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Vulnerability of flatfish and their fisheries to climate change

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ABSTRACT

Flatfishes (order Pleuonectiformes) are important to fisheries and contribute substantially to seafood production and people's livelihood. However, the sustainability of flatfish fisheries is being challenged by climate change, in addition to other non-climatic human stressors. There is an urgent need to expand our understanding of the vulnerability and risk of impacts of flatfishes and their fisheries to climate change, and identify possible options to moderate such impacts. In this paper, firstly, we explain the importance of ocean temperature and thermal characteristics of flatfishes in determining their biogeography. Secondly, we discuss the biological vulnerability of flatfishes in the world to climate change as indicated by quantitative indices estimated from a fuzzy logic algorithm. Thirdly, by presenting projections of future distribution and potential catches of exploited flatfishes from computer simulation models, we highlight specific regions and species that are expected to be most impacted by climate change. Finally, we discuss potential human interventions that could help reduce such impacts, including the potential for mariculture. This paper underscores the need for immediate actions to integrate climate change into flatfish conservation and fisheries management measures.

1. Introduction

Flatfishes (Order Pleuonectiformes) consist of 11 families, distributed globally in all climatic zones and are important food fish to human society (Pauly, 1994). Annual global fisheries catches of flatfish peaked around the 1970s at about three million tonnes and then decreased gradually to below two million tonnes in the 2000s (Fig. 1). Flatfish fisheries are largely commercial, with only a small (< 5%) proportion of catches that contribute to the subsistence sector. The most important flatfish family to fisheries (in terms of proportion contribution to total flatfish catches in the 2000s period) is Cynoglossidae (78.0%), followed by Pleuronectidate (10.4%) and Soleidae (2.6%), with Achiropsettidae contributing the least (< 0.1%) (Fig. 1b).

Besides capture fisheries, flatfish farming in the world is growing steadily. Between 2010 and 2015, the average annual growth rate of flatfish production from mariculture reached 3.3%, representing an almost 50% increase in growth rate relative to 2005 (Campbell and Pauly, 2013). In 2015, the sector accounted for about 150,000 t of fish food production, contributing about 1.1 billion USD to the economy of 19 producing countries (Fig. 1C and D). China is the largest producer by weight, accounting for 61% of the production, followed by South Korea and Spain with 31.5% and 5.3%, respectively. Currently, bastard halibut (*Paralichthys olivaceus*) is the main cultured species. Other farmed species include European turbot (*Scophthalmus maximus*), Atlantic halibut (*Hippoglossus hippoglossus*), common sole (*Solea solea*), Senegalese sole (*Solea senegalensis*) and European flounder (*Platichthys flesus*).

Climate change is threatening the viability of flatfish and their fisheries and aquaculture. Under climate change, the ocean is getting warmer, less oxygenated and with lower pH, impacting growth, reproduction and survivorship of fishes (Gattuso et al., 2015; Pörtner et al., 2014). These biological impacts ultimately affect the distribution, abundance, phenology, body size of fishes and ecosystem structure and functions. For example, marine fishes have been reported to shift in distributions by tens to hundreds of kilometers per decade towards higher latitude region (Cheung et al., 2009; Poloczanska et al., 2016) and into deeper waters (Dulvy et al., 2008) under ocean warning. In addition, ocean primary production is also altered by climate change that then affects upper trophic level production (Cheung et al., 2008; Stock et al., 2017). Globally, with shifts in biogeography and changes in net primary production, it is projected that total maximum catch potential (a proxy of maximum sustainable yield) would decrease by 3.1 million tonnes per degree Celsius of atmospheric warming (Cheung et al., 2016b). Based on indices of vulnerability and risk of impacts of climate change on marine fishes and invertebrates computed from a fuzzy logic expert system, almost one third of the analyzed exploited species are having high risk of impacts from climate change under the 'business-as-usual' greenhouse gas emission scenario (Representative Concentration Pathway or RCP 8.5) (Jones and Cheung, 2018).

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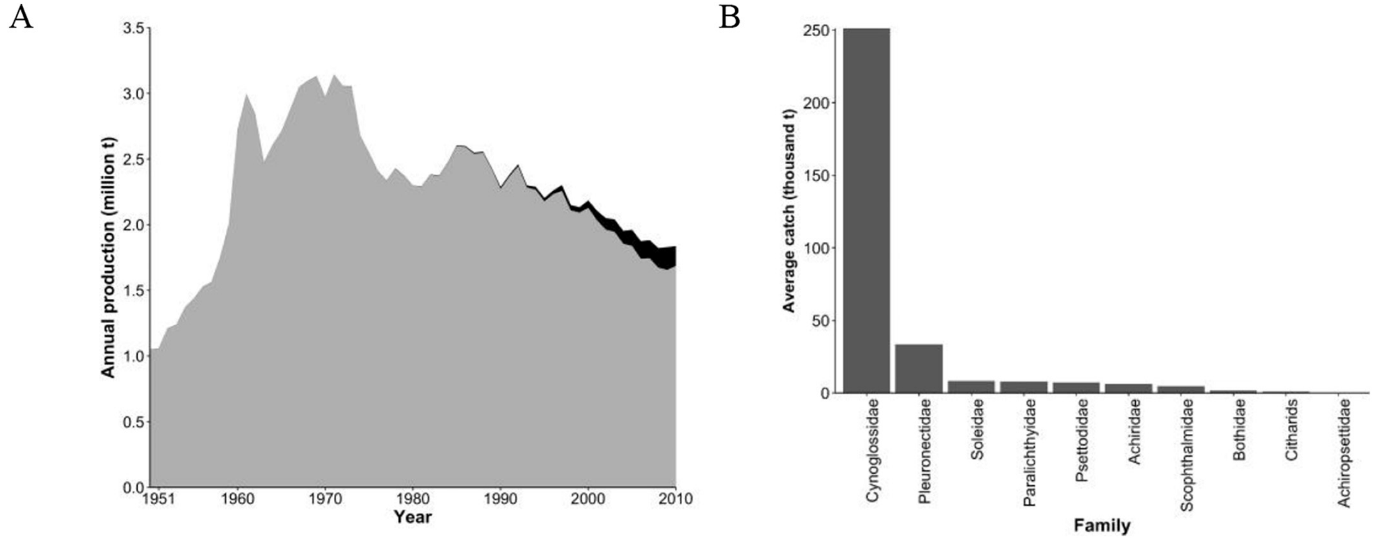

Fig. 1. Global fisheries and mariculture production of flatfish (Pleuonectiformes): (A) annual fisheries catches (grey area) and maricultur production (black area) from 1951 and 2010; (B) average annual catches between 2001 and 2010 by flatfish family. Data source of fisheries catch and mariculture production: Sea Around Us (www.seaaroundus.org). [black and white].

It is expected that flatfish will be impacted by climate change. Given the high importance of flatfish to fisheries and seafood production globally, systematic assessment of their vulnerability and risk of impacts across different species of flatfish can help understand the scale of the challenges and elucidate potential interventions that could help reduce the impacts. Specifically, flatfish includes species with a wide range of life history characteristics, ecology and distributions (Minami and Tanaka, 1992; Vinagre and Cabral, 2014), climate risk and vulnerabilities of different flatfish populations may vary substantially.

The objective of this study is to use existing modelling approaches and indices to assess the risk of climate change on the viability of flatfish species and the sustainability of their fisheries and aquaculture. These approaches range from vulnerability assessment to formal ecological modelling. The use of multiple assessment approaches helps elucidate the different dimensions of risks and vulnerability of flatfishes and their fisheries to climate change impacts. Specifically, using the fuzzy logic expert system described in Jones and Cheung (2018), we compared the vulnerability and risk of impacts of exploited flatfish in the world. Secondly, using a dynamic bioclimate envelope model, we projected future changes in the distribution and maximum catch potential of global flatfish fisheries. Finally, we examined how future flatfish aquaculture may be affected by climate change.

2. Method

2.1. Vulnerability and risk of impacts of flatfish to climate change

We computed indices of vulnerability and risk of impacts for 47 species of exploited flatfish i.e., species that were recorded in global fisheries statistics (see Appendix). We used the fuzzy logic algorithm developed by Jones and Cheung (2018). In short, exposure to hazard describes the extent to which species would be subjected to climate hazards (predicted changes in the physical environment). Climate hazards for flatfish were indicated by the physical and chemical ocean variables, including sea bottom (as all species included in this study are demersal), temperature, oxygen concentration, and pH. An exposure to hazard metric (*ExV*) for each variable (*V*):

$$ExV_i = \frac{|\overline{V}_{future,i} - \overline{V}_{historical,i}|}{\partial V_{historical,i}} \quad (1)$$

where $\overline{V}_{future}$ and $\overline{V}_{historical}$ are the mean annual value of an ocean variable for the future (2041–2060) and past (1951–2000), respectively. For oxygen and pH, if the difference between $\overline{V}_{future}$ and $\overline{V}_{historical}$ results in a positive value, the value is then set to 0. $\partial V_{historical}$ was the standard deviation of the annual detrended value of the ocean variable from 1951 to 2000. *ExV* was calculated for each 0.5° latitude × 0.5° longitude cell *i* of the global ocean where a species is predicted to occur.

To determine the species' current distribution range, we obtained current range boundary for each species as predicted using the Sea Around Us method (Jones et al., 2012). The range boundary was defined based on latitudinal and depth ranges, as well as expert-delineated range boundaries such as those published in FAO species catalogues. The range boundary was then subsequently rasterized on a 0.5° latitude × 0.5° longitude grid.

The levels of climate change, as well as categorizes of species' biological and ecological traits, are classified into levels of exposure to hazards, sensitivity, adaptive capacity and consequently, their vulnerability and risk of impacts based on pre-defined heuristic rules. These rules described the empirical and/or theoretical relationship between the traits and the expected levels of sensitivity, adaptive capacity and vulnerability of marine fishes. We used published heuristic rules described in Jones and Cheung (2018) (for climate change). For example, based on available literature, sensitivity of finfish to ocean acidification is relatively low (Kroeker et al., 2013). This is explicitly represented by the heuristic rules. Actions defined by each rule are operated when a threshold value of membership is exceeded, thereby defining the minimum required membership of the premise that an expert would expect for a particular rule to be fired. The algorithm accumulated the degree of membership associated with each level of conclusions from the rules using an algorithm called MYCIN (see Cheung et al., 2005), where:

$$AccMem_{(i+1)} = AccMem_{(i)} + Membership_{(i+1)} \times (1 - AccMem_{(i)}) \quad (2)$$

where *AccMem* is the accumulated membership of a particular conclusion (e.g., high vulnerability) and *i* denote one of the rules that has led to this conclusion.

Vulnerability and risk of impacts were expressed on a scale from 1 to 100, 100 being the most vulnerable. Index values (*Indval*) correspond to each linguistic vulnerability category (*x*) were Low = 1, Medium = 25, High = 75 and Very high = 100. The final index (*FlnInd*) of risk of impacts or vulnerability was calculated from the average of the index values weighted by their accumulated membership (Cheung et al., 2005):