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Current and future socio-ecological vulnerability and adaptation of artisanal fisheries communities in Peru, the case of the Huaura province

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ABSTRACT

Marine artisanal fisheries make vital contributions to food security, livelihoods, jobs, and income in coastal communities globally. However, resources vary as a result of changes in oceanographic conditions such as sea surface temperature or wind stress, which impacts communities and also makes them more sensitive to other stressors such as climate change. In Peru, small-scale fisheries are paramount to the country's economy and food security. They are also one of most globally affected by interannual changes and potentially impacted by climate change. Assessing their present and future vulnerability and finding adaptation strategies are key to the sustainability of the sector and the livelihoods of many. This study assesses the local vulnerability in the Huaura province, Peru, where three fishing communities of very different socio-economic characteristics share the same fishing ground. The region is very sensitive to changes associated with El Niño. We assess the ecological and socio-economic vulnerability using governmental and local information, to pinpoint the main drivers of vulnerability. We find stark differences between communities: Carquín shows the greatest dependence on artisanal fishing for income and a low adaptive capacity, whereas Huacho, a larger and more diversified economy, presents greater livelihood alternatives for the artisanal fishermen. The future vulnerability analysis highlights the need to implement adaptation measures, including: economic diversification; forms to add value to the artisanal fishing; sustainable management of fishing grounds; and actions that help manage shocks from interannual variations, such as monitoring and prediction systems, but also financing mechanisms that could attenuate the socio-economic impacts.

1. Introduction

Marine fisheries make vital contributions to food security, livelihoods, jobs, employment and income in coastal communities globally [1–5]. Global capture fisheries production was 93.7 million tons in 2011 [6] with an estimated annual gross revenue of about US$ 85 billion [7]. A large fraction of these fisheries is local and small-scale [3]. However, fisheries stock varies strongly associated to environmental changes and natural climate variability, such as El Niño Southern Oscillation (ENSO) cycle, through changes in sea surface temperature, wind stress, storm severity and ocean circulation [8–12]. This variability impacts the communities that depend on artisanal fishing. In Peru, fisheries are affected by strong variability associated to ENSO, making them more sensitive to additional stresses such as anthropogenic climate change [13]. Changes in climatic conditions may lead to changes in productivity, distribution and large-scale redistribution of global catch potential [14–17]. Furthermore, the increase of the frequency and intensity of extreme events will likely produce further impacts on the marine ecosystems and the communities that depend on them [18]. In addition to potential changes in the fishery resources, fishing communities may also

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suffer other impacts of climate change in coastal areas, such as sea level rise or increase in wave action, and can impact landing infrastructure, navigation and livelihoods [19–23].

In Peru, artisanal fishing reached in 2006 more than 400,000 tons, showing a steady increasing trend [11]. This rising trend is associated to a growth in the number of fishers (34% in the last 10 years) and artisanal boats with up to 30 tons of holding capacity [24]. Peru's fishery sector is a key economic factor for the country [25]. Small-scale fisheries constitute in Peru an important source of food and employment for coastal communities for which fish stock is the single most important natural resource [2].

Understanding where the effects of climate variability and change can have the greatest social and economic impact is crucial to prepare for present and future shocks [26]. For such assessment, vulnerability analyses are of great importance for comparing the magnitude and distribution of impacts of the climatic disturbances in the marine fisheries and coastal communities [21,27]. Vulnerability assessments are a tool to assimilate and analyze social, ecological, and economic information relevant to marine fisheries, helping to pinpoint priority areas for action and to implement adaptation strategies [28–30]. These analyses can also be used in adaptation policies and management plans to reduce the impacts of changing climate and disruption of livelihoods in fisheries-dependent communities. Vulnerability analyses usually differ in the indicators depending on the data availability in each case [31]. Local context-specific information, however, allows a more robust assessment of vulnerability, particularly on the local adaptive capacity, and help inform action to face the effects of climate variability and change [31].

Peru has been ranked in the first 10 most vulnerable countries to the impacts in fisheries-dependent economies [32] and will also be one of the most affected fisheries to climate change globally [4,33,34]. Therefore, (i) assessing the socio-ecological vulnerability of Peru's artisanal fishing communities to present and futures changes in the fishing resources and (ii) identifying adaptation strategies that will ensure the sustainability of the sector and the communities that depend on it, are two urgent needs. This study develops a local vulnerability assessment of artisanal fisheries in the Huaura province of Central Peru, which comprises three districts: Huacho, Carquín and Vegueta, each of them with very different socio-ecological characteristics. The fisheries in the region are also very sensitive to environmental changes such as ENSO events. Using governmental and local information, we compare the ecological and socio-economic vulnerability of each community at present and under two future scenarios associated to oceanographic changes and adaptation pathways. Different local adaptation options are also proposed to address the main factors of present and future vulnerability.

2. Material and methods

2.1. Description of the approach

Many studies have adopted the vulnerability framework proposed in the Third Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) in 2001 for assessing social and ecological vulnerability of fisheries at various scales: regionally [34–36], nationally [30,37,38] and locally [39]. However, the definition of vulnerability was revised in the IPCC's Special Report on Extreme events and in the Fight Assessment Report [40]. The conceptualizations and definition of vulnerability differ between frameworks, but the core of the evaluation remains relatively unchanged [31]. However, a majority of studies of the vulnerability of fisheries communities still use the original vulnerability framework (e.g. Refs. [4,30,37,82]), while the most recent proposed framework keeps a focus on climate risk and it is nor yeat as well established for vulnerability of fisheries. Therefore, in this analysis we follow the framework proposed in the Third Assessment Report and build from these previous assessments for fisheries communities for consistency.

Here, we calculate vulnerability as a function of three components: exposure, sensitivity and adaptive capacity. Exposure is the degree of climate stress upon local fisheries [4] and designates the magnitude, frequency, duration and/or extent in which the fishing community is in contact with, or subject to, such driver. Sensitivity is the degree of the community dependency on marine fisheries [4,37] and how it is affected by different oceanographic conditions and climatic stresses [29]. Exposure and Sensitivity define the Potential Impact. The Adaptive capacity is the capacity of a system to adapt to a changing environment. The Potential Impact combined with the Adaptive Capacity defines the overall Vulnerability. The indicators used to define each component are described below.

2.2. Exposure definition

To characterize the exposure to oceanographic changes, we used historical and future projections for sea surface temperature and upwelling. Historical sea surface temperature (SST) anomalies were calculated as a spatial average in the domain: 77°20' – 79°30′W; 10°50' – 11°30′S using data from satellites observations for the period 1997 to 2014: Pathfinder and Multi-scale Ultra-high Resolution (MUR) [41–43]. The upwelling index (UI) was calculated for the same spatial and temporal domain from the Bakun index [44] using data from the ERA Interim model [45,46]. A downscaling of the model IPSL-CM5A-MR provided regional projections of changes for the end of the century and was used to assess future changes in exposure.

Changes in SST and UI have a direct link with vulnerability of communities as they trigger biophysical and socio-economic impacts on fisheries [4]. Annual catches were calculated from the reported fish captures as a registered by the Peruvian Marine Research Institute (IMARPE) that registers: captures species, biomass and estimated location of the fishing ground. However, species diversity in artisanal fisheries in Huacho, Carquín and Vegueta is very high, and historical captures show large differences in catch volumes and management regimes. For this reason, we disaggregated the catches by their frequency and total number of annual catches, to identify the most dominant species, using the Olmstead Tukey diagram [47]. The species were organized by the frequency of the catches (y-axis) and the natural logarithm of the total annual catches (x-axis), and classified in four categories: dominant, constant, occasional and rare species.

The analysis of exposure and sensitivity focused on the dominant species as they represent the largest and most frequent catches for the local fishers. The influence of SST and UI in the dominant species was estimated through linear correlation between the time series of SST and UI; their standard deviation (as a measure of the variability in the signal); and the time series of catches for each dominant species.

Based on historical correlation between oceanographic changes and the catches (i.e. species and biomass), we proposed indices for present and future exposure. Table 1 outlines the indicators and data sources for the exposure definition.

2.3. Sensitivity definition

Fisheries are a crucial contributor to livelihoods because they create employment, economic value and food security [4]. The sensitivity was calculated using specific ecological and socio-economic indicators. The ecological sensitivity was defined as the availability of an ecological system to respond to different external and internal pressures [48–50]. It was quantified through different indicators weighted between 1 and 3. The indicators used for the calculation are outlined in Table 2, and included: change in the catch (decadal variations); change in variety of species available; quantity landed in each community over the total catch in the fishing ground; distance to fishing region and spatial distribution of catches (as a proxy of artisanal fishing effort); richness of the natural banks, mariculture and continental aquaculture; concentration

Table 1
Indicators of Exposure, and data sources, temporal coverage and spatial resolution.

INDICATORS	DATA SOURCE	COVERAGE	PERIOD USED FOR THE ANALYSIS	SPATIAL RESOLUTION
Changes in Sea Surface Temperature (°C)	Advanced Very High-Resolution Radiometer (AVHRR) – Pathfinder	1981–2012	1997–2002	0.036°
	Multi-scale Ultra-high Resolution (MUR)	2002 – Present	2003–2014	0.01°
	IPSL-CM5A-MR	2010–2100	2010–2100	0.111°
Change in upwelling (m^3/s^1/(100 m)^1)	European Centre for Medium-Range Weather Forecast (ECMWF) – ERA Interim	1979 - Present	1997–2014	0.753°

Table 2
Indicators of ecological sensitivity.

INDICATORS	VARIABLE	DESCRIPTION	CRITERIA		
			LOW (1)	MEDIUM (2)	HIGH (3)
Change in the catch	Ratio of composition of the catches of the last 10 years	The sensitivity of the marine species was quantified through variation of catches in a time interval (decadal variations), which are functions of the oceanographic changes in the fishing of the Huaura province.	ratio <1	ratio between from 1 to 1.4	ratio >1.4
Change in variety of species available	Index of species diversity	A lower diversity of captures represents higher sensitivity to oceanographic changes. An index of species diversity (1-D) was calculated through the Simpson Index (D) [52]	Species do not show marked variation and it has not been declining	Species show variation inter annual	Species show strong inter-annual variations and it has been declining.
Quantity of catches	Percentage of catches, averaging in recent history (18 years)	This indicator measures the variability of percentage of catches landed in each community over the total catch in the fishing ground, communities with greater catch present a higher sensitivity compared with other communities.	Less than 30% of catches	60 - 30% of catches	More than 60% catches
Distance to fishing region	Fishing analysis for cove and regions	Fishing region near the coast imply a lower fishing effort, which reduces the sensitivity of artisanal fishermen. We distinguish the fishing to catch zone, from the shore to 5 nm offshore, 10 nm and beyond (Supplementary Fig. 2).	Largest percentage of fisheries in the Region 1 (<1 nm)	Largest percentage of fisheries in the Region 2 (1–10 nm)	Largest percentage of fisheries in the Region 3 (>10 nm)
Spatial distribution of catches	Percentage of catch by region	The weighting is based on the distance between the fishing regions and the landing points, as a proxy of the fishing effort for artisanal fishermen. Currently, fishermen covering larger fishing zones represent a larger sensitivity to changes in fishing ground induced by climate change.	Largest percentage of catches in the region 1 (<1 nm)	Largest percentage of catches in the region 2 (1–10 nm)	Largest percentage of catches beyond the region 1 (>10 nm)
Richness of the natural banks	Distribution of the natural banks by locality (map)	The existence of natural banks represents a higher sensitivity, due to the fragility of species in face to climate impacts (Supplementary Fig. 1c).	1 or none	2–3 natural banks	>3 species in the town
Richness of mariculture	Mariculture areas (last 5 years)	The existence of mariculture represents a higher sensitivity, due to the fragility of species in face to climate impacts.	Does not exist	Exists and is small-scale	Exists and is large-scale
Richness of aquaculture (continental)	Aquaculture areas (last 5 years)	The existence of aquaculture represents a higher sensitivity, due to the fragility of species in face to climate impacts.	Does not exist	Exists and is small-scale	Exists and is large-scale
Concentration of catches	Moran Index of autocorrelation	It was calculated through the Moran Index of spatial autocorrelation, the index allows to evaluate autocorrelations among the values of the fishing grounds [54] and indicate whether the selected sample has lower or higher spatial concentration, and assuming a lower sensitivity for more concentrated catches [51].	Moran index is positive and above 0.3	Moran index between −0.1 and 0.3	Moran index indicate dispersion
Primary production	Chlorophyll-a concentration	A proxy for the determination of the regions with the highest concentration of biomass of the fishery resources.	Inside of 1 nm	Inside of 3 nm	Inside of 6 nm

of catches through the Moran Index of spatial autocorrelation of the fishing grounds [51]; and primary production. The fishing grounds were estimated from the reported fish captures and assigned a buffer zone of 0.5 nm of error margin. This margin relates to inaccuracies in the movement of fishers to the biomass stock each time the biomass catches are recorded [Supplementary Fig. 1e].

The change in variety of species was characterized by an index of species diversity (1-D) calculated through the Simpson Index (D) as [52]:

$$1 - D = 1 - \sum_{n=i}^{S} (p_i)^2 \quad \text{Where} \quad D = \sum_{n=i}^{S} (p_i)^2; p_i = \left(\frac{n_i}{N}\right) \tag{1}$$

where, "n" is the total number of organisms of a particular species and "N" is the total number of organisms of all species.

The socio-economic sensitivity for each community was defined based on the indicators outlined in Table 3: population density; proportion of artisanal fishers in the community to identify the dependence on the fishery resources; percentage of vessel respect of the total number of fishers; percentage of vessel of the total fishing area (as a proxy of

Table 3
Indicators of socio-economic sensitivity.

INDICATORS	VARIABLE	DESCRIPTION	CRITERIA		
			LOW (1)	MEDIUM (2)	HIGH (3)
Population density	Density (people/km2)	The population per unit area (people/km2) is an important indicator of the sensitivity [30], because communities with a larger number of members have a greater accessibility to resources, greater diversity of economic activities and therefore less sensitivity to anthropogenic and environmental impacts [34].	Less than 200 people/ km2	200–500 people/km2	>500 people/ km2
Proportion of artisanal fishers in the community	% artisanal fishermen within the community, with respect to the average of the province (three locations)	Identifies the areas with the largest dependence on the fishery resources, as well as the assessment of the population dedicated to it (% of artisanal fishermen within each community). Therefore, changes in the distribution of marine species would have direct effects on this part of the population, increasing its sensitivity to climate change.	<10%	10%–50%	>50%
Percentage of vessel respect of total fishers	Proportion of total of ship-owners-boats with respect to fishermen (boat/~fishermen)	A higher proportion of fishermen respect to the total number of ship owners represents more socio-economic sensitivity.	<20%	20–40%	>40%
Percentage of vessel of the total fishing area	Percentage of the total vessel	The number of artisanal vessels per fishing surface was used as a proxy of the extractive capacity of the fleet (number of vessel). A greater density of vessels increases the sensitivity to impacts.	<20%	20–40%	>40%
Port infrastructure	Type of landing and fishing infrastructure	The rapid accessibility of the landing of fishery resources allows a greater diversification of those resources, which generates higher economic income for artisanal fishermen. Having a better infrastructure is also key in the reduction of other impacts such as impacts from storms, erosion and flooding. Better infrastructure decreases the sensitivity (Supplementary Fig. 1d).	Port	Cove	Beach

extractive capacity of the fleet); and the availability of port infrastructure. We used local census data to calculate changes over time in population and density in each community. However, we did not consider any future socio-economic scenarios [e.g. 54] because we lacked projections of demographic changes and aimed to focus on the effect of changes in exposure and adaptive capacity in the overall vulnerability.

In Peru, fisheries comprise artisanal, small-scale, and industrial fleets [11]. Artisanal fisheries have exclusive rights up to 5 nm (nautical miles) from the coast [11] but in some cases, fishing can occur up to 100 nm offshore. This information was used to define regional areas for some of the indicators [Tables 2 and 3]. The sensitivity to changes in the habitat increases as the fishing grounds are farther from the communities because it involves a larger fishing effort (and cost) for artisanal fishermen [15]. For this reason, as an indicator of the accessibility to each fishing ground, the catches were classified into three zones as measured from the shore 5 nm, 10 nm and >10 nm from each community [Supplementary Fig. 2]. Catches and primary production were calculated in each of these zones for scoring.

2.4. *Adaptive capacity*

The adaptive capacity was defined as the potential to respond to and

Table 4
Indicators of ecological adaptive capacity.

INDICATORS	VARIABLE	DESCRIPTION	CRITERIA		
			LOW (1)	MEDIUM (2)	HIGH (3)
Proportion of dominant species	% Olmstead & Tukey diagram, with respect to others	The increase of the dominance of marine species generates a reduction in their diversity, due to declination of weak species by death or migration, reducing the adaptive capacity of coastal areas.	Dominant species less to 30%	Dominant species between 30 and 50%	Dominant species more than 50%
Presence of Protected Natural Areas (PNA)	Number of PNA in each locality	A greater number of PNA in a community, represents a lower lack of adaptive capacity, due to PNA foster the preservation and conservation of diverse areas of ecological and socio-economic importance and therefore decrease the sensitivity [56] (Supplementary Fig. 1a).	None	1 nearby area	+2 nearby areas
Size of PNA	Spatial scale category	Localities with greater extension of PNA have a greater adaptive capacity, because they allow the conservation of diversity of marine and coastal species.	Other	Regional	National
Recreational and tourist corridor	Number of tourist sites	Represent a proxy of more diversity of activities in the province and are also a measure of conservation and protection of wildlife zones, the measure of quantification of the corridors is based on preliminarily on the number of sites (wetlands or recreational areas) that exist within each district of Huaura (Supplementary Fig. 1b).	Does not exit	Exist but 4 or less	Exist, 5 or more sites
Wetland tourist corridor	Number of wetland tourist		Does not exit	Exist but 4 or less	Exist, 5 or more sites
Proportion of PNA to fishing zone	Ratio of PNA area to fishing zone area	Localities with greater extension of PNA in comparison with the fishing areas have a higher adaptive capacity.	<30%	30–50%	>50%
Use of selective fishing gears	Presence of selective fishing gears	Artisanal fisheries that take measures to protect juveniles can better maintain the reproductive processes of the species, making the fishing activity more sustainable in the long-term, and therefore more prepared to adapt to the impacts of climate change in the ecosystem.	Not used	Used in some species	Are always used in all species

recover from the impacts of climate change [4,37]. It was scored independently for the ecological and socio-economic system [Tables 4 and 5], using seven and two indicators, respectively. These indicators were different to those employed for the calculation of the sensitivity components to include the effect of adaptation measures to the variability of the resource in each community. The ecological adaptive capacity was defined as the availability of an ecological system to mitigate and adapt to the impact of climatic change [49]. The indicators used for the calculation of ecological adaptive capacity were [Table 4]: proportion of dominant species; presence of Protected Natural Area (PNA); the availability of recreational and tourist corridors; wetland corridors; size of PNA; proportion of PNA to fishing zone; and use of selective fishing gears.

The socio-economic adaptive capacity was calculated based on the level of dependence of human communities on marine resources [29, 55], and the capacity of these communities to minimize and adapt to the loss of fishing opportunities [28,32] using as indicators [Table 5]: economic diversification (access to other economic activities); and level of poverty in the region.

2.5. Calculation of vulnerability

The ecological and socio-economic potential impacts (PI_{eco} and PI_{soc}) were obtained as the average of exposure, ecological sensitivity (S_{eco}) and socio-economic sensitivity (S_{soc}), respectively [28,30]:

$$PI_{ECO} = (E + S_{ECO})/2 \text{ , and } PI_{SOC} = (E + S_{SOC})/2 \quad (2)$$

The PI was then combined with the lack of Adaptive Capacity (1-AC), to integrate the overall Vulnerability, ecological vulnerability (V_{ECO}) and socio-economic vulnerability (V_{SOC}):

$$V_{ECO} = [PI_{ECO} + (1 - AC_{ECO})]/2, \text{ and } V_{SOC} = [PI_{SOC} + (1 - AC_{SOC})]/2 \quad (3)$$

The overall integrated SEV was calculated as the average between the V_{ECO} and V_{SOC}. The integrated socio-ecological vulnerability can identify communities that may be disproportionately vulnerable to impacts associated with climate change from an ecological perspective or from their socio-economic characteristics. However, we note that the results could also be analyzed independently for the ecological and socio-economic indicators.

The indices were calculated as the unweighted mean of the standardized scores, ranging from 1 to 4 for Exposure and from 1 to 3 for Sensitivity and Adaptive Capacity [Tables 2–5]. We then calculated the average for all the indicators and per district (Huacho, Carquín and Vegueta) and rescaled the values from 0 to 1. The final quantitative values were also organized into five qualitative vulnerability categories: “very high” (1–0.800), “high” (0.799–0.600), “medium” (0.599–0.400), “low” (0.399–0.200) and “very low” (0.199–0). Fig. 1 provides a summary of the methodological approach.

2.6. Present and future vulnerability scenarios

The present vulnerability was calculated based on historical data of exposure variables, existing ecological conditions of the habitat and the current socio-economic characteristics for each community. However, long-term policy-relevant scenarios for the fisheries sector can be useful to assess the potential vulnerability of communities. ‘Oceanic System Pathways’ that account for the changes in the climate system (atmosphere-ocean-biogeochemistry) and the complex social-ecological dynamics have been presented as a tool to factor in long-term objectives into present day management an help find effective strategies towards sustainability, term visions or assessing alternative management options [53]. Here, we follow a similar approach and estimate future vulnerability under two scenarios that assume different magnitudes of the impact in exposure to climatic changes, and alternative pathways of human activities that influence the oceanic system and future management and adaptation.

First, a ‘pessimistic’ future scenario assumed a future pathway that accounts for (i) increased exposure to oceanographic changes from climate change for the Representative Concentration Pathways (RCP) 8.5 and (ii) decreased adaptive capacity. A second ‘optimistic’ scenario was considered for a more optimistic pathway of (i) increased exposure according to the RCP2.6 and (ii) increased adaptive capacity. The sensitivity was not changed for any of these scenarios because we aim to test the effect of changes in exposure and adaptation over the present sensitivity conditions.

The exposure to changes in the fishing resources was increased for both scenarios based on the expected changes in the oceanographic conditions. For the RCP2.6, expected changes in the exposure indicators of SST were increased by 15% and by 100% for the UI. For the RCP8.5, we assumed an exposure index where the present exposure is increased by 33% for SST and by 200% for UI. These estimates were based on dynamic projections that indicate that upwelling events frequency will be reduced associated to a warming along the Peruvian coast by a deepening of the thermocline, and a weakening of coastal winds, according to projected changes for the RCPs and a downscaling of the IPSL-CM5A-MR model [57].

For both future scenarios, the adaptive capacity was modified to account for the effect of adaptation. Table 6 outlines the indicators and the adaptive capacity adjustments for each scenario, as well as the associated environmental impacts and adaptation options. Under the ‘pessimistic’ scenario, the adaptive capacity was decreased assuming the management and conditions for fishing will continue deteriorating. The adaptive capacity was reduced by 10% for all indicators [Table 6], with the exception of economic diversification and the selective fishing techniques, which was decreased by 25%, assuming less capacity of the ecosystem to adapt in the future. For the ‘optimistic’ scenario, the adaptive capacity was increased assuming adaptation options [Table 6] were implemented to prevent the associated environmental impacts. The indicators of adaptive capacity were increased by 10%, although the selective fishing was increased by 50% because this is a measure that was considered more impactful.

3. Results

3.1. Exposure to oceanographic drivers

The Sea Surface Temperature (SST) time series in the Huaura region [Fig. 2a] shows strong interannual variations, with variations ranging from a minimum of 16 °C to a maximum of 26.7 °C in 1997–98. This variation is produced by the intrusion of warm water masses during El

Table 5
Indicators of socio-economic adaptive capacity.

INDICATORS	VARIABLE	DESCRIPTION	CRITERIA		
			LOW (1)	MEDIUM (2)	HIGH (3)
Economic diversification	Number economic activities	Access to other economic activities increases the capacity to adapt to future climatic stressors, due to a greater diversification of economic activities (e.g., agriculture, farming, construction etc.).	Less of 5 nearby activities	From 5 to 10 nearby activities	More of 10 nearby activities
Level of poverty in the region	Category of poverty	Higher levels of poverty in a community are used an indicator of less socio-economic adaptive capacity to adapt to the impacts of climate change.	Poor and very poor people	Regular and less poor people	Not poor people

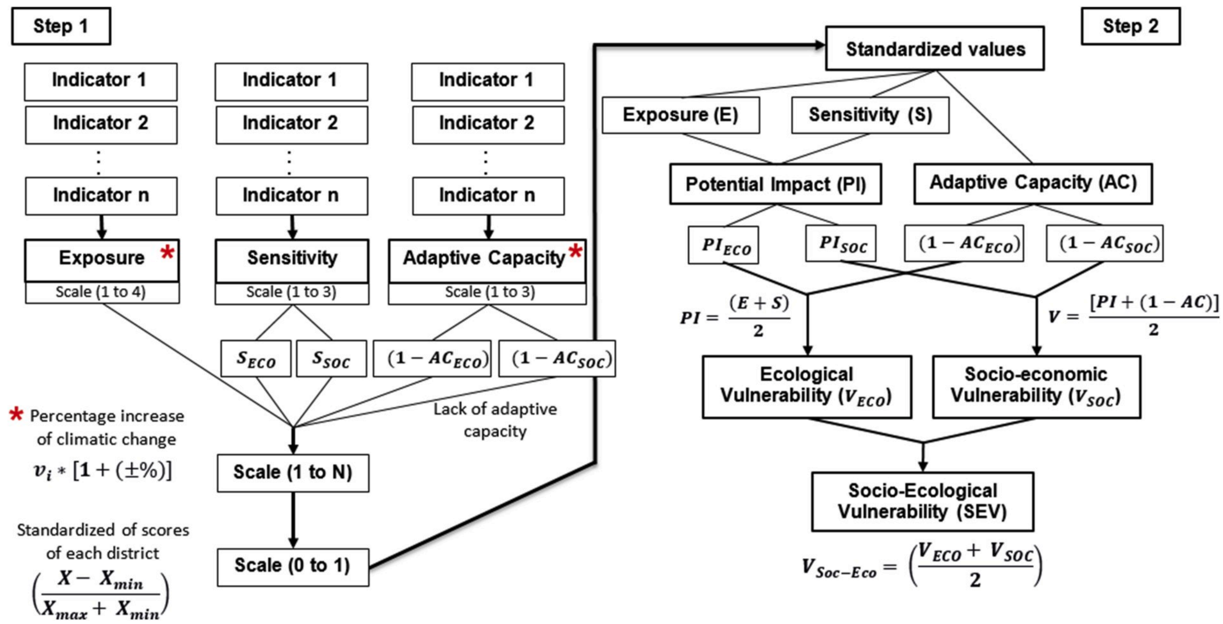

Fig. 1. Flowchart and summary of the calculation of the SEV assessment framework. Step 1, calculation of the vulnerability and process of standardization of data for each component (S, E, PI and AC); and Step 2, calculation of the SEV.

Table 6
Adaptation measures for each indicator of adaptive capacity.

INDICATORS	VARIABLE	ENVIRONMENTAL IMPACTS	ADAPTATION MEASURES	SCENARIO 1. PESSIMISTIC	SCENARIO 2. OPTIMISTIC
Ecological Adaptive Capacity					
Proportion of dominant species	Percentage of dominant species respect with total richness	Increase of invasive species [32], change in the dominance of the species and species losses [58,59]	Conservation and management of species of economic relevance (juveniles) and reduce the fishing effort [60].	−10%	0%
Presence of Protected Natural Area (PNA)	Number of PNA in each locality	Ocean acidification, long-term warming, extreme heat events [60], increase of predator populations [59].	Regulatory framework, control of larger predators (marine and terrestrial) [59], forbidden the extractive activities of relevant species [61].	−10%	+10%
Size of PNA	Spatial extent	Increase of recreational activities and intensive use of productive areas [62]; and lack of a regulatory framework for the creation and conservation of PNA	Improvement of the regulatory framework based on changes in marine species distribution and on the basis of extractive demands; and develop of new methodologies to evaluate the management effectiveness of PNA [63,64]	−10%	+10%
Proportion of PNA to fishing zone	Ratio of PNA area to total of fishing zone surface	Overlaps between urban expansion and increase of fishing activities [63], increase of biomass of marine species near the coast (inside of 5 nm).	Implementation of conservation measures for protected areas.	−10%	+5%
Use of selective fishing gears	Presence of selective fishing gear	Changes in the abundance of juveniles [32], encrusted lost trammel net on rocky bottoms [65]; and increase of by-catch and discarding [66,67]	Changes in legislation and regulation of use of selective fishing gears [68], reduce of impacts over the mortality of marine organisms [68].	−25%	+50%
Socio-economic Adaptive Capacity					
Economic diversification	Number of economic activities	Political instability, climate risk related with flood and drought.	Increase of fishing activities (artisanal and industrial), implementation of new zones for mariculture and aquaculture.	−25%	+10%
Level of poverty in the region	Category poverty	Increasing the level of poverty due to low development of different sectors (private and public)	Creation of social protection programs and labor market programs [69]	−10%	+10%

Niño [70–72], which also caused a significant reduction in coastal upwelling [73], as seen in Fig. 2b. UI showed a decrease during La Niña 1999 reaching a minimum of 50.3 $m^3/s/100$ m, when the SST also fell to 16 °C. Thereafter, from 2002 to 2005, SST values remained relatively constant between 19 and 21 °C. From 2000 to 2010 there was an increase in UI, which reached a maximum of 374.6 $m^3/s/100$ m in 2007.

We identify nine dominant species in the region (species of highest frequency and total catch) based on an Olmstead – Tukey diagram [Fig. 3]. For these species, the total biomass per year have changed substantially in the past associated to these oceanographic changes, as represented in Fig. 4a, but also in the relative weight of each during years.

Species of warm and cold waters coexist of the coast of Huaura province but are heavily dependent on oceanographic conditions. The catches of the dominant species showed a strong variability over the 18 years analyzed [Fig. 4a]. During 1997–98, there was a high dominance

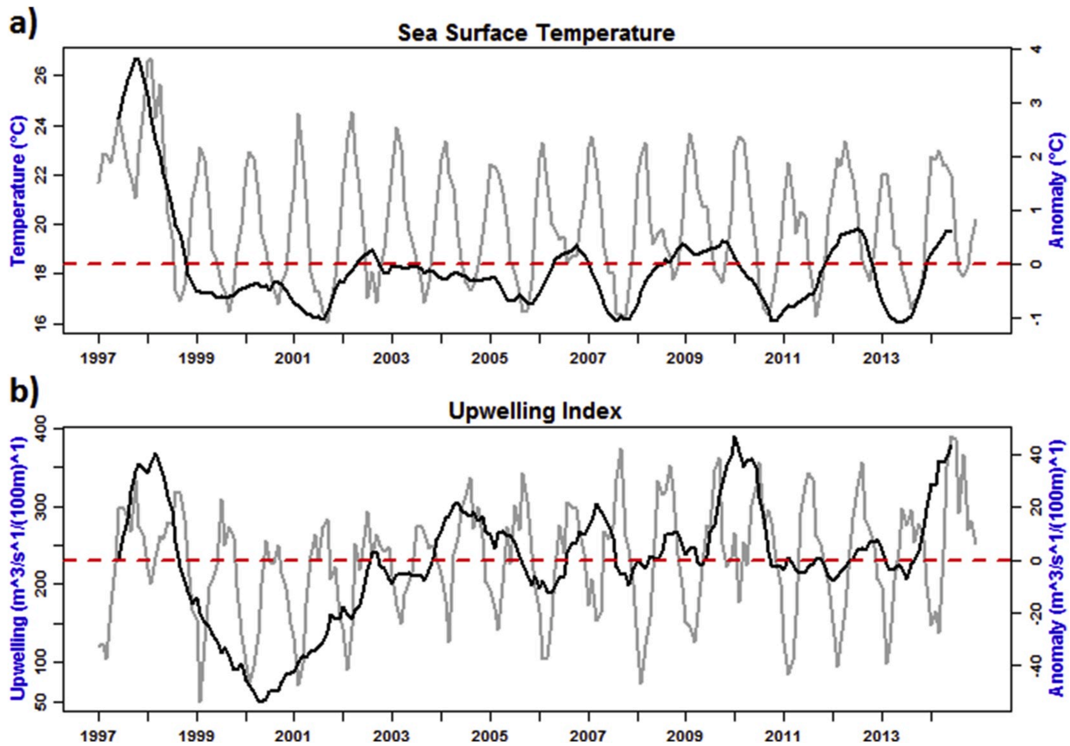

Fig. 2. Time series (left axis, black line) and variability of anomalies (right axis, gray line) of (a) Sea Surface Temperature and (b) Upwelling Index, from the coastline of Huaura province to 100 nautical miles (nm).

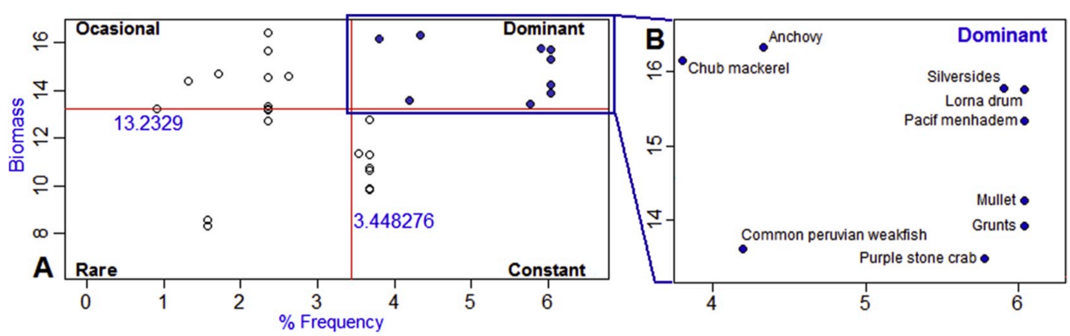

Fig. 3. Dominant species in the region, based on the Olmstead – Tukey diagram.

of chub mackerel (2386 tones representing 63.5% of the catch) due to the intrusion of warm water massed during El Niño. Despite the occurrence of El Niño, some cold waters species remained such as anchovy (16.1% of the catch in 1998) and pacific menhaden (19.3% of the catch in 1998) [Fig. 4b]. Thereafter, between 1999 and 2002, SST decreased [Fig. 4a], with increases of catches of anchovy (32.1% of the catch in 1999), Lorna drum (38.5% in 1999) and the pacific menhaden (59% in 2001). Catches increased since 2003, peaking in 2009, due to dominance of anchovy with 4227.3 tones (68.8% of catches). Between 2012 and 2014, warm water masses increased catches of chub mackerel (1394.1 tones up to 70.6% of the catch). Although total, catches of marine species (vertebrates and invertebrates) increased throughout the 18 years study period, diversity index showed a decreasing trend, because anchovy dominated from 2006 [Fig. 4].

An analysis of correlation of the different species confirms this high dependency with SST, UI and their standard variation [Fig. 5]. Peruvian weakfish showed moderate ($r = 0.636$, $p = 0.005$) and high ($r = 0.757$, $p = 0.0003$) correlations with SST, but non-significant correlation ($r = 0.1$, $p = 0.6$) with the UI. Catches of chub mackerel, a warm water species, had a moderate correlation with the SST ($r = 0.520$, $p = 0.027$) and a low correlation with UI ($r = 0.327$, $p = 0.185$). Mullet and silversides, cold water species, showed low correlations ($r = 0.289$, $p = 0.244$; and $r = 0.399$, $p = 0.1$) with UI [Fig. 5].

The diversity of species (1-D), shown in Fig. 6, has been decreasing over time associated to El Niño and La Niña events, nutrients availability and human and biological pressures. In 1997, an strong El Niño year, temperature anomalies increased in 5 °C [74], which generated a drop in the diversity of marine species (anchovy, mullet, silversides, etc.) that migrated southwards. This process occurred again, although with lesser intensity, in 2001, 2006, 2009 and 2012. However, between 2002 – 2005 and 2010–2011, diversity of species increased due to La Niña event associated to cold waters rich in nutrients. This long-term loss of biodiversity increases the sensitivity of the artisanal fishermen, given the variations in catches [Fig. 4].

Dynamic projections of temperatures for the RCP 2.6 and RCP 8.5 scenarios for the Central coast of Peru (7°S – 13°S) (M. Gévaudan com. pers.) show an increase in the stratification in the first meters of depth [75,76] and a decrease of coastal upwelling due to strong stratification and a less effective Ekman dynamics [77,78]. Future conditions in the SST and UI will therefore represent higher exposure to interannual

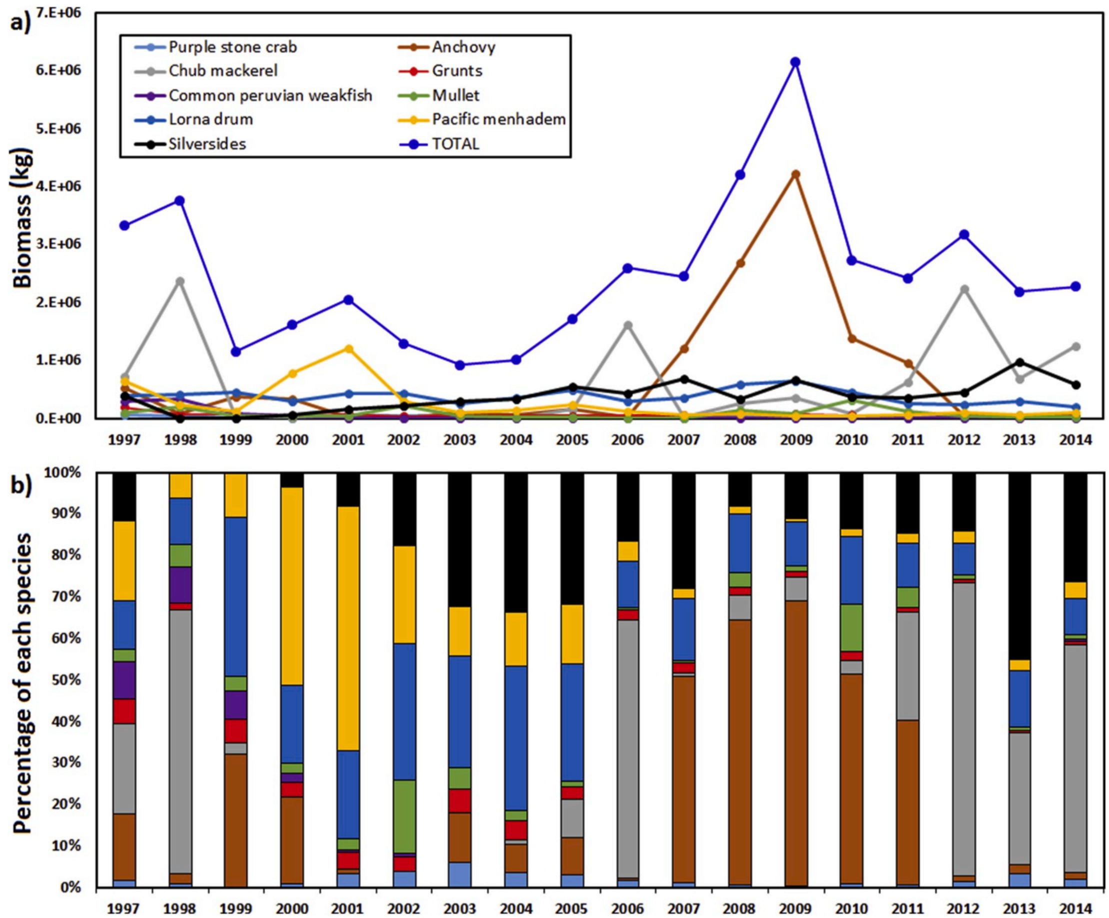

Fig. 4. Time series of catches of dominant species (a) total catches (kg) and (b) percentage of each species with respect to total catches per year.

variations in catches. Catches are expected to vary strongly with these future oceanographic conditions [7]. It is expected that a minor percentage of cold water marine species will migrate to deeper waters seeking optimal areas for their development, while a major percentage will migrate towards the south [60]. Also, an increase of mortality rates is expected due a low level of nutrients and primary productivity. On the other hand, warm water species will increase their biomass levels and will shift their distribution closer to the coast [58].

3.2. Sensitivity results

The proportion of artisanal fishers in each community, and therefore the importance of the artisanal fishery, increased between 2003 and 2012 [Fig. 7]. The number of boats increased from 2003 to 2012 by 41.66% in the port of Huacho (600 vessels), by 47.78% in Carquín cove (383 vessels) and 40.88% in the port of Vegueta (203 vessels) [Fig. 7a]. The increase in the number of artisanal fishermen (registered and non-registered) has a direct relationship with the increase in the number of vessels. From the three main landing sites, the port of Huacho presents the largest catches compared to the rest of ports located in Lima-North [79], and counts with the most population of the three communities. Despite artisanal fishery of anchovy in Huacho should be oriented to human consumption, the higher prices of anchovy for industrial fishmeal, generate a deviation towards indirect human consumption [80, 81].

Each community in the Huaura province presents very different socio-economics characteristics. Carquín has the largest number of artisanal fishermen with respect to the rest of the population (10.45%), but Huacho counts with more economic alternatives to artisanal fishing, with a low number of fishermen over its total population (0.76%) [Fig. 7 b,c].

We find the highest sensitivity to ecological changes in Carquín (“high”, 0.800) driven by a lower richness of the natural banks and continental aquaculture (continental), whereas the lowest S_{ECO} was obtained for Vegueta (“medium”, 0.500) because there are medium change in the catch, lower change in variety of species available [Fig. 6] and high richness of mariculture. The highest socio-economic sensitivity was obtained for Carquín (“medium”, 0.400) given the high population density, lack of wetland tourist corridors and lack of landing infrastructure. The lowest S_{SOC} was obtained equally for Vegueta and Huacho (“very low”, 0.100) given the lower population density, the availability of land and wetland tourist corridors and port infrastructure.

Population in the province has been steadily increasing over the last 40 years [Supplementary Fig. 3]. Vegueta presents the lowest population density (64 people/km^2). However, the highest level of population density today occurs in Carquín (2811 people/km2), due to its small surface in comparison to the others districts. Carquín counts with 2.04 km^2 of land whereas Huacho has 717.02 km^2 of land in the district. In general, smaller communities present lower possibilities of economic diversification (e.g., availability of land for agriculture or livestock), and will be the most affected by climate change in comparison to larger communities.

Availability of port and landing infrastructure ensure safety and sanity conditions. Huacho and Vegueta count with port infrastructure, which allows fast landings and greater opportunity of commercialization of the marine resources. Conversely, Carquín only has a cove where the landing of boats is more difficult and also limits boats with greater hold capacity.

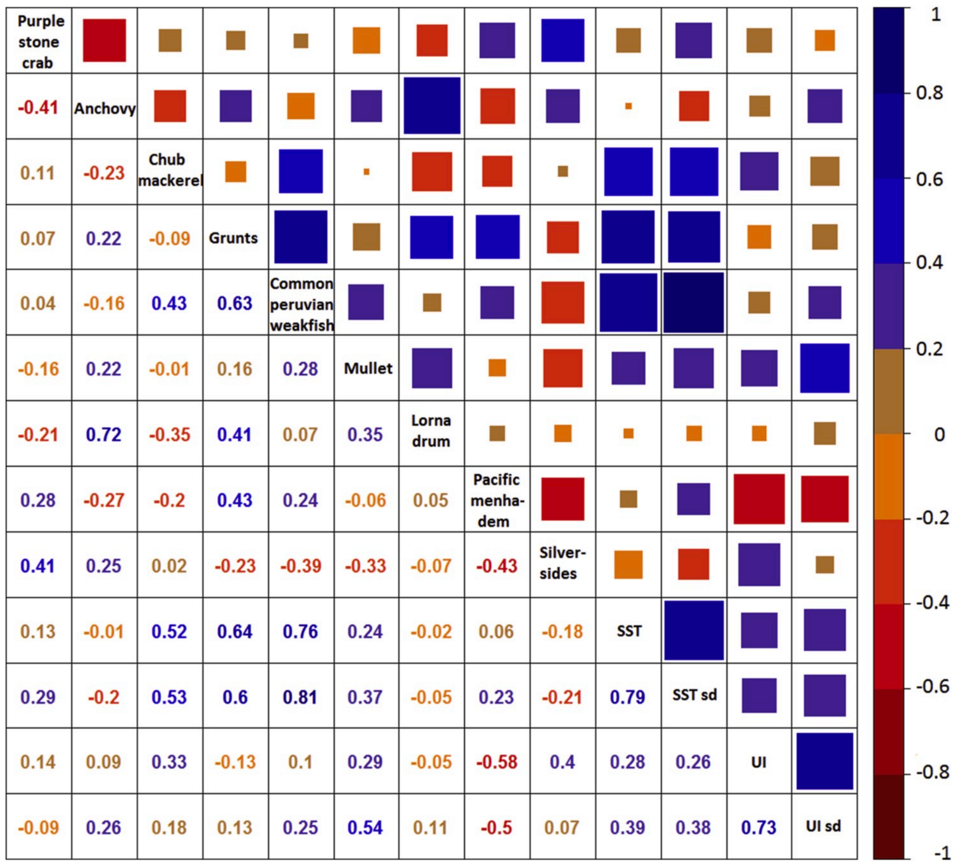

Fig. 5. Correlation matrix of dominant species with means and standard deviations (sd) of exposure variables: Sea Surface Temperature (SST) and Upwelling Index (UI).

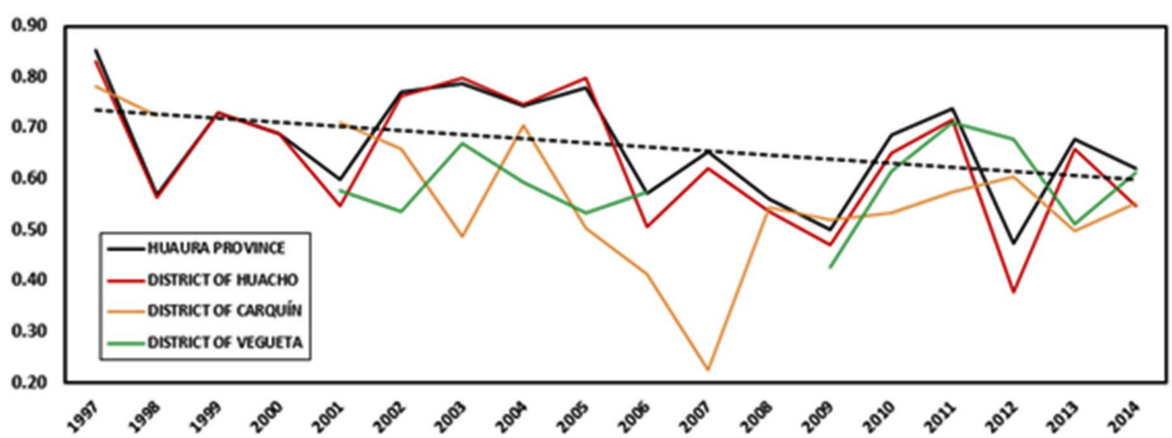

Fig. 6. Diversity index (1-D) for the dominant species on Huaura province (black), and calculated independently for each district: Huacho (red), Carquín (orange) and Vegueta (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.3. *Adaptive capacity to future changes*

At present, the lowest adaptive capacity to ecological changes was obtained for Carquín ("low", 0.357), due to the low proportion and size of PNA relative to the fishing zone. The largest number of Protected Natural Areas (PNA) which are areas for the conservation and protection of species [56], are in Huacho and Vegueta. Carquín lacks PNAs. The presence of PNA allows increasing the AC of each community, because they allow the protection and conservation of the biodiversity of marine and terrestrial species. The highest ecological capacity was obtained for Huacho, with a value of "very high" (0.857), due to the size and proportion of PNA relative to fishing zone (Huacho presents the largest extension of PNAs 19,277.8 ha), the size of PNA, and use of selective fishing gears in comparison with others districts. Huacho also presents the highest socio-economic adaptive capacity ("very high", 1.000) because it presents higher economic diversity, and lower level of poverty. Meanwhile, Carquín and Vegueta present low socio-economic capacity ("medium", 0.500) driven by a medium economic diversity and higher level of poverty [Fig. 8].

For a pessimistic future scenario, assuming low adaptation and higher exposure to the impacts of oceanographic changes and climate change, the highest and lowest ecological capacity were obtained for

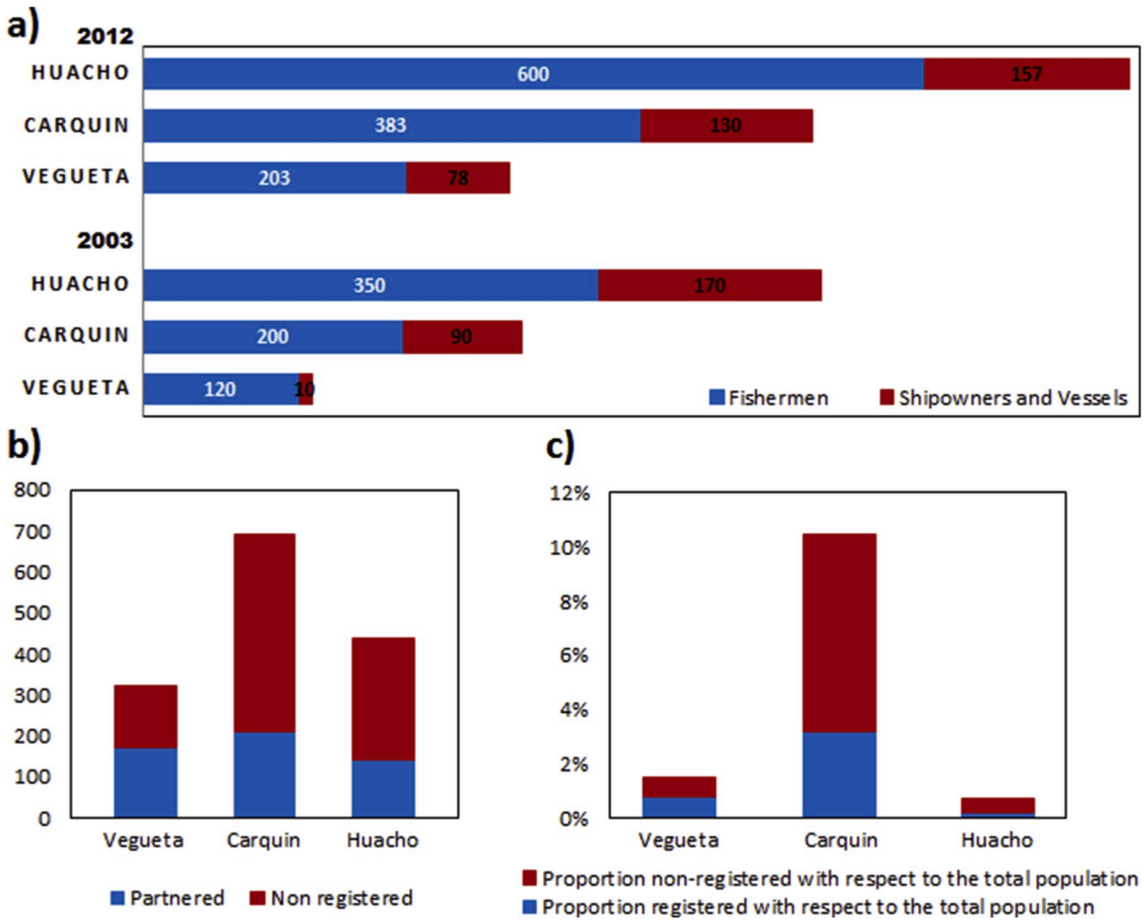

Fig. 7. Characteristics of the fishing sector in the province. (a) Number of vessels per district in the years 2003 and 2012, obtained from the first census of artisanal fishing in the maritime field; (b) Total number of artisanal fishermen registered in 2012; (c) Total number of artisanal fishermen with respect to the total population per district.

Huacho and Carquín, respectively ("high", 0.725 and "low", 0.268), whereas socio-economic capacity were highest for Huacho ("high", 0.738) and the lowest for Vegueta ("low", 0.288) [Fig. 9].

For an optimistic future scenario, with more effective adaptation and lower impact of oceanographic changes and climate change, the highest, both ecological and socio-economic, AC were obtained for Huacho and the lowest for Carquín. Unlike the pessimistic scenario, the optimistic scenario shows increases in AC of 29.29%, 27.14% and 21.43% for the three districts (Huacho, Vegueta and Carquín) for ecological changes and an increase of 41.25%, 31.25% and 27.5% for Huacho, Vegueta and Carquín for socio-economic adaption. These improvements are associated with the use of selective fishing gears, more economic diversification, reduction in level of poverty in the region, control plans for fishing quotas, increase in the PNA, better fishing practices that are selective on species and new policies to address the effects of climate change [Fig. 10].

3.4. Socio-ecological vulnerability

In the present conditions, the highest socio-ecological vulnerability was obtained in Carquín ("medium", 0.561) because it has the highest lack of adaptive capacity, due to the absence of PNA and a normative framework capable of protecting the most susceptible species from the effects of climate change. The lowest SEV occurs in Huacho ("low" 0.267) because it profits from a wide variety of alternatives activities such as agriculture, aquaculture, among others, perceiving higher income compared to Carquín. Thus, smaller communities, less diversified economically will also be the most affected by climate change in comparison to bigger communities.

In the future, under a RCP 2.6 scenario, the SEV values increase very little presenting increments in 3.87%, 4.58% and 2.44% for Vegueta, and Carquín and Huacho, respectively. However, under a RCP 8.5 scenario and with reduced adaptation, due to the strong increase in SST and decrease of UI in the region, SEV increase in 29.05%, 27.40% and 30.66% for Vegueta, Carquín and Huacho, respectively.

4. Discussion

Peru is a country with high dependency on fishing, and where artisanal fishing is a major contributor to local wellbeing. This study is the first in Peru to identify and measure socio-ecological vulnerability in any marine and coastal province. We adapted existing vulnerability frameworks previously applied to fisheries, such as Adger & Vincet [82] that was applied at a regional scale, and Mamauag et al. [30] that refined it for a local scale. Our analysis shows differences in vulnerability of local communities and substantial changes in scenarios associated to different factors.

The species and quantities captured vary strongly between years in direct correlation with changes in the SST [Fig. 2]. These variations were favored by the EN events, which will increase its frequency and intensity, contributing to a greater occurrence of warm waters species (e.g., dolphinfish [83], tuna). Ding et al. [4] argue that others direct effects could be the changes in reproduction, changes in the magnitude and range of distribution (horizontal and vertical) and variations of populations dynamics. Such variations indicate a sustained tendency to the increase of several warm water species, and a long term reduction of

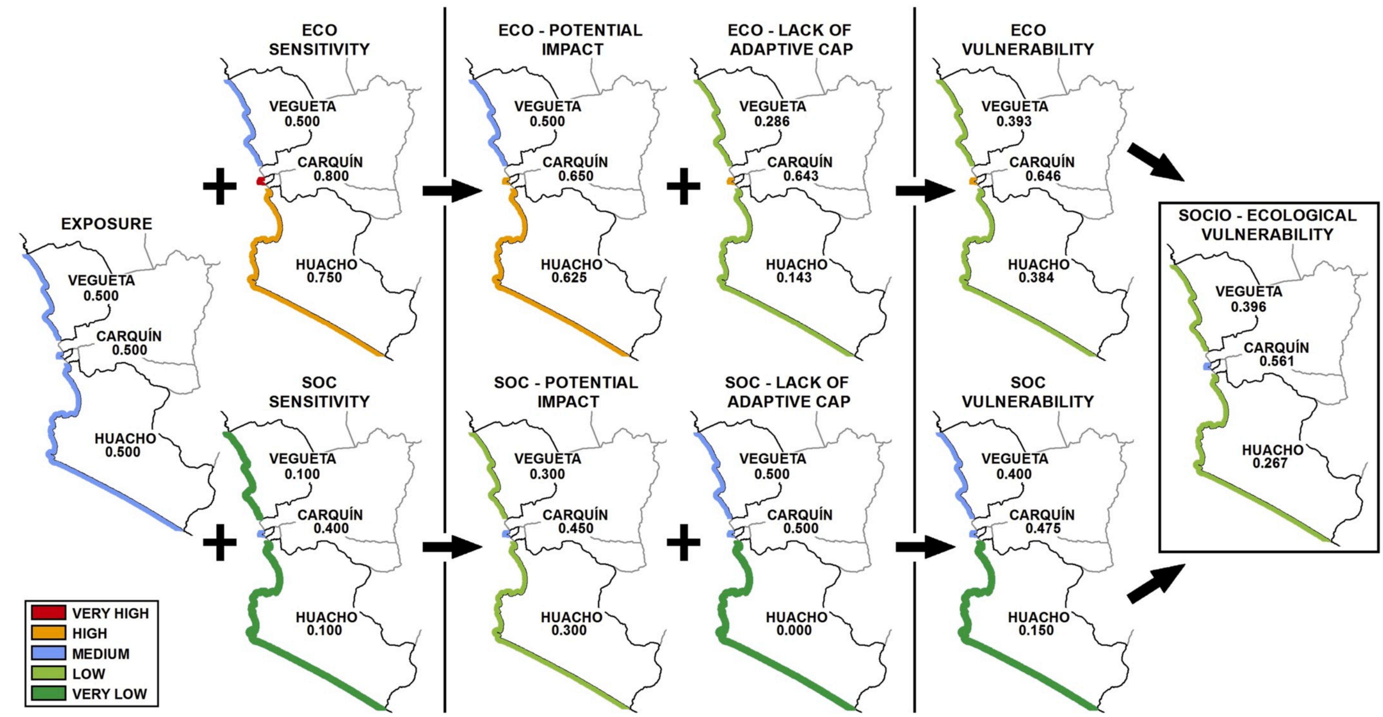

Fig. 8. Calculation of present SEV, using historical data of exposure (E) indicators, sensitivity (S), potential impact (PI) and present measures of adaptive capacity (AC).

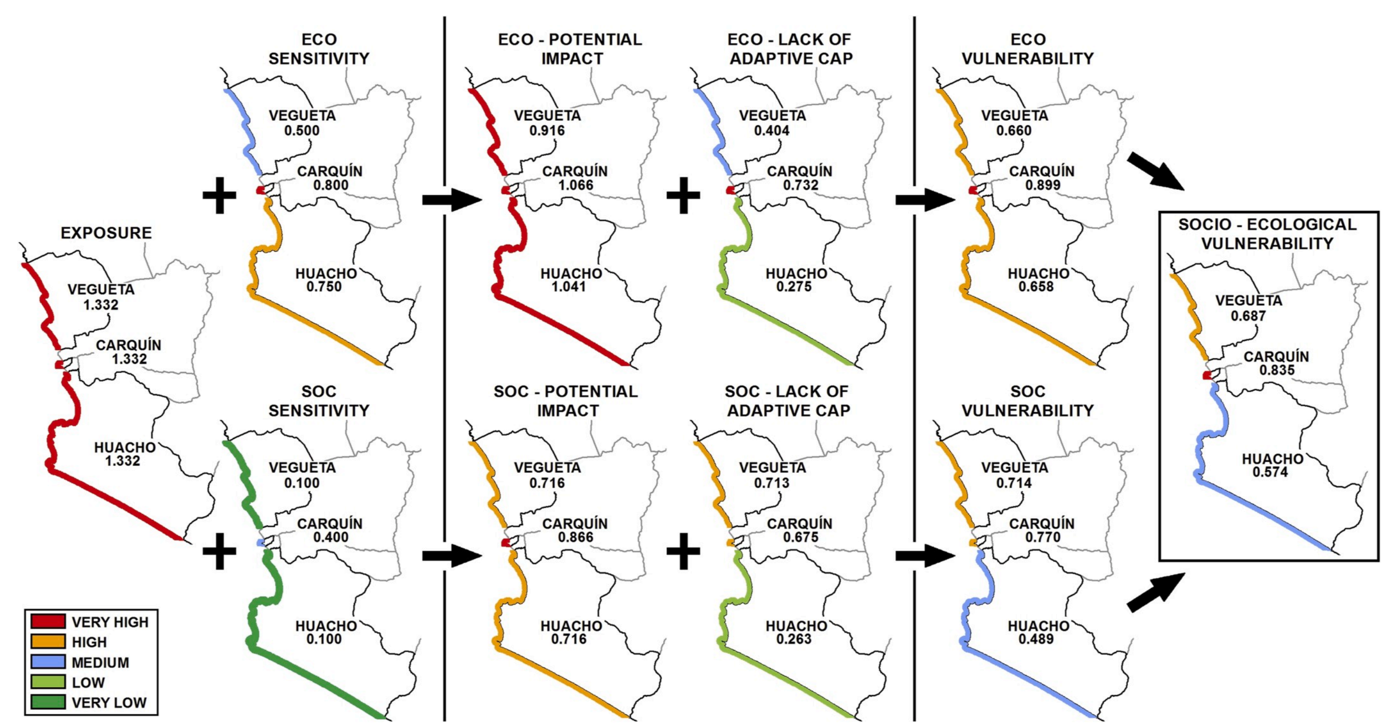

Fig. 9. Calculation of future SEV under a pessimistic scenario (RCP 8.5 and lower future adaptive capacity).

cold-water species (e.g., anchovy [84,85]). Given the dominance of some cold-water species and the increase of warmer waters in the future, the sensitivity to future changes in oceanographic conditions will be relatively high [86]. The reduction of species diversity could be harmful because less heterogeneous systems present lower capacity to adapt to future climate change. In addition to this, human population continues to grow [Supplementary Fig. 3], increasing direct and indirect dependencies on fishery resources.

Likewise, Alfaro-Shigueto et al. [2] reported that small-scale fishery population, existing along the Peruvian coast, increased in the last 10 years. This increasing trend of artisanal fishers will generate a great pressure over marine species, driving a prominent reduction of marine diversity [87–89], which will increase the socio-economic sensitivity to variations in future fishery resources [90].

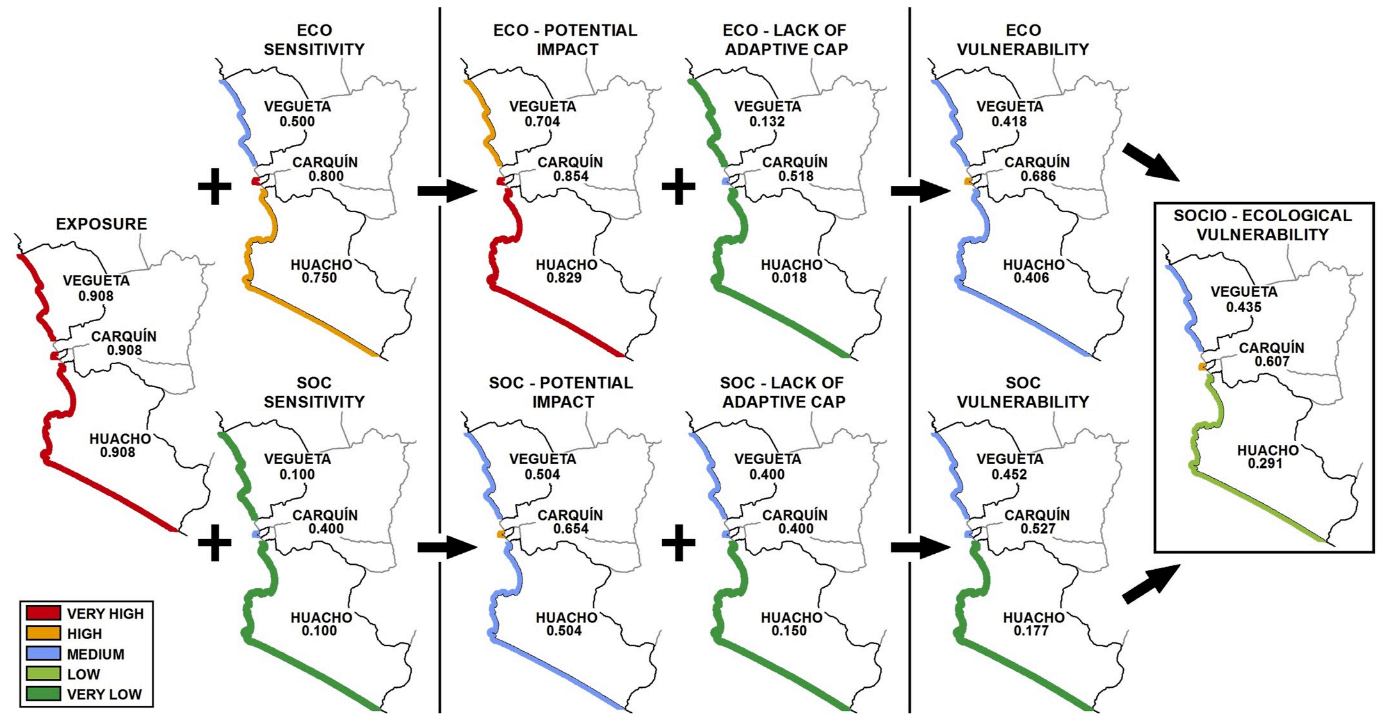

Fig. 10. Calculation of future SEV under optimistic scenario (RCP 2.6 and higher future adaptive capacity.

This is true in the determination of vulnerability at different spatial scales. Furthermore, each community or district respond of different way to climate change in function of different indicators of sensitivity and adaptive capacity [4,39].

Allison et al. [32] and Ding et al. [4] argued that the communities with high level of vulnerability are those that presented a high level of exposure and sensitivity, and a low or very low level of adaptive capacity. We found similar relationships when comparing the vulnerability of the three fishery localities analyzed in the present study: Carquín was the most vulnerable community followed by Vegueta and Huacho. Carquín was characterized by high quantity of catches, high population density and the highest proportion of artisanal fishers in the community, but it doesn't have PNAs, lacking of measurements to cushion the socio-economic impacts of artisanal fishing on representative species. In contrast, Huacho had the lowest values of vulnerability due to the presence of a great number of PNA's, favoring the conservation of marine diversity, port infrastructure and the largest economic diversification (fishermen could shift to agriculture, aquaculture, tourism, etc.). Huacho also has the largest number of natural banks, of several species (e.g., purple stone crab, hairy rock crab, chocolate rock shell, razor clam and sea cucumber) in comparison with the other two districts [Supplementary Fig. 1], whereas Vegueta counts with three natural banks and Carquín lacks natural banks [80].

This is consistent with the vulnerability assessment developed by Mamauag et al. [30] and Licuanan et al. [88], in small districts in the Philippines, where they found that high sensibility was associated to a low catch rate, high fishing effort and high reliance on the fishing resource, while a low adaptive capacity was associated to extraction of juveniles species, degradation of habitats and lack of economic diversification. In addition, Macusi et al. [87], evaluated different villages of Mindanao, Philippines, to find that the greatest impacts for fisheries were changes in species distribution, changes in reproductive patterns, increases in invasive species, decreases in rate catch by overfishing and disappearances of species. Moreover, Damasio et al. [91] found that for small-scale fisheries in Brazil the main impacts were the reduction in the amount of catches from overfishing, increased fishing competitiveness, increased distribution ranges and coastal degradation.

The highest level of population density occurred in Carquín due to its small surface in comparison to the others districts, which limits alternative sources of economic diversification (e.g., agriculture o livestock). In general, smaller communities present low economic diversification and will be the most affected by climate change [39]. Carquín also lacks port and landing infrastructure that ensure safety and sanity conditions, the cove makes the landing of boats more difficult and also limits access of boats with greater hold capacity [92].

Comparing present and future vulnerability scenarios, vulnerability will increase, but the vulnerability ranking of the three localities was maintained. The three localities are spatially close as to be equally exposed to changes in the resource. However, Carquín remains as the most vulnerable in any scenario. The largest changes in vulnerability were explained by a change in: sea surface temperature (E); richness of the natural banks and change in the catch (S_{ECO}); wetland tourist corridors, port infrastructure and population density (S_{SOC}); proportion of PNA relative to the fishing zones, presence and size of PNA (AC_{ECO}); level of poverty in the region and economic diversification (AC_{SOC}).

The vulnerability analysis of the province also contributed to understand the importance of adaptation. Huacho has the highest adaptive capacity given the high proportion of PNA relative to the fishing zone, high use of selective fishing gears and high presence and size of PNA. Its socio-economic adaptive capacity is also larger given its high economic diversification and low level of poverty. Carquín, on the contrary, presents the lowest level of AC_{ECO} given a low proportion of PNA relative to the fishing zone and small PNA, a great dependence on artisanal fishing and higher levels of poverty. These factors require urgent adaptation and upfront planning, which is discusses in the following section.

5. Adaptation recommendations

Daw et al. [93,94], established diverse adaptative measures for marine and freshwater fisheries potentially susceptible to climate change, which are: i) Increase of economic diversification on the basis of different sustainable development plans for small fisheries, ii) Management plans to possible environmental disasters, integrating prevention, precaution an mitigation plans, iii) Improvement of distribution channels and implementation of new technologies and iv) Establishment of fishing quotas as a function of annual potential ecosystem productivity and stocks volumes.

Our results indicate that the adaptive capacity of these three communities needs to increase to face the present and future climatic changes. The objectives and principles set out in the Peruvian National Strategy (ENCC) and the Lima Regional Strategy (ERCC) on climate change are fully applicable here. The public policy objectives of the Peruvian ENCC (2015): (i) increase awareness and adaptive capacity in the face of adverse effects but also the opportunities of climate change, in its dimensions of institutionally and governance, awareness and capacity building, knowledge and technology, and financing; and (ii) reduce emissions and conserve carbon stocks; as well as its means of implementation and increasing the resilience of ecosystems. The Lima ERCC (2015) also summarizes the international, national and regional regulatory framework for the implementation of adaptation, as well as management instruments in force in the Lima region. Given this frameworks, the adaptive capacity of the three communities analyzed in the present study need to be strengthened in face to present and future climate changes.

Increasing the adaptive capacity will require the implementation of different strategic adaptation measures: creation of PNA, protection of juveniles, ecosystem quotas, buffer zones, restoration of natural banks, sustainable aquaculture and co-management regulatory framework. Also, the socio-economic adaptive capacity could be enhanced by: reducing poverty levels, diversifying economic activities, increasing fishing income and added value, and developing better coastal infrastructure.

Based on these national and regional adaptation guides, the local socio-ecological vulnerability analysis, and the local economic activities and context, we summarize below some potential adaptation measures for the Huaura province that could address the increasing climate vulnerability:

1. Strengthening the capacity of organization and planning of the artisanal fishing communities, particularly in Huacho, in face to variations occurring in the resources based on monitoring oceanographic changes.
2. Co-management of fishery resources with fishers, such as silverside in Carquín and razor clam in Huacho, including the design and use of sustainable fishing gears, as artisanal fishing communities are key elements to better adapt to changes in the resources and they can help to support the implementation of sustainable management practices.
3. An oceanographic observation and forecasting modeling system for fishery planning prior to resources changes, as well as, pollution monitoring and treatment of wastewater, such as fishmeal effluents in Carquín, Vegueta and Huacho.
4. Strengthening sustainable aquaculture (e.g., scallops or mussels in Huacho) to complement fishing activities in the marine-coastal ecosystem and converting aquaculture and fishing residues into agricultural fertilizers using bacterial consortia.
5. Diversify and strengthen the economic added value of artisanal fishery products, for example using dried anchovy to promote direct human consumption of the Carquin's traditional meal called "charquican" [95], as well as with development of alternative economic activities of fishers (e.g. ecotourism in Don Martin island marine protected natural area near Vegueta).
6. Establishing mechanisms that can attenuate the socio-economic impact of inter-annual variations in the resource, such as insurance against extreme events and financing mechanisms planned to limit community dependence on third parties that can have leverage during disruptions periods in the fishing activity.

However, these adaptation actions should be taken as reference guidance and should be specially designed and adjusted locally according to the priorities established in each community. Furthermore, these adaptation options should be assessed with the participation of all stakeholders for their feasibility of implementation, as well as their cost-effectiveness. The Ministry of Production in agreement with the Peruvian Marine Research Institute (IMARPE) and the Ministry of Environment are executing two pilot projects to initiate some of these adaptation interventions, with the financial support of the Inter American Development Bank and the Adaptation Fund.

6. Conclusions

Historical data shows that artisanal fishing resources depend on the SST and UI in the Huaura province associated to El Niño and La Niña events. Carquín presents the highest vulnerability (0.561, "medium") driven by the highest proportion of artisanal fishers in the community in comparison with the other locations, a greater quantity of catches as their main source of income; and a low adaptive capacity. Huacho presents the lowest vulnerability overall (0.267, "low") because it has a small spatial distribution of catches and port infrastructure facilities. Moreover, its adaptive capacity is greater because it presents higher economic diversification and lower levels of poverty.

In the future, all localities will increase their vulnerability associated to an increase in the physical exposure, which will generate greater pressure on marine species that will change their distribution and will reduce the biomass of cold-water species. Carquín is expected to maintain the highest vulnerability, being very high (0.835) for pessimistc scenario and high (0.607) for an optimistic scenario. These results highlight the importance of implementing adaptation measures in order to counteract the impacts of climate change on livelihoods of the more vulnerable artisanal fishing communities.

Author statement

HJJ, JT and BGR conceptualized and designed the research, performed the analysis, developed the visualization and lead the writing of the manuscript. CYR, MG, FG, GC and AS provided information and insight. All authors contributed to the writing and the revision of the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpol.2020.104003.

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