# Chapter 30
# Adaptations to Climate Variability in Fisheries and Aquaculture Social-Ecological Systems in the Northern Humboldt Current Ecosystem: Challenges and Solutions

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**Significance Statement** The Peruvian Upwelling ecosystem is highly productive. El Niño variability affects species abundance and distribution, and thus marine activities. Climate change is modifying El Niño patterns, compromising the strategies of marine organisms and human activities to cope with its variability. We focus on three marine social-ecological systems to identify weaknesses and leverage points for adaptation and resilience. We find that (1) the Peruvian artisanal fishery and aquaculture sectors urgently need an institutional framework for adaptation to future environmental changes; (2) bottom-up adaptation strategies require institutional support, tailored to socio-ecological specificities; and (3) additional research on socio-ecological tipping points and their effects for human-nature interactions and societal repercussions is necessary. These finding may be useful in other systems undergoing similar challenges.

**Keywords** Resource use · Human-nature interaction · El Niño · Climate change adaptation

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## 1 The Northern Humboldt Current Social-Ecological System and Its Sensitivity to Climate

The Humboldt Current flows northward along the coast of Chile until Northern Peru, producing an upwelling of cold, nutrient-rich waters which allow sustained growth of phytoplankton. The upwelling supports one of the most productive systems globally, the Northern Humboldt Current Ecosystem (NHCE) (Chavez et al., 2008; FAO, 2020a). This system is home of the Peruvian anchovy or *anchoveta* (*Engraulis ringens*), a small, fast-growing pelagic fish, target of the largest single-species fishery worldwide. The Peruvian fishing sector provides jobs, revenues, and food, overall accounting for up to 3% in the national GDP (Central Reserve Bank of Peru, 2020). The *anchoveta* industrial fishery is the most important sector in terms of landings and revenues, while artisanal fisheries constitute an increasingly important employment option for coastal communities and aquaculture is a comparatively novel and rapidly growing activity in coastal areas. Industrial fishery for *anchoveta*, artisanal fishery and marine aquaculture are all embedded in distinct complex social-ecological systems, comprised of different stakeholders, target resources, value chains and drivers of change.

The NHCE is strongly subjected to El Niño Southern Oscillation (ENSO), a recurring climate-oceanic phenomenon in the Tropical Eastern Pacific that causes climatic fluctuations with a pseudo-cyclical appearance every 3–7 years. ENSO presents two alternating phases: an anomalous warm phase ("El Niño", EN) and an anomalous cool phase ("La Niña"). Different types of events exist, including Central Pacific warming (CP-EN or Niño Modoki), and Eastern Pacific El Niño (PE-EN), the most famous and visible, differentiated in moderate and extreme EN events. EN generally causes a warming of coastal waters that disrupts the upwelling in front of the Peruvian coast (Chavez et al., 2008; FAO, 2020a; Wolff et al., 2003). This interaction affects the local climate (e.g. increasing temperature and heavy rainfall with floods), the pelagic and coastal marine ecosystems and the human activities depending on them, thus impacting the whole social-ecological system. Although the full extent of EN impacts on ecosystems remains unclear, the most visible effects include changes in species distribution and abundance (e.g. FAO, 2020a; Ñiquen & Bouchon, 2004). The impact of ENSO on fisheries depends critically on the event type: landings can drop by 3 million tonnes during extreme EN events, and increase by 1.1 million tonnes during La Niña (FAO, 2020a). However, impacts differ greatly by spatial scale, location, species and activities, as shown by the contrasting response of scallops to EN events in different areas (Wolff, 1987; Wolff et al., 2007; See also Sects. 2 and 6).

Typically, EN events start with sea surface temperature (SST) anomalies in the Western Pacific Austral winter (JAS), hit the Peruvian coast in summer (JFM), and recede in autumn (AMJ) (Chavez et al., 2008). These first warning signals allow early detection and adaptive management measures (Oliveros-Ramos et al., 2021). However the intensity, duration, and typology of EN events cannot yet be well predicted (FAO, 2020a), and some events, such as the marine heatwave of 2017 develop too rapidly for marine activities and society to prepare in time.

The aim of this study is to compare differences and similarities between three Peruvian case studies of human use of marine resources: (i) the industrial, large scale fishery targeting *anchoveta*, operating offshore (ca. beyond 10 nm), and two inshore activities (ca. within 10 nm), namely (ii) the small-scale and artisanal fisheries (hereafter, artisanal fishery) and (iii) the scallop aquaculture (further described in Sect. 2). By looking at different social-ecological systems at large and small spatial scale, this cross-scale comparison highlights the challenges encountered in the past when being confronted with climate variability, the solutions applied to face these challenges, and the future outlook, using a social-ecological perspective.

## 2 Case Studies: *Anchoveta* Fishery, Artisanal Fishery and Scallop Aquaculture

The *anchoveta* fishery accounted for 86% of landings in Peru and 10% of global landing in 2018 (FAO, 2020b, c), resulting in 1% of the total national GDP (Christensen et al., 2014). Anchovies fuel the export-oriented fishmeal/fishoil industry for the global animal feed market, which produces about 50% of global fishmeal (FAO, 2020a, c). This activity is therefore of strategic economic and social importance for the country. The fishery started in the 1950s and rapidly developed thereafter, despite the stock fluctuations attributed to environmental variability (Arias Schreiber et al., 2011; Chavez et al., 2008), and EN-related stock collapses, notably in 1972–1973 and 1983–1984. However, favourable environmental and management circumstances during the EN of 1997–1998 allowed the stock to rapidly recover, permitting the fishery to resume (Arias Schreiber et al., 2011; Bertrand et al., 2004; Ñiquen & Bouchon, 2004). The advanced adaptive management strategy in place (see Sect. 4) likely facilitated the recovery, avoiding stock collapse (Bertrand et al., 2018). As such, the *anchoveta* fishery is considered to be a well-managed, sustainable fishery (FAO, 2020a; Oliveros-Ramos et al., 2021).

Artisanal fisheries vest a key role for food security and employment in Peruvian coastal communities (Alfaro-Shigueto et al., 2010; Jara et al., 2020), with increasing landings and employment trend in recent years (De la Puente et al., 2020; Guevara-carrasco & Bertrand, 2017). These fisheries are mostly informal and not extensively managed (Guevara-carrasco & Bertrand, 2017). Artisanal fishers have exclusive rights up to 5 nautical miles from the coast, where they target coastal fish and invertebrates with a variety of gears and metiers. Large and small pelagic fish seasonally migrating inshore complement local catches, while some fleets venture offshore to target pelagic species. 335 species are reportedly landed (7 species represent >80% of landings), for a total of over 430,000 tons in 2018 (IMARPE, 2018). While artisanal fisheries are important along the entire Peruvian coastline, the Piura region (*cf.* Fig. 30.1) represents a hotspot: this region hosts about one third of

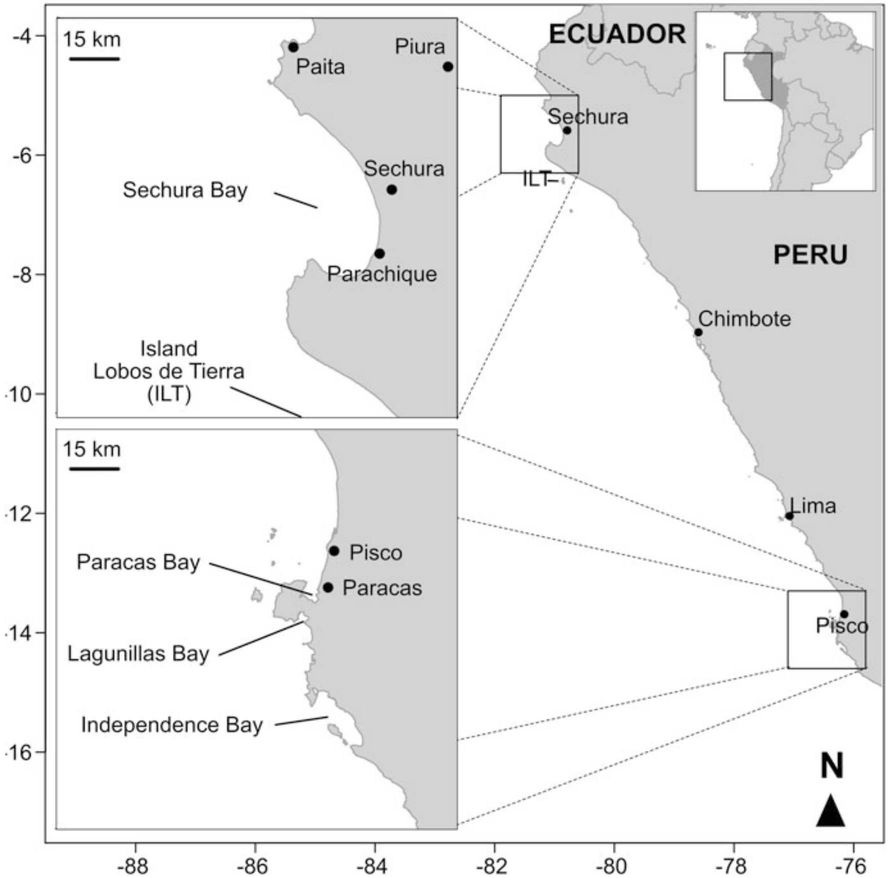


**Fig. 30.1** Map of the Peruvian coastline. The region of Piura and province of Pisco, key areas for artisanal fisheries and for scallop aquaculture, are showed in the insets (Figure constructed in the R environment (R Core Team, 2019) using the maps (Brownrigg, 2018) and TeachingDemos (Snow, 2016) packages and Peruvian administrative area (region-level) geographical information that was retrieved from the Database of Global Administrative Areas (GADM, www.gadm.org, subdivision level 1))

artisanal fishing vessels (over 5500 vessels in 2012; Guevara-carrasco & Bertrand, 2017) and a large part of the population depends on fisheries-related activities (Figs. 30.2 and 30.3).

The aquaculture sector targeting the Peruvian bay scallop (*Argopecten purpuratus*) has emerged in the past 20 years: the traditional scallop diving fishery within the region of Pisco (central Peru; Fig. 30.1) experienced a boom during the scallop stock outburst resulting from the strong El Niño events in 1983/84 and 1997/98 (Wolff, 1987; Wolff et al., 2007), which prompted cultivation attempts. Since the early 2000s, Sechura Bay (North Peru, Fig. 30.1) has developed into a hotspot for scallop culture, where it constitutes a locally important socio-economic

**Fig. 30.2** Artisanal purse seine fishing vessel operating in the waters of Northern Peru. (Photo: L.C. Kluger)

export-oriented activity, providing direct and indirect jobs to 25,000 people (Kluger et al., 2019a; Fig. 30.4). Sechura Bay is located in a transition zone, where the upwelling waters from the south meet warmer, equatorial waters from the north, creating favourable scallop culture conditions when compared to colder settings in the south. However, EN events impact drastically this region through torrential rains and substantial water temperature increase, causing die-offs of scallops and other benthic organisms. In Pisco, in contrast, scallops typically thrive during EN events. As a response, scallop fishers and farmers migrate between these locations according to changes in resource abundances (Kluger et al., 2020).

## 3 Challenges Posed by El Niño and Climate Change: Ecological Aspects

EN and climate change impact the NHCE through increase in temperature, frequency of tropical storms and of marine heatwaves and flooding events (Gutiérrez et al., 2019). Critically, these processes do not occur in isolation, and might interact and reinforce each other. For example, the localised but severe impact of the 2017

**Fig. 30.3** Small-scale fishing vessels awaiting their next trip; Laguna Grande/Independence Bay, Pisco. (Photo: L.C. Kluger)

**Fig. 30.4** Worker (Span. *tripulante*) on a scallop harvesting boat in Sechura Bay storing freshly harvested scallops in meshbags for transport ashore. (Photo: L.C. Kluger)

marine heatwave event might have been amplified by a climate change-related long-term warming of the ocean (Christidis et al., 2019).

Climate models do not allow accurate predictions about EN occurrence (amplitude, frequency and pattern) nor about EN interaction with climate change, however some studies propose an increase in frequency of extreme EN or suggest that climate change will drive a slight reduction of upwelling in the NHCE (Echevin et al., 2020; FAO, 2020a). These predicted patterns could negatively impact especially short-lived species such as anchovy, causing warming-induced reduction in abundance and southward spatial displacement (Gutiérrez et al., 2019; Oliveros-Ramos et al., 2021). Such effects are effectively observed during EN events; however, recent evidence suggests that *anchoveta* may be well adapted to the ENSO, having developed ecological mechanisms to cope with environmental variability at evolutionary time scale, such as the capability to find spatial-temporal windows of favourable conditions (e.g. seeking refuge in shallow, coastal areas) during EN years (Bertrand et al., 2004; Salvatteci et al., 2019). However, there is a risk that climate change may compromise the capability of anchovies to exploit refuge windows, eroding the resilience of the system to oscillations and increasing the risk of permanent stock collapse and regime shifts (Bertrand et al., 2018; Chavez et al., 2008). In addition, other pelagic species (e.g. mackerel, tuna, bonitos, dolphinfish, Humboldt jumbo squid) show apparent increasing or decreasing trends associated with EN events, potentially affecting predation pressure on *anchoveta* and causing unpredictable changes to the ecosystem dynamics.

During EN, enhanced equatorial subsurface countercurrents (SSCCs) carry eastward oxygen-rich waters contributing to ventilation in the otherwise poorly oxygenated NHCE (Espinoza-Morriberón et al., 2019). In the last decades, a change in ENSO nature was observed, with no extreme EN events occurring after 1997 and increasing predominance of the CEP-EN (Modoki). This novel pattern may be attributable to global climate change and, if currently observed trends continue, will lead to further deoxygenation of the ecosystem and the shrinkage of important habitats for fishery target species. Associated to this situation is the expected increase in the occurrence of extreme events such as anoxic and sulfidic events, which may cause mass mortality episodes (Wolff, 2018).

Coastal areas are influenced both by regional oceanic-atmosphere patterns and by local pressures. EN events can cause die-offs of benthic organisms, reduction or southward displacement of cold water species, and increase of tropical, warm-adapted species. These patterns are reflected in the variability of coastal species catches (Jara et al., 2020). Warming event types may affect coastal areas differently: marine heatwaves typically have a marginal influence on the offshore system (Bouchon et al., 2019), but affect substantially inshore areas in the North. During the 2017 marine heatwave, in Sechura Bay, the combination of increase in temperature, reduction in salinity caused by strong rains and river runoff and hypoxic conditions on the sea bottom caused a die-off affecting both farmed scallops and other bottom invertebrates, including locally important target species (Kluger et al., 2019a). The negative effect of EN on scallop farming in the North is contrasting to how the Southern part of the county is affected: here, increased temperature during EN leads to tremendous proliferations of scallops (Wolff, 1987; Wolff et al., 2007) attracting scallop fishers in the region. Such divergent response reflects the fine-scale spatial granularity of consequences of environmental disturbances along the long, diverse Peruvian coastline. The effects on local social-ecological– systems can thus hardly be predicted by regional patterns alone. Irrespectively, the predicted increase in frequency and intensity of EN events may drive larger variability and permanent changes to the coastal and bays ecosystems. However, the limited knowledge of ecosystem-environment dynamics hampers a better understanding of the plausible effects on individual systems.

# 4 Case Study 1: *Anchoveta* Fishery

## *4.1 Socio-economic Challenges*

The highly specialised *anchoveta* fishery is strongly dependent on the dynamics of its target species. Stock oscillations can be highly problematic for the industry: as an example, the 1972/73 anchovy collapse forced 1500 fishing vessels and 200 processing plants out of activity, leaving over 100,000 people unemployed (FAO, 2020a). The current management system focuses on long-term maintenance of the stock, with catch limitations during EN events to allow the stock to rebuild. These limitations can be a challenge for the industry that must adapt to fluctuations in allowed catch and in profit. The stock's spatial displacement during EN events, with fish moving southwards, represent another challenge, increasing fishing and labour costs, as well as logistics complexity.

## *4.2 Existing Adaptation Approaches and Outlook*

The anchovy fishery sector gradually constructed a robust set of institutional and industry-led measures to cope with climate variability and its impacts (Arias Schreiber et al., 2011; Oliveros-Ramos et al., 2021). These include an adaptive management approach with two stock assessments and seasonal catch limits per year, coupled with spatial-temporal fishing closures, based on near real-time monitoring of biological and environmental conditions. Early warning forecast of the ENSO conditions allows to implement further catch restrictions to protect the stock. Moreover, reduction of excess fleet and fish processing plant capacity, and an individual quota system were introduced to reduce the risk of overfishing (Bertrand et al., 2018; FAO, 2020a; Oliveros-Ramos et al., 2021).

Other adaptation strategies include exploration of alternative/complementary species for fishmeal production, such as mesopelagic fish, and the diversification of the production activity from fishmeal to food fish targeting species that increase during EN events (e.g. chub mackerel). However, entrepreneurs are as yet reluctant to adopt this strategy due to the lower profitability of food fish compared to anchovy for fishmeal (FAO, 2020a).

Industry-led adaptation strategies are manifold: for example, the availability of fishmeal processing facilities along the entire coast and the integration of all value chain steps into the same company allowed relocating the fishing activities southward following spatial displacement of anchovies in EN years (Arias Schreiber et al., 2011). A critical adaptation to catch fluctuation was the industry-led mechanism linking fishmeal price to anchovy catches volumes, which allowed compensating lower catches with higher prices.

Ad-hoc adaptation strategies are implemented at enterprise level (e.g. boats moving to tuna fisheries in the context of fleet capacity reduction) or even at individual level (e.g. fishers switching to small-scale fishing when losing their job due to temporary restrictions; Kluger et al., 2019a).

While no specific climate change-focused adaptation measures are in place, the currently operating management system and adaptation strategies was argued to potentially be well suited for coping with the challenges faced by the *anchoveta* fishery (Oliveros-Ramos et al., 2021). However, there is a risk that the effects of climate change may turn this management approach insufficient. Ongoing efforts for diversification of species for the fishmeal industry, and development of a market for warm-water species need to be strengthened and framed in a multispecies management system, in order to avoid the collapse of the productive system upon ecosystem changes. It can be expected that the industry will proactively develop and apply similar adaptation strategies, but institutional role is paramount in supporting such initiatives, and in particular in promoting research and monitoring of ecosystem dynamics in a changing climate.

## 5 Case Study 2: Artisanal Fisheries

### *5.1 Socio-economic Challenges*

Climate variability impacts coastal fisheries through alterations in catch composition and abundance, impacts on infrastructure and equipment, and increased risk at sea (FAO, 2020a). These changes may result in substantial economic and social impacts for fishers. For example, the 2017 marine heatwave hit hard the coastal fishery in Sechura (Kluger, et al., 2019a). Heavy rain halted fishing, damaging infrastructures and equipment. The road system disruption due to floods compromised access to fish markets, interrupting fisheries value chains. In areas where entire families rely on income generated by fishing, even a short interruption of the fishing season can have economically strong impacts, affecting provision of food and healthcare and worsening living conditions (Kluger et al., 2019a).

In addition, in EN years when other activities (e.g. *anchoveta* fishery) are impaired, artisanal fishing – with its low entry requirement – represents a safety option for many. It is likely that climate change will push many into this safety option (“refugee space”), increasing pressure on resources, leading to conflicts for resource use, ecosystem degradation, and ultimately increasing sensitivity of the socio-economic system to environmental variation (Jara et al., 2020; Kluger et al., 2019a).

### 5.2 Existing Adaptation Approaches and Outlook

In contrast to the industrial fishery, Peruvian artisanal fisheries has yet to implement an institutional framework for adapting to ENSO, let alone to climate change (FAO, 2020a). The sector relies on endogenous initiatives to withstand climate challenges. Adaptation capacity is related to individual or business-level disposition, financial capacity and independence, individual fishers' and community characteristics, and to market dynamics.

Artisanal fisheries are naturally dynamic and flexible, being adapted to inter-annual and seasonal stocks fluctuations. Individual fishers routinely switch gear types, fishing methods or target species to deal with these changes, or migrate towards other fishing areas (Guevara-carrasco & Bertrand, 2017; Jara et al., 2020; Kluger et al., 2019a; Kluger et al., 2020). Such flexibility proved a key factor to cope with ENSO-related oscillations or other occasional disturbances in the past. For example, artisanal fishery in Sechura Bay demonstrated a fast recovery within a few months after the marine heatwave event in 2017 (Kluger et al., 2019a). Seasonal and long term migrations are an important adaptation strategy: fishers move to other areas or other fisheries, while maintaining connection to the location where their family remains (Kluger et al., 2020). Though a successful individual coping mechanism, these migrations can also cause impacts on the receiving fishing community, e.g. increasing conflicts about resource access.

However, individual initiatives focus on ad-hoc, temporary solutions, lacking any strategic long-term horizon. The adaptive capacity of artisanal communities needs to be strengthened through institutional support, which has been limited in some cases, as reported by stakeholders in the aftermath of the 2017 marine heatwave in Sechura (Kluger et al., 2019a). Critically, adaptive capacity and resilience building must be rooted on both ecological and on social aspects, and tailored to the individual characteristics of each community. In fact, the characteristics of the community determine the vulnerability of the socio-ecological system to environmental change, and thus its adaptation potential. Jara et al. (2020) related the vulnerability and adaptation capacity of artisanal fishing communities to a combination of ecological factors, social factors, presence of infrastructures and conservation management. Vulnerability is predicted to increase with projected climate change. Action on the socio-economic characteristics may be the key to positively modify the path to adaptation, through increased biodiversity protection, economic diversification and poverty reduction measures. These measures need to be case-specific and tailored to the individual context, integrating the diverse local actors and players.

A number of adaptation measures for coastal fisheries susceptible to environmental variability are proposed for example by Daw et al. (2009), and Jara et al. (2020), also reported by FAO (2020a). These focus on strengthening the resilience of the local communities and of the fishery sector; establishing financial mechanisms to buffer the socio-economics effects of resource fluctuations; implementing the monitoring of oceanographic changes, and others. These mechanisms require, in parallel, the development of a management system with establishment of fishing limits under a co-management framework, with direct involvement of fishers in the co-design of sustainable fishing practices, to foster stewardship and increase compliance.

# 6 Case Study 3: Scallop Aquaculture

## *6.1 Socio-economic Challenges*

The scallop aquaculture sector is highly vulnerable towards any environmental change that threatens the survival of the target species: the Peruvian bay scallop. This dependency of an entire sector on a single species can be – similar to the *anchoveta* industry – a real challenge, especially if the dependency of the human community is as high as in Sechura Bay. EN events and climate change thus have strong socio-economic impact in this area (Kluger et al., 2019b). The marine heatwave of 2017 had drastic negative consequences for scallop farming in Sechura Bay, cascading to the entire industry and affecting the livelihood of over 25,000 people. Most scallop farmer associations stopped production, losing their investment, equipment, and, in some cases, their personal goods (e.g. houses), ultimately compromising their financial freedom (Kluger et al., 2019a).

## *6.2 Existing Adaptation Approaches and Outlook*

The high vulnerability of the scallop aquaculture activity prompted users to proactively develop autonomous adaptation strategies to limit financial losses during times of reduced scallop production. For example, after previous experience with moderate die-offs, several associations decided to delay the scallop grow-out period at the onset of the heatwave in 2017, effectively reducing their loss. Another adaptation strategy is the north-south migration under conditions of strong El Niño or La Niña, to exploit differential effects of EN on scallop productivity along the coastline. Species diversification is another adaptation strategy to contrast the single-species constraint: managers of scallop processing plants reported (in interviews with the second author) to have requested official permission to process a wide range of marine species in their facilities, in the perspective of future changes in farmed and fished species driven by environmental variability, reportedly to exploit a competitive advantage compared to other producers.

Kluger et al. (2019b) recommended a set of measures for a long-term adaptation strategy, which relate to environmental management, development of emergency plans and financial support and investment plans, and mitigation measures such as diversifying and spatially spreading the activity to reduce the risk. For larger scallop culture associations a "spreading the risk" strategy through activities along the whole Peruvian coastline may successfully compensate local mass mortalities with high yields in other areas (Kluger et al., 2019b). Such measures need to be embedded in a long-term adaptation strategy that should be co-designed by farmers associations and governance authorities in order to be economically, socially and ecologically resilient and successful.

## 7 Conclusion: What Can We Learn from the Cross-Scale Comparison? Challenges and Opportunities

This paper explores the challenges and the potential for adaptation to environmental variability and climate change across marine activities at different spatial scale in the Northern Humboldt Current Ecosystem. Adaptation strategies for coping with climate instability are already in place in all contexts, but are often based on bottom-up initiative. Strong action from institutions is needed to guide and help such bottom-up efforts, shaping a long-term management strategy to deal with environmental change in socio-ecological systems across spatial scales. For artisanal fisheries and aquaculture in particular, there is a strong need of locally developed, ad-hoc measures that can add robustness to the societies, also in light of vulnerable socio-economic situations in coastal communities.

Under this framework, three main take-home messages can be drawn about the three case studies presented:

1. The Peruvian *anchoveta* fishery is well managed under present environmental conditions, and it can be seen as an interesting model of adaptive fisheries management for fisheries targeting small pelagic fish subject to short-term fluctuations and environmental disturbances. However, with progressing climate change, the industrial fishery may need to diversify its target species, possibly requiring a shift to a multi-species management system.
2. Artisanal fisheries are more adaptable to climate change due to their multi-species/multi-gear nature. However, the intrinsic socio-economic vulnerability of coastal communities requires science-based management of important resources under present-day conditions, and the co-design of long-term adaptation planning strategies of resource users and governmental institutions in order to prepare these social-ecological systems for future change.
3. Entrepreneurs of scallop aquaculture must engage with long-term planning, accounting for increasing disturbance with local mortality events. Under future climate change scenario it is likely that the window of opportunity for scallop cultivation will shift from Sechura to the south. Conservation of natural banks, diversification of farmed species and spatial "risk spreading" strategies are therefore advisable.

In order to promote an ecosystem-informed, climate-change prepared fisheries and aquaculture management that can support institutional actions, more transdisciplinary research is needed. In particular, it is paramount to gain understanding of the socio-ecological systems dynamics and their cross-scale differences, and of the potential social and ecological tipping points under future climate change scenarios. Future multispecies fisheries management cannot be isolated from the complex human-nature interactions. This is of key importance in the Peruvian industrial fisheries as much as for the coastal small-scale fisheries, which provide food and income and an important safety option in coastal communities. Critically, these should be coupled with measures to reduce and manage conflicts for resource use, and institution-led initiatives for poverty reduction and enhancement of social resilience.

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