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# A framework for mapping local knowledge on ciguatera and artisanal fisheries to inform systematic conservation planning

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Millions of people's livelihoods rely on artisanal fisheries. However, in many regions fishers are increasingly facing ciguatera poisoning, a seafood-borne illness. The toxin, produced by benthic dinoflagellates, can spread through marine food webs and to humans by direct consumption. Ciguatera risk can play a major role in fisher's activities but has never been considered in any marine spatial plans thus far. To fill this gap, we examined if integrating ciguatera in systematic conservation plans could affect these decisions. We developed through map-based interviews, a novel seven-step framework to collect and map local knowledge on ciguatera risk and fisheries activities with two innovations: (i) better mapping of fishing grounds by combining geomorphological habitat and fishing gear information, and (ii) integrating ciguatera risk directly into systematic spatial planning designs and scenarios conceived to maximize benthic habitat conservation while minimizing impacts to fishers. The approach is illustrated for Raivavae Island, in French Polynesia, Pacific Ocean. We found that integrating ciguatera significantly improved prioritization solutions with a 24–38% decrease of costs to fishers compared with scenarios based solely on fishery data. This framework was designed for scientists and managers to optimize the implementation of conservation plans and could be generalized to ciguatera-prone areas.

**Keywords:** French Polynesia, marine biotoxins, marine-protected area, Marxan, Raivavae Island, small-scale fisheries

## Introduction

Ciguatera poisoning is the most prevalent, phycotoxin-related seafood poisoning worldwide. It affects an estimated 10 000–50 000 people annually (Friedman *et al.*, 2008) and thus represents a major threat to many fisheries and consumers. Originally limited to tropical and inter-tropical regions of the world such as the Pacific Ocean, Caribbean Sea, and Indian Ocean, a geographic extension of ciguatera outbreaks to temperate areas has been observed since

2000, which could be explained by climate change (Friedman *et al.*, 2017), as well as the expansion of travel, tourism, and increased importation of fish from endemic regions. Ciguatera originates from marine biotoxins, namely ciguatoxins, produced by dinoflagellates microalgae in the genera *Gambierdiscus* and *Fukuyoa* (Chinain *et al.*, 2020a). These microalgae develop on dead corals colonized by macro-algae, which are grazed upon by herbivorous fish or various marine invertebrates (Darius *et al.*, 2018). Ciguatoxins further accumulate in marine organisms' tissues all along the food web, thus rendering catches unsuitable for consumption, causing a combination of gastrointestinal, cardiovascular and neurological symptoms (Gatti *et al.*, 2008). In ciguatera-endemic areas where inhabitants rely heavily on local marine resources for their subsistence, ciguatera outbreaks such as in Raivavae Island, (Chinain *et al.*, 2010), or Rapa (Iti) Island (Chinain *et al.*, 2020b), French Polynesia, can significantly impact the small local economy by the cost of the illness (Rongo and van Woesik 2012; Morin *et al* 2016), loss of a food sources, decrease of professional fishers revenues, and slowdown in tourism and recreational activities. It also carries major health risk, compelling inhabitants to modify their dietary patterns, as shown by the progressive shift from high-nutritional value food resources towards less healthy products such as imported and/or canned products, with the risk of increasing sugar and fat intake (Lewis and Ruff, 1993).

Ciguatera risk is often limited to localized, specific areas and, when known, they are avoided as much as possible by fishers. In the tropical islands and coastal regions where it occurs, artisanal fishers have to deal with this constraint, relying on their knowledge and experience to develop ciguatera avoidance strategies (Chinain *et al.*, 2010; Friedman *et al.*, 2017). Local knowledge is increasingly recognized as a reliable source of information for scientific studies as well as for environmental management and conservation (Ban *et al.*, 2009; Green *et al.*, 2009). Owing to its impacts on artisanal fisheries and affected communities livelihoods, it can be useful to integrate ciguatera local knowledge into marine spatial planning decisions as ciguatera risk significantly reduces the spatial extent of safe fishing grounds for fishers. Hereafter, we develop this idea within the context of systematic conservation planning (SCP).

SCP has been initially developed to identify areas that meet predefined conservation objectives while minimizing the induced constraints for society (Margules and Pressey, 2000; Moilanen *et al.*, 2009; Pressey and Bottrill, 2009). This domain has since extended beyond the only aspect of identifying protected areas while minimizing constraints (Kukkala and Moilanen, 2013), but this concept remains central to SCP. This approach relies on optimization algorithms to find the best solutions in the spatial domain at stake. Conservation objectives often focus on biodiversity representation and rely on proxies such as habitat maps or abundance of selected taxa. Constraints to minimize are often measured through opportunity costs (Naidoo *et al.*, 2006). In a marine realm, opportunity costs to fishers are often used. These costs translate the loss of access to fishing grounds selected for conservation and closed to extractive activities. Many marine SCP examples have emerged in the past decade, using simple to complex scenarios in terms of scales, objectives, and cost functions (Ban and Klein, 2009; Magris *et al.*, 2014; Álvarez-Romero *et al.*, 2018; André *et al.*, 2021).

In marine tropical regions, insular and coastal ecosystems often include coral reefs, which are remarkable reservoirs of biodiversity providing valuable ecosystem services for coastal or insular communities (in Oceania, see Payri and Vidal, 2019). Often, biodiversity conservation plans are in conflict with human activities, and SCP is increasingly used in these conflicting areas to help finding solutions. However, accessing accurate and reliable data represents a true challenge for SCP, particularly on opportunity costs to fishers (Ban *et al.*, 2009; Deas *et al.*, 2014; André *et al.*, 2021). Indeed, apart from some exceptions, there is a substantial lack of available and updated knowledge on artisanal fisheries worldwide (Jacquet and Pauly, 2008; FAO, 2018) despite they directly employ and support food security for millions of people (FAO, 2017). For example, in Oceania, the PROCFish program (https://coastfish.spc.int/en/projects/procfish) collected consequent data on coastal fisheries, but these are now 15 years old or more (Kronen *et al.*, 2009) and have not been updated since. Coral reef fishery data are also virtually never spatially explicit (see for instance Cinner *et al.*, 2009), and few examples of fishery atlases can be pointed out, such as the non-professional lagoon fishery atlas for the North of New Caledonia (Guillemot and Léopold, 2010). Proxies can be used instead of fishery data (Mills *et al.*, 2010; Weeks et al., 2010), but the use of an inadequate proxy can considerably bias planning scenario outcomes (Deas *et al.*, 2014).

Updated and reliable information can be acquired from fishers' interviews (Wendt et al., 2016; Aylesworth *et al.*, 2017), providing values of catch and data to characterize fisheries (McCluskey and Lewison, 2008). To promote accurate spatial data acquisition on catches directly from fishers, a first step-by-step protocol to integrate local knowledge into a spatial reference using a Geographic Information System (GIS) was proposed by Close and Hall (2006). On this basis, Léopold *et al.* (2014) proposed a five-step framework to define a stratified random sampling of coastal regular fishers, conduct map-based interviews, integrate the collected information into GIS layers, make statistical extrapolation of fisher data to the fishery scale and map catch, effort and catch per unit effort. This information allows describing spatially catch, gear, effort and fishing grounds. However, that framework did not include the collection of other forms of related environmental knowledge, such as ciguatera, and it was not specifically thought to be an integral part of a SCP project. To fill these gaps, and include for the first time ciguatera, we built upon Léopold *et al.* (2014) and provide a new formalized framework including seven steps, which altogether also provide a method to foster SCP projects in a more integrated fashion. When compared with Léopold *et al.* (2014), we aim to focus on three major improvements. First, along with fisheries information, we collected ciguatera local knowledge through map-based interviews with precision on the nature of the risk: suspected vs. proven ciguatera risk. Second, we refined the mapping of the fishing activity by using habitat maps that indirectly inform on where the different fishing gears can be practically used (Okada *et al.*, 2005). Third, we built a function of cost that modulates opportunity cost to fishers according to ciguatera risk, for SCP applications. The benefit of using this cost function is demonstrated for a French Polynesian island affected by ciguatera and where artisanal fishing is extensive. Through the SCP scenarios, a sensitivity analysis was carried out for different values of conservation targets (representing habitat diversity) and for different levels of importance allocated to the ciguatera risk in the fishing activity. Finally, we discussed the implications of our findings for planning approaches in the context of artisanal fisheries exposed to ciguatera.

## Material and methods

### Study area

The study was performed in French Polynesia in the South Central Pacific Ocean. We focused on Raivavae Island (23°50′S, 140°40′W) located in The Austral Archipelago, 710 km south of Tahiti (Figure 1a). This 15 km$^2$ high island of volcanic origin is home to 903 inhabitants, 255 households [census 2017; ISPF (Institut de la Statistique de la Polynésie Française), 2020], mainly settled along the shore. Raivavae has a 86 km$^2$ reef and lagoon system, with fringing reefs, a lagoon with shallow flats, and a barrier reef delimited by reef crests and the oceanic reef slope. The barrier reef is punctuated by a number of *motu* (reef islands) and by one main pass and two small passes (Figure 1b). Islanders' livelihood mainly relies on artisanal fisheries, traditional agriculture and handicraft (Kronen *et al.*, 2009).

Raivavae marine resources were previously studied three times, due to the especially active reef-fisheries of this island. It was first surveyed by the reef fishery ProcFish programme in 2004. The survey draws out high abundances of finfish and invertebrates, especially giant clams (Kronen *et al.*, 2009). Second, the giant clam stocks were also specifically surveyed and quantified twice, in 2005 and 2010 (Andréfouët *et al.*, 2009, Van Wynsberge *et al.*, 2013).

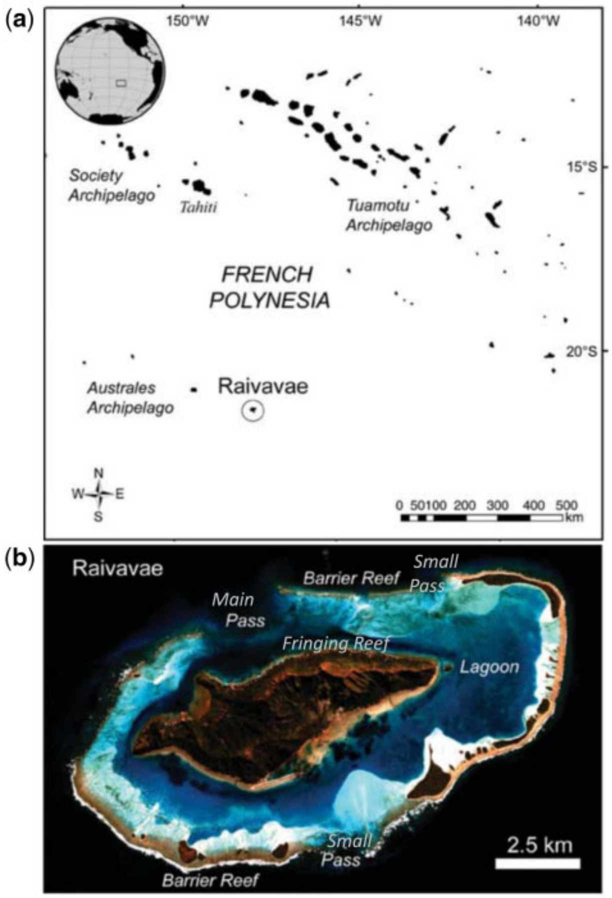

**Figure 1.** (a) Location of Raivavae in French Polynesia; (b) Satellite view of Raivavae Island, with main features (from Andréfouët *et al.*, 2009).

Raivavae was affected in 2007–2008 by a major ciguatera poisoning outbreak. The Raivavae lagoon was studied to characterize both the distribution and abundance of *Gambierdiscus* spp. populations and the toxic status of a variety of finfish species highly prized by the local community (Chinain *et al.*, 2010). Since then, ciguatera has been a major concern for the population, with numerous cases of poisoning, including also from giant clams (Laurent *et al.*, 2012).

### The seven-step framework

We developed a seven-step framework for mapping artisanal fisheries and ciguatera risk based on fishers' knowledge and to inform SCP projects. The framework builds on Léopold *et al.* (2014) but includes several novelties which are highlighted throughout. For clarity sake, we describe hereafter, within the framework, some aspects that are specific to Raivavae Island (e.g. types of fishing gears) and could differ elsewhere.

#### *Interview ethics*

Data collection, storage and process were conducted following the European Data Protection Regulation guidelines (European Union, 2016). Participants were previously informed of the aims of the study, their rights regarding data modification, possibility to further retract from the study, then, were invited to sign a consent form. To ensure they remained anonymous, a survey number was assigned to each participant at the beginning of the interview. All interviews were voluntary, without rewards.

### Step 1. Sampling design and data collection

**Sampling unit.** For the framework to be adapted to artisanal fisheries, we considered individual fishers as the relevant sampling unit instead of outboard powered vessels as in some studies (e.g. Léopold *et al.* 2014). Artisanal fishers in Raivavae, like in most Oceania islands, do not always have powered means of transportation, which can be multiple (e.g. use of *va'a*, which is the traditional outrigger, kayak, shore fishing, or snorkelling from the shore).

**Sampling strategy**. Priority when sampling was given to key informants identified as the most productive fishers, by reputation. To identify these fishers we relied on (i) the fishers themselves, who could point to individuals known to be productive fishers, (ii) the townhall staff, (iii) via randomly interviewing people met in public places such as the townhall, public square, churches, main or secondary roads and, when presents, wharfs and fish markets. We also paid attention to interview fishers representing the different villages all around the island, as a geographic representation criteria.

**Interviews duration.** We followed practical recommendations of Close and Hall (2006). Questionnaires, in French, (translated in English in Supplementary Material S1a) were kept as brief as possible, while still including a minimum of crossed questions to cross-check answers, and lasted between 30 min and 1 h 30 min, depending on the reactivity of fishers and the diversity of their fishing practices. Interviews were conducted in French, or in local Raivavae dialect with the help of an interpreter.

**Description of the fishery.** Open-ended and structured questions were used (e.g. Aswani and Hamilton, 2004) to identify the diversity of fisheries conducted by the fisher and collect qualitative and quantitative data on each of them. For each fisher, the diversity of fishery activity was defined by (i) fishing purposes (i.e.

self-consumption at the household level, or for sale or gift to local vs. remote residents); (ii) fishing location; (iii) fishing gears; (iv) means of transportations; (v) fishing frequency; and (vi) species, size and volume usually harvested. Fishers declared the average perceived catch per unit fishing trip. About the species caught, vernacular names referring to monophyletic or polyphyletic taxonomic groups were collected and the species were identified during the interview, with reference to taxonomy (Bacchet *et al.*, 2010).

To facilitate comparison with other sites, we also characterized the Raivavae fishery using the FAO matrix scoring method. This method was developed as a Sustainable Development Goal 14 Indicator, to enhance policy and management, and to promote knowledge about small-scale fisheries. This matrix uses 13 characteristics related to fishing (vessel, gear, storage, crew, time commitment, etc.), each one having four description levels and a score from 0 to 3. Aggregate score characterizes the fishing unit from small-scale to industrial (aggregated score between 0 and 39; FAO CWP Secretariat, 2019; Savoré, 2019).

**Fishery grounds.** A base map was designed following Close and Hall (2006) recommendations, and adapted to highlight optimally the different types of reefs (fringing, patch, barrier reef, and pass). A true-color view of a Quickbird satellite image of the whole island (see Figure 1b) was printed on A1 format (1:15.000$^{e}$ scale; Supplementary Material S1b), including relevant points of reference and localities name. Enlargements were also printed for some portions of the island such as the village surroundings, for specific reefs and for the pass. The prints were laminated to allow drawing on them with whiteboard markers and wiping off the information after each interview.

Fishers were asked to delineate the different places where they fished, one by one, on the map. For each place, fishers were asked to describe the corresponding fishing activity (gear, frequency, species targeted, etc.), for which a unique code was assigned. For a given fishing activity, a fisher would often visit multiple places, corresponding to multiple fishing activity polygons. These were grouped under the same code corresponding to a unique fishing zone. All fishing polygons drawn by one fisher correspond to this fisher's fishing ground. All fishing polygons drawn by all fishers correspond to the island fishing grounds (Figure 2). After each interview, the resulting map of the informant was photographed and archived.

**Fishery temporality.** To gather information on fishing productivity on a yearly basis, we asked about frequency of each fishing activity. We partly followed the recall technique through short-term memory (Brennan *et al.*, 1996). The first questions concerned the most recent fishing trip and the usual frequency of each fishing activity. Then, we used the map as a base to identify additional fishing zones and detail each fishing activity, going back in time. Last, we used cross-checked questions about fishing habits and temporalities per week and/or per month, by season and all year round.

**Description of ciguatera.** After assuring that each informant interviewed knew what ciguatera was, they were invited to provide the following information: (i) did anyone (himself or among close relatives) had already been affected by ciguatera poisoning? If yes, when did it happen? Where was the fishing area? Which species was involved and at what size? (ii) Nowadays, are there areas where he/she avoids to fish because of the ciguatera risk? These information were used to characterize sites with (i) "proven" and (ii) "suspected" ciguatera risk, respectively.

**Ciguatera spatial domains.** On the map previously used to collect fishery information, fishers were asked to indicate with a red marker the "proven" or "suspected" ciguatera risk zones. Each ciguatera zone was assigned a specific code.

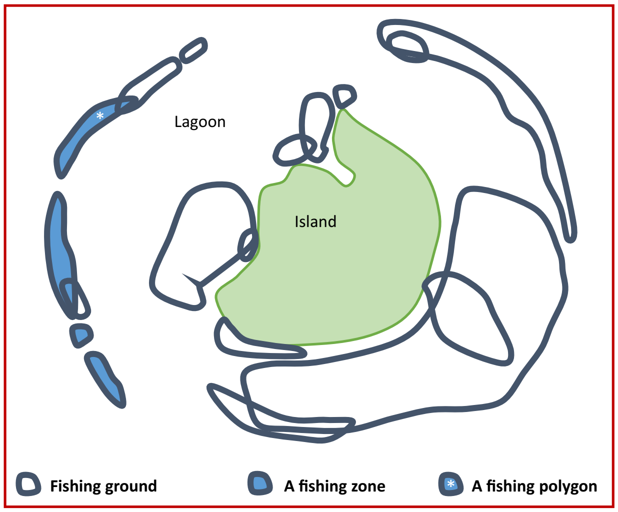

**Figure 2.** Illustrated definition of fishing polygon, fishing zone, and fishing ground. "Fishing ground" refers to all the places where a given fisher goes fishing. A "fishing zone" refers to the place(s) of a unique fishing activity, characterized by one gear, type of species caught, mean weight of catch, and frequency. If the fishing zone is composed of multiple places, each place corresponds to a "fishing polygon".

**Representativeness of the sampling effort.** The representativeness of the sampling effort was checked by plotting the cumulated total areal cover of fishing grounds as a function of the number of interviews performed. The accumulation curve was expected to be asymptotic if the sampling was adequate, with new interviews providing only negligible extension of the fishing grounds. This exercise was performed for all fishing activities confounded.

## Step 2. Integration of fisher's knowledge into a Geodatabase

After all questionnaires were completed for each fishing activity, the quantitative and qualitative information was homogenized to exhaustively render the modalities of each described fishing gear (similar gears collated under the same generic name), fishing effort frequency (homogenization to the same unit of time), weight of catch per fishing trip (homogenization to the same unit of weight), scientific and local species names (homogenization to a unique designation for each species or group of species). For group fishing sessions, we divided the total catch between the numbers of participants and considered these values as attributes of each fishing zone.

For each fisher, each fishing polygon as it was drawn on the map by the fisher, was digitized into GIS vector polygons, using as a background the same satellite image used as prints for the surveys (Supplementary Material S1b).

Eventually, each digitized fishing zone was systematically associated with:

- a fishing gear;
- an annual fishing effort $f_z$ (number of fishing trip per year per fisher per fishing zone);
- a CPUE (catch per unit effort, expressed in kg per fishing trip per fisher per fishing zone); and
- a list of species caught (or group of species).

To estimate the annual catch per fishing zone per fisher ($c_z$), we used the homogenized descriptors of annual fishing effort $f_z$ and CPUE [Equation (1)].

$$c_z = f_z * CPUE \quad (1)$$

Note that $c_z$ usually referred to a group of several species rather than to species-specific catches.

## Step 3. Refinement of fishing polygons using reef geomorphology information

This step is an addition to the Léopold *et al.* (2014) framework.

Each fishing gear is typically used in some specific types of environments. For instance, harpoons thrown by hand (or *pātia*) are used in shallow water when walking along the shallowest parts of the reefs. However, areas drawn by fishers on the printed map were generally coarsely delineated and inclusive of environments where the mentioned fishing gear would unlikely be used (such as deep areas for the aforementioned *pātia*). Therefore, to define a plausible environment for each fishing gear, the outline of each polygon was refined using a geomorphological map (Figure 3). In Raivavae, such map was available (Andréfouët *et al.*, 2009). It describes shallow vs. deep areas, and the main reef types (fringing, barrier, and patch) and their different geomorphological units (reef flats, slopes, etc.). A correspondence between each fishing gear and the different geomorphological units was generated (Table 1) and used to refine each fishing polygon based on its intersection with each of the relevant geomorphological unit.

To practically refine fishing zones according to the geomorphological strata relevant to each fishing gear in a time-effective way, all the fishing polygons drawn by the fishers were merged by fishing gear, allowing to produce one map for each fishing gear. Then, these maps were intersected by the corresponding geomorphological maps with a GIS tool, resulting in new sets of polygons with more accurate contours ($S_p$) (Figure 4).

To estimate the annual catch per refined fishing polygon $p$ ($c_p$ ) from the annual catch per fishing zone ($c_z$), the later was weighted by the proportion of the fishing zone's area ($S_z$) corresponding to the refined polygon $p$ ($S_p$) [Equation (2)].

$$c_p = c_z * \frac{S_p}{S_z} \quad (2)$$

## Step 4. Integration of fisher's knowledge about ciguatera into a Geodatabase

This step is an addition to the Léopold *et al.* (2014) framework.

For each fisher providing spatial information on ciguatera, each zone was digitized into GIS polygons $S_c$ , similarly to the fishing zones. Each ciguatera polygon was systematically characterized by the type of risk, which was either:

- proven risk, described by the species responsible for a reported human poisoning event, and date of poisoning and
- suspected risk, a zone currently avoided due to habit or hearsay.

To produce a single ciguatera map, we integrated these information into a single layer, applying different coefficients, depending on the relative importance/potential impact on fishers' practices, and to take into account the potential temporal variability of ciguatera (Table 2). These coefficients yielded a quantitative risk $r_p$ value for each polygon.

## Step 5. Planning unit overlay procedure for fisheries

Numerous fishing activity polygons can overlap. To produce a comprehensive map of the summed fisheries, the refined fishing polygon layers were overlaid with a grid of hexagonal cells following the GIS procedure of Goñi *et al.* (2008), also followed by Léopold *et al.* (2014). Within a SCP project, these hexagonal cells are called planning units (PUs). The PU size should be chosen in light of the fishing polygons size, ideally to best represent the data spatial variation (Van Wynsberge *et al.* 2015). In Raivavae, an adequate PU was 1 km$^2$ size and of hexagonal shape. The reef and lagoon domain was covered by 111 PUs, some being clipped to follow the outer habitats and land limits. When these clipped PUs were smaller than 0.1 km$^2$, they were merged to the neighbouring one sharing the longest boundary length.

For each fishing gear, the values of annual catch [$c_p$ from Equation (2)] for each refined fishing polygon ($S_p$) were assigned to PUs ($k$), proportionally to their surface area intersecting each PU ($S_{p,k}$) [Equation (3)].

$$c_{p,k} = c_p * \frac{S_{p,k}}{S_p} \quad (3)$$

The within-PU estimates of annual catch were then summed among all the resulting fractions of polygons to obtain the value of total annual catch for each PU ($c_k$ ) [Equation (4)].

$$c_k = \sum_p c_{p,k} \quad (4)$$

Adapting Léopold *et al.* (2014) methodology and following Walters (2003)'s recommendations, the spatial estimates of annual catch in each PU were expressed per unit surface area (km$^2$) on the basis of the PU surface area, producing an index of catch per unit of surface area ($c_k$ =CaPUS index, in kg·km$^{-2}$·year$^{-1}$). This resulting index can then be used as a value to estimate the spatial opportunity cost to fishers.

## Step 6. Planning unit overlay procedure for ciguatera

Regarding ciguatera, we considered that the risk was not a function of the proportion of the polygon surface area intersecting the PUs defined at the previous steps. As a ciguatera polygon could either be very small, encircled by fishers with precise memory of the place where the toxic fish was captured, or quite large by others, we generalized the spatial information by spreading the risk to the whole PU. The risk $r_p$ attributed to each polygon was then directly assigned to the intersecting PU(s) $r_{p,k}$ [Equation (5)]. The within-PU estimate of ciguatera risk was then summed among each PU to obtain $r_k$ , the ciguatera risk per unit of surface area ($r_k$ =CiPUS index of relative ciguatera risk·km$^{-2}$) [Equation (6)].

$$r_{p,k} = r_p \quad (5)$$

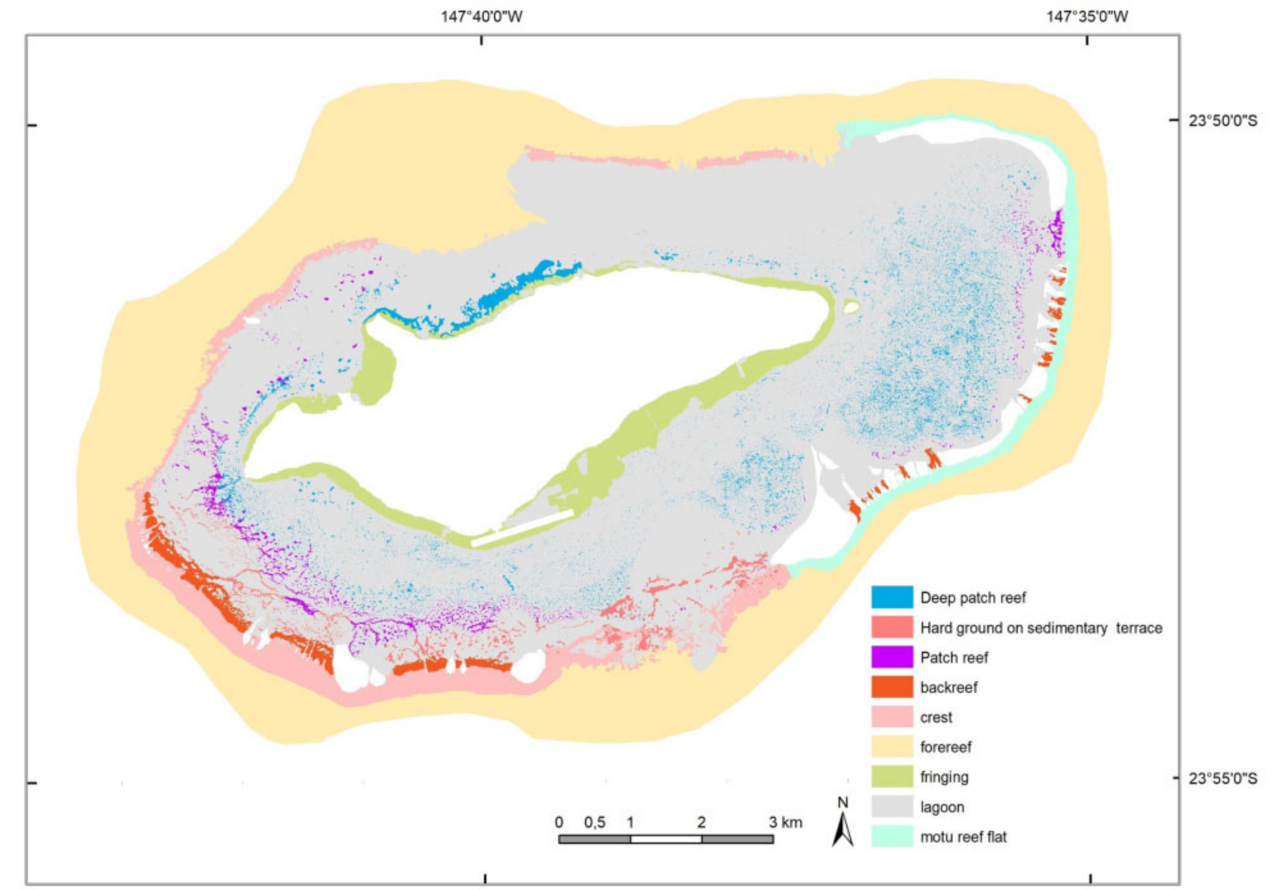

**Figure 3.** Location of the different geomorphological strata, on Raivavae Island (geomorphological habitat map consistent with the Coral Reef Millennium Mapping Project, Andréfouët *et al.*, 2006), used to refine fishing zones according to the fishing gear used (Table 1).

**Table 1.** Correspondence between fishing gears and geomorphological strata.

| | Geomorphological strata | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Gears** | **Forereef** | **Crest** | **Motu reef flat** | **Backreef** | **Hard ground on sedimentary terrace** | **Lagoon** | **Patch reef** | **Deep patch reef** | **Fringing reef** |
| Spear gun | X | | | X | X | X | X | X | X |
| *Pana* | X | X | X | X | X | X | X | X | X |
| *Pātia* | | X | X | X | X | | | | X |
| Line | X | | | X | X | X | X | X | X |
| Gillnet | X | X | X | X | X | X | X | X | X |
| Hand harvest | | X | X | X | X | | X | | X |
| *Auihopu* | X | X | X | X | X | X | X | X | X |

*Pana* is a spike used to extract giant clams. *Pātia* is a hand harpoon. *Line*: nylon in hand or downrigger. *Hand harvest* is mainly for lobsters. *Auihopu* is a specific tool to catch octopus. The geomorphological strata are located on the habitat map of *Raivavae* (Figure 3).

$$r_k = \sum_p r_{p,k} \tag{6}$$

## Step 7. Conservation scenarios based on habitats, fisheries, and ciguatera spatial information

The final step of the framework consisted in establishing a conservation scenario using SCP principles with the collected information. Specifically, we assessed the interest of integrating fisher's knowledge and ciguatera risk spatial data, based on the hypothesis that ciguatera zones were known and avoided by fishers, and consequently were characterized by a lower cost of conservation than fished zones. To demonstrate the importance of taking into account ciguatera risk in SCP, we also compared the spatial distribution of the conservation solutions between scenarios with and without ciguatera. SCP scenarios were run with Marxan software, which is intended to deliver decision support for reserve system design (Possingham *et al.*, 2000). Marxan considers a series of planning units for the domain of interest, each one being

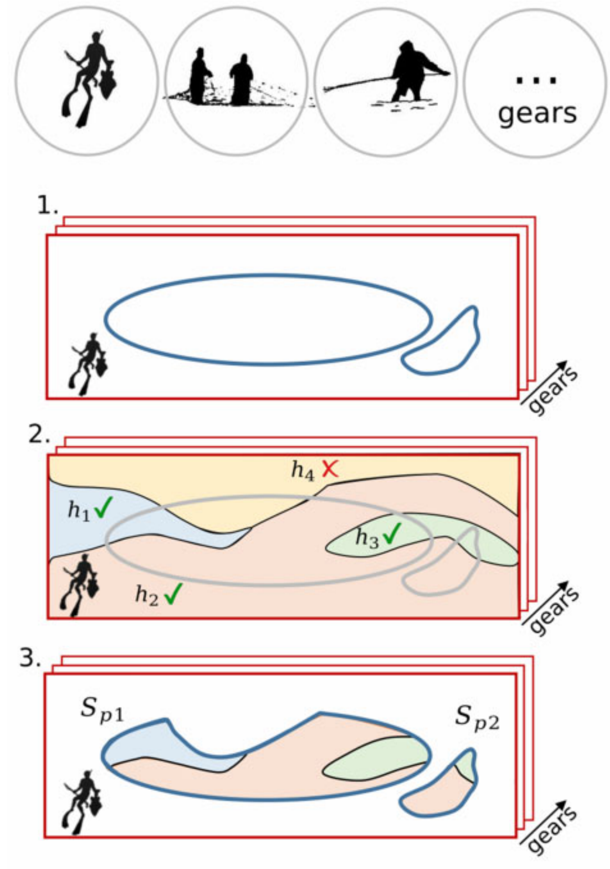

**Figure 4.** Procedure to refine fishing polygons according to geomorphological strata. 1. All fishing polygons were grouped by fishing gear (e.g. spear gun), to produce a single map for each fishing gear. 2. For each fishing gear, the corresponding geomorphological strata were selected. 3. These were intersected with the fishing gear map to produce more accurate fishing grounds. In this example, strata $h_1$ *to* $h_3$ were relevant to spear gun while stratum $h_4$ was not.

**Table 2.** Coefficients of risk ($r_p$ ) attributed to ciguatera zones, depending on their types.

| Type of ciguatera zone | $r_p$ |
|---|---|
| Proven poisoning 0–5 years ago | 10 |
| Proven poisoning 6–10 years ago | 5 |
| Proven poisoning 11+ years ago | 2 |
| Suspected risk, currently avoided zone | 1 |

assigned a value in terms of conservation objective (e.g. representation of biodiversity) and socio-economic cost (e.g. opportunity cost to fishers). In this study, we used the diversity of habitats as a conservation objective, considering habitats as proxies of the biodiversity they host. A quantitative objective (target) must be set, along with a number of parameters such as the compactness of the network. Marxan implements an algorithm with a given number of repetitions to solve the problem and find prioritization solutions, which are a series of planning units that altogether will meet the objective at the lowest possible cost. Marxan provides two types of outputs. First, the *best solution* is the network that provides best compromise between objective met and cost of conservation. Second, a *selection frequency* of each planning unit, which describes how frequently a planning unit is included in the solution for the given number of repetitions. The most frequently selected planning units are generally prioritized in a conservation network if the best solution is not kept for some reasons.

The scenarios included:

- conservation objectives that should include 10%, 20%, and 30% of the area of each mapped habitats, using this time a detailed habitat map from Purkis *et al.* (2019). This Raivavae habitat map included 21 habitats defined by their geomorphologic and benthic attributes. These levels of target were chosen as they are commonly used in SCP conservation scenario and can refer to international guidelines (e.g. see Gairin and Andréfouët, 2020);
- spatially explicit cost, integrating a combination of fishery, and ciguatera knowledge, as described earlier.

To parameterize the costs while integrating the ciguatera risk, we stated that opportunity costs to fishers were modulated by the ciguatera risk. We built a cost function using the CaPUS and CiPUS factors calculated above [Equations (4) and (6)]. CiPUS values were log-transformed to lessen the effects of high values. The terms were also normalized, to bring the values to a common scale. To test the sensitivity of this new cost function to the ciguatera parameter, we used a coefficient *a* to represent the importance of ciguatera relative to the fishing activity factor. We tested three values for *a* [0, 0.5 and 1; Equation (7)], respectively generating scenarios with three different cost factors: (i) only opportunity cost to fishers (no ciguatera), (ii) opportunity cost to fishers modulated by half weight ciguatera, and (iii) opportunity cost to fishers equally modulated by ciguatera. The bar above the terms in Equation (7) refers to the normalisation of terms by their maximal value.

$$\text{cost factor} = \overline{\overline{\text{CaPUS}} + a \times \left(1 - \overline{\text{Log}(1 + \text{CiPUS})}\right)} \qquad (7)$$
$$\text{with} \quad \text{a} = \{0;\ 0.5;\ 1\}$$

As for Marxan settings, in order to avoid the introduction of other factors of variation Boundary Length Modifier (the compactness parameter) was set at 0, and SPF (Species Penalty Factor, a penalizing parameter if the objective is not met) was set at fixed values for all scenarios, and calibrated for the most constraining scenario (Scenario 7; Table 3). Therefore, any variation would only be due to either the change of type of costs or the change of the value of the target. Calibration of SPF was done following the

**Table 3.** List of scenarios implemented to test the effect of ciguatera in conservation plans, with different values of the ciguatera coefficient *a*, in the cost function.

| Scenario | Target | *a* |
|---|---|---|
| Sc 1 | 10% | 0 (Fisheries only) |
| Sc 2 | 10% | 0.5 (Fisheries and $^1/_2$ ciguatera) |
| Sc 3 | 10% | 1 (Fisheries and ciguatera) |
| Sc 4 | 20% | 0 (Fisheries only) |
| Sc 5 | 20% | 0.5 (Fisheries and $^1/_2$ ciguatera) |
| Sc 6 | 20% | 1 (Fisheries and ciguatera) |
| Sc 7 | 30% | 0 (Fisheries only) |
| Sc 8 | 30% | 0.5 (Fisheries and $^1/_2$ ciguatera) |
| Sc 9 | 30% | 1 (Fisheries and ciguatera) |

suggested procedure from Ardron *et al.* (2010). Number of repetitions was set to 1000 to avoid local minima while keeping a reasonable calculation time. Table 3 summarizes the different scenarios applied.

The importance of taking into account ciguatera risk in SCP was tested on the basis of two criteria. First, for each target (i.e. 10%, 20%, or 30%), a Chi-square test was computed to compare the spatial distribution of the selection frequencies of prioritized PUs between each of the different scenario [$a = 0$; $a = 0.5$; $a = 1$ in Equation (7)]. Second, to assess the effectiveness of these cost factors, the same approach as Weeks *et al.* (2010) was followed. Considering the cost that takes ciguatera risk into account [$a = 1$ in Equation (7)] as the "true" cost of planning units, we assessed the differences of true costs between (i) the best solution networks from scenarios based only on fishery opportunity costs and (ii) scenarios based on fishery and ciguatera costs. This was done for the three levels of conservation targets (Table 4).

## Results

### Fishery assets and fishing grounds

Overall, among the 903 inhabitants, 59 fishers were interviewed all around the island, representing the inhabited area completely. Considering there is typically one main fisher per household and an average of five persons per household, this sampling covers approximately one-third of the fishers on the island. In contrast, ProcFish estimated that they surveyed 14% of the total population (30 out of 212 households, for a total of 1074 persons as in 2004; Kronen *et al.*, 2009). No woman was interviewed, as none of them appeared to be main fisher or had regular fishing activity. Fishing was mainly for subsistence (83% of overall catches) and partly for gift/selling locally, notably for parish fairs (4% of overall catches), or, to a lesser extent, export to Tahiti (13% of overall catches). Fishers declared using a variety of fishing gears, three targeting finfish (i.e. Spear gun, *Pātia*, Line, Gillnet) and three targeting invertebrates (*Pana*, *Auihopu*, and Hand harvest). According to the FAO matrix scores instantiated using the questionnaire results, the fishery in Raivavae was of an artisanal dimension, with most of aggregated scores at 0 (only twice, aggregated scores reached 7). This classification as a small-scale fishery resulted from the characteristics highlighted by the matrix, such as a generally short time commitment, mainly direct consumption (sometimes frozen storage), and mostly household consumption (sometimes sale to traders in Tahiti). Raivavae fishing ground as a whole (finfish and invertebrates including clams and lobsters) reached 120 tons yield annually (i.e. averaging 1.4 t·km$^{-2}$·year$^{-1}$).

**Table 4.** Comparison of the cost for fishers (cost based on fishery cost and ciguatera risk) of SCP best solution networks from scenarios that did not take ciguatera into account ($a = 0$), vs. those that took ciguatera into account ($a = 1$).

| SCP scenario | Cost for fishers |
|---|---|
| Conservation target: 10% | |
| Without ciguatera ($a = 0$) | 6.69 |
| With ciguatera ($a = 1$) | 4.63 (−30%) |
| Conservation target: 20% | |
| Without ciguatera ($a = 0$) | 12.25 |
| With ciguatera ($a = 1$) | 7.60 (−38%) |
| Conservation target: 30% | |
| Without ciguatera ($a = 0$) | 15.76 |
| With ciguatera ($a = 1$) | 12.02 (−24%) |

In bracket is the relative difference of cost between scenario with ciguatera and without ciguatera.

The 59 fishers interviewed described 359 fishing grounds. The survey was spatially representative of Raivavae fishery, as the cumulative curve of total fishing grounds area reached an asymptote at 81 km$^2$ (from 86 km$^2$ of the lagoon surface area), with most of the total fishing grounds area already captured by the 20th most informative interviews (Figure 5). Fishing activity took place all around the lagoon, and on the different reef geomorphological strata.

Steps 2 and 3 of the framework provided spatially realistic maps of fishers' fishing grounds at various levels of integration (per fishing gear, per fisher, per village, for the whole island, etc.; Figure 6). Step 3 particularly refined the fishing grounds for gears employed for resources found in specific geomorphologic habitats. It decreased the fishing grounds surface areas by 0 to 84% depending on fishers and fishing gears, with an overall average of 7% decrease. The fishing gears that were concerned the most by surface area decrease were *Pātia* and Hand Harvest (with maximum reduction of 83.8% and 83.6% respectively; 16% and 13% on average) and, to a lower extend, Spear gun (with 64% maximum reduction and 9% on average). The fishing gears that were concerned the least by surface area decrease were *Pana, Auihopu* and Line (1–2% on average).

Among the 111 planning units generated by the overlay procedure (step 5), only one had no fishery catch at all, and was located at the forereef side of the main pass. Thus, the Raivavae lagoon and reef ecosystems were virtually fully used for fishing activities. The highest total catch per unit of surface area (CaPUS) reached 9,009 kg·km$^{-2}$·year$^{-1}$, and was located in the western part of the lagoon, in a planning unit including lagoon, reef crest and forereef. High values of CaPUS were also found in the South and South-western parts of the lagoon (Figure 7a).

### Mapping ciguatera risk

The 59 fishers interviewed identified 148 ciguatera zones, including 80 and 68 zones of proven risk and suspected risk, respectively. Among the proven ciguatera zones, poisoning occurred in 39, 11, and 30 zones 0–5, 6-10, and 11+ years before, respectively.

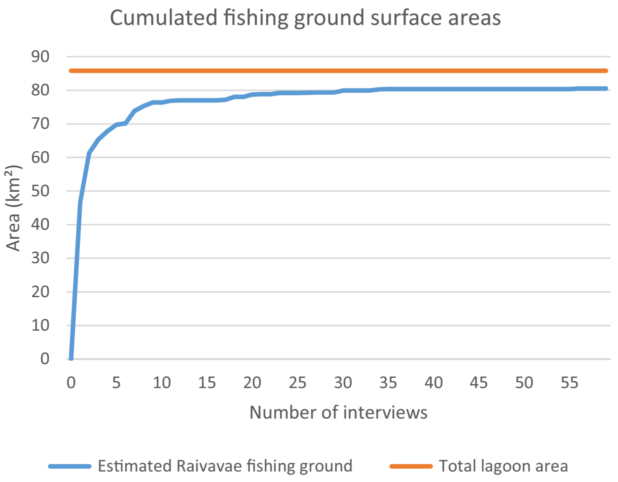

**Figure 5.** Cumulated fishing ground surface areas as a function of the number of interviews. It reaches an asymptote at 81 km$^2$. The total lagoon surface area, reaching 86 km$^2$, is displayed for comparison purpose.

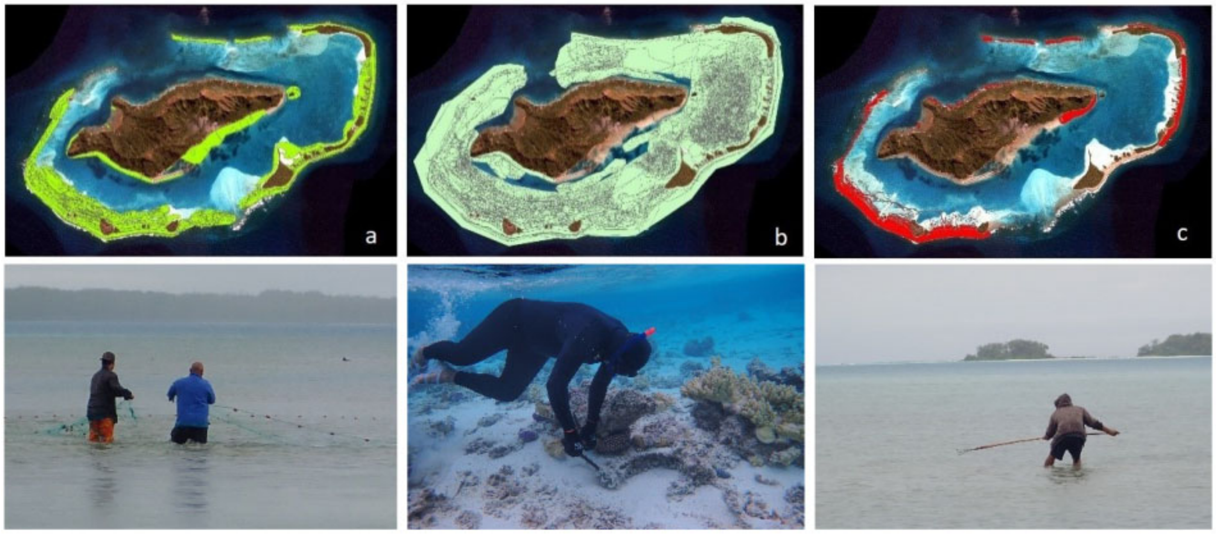

**Figure 6.** Examples of fishing grounds grouped by fishing gear, and refined by geomorphological strata: (a) fishing grounds with fishing net, in shallow areas; (b) fishing grounds with *pana* to collect giant clams, in both shallow and deep areas; (c). fishing grounds with *pātia* hand harpoon. Below each map, fishing activity with the relevant gear (Photos *L. V. André*, November 2019).

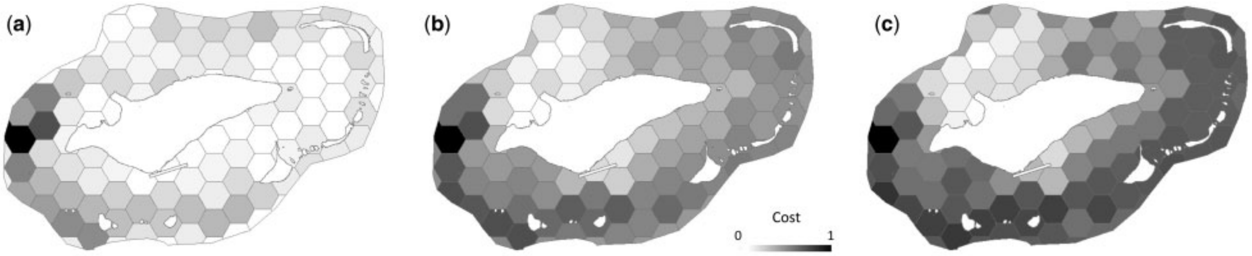

**Figure 7.** Maps of opportunity costs to fishers (unitless, from 0 to 1), calculated as fisheries modulated by ciguatera [see Equation (6)] with different relative weights of ciguatera: (a). relative ciguatera weight $a = 0$ (only fisheries as a cost); (b) $a = 0.5$; (c) $a = 1$. In each case, values are normalised by the maximal value.

Ciguatera was still regarded in 2019 as a prominent issue in terms of fishing activity with a distinct spatial signature for most fishers. Areas with the highest risks were the main pass and the Northwest quarter of the lagoon, then, at a secondary level of risk the airport zone and the northern small pass, and, to a lower level, the zone of the South-western reef (Figure 8). In particular, the main northern pass, previously identified as a high risk zone since 2007 (Chinain *et al.*, 2010), has still been largely designated by fishers during the 2019 survey as an area to avoid. Interestingly, the high ciguatera risk (coefficient) that appears in the main northern pass (covering seven planning units, Figure 8) resulted at 96% from zones of suspected risk, vs. only 4% from proven risk. Conversely, in the northern small pass, the relatively high ciguatera coefficient was explained at 99% from proven risk. If we consider only proven risk, this latter zone becomes the highest risk zone, followed by the North-western reef, and then the North-western fringing reef. Ciguatera zones were widely distributed and many overlapped the fishing grounds. After the PU overlay procedure (step 6), ciguatera-free zones occupied only 34 planning units. Thus, 75% of the reef and lagoon ecosystems area was considered at risk by fishers ($r_k > 0$), through their aggregated knowledge (Figure 8).

## Effect of ciguatera on SCP solutions

Taking into account ciguatera in the calculation of costs [Equation (7)] modified the spatial distribution of the solutions (Figure 7b and 7c). In particular, the northern part of the lagoon around the main reef pass, identified with high ciguatera risk alleviated the fishery costs, except for the planning units affected by the highest fishing effort, which were located in the western part of the lagoon. This area was also characterized by a low risk of ciguatera. These results were observed for both weight factors assigned to ciguatera risk ($a = 0.5$ and 1).

Selection frequencies and best solutions from SCP scenarios (see Table 3) appear in Figure 9. The distribution of planning units selection frequencies were significantly different between scenarios that took ciguatera risk into account and scenarios that did not (Chi$^2$ test, $p < 0.001$). Regarding best solutions, the SCP scenarios that do not account for ciguatera risk suggested prioritizing planning units located in the North-western part and the Eastern part of the lagoon (Figure 9a, d, and g). In contrast, the SCP scenarios that accounted for ciguatera risk suggested prioritizing, in addition, the northern part and the South-western part of the lagoon (Figure 9c, f, and i). These results were consistent for all conservation targets (10%, 20%, and 30%).

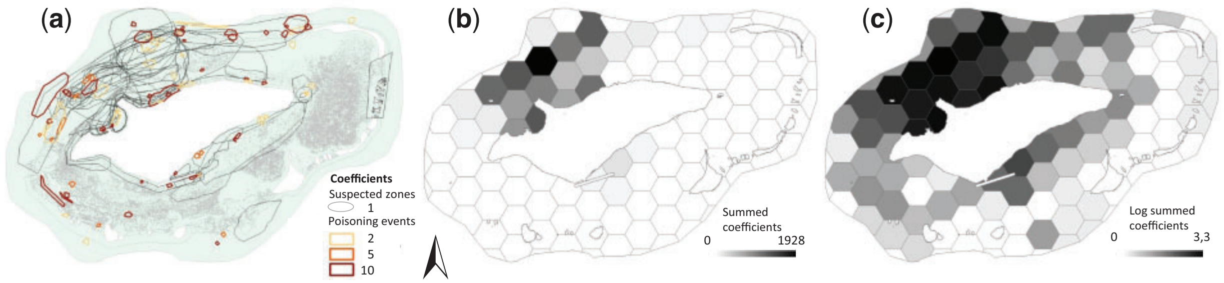

**Figure 8.** Maps of ciguatera: (a) as described by fishers, with coefficients from 1 to 10 depending on the nature of the risk (see Table 2); (b) with planning unit overlay, the values in grey-scale are the coefficients summed among each planning unit; (c) with planning unit overlay and values log transformed.

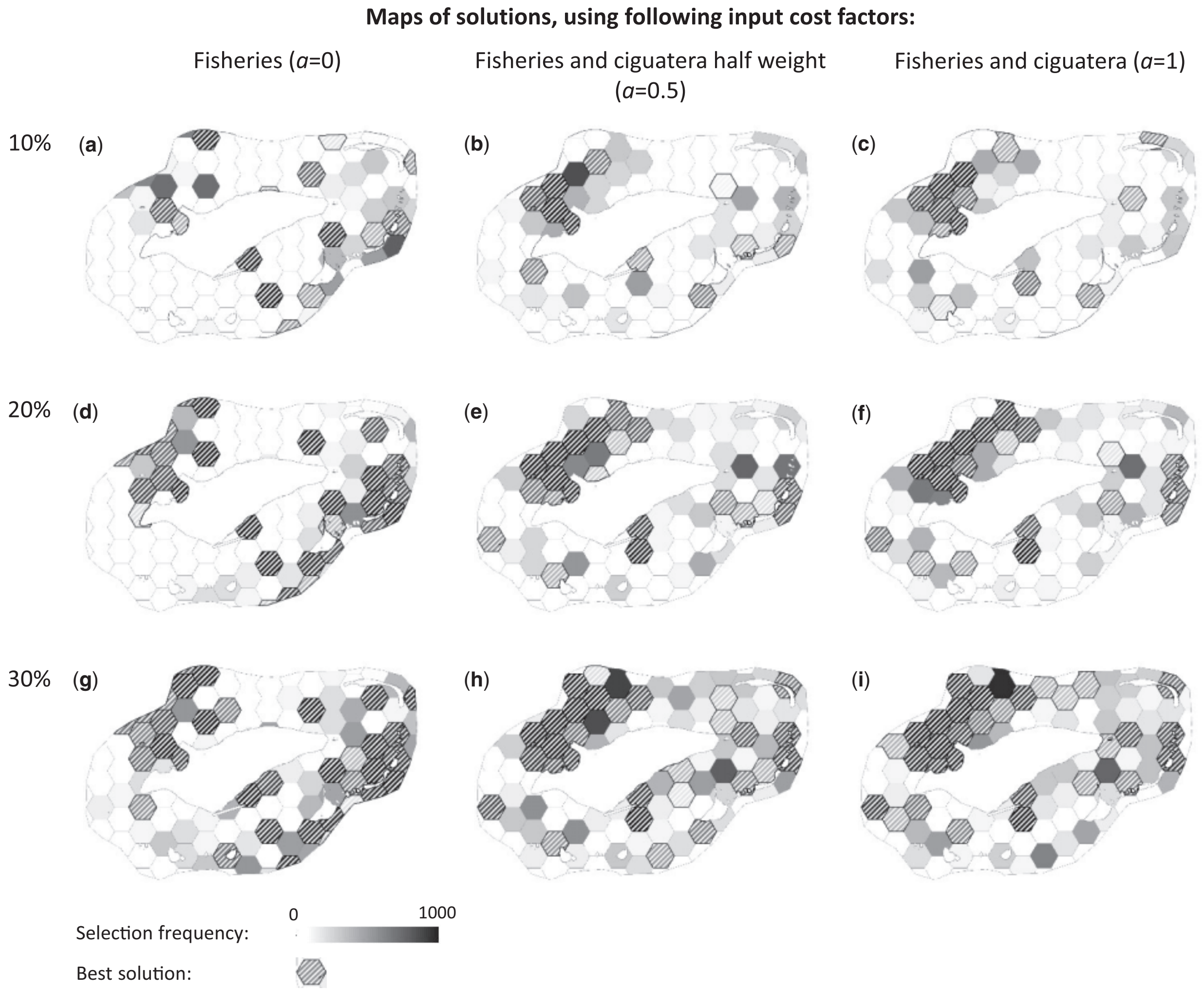

**Figure 9.** The solutions from the nine scenarios comparing three targets (10%, 20%, and 30%) and three maps of costs used as inputs. Darker planning units have a higher selection frequency, among the 1000 repetitions. Best network is symbolized by hatched planning units, for each scenario. Upper panels (a–c) refer to the 10%-conservation-target-scenarios. Middle panels (d–f) refer to the 20% -conservation-target-scenarios. Lower panels (g–i) refer to the 30% -conservation-target-scenarios. Left panels (a, d, and g) are solutions to SCP scenarios that consider the fisheries cost factor as input cost, whereas the other panels are solutions to SCP scenarios that consider ciguatera in the definition of cost, with lower importance than fishery cost ($a = 0.5$; panels b, e, and h), and with as much importance as fishery cost ($a = 1$; panels c, f, and i).

When considering ciguatera risk, the costs of best solutions for fishers dropped by 30%, 38%, and 24% compared with the cost of best solutions provided by scenarios that did not considered ciguatera risk, at conservation targets of 10%, 20%, and 30%, respectively (Table 4).

## Discussion

The seven-step framework performed in this study enriched the framework proposed by Léopold *et al.* (2014) for mapping artisanal fisheries using local knowledge. The framework was improved by taking into account habitat delineation, thus providing more accurate maps of fishing effort. The framework was also extended by taking into account for the first time the ciguatera risk. We discuss these points hereafter, as well as the implications for SCP in areas affected by ciguatera.

### Mapping fisheries using local knowledge

Raivavae Island was known for its active artisanal fishery and this still proved to be the case in 2019. The cumulative curve of total fishing grounds area reached an asymptote at 81 km$^2$, which was close to the total lagoon surface area (86 km$^2$; Figure 5). This suggests that very few areas are exempt of fishing pressure. Our quantitative estimates (1.4 t·km$^{-2}$·year$^{-1}$) are consistent with the ProcFish study (Kronen *et al.*, 2009) which found, with a different method of investigation, that total fishing yield (for subsistence and exportations) on the total reef system surface area was 1.5 t·km$^{-2}$·year$^{-1}$. These estimates are also in the same range as that of Newton et al. (2007) who concluded to a fishing pressure <1 t·km$^{-2}$·year$^{-1}$ on average for French Polynesia. Although Raivavae population heavily relies on lagoon and reef resources, the level of exploitation appears sustainable since it is below 5 t·km$^{-2}$·year$^{-1}$, the estimated maximum sustainable yield for island coral reef fisheries (Newton et al., 2007).

In this study, an original step was added to Léopold *et al.*'s (2014) framework, which increased the accuracy of mapping fishing grounds with geomorphological strata. The process was significant for some fishing gears, such as *Pātia*, Hand harvest and Spear gun (16%, 13%, and 9% of surface reduction on average, respectively), which are deployed and used on specific geomorphological strata such as reef crests, flats, and patch reefs. This step could be of particular interest if the planning unit shapes are based on data outlines and distribution, as advocated by Van Wynsberge *et al.* (2015). More broadly, whatever the planning unit shapes, the interest of this step may depend on the scale and the precision required to solve the problem, on the precision with which fishers represent their fishing grounds, and the quality and scale of the printed map.

Léopold *et al.*'s (2014) step of statistical generaliation from the surveyed sample to the scale of the entire island could not be followed here because it requires quantitative integrated data on the whole fishery (e.g. available from official catch records), which were lacking for Raivavae. However, this lack of inference does not undermine our conclusions. Indeed, first, the accumulation curve (Figure 5) shows that the sample size allowed to reach a good representative level of the fishing efforts on the island, at least spatially; second, we interviewed 6.5% of the total population, representing 23% of the households, from all villages, which is a satisfactory level of population sampling. Hence, it is likely that the trends emerging from the present survey would match data from a more intensive population survey. Finally, the ultimate goal of the fishery and ciguatera survey was a SCP application, which primarily requires hierarchizing the spatial distribution of fishing effort, but not necessarily the total quantities of catches. When total quantities become a critical management information (e.g. to establish quotas), the statistical generalization step could be required and could be performed following Léopold *et al.* (2014) when enough information is available, or by extrapolating estimates at population scale from catch accumulation curves.

### Mapping ciguatera risk using local knowledge

Despite the threat that ciguatera poses to artisanal fisheries and consumers and despite its inherent spatial component, ciguatera had never been integrated into a SCP before. This can be explained by the fact that acquiring ciguatera-related field data is a time consuming, costly task. Toxicological analysis of macroalgal host samples and fish tissue, as in Chinain *et al.* (2010) cannot be replicated widely. Mapping ciguatera risk at fine spatial resolution to produce relevant spatial information, for an island like Raivavae or for an entire archipelago, is not possible with available resources. Conversely, the present work demonstrates that collecting spatial information on ciguatera from local knowledge is an alternative of interest to comply with cost and time constraints. However, it does not provide exact and verified information on ciguatera and, hence, should be used with caution and within appropriate limits, e.g. it cannot be used for public health or food safety management programs.

The results highlight that ciguateric areas overlap fishing grounds in Raivavae. This aggregated fishers' knowledge shows that the two types of zones are not mutually exclusive and that their spatial co-distribution is complex, different fishers having different and complementary knowledge. Furthermore, some fishers could have disparate levels of knowledge on ciguatera risk (precise or vague on time and space, consistent or not between suspected risk with proven risk).

This local knowledge approach proved useful since it led to the identification of ciguatera risk areas that are consistent with the ciguatera risk map provided by Chinain *et al.* (2010). Indeed, both point out to the main pass, the North-western quarter of the lagoon and the airport zone as areas being most prone to ciguatera poisoning. Conversely, two zones previously identified as at low risk of ciguatera by Chinain *et al.* (2010), i.e. the northern small pass and the South-western reef, were reportedly the sites of recent cases of ciguatera poisoning. These apparent discrepancies between the ciguatera status of Raivavae in 2007–2008 vs. 2019 are consistent with previous observations that ciguatera risk can be spatially and temporally dynamic (Bienfang *et al.*, 2008).

We could not yet report to the population our findings, but it would be useful to get feedback on both the map of ciguatera risk and the fishing maps. Validation from the fishers first, and possibly from the authorities and the general population, would be useful as a first step towards the development of management plans with their approval. This step could not be realized yet after the present study but is meant to be conducted in the near future with French Polynesia authorities in charge of the management of lagoon resources.

## Conclusion

### Consequences for SCP applications

In SCP, costs always influence greatly the solutions (Deas *et al.*, 2014; Gurney *et al.*, 2015; Cheok *et al.*, 2016). Although proxies are usually used to model the distribution of fishing efforts, a poor choice of proxy could disadvantage fishers even more than a scenario constrained without any proxy (Weeks *et al.*, 2010; Deas *et al.*, 2014). The framework provided in this study allows for collecting empirical spatialized information to build cost layers for SCP. As ciguatera zones were mapped via local knowledge, they are a proxy for true occurrence of ciguatera. However, despite this limitation, this proxy from local knowledge remains interesting to minimize the socio-economic cost of conservation for fishers.

Interestingly, as fishers not all have the same spatial perception of ciguatera risk in the lagoon, some of them may not recognise their own vision of ciguatera in the aggregated map of costs, which can decrease some fishers compliance to the conservation solutions. But, this is the natural consequences when merging multiple perceptions and searching solutions that represent the overall population.

Our results highlight the fact that, for similar conservation objectives, integrating ciguatera local knowledge in the cost function resulted in a 24–38% decrease of costs to fishers compared with scenarios based solely on fishery data. This confirms that the challenge of balancing the distribution of areas to protect with fishers interests can be locally optimized by taking into account the distribution of areas with either proven or suspected ciguatera risk. In other words, there is direct value in promoting conservation for areas neglected by fishers due to the presence of ciguatera. However, this conclusion should be taken with adequate precautions. Indeed, in some instances, ciguatera outbreaks occur in degraded environmental conditions, after major disturbances of either natural or anthropogenic origin (Friedman *et al.*, 2017, for review and references therein). In that case, strategy questions arise of whether protecting a degraded zone for recovery, or prioritizing healthy ecosystems as refuge areas (Sacre *et al.*, 2019).

This study relies on empirical costs that were measured through information specifically collected on the study site. It allowed producing a fishery atlas, with spatially explicit information on the island fishing ground and fishing activity (gears, CPUE, annual frequency, mean of transportation, species caught, etc.). Fishery atlases exist for small-scale fisheries (Guillemot and Léopold, 2010), but they are a rare, valued baseline that are subject to changes over the years. The temporal variability of fishing activity is intertwined with the temporal variation of ciguatera risk, among other factors. Both types of information require regular updates. Adaptive planning, which is increasingly recommended in SCP (Mills *et al.*, 2015) to adjust planning to recipient expectations and changing environmental conditions, is definitely another framework layer to add in this context.

## Possible extension of the framework to other sites

Several points must be considered to apply the framework proposed here to other sites and contexts. Here, fishing and ciguatera were factors well adapted for the Raivavae case study. Elsewhere, other factors may be also relevant, including different economic activities (tourism, mariculture, ports, etc.). Another emergent recommendation is that it can be necessary to integrate, in the design, how people value and are attached to their environment (Buijs, 2009; Charles and Wilson, 2009). Indeed, a case study of marine planning in Fiji (Gurney *et al.*, 2015) showed that integrating how fishers value their fishing grounds, led to a considerable change in protected area locations, and potentially more equity. Their results show that CPUE under a single cost scenario was 12–64% less than under a multiple costs scenario. Likewise, in Papua New-Guinea, Hamel *et al.* (2018) showed that scenarios with commonly used fishery cost proxies (such as distance to landing sites) generated larger incidental costs than when considering the perceived value of fishing areas by households.

Second, in this study several choices in the methodology were made specifically for Raivavae Island. This includes how we defined the cost function using ciguatera and the weight of ciguatera vs. fishery, or the type of habitats used to refine fishing grounds for each fishing gear. Sensitivity analyses (not shown) were performed to evaluate the extent by which these parameters may change the conclusions. These choices, however, may require some adaptations when applying the framework to other sites.

Third, application to other sites should consider the reliability of local knowledge, which may be site- and context-dependant. A study conducted in Solomon Islands assessed indigenous knowledge on long-term ecological change occurring to seagrass meadows, compared with historical aerial photographs and showed that fishers would generally track ecological change successfully, but levels of local knowledge could vary, even in small and culturally homogenous communities (Lauer and Aswani, 2010). The nature of the information collected from local knowledge is inherently driven by human perception dimension and historical or personal experience background. For example, in this study, the northern pass zone reached the highest ciguatera risk coefficient because it was very frequently pointed out as a zone with suspected risk, though few poisoning cases have been actually reported. Indeed, in the past, ciguatera outbreaks had previously occurred near the northern pass (Chinain *et al.*, 2010), but current risk of ciguatera in this zone seems to have decreased due to the low proven cases in our survey. As historical perceptions may no longer be relevant, we tried to down play the perception of risk by attributing a relatively small weight to areas with suspected ciguatera risk vs. those with proven ciguatera risk. This allowed standing out some proven risk zones, as mentioned earlier, but it reached its limit for the main pass zone. Another interpretation could be that ciguatera could still be present in this zone but thanks to the avoidance behaviour of fishers, few poisoning events actually occurred recently. In any case, if the pass is still considered ciguatoxic by fishers, it is important to integrate that information in the SCP framework.

Finally, the FAO Matrix, which provides a clear cut-off for differentiating large- from small-scale fisheries, definitely identified Raivavae fishery as a small-scale fishery. It is a new, useful tool to characterize the small-scale or artisanal character of a fishery and it can serve as a quantitative reference for comparison with other contexts, or to identify fishery sites with similar characteristics. To investigate where the present framework could be applied, it is worth searching which sites would be characterized as small-scale fisheries with very low FAO Matrix scores, and simultaneously affected by ciguatera.

## Further recommendations

Based on the discussion above, several aspects should be emphasized for this framework to be implemented with maximum benefits.

First, increasing the accuracy when mapping fishing grounds (step 3 of the framework) is particularly useful and easy to implement, even with fairly simple map based on reef unit geomorphology that are relevant to fishing gears. It is also possible to minimize the requirement for this step 3 if the fishers draw carefully their activities on the printed satellite image used for background. Therefore, this step should not be seen as an obstacle to apply the framework.

Second, local knowledge on ciguatera must be gathered from fishers representing the entire study domain, each fisher holding a partial knowledge related to his reference zone.

Third, fisheries and ciguatera status should be reassessed periodically as they can vary quickly over time and space. Fishing grounds and catch intensity depend on legal regulations, socioeconomic drivers (e.g. population pressure, development of fishing methods, access to distribution markets, economic crisis), and environmental changes; among other factors. Similarly, ciguatera distribution and intensity vary over time, and should be regularly reassessed. In French Polynesia, inhabitants and medical staff are encouraged to report poisoning cases to health authorities through an online declaration form (www.ciguatera.pf). Although data collected in the frame of this community-based participatory program are not exhaustive, they give a complementary indicator and can contribute to raise a red flag in case of mass poisoning outbreaks to implement further *in situ* investigations, like recently in the Marquesas archipelago (Darius *et al.*, 2018). Surveys should be developed and implemented in other ciguateric regions. For sound planning, we thus recommend reevaluating the fishery and ciguatera situation every 5–10 years, or each time a major change (social or environmental) is reported in the island that may impact the status of fishing grounds and ciguatera.

## Data availability

Data are available on request from the authors.

## Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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