Année universitaire: 2019-2020 Spécialité: Sciences Halieutiques et Aquacoles Spécialisation (et option éventuelle : Ressources Ecosystémiques et Aquatiques	**Mémoire de fin d'études** ☐ d'ingénieur de l'École nationale supérieure des sciences agronomiques, agroalimentaires, horticoles et du paysage (AGROCAMPUS OUEST), école interne de l'institut national d'enseignement supérieur pour l'agriculture, l'alimentation et l'environnement ☐ de master de l'École nationale supérieure des sciences agronomiques, agroalimentaires, horticoles et du paysage (AGROCAMPUS OUEST), école interne de l'institut national d'enseignement supérieur pour l'agriculture, l'alimentation et l'environnement ☐ d'un autre établissement (étudiant arrivé en M2)

Vulnérabilité présente et latente des systèmes socio-écologiques littoraux, concepts et application à Moorea, Polynésie Française

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Soutenu à Rennes le 17/09/2020

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Acknowledgments

First, I would like to thank my supervisor Joachim Claudet and co-supervisor Victor Brun for their mentorship, kindness and their availability to help me at any time. I am really grateful for your constant support even when I was working remotely. It was particularly appreciated in difficult times like these, with the on-going COVID-19 situation.

I am also grateful for the opportunity to work on the research project of Acid Reefs, coordinated by Laetitia Hedouin. Thanks to Laetitia Hedouin and Yannick Chancerelle for their support, advices, and openness while I was at the CRIOBE research center in Moorea. I would also like to thank Julien Vucher for sharing his knowledge with me about the social and economical part of my project and for always being available even during the lockdown in Tahiti.

Finally, special thanks to Charles Loiseau and Lauric Thiault for helping me with spatial analyses.

1. Introduction

Coastal ecosystems offer many ecosystem services but are vulnerable to increasing local and global pressures (Graham et al., 2011; Ban et al., 2014; Hare et al. 2016; Leenhardt et al., 2017a) These pressures can result from direct anthropogenic threats such as fishing pressures or indirect, such as climate change (e.g. through increase in water temperature or ocean acidification (Cheung et al., 2010; Hughes et al., 2003). These threats impact the ecosystems, the ecosystem services they deliver, and the coastal communities who depend on it for their livelihood and wellbeing (Cinner et al., 2013).

The sustainability of coastal social-ecological systems is at stake. Social-ecological systems (SESs) are a conceptual framework that describes and characterizes human-nature interactions as linked social and ecological systems. Studies aimed at tacking sustainability problems must take into account both social and ecological sub-systems, where people and the natural environment are equally important and can be linked through the concept of ecosystem services (Bennett et al., 2016).

Vulnerability assessments are a useful approach to diagnose social-ecological systems and guide sustainability interventions (Thiault, 2017). The vulnerability of a system can be described as a function of three dimensions: the exposure of a system to one or multiple factors, the susceptibility of this system to be affected by these stressors (sensitivity) and its ability to adapt and cope with changes (adaptive capacity) (Adger, 2006; Bennett et al., 2016; Cinner et al., 2013). Social-ecological vulnerability assessments are a widely used tool to measure vulnerability because they allow breaking the SES down into different functional components. Therefore, assessing each dimension of the vulnerability is a way to guide management decision-making (Thiault et al., 2017). If lowering vulnerability is the goal, then management actions can achieve this by reducing exposure and/or decreasing sensitivity and/or increasing adaptive capacity. Social-ecological vulnerability assessments offer an approach for decision-makers to understand which areas are socially and/or ecologically vulnerable to different stressors. Vulnerability assessments also help them to understand why and how they are so vulnerable and can hence help them target management actions.

However, SES are complex systems with emergent properties, non-linearities, and cross-scale linkages, hence the importance of accounting for different temporalities (Bennett et al., 2016). Such complex systems are structured, evolve over time and respond with possible time lags to different stressors. This is even more noticeable in the case of climate change. Thus, studying a SES requires ensuring that the spatial and temporal boundaries of the case study that is being assessed capture events or sites that can affect the core SES of interest.

The dynamics of the linked social-ecological vulnerability can be mapped considering the impact of past and present threats (Thiault et al., 2018b) The future impact of climate change has also been studied in social-ecological systems with climate change scenarios (Cao & Caldeira, 2008; Cheung et al., 2009; Doney et al., 2012). However, only the future threats as ecological exposure tend to be incorporated into such evaluations, ignoring the potential future evolution of sensitivity and adaptive capacity (Cardona et al., 2012; Jurgilevich et al., 2017). These studies dot not fully account for all the latent aspects of vulnerability, upon which management interventions could be taken. Current approaches are mostly just static snapshots of the present (Cinner et al., 2013) and lack to properly account for social-ecological temporal dynamics and interactions. Ignoring the latent evolution of sensitivity or adaptive capacity equals to considering that all entities of a SES respond equally to a stressor. Consequently, the potential impact of a stressor will be biased, without accounting for interactions, other drivers of change, future potential policies and management actions.

Here, we look into possible ways to incorporating the latent effects of climate change and anthropogenic threats in social-ecological vulnerability assessments. Our approach incorporates exposure, sensitivity and adaptive capacity in order to determine the vulnerability of a SES to different stressors. We introduce the concept of latent vulnerability in social-ecological vulnerability assessments. We study vulnerability through a timely explicit assessment, focusing on the present and latent vulnerability of SESs to different stressors.

We used a Pacific island territory as a case study. Pacific islands are particularly at risk both to local anthropogenic threats, and to the already measurable impacts of climate change (Asch et al., 2018). Moorea is an island located in French Polynesia, where there is a strong relationship between people and the sea. As a volcanic island, only the coast is inhabited. Fishing has always played an essential role in the Polynesian societies and remains mainly a subsidence activity. 35% of the households of Moorea are engaged in fishery related activities (Thiault et al., 2017). Income from coral reef-associated activities is the main economic resource of the island. Resource users include Moorea residents, Polynesian habitants from the others islands (mainly Tahiti) and international tourists. Snorkeling, scuba diving, and boating are the main recreational activities. Cofals reefs of Moorea are highly exposed to economic development, anthropogenic pressures and climate change stressors (Thiault, 2017). We discuss here the different components of present and latent vulnerability at a very specific local scale, which is the SES of Moorea. We investigate how vulnerability can evolve in the future as a complex SES facing different stressors, and we especially focus on the resilience of this system.

2. Materials and methods

2.1. Social-ecological vulnerability

2.1.1. Defining the conceptual framework of social ecological vulnerability

As defined by the Intergovernmental Panel on Climate Change (IPCC, 2001; FAO, 2005) vulnerability is a function of three dimensions: a system's exposure to a stressor, its sensitivity to such stressor and its capacity to adapt to it (adaptive capacity) (Fig1). Exposure is defined as the probability for the system to be subject to a stressor. The stressor can by bio-physical (e.g. the ocean acidification) or socio-economic (e.g. fishing pressure). On the other hand, sensitivity describes the susceptibility of this system to this driver. Adaptive capacity refers to the ability of the system or individual to adapt and cope with change(s) (Adger, 2006).

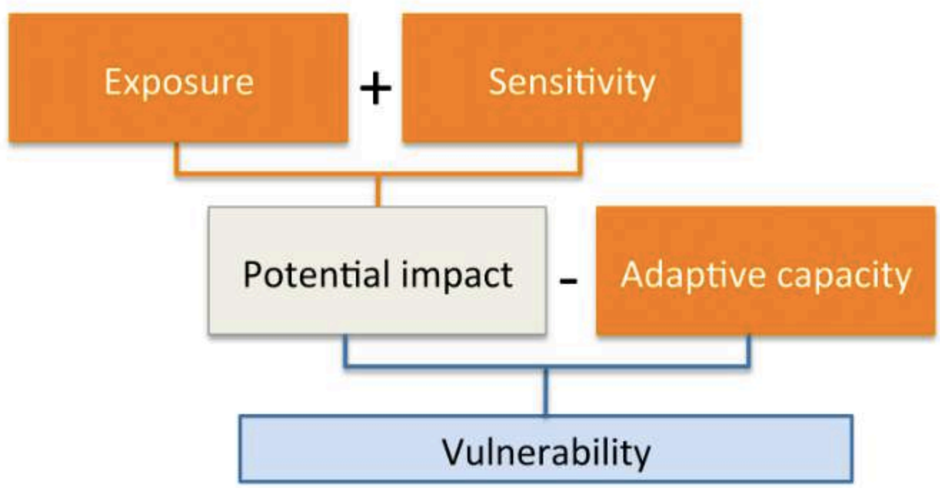

Figure 1: The concept of vulnerability as defined by the Intergovernmental Panel on Climate Change (IPCC) in 2001 (IPCC, 2001). The vulnerability is considered as a function of three dimensions: the probably of a system to be subject to a stressor: exposure, its sensitivity to such stressor and its adaptive capacity.

Social-ecological systems (SESs) characterize human-nature interactions as linked social and ecological sub-systems. The combination of ecological exposure, sensitivity and adaptive capacity describes the ecological vulnerability. The overall ecological vulnerability of the ecological sub-system refers to the ability of this ecological system to provide ecosystem services, which defines the social exposure in the social sub-system (Cinner et al., 2013; Thiault et al., 2018a). In the social sub-system, the combination of social exposure, social sensitivity and social adaptive capacity defines social vulnerability (i.e the extent to which the social system can be affected by the loss of ecosystem services) (Adger, 2006).

Ecological and social vulnerability are strongly linked. The ecological vulnerability affects social vulnerability through ecosystem services delivery, whereas social vulnerability affects ecological exposure through ecosystem services use (Fig 2) (Bennett et al., 2016).

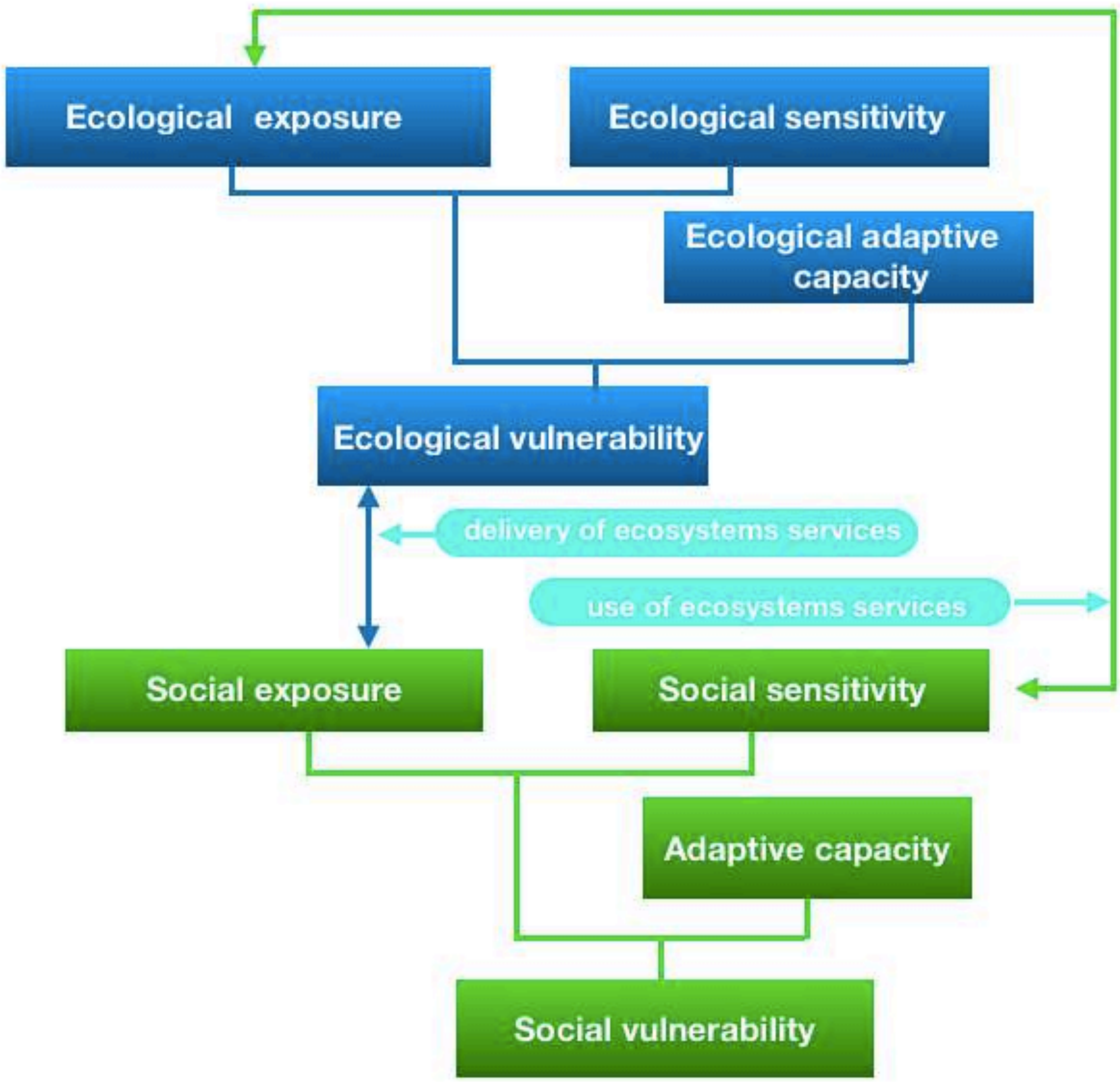

Figure 2: Conceptual social-ecological vulnerability framework used to link human-nature dependencies (adapted from Marshall et al. 2010, Cinner et al. 2013, Thiault et al., 2017).

2.1.2. Latent vulnerability

Present vulnerability depends on past drivers of change and future vulnerability is influenced by present stressors. These drivers of change are constantly shaping the future. We look at the result of these present drivers of change on potential future vulnerability. Latent vulnerability takes into account the possible future evolution of vulnerability (Brun et al., in prep). It combines the potential changes in exposure, sensitivity and adaptive capacity. It is a temporally explicit assessment of social-ecological vulnerability. In the face of global environmental changes, it is essential to look further than climate scenarios and look at the possible future trends of vulnerability (Jurgilevich et al., 2017).

2.2. Applying and mapping the framework in the case study Moorea

The social-ecological vulnerability framework was then applied from a conceptual model to a quantifiable and spatial explicit model for the SES of Moorea (Fig3) (Leenhardt et al., 2017a; Thiault et al., 2018a). We developed metrics to measure and explain key aspects of the vulnerability based on previous work (Cinner et al., 2013; Halpern et al., 2008; Thiault et al., 2018a). Each dimension of vulnerability (exposure, sensitivity and adaptive capacity) was characterized by quantitative indicators at the level of Moorea (Annex I). These indicators cover each municipality of the island of Moorea and the entire reef surrounding it at a 5m resolution (Fig 3).

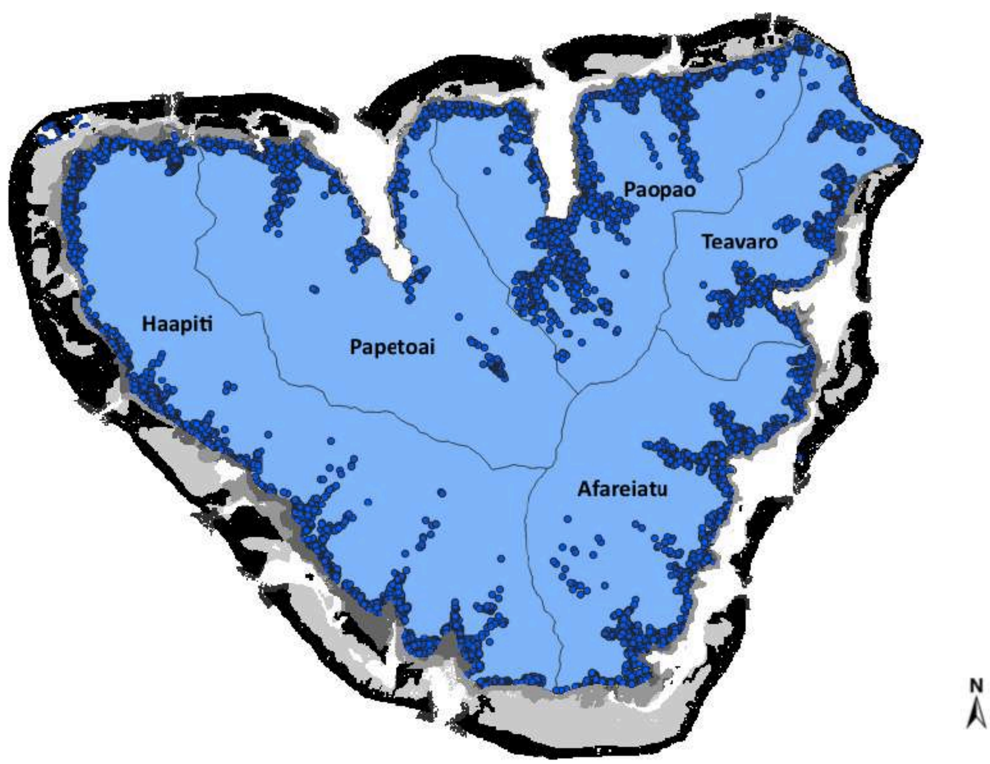

Figure 3: Map of Moorea Island, French Polynesia. Lines denote municipality boundaries, dots denote households and the black and grey pattern around Moorea represents the reef.

Data from 2007, 2012 and 2017 were collected and processed at the local scale to derive these spatially-explicit indicators of the vulnerability. This list of indicators captures important aspects of social ecological vulnerability in Moorea regarding the impact of human threats and climate change on the ecosystems (Annex I).

2.2.1. Ecological exposure

Ecological exposure was measured at the local scale. Different anthropogenic stressors were studied: anchoring, diving, feeding activities, fishing, marina, sedimentation, shipping, shoreline, trampling, and urbanization. We used a model of spatial patterns of cumulated impacts around Moorea to map these anthropogenic threats at the local scale (Loiseau et al., in prep). However, no data of water temperature and ocean acidification is available and specific enough at the scale of Moorea. The only data available is at the scale of French Polynesia. Since our study focuses on the spatial heterogeneity of the vulnerability in Moorea, the present exposure to climate change was considered as equal and homogeneous all around Moorea.

The indicators of ecological exposure we used for the SES of Moorea were: anchoring, diving, feeding activities, fishing, marina, sedimentation, shipping, shoreline, trampling, coastal urbanization, water temperature, ocean acidification (Annex I).
The map of present ecological exposure was produced using R and is presented in Annex 2.

2.2.2. Ecological resilience

2.2.2.1. Definition

We combined here ecological sensitivity and ecological adaptive sensitivity in one single measure of ecological resilience following previous work (Thiault et al., 2018a). The IPCC defines ecological resilience as the capacity of the ecological system to "cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure, while maintaining the capacity for adaptation, learning and transformation" (Sutton et al., 2011, p.5).
To study the ecological resilience of Moorea, different indicators were taken into account: resilience of fish assemblages to fishing, resilience of fish assemblages to climate change, and resilience of coral reefs to climate change and anthropogenic stressors.

2.2.2.2. Data collection and site selection

Fish assemblages were sampled from 2004 to 2019 by the CRIOBE research center of Moorea and by the Gump Station of California, located in Moorea (LTER program).

At each sampling site, one location on the outer slope (forereef) and two locations in the lagoon (fringing reef and backreef) were sampled. Fish species were identified and counted along 3 underwater transects at each location. Transects were 3 transects of 25x2m for the CRIOBE whereas the ones from LTER program were 5x50 m transects. Total length of each fish was estimated to the nearest centimeter. The map of the location of sampling sites used to calculate the ecological resilience index can be found in Annex III.

The hard coral cover and ratio of coral to macroalgae were also quantified during the CRIOBE sampling surveys and during the LTER research program (Edmunds, 2020) from 2004 to 2019 . Coral cover was estimated using a 50 points- intercept transect method, along the same 25-meter lines that were used for fish transects. This was done after the fish surveys to minimize disruption to the fish assemblages.

2.2.2.3. Ecological resilience to fishing of the fish assemblages of Moorea

To map ecological resilience, we first created an index of resilience R as a measure of the resilience of the fish assemblage to fishing using the following formula (Thiault et al., 2017):

$$Rf_{\mathrm{a}} = \sum_{i=1}^{s_{\mathrm{a}}} \left(1 - vf_{\mathrm{i,a}}\right) \times n_{\mathrm{i,a}}$$

Where $Rf_{\mathrm{a}}$is the resilience of the fish assemblage to fishing at the site a, $vf_{\mathrm{i,a}}$ is the normalized (scaled between 0 and 1) vulnerability to fishing (Cheung et al., 2005) of the species s present in the fish assemblage at the site a, and $n_{\mathrm{i,a}}$ is the log-transformed and normalized abundance (scaled between 0 and 1) of the species s present in the fish assemblage at the site a. The vulnerability index is calculated based on eight life-history parameters which are: age at first maturity, natural mortality rate, maximum body length, von Bertalanffy growth parameter K, geographic range, maximum age, annual fecundity and strength of aggregation behavior (Cheung et al., 2005). This resilience was quantified for 363 fish species of Moorea but we then only focused on the fish species targeted by fishing in Moorea.

2.2.2.4. Ecological resilience to climate change of the fish assemblages of Moorea

The same method was applied to calculate the resilience of fish assemblages to climate change. We created an index based on previous published work (Graham et al., 2011). Based on theory and published empirical assessments, three variables were included in the climate resilience index: diet specialization, habitat specialization and body size. These variables are known to be linked to a decline of population following disturbances such as climate change (Graham et al., 2011).

These three variables were quantified for 363 fish species of Moorea. These variables were then combined using ranked weighting scheme from previous (Graham et al., 2011). The resultant weighting for our climate vulnerability index were: 0.42 for diet specialization, 0.36 for habitat specialization and 0.22 for body size. The diet specialization has the strongest impact on the resilience of a species. These weightings were used to calculate the final resilience to climate change of each species with a resilience calculated as the weighted sum of the three variables. We measure here the incremental impact of coral reefs degradation on fish assemblages.

The resilience to climate change of fish assemblages was calculated using the same formula as before (Thiault et al, 2017):

$$Rf2_{\mathrm{a}} = \sum_{i=1}^{s_{\mathrm{a}}} \left(1 - vf2_{\mathrm{i,a}}\right) \times n_{\mathrm{i,a}}$$

Where $Rf2_{\mathrm{a}}$ is the resilience of the fish assemblage to climate change at the site a, $vf2_{\mathrm{i,a}}$ is the normalized (scaled between 0 and 1) vulnerability to climate change of the species *s* present in the fish assemblage at the site a, and $n_{\mathrm{i,a}}$ is the log-transformed and normalized relative abundance (scaled between 0 and 1) of the species *s* present in the fish assemblage at the site a.

2.2.2.5. Ecological resilience of corals to climate change and anthropogenic stressors in Moorea

The resilience of corals to climate change and anthropogenic stressors was calculated using previously published work on coral trait species (Darling et al. 2012). We sorted the corals of Moorea in 4 types of corals: competitive, weedy, generalists, and stress-tolerant. Competitive species can dominate less impacted reefs. Yet, these species are more likely to disappear when anthropogenic and environmental stress and disturbances increase, hence the loss of these sensitive competitive corals in such conditions. These species are then replaced with generalist, weedy and generalist species (Darling, 2012).
We created an index of resilience to climate change (between 0 and 1) depending of the coral traits species (0: competitive, 0.50 : weedy, 0.75 generalist, 1 stress tolerant).

The resilience to climate change of coral reefs was then calculated using the same formula as before (Thiault et al., 2007):

$$Rc_{\mathrm{a}} = \sum_{i=1}^{s_{\mathrm{a}}} \left(1 - vc_{\mathrm{i,a}}\right) \times n_{\mathrm{i,a}}$$

Where Rc_a is the resilience of coral reefs at the site a, $vc_{i,a}$ is the normalized (scaled between 0 and 1) vulnerability to climate change of the species *s* present in the coral reefs at the site a, and $n_{i,a}$ is the log-transformed and normalized hard coral cover (scaled between 0 and 1) of the species *s* present in the coral reef at the site a.

2.2.2.6. Models of spatial ecological resilience in Moorea

The fish resilience to fishing was then predicted at unsampled sites using seven spatially explicit predictors in a boosted regression trees model (Elith et al., 2008, Thiault et al., 2018a). The predictors (depth, slope, coral cover, sediment cover, distance to the shore, distance to the closest pass, access and rugosity of the seafloor) were obtained from previous work (Collin & Hench, 2015; Thiault et al., 2018a). The same method was used to map the fish resilience to climate change at unsampled sites and the coral reefs resilience to climate change.

Boosted regression trees use the technique of boosting to combine many tree models adaptively, in order to optimize the overall predictive performance (Elith et al., 2008). Boosted regression trees can fit complex relationships, handle non-linearity and interaction effects between predictors. Therefore, they are commonly used in statistical models because they better handle interactions and non-linearity than regressions (Elith et al., 2008; Thiault et al., 2020). Since social-ecological systems are complex systems with many interactions and non-linearities, it was relevant to use a boosted regression model in our study.

Models were run in R 3.6.3 using the *gbm* package. Cross validation (CV) was used to evaluate the predictive capacity of the models. The total numbers of trees was determined using k-fold cross-validation. Models were developed using a randomly selected 80% of the data (0.8 bag fraction). All other parameters (tree complexity tc=4, learning rate lr=0.0005) were set according to Elith et al. (2008)'s guidelines. According to our data sets, models were fitted to a response type Gaussian. For each model, access and depth were the variable with the highest contribution to the model (48.9% and 40.7%) followed by the distance to the closest pass. The relationship between predicted and observed resilience was high (R^2=0.81 for the resilience of fish assemblages to fishing, R^2=0.4 for the resilience of fish to climate change and R^2=0.72 for the resilience of corals to climate change and anthropogenic stressors).

2.2.3. Ecological vulnerability

The ecological vulnerability was measured using the following formula:

$$EV = EE - ER$$

With EE: ecological exposure, ER: ecological resilience (as the sum of fish resilience to fishing, fish resilience to climate change and coral reefs resilience to climate change)

The ecological vulnerability was calculated with an additive model using equal weighting among components. The maps of exposure, resilience and present ecological vulnerability were mapped in R (Annex IV)

2.2.4. Social exposure

As a small-scale fishery, fishing in Moorea involves simple technologies and is either for subsidence or to supply roadside sellers. Therefore, fishing is characterized by short trips starting in front of people's houses (Leenhardt et al., 2016), hence a spatially limited potential fishing area. Thus, the social exposure of households is measured as the average ecological vulnerability in front of each municipality.

2.2.5. Social dependence

Social-economic data was collected from the ISPF (Insitut Statistiques Polynesie Francaise) to evaluate people dependence on marine ecosystems, hence social sensitivity in Moorea. Datasets resulted from island-wide surveys conducted in 2007,2012 and 2017 on the entire population of Moorea. The indicators selected were chosen regarding the data availability, expert opinion, and previously published studies (Annex I).

The indicators of social sensitivity used for the SES of Moorea were: the number of people with a primary or secondary activity linked to fishing, the number of people with an activity, the number of people with no activity, the population and the number of touristic hotels.

Social sensitivity was calculated using a formula adapted from Thiault (2017) and Cinner (2013). It was calculated as a function of (1) the proportion of people engaged in fisheries (as a primary or secondary activity), (2) the extent to which people engaged in fisheries also engage in non-fishery occupations, (3) the ratio of inactive people in the population and (4) the dependence on tourism.

$$S = \frac{F}{(F+NF)} \times \frac{Na}{(F+NF)} \times \frac{U}{N} \times Ft$$

where S is the sensitivity metric at the municipality scale, F is the number of people in this municipality having fishing as its primary or secondary livelihood activity, NF is the number of people in this municipality having non-fishery-related occupation as its primary or secondary livelihood activity, Na is the number of people in this municipality having an activity, U is the number of people in this municipality having no activity; and N is the total number of people in the municipality, Ft is the tourist dependence by municipality (number of touristic hotels per municipalities) (Thiault et al. 2017).

2.2.6. Social adaptive capacity

Social-economic data was collected from the ISPF (Insitut Statistiques Polynesie Francaise) to evaluate people adaptive capacity in Moorea. Adaptive capacity was assessed by combining different factors at the scale of Moorea: employment, flexibility to get another job, level of education, language spoken, material assets and spatial mobility.

Indicators of social adaptive capacity used for the SES of Moorea were: level of education, number of people having an activity linked to fisheries, number of people having a primary activity, number of people owning a motorized boat, number of people owning a non-motorized boat, number of people owning a car.

Each indicator was assigned a score between 0 and 1, depending on whether they contributed (1) or not (0) to the overall adaptive capacity. The final social adaptive capacity score was calculated as the average of each indicator weighted by their relative importance, at the municipality level (Annex V). Their relative importance was taken from previously published work (Thiault et al, 2017, Saaty 1980).

2.2.7 Social vulnerability

Social vulnerability is the potential degree to which the social system is expected to be affected by the loss of ecosystem services (Thiault et al., 2017). The social vulnerability was measured using the following formula:

$$SV = SE + SS - SAC$$

with SE: social exposure, SS: social sensitivity and SAC: social adaptive capacity.

Data was log-transformed to combine the disparate metrics of the social vulnerability components. Hence, each value was rescaled between 0 (low vulnerability) to 1 (high vulnerability). The social vulnerability was then calculated with an additive model using equal weighting among components.

2.3. Latent vulnerability

2.3.1. Components of latent vulnerability

The same indicators as the ones from the present vulnerability were used for the latent vulnerability (Annex I). No climate change scenario is available and specific enough at the scale of Moorea. The only scenarios available are at the scale of French Polynesia. Since our study focuses on the spatial heterogeneity of the vulnerability in Moorea, the latent exposure to climate change was considered as equal and homogeneous all around Moorea. Thus, only the resilience to climate change was taken into account here as spatially heterogeneous.

2.3.2. Expert elicitation

To evaluate the potential future trends of vulnerability, we used a method called expert elicitation. Experts are people having an extensive knowledge of the topic of interest that they acquired through their life experience, education or training (Garthwaite et al., 2005). This method has often been used to gather insight on the subject of matter. It is particularly suitable to research on complex issues with many uncertainties and a lack of data (Hattam et al., 2020).

A total of 15 regional experts with knowledge of the social and ecological vulnerability of Moorea were interviewed. The list of questions is available in Annex VI. Participants included representatives from multiple backgrounds. The pool of experts was composed of marine scientists (n=5), an anthropologist (n=1), national statistics experts/economists (n=2), a user of the lagoon (n=1), fisheries managers/policymakers (n=4), and environmental organizations representatives (n=2). The advantage of interviewing multiple experts is that responses can be aggregated by taking the mean and the variance (Annex VIII) can be used as a measure of uncertainty. The expert selection has been made to ensure the diversity of expertise and opinion. Upon each interview, detailed notes were taken for analysis. Each expert was asked to describe the potential future trajectory of each indicator of the vulnerability by 2050 (Annex VII). 2050 was chosen since it is a date used in many climate change scenarios.

2.3.3. Calculate latent vulnerability

Each expert described the potential future trajectory of each indicator of the social-ecological vulnerability in Moorea: sharp decline, small decline, constant evolution, small increase or sharp increase. A score was attributed for each evolution: 0 for sharp decline, 0.5 for small decline, 1 for constant evolution, 1.5 for small increase, 2 for sharp increase. The mean evolution was calculated for each indicator after expert elicitation (Annexe VIII). To calculate latent vulnerability, indicators of the present vulnerability were then multiplied by their mean potential future evolution.

2.4. Spatial temporal dynamics of vulnerability

We adopted a commonly used approach that combines vulnerability components into a single index of vulnerability to map the present vulnerability to multiple stressors (Cinner et al., 2012; Cinner et al., 2013; Thiault, 2017). All indicators of exposure, sensitivity and adaptive capacity were normalized to a scale ranging from 0 to 1 so they could be combined and compared (0 being the lowest contribution to vulnerability, 1 the highest). For each driver, each of the three dimensions of vulnerability has a cumulative weight score of one (Thiault et al. 2017, J. E. Cinner et al. 2012). The same approach was used to map the latent vulnerability. Following Halpern *et al.*'s (2015) approach, we then mapped and combined the current vulnerability and the vulnerability trend by 2050. The present vulnerability showcases the current state of vulnerability while the vulnerability trend provides information on the location, magnitude and direction of change originated by external stressors. Areas of high and low present vulnerability (respectively above the 75% quartile and below the 25% quartile) were pointed out and the vulnerability trajectory was then evaluated. Areas where latent vulnerability would increase or decrease by 2050 were assessed. The map shows which habitats and municipalities are currently the most vulnerable and their trajectories over time. All statistical and spatial analyses were executed in the R software using the raster and rgdal packages.

2.5. Profiles of vulnerability to inform adaptation pathways

Four profiles of vulnerability can be differentiated by plotting the latent states of vulnerability against the present ones (Brun et al., in prep).

- Profiles of lowest concern for areas with both low present and latent vulnerability: characterized by relatively low exposure to threats and a good resilience.
- Profiles of present vulnerability where latent vulnerability is not much higher than the present one. Vulnerability dimensions are not expected to get worse in the future.
- Profiles of latent vulnerability where there is a low present vulnerability but a high latent vulnerability.
- Profiles of highest concern where there is a high present and latent vulnerability. The areas are currently highly vulnerable and have the highest latent vulnerability trend. Latent threats are adding to the present ones.

3. Results

3.1. Ecological resilience

Fish assemblages appear to be more vulnerable near the coast and more resilient on the outer slope (Fig 4a and 4b). Fish assemblages seem more resilient to fishing in the south of Moorea (Fig 4b). On the other hand, coral reefs are more vulnerable on the outer slope but more resilient on the fringing reef and lagoon where the local threats are the biggest (Fig 4c).

a)

b)

c)

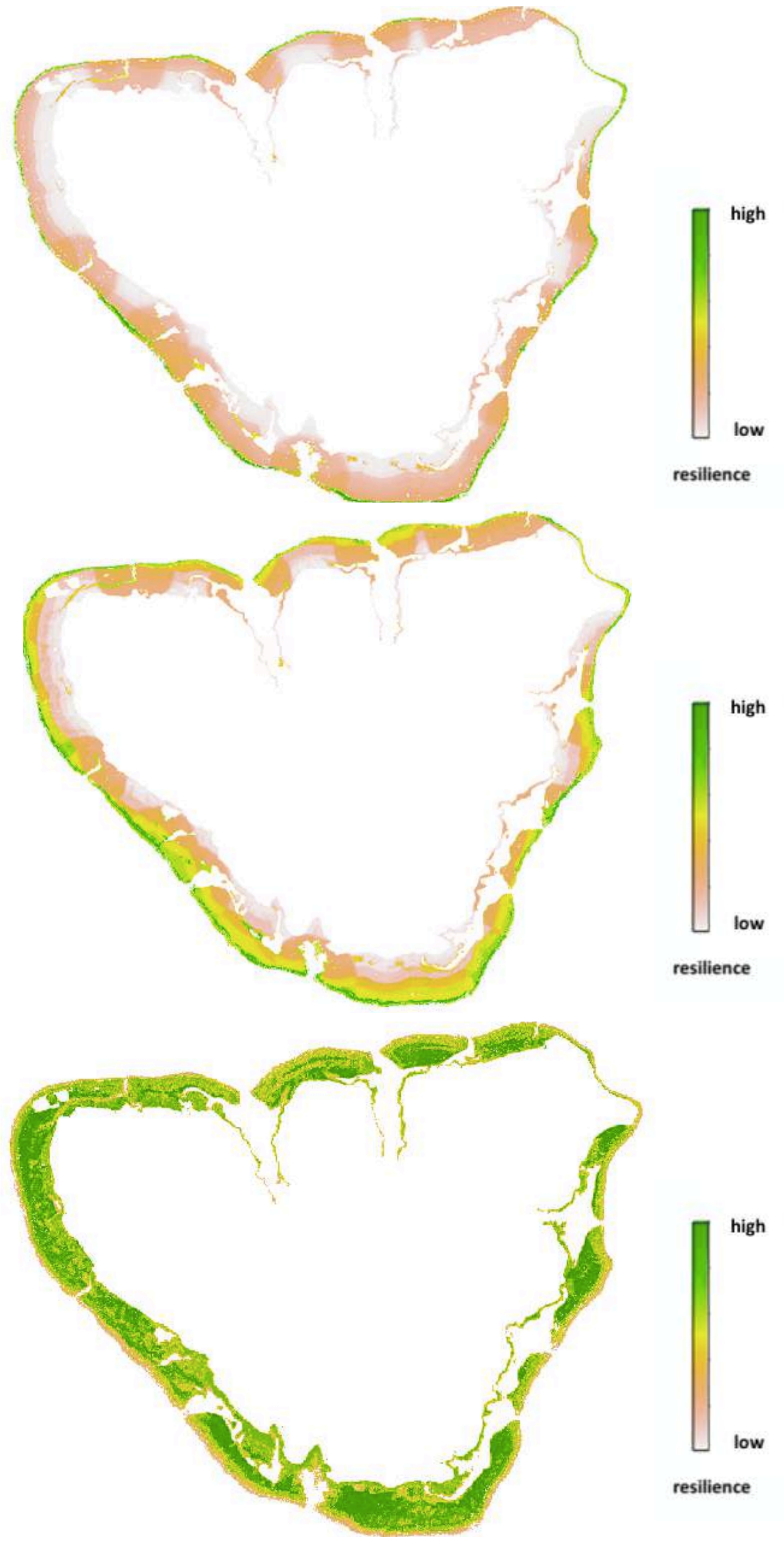

Figure 4: Maps of resilience in Moorea: (a) resilience of fish assemblages to climate change (b) resilience of fish assemblages to fishing (c) resilience of corals to climate change and anthropogenic stressors.

3.2. Present social-ecological vulnerability of Moorea

Here, we looked at the spatial heterogeneities in vulnerability at the scale of Moorea. There is a strong spatial heterogeneity of social-ecological vulnerability around Moorea. We found strong variability in social vulnerability among municipalities across the entire island. Highly vulnerable municipalities are municipalities with high exposure, high sensitivity and low adaptive capacity.

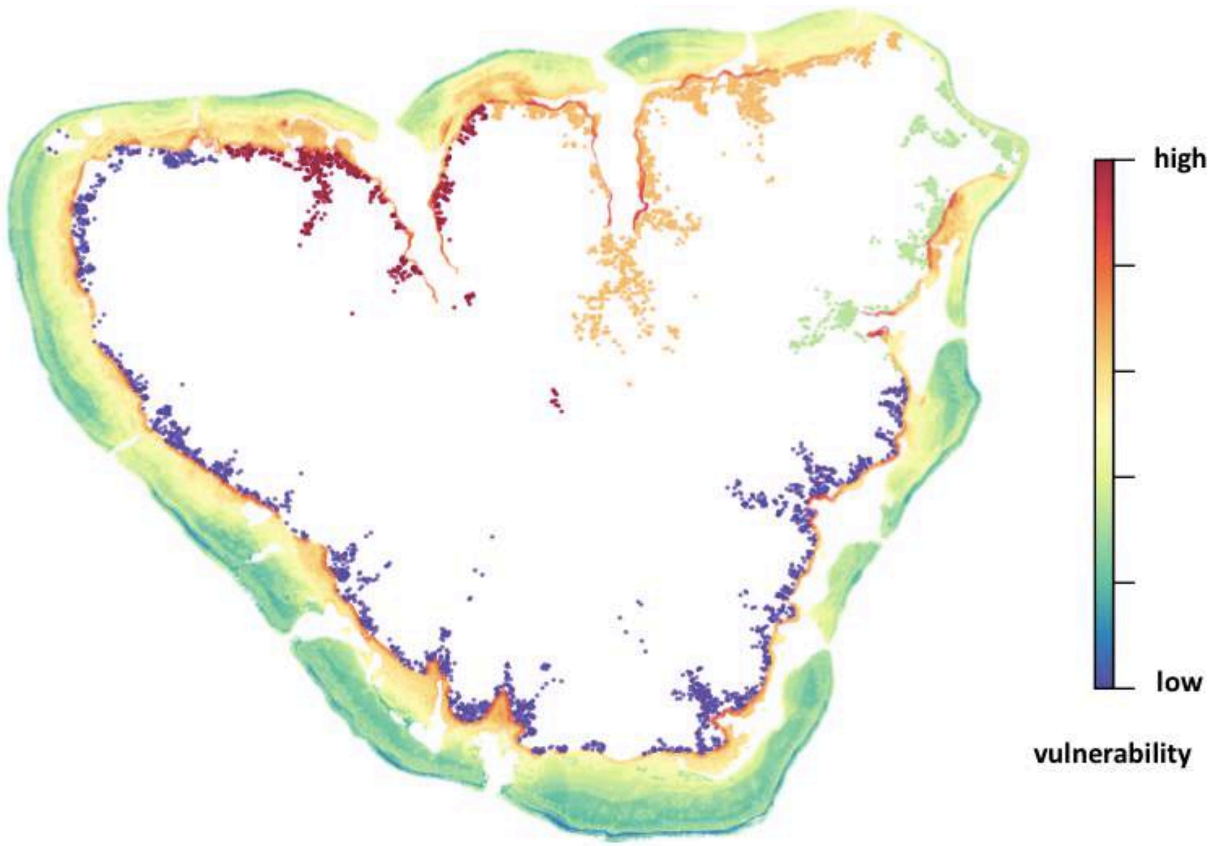

Figure 5: Present social-ecological vulnerability in Moorea to multiple stressors
Dots located on land represent individual households.

Highly vulnerable populations are not always located in front of ecologically vulnerable areas. For instance, the highly vulnerable ecological area of Temae is facing a less socially vulnerable population. The most vulnerable municipality is Papetoai, followed by Paopao. Haapiti and Afareitu are the less vulnerable municipalities.

Ecological vulnerability had a more even distribution. The highest ecological vulnerability is generally located close to shore where the anthropogenic threats are the highest and where fish assemblages are poorly resilient (Fig 4a, Fig 4b and Annex II). As a consequence, fringing habitats (i.e., both reef and sand) display the highest levels of vulnerability (Fig 6). A vulnerability score of 0 is considered as low vulnerability whereas a score of 1 is considered as high vulnerability. Ecological vulnerability is particularly high in front of Papetoai and Paopao whereas it is lower in the south of Moorea (Fig 6).

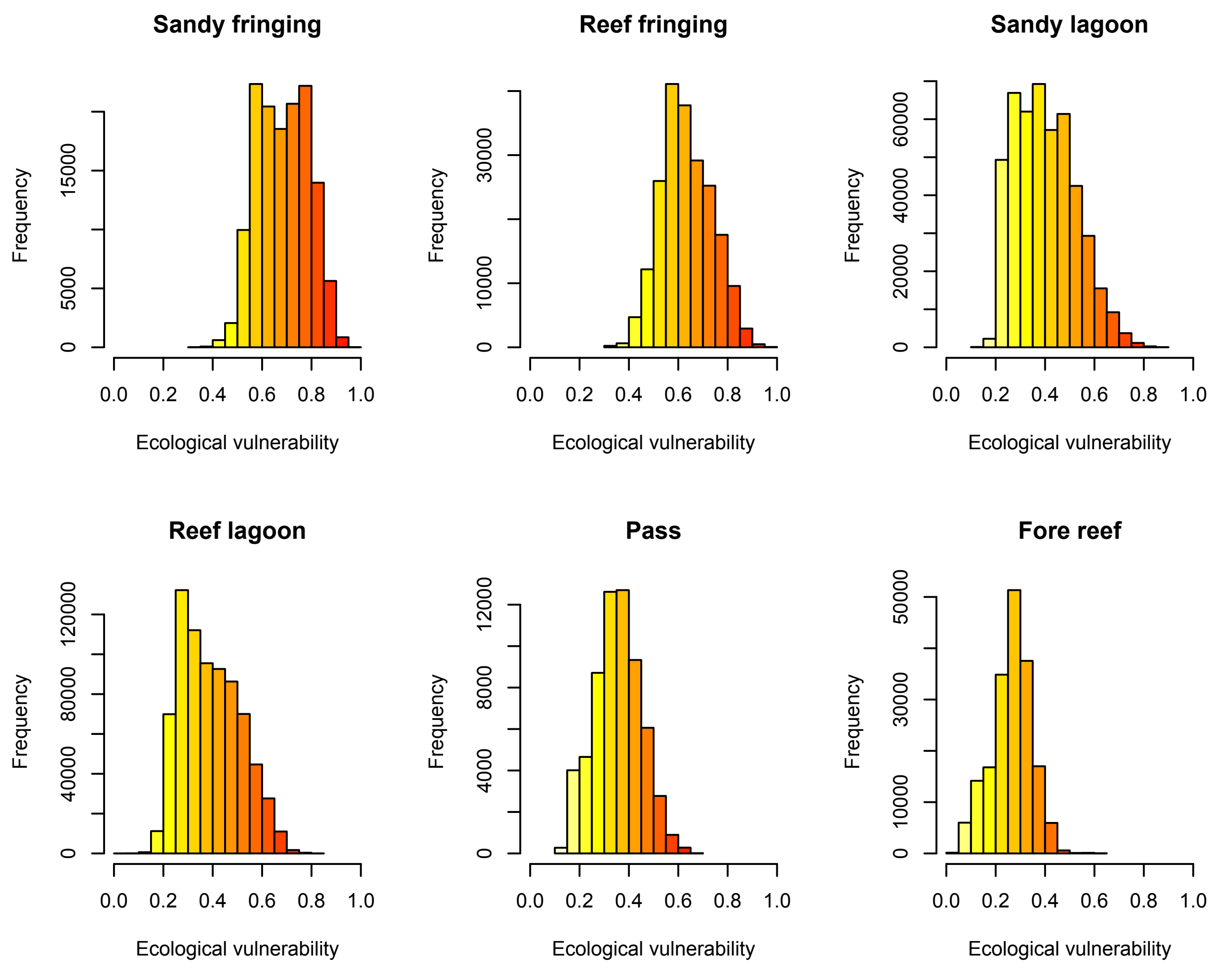

Figure 6: Ecological distribution of vulnerability per habitat.

The lagoon habitats appear to be the second most vulnerable habitats whereas the pass and outer slope are less vulnerable (Fig 6).

3.3. Components of the latent social-ecological vulnerability of Moorea

As a result from expert elicitation, the overall ecological exposure will slightly increase in the future (Annex VIII). We considered the resilience of coral reefs and fish assemblages constant over time. As a result, the overall latent vulnerability is globally proportional to the present vulnerability but will increase moderately by 2050. Thus, areas like the reef in front of Papetoai and Paopao that are highly vulnerable today will be even more vulnerable in the future. Areas that are less vulnerable today will be more vulnerable in the future as well. Furthermore, there will still be a strong variability in social vulnerability among municipalities across the entire island. Yet, there is a shift in vulnerability among the municipalities. Paopao is expected to be the most vulnerable municipality by 2050, followed by Afareaitu. On the other hand, Teavaro and Haapiti are expected to be the less vulnerable municipalities.

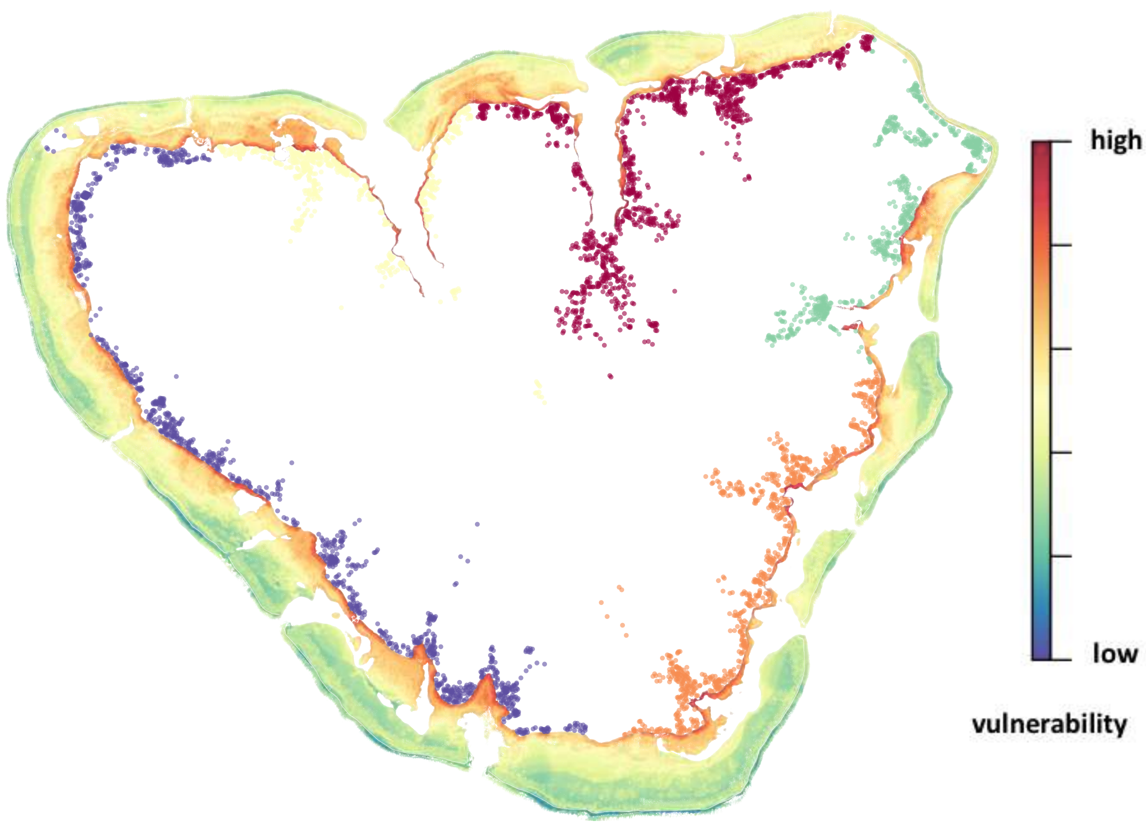

Figure 7: Latent social-ecological vulnerability in Moorea, expected by 2050 according to expert insight (Annex VI). Circles located on land represent individual households and cells surrounding the land represent the reefs.

3.4. Latent trajectory of the vulnerability in Moorea

Island-wide, ecological vulnerability increases overall, whether the vulnerability is currently high or low (Fig 8). Between 2017 and 2050, reef areas with highest vulnerability will generally become more vulnerable on the back reef near the coast. Least vulnerable habitats on the outer slope will experience increased vulnerability, especially in the south-west of Moorea**.** Only a few areas north of Moorea with high vulnerability are following a decreasing trend.

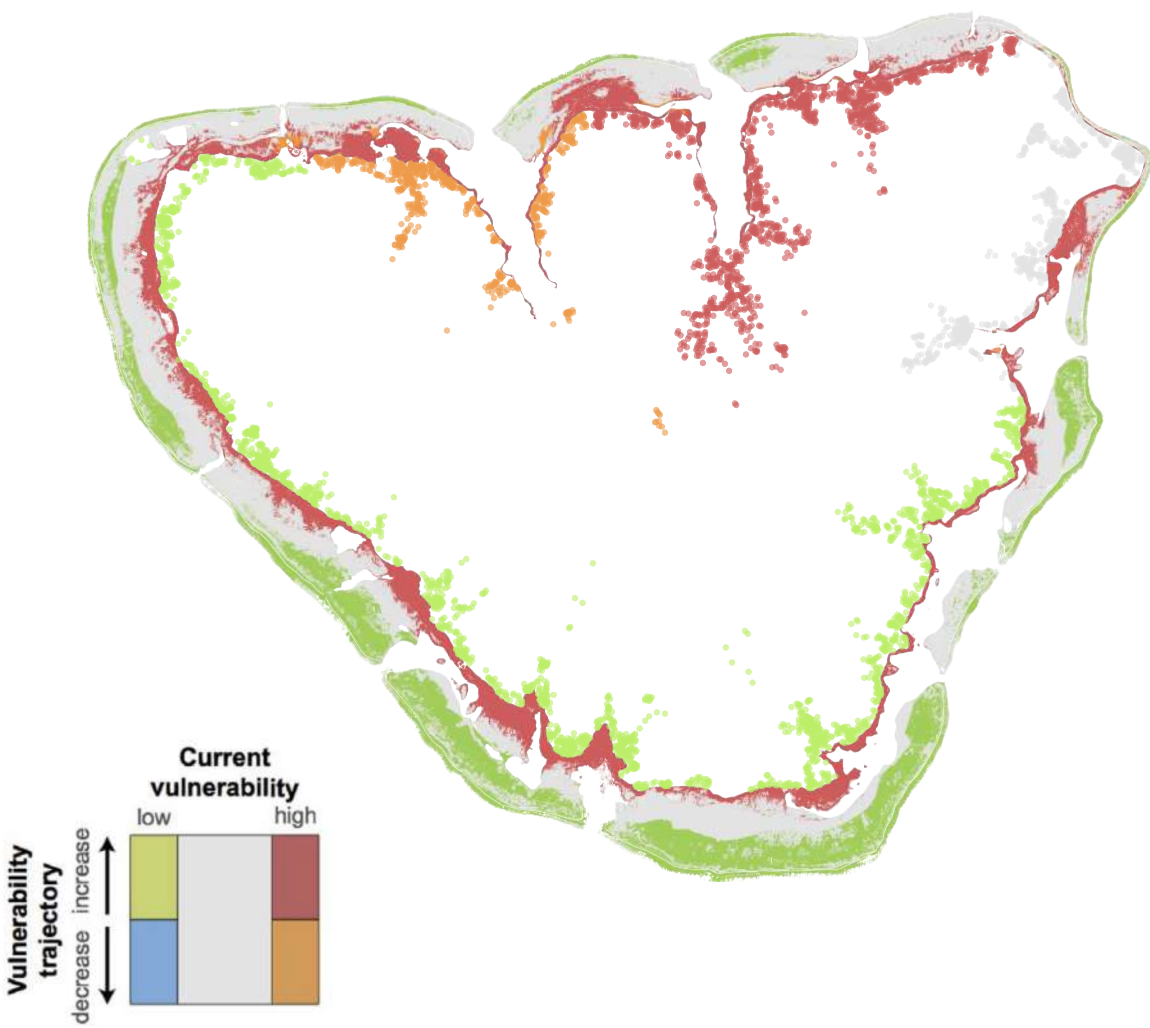

Figure 8: Combination of current social-ecological vulnerability (2017) and social-ecological vulnerability latent trajectories. They include areas with combinations of the highest (top quartile) and lowest (bottom quartile) vulnerability and increasing and decreasing vulnerability over the 2017-2050 time period. Results are summarized for each natural habitat (ecological vulnerability) and municipality (social vulnerability).

Households of high vulnerability following an increasing trend can be found in Paopao. They are among the most vulnerable households of Moorea (Fig 8). In households with currently low vulnerability such as Haapiti or Afareiatu, vulnerability is expected to increase by 2050. On the other hand, households with high current social vulnerability and following a decreasing trend are located in Papetoai. The vulnerability of Teavaro is expected to remain globally the same by 2050.

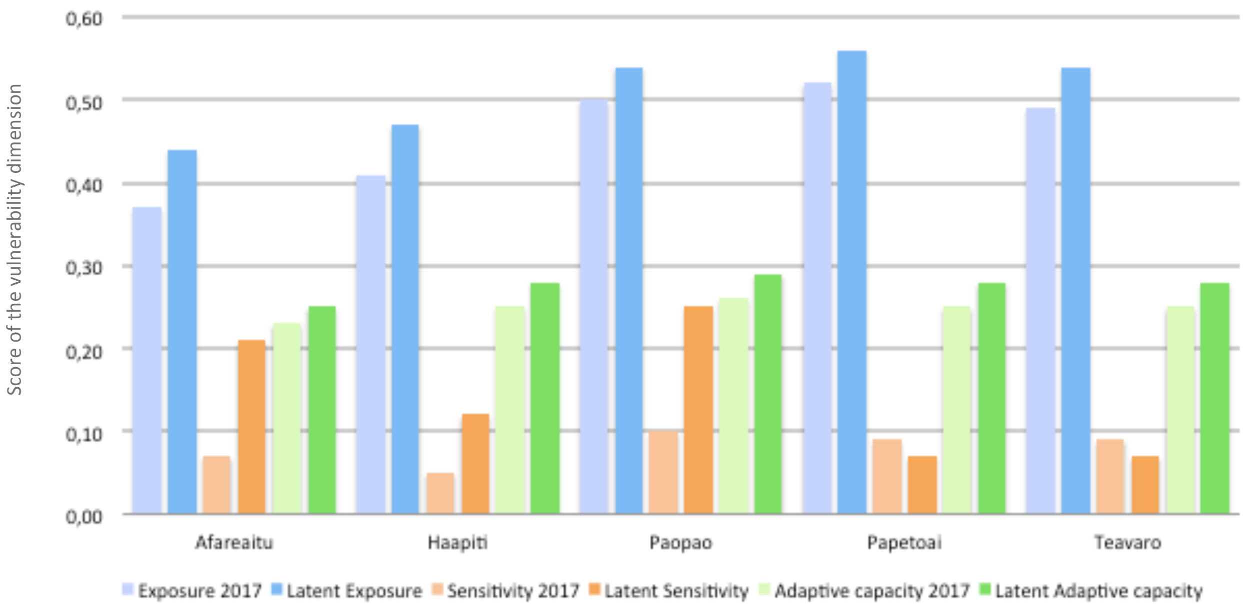

Figure 9: Present and latent scores of the three social vulnerability dimensions: exposure, sensitivity and adaptive capacity, in 2017 and 2050.

The latent evolution of the different vulnerability dimensions varies among the different municipalities (Fig 9). The exposure and adaptive capacity are expected to slightly increase for all the municipalities from 2017 to 2050. However, the latent evolution of sensitivity differs depending on the municipality. The dependence of Afareiatu, Haapiti and Paopao is expected to increase in the future. This increase is particularly significant for Afareiatu and Paopao. On the contrary, the dependence of Papetoai and Teavaro is expected to slowly decrease in the future.

3.5. Profiles of vulnerability to inform adaptation pathways

Results of latent vulnerability trajectories should further guide decision-makers on adaptation. Different profiles of vulnerability can help achieving that.

An assessment of the vulnerability profiles of each municipality of Moorea shows that Haapiti is the only municipality of lowest concern (Fig 10). It has the lowest present and latent vulnerability. A management goal could be to maintain this state of lowest concern in the future and use it as an example for adaptation planning. Teavaro has a profile where present vulnerability is high but latent vulnerability is low (Fig 10): current threats are high and resilience is low but the latent vulnerability is not supposed to get much worse. On the other other hand, Paopao, Papetoai and Afareiatu are of highest concern (Fig 10). These municipalities need more attention since they are currently highly vulnerable and their latent vulnerability is expected to get worse. It is urgent to plan timely explicit adaptation actions for these three municipalities.

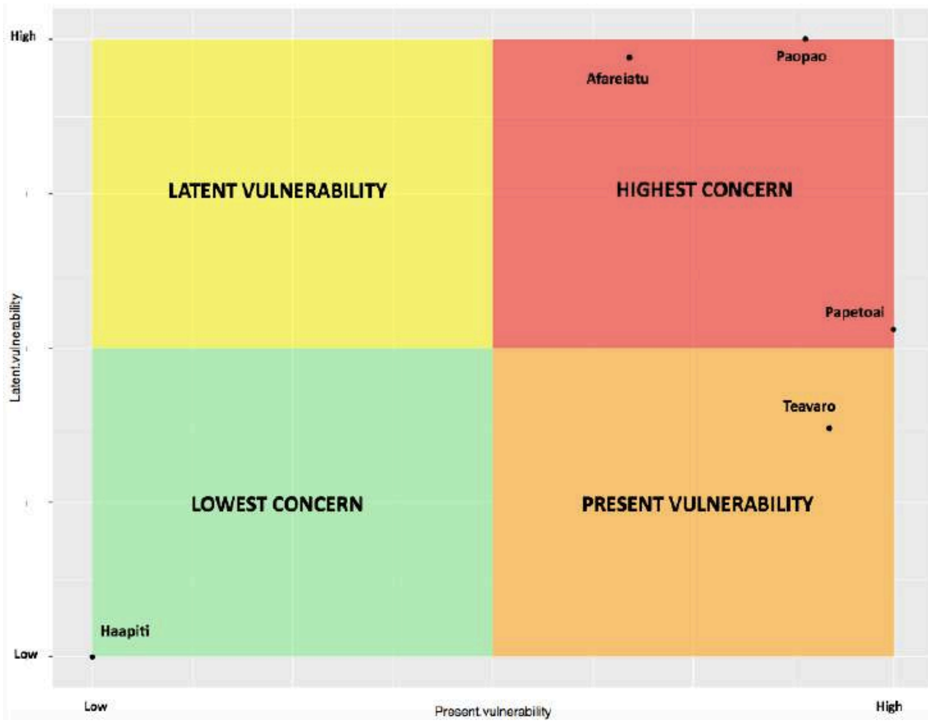

Figure 10: Framework used to classify the five municipalities of Moorea according to four vulnerability profiles

4. Discussion

4.1. Mapping social-ecological vulnerability to inform local decision-making

When studying the sustainability of social-ecological systems, interactions and trade-offs between ecosystems processes and human activities have to be taken into account (Bennett et al., 2016). People affect and get affected by ecological processes at the same time. Social and ecological systems constantly interweave with one another and create spatial patterns. These interactions are highly dynamic across scales, in space and over time. This study has demonstrated how integrated social-ecological vulnerability analysis can be calculated at the scale of habitats and municipalities. Such analyses provide a better understanding of social-ecological changes over time as a result of exposure to multiple stressors.

To address these challenges, our approach focuses on three levels. First, we studied the three dimensions of vulnerability: exposure, sensitivity and adaptive capacity, both at the social and ecological level. Then, we mapped the social-ecological vulnerability to identify the spatial heterogeneities of the vulnerability: vulnerability in the different ecological habitats and in the different social municipalities. Finally, we approached temporal dynamics of the vulnerability by mapping the latent trend of vulnerability. We looked at the social-ecological vulnerability trajectories over time to reveal potential changes in the future vulnerability. These insights about future potential vulnerable habitats and municipalities can help decision-makers deciding about management actions. It offers early warnings of deleterious trends of vulnerability and highlights areas that might need adaptive management interventions. Latent vulnerability has to be considered as a warning of evolving and additive threats and as an opportunity for adaption in the face of potential future threats and weaknesses.

Understanding social-ecological vulnerability and its latent trajectory is essential in the real-world decision-making. We showed that social and ecological vulnerability in Moorea is globally expected to increase in the future. Yet, the direction and magnitude of the changes will be different according to the different habitats and municipalities. Our study can help decision-makers to identify which areas are the most socially and ecologically vulnerable and why. This tool can be used to better understand the social-ecological system's dynamics and guide actions that can build local resilience to local and global stressors. Therefore, local-level actions at the municipality scale can help to reduce the vulnerability of coastal communities to climate change and anthropogenic stressors. This is particularly helpful in Moorea where management decisions are taken at the municipality scale in the spatially explicit management plan PGEM (Plan de Gestion de l'Espace Maritime). By identifying why the different municipalities are vulnerable (Fig 9), different policy priorities and necessary management plans become apparent.

4.2. Expert elicitation

Even though the strength of expert elicitation has been demonstrated many times (Garthwaite et al., 2005; Hattam et al., 2020; Kuhnert et al., 2010), it is essential to acknowledge the bias in an elicitation. Heuristics and judgments that experts use to base their response on contribute to the uncertainty surrounding expert opinion. Words also often have different meanings for different people, which result in linguistic uncertainty. Thus, understanding the question right and in the same way for everyone is the most difficult part of the process. Ignorance and subjectivity on the matter of interest also contributes a lot to the uncertainty. It is essential to consider these uncertainties carefully to avoid any unwanted bias during expert elicitation and the analysis of results (Kuhnert et al., 2010).

Furthermore, expert elicitation and participatory methods engaging with scientific experts and other stakeholder groups are quite challenging and time-consuming (Leenhardt et al., 2017b). It was even more challenging with the COVID-19 situation. Interviews had to be done over phone calls and video calls due to the sanitary concerns. Unfortunately, fishermen could not be reached over the phone. Thus, they were not interviewed even though it was initially a primary focus of our study as their ecological knowledge would have been a great asset in our model. We still interviewed a wide range of experts from researchers and environmental organizations to governmental agencies and management bodies. This allowed us to have different insights on the social-ecological system studied and to engage discussion around the subject.

4.3. Future research priorities

Our work illustrates the necessity of an effective and adaptive management plan to reduce the social-ecological vulnerability of Moorea in the future. There is a spatial and temporal heterogeneity that decision-makers have to take into account over the long term.
However, specific climate data was lacking to measure more precisely the latent exposure to climate change at the scale of the different municipalities of Moorea. Since the decisions in Moorea are made at the municipality scale, it is important to get climate data at the same scale for vulnerability assessments. In our study, the climate change threats were considered equals in all municipalities. Yet, this is most likely not accurate. Therefore, future research should focus into developing specific climate models at the scale of Moorea in order to fully apprehend the evolution of the latent climate change exposure. It would be interesting to add the impact of storms and crown-of-thorns starfish outbreaks as well. Future work should also incorporate some other social factors of vulnerability that we did not take into account here. Some of these factors may include storms on coral reefs or crown-of-thorns starfish outbreaks as drivers of exposure. The power of Polynesian communities helping each other as driver of adaptive capacity could also be taken into account. Incorporating this kind of data would better reflect the actual resilience of population to changes. Yet, this factor, which is not available at the moment, would be hard to measure and associated uncertainty would be high.

In 2020, the world was hit by the COVID-19 pandemic and completely shut down, which led to extensive social and economic effects. The consequences are particularly important for small-scale fisheries (Bennet et al, 2020) such as Moorea. At the end of March, the island implemented a strict lockdown, air traffic shut down, and no tourist was allowed for a period of 3 months. Some negative outcomes of the pandemic on small-scale fisheries include shutdowns of some fisheries, increase of illegal and unreported fishing, market disruptions (Bennett et al., 2020) … During the lockdown in Moorea, we noticed a huge increase of fishermen in the lagoon for instance. Therefore, the fishing pressure in Moorea was extremely high during this time, which increased the exposure on coral reefs and fish. However, there were some positive consequences as well, such as food sharing between communities and sometimes a decrease of some threats (e.g. tourism) on the ecosystems (Bennett et al., 2020). In Moorea, the impact of tourism was null as there had been no tourist on the island for 3 months. On the social-economic side, one of the main hotels of Moorea shut down during the pandemic and many people went unemployed. This pandemic was unexpected and it completely reversed the usual habits of the population in only 3 months. Thus, it would be interesting that future research focuses on the impact of pandemics like this one on the social-ecological system of Moorea. Indeed, the future vulnerability of the island will depend on potential pandemics and how populations respond and adapt to it.

5. Conclusion

Our approach illustrates how mapping present social-ecological vulnerability to multiple stressors and its latent trajectory can provide valuable information to help decision-making. Integrated vulnerability assessments are not the only way to model social-ecological systems but their efficacy has been proven. This study displays both spatial and temporal magnitude and direction of change (positive or negative) in the social and ecological subsystems. Furthermore, it takes into account interdependencies between the social and ecological systems through ecosystems services. The latent vulnerability trend illustrates which habitats and municipalities might be the most vulnerable in the future and why. It helps identifying potential future negative trends, which can help guide adaptive and targeted management actions. Thus, local managers can use these vulnerability assessments as a tool to identify where management should focus in priority (social and/or ecological areas). It enables them to understand the vulnerability response to multiple stressors and to understand which drivers of change can be directly addressed in management decisions (fishing pressure, pollution, etc.). In the context of the covid-19 pandemic that happened in 2020, it would be interesting that future research focuses on the impact of Covid-19 on the social-ecological vulnerability of Moorea.

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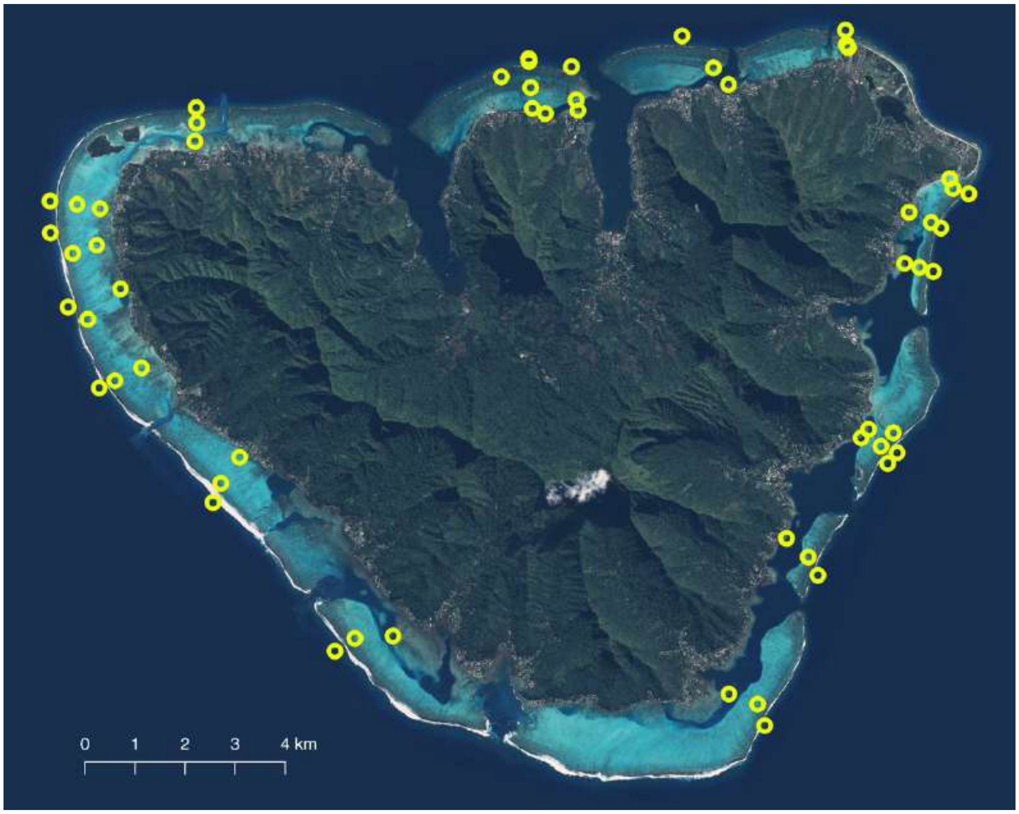
Appendix

Annex I – Indicators of vulnerability for the SES of Moorea

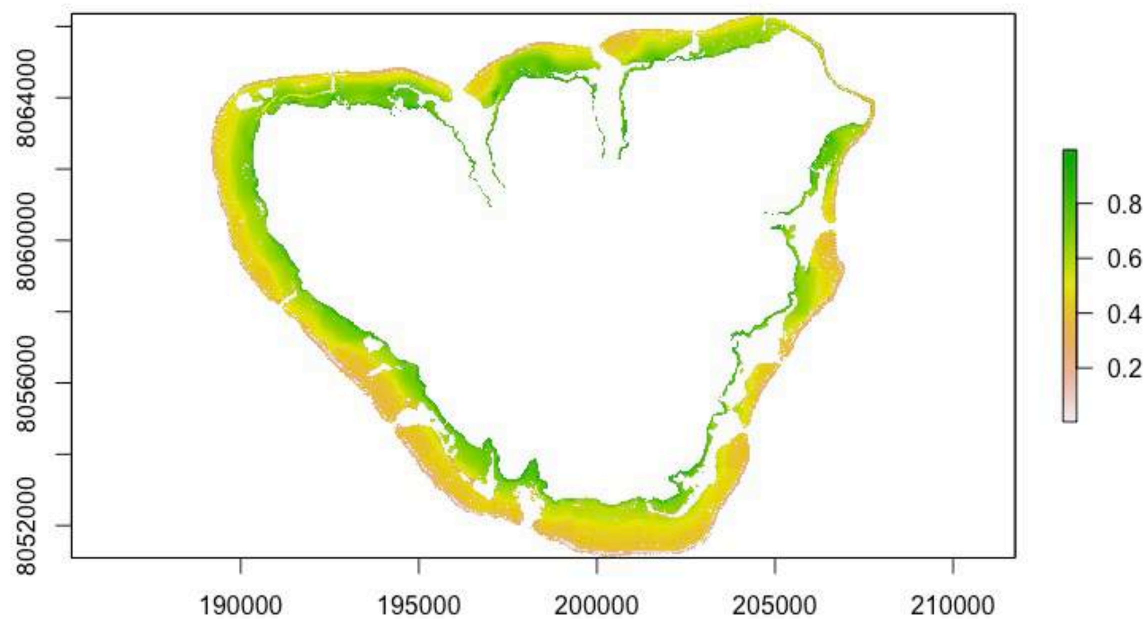
SES system	Vulnerability dimension	Indicators
Ecological	Ecological exposure	Anchoring
		Diving
		Feeding activities
		Fishing
		Marina
		Sedimentation
		Shipping
		Shoreline
		Trampling
		Coastal urbanization
		Water temperature
		Ocean acidification
	Ecological resilience	Fish resilience to fishing
		Fish resilience to climate change
		Resilience of corals to climate change and anthropogenic stressors
Social	Social exposure	Mean ecological vulnerability
	Social sensitivity	Number of people with a primary or secondary activity linked to fishing
		Number of people with an activity (primary or secondary) not linked to fishing
		Number of people with an activity
		Number of people with no activity
		Population
		Numbers of touristic hotels
	Social adaptive capacity	Language spoken
		Level of education
		Number of people having an activity linked to fisheries
		Number of people having a primary activity
		Motorized boat ownership
		Non-motorized boat ownership
		Type of house
		Number of people with a secondary activity
		Car ownership

Annex II - Present ecological exposure of Moorea

Annex III - Location of sampling sites used to calculate the ecological resilience index in Moorea.



Annex IV - Map of present ecological vulnerability in Moorea



Annex V - Adaptive capacity indicators and their weightings

Indicators	Bounding	Weight
Motorized boat ownership	Binomial: no=0, yes=1	0.12
Non-motorized boat ownership	Binomial: no=0, yes=1	0.02
Primary activity	Binomial: no=0, yes=1	0.235
Secondary activity	Binomial: no=0, yes=1	0.15
Type of house (concrete)	Binomial: no=0, yes=1	0.01
Car ownership	Binomial: no=0, yes=1	0.035
Language spoken (French)	Binomial: no=0, yes=1	0.07
Level of education (>Highschool)	Binomial: no=0, yes=1	0.35

Annex VI - Questions used during each interview for the expert elicitation

1) Nombres de pêcheurs/Number of fishermen
- Selon vous, comment évoluera le nombre de pêcheurs d'ici 2050 à Moorea?
- Notez l'évolution selon les critères suivants : forte diminution, faible diminution, évolution constante, faible augmentation, forte augmentation?
- Si vous pensez que cette évolution puisse être différente pour certaines communes de Moorea, merci de l'indiquer (vous pouvez remplir l'information pour une seule ou plusieurs communes, pour les activités que vous souhaitez).

2) Zones d'ancrages/anchoring
- Selon vous, comment évoluera le nombre et l'étendue des zones d'ancrage des bateaux d'ici 2050 à Moorea?
- Notez l'évolution selon les critères suivants : forte diminution, faible diminution, évolution constante, faible augmentation, forte augmentation?
- Si vous pensez que cette évolution puisse être différente pour certaines communes de Moorea, merci de l'indiquer (vous pouvez remplir l'information pour une seule ou plusieurs communes, pour les activités que vous souhaitez).

3) Articificialisation du littoral / Urbanization
- Selon vous, comment évoluera l'artificialisation du littoral d'ici 2050 à Moorea?
- Notez l'évolution selon les critères suivants : forte diminution, faible diminution, évolution constante, faible augmentation, forte augmentation?
    - Si vous pensez que cette évolution puisse être différente pour certaines communes de Moorea, merci de l'indiquer (vous pouvez remplir l'information pour une seule ou plusieurs communes, pour les activités que vous souhaitez).

4) Tourisme côtier (baignade)/ Trampling
- Selon vous, comment évoluera le tourisme côtier (baignade) d'ici 2050 à Moorea?
- Notez l'évolution selon les critères suivants : forte diminution, faible diminution, évolution constante, faible augmentation, forte augmentation?
- Si vous pensez que cette évolution puisse être différente pour certaines communes de Moorea, merci de l'indiquer (vous pouvez remplir l'information pour une seule ou plusieurs communes, pour les activités que vous souhaitez).

5) Tourisme pour la plongée / Diving
- Selon vous, comment évoluera le tourisme (plongée) d'ici 2050 à Moorea?
- Notez l'évolution selon les critères suivants : forte diminution, faible diminution, évolution constante, faible augmentation, forte augmentation?
- Si vous pensez que cette évolution puisse être différente pour certaines communes de Moorea, merci de l'indiquer (vous pouvez remplir l'information pour une seule ou plusieurs communes, pour les activités que vous souhaitez).

6) Tourisme impliquant le feeding/ Feeding
- Selon vous, comment évolueront les activités d'observation d'animaux marins (sans faire de plongée) d'ici 2050 à Moorea?

- Notez l'évolution selon les critères suivants : forte diminution, faible diminution, évolution constante, faible augmentation, forte augmentation?
- Si vous pensez que cette évolution puisse être différente pour certaines communes de Moorea, merci de l'indiquer (vous pouvez remplir l'information pour une seule ou plusieurs communes, pour les activités que vous souhaitez).

7) Pratiques agricoles / Agriculture/ Sedimentation

- Selon vous, comment évolueront les pratiques agricoles d'ici 2050 à Moorea?
- Notez l'évolution selon les critères suivants : forte diminution, faible diminution, évolution constante, faible augmentation, forte augmentation?
- Si vous pensez que cette évolution puisse être différente pour certaines communes de Moorea, merci de l'indiquer (vous pouvez remplir l'information pour une seule ou plusieurs communes, pour les activités que vous souhaitez).

8) Température de l'eau / Water temperature

- Selon vous, comment évoluera la température de l'eau d'ici 2050 à Moorea?
- Notez l'évolution selon les critères suivants : forte diminution, faible diminution, évolution constante, faible augmentation, forte augmentation?
- Si vous pensez que cette évolution puisse être différente pour certaines communes de Moorea, merci de l'indiquer (vous pouvez remplir l'information pour une seule ou plusieurs communes, pour les activités que vous souhaitez).

9) Acidification des oceans / Ocean acidification

- Selon vous, comment évoluera l'acidification des océans d'ici 2050 à Moorea?
- Notez l'évolution selon les critères suivants : forte diminution, faible diminution, évolution constante, faible augmentation, forte augmentation?
- Si vous pensez que cette évolution puisse être différente pour certaines communes de Moorea, merci de l'indiquer (vous pouvez remplir l'information pour une seule ou plusieurs communes, pour les activités que vous souhaitez).

10) Population

- Selon vous, comment évoluera le nombre d'habitants d'ici 2050 à Moorea?
- Notez l'évolution selon les critères suivants : forte diminution, faible diminution, évolution constante, faible augmentation, forte augmentation?
- Si vous pensez que cette évolution puisse être différente pour certaines communes de Moorea, merci de l'indiquer (vous pouvez remplir l'information pour une seule ou plusieurs communes, pour les activités que vous souhaitez).

11) Emplois liés à la pêche/ Fisheries activities

- Selon vous, comment évoluera le nombre d'emplois liés a la pêche d'ici 2050 à Moorea?
- Notez l'évolution selon les critères suivants : forte diminution, faible diminution, évolution constante, faible augmentation, forte augmentation?
- Si vous pensez que cette évolution puisse être différente pour certaines communes de Moorea, merci de l'indiquer (vous pouvez remplir l'information pour une seule ou plusieurs communes, pour les activités que vous souhaitez).

12) Pluriactivité/ Secondary activities

- Selon vous, comment évoluera le nombre d'activités professionnelles par personne d'ici 2050 à Moorea?
- Notez l'évolution selon les critères suivants : forte diminution, faible diminution, évolution constante, faible augmentation, forte augmentation?
- Si vous pensez que cette évolution puisse être différente pour certaines communes de Moorea, merci de l'indiquer (vous pouvez remplir l'information pour une seule ou plusieurs communes, pour les activités que vous souhaitez).

13) Niveau de vie/ Standard of living/Type of house

- Selon vous, comment évoluera le niveau de vie par foyer d'ici 2050 à Moorea?
- Notez l'évolution selon les critères suivants : forte diminution, faible diminution, évolution constante, faible augmentation, forte augmentation?
- Si vous pensez que cette évolution puisse être différente pour certaines communes de Moorea, merci de l'indiquer (vous pouvez remplir l'information pour une seule ou plusieurs communes, pour les activités que vous souhaitez).

14) Niveau d'éducation supérieur au bac / Level of education

- Selon vous, comment évoluera le nombre de personnes ayant un diplôme supérieur au BAC d'ici 2050 à Moorea?
- Notez l'évolution selon les critères suivants : forte diminution, faible diminution, évolution constante, faible augmentation, forte augmentation?
- Si vous pensez que cette évolution puisse être différente pour certaines communes de Moorea, merci de l'indiquer (vous pouvez remplir l'information pour une seule ou plusieurs communes, pour les activités que vous souhaitez).

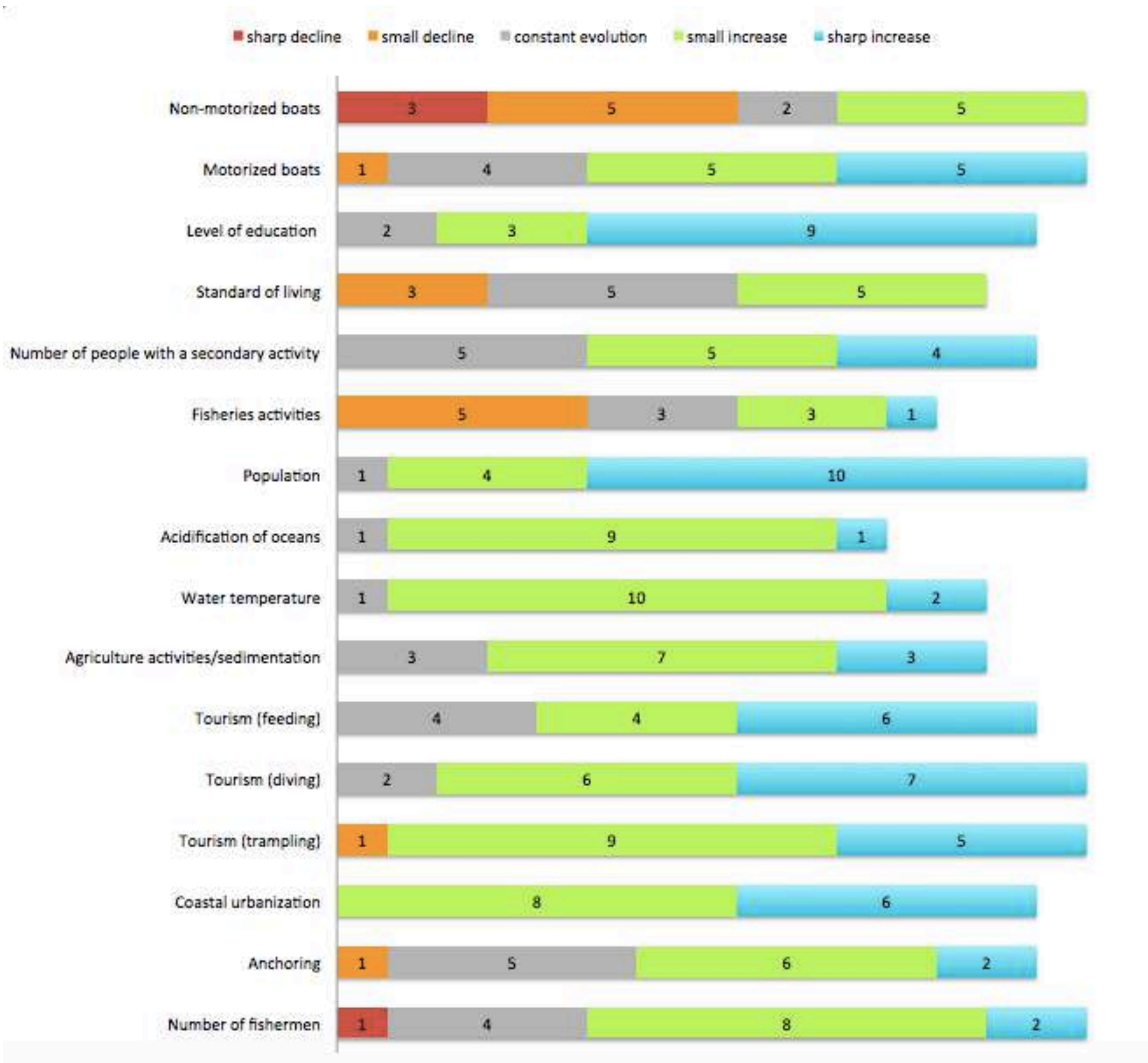
15) Bateaux à moteurs / Motorized boats

- Selon vous, comment évoluera le nombre de bateaux à moteur d'ici 2050 à Moorea?
- Notez l'évolution selon les critères suivants : forte diminution, faible diminution, évolution constante, faible augmentation, forte augmentation?
- Si vous pensez que cette évolution puisse être différente pour certaines communes de Moorea, merci de l'indiquer (vous pouvez remplir l'information pour une seule ou plusieurs communes, pour les activités que vous souhaitez).

16) Bateaux non motorisés/ Pirogues traditionnelles / Non-motorized boats

- Selon vous, comment évoluera le nombre de pirogues d'ici 2050 à Moorea?
- Notez l'évolution selon les critères suivants : forte diminution, faible diminution, évolution constante, faible augmentation, forte augmentation?
- Si vous pensez que cette évolution puisse être différente pour certaines communes de Moorea, merci de l'indiquer (vous pouvez remplir l'information pour une seule ou plusieurs communes, pour les activités que vous souhaitez).

Annex VII - results of the expert elicitation showing the number of answers for each evolution of the indicators by 2050



Annex VIII - mean and variance for the results of the expert elicitation (N=15)
(scores assigned to each potential evolution : sharp decline - 0, small decline – 0.5, constant evolution – 1, small increase – 1.5, sharp increase – 2)

Indicators	Mean potential evolution	Variance
Non-motorized boats	0.80	0.33
Motorized boats	1.47	0.22
Level of education	1.75	0.14
Standard of living	1.08	0.15
Number of people with a secondary activity	1.46	0.16
Fisheries activities	1	0.25
Population	1.80	0.09
Acidification of oceans	1.38	0.06
Water temperature	1.54	0.06
Agriculture activities/Sedimentation	1.5	0.11
Tourism (feeding)	1.57	0.17
Tourism (diving)	1.67	0.12
Tourism (trampling)	1.6	0.14
Coastal urbanization	1.71	0.06
Anchoring	1.32	0.16
Number of fishermen	1.33	0.22

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Titre français : Vulnérabilité présente et latente des systèmes socio-écologiques littoraux : concepts et application à Moorea, Polynésie Française

Titre anglais : Present and latent vulnerability of coastal socio-ecological systems, concepts and application in Moorea, French Polynésia

Résumé : Les systèmes socio-écologiques (SSE) décrivent et caractérisent les interactions entre l'Homme et la nature en reliant les systèmes sociaux et écologiques. Evaluer les SEE et leurs dynamiques spatio-temporelles est un exercice difficile mais pertinent pour informer et guider la prise de décision à l'échelle locale. Le concept de vulnérabilité socio-écologique permet d'identifier les interactions au sein du système, ce qui peut aider à cibler des actions de gestion. Les SSE sont complexes, évoluent à tous instants avec différents décalages temporels en réponse à différents facteurs de stress. Cependant, les approches actuelles étudiant les dynamiques temporelles ne prennent pas en compte toutes les aspects latents de la vulnérabilité. Elles ignorent l'évolution latente de la dépendance et de la capacité d'adaptation. Nous avons développé une méthode pour cartographier la vulnérabilité socio-écologique de Moorea, situé en Polynésie Française. Nous avons combiné des indicateurs spatialement explicites de chaque dimension de la vulnérabilité (exposition, dépendance, capacité d'adaptation) sur le plan écologique et social pour obtenir des cartes de vulnérabilité présente et latente. Nos résultats ont révélé une forte hétérogénéité entre les habitats écologiques ainsi qu'entre les différentes municipalités de Moorea dans le présent et dans le futur. Cela a mis en évidence des espaces particulièrement vulnérables qui nécessitent donc une attention particulière en terme de gestion. Les résultats ont également révélé des zones où la vulnérabilité déjà forte dans le présent continuerait d'augmenter dans le futur. Des actions de gestion locales et spécifiques urgentes y sont donc nécessaires. Cartographier la vulnérabilité socio-écologique dans l'espace et dans le temps offre une perspective pour éviter des situations non-durable.

Abstract : Social-ecological systems (SES) are a conceptual framework that describes and characterizes human-nature interactions as linked social and ecological systems. SES assessments and their spatial-temporal dynamics are challenging but are highly relevant to inform and guide decision-making. Social-ecological vulnerability is a valuable framework for identifying interactions and linkages, which can help target management actions. SES are complex, evolve over time and respond with possible time lags to different stressors. Yet, studies taking into account temporal dynamics do not fully account for all the latent aspects of vulnerability, upon which management interventions could be taken. Current approaches are mostly just static snapshots of the present and ignore the latent evolution of sensitivity and adaptive capacity. We developed a method to map social-ecological vulnerability and account for spatial and temporal dynamics, focusing on present and latent vulnerability to different stressors. We applied out method to the small-scale fishery of Moorea, located in French Polynesia by combining spatially explicit indicators for each dimension of the vulnerability: exposure, sensitivity and adaptive capacity, both at the social and ecological scale. Our results revealed a strong heterogeneity between ecological habitats and social municipalities, both in the present and in the future. It highlighted areas highly vulnerable areas of higher concern for management actions. The results also revealed high and increasing local levels of vulnerability, which provides early warnings for these areas where local and targeted management planning is urgent. Mapping social-ecological vulnerability in space and time while taking into account the latent trend of vulnerability provides a perspective for possible future unsustainable situations.

Mots-clés: systèmes socio-écologiques, vulnérabilité, évolution latente, analyse spatiale, systèmes écosystémiques

Key Words: social-ecological systems, vulnerability, latent evolution, spatial analysis, ecosystem services