation Decision Framework

Table 1: Management Controls in Fisheries

Catch Controls	**Input Controls**	**Technical & Temporal Controls**	**Spatial Controls**
Total allowable catch (TAC)	Vessel licence controls	Season length	'No take' areas
Dedicated catch shares	Effort quotas	Fishing gear specifications	Territorial user rights in fisheries
Trip catch limits	Gear and vessel restrictions	Size and gender selectivity restrictions	Individual vessel spatial licencing

Adapted from OECD [42]

Figure 1: Managing Climate Change Risks in Marine Capture Fisheries

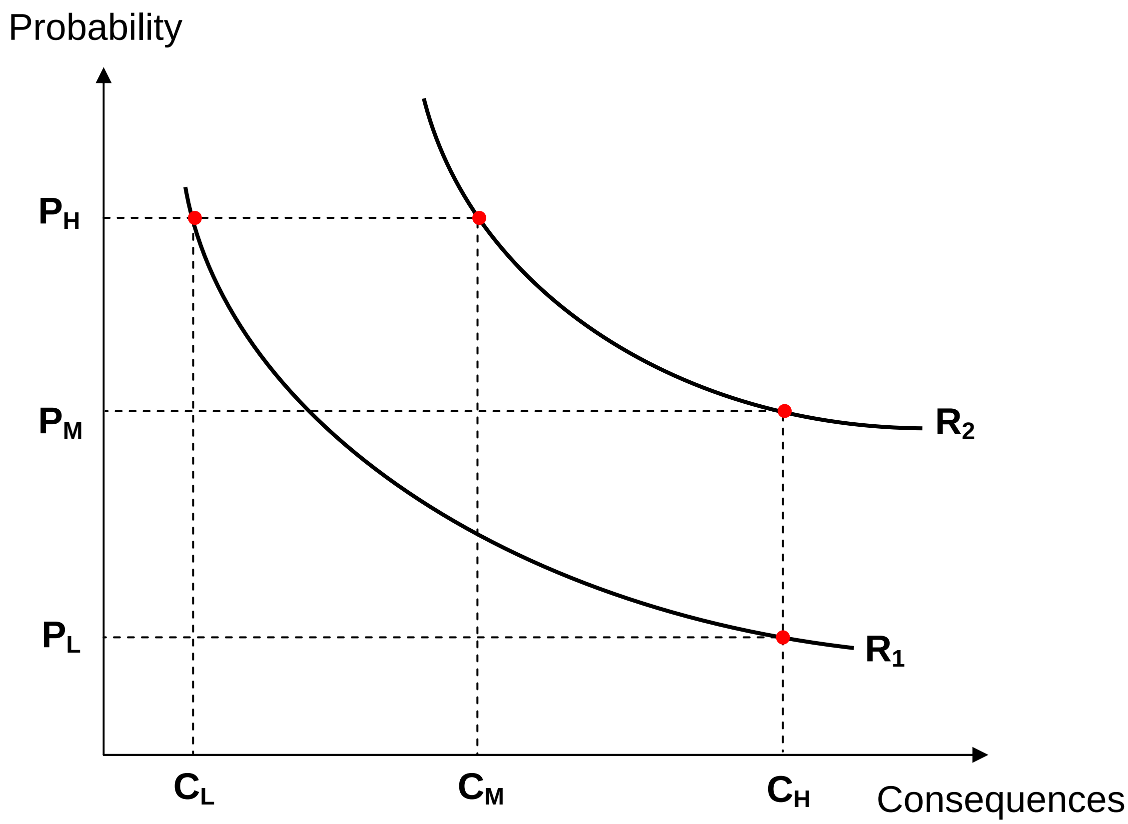
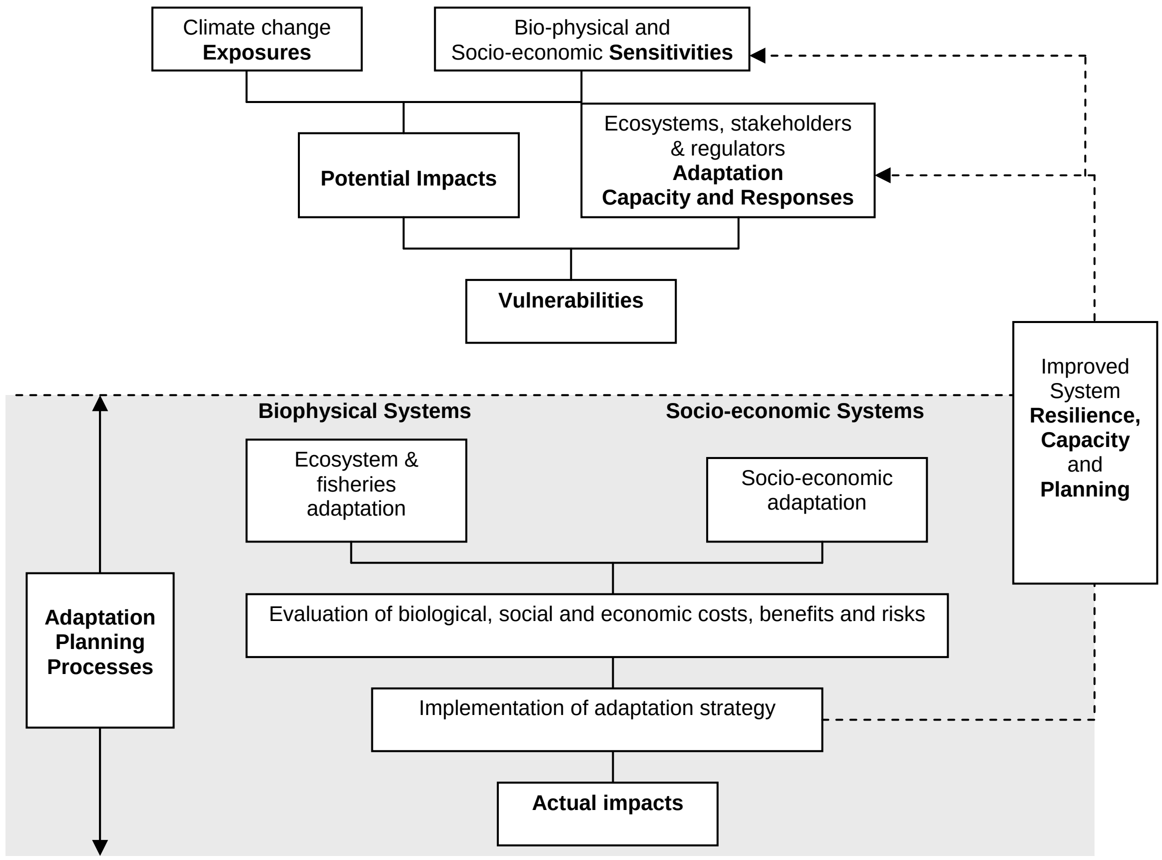
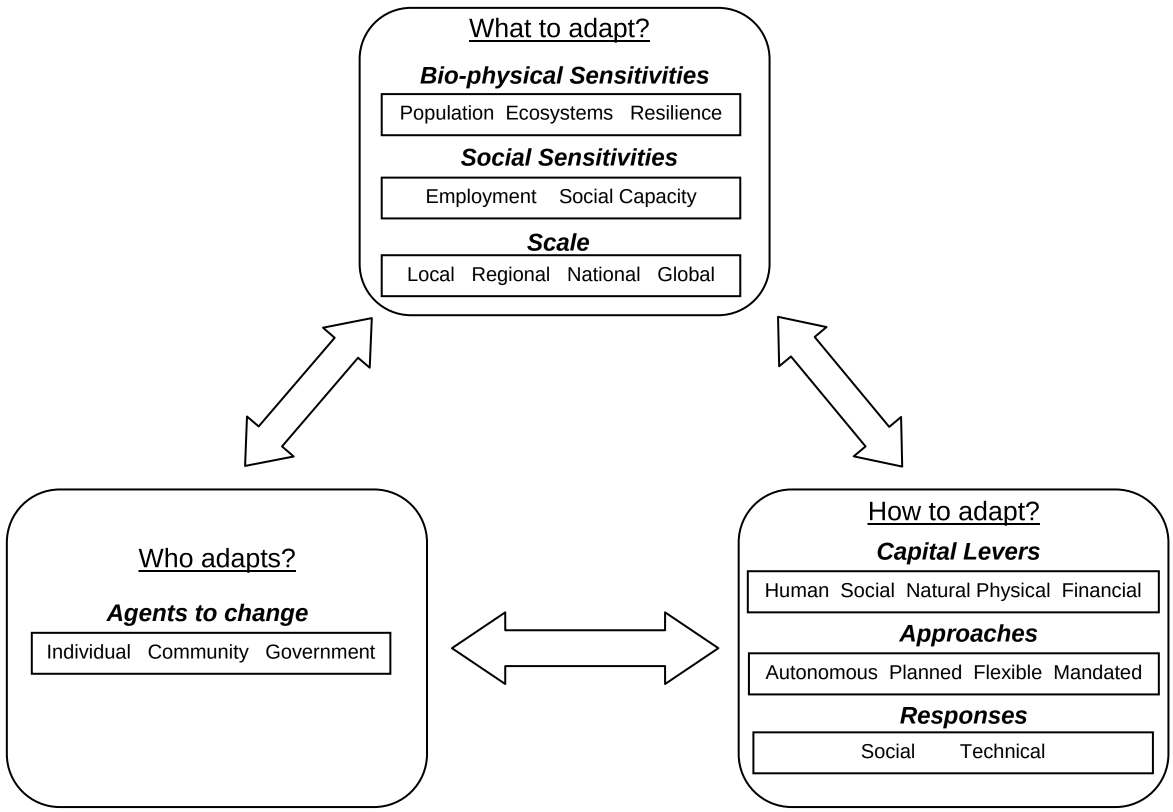


Figure 2: Adaptation Capacity, Planning and Vulnerabilities to Climate Change



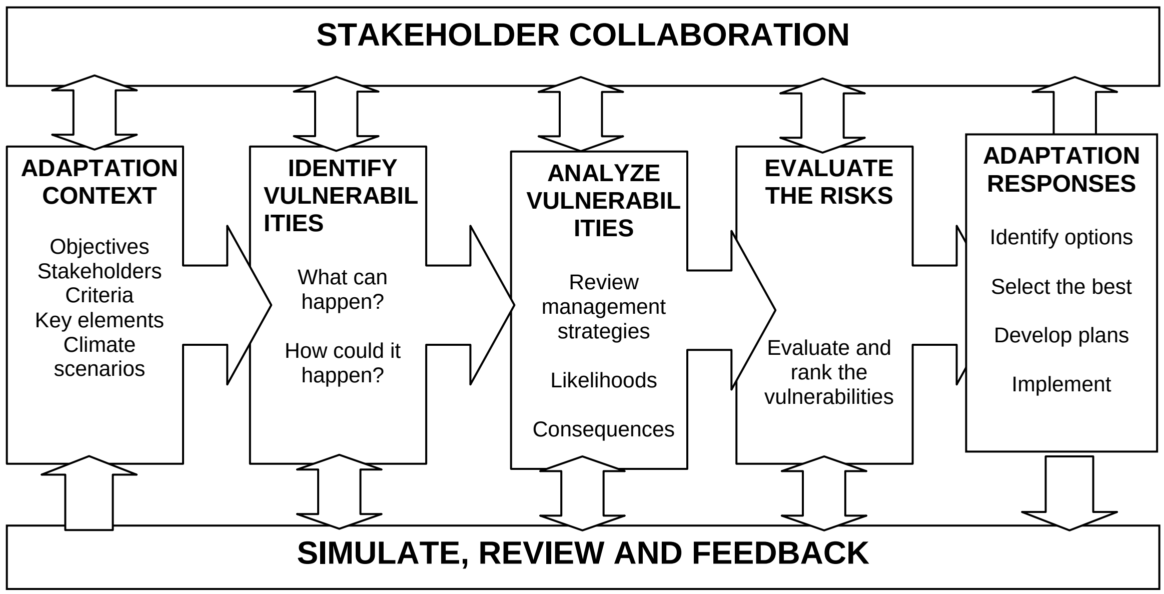
Adapted from Pecl et al. [15]

Figure 3: The 'Triangular' Adaptation Process



Source: Adapted from Preston and Stafford-Smith [19]

Figure 4: Vulnerability Assessment and the Adaptation Decision-making Process



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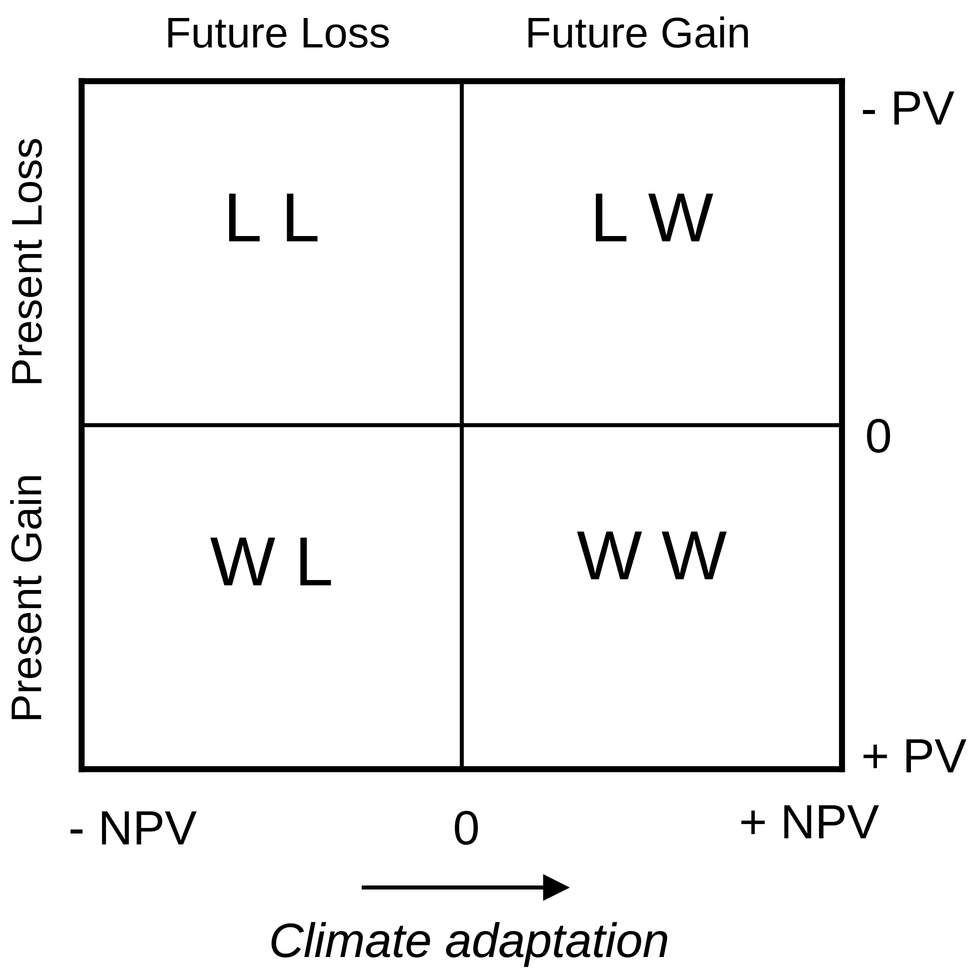

Figure 6: Probability Density Function of a Hypothetical Vulnerability (Triangular Distribution)