A Review of economic analysis of climate change impacts and adaptation in fisheries and aquaculture

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Abstract

Focusing on economic methods, this study provides a comprehensive review of the current research in fisheries and aquaculture within the context of climate change. We find there has been remarkable progress in evaluating the biophysical impacts of climate change on fish. However, the effect those impacts have on future fish stocks, yields, and dynamics are less understood. Climate change adaptation strategies in fisheries and aquaculture lack quantitative assessment, while current vulnerability indices rely heavily on subjective weighting schemes. Economic studies involving fisheries and aquaculture have seen some recent advancements but can be improved through incorporating methods from other disciplines, notably agricultural economics. Relative to its increasingly large role in global fish supply, the aquaculture sector is found to be under-represented in the economic literature. We suggest that future research in fisheries and aquaculture should further incorporate methods from agricultural economics, focus on the economics of aquaculture, and refine interdisciplinary research methods such as bioeconomic modelling.

Key words: fisheries, aquaculture, climate change, adaptation, economics

JEL code: Q21, Q22, Q18, Q54

1. Introduction

Mounting scientific evidence confirms that human-induced global climate change with measurable and increasing effects is happening (Cook et al., 2013; Hulme, 2009; IPCC, 2014, 2021). Delaying action to address this global challenge is becoming increasingly costly (IPCC, 2018; Shiferaw et al., 2014). At the same time, there is a paucity of empirical evidence about the interactions between climate change and economic sectors, especially those highly dependent on natural resources and ecosystems. Due to these reasons, it is important to improve scientific evidence and methods for developing sector-specific climate change adaptation and mitigation actions.

Fisheries and aquaculture play an essential role in food and nutrition security, as well as poverty reduction and livelihoods in developing countries. These two sectors, at a global scale, directly employ 59.5 million people and create livelihood opportunities for nearly 200 million people along their supply chains (FAO, 2020). In Africa and Asia, over 20 percent of total animal protein intake comes from seafood (FAO, 2020). Seafood and aquatic products are critical sources of essential micronutrients for developing countries' populations, particularly poor people, women and children.

Fisheries and aquaculture have been facing enormous climate-related stressors. These stressors include altered rainfall patterns (droughts or flooding), greater evaporation and drying trends, increased oxygen demand, decreased pH, extreme weather events, sea-level rise, and ocean acidification (Ahmed et al., 2019; Brander, 2012; Brander, 2007; Cooley & Doney, 2009; Doney et al., 2012). These climate change manifestations directly affect growth, development, reproductive capacity, mortality, and distribution of fish. These climatic shocks also indirectly disturb

fish via their negative impacts on ecosystems including coral reefs and mangrove/estuarine ecosystems that fish, crustaceans, and molluscs depend on for food and shelter (Badjeck et al., 2010; Brander, 2007; Savo et al., 2017). In addition, damages to infrastructure and equipment as well as disruptions in households' fishing and aquaculture activities have negatively affected livelihoods and increased vulnerability to climate uncertainty (Ahmed et al., 2019; Allison et al., 2009; Kam et al., 2012).

Beyond biophysical effects, climate change has direct and indirect economic consequences on actors, societies, and countries. Understanding the economics of climate change in fisheries and aquaculture is critical for informing policy and decision-makers when developing cost-effective adaptation and mitigation strategies. To date, a few studies have used economic methods to examine: a) the impacts of climate change on fisheries and aquaculture (Briones, 2006; Dey, Gosh, et al., 2016; Dey, Rosegrant, et al., 2016; Lam et al., 2012); b) the cost of climate change adaptation in fisheries and aquaculture (Narain et al., 2011; Rosegrant et al., 2016); and c) profitability and welfare implications of climate change adaptation strategies (Dey, Rosegrant, et al., 2016; Lan et al., 2018). These studies provide insights into and enhance our knowledge of the impacts of climate change on fishing incomes and the returns to investment in adaptation strategies. However, empirical evidence on the economic impacts of climate change and adaptation strategies in fisheries and aquaculture is still limited.

This paper contributes to the literature on economic analysis of climate change impacts and adaptation in fisheries and aquaculture in three ways. First, we synthesize the current state of knowledge in relation to the biophysical and economic impacts of climate change on fisheries and aquaculture, the vulnerability of communities,

systems, and livelihoods to such impacts, and possible adaptation strategies that will improve the resilience of fish value chains. Second, we examine applicable economic methods for evaluating the impacts of climate change and adaptation interventions on the fish sector. Finally, we identify priorities for future economic research to support the design and development of climate-related policies.

2. Methodology

Our review consists of two sections. The first section provides an extensive literature review regarding the impacts of climate change on fisheries and aquaculture, their vulnerability and adaptive capacity/strategies to climatic change. The second section summarizes the applicable economic methodologies for evaluating: (1) impacts of climate change on fisheries and aquaculture and (2) impacts of interventions implemented in response to climatic shocks. While the scope of the review is broad, we only include studies that conform to three main inclusion criteria: (1) focuses on fisheries, aquaculture, and or agriculture; (2) includes information on the impact of climate change, vulnerability to climate change, adaptation or mitigation strategies, or climate-smart agriculture; and (3) the study design includes primary and/or secondary data. Research papers focused on agriculture were included if their research methodologies and/or findings are applicable to the issues facing fisheries and aquaculture because the literature on economic analysis of agriculture and climate change is more developed. Definitions of key terms are provided in Table 1.

<<insert Table 1 here>>

Literature searches were conducted in English language peer-reviewed journals accessible on the internet. In addition, the review included grey literature such as institutional reports, academic dissertations and working papers. There was no

limitation in terms of the year of publication for the reviewed literature. Table 2 lists the search terms used to identify articles for the review. The search term “OR” was used for those words that have multiple stylizations (for example, climate smart OR climate-smart). Search strings consisted of the following components, namely ‘climate change’ AND fisheries OR ‘aquaculture’ AND ‘impact’ OR ‘vulnerability’ OR ‘adaptation’ OR ‘mitigation’ OR ‘climate-smart’ OR ‘climate smart’, OR ‘economics’ OR ‘economic impact’. We created separate search strings for the impact of climate change, vulnerability to climate change, adaptation or mitigation options, and climate-smart agriculture. The search strings were then combined using the ‘AND’ operator for input in the search engines (Table 2).

We undertook a two-stage screening procedure to determine the relevance of literature material returned from search strings. First, abstracts and titles were screened according to the predetermined inclusion criteria. Second, the full texts for those abstracts were downloaded and screened by the same eligibility criteria. Each publication included in the review after full-text screening entered data extraction—the process of gathering information from the papers.

<<Insert Table 2 here>>

After the screening procedure, we obtained 121 publications, encompassing both published and grey literature. The distribution of article topics is displayed in Table 3. A majority of these publications (97) are directly related to fisheries and aquaculture, and the remaining 24 publications are economic analyses of climate change impacts and adaptations in agriculture and indirectly related to the fisheries sector. Among the 97 articles related to fisheries, 62 are about capture fisheries while only 37 are related to aquaculture. This distribution reflects the novel nature of aquaculture as a fast growing more recent practice which has not been researched as extensively as marine capture fisheries, especially in regards to economics, a finding also found by Anderson et al. (2018). Furthermore, the majority of papers included are related to climate change adaptation and mitigation. Only nine papers focus on climate-smart agriculture, the least number of all considered topics. The distribution of topics amongst the publications can be found in Table 3. It should be noted that topics are not mutually exclusive, that is, a publication can have multiple topics.

<<Insert Table 3 here>>

3. Results

3.1 Impact of Climate Change

Our review shows that global climate change can have short-term, medium-term, and long-term impacts on fisheries and aquaculture at multiple scales (Barange et al., 2018; Brander, 2010; FAO, 2020). Such impacts primarily manifest through reduced precipitation, greater evaporation caused by increased air and water temperatures, increased oxygen demand, decreased pH, extreme weather events, sea-level rise, and ocean acidification. Five papers out of 39 publications about the impacts of climate change found that changes in climate directly affect fisheries and aquaculture via fish physiology—growth, development, reproduction and diseases—

and ecology—organic and inorganic cycles, predation and ecosystems (Brander, 2010; Brander, 2007; Cheung et al., 2009; Doney et al., 2012; Merino et al., 2010). Portner and Peck (2010) find that physiological responses of organisms to environmental perturbations at different levels in the food web may affect productivity and food web interactions. Another group of publications focus on the impacts of climate change on marine and estuarine fisheries including increased oxygen consumption rates and changing migration patterns of fish, which may adversely affect fishing communities dependent on both coastal and pelagic fish stocks (Munday et al., 2008; Perry et al., 2005; Pratchett et al., 2008; Roessig et al., 2004). Some authors have also pointed out the declining fish productivity in lakes caused by global warming (O'Reilly et al., 2003; Vollmer et al., 2005).

Several studies show the economic impacts of climate change due to decreased production and seafood supply. For example, Dey and Rosegrant et al. (2016) estimate a substantial increase in the demand for fish due to increases in population and per capita income. However, climate change's effect on the supply of fish consequently makes countries net importers and compromises their ability to achieve food security, thus decreasing per capita consumption in many countries. In another study, Briones (2006) shows that climate change can cause a decline in fish supply that remains persistent even after the shock disappears, implying that climate change can cause permanent losses in productivity. Lam *et al.* (2012) project a substantial reduction in marine fish production and decline in fish protein supply in West Africa by the 2050s under climate change. This study further finds that climate change can lead to a 21% drop in annual landed value, 50% decline in fisheries-related jobs and a total annual loss of US\$311 million in the whole economy of West Africa.

Climate change can directly affect fishery and fish farming households, particularly along exposed coasts. These effects include significant risks to safety at sea due to increasing bad weather, increased rates of disease transmission by insects, loss of fishing/aquaculture equipment and physical capital, and loss of revenue from closure or reduction of fishery activities (Badjeck et al., 2010; Jallow et al., 1999). Increased extreme weather can also damage installed infrastructure, reduce farming capacity, result in crop loss due to flooding, and hamper access to markets (Ahmed et al., 2019; Iwasaki et al., 2009). Damages to non-productive physical assets such as housing and community infrastructure including hospitals, schools, and sewage systems can disrupt livelihoods through non-voluntary resettlement and displacement (Badjeck et al., 2010). Due to climate change, decreased availability of fish products can affect incomes among fishers and fish farmers, potentially setting off a cascade of ecological consequences as desperate people resort to desperate measures to survive. For example, extreme weather events in Bangladesh were found to drive individuals into illegal activities such as logging, and arresting such vulnerable populations further deepened poverty traps (Ahmed et al., 2019).

3.2 Vulnerability to Climate Change

Natural resource-based livelihoods, including fisheries and aquaculture, are highly vulnerable to climate change. The increasingly adverse impacts of climate change on livelihoods have triggered active research in vulnerability assessment (Adhikari & Taylor, 2012; Allison et al., 2009). Assessing the vulnerability of fisheries and aquaculture to climate change can help identify countries, regions, communities, and households highly dependent on these sectors for their livelihoods. This assessment can also assist in developing policy responses and adaptive management strategies to reduce vulnerability (Ding et al., 2017).

The vulnerability of fisheries to climate change may vary across regions and countries. Allison *et al.* (2009), by investigating the vulnerability of 132 countries to climate change impacts on fisheries with comparative indicators, find that fisheries in Africa, South America and Asia are the most vulnerable. Cinner *et al.* (2013) examine the vulnerability of 29 coastal communities in five western Indian Ocean countries to the impacts of coral bleaching on fishery returns. Their findings suggest that Kenya has the highest overall vulnerability, followed by Tanzania, Madagascar, Seychelles, and Mauritius. Similarly, Ding *et al.* (2017) apply a vulnerability assessment framework in 109 countries to examine the level of vulnerability of marine fisheries to climate change in the context of food security. Their study shows that vulnerability to marine fisheries-related food insecurity due to climate change closely parallels the national development status with continents with a higher proportion of developing countries such as Africa, Asia, Oceania, and Latin America appearing to be the most vulnerable. According to the study, vulnerability is also strongly correlated with adaptive capacity and sensitivity. Several studies have also focused on assessing the vulnerability to climate shocks at national and sub-national levels (Adelekan & Fregene, 2014; Morand *et al.*, 2012; Senapati & Gupta, 2017).

While previous vulnerability assessments have undoubtedly improved our understanding of the impacts of climate change and helped formulate appropriate management strategies, the lack of a clear approach to generate objective and meaningful weights for vulnerability indicators while constructing subsequent indices remains a challenge. Continued reliance on subjective weights may mislead conclusions about the vulnerability of populations and production systems. Climate change vulnerability assessment of fisheries and aquaculture may benefit from economic studies, especially the poverty economics literature, where weighting

schemes for livelihood indexes generally use established quantitative to estimate the marginal effects of indicators that are used to define livelihood (Adato et al., 2006; Giesbert & Schindler, 2012). One approach would be to weigh indicators of exposure, sensitivity, and adaptive capacity objectively by their marginal contribution to households' wellbeing with explicit attention to the greater vulnerability of poor households.

3.3 Adaptation and Resiliency to Climate Change

Adaptation is crucial for reducing vulnerability to climate change in fisheries and aquaculture. Adaptation measures can be categorised into two main groups, namely incremental and transformational adaptation (Park et al., 2012). The former is characterised by continued responses to climatic risks within an existing system whereas the latter is a process that results in changes in the biophysical, social, or economic components of a system (Park et al., 2012). Adaptation can further be distinguished into reactive versus proactive and private (autonomous) versus public (planned) (Grothmann & Patt, 2005). The reactive-proactive classification refers to the timing of adaptation, i.e. whether the adaption measure is motivated by predictions of an event occurring at an undetermined time in the future, or by the onset of the event itself. The private-public classification refers to the actors, and therefore to the question of who adapts (Grothmann & Patt, 2005). In recent years, a seafood supply crisis has been predicted as a looming threat, but with technological adaptations and improved management of commons like the ocean, fish supply may be allowed to remain sufficient (Asche & Smith, 2018).

A number of studies investigate climate change adaptation in fisheries and aquaculture. Most studies use descriptive analysis to characterise the adaptation behaviour of households and communities (Coulthard, 2008; Grafton, 2010; Islam et

al., 2018; Islam et al., 2014; Shaffril et al., 2017a). These studies highlight important constraints to and opportunities for adaptation related to socioeconomic characteristics of households, human, social, physical, and financial capital as well as infrastructure and access to markets. One such example of household-level adaptation is the diversification of fisherman livelihoods to combat possible long-term declines in productivity due to climate change as well as short term productivity shocks. Introducing non-fishing income streams in local fishers' households can increase resilience to climate-related production shocks (Badjeck et al., 2010; Shaffril et al., 2017b). Other studies emphasize the need for community-based adaptation (CBA) (Ahmed et al., 2013; Ensor et al., 2016; Hagedoorn et al., 2019). CBA is a community-led process based on the priorities, needs, knowledge, and capacity of the community (Reid et al., 2009). It is a participatory approach to adaptation requiring practitioners and communities to explore climate change impacts and appropriate responses together (Ensor et al., 2016). Ahmed et al. (2013) discuss several CBA strategies in coastal Bangladesh, including integrated agroecosystems that combine aquaculture with agriculture, and introducing salt-tolerant species of rice to combat salt-water intrusion due to sea-level rise. Many studies attempt to explore approaches to elicit local knowledge and understanding of the complex relationship between climate change hazards and livelihoods (Pringle & Conway, 2012). Other studies propose methods to identify barriers to adaptation that arise from poor communication between those who create and those who use climate information (Ensor et al., 2016; Spires et al., 2014).

Another body of literature analyses the economic consequences and possible determinants of adaptation (Dey, Rosegrant, et al., 2016; Mabe & Asase, 2020; Oparinde, 2021; Rosegrant et al., 2016). Dey and Gosh et al. (2016) assess the

potential economic impact of climate change adaptation through natural resource management (NRM), fish aggregating devices (FAD), and aquaculture in the Solomon Islands and find that without appropriate climate adaptation strategies, per capita consumption of domestically produced fish will decline. In their model, FADs are the most effective at both decreasing prices and increasing oceanic fish supply, while aquaculture is found to decrease prices of coastal invertebrates. Adaptations in the aquaculture sector increase domestic fish consumption, while the other methods (FAD and NRM) replace fish imports with domestic supply (Dey, Gosh, et al., 2016). Using economic modelling and focusing on similar strategies, Rosegrant *et al.* (2016) show that aquaculture development, NRM, and FADs can enable Vanuatu and Timor-Leste to improve coastal and freshwater fish production in the medium-term and long-term (2035-2050). In addition to increasing fish production, implementing NRM and FADs is predicted to decrease fish prices and have positive impacts on poorer communities. Oparinde (2021) uses a multinomial regression model to analyse the impacts of three aquaculture adaptation strategies in Nigeria: 1) bore-hole construction, 2) stocking time adjustment, and 3) embankment creation. The model suggests that these adaptations increase food security and reduce the poverty gap, significantly increasing the fishers' welfare in the community.

Quantitative assessment of adaptive capacity in fisheries and aquaculture is inadequate. Notable exceptions include (Béné et al., 2016; Dey, Gosh, et al., 2016; Dueri et al., 2016; Rosegrant et al., 2016). Béné *et al.* (2016) construct a subjective resilience index and assessed its correlation with household factors in Fiji, Ghana, Sri Lanka and Vietnam. The authors find a positive correlation between wealth and the resilience index. They further argue that assets are not in themselves sufficient to ensure resilience and that successful adaptation largely depends on the capacity of

individuals and communities to coordinate decision-making, act collectively, foster innovation and experimentation, and exploit new opportunities. However, endogeneity bias and subjectivity remain possible. Developing a theory-based economic approach to estimating resilience could improve the accuracy of such indices (see, for example, Barrett and Conostas, 2014); Upton et al., 2016). Furthermore, determinants of resilience may differ at different levels beyond the household (e.g., Coulthard, 2008; Shikuku and Winowiecki et al., 2017).

3.3 Climate-Smart Aquaculture and Fisheries

The relationship between fisheries and aquaculture and climate change is not unidirectional. These food systems contribute to global anthropogenic GHG emissions and are simultaneously vulnerable to climatic shocks and stresses. The approach of climate-smart agriculture (CSA) recognizes the imperative need to not only increase food security and enhance resilience to climate change but to also contribute mitigation co-benefits where possible (FAO, 2013). The CSA approach involves three main objectives: 1) the sustainable intensification of production, 2) reducing vulnerability and increasing resilience, and 3) reducing or removing GHG emissions (FAO, 2013). However, not all CSA systems must achieve all three objectives (FAO, 2013; Lipper et al., 2014). The relative importance of each objective may vary across locations—synergies exist between the three pillars of CSA, but trade-offs are possible depending on the specific context. For example, in developing countries where food security and poverty reduction are of high priority, CSA interventions can stabilise and sustainably increase productivity, improve income, and build adaptive capacity. In contrast, CSA approaches in developed countries may emphasize climate change mitigation through increasing production efficiency and reducing or removing GHG emissions from agriculture (Lipper *et al.*, 2014; Steenwerth et al., 2014).

In aquaculture, various strategies have been suggested in order to meet the three objectives outlined by the CSA approach (FAO, 2013). In relation to sustainable productivity improvement, strategies include using integrated systems, improving stocks, making feeding more efficient, and reducing losses from disease. To reduce vulnerability and increase resilience in the aquaculture sector, improvements in farm site selection and design, insurance, utilization of indigenous or non-reproducing stocks to minimize biodiversity impacts, increasing the efficiency of water use and water-sharing (FAO, 2013), selection for short-cycle production, and improvements in seed quality and efficiency are recommended. Integrated multi-trophic aquaculture and better pond management are being undertaken to accomplish the third objective of emission reduction and/or removal. Technological progress and improvements in production practices can reduce energy consumption and contribute to carbon sequestration (FAO, 2013). To date, however, empirical studies that evaluate the adoption and impacts of these practices and technologies are missing. One of the only studies assessing the CSA approach in aquaculture is provided by Tran et al. (2020), who find that CSA practice are not only profitable but also enhance perceived adaptive and resilient capacity of coastal farming households in Vietnam.

In regards to fisheries, new strategies are needed to achieve the CSA objectives. Some guidelines and practices are recommended though literature is scarce. Increasing yields through increased productivity in the capture fishery sector is not a viable option due to the global overexploitation of many commercial fish stocks leading to a recent stagnation in productivity (Asche & Smith, 2018; FAO, 2016). However, other approaches to increase absolute yields of viable fish products including reducing excess capacity, improving fishery management to ensure long-term stock viability, reducing fuel cost and usage, improving fish handling during and

post-harvest to reduce waste, and limiting or better-utilizing bycatch can be implemented (FAO 2013). Costello and Deacon (2007) demonstrate that efficiency gains are possible through the precise, spatial delineation of rights to fishers. Such gains are realized through enhanced rent capture and more efficient search behaviour. To accomplish the second CSA objective of reducing the vulnerability and increasing the resilience of capture fisheries, possible approaches include shifting/widening target species, diversifying livelihoods, insurance, migrating fishing efforts, and weather warning systems to combat increased bad weather events (FAO, 2013). The role of capture fisheries in CSA's objective of mitigating climate change mostly centres around the reduction of GHG emissions rather than removal. Advanced technology, and better management of fishery stocks and fishing rights to limit the distance travelled to access such stocks can be an option to reduce fuel usage (FAO, 2013). For instance, Suuronen et al. (2012) reports that tests of modifications to trawl fishing gear in several South American countries resulted in fuel savings of up to 43%.

4. Applicable Economic Methods to Assess Climate Change Impacts and Adaptation Measures

4.1. Cost-benefit analysis

Cost and benefit analysis (CBA) is a popular approach in evaluating the suitability of adaptation options (e.g., Lan et al., 2018; Sain et al., 2017). The CBA methodology involves calculating in monetary terms all costs and benefits of an adaptation option. The cost of adaptation involves expenditure on planning, preparing for, facilitating, and implementing adaptation measures, including transition costs. The benefits of adaptation include the avoided damage costs or the accrued benefits following the adoption and implementation of adaptation measures (UNFCCC, 2011). Mathematically, if V and F are the sum of expected discounted streams of benefits

(B_t) and costs (C_t), respectively where t indicates time and r is the discount rate¹, that is

$$V = \sum_{t=0}^T \frac{B_t}{(1+r)^t}, \text{ and } F = \sum_{t=0}^T \frac{C_t}{(1+r)^t}$$

then an adaptation option would present a good investment if the net present value (NPV)² exceeded the discounted aggregate costs ($NPV = V - F > 0$) or the benefit-cost ratio (BCR) is greater than the unity ($BCR = V/F > 1$), or the internal rate of return (IRR)³ is greater than the interest rate. The choice of discount rate (r) will affect the optimality of a given climate policy (UNFCCC, 2011).

At the global level, CBA studies are broadly classified into two strands: (1) investment and financial flow (IFF) analyses, and (2) economic integrated assessment models (IAM). The IAMs consist of an explicit economic framework, and they have been used to assess the global costs and benefits of adaptation over long time-scales (Füssel, 2010; Nordhaus, 2007). These studies are useful in providing initial information on adaptation, especially in the absence of detailed disaggregated analysis. However, the consideration of uncertainty is limited at the global level (Stern, 2006). Consequently, most global studies only provide partial coverage of the issues raised in terms of economic valuation and efficiency (Ackerman et al., 2009).

Empirical analysis at the national level includes, for example, an evaluation of the costs and benefits of adaptation and low carbon growth for South-East Asia (ADB, 2009) and estimates of adaptation costs in the Netherlands to link assessments of adaptation options with spatial planning (de Bruin et al., 2009). Most studies focus on

¹ The rate at which future profits/costs are discounted

² The present value of the difference between a series of benefits and costs over a period of time.

³ the discount rate that makes the NPV equal to zero.

the costs of climate change rather than the benefit of adaptation, partly because of difficulties in collecting data for estimating economic benefits.

CBA has been used to analyse agricultural adaptations at both the global level (Füssel, 2010; Nordhaus, 2007) and the national level (ADB, 2009; de Bruin et al., 2009). Furthermore, some authors have been successful in modelling climatic uncertainty with CBA (Stern, 2006). With further advancements and the inclusion of environmental and social costs, CBA can play a large role in fisheries policy decisions of the future.

CBA has seen limited applications amongst the fisheries literature, exclusively applied to aquaculture (Kam et al., 2012; Tran et al., 2020). Kam *et al.* (2012) conduct farm-level CBA of aquaculture production systems in the Mekong Delta of Vietnam under climate change. Tran *et al.* (2020) assess the profitability of integrated shrimp-tilapia-seaweed climate-smart aquaculture (CSA) production in Vietnam. This study shows that adoption of integrated systems can be more profitable—with a positive net present value and an internal rate of return greater than the discount rate, suggesting that the practice is financially feasible. Tran *et al.* (2020) also controls for drivers of adoption by first matching households based on observable covariates and then applying CBA on the matched sample of observations.

While CBA is a useful tool for policy making for adaptation, it may not be applicable when costs and benefits cannot be reflected in monetary terms, such as bio-ecological impacts. Furthermore, CBA largely ignores important aspects that influence factors that can affect welfare and well-being such as poverty alleviation and food security. The latter concern is partly because of the difficulty involved in calculating the imputed values of externalities. A narrow, but rapidly growing literature

in agriculture has attempted to extend CBA beyond private profitability analysis to include social and environmental benefits and costs (Sain et al., 2017).

4.2. Structural simulation models

Simulation and econometric methods are used to estimate the impact of climate change and cost of adaptation (Mendelsohn et al., 1994; Seo & Mendelsohn, 2008). Although much empirical evidence in fisheries is missing, simulation studies investigate the response of crops, crop varieties, livestock and livestock breeds to changes in climate-related conditions. Simulation models can estimate the likely effects of climate change on yields (Adams et al., 1998; Shikuku and Valdivia, et al., 2017) and use the simulated yield changes to assess economic impacts. Simulation models can also evaluate farm or household-level practices for climate change adaptation and mitigation.

An example of these models which may be useful in the aquaculture sector is the Trade-off Analysis Model for Multidimensional Impact Assessment (TOA-MD) (Antle et al., 2014; Antle & Valdivia, 2006). This model represents a whole farm production system which can be composed of an aquaculture sub-system with multiple fish species, a crop sub-system containing multiple crops, a livestock sub-system with multiple livestock species, and the farm household characteristics (e.g. household size and off-farm income). Furthermore, the TOA-MD is a model of a population of farms, not a model of an individual or “representative” farm. Accordingly, the fundamental parameters of the model are population statistics — means, variances and correlations of the economic variables in the models and the associated outcome variables of interest. With suitable biophysical and economic data, TOA-MD estimates these statistical parameters for an observable production system. Another unique feature of the TOA-MD model is its parsimonious, generic structure, which means that it can be

used to simulate any farm system. One virtue of this model design is that, unlike many large, complex simulation models, it is easy to address the inherent uncertainty in impact assessments by using a set of minimum data and sensitivity analysis to explore how results change with the relatively small number of model parameters (Antle et al., 2010). This is an advantage of the TOA-MD over many large and complex simulation models.

While used extensively in the agricultural sector, only a few studies have applied TOA-MD analysis in fisheries (Murshed-E-Jahan et al., 2013; Tran et al., 2013). These studies show the important contribution of aquaculture interventions on increasing income and reducing poverty, however climate change was not the focus of these studies, and as such they do not incorporate climate change. Accounting for climatic shocks and adaptation will require improvement in biological forecasting to generate simulated yields under different climate change and adaptation scenarios. Predicting the effect of climate change on aquaculture yields is subject to a high degree of uncertainty, and because of this, further research into the long-term effects of climate change on fish mortality, reproductive rates and yields will be important. Fisheries performance indicators (FPI), which were developed to advance the analysis of individual fishery performance in data-poor countries, may provide a useful framework for the future in developing countries lacking comprehensive data (Anderson et al., 2015).

Capture fisheries require different simulation techniques because their dynamics depend on ecological systems where the future is endogenous to historical production intensity. As such, accurately estimating climate change's economic impact on capture fisheries requires modelling fish stock dynamics in conjunction with economic analysis. Bio-economic modelling integrates both biophysical and economic

components. This class of models are useful for the optimisation of biological resources as inputs in production. While the majority of studies focus on the national (Briones, 2006; Garza-Gil et al., 2010; Lam et al., 2012), some studies encapsulate a multi-national or global scale (e.g. (Gaines et al., 2018; Lehodey et al., 2012). Bio-economic models integrated with socio-economic variables are useful in assessing both economic and biological sensitivity of fishing activities to external stimuli. Nevertheless, while incorporating stock dynamics, bioeconomic models typically omit price adjustment arising from the interaction of demand and supply (Briones, 2006). In response to this drawback, Briones (2006) and Lam *et al.* (2012) apply bioeconomic modelling to examine the impacts of climate change on fish supply and demand. Both studies find declining fish supply with climate change, suggesting serious consequences on food and nutrition security. Combining bioeconomic modelling with supply-demand models may be more appropriate, as in section 4.4.

Some studies combine simulation techniques with production function analysis. In this approach, outputs are determined under a variety of environmental conditions, using carefully calibrated yield models. A basic production function is then estimated, with climate-related variables such as temperature and precipitation, among other explanatory variables, to assess the observed impact of climate change on yield. For example, Ha (2017) use production function analysis to analyse the long-run implications of possible climate change effects including increased surface sea temperature (SST) and precipitation on fishery output in Vietnam, encompassing both capture fisheries and aquaculture. In this study the production function is estimated using an autoregressive distributed lag model (ARDL) to predict the effect of the previous year(s) on fishery yields. However, Mendelsohn *et al.* (1994) indicate that, while providing useful baselines for approximating the impact of climate change on

agriculture, these models reflect an intrinsic bias and likely overvalue damage associated with climate change. For this reason, their estimates do not control for adaptation and will tend to predict severe yield reductions because of global warming. To the best of our knowledge, applications in the aquaculture sector are not present.

4.3 Econometric analysis

Spatial econometric models have been used to assess the impacts of climate change in agriculture, but empirical applications in fisheries are limited. By applying statistical analysis across geographic regions, spatial econometrics provide direct evidence on farmers' responses to climatic conditions (Mendelsohn *et al.*, 1994; Mendelsohn & Dinar, 2003). This approach further considers factors such as land quality independently to isolate the effects of climate change. An example is the Ricardian cross-sectional approach that measures the performance of farm households and firms across spatial scales under different climates. The Ricardian approach survey or country-level data to analyse the relationships between agricultural capacity (e.g. land value) and climate variables (e.g. temperature and precipitation). Instead of focusing on yields of specific crops, this model uses economic data on the value of net rent or farmland to correct biases in the production-function technique.

Despite many studies applying the Ricardian approach to agriculture (Mendelsohn *et al.*, 1994; Nhemachena *et al.*, 2010; Thapa & Joshi, 2010; Zhai & Zhuang, 2009), applications in the fishery sector are scarce. Huong *et al.* (2019) provide a rare example using a cross-sectional modified Ricardian approach to investigate the effect of climate-change related variables on 1055 households in northwest Vietnam's agricultural sector (including fisheries). The authors find that both increased temperature and precipitation negatively affect farmers net revenue. Further

use of this approach to analyse the impact of climate change on the fishery sector as well as the resiliency of specific fish production strategies would provide valuable insight, similar to what has been done in crop and livestock systems. For example, Nhemachena *et al.* (2010) use the Ricardian approach to analyse the effects of climate change on certain production systems and find that mixed crop-livestock systems are the most resilient to the adverse effects of climate change, while specialized crop systems are the most vulnerable. A similar analysis could be conducted on various aquaculture production strategies and capture fishery methods, however data requirements may be restrictive.

Ricardian economic modelling can be considered a top-down approach for calculating changes in farmers' welfare under climate change (Watkiss & Downing, 2008). This method aims to estimate the long run economic impact of climate change on agricultural land value and equates this to costs of autonomous adaptation to climate change (Hertel & Rosch, 2010). The use of Ricardian economics at the fisher level might entail higher levels of complexity and data requirements.

Researchers have used time series econometrics to analyse the impacts of climate change on capture fisheries, though the number of those studies is modest. Gamito *et al.* (2015) use time-series data from 1927-2012 in Portugal to explore the relationship between landings per unit of effort (LPEU) of certain fish species and climate variables (sea surface temperature (SST) and the North Atlantic Oscillation (NAO) index. With an autocorrelation function, the authors find significant correlation between the landings of certain fish species (particularly sardines and mackerel) and environmental variables. However, time series analysis in aquaculture is scant. Future research may adapt some time-series approaches from agricultural analysis to the fisheries sector. For example, Nordhaus (1999) who examines the relationship

between annual GDP growth and global average temperature, determines whether there is evidence of a relationship between economic activity and short-run weather. Joshi *et al.* (2011) use historical data (1978-2008) to assess the effect of observed climate variables on yields of major food-crops in Nepal. Time series analysis is an important tool for analysing long-run relationships between climatic factors and fishery production, subject to data availability.

Some studies combine time-series with cross-sectional data. For example, Speers *et al.* (2016) use a cross-sectional time series data to analyse the impacts of climate-induced ocean acidification on various economic measures. With cross-sectional fishery landings and price data from 1960 to 2006, the authors model demand for coral reef fish. In combination with three separate scenarios of coral reef bleaching derived from Monte Carlo CO₂-COST simulations, the authors find significant consumer welfare losses in all three scenarios. Literature applying time-series analysis to aquaculture is however non-existent. While the agricultural literature using time series is rich (Lee *et al.*, 2012; Li *et al.*, 2011), examples in the aquaculture sector are not present.

Other authors have also used econometric techniques to assess the determinants and impacts of adaptation strategies in fishing communities (Mabe & Asase, 2020; Oparinde, 2021). An example is a study by Oparinde (2021), who uses a multinomial endogenous switching regression model to hypothesize the determinants and effects of fish farmers' choices among aquaculture adaptation strategies in Nigeria. Oparinde (2021) employs a two-step approach, controlling for selection bias and unobserved heterogeneity. They find that gender, education level and non-farm income are among the factors that influence the likelihood of implementing adaptation strategies. In a similar fashion, Mabe & Asase, (2020) use a

Conditional Mixed Process (CMP) framework with an ordered probit regression to estimate the determinants and effects of various climate change adaptation strategies in Ghana. They find that, among other factors, knowledge of climate change, fishing experience and educational achievement positively influence the number of adaptation strategies implemented by the fishers. Further refinement of these techniques may provide additional insights into fishery adaptations and their effectiveness. For instance, Falco and Veronesi (2013) analyse the impact and likelihood of adopting adaptation strategies in combinations rather than in isolation while accounting for selection bias in the Nile Basin of Ethiopia. The authors estimate a selectivity-corrected endogenous switching regression model in a two-step procedure and find that adaptation strategies implemented as a package have greater positive impacts on crop revenue than those implemented in isolation. Further research along this theme in the fisheries sector is recommended to yield useful information for successful implementation of adaptation strategies.

4.4 Supply and demand models

A large body of literature utilizes the economic relationship between supply and demand to predict the effects of climate change (Dey and Rosegrant, et al., 2016; Rosegrant et al., 2016; Suh & Pomeroy, 2020). Market supply–demand models incorporate climate change in terms of supply shocks, and estimate its economic consequences using the microeconomic tools of supply and demand (Dey and Rosegrant, et al., 2016). The advantage of this approach is that it can incorporate price responses and interactions across sectors, including both aquaculture and capture fisheries. Dey and Rosegrant et al. (2016) follow three steps to implement a supply–demand approach in the analysis of potential impacts of various climate change adaptation strategies. First, a baseline model of the fisheries sector is developed.

Second, data is collected for model parameters, exogenous variables, and ex-ante impact indicators of various climate change adaptation strategies. Third, impacts of climate change adaptation strategies are analysed by incorporating the *ex-ante* impact indicators into the fisheries sector model. Using a similar approach, Rosegrant et al. (2016) examine the impacts of climate change and adaptation strategies in Vanuatu and Timor-Leste. Both studies find that climate change will adversely reduce the supply of fish consequently reducing food and nutrition security. Rosegrant *et al.* (2016) show that timely implementation of appropriate adaptation measures can reduce the negative impacts of climate change. However, Briones (2006) argues that supply-demand models often ignore stock dynamics and instead address threats to sustainability due to declining fish stocks by exogenous changes in resource productivity. Briones (2006) further indicates that such approaches are ad-hoc, leaving it unclear whether the assumed shifts are consistent with known patterns of fish population adjustment.

Finally, a few studies combined bioeconomic and supply-demand analysis to examine impacts of climate change on fish production and consumption. For example, Briones (2006) shows a persistent decline in fish supply using a bioeconomic supply-demand model. Lam et al. (2012) also report similar findings in West Africa. However, lack of data on resource and ecosystem interactions may limit usage of this approach.

5. Discussion and Implications for Research Priorities

The economics of climate change is essential to support decision making to address the adverse impacts of climate change and design adaptation strategies. Methodological limitations, however, hinder the ability of researchers in fisheries and aquaculture to empirically evaluate the impacts of climate change on these sectors

and adaptation options. Consequently, it is not well understood (1) how fisheries and aquaculture will respond to climate change and (2) how involved stakeholders (e.g., fishing communities and aquaculture farmers) will behave given climate change threats; this is especially relevant for aquaculture. This review has summarized existing knowledge about biophysical and economic impacts of climate change, vulnerability, and the adaptation strategies on fisheries and aquaculture. We further looked at economic methodologies that have been used and that may prove useful in analysing the effects of climate change and related adaptation strategies applicable to the fisheries and aquaculture sectors.

Our review highlights that the impacts of climate change may play out on a fish physiological level (i.e. changing growth rates and reproduction rates, etc.) have been relatively well investigated and understood. However the literature assessing the effects of climate change on specific fish stocks and yields is more limited, especially in the aquaculture sector. This information is crucial for designing and implementing effective and efficient adaptation strategies to increase food security. International and interdisciplinary cooperation is needed to curate reliable data for the projection of fish stock dynamics to effectively estimate future impacts of climate change on global fisheries.

While several approaches have been applied to understand the vulnerability of households and communities to climate change, empirical literature continues to rely on subjective weighting of the three dimensions of vulnerability, namely exposure, sensitivity, and adaptive capacity. We suggest that insights from other social science disciplines (poverty economics, anthropology, sociology, geography and political science) should be incorporated to improve such assessments. Using weights

generated according to the marginal contribution of the different integral components of vulnerability to a household's wellbeing is both intuitive and less subjective.

We also find that literature on adaptation to climate change in fisheries and aquaculture is largely descriptive, and existing quantitative estimates likely suffer from unobserved heterogeneity bias. Furthermore, determinants of adaptation will likely differ at different levels (see, for example, Coulthard, 2008). A related issue to adaptation analysis is the process of identifying appropriate adaptation options. A two-step procedure involving (1) prioritization of adaptation strategies by local communities and (2) rigorous evaluation of the impacts of adaptation strategies is required. This highlights the importance of a more integrated and multi-disciplinary approach to the assessment of climate change impacts and adaptation. Additionally, increasing adaptive capacity in fisheries and aquaculture can be achieved at different levels: from households to national government agencies and regional economic zones. It is also important to consider adaptation not only at the production level but also throughout the value chain. The adaptive capabilities of fisheries and aquaculture communities to climate change further depend on non-climatic factors such as population growth, political and institutional factors, and deficiencies in monitoring and early-warning systems, or in emergency and risk planning. However, new opportunities and positive impacts are emerging from changes in species and new markets. So far, these opportunities are not well understood.

While several methods have been proposed for economic analysis of the impacts of climate change, they will need to be strengthened for applications in the aquaculture sector. Cost-benefit analysis (CBA) is a popular tool in environmental and climate change economics. Expanding this methodology to address uncertainties and account for externalities would greatly enhance our understanding of economic, social,

and environmental impacts associated with adaptation strategies to climate change. At the same time, CBA should be expanded to control for differences in household characteristics of those engaged in both fisheries and aquaculture, such as age, education, wealth, and farm size. Employing a two-step procedure that combines matching techniques with CBA could be an option. Some other methodologies can also be adapted from studies in agriculture (e.g., Sain *et al.*, 2017).

Simulation models are increasingly useful for fisheries. However, established simulation methods from the agricultural sector such as the TOA-MD model have yet to be applied extensively for aquaculture. Data limitations may be to blame for this, as TOA-MD would require computation of yields with and without climate change. Strengthening the capacity of fish breeders to develop analytical approaches for generating such information is urgently required in aquaculture. Further developing simulation models and other tools to be used for assessing impacts of climate change on aquaculture will greatly increase the effectiveness of future policies and adaptation strategies. On the other hand, bioeconomic modelling and simulation techniques have been established in capture fisheries. Better and more reliable data, and close collaboration between economists and fishery scientists will improve forecasting ability and facilitate positive change in policy development. Furthermore, expanding upon the existing literature on bioeconomic supply-demand analysis may help reduce methodological limitations while strengthening our predictive capacity and accuracy. Applications of discrete choice modelling are absent from fishery literature. As choice modelling has proven useful in describing and predicting farmer's behaviours under climate caused uncertainty (Calatrava & Garrido, 2005; Dono & Mazzapicchio, 2010; Jacque & Pluvinaud, 1997), researchers in the fisheries sector may benefit from this technique. For instance, applying discrete stochastic programming methods could

help explain choices of producers in fisheries and aquaculture sectors to adapt to market price, which is usually adjusted when yields of larger-scale farming activities change following changes in climate and weather conditions.

Our review shows that econometric models have been applied mostly with cross-sectional data, and time series analysis is increasingly important in aquatic food systems. As data sets become available, time series analysis can provide valuable insight into the impacts of climate change on fish farmers and fishing communities, and their responses to climate change. Besides investigating input-output relationships in conventional production forms, relationships between capture fisheries, aquaculture, and climatic conditions may be explored via production functions. From that, researchers can predict trends of fishery/aquaculture sectors once changes in climate conditions are predetermined. Choice models using probit/logit regression have recently become a popular econometric model for assessing the economic effects of adaptation strategies as well as their determinants. However, the agricultural literature may provide some insights into the structural effectiveness of adaptation strategies.

Finally, market supply-demand analysis is one of the foremost economic tools used to build and analyse future projections of total fishery yields and profits (capture and aquaculture) at multiple scales. However, due to the purely economic nature of supply-demand models they may not be able to capture the biological consequences of climate change and other anthropogenic effects on fish stocks such as over-exploitation, leading to the reliance on economic hypotheticals to simulate exogenous effects. Due to this limitation, a combination of supply-demand and bioeconomic modelling is highly recommended. Bioeconomic supply-demand models have the

potential to assess economic impacts of climate change calibrated to the current known and predicted biological status of fish physiology and stock dynamics.

Overall in the economic literature, we find that the aquaculture sector is underrepresented compared to capture fisheries. This lack of economic publications pertaining to aquaculture has also been found by Anderson et al. (2019). They attribute this finding to underfunding, for example, only 0.1% of US federal grants for agricultural food and research were spent on aquaculture economics in 2018. Most funding concerning fisheries is allocated to traditional capture fisheries (Anderson et al., 2019). This paucity of research is concerning given the growing role of aquaculture in fish supply, estimated to surpass fisheries production in the 2020's (FAO, 2018).

6. Conclusions

Fisheries are among the vulnerable economic sectors to climate change. Through a thematic review of economic analysis of climate change impacts and adaptation in fisheries and aquaculture, we have summarized the existing knowledge pertaining to the impact, vulnerability, adaptations and resiliency of the fishery sector to climate change as well as methods and tools used for this purpose. The well-known aspects of climate change including sea-level rise, sea surface temperature changes and increased precipitation have both physiological impacts on fish (i.e. altered growth rates and changing migration patterns, etc.) and economic impacts on the fishery sector (i.e. reduced yields, higher costs, changing species, etc.). The literature identifies links between national development status and vulnerability to climate change, with the most vulnerable countries belonging to less developed regions such as Africa and South America. Research of adaptation strategies in the fisheries and aquaculture sectors has the potential for important contributions to the current

knowledge base and practical decision-making, but there are many unexplored questions. Specific strategies range from the household level (e.g. livelihood diversification) to national or regional strategies (e.g. natural resource management). The economic effects of adaptation both at the household and national levels have been estimated to increase fisher and aquaculture farmer welfare and avoid losses in fish consumption, respectively.

In regards to the economic methods to evaluate climate change impacts and adaptations in the fisheries sector, the body of literature is relatively small. However, methods from the agricultural economics literature may be used or adapted to fill knowledge gaps. Long-run projections of fisheries production and output are provided by bio-econometric models, time-series analysis, cross-sectional time-series analysis and production function models. The effect and determinants of varying adaptation strategies have been estimated using market supply-demand models, and various forms of choice modelling with probability regression. Aquaculture stands to benefit the most from a more rigorous research agenda as most economic analysis of fisheries is centred on capture fisheries. In general, further research and cooperation between disciplines are needed to refine such methodologies as bioeconomic modelling and discrete stochastic programming, especially pertaining to aquaculture. Agricultural literature can inspire a more robust and varied body of work in regards to climate change and fisheries.

The analysis of the impacts, vulnerability and adaptations of fisheries and aquaculture in response to climate change should be treated as a learning and knowledge sharing process. In order to successfully understand the relationships and interactions between the biological and economic components of fisheries and aquaculture in relation to climate change, it is important to design integrated research

programs structured around interdisciplinary scientific hypotheses. Accomplishing this will allow us to provide policymakers with more accurate and reliable information that can be used to design policies of the future. A research strategy aimed at setting up a network of research sites for collecting comparable datasets to identify plausible options and strategies for adapting fisheries and aquaculture to climate change will be helpful.

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Table 1: Key Definitions

<i>Climate Impacts</i>	⇒ Environmental and/or economic effects directly caused by anthropogenic climate change (IPCC, 2014, 2021).
<i>Climate Vulnerability</i>	⇒ The degree to which a system is susceptible to or unable to cope with, adverse effects of climate change, including climate variability and extremes (IPCC, 2001).
<i>Climate Adaptation</i>	⇒ Adjustments in human–environmental systems in response to observed or expected changes in climatic stimuli (Below et al., 2012; IPCC, 2001; Wheeler et al., 2013).

Table 2: Search Topics and Terms Used in Search

Topic	Search terms
Climate change	“climate* change” OR “global warming”
Aquaculture/Fisheries	“aquaculture” OR “fisheries*”
Impact	“impact*” OR “effect”
Adaptation	“adaptation” OR “mitigation” OR “resilience”
Climate-Smart	(“climate-smart” OR “climate smart”) AND “aquaculture”
Agriculture/Fisheries	OR “fisheries” OR “agriculture”
Economics	“economics” OR “economic impact”

Table 3: Distribution of Research Topics

Topic	Capture	Aquaculture	Agriculture	Total
<i>Impact</i>	27	12	9	36
<i>Vulnerability</i>	15	4	2	21
<i>Adaptation</i>	22	18	5	41
<i>Climate Smart</i>	2	5	4	9
<i>Economics</i>	18	12	10	45
Total	62	37	24	121