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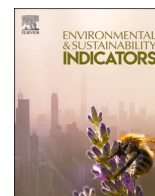
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# A holistic approach to evaluating climate vulnerability of French Polynesia pearl oyster farming: Bridging communities and scientific knowledge

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## ABSTRACT

While there is wide consensus about the reliance of climate projections at global scale, there is still uncertainty about changes at finer scale and even less on the effects of such fluctuations for local economies and societies. The vulnerability of social-ecological systems (SES) to climate change is a framework that takes into account the strong link between environment and local communities that depend on ecosystem services to ensure their livelihoods. This study explores the vulnerability of pearl farming SES to climate change, combining scientific insights with local knowledge from French Polynesian communities. A preliminary list of eighty-two criteria of exposure, sensitivity and adaptive capacity, identified through a targeted scoping review, was used to develop the interview guide that informed fifty-six face-to-face interviews and workshops conducted in 2020 and 2025. Using a combination of ranking questions and open-ended responses, the results highlight differences in the perceived exposure between scientific/institutional actors and local communities, which is reflected in the degree of sensitivity of the SES to climate drivers. Expectedly, the priorities given to adaptation measures were also different. The thematic analysis of the responses, however, shows that the two parties are aware of their own limitations in understanding the effects of climate change and recognise the need to fill mutual gaps through a collaborative production of knowledge. By integrating complementary forms of knowledge, this approach may help overcome the limitations of vulnerability assessments based exclusively on scientific expertise, and support the development of climate policies that are scientifically sound and socially accepted.

## 1. Introduction

The last assessment of the Intergovernmental Panel on Climate Change shows a broader consensus within the scientific community about the changes in the climatic conditions resulting from the increasing carbon emissions (Intergovernmental Panel on Climate Change (IPCC), 2023). However, considerable uncertainty remains regarding the consequences for marine ecosystems at basin scales, and how human societies will respond to such fluctuations (Ommer et al., 2011). Assessing the effects of climate change requires a holistic approach that recognises the dependence of local communities from marine ecosystems services to ensure their livelihoods (Elliott et al., 2017). About three decades ago, Berkes et al. (1998) developed an analytical framework to describe the linkage between social and ecological sub-systems (SESs) that they define as two equally important

parts, which function as a coupled and interdependent system - “human actions affect biophysical systems, biophysical factors affect human well-being, and humans in turn respond to these factors” (Berkes, 2011). While the SES framework has been traditionally used in fisheries management, it has more recently been adopted to understand the impact of climate variability on ecosystems and people (Bograd et al., 2019; Fedele et al., 2019; Metcalf et al., 2015). Scholars are now calling for more local-level studies to identify at-risk populations and economies and set locally adapted prevention measures (Garcia and Fearnley, 2012; Shi and Moser, 2021).

Pacific Island Countries and Territories (PICTs) are considered among the most vulnerable to the effects of climate changes because of their geographic isolation and geomorphological characteristics (Johnson et al., 2013). French Polynesia is one of the PICTs exposed to multiple natural hazards, namely the rise of sea level, storm surges,

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floods, droughts, salinity intrusion, landslides etc ... (Magnan et al., 2022), and predicting the effects on local ecosystems and communities is particularly challenging in this extensive territory with such heterogeneous oceanographic conditions. In this contribution, we focus on a key socio-economic activity of French Polynesia, as well as of a number of other PICTs, the black pearl farming aquaculture. Pearl-based livelihoods are threatened by endogenous factors, such as economic loss and mismanagement, and by exogenous factors, like changes in climatic conditions (Hilsenroth et al., 2021). The purpose of this research is to assess the vulnerability of the French Polynesian pearl farming SES to climate change by integrating scientific knowledge with the perceptions, observation and experience of local producers and communities. This study represents an essential first step toward more quantitative assessments of climate vulnerability, by identifying locally relevant vulnerability criteria and highlighting critical gaps in the data required for future analytical work. By combining different forms of knowledge, this approach contributes to climate vulnerability assessments that are scientifically robust while remaining socially and culturally inclusive.

The paper is organised as follows: the present introduction followed by a descriptive section of the pearl farming sector of French Polynesia (Section 1.1). Section 2 presents the vulnerability framework, its three components, exposure, sensitivity and adaptive capacity and a list of criteria resulted from the literature review for each component. A brief overview of the methodology underpinning the paper (Section 3) including an explanation on data collection, coding and analysis. The results (Section 4) present the analysis of the interviews and Section 6 provides a discussion of the identified differences among the answers. The final section draws the main concluding remarks.

### 1.1. French Polynesia pearl farming

Located in the South Pacific, French Polynesia covers a maritime area of almost 5 million km<sup>2</sup> and comprises 118 islands, 67 of which inhabited. A population of 276 000 inhabitants is dispersed among the five archipelagos - Marquesas, Tuamotu, Gambier, Austral and Society. In this last one, is concentrated 85% of the people, 75% of which on the main island of Tahiti (CEROM and Polynésie Française, 2020). The Tuamotu is the most widespread archipelago dominated by coral atolls, while the other archipelagos are composed primarily of higher islands. Because of the geomorphological characteristic and the inherent vulnerability of isolated atolls and small islands, the entire French Polynesia territory is exposed to multiple effects of climate changes. The management of natural risks is a shared competence between the State (État) and the Country (Pays or *le Territoire*) while an intricate net of institutions are in charge of implementing policies at local level (municipalities) and for economic sectors (agencies) (Magnan et al., 2022).

From a family economy founded on fishing and agriculture, French

Polynesia moved to a monetarised, commercial economy combining massive imports, unrestrained consumption and rapid growth of the public administration (Juergensmeyer and Roof, 2011). Its history can be broken down into three economic periods, phosphate (1960), the establishment of the Centre for Nuclear Experimentation of the Pacific (1963) and the current economic re-conversion to tourism and pearl farming (Juergensmeyer and Roof, 2011). At each transition, the political, social and economic structure has changed radically (CEROM and Polynésie Française, 2020).

Pearl culture began to develop in the early 1970s and follows a rapid expansion between 1995 and 2003 (Gueguen et al., 2016). In 2024, the total area authorised for pearl farming was 7497 ha (Direction des Ressources Marines PU FA'AHOTU MOANA and Statistiquesjuillet, 2024). Only 505 of the 2700 concessions active in 1999 are still producing, while the pearl has lost 54% of its value in 30 years passing from 3506 CFP in 1993 to 1600 CFP in 2023 (Fig. 1).

The sector is mainly located in the Tuamotu-Gambier archipelagos with half of the production carried out in 4 islands: Mangareva, Arutua, Marutea Sud and Ahe (ISPF et al., 2018). Pearl production is the second most important activity after tourism and pearls are the main exported product, with Hong Kong and Japan being the main customers for raw pearls, accounting for 98% of the market (ISPF et al., 2018).

## 2. Vulnerability framework

SESs are based on the concept that humans are a part of nature, thus the delineation between social systems and natural systems is arbitrary and artificial (Berkes et al., 1998). Vulnerability of a SES can be defined as the degree to which a natural and social system is susceptible to the adverse effects of climate change, including the variation of physics and chemical components as well as the frequency and intensity of extreme events (McCarthy and I.P. on C.C.W.G. II, 2001). The FAO definition of climate vulnerability applied to both fisheries and aquaculture, includes three core concepts: exposure, sensitivity and adaptive capacity (FAO, 2007) (Fig. 2). It defines exposure as the nature and degree to which a natural or social system is concerned by direct or indirect effects of a changing climate. Sensitive habitats and societies are highly responsive to such effects and can be significantly affected by small changes. To be assessed, sensitivity requires a knowledge of the thresholds at which these changes occur and an understanding of whether these adjustments are reversible or permanent. Consequently, the potential impact will depend on the level of exposure and sensitivity of a system, which will affect its capacity to adapt. Finally, the adaptive capacity is the ability of a system to adjust to climate changes with autonomous (e.g., voluntary reaction) or planned actions, with the latter being more costly and which benefits are expected over a longer term (Shelton). However, vulnerability is not only hazard-driven, but also depends on socio-political and

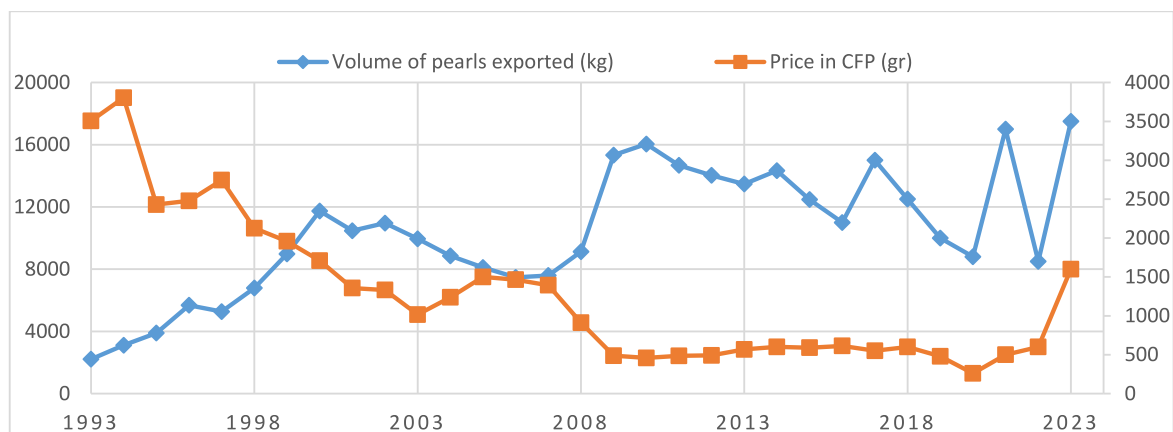


Fig. 1. Trend of pearl oyster farming market for the period 1993-2023 (ISPF, 2021).

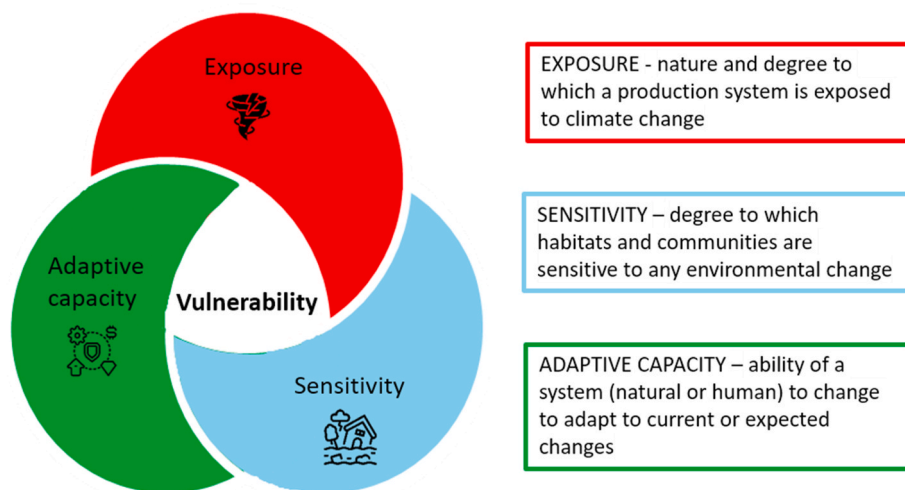


Fig. 2. Framework to assess vulnerability and its components adapted from FAO (FAO, 2007) and IPCC (McCarthy and I.P. on C.C.W.G. II, 2001).

economic attributes that evolve with the changing societal and institutional conditions, and for that, it needs to align climate projections with socio-economic scenarios (IPCC, 2014).

### 2.1. Vulnerability criteria

Vulnerability can be evaluated by criteria and indicators which are selected and aggregated through deductive and inductive approaches (Hinkel, 2011; Vincent, 2007). We conducted a targeted scoping review to identify conceptually relevant vulnerability criteria rather than exhaustively synthesising all available studies. Literature searches included peer-reviewed, institutional, and grey literature sources (e.g. FAO, IPCC, and regional Pacific repositories), and were conducted primarily in Web of Science and Google Scholar. The review focused on publications from approximately 2000 to 2024, with earlier seminal works included where conceptually relevant. First, we searched for studies linking climate change drivers with the biology and ecology of *Pinctada margaritifera* to document exposure and sensitivity of oysters and pearls (Appendix A – Exposure criteria). Second, to characterise community-level sensitivity, we targeted literature on climate vulnerability in Pacific Island communities, focusing on studies of livelihoods, income dependency, cultural practices, migration, and socio-economic resilience (Appendix A – Sensitivity criteria). Third, for adaptation strategies, we combined both ecological and socio-economic literature, identifying adaptation criteria and measures proposed within aquaculture, fisheries, and Pacific livelihoods (Appendix A – Adaptation criteria). Across these search streams, approximately 200–250 records were screened, from which around 80–100 sources were retained to inform the final set of criteria. Finally, we used a snowballing technique by reviewing the reference lists of the most relevant papers to identify additional sources.

#### 2.1.1. Exposure

The extensive area covered by French Polynesia archipelagos is exposed to several climate hazards, with high islands vulnerable to heavy tropical rainfalls, flooding and landslides and atolls impacted by the increase of sea level and erosion (PCSPF, 2012). The long-term observational record (1950–2024) shows a clear warming trend in French Polynesia, with annual mean air temperatures increasing by approximately 0.8–1.0 °C over the period (French Polynesia - Climatology (ERA5)). While interannual variability remains substantial, the warmest years have occurred during the last decade, indicating a sustained rise consistent with broader Pacific climate trends (French Polynesia - Climatology (ERA5)). The sea level raised of +7 cm between 1975 and 2005 (PCSPF, 2012) and the territory is also regularly affected

by depressions that cause strong winds and waves, while the frequency of cyclones is relatively stable since 1970 (BRGM and Risques naturels en Polynésie française, 2010). The period 1982-1983 is one of the most remarkable when the Tuamotu and the Society archipelagos were invested by 5 powerful tropical cyclones, Nano, Orama, Reva, Veena followed by Lisa at the end of 1982. Local studies have detected a seasonal variation of 2–3 °C with a mean temperature of 28.5 °C in the Northern Tuamotu Archipelago (Hilsenroth et al., 2021; Sangare et al., 2020) and future sea surface temperature (SST) expected to increase as much as 3.0 °C by 2100 (Ganachaud et al., 2007; Lough et al., 2011; Pachauri and Mayer, 2015). Here, SST projections over the 21st century have been extracted from 14 Earth System Models under the international Coupled Model Intercomparison Project 6 (CMIP6) (O'Neill et al., 2016)). The SSP5-8.5 scenario, representing a high-emission pathway and often referred to as a “business-as-usual” scenario, with significant increases in greenhouse gas concentrations (Data and Station Information for) has been considered. SST projections from these 14 models

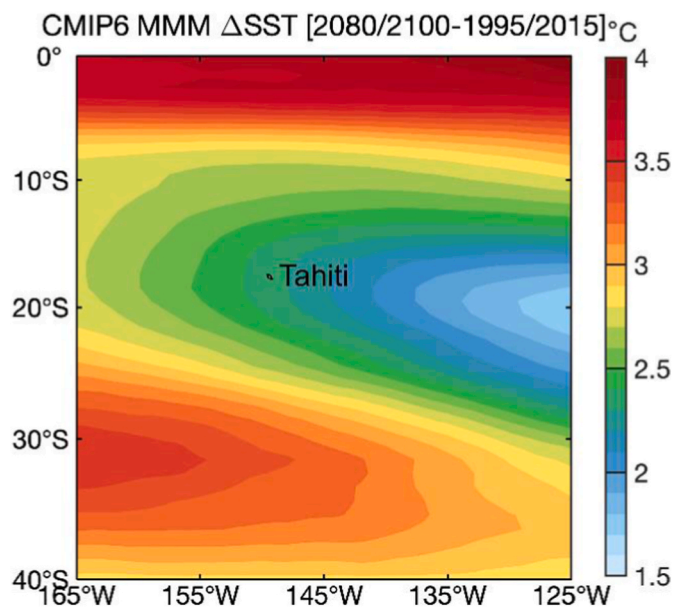


Fig. 3. Mean Sea Surface Temperature-SST difference between the [2080-2100] and the [2015-1995] time periods over French Polynesia (average SST is obtained from 14 models of the Coupled Model Intercomparison Project V6- CMIP6).

have been averaged and extracted for the French Polynesia region. Fig. 3 shows changes in SST from the historical period to the end of the century. The warming pattern across French Polynesia is spatially heterogeneous but uniformly positive, indicating that all parts of the region are projected to experience substantial surface ocean warming by the end of the century.

A relative mean sea level rise of +2.16 mm/year was measured at the tide gauge between 1969 and 2018 in the Gambier archipelago (Source National Oceanographic Center website ([Southern Hemisphere Tropical Cyclone Data](#))). On the other hand, the Gambier is protected from cyclones by the southeast Pacific anticyclone and, historically, no cyclone has hit the Gambier except for cyclone Rita, which passed over in 2001 at the depression stage (Bureau of Meteorology – Government of Australia ([Chávez-Villalba et al., 2013](#))).

### 2.1.2. Sensitivity

Here, sensitivity includes 3 subcomponents: sensitivity of pearls and oysters, sensitivity of farming system and sensitivity of pearl-farming dependent communities.

**2.1.2.1. Pearl and oyster.** The current and projected changes in seawater temperature, salinity, pH and currents, are expected to have direct consequences on the black-lip pearl oyster *Pinctada margaritifera*. This is a protandrous hermaphrodite species with a sex ratio dominated by male for both natural and cultivated conditions ([Chávez-Villalba et al., 2013](#)). Sex determination can be influenced by temperature as well as farming practices, e.g., grafting ([Chávez-Villalba et al., 2011](#)). Most of the effects are related to the increase of sea temperature ([Le Moullac et al., 2016a, 2016b](#)) which play a key role in the growth rate, resistance to diseases, and consequent mortality rates ([Johnson et al., 2013](#); [Hilsenroth et al., 2021](#); [Yukihira et al., 2000](#)). Mass mortality of oyster is also connected to the reduced salinity and increased sedimentation resulting from heavy rainfall ([Johnson et al., 2013](#)). According to estimations ([Pörtner et al., 2019](#)) in 2035 pearl oysters will live above their optimal thermal range for 210 days out of the year in the Tuamotu archipelago, leading to a drastic reduction of the oysters and pearls growth rates ([Hilsenroth et al., 2021](#); [Gueguen et al., 2016](#); [Sangare et al., 2020](#); [Doroudi et al., 1999](#); [Le Moullac et al., 2018](#); [Pouvreau and Prasil, 2001](#)). Furthermore, pearl colour, surface irregularities, and lustre seem to be particularly affected by small increases of temperature ([Johnson et al., 2013](#); [Latchere et al., 2018](#)). The combined effect of warmer seawater and acidification will affect food availability, the frequency of harmful algal blooms, and the spread of invasive species ([Karvonen et al., 2010](#)). There are evidences that oyster spats are even more sensitive to the effect of seasonal changes in seawater temperature and acidification ([Ky et al., 2014](#); [Lugue et al., 2024](#); [Southgate and Lucas, 2008](#); [Watson et al., 2009](#)).

**2.1.2.2. Pearl farming.** The combined effect of the increase of water temperature and decrease of pH on pearl quality and oyster growth are expected to extend the time required to produce a pearl of marketable size, threatening the profitability of black pearls in the Pacific ([Hilsenroth et al., 2021](#)). Moreover, direct impacts on farms facilities and related infrastructures (e.g., ports) may result from the increase of the sea level and the intensity and frequency of storms ([Brugère, 2015](#); [Brugère and De Young, 2015](#); [Stewart-Sinclair et al., 2020](#)). The adverse effects on coastal habitats, e.g., coral bleaching and destruction, might increase the exposure of farms to the action of wind and waves, and erosion ([Pörtner et al., 2019](#)). Higher costs for pearl producers might derive from an increasing competition for skilled grafters and production of oysters in hatcheries due to the decrease of wild oysters availability ([Hilsenroth et al., 2021](#)). A bigger impact on small, family-owned businesses is also expected since the market is dominated by a few major producers. The social consequences of such imbalance might lead to an increase in human migration from smaller islands to Tahiti ([Gueguen](#)

[et al., 2016](#)).

**2.1.2.3. Local communities.** Coastal communities' wellbeing of such isolated places is undermined by the increasing frequency and intensity of extreme climate events but also by the gradually change in physico-chemical conditions. For instance, the degradation of coral reefs threatens the access and availability of goods and services, including protection ([Harris et al., 2018](#); [Yates et al., 2017](#)) and food provision ([Johnson et al., 2013](#); [Agostini et al., 2018](#); [Kleypas, 2019](#); [Kubicek et al., 2019](#); [Rinkevich, 2019](#)). The rise of sea level and variations in precipitation patterns are expected to cause salinization of groundwater and lack of drinkable water ([Bailey et al., 2011](#); [Gingerich et al., 2017](#); [Holding et al., 2016](#); [Taylor et al., 2013](#)). Impacts on food and water safety, thus on human health, are also related to the increased occurrence of harmful algal blooms (HABs) and pathogenic organisms (e.g., *Vibrio*) as well as the bioaccumulation of contaminants in response to warming, deoxygenation and eutrophication ([Pörtner et al., 2019](#)). Increasing financial investments will be necessary to fix or relocate settlements and public infrastructures such as water storages and sewage treatment, roads, airports and harbours ([Lane et al., 2013](#); [Zackhras et al., 2018](#)). Finally, key cultural assets can be also eroded, e.g., local knowledge and indigenous traditions ([Bambridge and Le Meur, 2018](#); [Roué, 2012](#)) and aesthetic and spiritual value ([Camus et al., 2016](#); [Kench et al., 2018](#)).

### 2.1.3. Adaptation

A wide range of criteria exists to assess the capacity of a sector, for instance fisheries or agriculture, or a local community, to cope with or to adapt to one or several climate changes. This section presents a selection of adaptation measures aligned with the criteria of exposure and sensitivity described in the previous sections.

**2.1.3.1. Pearl farming.** Adaptation strategies to reduce the vulnerability of the sector should address technical issues but also the socio-economic problems deriving from the expected loss of productivity. The FAO proposes priority adaptation actions which aim to 1) increase spat production in hatcheries, 2) growing oysters in deeper waters during warmer periods, 3) harvest pearls in the cool season, 4) relocating pearl culture operations to sites where aragonite saturation levels remain high enough for adequate growth and survival of oysters ([Johnson et al., 2013](#)). Local strategies to prevent economic losses under projected temperature in the northern Tuamotu consist in grafting the whole cohort in September and harvesting year-round ([Hilsenroth et al., 2021](#)). Measures to enhance the economic and social adaptation of the sector should focus on optimising the number of jobs within each business, improve technical and business skills of communities, and train people to diversify into the broader range of pearl farming operations ([Johnson et al., 2013](#)). Policy actions consist of integrating the sector into climate change policies and practices (building capacity) ([Gueguen et al., 2016](#)) and consider micro-financial schemes to assist individual adaptation measures ([U.S. Indian Ocean Tsunami Warning System Program, 2007](#)). Regular monitoring, maintenance, and upgrade of onshore storage facilities for boats and other infrastructures can prevent loss or damage from extreme events ([Shelton](#)). A number of recommendations have been advanced by local institutions to enhance the performance of the sector ([PCPF, 2024](#)) that will also contribute to its adaptive capacity to climate change. Some of those consist of promoting sustainable practices (reduce waste), restore habitats (cleaning of the lagoons), monitoring of the sea quality status, sustainability labels, valorisation of the sub-products and local training ([Cambre territoriale des comptes PF et al., 2021](#)).

**2.1.3.2. Local communities.** More often, adaptation strategies are proposed for fisheries and aquaculture associated communities while specific strategies for the pearl oyster farming communities are scarce in the

literature and in policy (Charles, 2016). However, a wide range of adaptation strategies for communities of small Pacific countries that rely on aquaculture and fisheries are already implemented and their effectiveness assessed by specific studies (Shelton; Lane et al., 2013). Such measures can potentially be adapted to reduce the vulnerability of pearl oyster farming dependent communities. Primary strategies should allow the early identification of climate change hazards (cyclones) to prevent physical harm to locals. Specific indicators needs to be adopted to assess the ability of locals to cope, resist and recover from the impact of extreme events (emergency preparedness) (Lane et al., 2013). Actions to protect coastal communities are the construction of artificial coastal defences (e.g., dikes, seawalls, storm surge barriers, breakwaters, beach dune systems, etc.) or the conservation and restoration of ecosystems such as reefs that represent natural buffers areas. Preventing pollution and managing waste could also contribute to resilience of coral reefs (Terorotua et al., 2020). To enhance adaptation over the long-term, coastal communities should be encouraged to develop sustainable livelihood based on small-scale aquaculture and fisheries and traditional land farming to diversify their source of incomes. Another measure consists in a well-established community-research and institutions alliances to support collaboration, communication, and share information on global research on the effect of climate change both in the short and long term, with the purpose of identifying and prioritising potential interventions based on the local needs (Lane et al., 2013). Integrating local and indigenous knowledge, including people's observations, perceptions and values, with scientific knowledge can benefit one another to fill gaps on climate related impacts (Burnham et al., 2015; Crate and Fedorov, 2013; Huntington, 2000) especially at local level.

### 3. Data collection and analysis

The criteria derived from the literature were used as guiding prompts within the semi-structured questionnaire carried out in 2020. The participants covered three main sites, the Society, Tuamotu and the Gambier archipelagos. Data were collected through fifty-six face-to-face interviews, but in some cases, participants were invited to fill in the online version of the questionnaire when it was not possible to meet them in person due to the COVID-19 restrictions (e.g., people working remotely, lack of flights, health measures). The sampling frame consisted of individuals directly or indirectly involved in black pearl farming, covering both scientific/administrative actors and locals (farmers and community members) to represents the two main knowledge systems —scientific/institutional and local observation/perceptions and experience. Interviewees were selected using a combination of purposive sampling and snowballing. Each interview started with a presentation of the interviewer and the affiliation, the project and its scope, and the way data will be analysed, as well as a written or oral consent form. All interviews were conducted in French and quotations were translated as literally as possible, with only minimal interpretive adjustments made to ensure clarity and contextual relevance. Answers were analysed using a mix of quantitative (ranking) and qualitative (thematic analysis) methods (Table 1). Appendix B presents a complete list of codes and extracts of the interviews.

The development of the questionnaire, the interviews and the analysis (manual coding) were performed by the same researcher. Responses were analysed following the indications of (Saldaña, 2013) and (Braun and Clarke, 2006) (Fig. 4). According to (Saldaña, 2013) deductive coding is recommended when the research questions suggest that certain codes and themes are likely to appear in the collected data. Thus, a provisional list of codes prior to fieldwork was generated based on the pre-identified criteria from the literature (deductive) (Appendix A) while others were identified by respondents in the open answers (inductive) (Appendix B).

A follow-up fieldwork campaign was conducted in 2025 to present the results of the 2020 interviews and to document the socio-economic evolution of the sector and any changes in perceptions of climate change

**Table 1**  
Scheme of the semi-structured questionnaire and analytic methods.

Thematic	Type of answer	Criteria (codes)	Type of analysis
1. Background questions • Pearl oyster producers/local communities: age, gender, place, job, years of experience • Experts: type of expertise	Multiple choice/open		Thematic analysis
2. Evolution of the sector during the last decades	Open		Thematic analysis and ranking of codes
3. Exposure of French Polynesia territory to climate drivers	Likert scale (1-no/slightly exposed, 2-exposed, 3-very exposed)/open	Appendix A - exposure	Thematic analysis and ranking of codes
4. Sensitivity • Oysters and pearls • Pearl oyster sector • Local communities	Likert scale (1-no/little impact, 2- moderate impact, 3- big impact)/open	Appendix A – Sensitivity of oyster and pearls Appendix A – Sensitivity of pearls farming Appendix A – Sensitivity of local communities	Thematic analysis and ranking of codes
5. Adaptation strategies • Sector • Local communities	Ranking order	Appendix A – Adaptive capacity	Thematic analysis and ranking of codes

vulnerability. We organised a public meeting in Mangareva, inviting all producers and community members to attend and contribute to the discussion. The results were also presented and discussed with scientific/institutional actors during a meeting held in Tahiti in June. Some extracts of those meetings have been incorporated into the analysis.

## 4. Results

### 4.1. Background information

The “scientific/institutional actors” category (Exp\_number of the interview, year) includes specialists on scientific and human science disciplines from different research institutions of French Polynesia and France and from the local administrations (Fig. 5). Participants from the pearl oyster farming sector, here referred as “producers” or “farmers” (Prod\_number of the interview, year), include owners or employees of business of all dimensions, spat harvesters, grafters, sellers, jewellery makers, representatives of associations and unions. Some community members were also interviewed to include people that are indirectly related to pearl farming, namely ex workers, producers’ relatives, local administrations, tourism sector, NGOs. Both producers and members of the communities are referred as “locals”. The participants are distributed across seven islands, three of which represent the most important pearls producers, namely Ahe, Arutua and Mangareva. The average age range of locals interviewed is 30-40 and the 61% of men. Most of them have small family businesses while few have considered themselves as medium producers given that the production is carried out in several islands and they are sellers and affirmed jewellery makers.

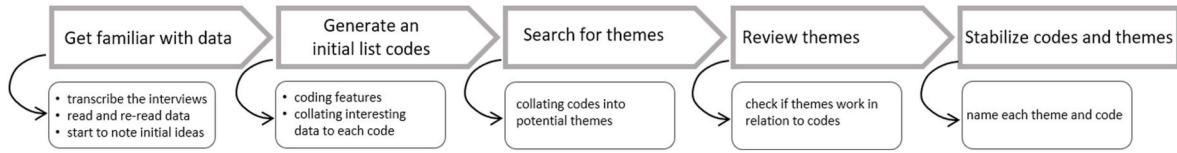


Fig. 4. Steps in the thematic analysis used to analyse qualitative responses (Adapted from (Braun and Clarke, 2006).



Fig. 5. Background information of the research participants (in bracket the category).

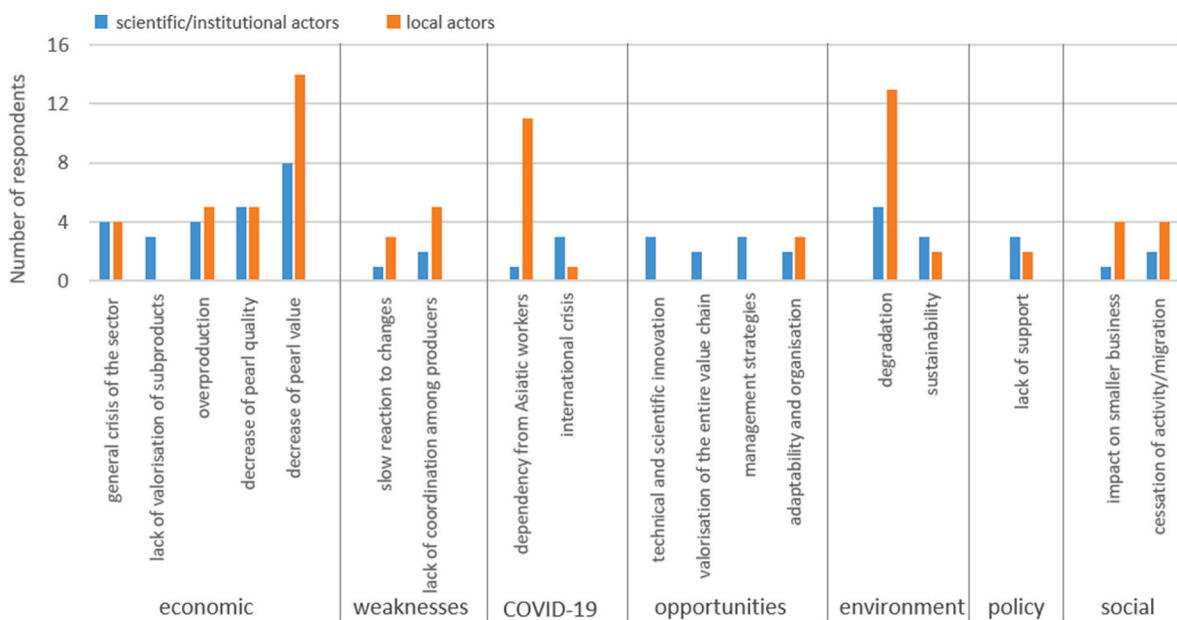


Fig. 6. Histogram chart illustrating the perceived evolution of the pearl farming sector over the last decades based on 2020 interviews. The x-axis presents codes that are grouped in the corresponding themes. In the y-axis is the number of scientific/institutional actors (in blue) and locals (in orange) that have mentioned each code.

4.2. Evolution of the sector: weaknesses and opportunities

There is agreement between both categories about the ups and downs of the sector since its development in the 70's (Fig. 6) (Appendix B - Section 4.2 Evolution of the sector: weaknesses and opportunities). Pearl farming went through multiple crises related to the overproduction, pearl quality, and the drop of pearl value. The environmental degradation resulting from overproduction and overexploitation of the lagoons is also frequently associated to the decreased quality of pearls and oysters' mortality and the consequent loss of revenues. The global economic crises that had an impact on the markets, notably in 2008, made the situation unsustainable for some producers. The COVID-19 pandemic has emphasised some weaknesses of the sector related to the dependency from the Asiatic market and from the Chinese grafters that were not able to come back to French Polynesia for many months. The 2025 outputs suggest that although the immediate effects of COVID-19 have largely been overcome, the sector remains highly vulnerable to fluctuations in international markets. As one producer explained, "we accumulated pearls during the COVID-19 period because prices were very low and we preferred not to sell, but export opportunities were also limited. Consequently, in 2021 a large quantity of pearls entered the market at once, causing prices to fall" (Prod\_12, 2025). This is consistent with statistics showing that in 2021 pearl exports reached their highest volume—almost 17 tonnes—while prices dropped below 300 CFP/gr (Bulletin Statistique, 2022). The sector struggles to find a suitable coordination in the production and market despite the multiple producers' organisations and unions in place. While the general perception is that the pearl farming has received growing support from the government and competent authority in the last years, there is a still distrust and disappointment from decisions that were taken in the past. Both scientific/institutional actors and producers consider that the lack of a proper supervision by the competent authorities has contributed to the sector instability that has advantaged big businesses.

4.3. Exposure

The comparative analysis shows differences in the observed or perceived exposure of French Polynesia to climate drivers between experts and locals. Such differences concern the temporal and the spatial scale. In fact, scientific/institutional actors have referred to the future

exposure, while locals have described past experiences, the present observations and the near future predictions. Unsurprisingly scientific/institutional actors were able to integrate the entire territory of French Polynesia in their exposure projections, while locals mentioned the changes in their island, recognising their limited knowledge of the situation elsewhere. Further divergences emerged in the ranking of each of the seven climate drivers (Fig. 7) and from the thematic analysis of the comments (Appendix B - Section 4.3 - Exposure). The most marked differences are related to the increase of sea level and the change in seasons, which is considered an element of major concerns for locals "I noticed a change in the seasons that are not fixed anymore (...) an increase of temperature during some seasons, which are difficult to predict as we used to do before" (Comm\_5, 2020). One anthropologist explained that "in the Tuamotu, they have some perception of the problem of climate change, but it is not a big deal (...) old people realise that there has been a change in the erosion of beaches" (Exp\_11, 2020).

On the other hand, scientific/institutional actors suggest that in general, the territory is exposed or very exposed to each of the variables but with substantial differences among islands for their geomorphology and their geographical position. Ten out of 19 scientific/institutional actors consider that the country is heavily exposed to the increase of extreme climate events, namely cyclones and strong winds while 12 out of 19 are concerned about the exposure to acidification. In contrast, issues like the increase of extreme climate events have barely been mentioned by locals, since only few experienced cyclones or big storms.

4.4. Sensitivity

4.4.1. Sensitivity of oyster and pearl

According to scientific/institutional respondents, the most relevant impacts are on the oysters' source of food and an increase of oysters' mortality linked to higher exposition to diseases and less resistance to environmental stressors (Fig. 8). Spats availability and larvae development are also negatively affected by the change of environmental conditions according to most of the scientific/institutional participants. The growth rate of pearls and oysters might slow down as an effect of ocean acidification on the calcification process. The competition with non-indigenous species may also represent a problem for 12 scientific/institutional category. On the other hand, issues like increase of depredation and increase of epiphytes do not seem to be related to climate

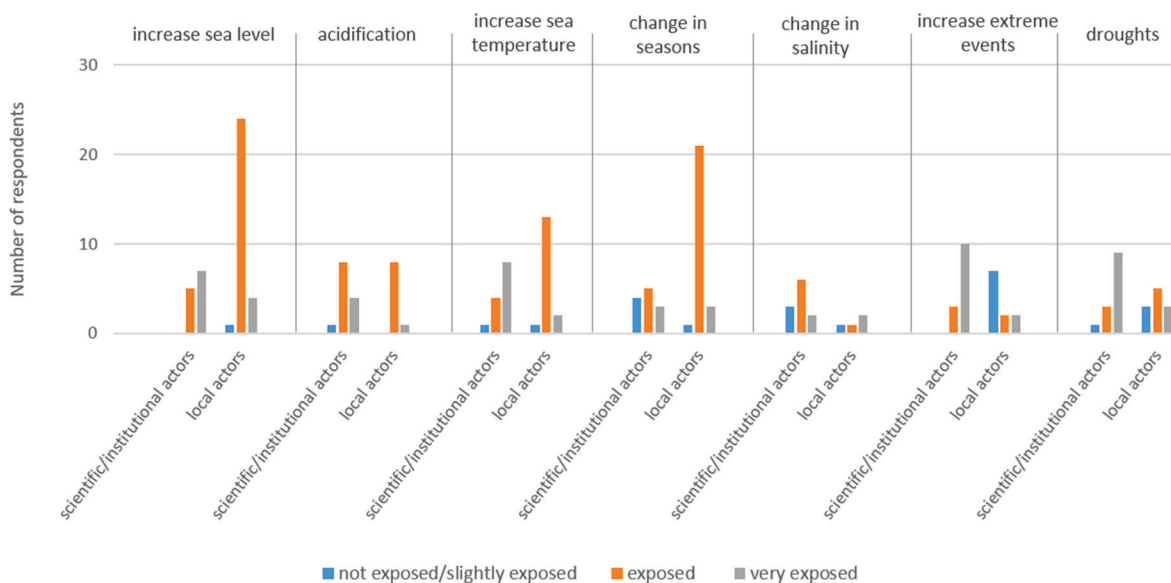


Fig. 7. Levels of exposure of French Polynesia to different climate drivers according to scientific/institutional and local respondents in 2020 interviews. The x-axis presents the climate drivers, and the y-axis shows the number of respondents for each exposure level: not/slightly exposed (blue), exposed (orange), and very exposed (grey).

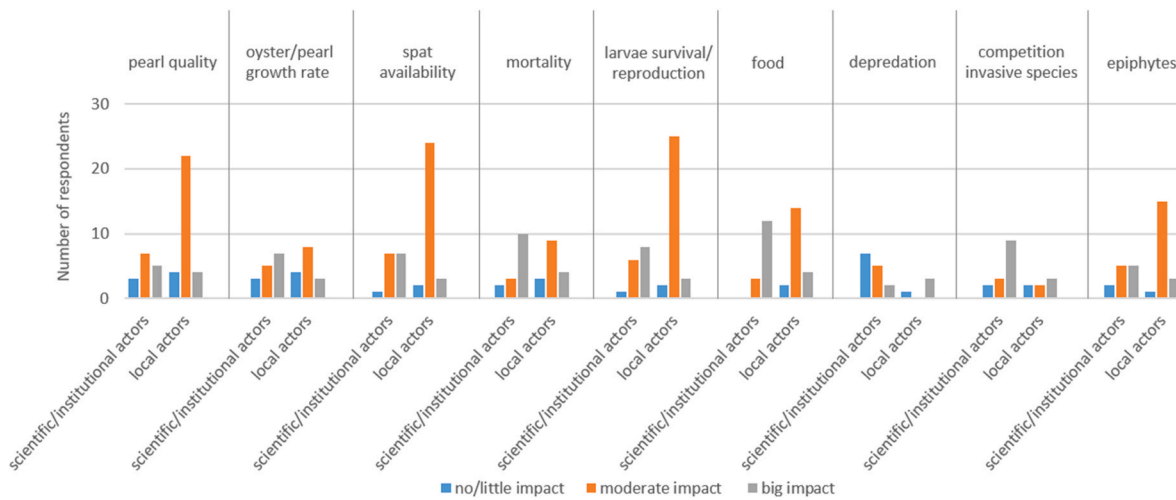


Fig. 8. Effects of climate change on pearls and oysters according to scientific/institutional and local respondents in 2020 interviews. The x-axis lists the sensitivity criteria, and the y-axis indicates the number of respondents reporting each impact level: no/little impact (blue), moderate impact (orange), and big impact (grey).

change.

For locals, the most important effects result in the success of reproduction, decrease of spats availability and larvae survival. These changes have already been noticed by most of the producers, especially those that make spat collection in the Tuamotu, which observed a shift in oyster reproduction period and the lack of spats in the collectors. Such change is a consequence of the shift of seasons associated to more extreme temperatures in the dry season “the biggest change is the shift in seasons that has led to a shift in the reproduction period and we are not sure when to put the spat collectors in the sea” (Prod\_28, 2020) (Appendix B – Sensitivity of oyster and pearl). Scientifics and institutions suggest that temperature affects reproduction by influencing sex determination “in the Gambier, farmed oysters are mostly males and the strategies adopted by farmers to graft smaller individuals may have contributed to the lack of females both in the farms and in the surrounding natural environment” (Exp\_3, 2025).

Producers recognise the strict correlation between water temperature and growth rate (Appendix B – Sensitivity of oyster and pearl) but less to pearl quality, which seems to be largely related to the quality of

grafting. Previous episodes of oysters’ mortality due to diseases were associated to the lack of defences due to stressing conditions resulting from environmental degradation “if temperature will increase, there will be an increase of diseases and thus mortality since oyster will be more stressed and less resistant (...) some periods of mass mortality have already been experienced” (Prod\_5, 2020).

The relationship between heatwaves, acidification and phytoplankton availability is known by most of the farmers. According to them, in fact, oyster growth is mostly linked to food availability that is also affected by the overexploitation of the lagoons: “I think that the availability of food has not changed, but since there are too many farms, there is not enough food for all the oysters and they grow less” (Prod\_8, 2020). As for epiphytes, especially in the workshops made in 2025, some noticed an increase and change in species composition in the collectors that prevent oyster spats to access to food, influencing growth and survival rate in the early stages. No invasive species have been noticed as a result of climate change but rather as a result of the bad practice to move oysters from an atoll to another in the past.

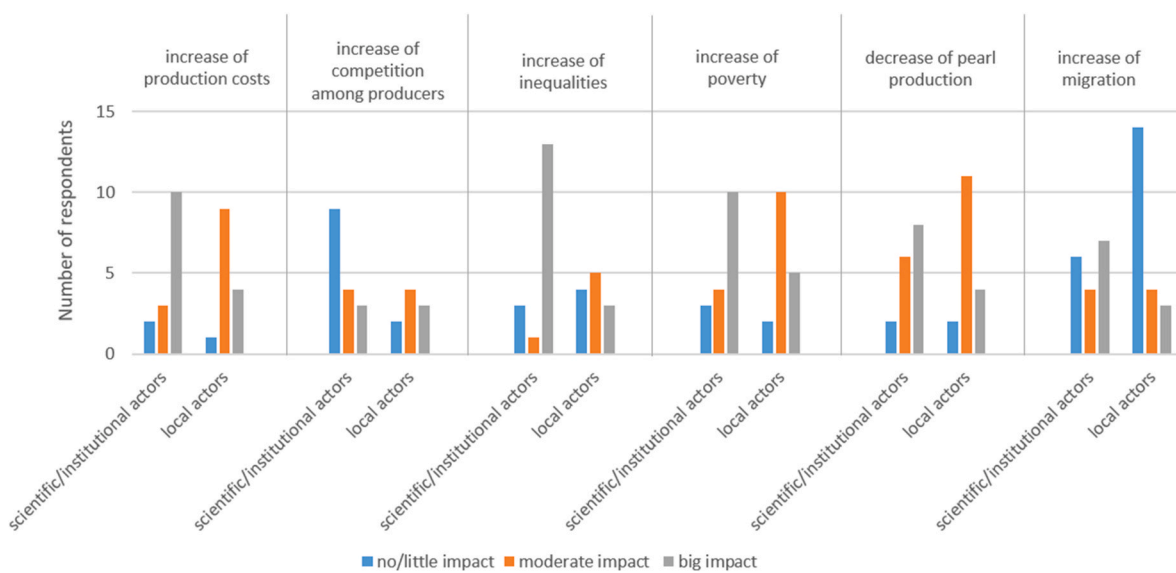


Fig. 9. Effects of climate change on pearl farming activity according to scientific/institutional and local respondents in 2020 interviews. The x-axis lists the sensitivity criteria, and the y-axis shows the number of respondents reporting each impact level: no/little impact (blue), moderate impact (orange), and big impact (grey).

#### 4.4.2. Sensitivity of the sector

Increase of poverty and inequalities among pearl oyster farmers are among the most relevant impacts derived from climate change according to scientific/institutional respondents (Fig. 9). An increase of production costs could also result from the exposition to certain impacts, namely extreme weather episodes that may damage infrastructures and farms.

Producers have a different view about the consequences of the climate change on their activity (Appendix B – Sensitivity of the sector). For instance, if there is agreement about the increase of production costs, the reason behind such increase differ between the two categories. In fact, increasing costs are related to the change in oyster reproduction period and lack of spats that force farmers to put more collectors “before, we did not need to put many lines because there was a high percentage of adult oysters. Now we are obliged to put more to have the same number of oysters” (Prod\_6, 2020). Increase of production costs and time dedication are the result of the growth of epiphytes that needs to be removed from longlines and spat collectors “if we do not clean anemones every 2/3 months they will prevent oysters to feed, the lines will become heavier and sink and we are not able to replace them” (Prod\_2, 2020). Unlike experts, only few producers see extreme weather as a major treat in the present time and they are mostly from the Tuamotu.

Differences in the degree of sensitivity among interviewees concern the increase of inequalities and migration that seems to be more relevant for scientific/institutional participants than for locals. However, there is agreement about the type of farmer more willing to migrate (Appendix B – Sensitivity of pearl farming). Native farmers of a given island will not migrate and they rather abandon the activity to work on something else (e.g., fishery or land farming). On the other hand, migrant farmers from other islands will move away when conditions are not suitable to keep the production. Nonetheless, migration to other islands seems unlikely nowadays due to “the increased reluctance of islanders to host new farms that produce waste in the lagoons” (Exp\_4, 2020). This opposition was already observed with the previous economic and environmental crisis, e.g., Takaroa and Takapoto. For locals the possible migratory flux could be from the Tuamotu to the Gambier where sea temperature is lower and the archipelago is less exposed to cyclones. Such migration will concern medium and big farmers that have the resources to reinvest somewhere else “only big producers will have the possibility to recover from climate change impacts and the small one will be forced to replace pearl farming with other activities if permanent changes will not allow them to recover”

(Prod\_15, 2020).

#### 4.4.3. Sensitivity of local communities

There is a general agreement among scientific/institutional participants that the most relevant effects of the above-mentioned drivers on local communities will be the lack of availability or access to essential goods, like water and food (Fig. 10). According to a respondent from the administration “the decrease or even disappearance of the phreatic zone on the surface of the atolls will have direct consequences on the fall in productivity of the coconut plantations, while the warming of the sea will have repercussions on the reef ecosystem services” (Exp\_1, 2020). Other comments suggest that most of the impacts are related to ocean acidification and increase of water temperature on coral reefs with consequences on fisheries. A decrease of jobs opportunities and economic decline “will be a consequence of the crisis of the pearl oyster farming that will have a cascade effect on several socio-economic activities of French Polynesia” (Exp\_7, 2020). The migration of atolls population is also considered a consequence of one or several climate change related impact: “we expect future desertion (of people) from the very low atolls to Tahiti” (Exp\_2, 2020).

The thematic analysis of producers and community members’ responses confirms the perceived impact of climate change on public infrastructures (Appendix B – Sensitivity of communities). Locals have already noticed damages on airports and houses resulting from the increase of sea level and waves actions but less from extreme climate events “in some cases, the roads have been destroyed as well as houses and docks that have been rebuilt” (Comm\_6, 2020). Locals recognise that a decline in pearl production due to permanent changes in climatic conditions will be devastating for the economy of the islands where it occurs since the entire population is directly or indirectly linked to this activity “if the pearl farming ends, there will be a loss of the 80% of revenues of the archipelago (Comm\_5, 2020)”. Similarly, there will be a lack of job opportunities, especially for youths and more specialised people, while for others land farming and fishing represent a valid alternative “people that have lived or have relatives in Ahe will stay as far as they can buy a piece of land, build a house, go fishing, and do copra” (Prod\_7, 2020). On the other hand, there is a certain confidence of locals about the availability of water and food, thus the capacity of nature to provide essential goods and services. As in the case of the sensitivity of pearl oyster farmers, there are contrasting views about migration as a consequence of climate changes, moderate or big impact for scientific/institutional respondents and no or little impact for most of the locals (Fig. 10).

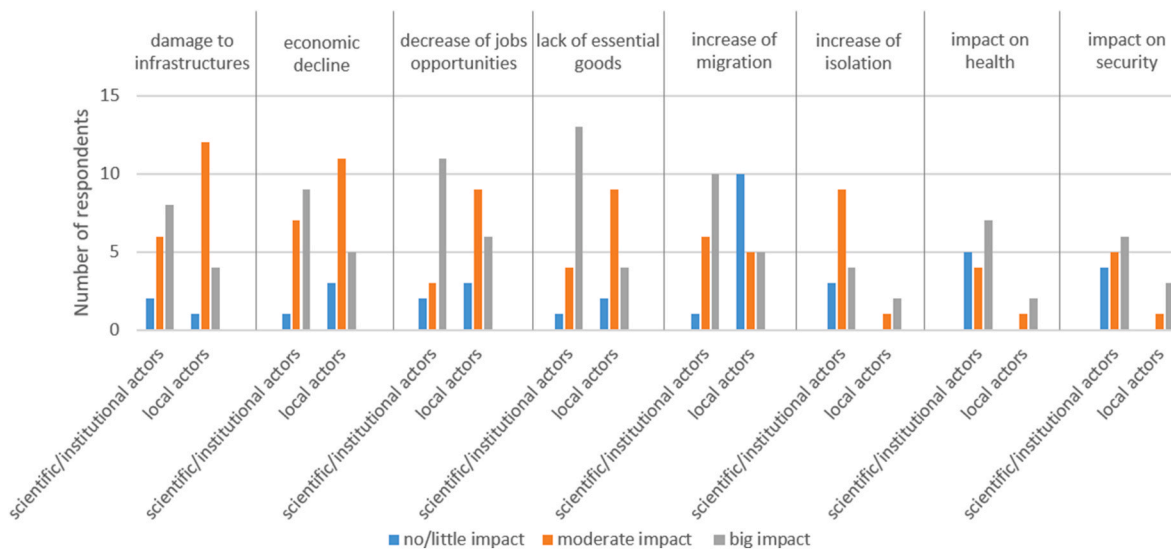


Fig. 10. Effects of climate change on pearl farming dependent communities according to scientific/institutional and local respondents in 2020 interviews. The x-axis lists the sensitivity criteria, and the y-axis shows the number of respondents reporting each impact level: no/little impact (blue), moderate impact (orange), and big impact (grey).

### 4.5. Adaptation

The third round of questions was aimed at identifying the most suitable measures to be implemented to reduce sensitivity and enhance adaptation of the sector and the associated communities to climate change. The complete list of twenty-five measures identified by respondents is presented in Appendix B – Adaptation while Fig. 11 represents the differences between respondents about the most frequently suggested measures.

#### 4.5.1. Adaptation strategies for the sector

Suggested strategies and measures are coherent with the identified weaknesses and problems the sector has experienced in the past. Some of these, in fact, although not specific to climate change, are considered useful to prepare the sector to face several obstacles. To enhance its adaptive capacity, the pearl farming must go through a deep reform of practices and way of producing to increase its competitiveness and to reduce the pressure on the environment. Producers recognise that oysters are more resilient, and pearls have better quality when the environment is preserved, with the derived benefits for the other activities and the local population (Section 4.5 Adaptation measures). The optimisation of the production requires the reduction of the density of oysters and number of longlines as well as valorise pearls and other subproducts. While allowing the environment to recover, such measures will also enhance the economic profitability of the sector with less pearls of better quality sold a higher price *“the reduction of the number of pearls produced must be the objective (...) as well as less intensive production systems. It will have a positive impact on the quality but also on the value of pearls”* (Exp\_3, 2020).

The multiple economic crises that hit the sector in the last 20 years, have reduced its profitability and the capability of businesses to invest. Both respondents' categories consider that a growing support from the state and banks will be necessary to adapt farms and infrastructures to future climatic conditions (e.g., higher sea level) *“it's important to have money in case of catastrophe to rebuild/repair the damage very quickly*

*because the production cannot be stopped”* (Prod\_12, 2020). Some of the suggested measures aim to reduce taxation and create a fund that allows reinvesting the revenues of the pearl market in local public infrastructures. The creation of a label, which ensures the pearl quality but also the environmental and social sustainability throughout the entire production process, has been considered in the past but has not found enough support so far.

According to locals, business-scale measures should be supported and encouraged by the government since they address specific problems at local level, are adapted to their needs and capacity, e.g., displace longlines, move oysters deeper during heatwaves, put production in stand-by or select natural oysters that are more resistant to the increase of temperature. These are typically low budget and diversified measures that allow adjusting production during crises and that proven to be efficient to overcome problems over the short-term.

To enhance the ability of the sector to recover after extreme climate events, current insurance systems should be adjusted to include damages to farms and related infrastructures.

In 2020 there was difference between producers and scientific/institutional' responses about the opportunities offered by the genetic selection of oysters and their reproduction in hatcheries. In fact, the administration and research institutions have been working on hatcheries to select a more resistant oyster to an increase of temperature. On the other hand, producers had little trust in this technology due to the low survival rate of spats grown in laboratory into the natural environment, thus their preferred to do their own section of wild oysters that are naturally resistant. In the interview round carried out in 2025, the producers' view on this issue has radically changed in the Gambier archipelago with the development of local hatcheries in response of the alarming decrease of natural oysters' population and the consequent spat availability.

The displacement of farms and business to other islands as a form of adaptation could be considered only for highly specialised farmers and those that are not native of the islands where they are producing. In fact, for family businesses this would be the very last option in case of drastic

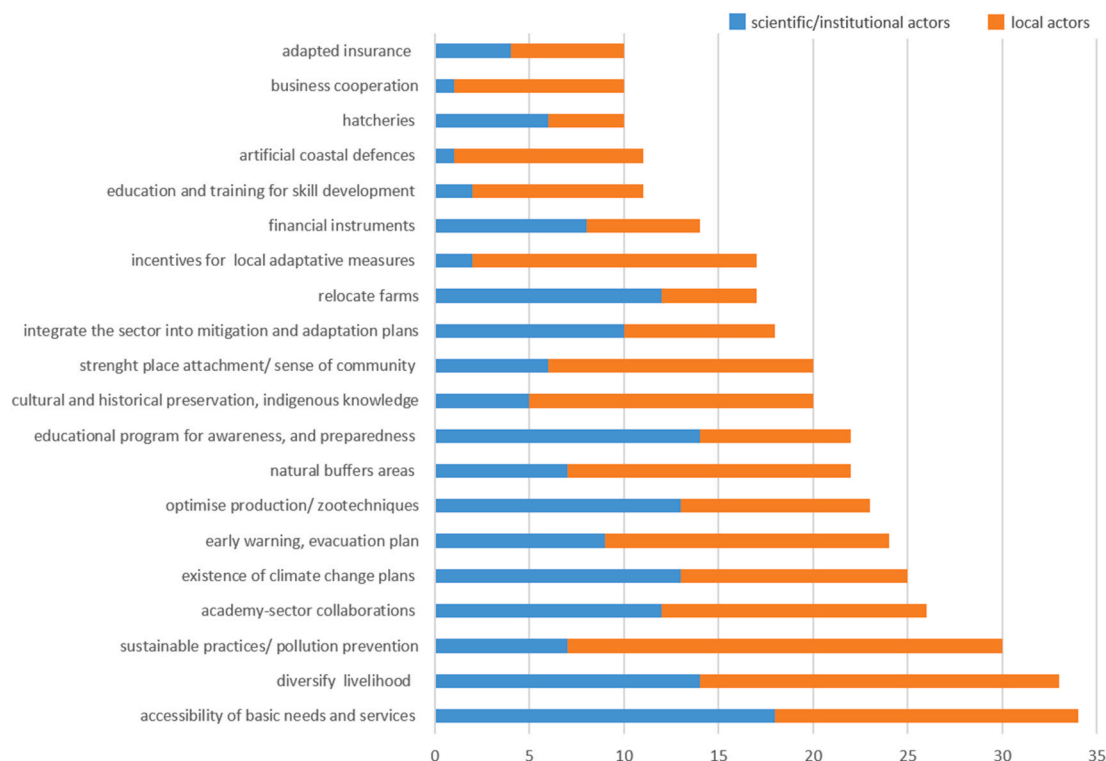


Fig. 11. Histogram chart on the adaptation measures to climate change effects, according to scientific/institutional (in blue) and locals (in orange). In the y-axis are listed the twenty most relevant measures and the x-axis are the number of times each measure has been suggested by each respondent category in 2020 interviews.

changes in environmental conditions. The sector needs to find a way to coordinate the many associations and unions and to work on mechanisms of conflicts prevention and resolution among different type of producers to overcome individualism. Finally, pearl oyster farming, especially small business, would benefit from a better support from research institutions that is adapted to their needs, and to establish a long-term collaboration to fill mutual gaps in knowledge.

#### 4.5.2. Adaptation strategies for local communities

Adaptation measures for local communities strongly dependent from pearl oyster farming, are divided into three main themes. First i) those aiming at protecting people and public spaces and others ii) at creating economic alternatives while ensuring access to basic needs; finally, iii) supporting the inherent ability of French Polynesian societies to observe changes in environmental conditions and to cope with them (Section 4.5 Adaptation measures).

The presence of early warning systems is considered important by all categories but, given the little exposition of those islands to extreme climate events, they are not seen as a priority to protect populations. Locals also believe that the systems that are in place are already sufficient and so far, little used. Monitoring and maintenance are required to prevent a further degradation of local public infrastructure (e.g., airports and roads) resulting from the increase of the sea level and waves action. While artificial protections are considered useful in the short-term and to protect certain infrastructures, natural solution are preferred by most of the participants that recognise the effectiveness of coral reefs restoration with benefits for the ecosystem and associated socio-economic activities, such as fisheries and pearl oyster farming itself. When either natural and artificial protection are not sufficient, the displacement of villages and infrastructure in less exposed areas should be considered. To this end, the willingness of the government to review the way lands are attributed will be essential to identify safer settlement areas.

While ensuring availability and accessibility to basic needs is essential, other type of services, such as information, transportation, medical assistance, and education are considered important by most of the interviewees but there is a general satisfaction among locals with the current way these services are delivered. There is large consensus among all participants that local populations need to reduce their dependence from pearl oyster farming and diversify their source of incomes. Many producers have declared that within their family they have already integrated another activity, like fisheries and agriculture that contribute to food security of the household.

While the migration of high specialised farmers might be a necessary step to ensure the persistence of the sector in French Polynesia, the displacement of local families from an island to another is only considered in case of threaten to lives and livelihoods.

The Tuamotu populations are considered among the most exposed to climate hazards but they are also the most capable to perceive changes, to cope with and to adapt to. Such inherent capacity of French Polynesia communities to respond to environmental variation should be supported by preserving their knowledge and traditions. Nonetheless, the sensibilization of local communities and producers, e.g., rising awareness and preparedness, is considered crucial to adapt such knowledge to ongoing changes.

## 5. Discussion

We have conceived this study to collect scientific and local knowledge to produce a holistic assessment of vulnerability of pearl oyster farming SES to climate change. Firstly, the analysis of such information has allowed us to identify a list of criteria that could be used to make future assessment in French Polynesia and adapted to other Pacific countries producers of pearls (Section 5.2). In a second place, it allowed to understand differences in perception about the relevance of each criteria both at the scale of the country and at local level (Section 5.3).

Vulnerability is typically assessed on the bases of socio-demographic

and economic criteria (sex, age, level of educations, income, housing etc ...) while only few integrate community perceptions of risk, despite this being a key determinant of local adaptation (Bickerstaff et al., 2008; Leiserowitz, 2006). Acknowledging the different views among the participants has allowed the identification of vulnerability criteria that are scientifically grounded and also perceived as meaningful by local populations and businesses in each island. Moreover, asking both respondents' categories the degree of exposure and sensitivity to climate change, helped explain divergences in how adaptation measures are prioritized. The qualitative approach in co-production of knowledge proved to be useful in a similar study aiming at assessing the Ecosystem-based Adaptation to climate change in the Samoa and Vanuatu by comparing the findings from the literature analysis, and fieldwork data from experts and indigenous communities (Nalau et al., 2018). Similarly, other authors have collected perception of institutional actors of French Polynesia on climate change vulnerability (Terorotua et al., 2020).

An element to take into consideration when drawing conclusion of this research was the period during which it was conducted, the COVID-19 pandemic in 2020. In fact, its conception was in February-July, the fieldwork in September-November and the analysis in December, when all economic sectors and local communities of French Polynesia were heavily impacted. The pandemic influenced perceptions of sensitivity, particularly regarding dependence on international markets for pearls and tourism. At the same time, the crisis revealed the resilience of both the sector and communities through strengthened solidarity, social cohesion, and place attachment (Appendix B, Section 4.4.2 – Code: Competition among farmers is unlikely). The fieldwork carried out in 2025 shows that the sector is recovering from this crisis but it remains vulnerable to international market fluctuations and to the reduced availability of natural oyster populations, particularly in the Gambier archipelago.

Finally, some differences may exist between small/medium and big business that were not fully explored in this study due to the lack of participation of the last one.

### 5.1. Endogenous or exogenous threats?

Factors like population growth, patterns of economic development, governance and political stability, markets and trade, fuel costs etc. can potentially affect fisheries and aquaculture in the Pacific area before climate changes (Gillett and Cartwright, 2010; Hall, 2011; Hunt, 2003). In Section 4.2, which examines the evolution of the sector, interviewees consistently confirmed that climate change is not the primary driver of the sector's decline but rather acts as an amplifier of existing problems. Producers and scientists/institutions alike noted that several effects attributed to climate change—such as reduced spat availability, oyster mortality, and lower pearl quality—are tightly linked to overproduction, overexploitation of natural resources, and lagoon pollution (Section 4.4.1).

### 5.2. Vulnerability

The literature review illustrates the uncertainty of climate projections at local scales (see also (Magnan et al., 2022) and the scientific gaps that remain regarding the effects of global processes on biological systems underpinning local livelihoods (Bell et al., 2011). Our approach combines scientific insights with local observations to define a list of criteria to provide the first evaluation of pearl farming SES vulnerability in French Polynesia.

#### 5.2.1. Vulnerability of oyster and oyster farming

Marine species have different inherent capacity to adapt to changing physic-chemical conditions (Pörtner and Farrell, 2008) and, those with a wider habitat range, like the black-lip pearl oyster *Pinctada margaritifera*, are considered less sensitive. Nevertheless, French Polynesia is exposed

or very exposed to multiple climate drivers, but with substantial differences among islands for their geomorphology and their geographical position (Section 2.1.1). Here we have two archipelagos, the Tuamotu dominated by atolls, and the Gambier made of high islands protected by a coral ring. The Gambier seems less exposed to climate drivers due to its fresher waters, which benefit oyster wellbeing and pearl quality, and its position out of cyclones trajectories, which protect farms and infrastructures (Section 4.3). The change in seasonality, on the other hand, seems to affect both geographic areas with consequences on the oyster reproduction systems and spat availability.

While the effects of these climate variables have already been observed by participants, they are expected to play a significant role on pearl production in the future and their cumulative effects represent the worst scenario for the sector across the entire territory. For instance, oyster mortality could be the result of the combined effect of the increase of ocean temperature and decrease of pH on oyster source of food. Similarly, variations in temperature and pH can create the conditions for the proliferation of HABs that causes oysters mortality (Appendix B – Section 4.4.1, code: Increase of mortality/disease). Multiple factors are also responsible for the shift on oyster reproduction period and spat availability. Such impacts on oysters and pearls have consequences for the entire production system with a decrease of revenues and additional cost in terms of money, time and workforce.

Climate-related changes are also perceived as amplifying socioeconomic weaknesses inherited from past crises, contributing to rising inequality, competition and poverty among producers (Fig. 6). Migration is likely to affect primarily highly skilled or non-native farmers, whereas small, native farmers would cease the activity to dedicate to land farming and fishing and consider coming back to pearl farming when conditions are more favourable (Appendix B – Section 4.4.2 Sensitivity of pearl farming). In conclusion, the Gambier archipelago is considered to have the best conditions to produce high quality pearl, but little space is left for new coming producers and even the expansion of existing one.

A wide range of individual and collective measures has been proposed to improve the adaptation of the pearl farming (Fig. 11 and Appendix B – Section 4.5 Adaptation measures). Unsurprisingly, the proposed measures are not directly aiming at reducing the sensitivity of the sector to climate change but rather to address the environmental, economic and management weaknesses that will indirectly enhance the adaptive capacity, namely dedicated financial instruments, optimise production, expand market, promote sustainable practices and better cooperation among pearl farmers. To enhance its chance to overcome present and future crises, the sector must go under radical changes in the production systems that allow adjusting production to demand, ensuring pearls of quality and expanding the international market. Pearl farming could benefit from a diversification and specialisation of pearl-based livelihood, including spat collection, blister pearl “mabe” pearl production, pearl jewellery and pearl shell handicraft production. Other studies demonstrate that pearl-based livelihoods provide substantial supplementary income for locals and have the potential to boost family incomes in pacific countries (Mikhailovich et al., 2021).

The strategies adopted by some family businesses in the two archipelagos to cope with changes are set day-by-day and the decrease of income do not allow them to plan long-term investments. Increasing number of scholars support the effectiveness of bottom-up adaptation strategies (Clarke et al., 2019; Kirkby et al., 2018; McMillen et al., 2014; McNamara and Buggy, 2017) and suggest governments to empower locals in setting up flexible and low-cost and adaptation measures (Forsyth, 2013; Magee, 2013; Sovacool, 2011; Sterling et al., 2017).

Improving access to capital and dedicated state funding would help business to adapt production and infrastructure to the changing conditions. The creation of local pearl hubs, such as the GIE Poe O Rikitea, or the establishment of a label, should be supported, not only to ensure a fair market price and pearl quality, but also an efficient use of natural resources and a fair distribution of benefit across each community.

However, the impact both positive and negative of subsidies and certifications should be carefully assessed across time to avoid creating further competition and inequalities among producers and mechanisms of attribution should be established in coordination among the different associations and unions.

### 5.2.2. Vulnerability of pearl farming dependent communities

Local communities of islands where pearl farming is the main activity are heavily affected by the instability of the sector performances, which, as in the cases of the Gambier archipelago, represents the 90% of the revenues. The decline of pearl oyster farming is expected to lead to a decrease of job opportunities, which in some cases could contribute to migration, especially of youths (Fig. 10).

According to interviewees, the cumulative effect of the rise of sea level (intrusion of salty water), droughts and the shift of seasons, is having an impact on water availability as well as food production, with direct impact on human health and local livelihoods (Appendix B – Section 4.4.3, Code: lack of availability of essential goods). Ensuring the accessibility and availability of basic needs and services has been suggested as a priority measures that can be achieved with both the improvement of shipping and the diversification of livelihood to ensure local food production. While in the past 20 years the entire household dedicated to pearl farming, now members of the same family perform different activities, mostly agriculture and tourism, and such shift was particularly marked during the COVID-19 pandemic (Appendix B – Section 4.5, Code: diverse livelihood strategies). Producers and community members, however, recognise that it is more difficult for youths to come back to traditional activities that are not as profitable as pearl farming. Ensuring water provision, remains a big challenge especially in the atolls and a shift to intensive agriculture could further worsen the situation. The projected increase of tuna stock in the waters of French Polynesia as well as the development of other mariculture products could represent an opportunity for the economic diversification and local food security.

The observed occasional damages to airports, roads, docks and houses exposed to the combined actions of waves and the increase of the sea level, demand more investments in coastal protection with different options considered depending on type of exposition (Fig. 10). The natural-based solution of coastal protection represented by the restoration of marine ecosystems, coral reef in this case, has the advantage of contributing to conservation goals, carbon sequestration and improve water quality (Pörtner et al., 2019) and atolls regeneration. Hard artificial structures, on the other hand, are a short-term strategy to mitigate imminent impacts and to protect public infrastructure. Responses of the local producers and communities point out that artificial and natural protection can be combined and would be more accepted by locals (Appendix B – Section 4.5).

Semi-permanent displacement of people during the cyclones period is an option to escape danger and to come back when they have passed. The lack of space to accommodate new houses both in high islands and atolls has emerged as an important impediment to coastal relocation due to the historic problems of land attribution that concern the entire French Polynesia territory. Even in the main island of the Gambier, Mangareva, the option of moving infrastructure and houses up in the mountains is hindered by the lack of space, landslides, and lack of infrastructure.

### 5.3. Bridging traditional and scientific knowledge

The comparative analysis of the answers provided by the two categories of respondents highlighted the differences in perceptions and knowledge between scientists and local communities on climate vulnerability and the related opportunities associated to such differences (Fig. 12).

On the actual and perceived exposure of French Polynesia to certain climate impacts, mostly scientific/institutional actors are concerned

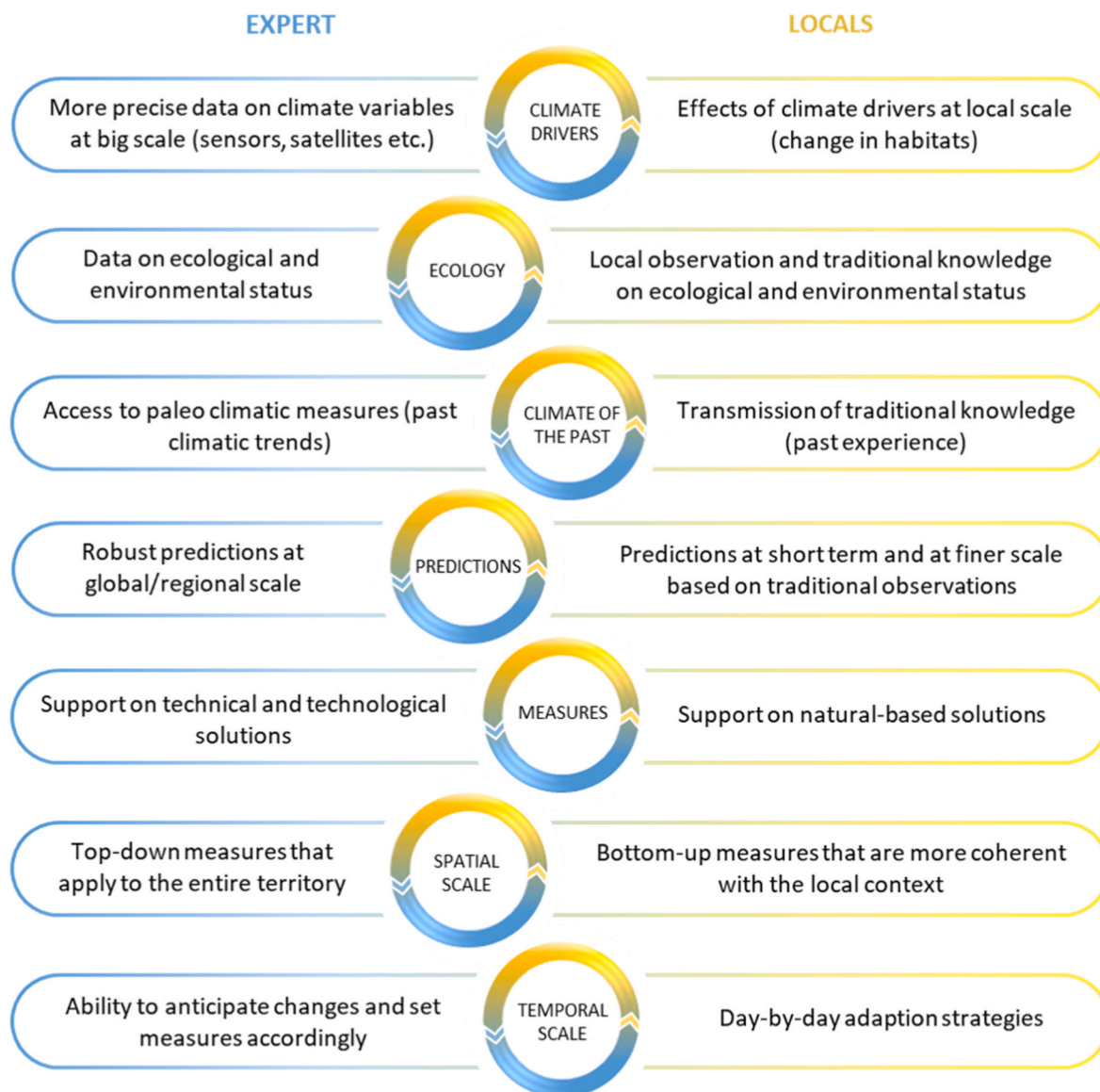


Fig. 12. Differences and opportunities of co-production of knowledge to address climate vulnerability.

about the projected increase in intensity and frequency of cyclones and storms, especially for the Tuamotu atolls, while this is not a major preoccupation for producers and local communities (Fig. 7). This difference could be explained by the fact that more than half of the locals interviewed were under the age of 45 and have little memory of the cyclones that have devastated the territory in the 80s. Moreover, considering that pearl farming has led to migrations from one island to another, most of the producers and their families have no experience with cyclones that hit the Tuamotu in the past. The other explanation is that the Gambier archipelago, where most of our interviewees were carried out, are not concerned by cyclones. The loss of risk memory is considered having played a role in the disaster caused by the hurricane Katrina in 2005 in the US (Burby, 2006; Kates et al., 2006) and Storm Xynthia in 2010 in France (Chadenas et al., 2013).

A recent Australian study demonstrates that while people consider they are prepared to cope with an extreme event already experienced, they are less confident when it comes to the rise of sea level (Elrick-Barr et al., 2017). We have collected similar perceptions among local communities that feel more vulnerable to slow but permanent changes in environmental conditions, while they are less concerned by the effect of extreme climate events. In our study, the threats represented by the rise

of sea level have become more evident in the last 20 years with water intrusion on land during storms where not long time ago there used to be beaches, trees or houses.

The other major difference in the exposure perception between the two categories is the increase of the sea and air temperature. While locals are aware of the increase of temperature due to the sensibilization made by the local medias and researchers in the last years, they admit that such differences of few degrees are difficult to detect. On the other hand, local respondents have observed the results of these small changes in the oyster reproduction as well as in fish behaviour and land farming. Indigenous farmers traditionally observe and predict changes in seasons through local natural variables such as the behave of plants and animals (Chand et al., 2014) or astronomical markers as moon and stars (Green et al., 2010; Lefale, 2010). Nonetheless, while traditional knowledge for seasonal climate forecasting has contributed to reduce the risk of local communities in the past (Mogotsi et al., 2011; Risiro et al., 2012; Shoko and Shoko, 2013) climate changes may reduce the effectiveness of such traditional indicators to predict (Chinlamianga, 2011; King et al., 2008). Our findings confirm the compatibility and complementarity of local knowledge and scientific measurements (see also (Orlove et al., 2000)). Beside the huge potential for researchers and local communities

to coproduce knowledge on local climate risk, scientific forecasting dominates and the utility of indigenous forecasting lacks of recognition and remains largely unexplored (Chand et al., 2014).

There is a certain coherence among the ranking of sensitivity criteria of oysters and pearl with more marked difference about the decrease of spat availability, according to locals and loss of pearl oyster foods for scientific/institutional respondents (Fig. 8). However, both categories recognise the challenge in differentiate climate vs anthropogenic impact as well as the cumulative effect of the two on the oysters and pearls.

Much differences can be seen in the criteria of sensitivity of pearl farmers (Fig. 9). Inequalities among producers is the main effect of climate change for scientists and institutions respondents, while for locals the cessation of activities and migration of skilled farmers seem to be the most likely consequence.

Views about the effect of climate change on communities are not so marked between the two groups but there is one criterion in particular that highlights contrasting views, migration. Migration is more likely for the youths and it is related to the reduced economic opportunities that will push them to find employment in Tahiti or in France. However, the COVID-19 crisis has shown an inverse dynamic where young people came back to their islands of origin due to the drops of employments from tourism during lockdown, supporting the point of view of locals about community and place attachment. Migration as a direct or indirect consequence of climate change remain a very complex issue and its tendency needs to be investigated with specific social studies over the long term.

The differences in the type of exposure and sensitivity of oyster and pearl production perceived by the two main categories of participants are, as expected, reflected in the suggested measures of adaptation (Fig. 11). The scientific/institutional respondents, in general propose large-scale (national) and long-term (next 20-50 years) measures that should already be implemented to prepare the sector to adapt to future climatic conditions, namely more investment in awareness, research and innovation, relocate farms, develop hatcheries etc. In general, researchers, governments or practitioners favour hard engineering solutions to climate risks based on western scientific assessments, leaving indigenous practices underutilized (Nalau et al., 2018). In fact, for producers, more financial and political support to autonomous and locally adapted measures is a priority since these have already demonstrated to be useful to overcome difficulties in the past. These actions require little investments and are adapted to the financial possibility of each business as well as local needs and impacts.

Another priority of locals is the environmental restoration and the adoption of more sustainable practices by all economic sectors to preserve the resources increasing their ability to recover from perturbations. Indigenous communities are not simply passive victims of climate hazards (Warrick et al., 2017) and instead of emphasizing their vulnerability, researchers and practitioners should consider their intrinsic capacities to adapt acquired over millennia (Nalau et al., 2018). To be really useful in climate risk assessment, local traditional information should not be limited to an opportunistic collection of environmental information to be integrated with Western scientific knowledge. Instead, it should be part of nested knowledge systems and be part of co-designed adaptation strategies (Nalau et al., 2018).

The preference by locals for nature-based solutions is in contrast with more technical solutions prioritized by the scientific/institutional category. The effectiveness of those actions however will depend on the speed at which changes will occur, giving the oysters and the surrounding environment time to adapt. The identification of adaptation solutions should not be only based on technology and innovation, given the potential social barriers that can limit community acceptance and participation in the implementation of such measures (Adger et al., 2009; Moser and Ekstrom, 2010).

## 6. Conclusion

To our knowledge, this study provides the first comprehensive assessment of the vulnerability of French Polynesia's pearl oyster farming system to climate change based on the integration of scientific knowledge and the lived experience and perception of local producers and communities. The results show that both groups observe clear impacts of environmental change on oysters, pearls and farming activities, but they interpret the relevance and severity of these impacts differently. Experts for research and institutions tend to emphasise projected increases in extreme events and long-term climate drivers such as rising temperatures, acidification or cyclone risks, whereas local communities express greater concern for gradual, permanent changes, including shifts in seasonality, sea-level rise, and the growing difficulty of maintaining oyster reproduction and spat availability. The results also highlight that the sensitivity of oysters, farms and communities is shaped by the interaction between climate drivers and pre-existing environmental and economic weaknesses. Farmers report increased costs and workload due to reduced spat availability, greater epiphyte growth and more frequent cleaning requirements, while scientific/institutional actors emphasise the potential rise of inequalities within the sector. Communities already dependent on pearl farming anticipate income instability and reduced job opportunities, which may contribute to migration among younger generations. These findings illustrate that climate vulnerability is not a standalone issue but is closely linked to the structural fragilities of the sector.

Furthermore, the results show that scientific/institutional and producers respondents categories differ in their preferred adaptation strategies. *Experts* predominantly propose large-scale, long-term actions—such as farm relocation, increased research and innovation, or hatchery development—whereas producers favour low-cost, autonomous measures that have proven effective in past disruptions, and which align with their financial capacity and daily constraints. This divergence reflects the different temporal, financial and cultural contexts of each group and demonstrates the importance of integrating both viewpoints when designing adaptation pathways.

This integrated approach helps to address the limitations of vulnerability assessments based exclusively on local concerns or on scientific knowledge in the development of climate policy and plans. The outcomes of this research will contribute to acknowledging the complexity of climate vulnerability of French Polynesia ecosystems and societies and emphasises the need to investigate the role of community's sense of risk in shaping the sensitivity and adaptive capacity. The resulting list of criteria can be adopted to support long-term vulnerability assessments of pearl oyster farming in French Polynesia and may also inform similar assessments in other Pacific pearl-producing countries. However, its application beyond this case study requires adaptation to sector-specific characteristics and careful consideration of local governance structures, ecological conditions, and the particular vulnerability of each community. By establishing the key criteria, this exploratory assessment lays the foundation for a subsequent phase of research that will strengthen quantitative data collection and support the development of a climate vulnerability index for French Polynesia's pearl farming sector.

To be useful, climate vulnerability assessments should be coupled with the socio-economic evaluations of the sector and measures aimed to enhance the climate adaptation should also contribute to enhance businesses resilience.

### CRedit authorship contribution statement

**Marianna Cavallo:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Pascal Raux:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization. **Elodie Martinez:** Visualization, Validation, Software, Data curation.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.indic.2026.101202>.

## Data availability

Codes and anonymised interview excerpts are provided in the article and supplementary materials. Full transcripts are not shared to protect participant confidentiality.

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