

Vulnerability to impacts of climate change on marine fisheries and food security



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ABSTRACT

Assessment of fisheries vulnerability to climate change is an important step for enhancing the understanding and decision-making to reduce such vulnerability. This study aimed to provide an analysis of country level vulnerability focusing on food security implications of climatic disturbances on marine fisheries. The comparative magnitude and distribution of potential food security impacts of climatic disturbances on marine fisheries were assessed for 109 countries by scoring and ranking countries against a set of vulnerability criteria including metrics of national exposure, sensitivity and adaptive capacity, highlighting the contribution of marine fisheries to national food and nutrition security. Results showed that developing countries in Africa, Asia, Oceania, and Latin America appeared to be most vulnerable, and the key sources of vulnerability differed considerably among the countries. For countries most vulnerable to climate-induced effects on marine fisheries, more than two-thirds of them depended on domestic marine fisheries as a main source of fish supply. Developing appropriate adaptation policies and management plans to reduce the impacts of changing climate is of great importance to sustain food security in these highly vulnerable and heavy marine fisheries-dependent countries.

1. Introduction

Marine fisheries make vital contributions to food security – both as a direct source of protein, essential fatty acids and micronutrients, and indirectly via employment and income for food purchases [1–3]. Global marine capture fisheries supply the world with approximately 80 million tons of protein and micronutrient rich food for human consumption per year [4,5]. Marine fisheries also provide full-time and part-time jobs to an estimated 260 million people, and a large fraction of these are fishers engaged in small-scale fisheries [6]. In addition, these fisheries support global economies with an estimated annual gross revenue of US\$ 80–85 billion [4]. However, world's marine fisheries are now underperforming economically, mainly because of overfishing, but also because of habitat loss and pollution [7–9]. Added to these threats is the looming challenge of climate change, which complicates the challenges currently facing global marine fisheries and is now considered to pose the greatest long-term threat to marine ecosystems [1,4,10].

There is compelling evidence that climate change caused significant changes in the global oceans such as increase in ocean temperature,

ocean acidification and sea level rise during the twentieth century [4,11], and these trends are expected to continue into the next century under the climate change scenarios considered by the Intergovernmental Panel on Climate Change [11]. Climate change is expected to affect target species through a range of direct and indirect mechanisms. Direct effects include changes in reproduction, distribution and population dynamics of fish stocks [10,12–14]. Indirect effects include changes in productivity and composition of the ecosystems on which fish depend for food and shelter [15–17]. In addition to the above biophysical impacts on fisheries, climate change also affects the economics of fisheries, because both the quantity and quality of marine catches and its distribution within and between nations' exclusive economic zones will be impacted by it [4,18]. Understanding where the impacts of climate change on the fisheries sector have greatest social and economic significance is crucial as fisheries are important for food security, livelihoods and employment [3,19,20]. Growing international and national efforts have documented the implications of climate change for marine fisheries and discuss the need for new directions in fisheries management [1,5,21,22].

Vulnerability assessment is a form of integrated assessment that

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Table 1

Summary of variables and data sources used to calculate exposure, sensitivity and adaptive capacity of countries to food security vulnerabilities associated with impacts of climate change on marine fisheries.

Component	Interpretation	Variable	Data sources
Exposure	Gross indicator of climate change	Sea surface temperature Ocean acidification UV radiation Sea level rise	Ocean Health Index [29]
Sensitivity	Food security dependency (2011–2013)	$\frac{\text{fish protein intake}/\text{total animal protein intake}}{\text{total animal protein intake}/\text{required animal protein intake}}$	FAO [27]
	Employment dependency	People working in marine fisheries (2003) as % of total economic active population (2002–2004)	Teh and Sumaila [6]
	Economic dependency (2008–2010)	Value of marine fish landings as % of GDP	Pauly and Zeller [31] and FAOSTAT [32]
Adaptive capacity	Assets (2011–2013)	GDP per capita	FAOSTAT [32]
	Flexibility (2013–2015)	Life expectancy at birth	World Bank [30]
	Social organization (2012–2014)	Worldwide Governance Indicators	World Bank [30]
	Learning (2012–2014)	Human Development Index	UNDP [35]

assimilates social, ecological, and economic information and can be applied to marine fisheries globally, or more specifically to an individual fishery region [19,23–25]. Assessing fisheries vulnerability to climate change can identify countries that highly exposed to hazards related to climate change, countries that highly dependent on fisheries for food security, employment and economic value, and countries that limited resources and societal capacity constrain adaptation, thus enhancing the need for decision-making to reduce such vulnerability and secure the future sustainability of marine fisheries [19]. Vulnerability assessments are at the heart of efforts to prioritize and execute adaptation investments from scarce global funding in ways that address those who most need it, and they have been receiving increasing attention from policy-makers and academics [3,5].

Since Allison et al. [19] first conducted global vulnerability assessments for fisheries sectors, numerous authors have conducted fisheries vulnerability assessments at the various scales [21,23,24,26]. Assessing vulnerability at the country level can be used to identify particularly vulnerable groups of countries, thus help guide national-level policy responses and adaptive management strategies. In addition, Allison et al. [19] suggested that future macro-level analysis should separate marine and inland fisheries to use the most relevant climate drivers in that system. Globally, 57% of the total production of fish, crustaceans, and mollusks came from capture fisheries, and the remaining 43% came from aquaculture in 2013 [27]. What is more, 87% of the total global capture production was from marine waters, and the remaining 13% was from inland waters [27]. The share of marine fisheries in total production varies significantly among global countries, so different countries may suffer from varying degrees of food security disturbances in the face of the same vulnerability score associate with impacts of climate changes on marine fisheries. To our knowledge, the study of Allison et al. [19], the study of Monnereau et al. [28], and the study of Barange et al. [17] are the only three published studies to undertake vulnerability assessments at the national-global level. However, none of those previous studies clearly clarified the importance of marine fishery for fishery industry and food security in each country, and these studies also failed to address sector-specific policy needs which is also a frequent deficiency in the vulnerability literature.

Using a vulnerability assessment framework, this paper examines the level of vulnerability of marine fisheries to climate change in the context of food security in 109 countries, which yielded approximately 92% of global marine catches in 2013. It begins with evaluation of the importance of marine fisheries for total fish production in the 109 countries. Contrary to the previous study of Allison et al. [19], in which only projected mean surface air temperature was used as the exposure indicator, this paper further evaluates the vulnerability of marine fisheries to climate change using four environmental indicators, which

are expected to have more direct and profound impacts on fisheries sectors: (i) sea surface temperature anomalies; (ii) UV radiation; (iii) ocean acidification, and (iv) sea level rise. The aim of this study is to identify areas in greatest need for intervention and understand the drivers of vulnerability to identify future research directions. This paper highlights opportunities and constraints to supply-side mitigation strategies for the key areas of vulnerability considering that food and nutrition security is a key global policy concern currently.

2. Materials and methods

This paper scales national vulnerability to potential impact of climate change on marine fisheries to understand the causes of vulnerability, and highlight the role of marine fisheries in fishery industry and food security in the global countries. It began with an evaluation of the contribution of marine fisheries to domestic food and nutrition security in each country. To do this our study first examined the size and direction of the trade balance for each country and compared this with total fishery production, thus understanding the role of domestic fish production and fishery trade as a direct food provider for each country. All of these fishery production and trade databases were obtained from the Food and Agriculture Organization of the United Nations (FAO) [27], averaged over 2011–2013. It then assessed the contribution of marine fisheries to total fish production in the countries where domestic production was greater than 50% of total fish supply for human consumption. Our study used the proportion of fish production supplied by marine fisheries at country level according to the fishery statistics collected by FAO [27], also averaged over 2011–2013. This paper subsequently assessed the comparative magnitude and distribution of potential food security impacts of climate change for global countries by classifying the vulnerability of 109 countries in terms of three components: a country's exposure to environmental change and disturbances, its sensitivity to this change, and its adaptive capacity, or potential to offset the impact of climate change (Table 1).

2.1. Exposure

Exposure was defined as the degree of climate stress upon a country's marine fisheries. In this study, we used sea surface temperature anomalies, ocean acidification, sea level rise, and UV radiation as the exposure component indicators, which were expected to have a more direct link with fisheries sector vulnerability by triggering a series of biophysical and socio-economic impacts on national fisheries. All these exposure indicators were obtained from the Ocean Health Index in 2015 [29]. Sea surface temperature anomalies was measured as the

number of positive temperature anomalies that exceed the natural range of variation for a given area. Ocean acidification was measured as the difference in global distribution changes in the aragonite saturation state between pre-industrial and modern times. Sea level rise was measured as the positive sea level rise value over the study period (October 1992 through December 2012). UV radiation was measured as the number of times in each 1-degree cell that the monthly average exceeded the climatological mean +1 standard deviation, and these values were summed across the 12 months to provide a single value. A higher value indicates a country whose marine fisheries are subject to greater exposure to climate changes.

2.2. Sensitivity

Sensitivity was defined as the degree of a country's societies dependent on marine fisheries. Fisheries contribute to economies and societies by creating employment, adding economic value and contributing to food security [17]. Thus, sensitivity was calculated using three indices: employment dependency, economic dependency, and food security dependency. This study assumed that high contribution to employment, value of fish landings, and animal protein supply implied a high dependence of the economies and societies on the fisheries sectors and hence a high sensitivity to climate changes in the fisheries sector.

Employment dependency was represented using people working in marine fisheries as a percentage of total economic active population. Fisheries employment data were derived by taking the average value of FAO country profile data and the data which compensate for the underestimation of small-scale fishery (baseline 2003) estimated by Teh and Sumaila [6]. Total economically active population was obtained from the World Bank [30], averaged over 2002–2004. Economic dependency was calculated based on the value of marine fish landings as a percentage of GDP. Values of marine fish landings were provided by the Sea Around Us project [31], GDP values were derived from the FAO [32], and both indicators were averaged over 2008–2010. Food security dependency was calculated following the methodology used by Barange et al. [17] as follows:

$$\text{Food security dependency} = \frac{\text{fish protein intake/total animal protein intake}}{\text{total animal protein intake/required animal protein intake}} \quad (1)$$

Fish protein and total animal protein consumption data between 2009 and 2011 were obtained from FAO food balance sheets. This study used a minimum requirement of 36 g animal protein per capita day for an average adult [33]. For each indicator, an average value in the most recent three years was used to counter inter-annual variability.

2.3. Adaptive capacity

Adaptive capacity was defined as a country's potential ability to respond to and recover from the climate change. Countries with high adaptive capacity are less likely to suffer from environmental disturbances and are therefore better able to take advantage of the opportunities to increase their social-economic benefits. The adaptive capacity index was constructed from the following four categories: assets, flexibility, learning, and social organization [34]. Here adaptive capacity was calculated using four key indicators in the above four categories: GDP per capita, life expectancy at birth, Worldwide Governance Indicators (WGI), and Human Development Index (HDI). As an indicator of a country's financial assets, this study used average GDP per capita from 2011 to 2013 as reported by FAO [32]. The variable 'life expectancy at birth' was used as an indirect measure of flexibility, and the data were available from the World Bank [30]. Human Development Index was used as an indirect but critical measure of learning [35]. Worldwide Governance Indicators, developed by the

World Bank [30], was used as a metric for social organization. These variables were chosen on the assumption that countries with high levels of economic and human development have the resources and institutions necessary to undertake planned adaptation.

2.4. Calculating vulnerability

Full datasets were available for 109 countries. Variables were standardized based on maximum values in our dataset and placed on a scale of 0–1 using the following conversion: $(X - X_{\min}) / (X_{\max} - X_{\min})$. The exposure (E), sensitivity (S) and adaptive capacity (AC) indices were calculated as the unweighted mean of the standardized variables, with larger values representing higher levels for a given index. Vulnerability was calculated following the Intergovernmental Panel on Climate Change [36]:

$$\text{Vulnerability} = (\text{Exposure} + \text{Sensitivity}) - \text{Adaptive Capacity} \quad (2)$$

The three components were treated equally and each normalized to 0–1 scale. Final vulnerability scores were highest for the most vulnerable countries and lowest for the least vulnerable countries. For presentation, final indicator scores were categorized into 'high', 'moderate', 'low' and 'very low' vulnerability quartiles. On this basis, this paper identifies those countries that may be disproportionately vulnerable to food security impacts associated with climate changes.

3. Results

To evaluate the contribution of marine fisheries to domestic food and nutrition security in the 109 countries, this study first considered the relationship between domestic fisheries production and trade balance. We divided these countries into two groups: net fish importers and net fish exporters (Fig. 1A). For 64 net fish importers, two types were apparent: those for whom net imports exceeded domestic supply and those for whom it did not. Twenty-nine countries were in the first category for which changes in trade flows might have a more significant impact on food security. For the other 35 countries in the second

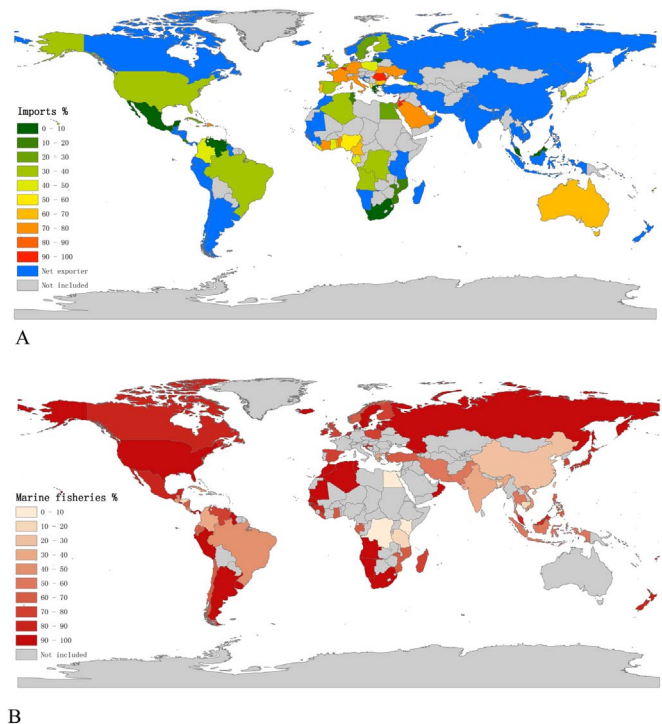


Fig. 1. Graph of trade balance against total domestic fish production in the global countries (A); graph of marine fisheries production as a proportion of total domestic fish production (B).

category, domestic fisheries production remained the dominant suppliers for the fish protein in the diet. In addition, for the 45 net fish exporters, domestic production was clearly of great importance to food security of the local populations.

The role of marine fisheries was evaluated for the above 80 countries where domestic production was the major source of fish supply. Results showed that marine fisheries played a significant role in fish supply for the majority of countries that most depend on domestic fish to meet the nutritional requirements of their populations (Fig. 1B). Specifically, for the 64 out of 80 countries in our study, marine fisheries contributed more than 50% of total production. The remaining 16 countries were mainly dependent on inland fisheries and/or aquaculture for protein, of which Europe, North America, South America, Africa, Asia and Oceania accounted for 1 (Greece), 4 (Costa Rica, Cuba, Guatemala, Honduras), 2 (Brazil, Colombia), 4 (Democratic Republic of Congo, Egypt, Kenya, Tanzania), 5 (Bangladesh, Cambodia, China, India, Vietnam), and 0 countries, respectively (Fig. 1B).

In order to provide a broad overview of current vulnerability patterns under climate change, this study undertook a nation-scale assessment of food security vulnerability using an indicator-based approach. Results suggested that vulnerability to marine fisheries-related food security as a result of climate change closely paralleled the national development status (Fig. 2B). Developing countries in Africa, Asia, Oceania, and Latin America appeared to be most vulnerable, whereas the most developed countries were generally least vulnerable (Fig. 2A). Vulnerability was most strongly correlated with adaptive capacity ($R^2=0.64$), followed by sensitivity ($R^2=0.57$). The relationship between exposure and vulnerability was relatively weak ($R^2=0.42$) (Table 2). Twenty-three out of 27 countries identified as most vulnerable were also classified as the most sensitive countries. The strongest predictors of the vulnerability of national food security to climate impacts on marine fisheries were the Human Development Index ($R^2=0.64$), followed by Worldwide Governance Indicators ($R^2=0.50$) and Life expectancy at birth ($R^2=0.49$) (Table 2). In other words, countries which are most developed, have strong governance, and have long and healthy life are least likely to suffer increased food security risks as a result of climate change.

Table 2

Coefficients of determinant for individual indicators in predicting overall country vulnerability to food security risks associated with impacts of climate change on marine fisheries.

Indicator	R^2 value
Exposure	0.42
Sea surface temperature	0.07
Ocean acidification	0.26
UV radiation	0.09
Sea level rise	0.19
Sensitivity	0.57
Food security dependency	0.31
Employment dependency	0.30
Economic dependency	0.26
Adaptive capacity	0.64
GDP per capita	0.46
Life expectancy at birth	0.49
Worldwide Governance Indicators	0.50
Human Development Index	0.64

The component scores for each country indicated that there was no single driver of vulnerability that makes a country most at risk to hazards related to climate change. Instead, countries experienced vulnerability as the result of a unique combination of exposure, sensitivity and adaptive capacity. In this way we identified countries whose particular combination of factors warranted greater attention. None of the European countries was identified as the most vulnerable countries due to the relatively low level of exposure to climate change, low sensitivity and high adaptive capacity (Fig. 2). High sensitivity in Iceland was mainly attributed to the high contribution of marine fish landings to the national GDP. The moderate level of exposure in Bulgaria, Greece, Iceland, and Romania was counterbalanced by the relatively low fisheries dependence and high adaptive capacity, and these countries ranked as low to very low vulnerability (Fig. 2).

In general, countries in North America had relatively low marine fishery dependence, and none of the countries had high sensitivity (Fig. 2). Barbados, Dominican Republic, and Trinidad and Tobago had high exposure level that was nonetheless offset to some extent by its

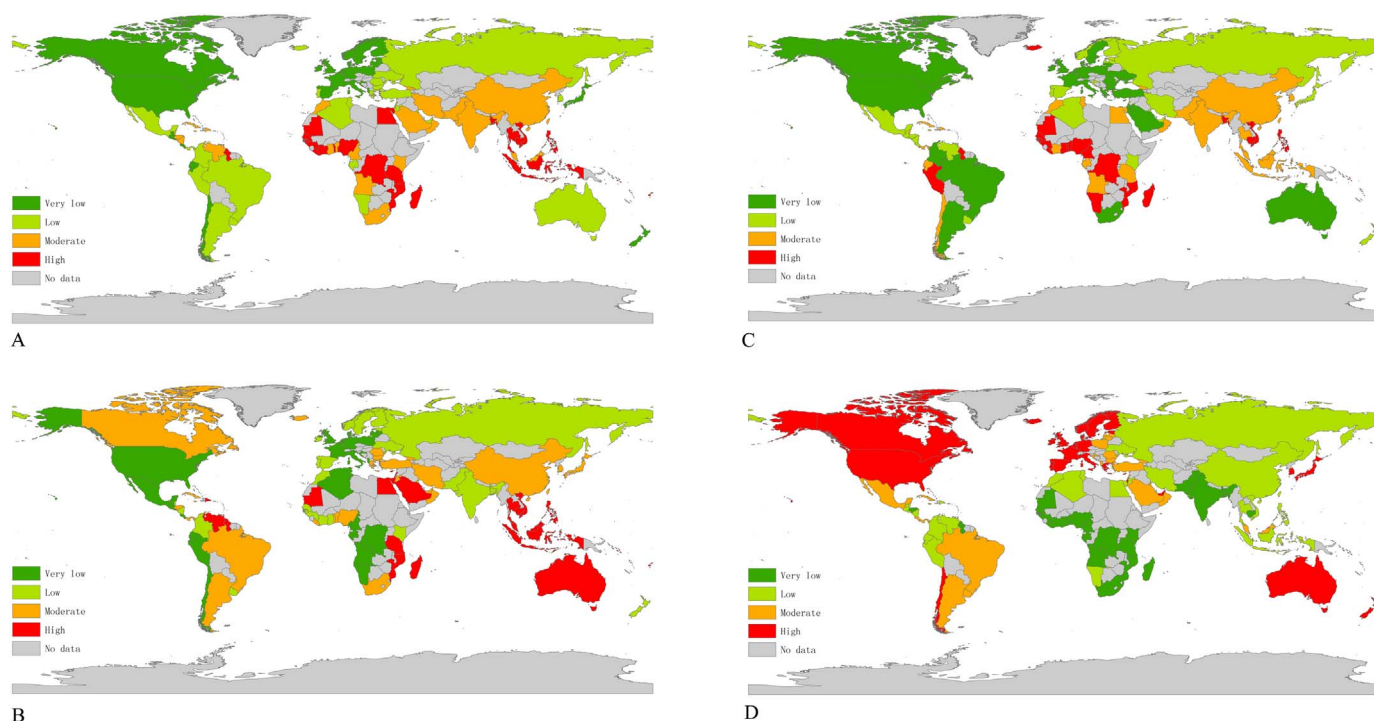


Fig. 2. Overall vulnerability (A), exposure (B), sensitivity (C), and adaptive capacity (D) of 109 countries to fisheries-related food security risks associated with climate changes, reported in quartiles.

moderate adaptive capacity associated with the relatively high life expectancy at birth, governance ability and/or development level. The very low adaption capacity together with moderate exposure resulted in Honduras had moderate level of vulnerability. There were other 7 countries also seemingly to be moderately vulnerable (Fig. 2). However, the drivers of their high levels of vulnerability were different. Cuba, Jamaica, Saint Vincent and the Grenadines had relatively high-level of exposure and were heavily dependent on fisheries for employment, while vulnerability in Belize, Honduras, and Nicaragua mainly resulted from the low level of GDP per capita under relatively high exposure.

Guyana was identified as the most vulnerable country in South America due to a combination of high exposure to climate-induced changes, high sensitivity that was largely the result of high employment dependency, and very low adaptive capacity (Fig. 2). Although Venezuela also had the highest exposure level, the low level of sensitivity together with the moderate adaptive capacity made it moderately vulnerable to climate change. The high percentage of fisheries landing value (about 11%) in national GDP resulted in Peru being listed as the highest sensitivity country.

In general, African countries were particularly vulnerable. More than half of the most vulnerable countries (15 out of 27) were from Africa. Mauritania and Mozambique had the highest overall national-level vulnerability of the 109 countries (Fig. 2). The high vulnerability of African countries were mainly due to its high exposure to the climate changes coupled with high fisheries dependence and limited societal capacity to adapt to the potential impacts. African countries were heavily dependent on fisheries as a source of employment, economy and food security. For example, marine fisheries contributed to about 59% of total employment in Guinea Bissau. Economic value of marine fisheries landings in Mauritania accounted for 23% of its national GDP. Average daily animal protein intake in Democratic Republic of Congo was only 4.3 g, and 38% of the animal protein was derived from fish. In addition, countries with the lowest adaptive capacity were concentrated almost exclusively in Africa (20 out of 27) (Fig. 2D).

A number of Asian countries, including Bangladesh, Cambodia, Maldives, Philippines, Vietnam, Thailand, and Indonesia had high vulnerability (Fig. 2). Among them, the first five countries were also heavily dependent on marine fisheries for employment, economy and protein source. Ten out of 25 Asian countries had the highest exposure level (Fig. 2B), but the high exposure in Cyprus and Israel was offset to a certain degree by the low fishery dependence and high levels of adaptive capacity.

Virtually all Oceanian countries except New Zealand were highly exposed to the climate changes (Fig. 2B). The high exposure in Australia was counterbalanced by the very low sensitivity to changing climate conditions, coupled with high adaptive capacity. However, under the context of high exposure to climate change, Fiji, Samoa, Solomon Islands, and Vanuatu heavily relied on marine fisheries for protein and livelihoods, but their adaptive capacity were limited by the weak economic and social indices (Fig. 2).

4. Discussion

Understanding where the impacts of climate change on marine fisheries have the greatest social significance and what makes these countries vulnerable to aspects of climate change provides a useful starting point for directing future research and developing capacity for climate change adaptation and mitigation initiatives [1,3,5]. This paper developed a vulnerability assessment framework focused on food security implications of climatic disturbances on marine fisheries, and further examined trade balance and the contribution of marine fisheries to total domestic production in the global countries. Our analysis suggested that country-level vulnerability to fisheries-related food security risks as a result of climate-induced changes closely paralleled the national development status, with developing countries in Africa, Asia, Oceania, and Latin America appearing to be most vulnerable. For

countries with food security most vulnerable to climate-induced effects on marine fisheries, African countries (Cape Verde, Gambia, Guinea, Guinea Bissau, Guyana, Mauritania, Senegal), Asian countries (Maldives) and Oceanian countries (Fiji, Samoa, Solomon Islands, Vanuatu) were heavily dependent on marine fishery to meet the nutritional requirements of their population. For these countries, the domestic fish production was the dominant source of fish protein supply and marine fisheries contributed more than 85% of total production.

The role of climate change in fisheries sustainability has received considerable attention recently [37,38]. The study by Allison et al. [19] in particular, with more than 600 citations at the time of this study, has been influential in both the international policy-making stage and in the redistribution of international funding available to countries for adaptation to climate change. However, Allison et al. [19] failed to emphasize the role of fisheries as a source of food and economic development in different countries. They found that countries most vulnerable to the climate-induced changes in fisheries were in Asia, Africa, and northwestern South America, with Bangladesh and Vietnam included in the most vulnerable quartile. However, countries such as Bangladesh and Vietnam have sizable aquaculture production (49% and 53% of total fish production respectively). These countries may not be severely affected by climate-related changes in fisheries as other vulnerable countries which are mainly dependent on capture fisheries for food and nutrition source. Additionally, at the global scale, and considering both marine and inland fisheries, Allison et al. [19] used changes in atmospheric surface temperature over countries' landmasses as the underlying indicator of exposure to climate change. However, it would be more appropriate to partition marine and inland fisheries due to the differences of most relevant climate drivers in these systems. Atmospheric surface temperature may be the appropriate exposure indicators for inland fisheries, but sea surface temperature seems to be more appropriate for marine fisheries.

Countries most vulnerable to climate-induced changes in marine fisheries had relatively high levels of sensitivity and low to very low levels of adaptive capacity in this study. We can broadly divide these most vulnerable countries into three categories based on the major source of fish supply: those for whom dominant source of fish consumption come from imported fish and fishery products, those for whom aquaculture and/or inland fishery to be the dominant source of fish consumption, and those for whom marine fishery makes a major contribution to national fish consumption. Three countries were in the first category, all from Africa: Cote d'Ivoire, Nigeria, and Togo. Changes in trade flows have more significant impacts on the food and nutrition security in these regions. Six countries were in the second category, of which inland fisheries constitutes the greatest proportion of total fish production in Cambodia, Democratic Republic of Congo and Tanzania (72%, 97% and 82% in 2013, respectively). Additionally, aquaculture makes the largest proportion of total fish supply in Bangladesh, Egypt, and Vietnam (55%, 75% and 53% in 2013, respectively). For these regions, climate exposure indices relevant to inland fisheries or aquaculture are likely to have a major impact on the national food security. Eighteen countries were in the third category, reducing the vulnerability of marine fisheries-related food security risks as result of climate changes in these regions are clearly of greatest importance to local population.

The types of overall vulnerability measures provide useful information about the relative state of susceptibility to harm from specific impacts, but each studied country has a unique suite of factors underlying its vulnerability scores, particularly for those countries at the higher end of the vulnerability spectrum. These distinctions in the underlying sources of vulnerability are important because specific policy actions may be required to address different dimensions of vulnerability [1,21,23]. For example, Hughes et al. [21] conducted a national-level vulnerability analysis specific to the food security for coral reef fisheries, and found that there were generally two common national vulnerability characterizations: low-income countries with low

adaptive capacity and middle-income countries with higher adaptive capacity but high sensitivity. The authors, therefore, suggested using the results to develop context specific actions to build adaptive capacity in the low-income countries and to reduce sensitivity in the middle-income countries. In this study, countries classified as particularly vulnerable were due to a combination of high levels of sensitivity to climate-induced changes and low levels of adaptive capacity. In such cases, policy interventions should focus first on reducing sensitivity and second on increasing adaptive capacity [21]. This paper describes key policy actions that can help reduce the vulnerability to the impacts of climate changes.

High employment dependency in marine fisheries made the largest contribution to the high sensitivity in Cape Verde, Fiji, Guinea Bissau, Guyana, Indonesia, Maldives, Philippines, Samoa, and Vanuatu. Alternative or supplemental livelihood activities can reduce employment dependency by linking fishing households to new occupational sectors [1,23]. In addition, flexible livelihood strategies that combine a range of food production systems based on resource availability and condition, such as combining fishing, aquaculture, and agriculture or changing the seasonal patterns of fishing activities, can make them more resilient to environmental change [39]. High economic dependency had the greatest effect on the sensitivity in Gambia, Guinea, Mauritania, and Senegal. Policy on reduced economic dependency often includes diversifying highly specialized fisheries to multispecies fisheries [40]. This may be achieved through actions that encourage landing bycatch and discards in commercial fisheries to provide an alternative fish source for local communities, or substituting target species to take advantage of fish species that benefit from climate change in the short term [1]. Food security dependency played the largest role in the high sensitivity level in Liberia, Madagascar, Mozambique, Solomon Islands, and Thailand. With the decreasing dependence of aquaculture on wild-caught fishmeal, aquaculture expansion could make a significant contribution to food security as the regions adapt to climate change. Aquaculture is likely to be most useful in regions with medium to high human capital and adaptive capacity, high domestic demand or good trade links, and a poorer state of the wild capture fisheries or dependence on imports [41].

Adaptive capacity is critical to reduce food insecurity, countries with high adaptive capacity are less likely to suffer from environmental disturbances and therefore better able to take advantage of the opportunities to increase national food security [3,42]. Vulnerability was most strongly predicted by country-specific Human Development Index and Worldwide Governance Indicators, as well as life expectancy at birth. Policy and development efforts to promote food security may benefit most from a primary focus on developing the above three aspects. Actions may include investments in education and literacy, improving governance, poverty reduction and enhance capacities and health status of fishing communities.

Our study provides the most comprehensive analysis of the relative vulnerabilities of national food security to potential climate change impacts on marine fisheries at a global-scale. However, there are several caveats about our approach and methodology that are important to acknowledge. The major limitation of this study, and likely of other efforts to produce country-scale, policy-specific vulnerability metrics, is the lack of detailed social and economic statistics on fisheries sector. The data deficiency is particularly prominent for the Least Developed Countries and Small Island Developing States, which are particularly dependent on marine fisheries for food, and many of these countries are likely to be included in the top quartile of 'highly' vulnerable countries.

For countries that are data limited and require urgent preparation for climate change, semi-quantitative approach that uses representative, expert-based, and locally relevant information is suggested for the assessment of vulnerability, thus helping inform mitigation and adaptation responses [1]. In addition, due to the clear movement of fishing effort from industrialized countries to the developing world, the fishing

sector and its food contribution may be affected by climate changes in other countries [43]. Assessing in details the potential scale of distant-water fishery impacts is beyond the scope of this study, but distant-water marine landings typically represent a small proportion of total marine catches and is unlikely to have a major impact on our overall conclusions [19].

5. Conclusion

Conducting vulnerability assessments at the country-level is of great importance. Indeed, it is at this level that policies are formulated and implemented to secure trade, food production and food security [25]. This study first systematically assessed the comparative magnitude and distribution of potential food security impacts of climate disturbance at a global scale, and highlighted the role of marine fisheries as a direct fish provider in the global countries. Our analysis suggests that country-level vulnerability to marine fisheries-related food security risks as a result of changing climate closely paralleled the national development status, with developing countries in Africa, Asia, Oceania, and Latin America appearing to be most vulnerable because of their greater nutritional dependence on fish and fewer available resources to invest in climate adaptation. In addition, the contribution of marine fisheries to domestic food and nutrition security vary considerably among the highly vulnerable countries. Specifically, African countries (Cape Verde, Gambia, Guinea, Guinea Bissau, Guyana, Liberia, Madagascar, Mauritania, Mozambique, and Senegal), Asian countries (Indonesia, Maldives, Philippines, and Thailand) and Oceanian countries (Fiji, Samoa, Solomon Islands, and Vanuatu) were mainly dependent on marine fishery to meet the nutritional requirements of their population. In contrast, changes in trade flows made the largest contribution to the food and nutrition security in Cote d'Ivoire, Nigeria, and Togo. Inland fisheries constituted the greatest proportion of total fish production in Cambodia, Democratic Republic of Congo and Tanzania. Aquaculture made the largest proportion of total fish supply in Bangladesh, Egypt, and Vietnam. As demand for fish continues to grow, conducting linked social-ecological assessments such as this study is essential to prioritize systems in the greatest need of intervention, understand the drivers of vulnerability to identify future research directions, and implement climate change mitigation and adaptation policies that will be effective in securing the future sustainability of marine fisheries.

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