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Benefits of collaboration between indigenous fishery management and data-driven spatial planning approaches: the case of a Polynesian traditional design (*rāhui*)

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Abstract :

Traditional fishery management schemes have gained increasing recognition worldwide. It can be explained by a better compliance to ancient cultural practices, still rooted in present-day coastal communities despite globalization and modern livelihoods. This revival is widespread and welcome by policy makers, scientists, and the communities themselves. However, current environmental and socio-economic contexts are often not conform to ancient-time situations. Baselines are different. Effective adjustments of traditional practices may be advocated. Re-establishment of traditional schemes 'as such' warrants further investigations and modern quantitative assessment and management approaches can help. A demonstration is provided here for a rural Polynesian island that faces declining marine resources. Recently, local fishers discussed the implementation of a traditional system (called rāhui) to preserve the island lagoon resources, based on the rotational closure of an arbitrary 50% of each lagoon subdivision. Upon the fishers' request who questioned a traditional scheme that has not been applied for decades and seeked some scientific approval, we used systematic conservation planning (SCP) tools to explore potential optimisation pathways. All quantitative conservation objectives being equal, SCP suggested reserve sizes and opportunity costs on average 7 and 5 times lower than the traditional design. Traditional management federates communities and is strongly encouraged, but fishers are now aware that effective alternative designs are possible. A hybrid design mixing traditional practices and data-based optimizations is advocated. Similar findings and recommendations can be expected in other regions.

Highlights

► Fishers in Raivavae island aim for a traditional rotational fishery closure. ► Fishers are also in demand of an optimization of this traditional approach. ► Systematic Conservation Planning (SCP) and Marxan can provide valuable insights. ► Marxan reproduced the inputs and enhanced the outputs of the traditional design. ► Traditional management and SCP can be used together to co-maximize their strengths.

Keywords : Raivavae, Systematic conservation planning, Marxan, Artisanal fisheries, Ciguatera, Locally managed marine area

1. Introduction

Marine fishery resources need to be better managed worldwide to primarily counteract overfishing and on-going negative environmental changes (Jackson et al., 2001; Link and Watson, 2019). Despite contrasted status between countries and some success stories of effective management and documented stock rebounds through, for instance, marine protected areas (e.g., Anderson et al., 2014; Cochrane, 2021; Hilborn et al., 2020), a general trend is a worldwide decrease in the quality and quantity of catches (Pauly and Zeller, 2016). Better management is called upon at all geographical scales and a wide range of fishery types, from offshore industrial fisheries in the high latitude seas (McBride et al., 2014) to small scale fisheries such as in Europe (Frangoudes et al., 2020; García-Lorenzo et al., 2019) or traditional artisanal fisheries in remote tropical tenures, for both finfish and invertebrates (Alati et al., 2020; Warren and Steenbergen, 2021). Sustainable fishing and stock management can be promoted using a variety of political, socio-economic and environmental measures, several directly targeting the fishing activity itself such as quotas, minimum/maximum catch sizes, and others focusing on spatial and temporal closure of fishing grounds. In order to take informed decisions, a vast array of data may be needed and modern management is, or should be, driven by data (Pauly and Zeller, 2016). Ideally, critical socio-economic, biological and ecosystem data, should be collected from traditional knowledge, scientific observations and models, and channelled to decision-support tools used by managers and fishers.

In freshwater and marine coastal areas, local management measures of small tenures are common (e.g., in Oceania, Karcher et al., 2020; in Indonesia, Evans et al., 1997). They emerge from local decisions, through participatory and community-driven discussions, that themselves often follow traditional protocols and practices. In the past decades, these traditional approaches have been increasingly recognised worldwide as efficient ways to manage fishery resources (Johannes, 2002; Kuemlangan, 2004). Level of compliance to restrictions are higher, local relevant knowledge is used, and information is shared across the different social and governance layers of the community (Fache and Pauwels, 2020; Sangha et al., 2019; Smallhorn-West et al., 2020a). Indeed, in many countries with low enforcement capacities, top-down decisions may even be unheard of by local remote communities. The benefits of traditional indigenous management, both inland and coastal, and how it can serve biodiversity conservation in its broad sense (including fishery resources) is reviewed in Gurney et al. (2021) in the context of Other Effective Area-Based Conservation Measures (OECM).

In the case of small-scale fishery systems that are locally managed, the 'tropical' focus of our study, particularly on Oceania, is explained by the fact that traditional management, in the sense of indigenous management led or co-led by local communities, is still quite widely practiced. In this context the spatial management units can follow a narrow coherent set of characteristics based on resources, human, geographical and environmental features (Savoré et al., 2019). This can lead to the fragmentation of the domain, with a specific management scheme applied for each spatial unit (Cinner et al., 2012). Such a scheme can have inherent limits (Léopold et al., 2013), which may lead to inefficient protection, for instance when tenures are too small to protect marine species that are mobile across these tenures. For instance, in Vanuatu, the micro-local management of numerous very small customary tenures (< 1 km²) precludes the effectiveness of these individually managed areas in sustaining resources at a larger scale (Dumas et al., 2010; Léopold et al., 2013). Maintaining traditional rules can also be irrelevant considering all the pressures that are new to previously isolated or much simpler socio-ecosystems. Changes can be related to new pressure on stocks due to increased demography, or more efficient fishing gears and equipment. New spatially conflicting activities may have developed, ancient ones have disappeared, and global changes such as global warming may have already altered local ecosystems. Another aspect is that customary decisions can be taken without critical adequate information, especially on biological aspects. Typically, new updated baselines should be considered, such as level of stocks, reproduction potential, or new factors of mortalities that can be unknown from the locals (Lauer and Aswani, 2010). For instance, in French Polynesia, Andréfouët et al. (2013) reported that a 90% giant clam mass mortality was totally missed by local population even if they depended on this important resource.

When the traditional management process is re-established after decades of interruption, as is the case in many localities in Oceania (Johannes, 1978; 2002), it is especially critical to take into account relevant ecological observations and measures. This advocates for a strengthened approach built upon a synergy between recent data and traditional knowledge (Andréfouët et al., 2018; Aswani and Hamilton, 2004; Close et al., 2006; Jupiter et al. 2014; Weeks and Jupiter, 2013). For tropical lagoons and coral reefs, there are still very few studies aiming to combine a data driven approach with the traditional practices, (e.g. Aswani and Hamilton, 2004; Davies et al., 2020; Horigue et al., 2015; Smallhorn-West et al., 2019; Weeks and Jupiter 2013; Wendth et al. 2016). This general issue was identified as a priority for Oceania in Weeks and Adams (2018, Question 34: '*How can we combine the best modern science with the best indigenous and local knowledge as a basis for biodiversity conservation and sustainable use in Oceania?*'). Recently, Gurney et al. (2021) advocated to co-build multiple indicators of effectiveness for existing OECM, but the case of the re-establishment of locally managed areas is not discussed in the existing literature. In this context, we suggest to use spatial prioritization methods to promote management decisions based on a data driven approach combined with the revival of traditional practices.

With the aim of preserving biodiversity and resources, a structured data-driven approach for identifying conservation areas is systematic conservation planning (SCP). This analytic approach uses spatial information to provide transparent and data-driven solutions. Importantly, SCP was initially developed to enhance locating and designing reserves for the conservation of biodiversity (Margules and Pressey, 2000), but it was less used to specifically set an objective on fishery resources (but see for instance Kabbadj et al., 2018). Briefly, after defining the questions, targets (i.e. quantified features of biodiversity or fishery stock to protect), spatial domain, and group of stakeholders involved (Pressey and Bottril, 2009), the selection of conservation priority areas through a SCP framework first requires dividing the study area into small units called planning units (PU), each characterized by attributes related to biodiversity or fishery targets and constraints. Then, prioritisation algorithms are applied to identify the best minimum number of PUs as a solution able to meet the objectives ('SCP best solution'), while minimising the cost of the reserve (Kukkala and Moilanen, 2013; Margules and Pressey, 2000). These costs can be the lost opportunities for human activities, in particular for fisheries. The loss of opportunities in terms of fish catches is a frequent metrics used in spatial planning in the Pacific Islands (André et al., 2021a). Finding these best trade-offs is done through numerical optimization (Moilanen et al., 2009).

Here, using a French Polynesian case study, we present how a committee of indigenous fishers, curious about confronting their traditional design with scientific knowledge, can collaborate with spatial planning scientists having access to spatialized data, to identify optimised solutions, hence potentially strengthening the traditional fishers approach to fisheries management. We discuss the limits and benefits of this specific exercise for the studied island and emphasize the potential of this combined approach if it is generalized elsewhere.

2. Material and Methods

2.1 The traditional rāhui fishery management and Raivavae study site

In the Pacific Ocean, many islands have maintained or re-introduced some form of traditional spatial management of marine areas as part of cultural revival movements that have emerged since the late 1990's (Johannes, 2002). These include *tapu* areas (taboos), *bul* in Palau (Friedlander et al., 2017; Gruby et al., 2013; Pilbeam et al., 2019) and *rāhui* in Polynesia (Polynesia *sensu* the cultural area, extending from New Zealand to Hawaii and Easter Island) (Bambridge, 2016; McCormack, 2011). All these instruments imply some sort of closures (temporal and/or spatial) with specific targets and sets of rules that can be very local. They have been designated in international nomenclature as indigenous and community conserved areas (ICCAs) or locally managed marine areas (LMMAs) (Govan, 2009). In this study, we are particularly interested in rāhui, which originally involved a restriction of access to a territory or resources during a period of time, imposed by political authorities. It could take the form of a temporary ban, periodically harvested closures or rotating closures (Bambridge et al., 2016, 2021; Cohen and Foale, 2013). It could have different objectives such as to impose a ban on access to a certain territory after a drowning nearby, or to ban fishery resource extraction of a specific or all marine species, for stock replenishment, for example in anticipation of a celebration expected to require substantial amount of food (Conte, 2016; Ghasarian, 2016; McCormack, 2011).

Rāhui is an ancient concept but it has evolved with the modern society rationales and constraints, and it can take different forms depending on the people's conceptions, perceptions and expectations, including now ecosystem conservation (Bambridge et al., 2021; Fabre et al., 2021). Hereafter, in agreement with local habits, we use the word rāhui both as a management approach and as the spatial area under protection. In the current international context, which promotes conservation initiatives and sustainable fisheries management, and recognizes the merit of community-based management, several rāhui have been re-established in the Polynesian region to manage marine resource stocks with a traditional grounding (i.e. in French Polynesia: Bambridge, 2016; Fabre et al. 2022; in New Zealand: Gnanalingam et al., 2021). The traditional dimension is highlighted and promoted, and these local initiatives generally benefit from good support from local communities (Govan, 2009). In French Polynesia, rāhui is legally recognised by the French Polynesian technical service in charge of marine resource management, *Direction des Ressources Marines* (DRM, 2021) and gazetted in official texts.

In the past decades, different rāhui initiatives were implemented, supported by the inhabitants, local management committees or municipal staffs. An emblematic example is the traditional rāhui that was re-implemented in Rapa iti Island (Austral Islands) in the 1980s, from the population initiative, to protect and sustain marine resources they rely strongly on, and avoid potential overexploitation due to the introduction of modern fishing techniques and frozen storage equipment (Ghasarian, 2016; Salvat et al., 2015). In the main French Polynesia Island, Tahiti (Society Archipelago), a rāhui was implemented in Teahupoo locality in 2014. It has been successful thus far in terms of marine resources replenishment and now constitutes a model that other municipalities wish to follow (DRM pers. com., Nov. 2019). It is not a rotating scheme, and it is now evolving into a permanent reserve (DRM, pers. com). A rāhui aiming at biodiversity conservation purpose has been implemented recently in Tautira district, Tahiti (Bambridge et al., 2019), whereas a rāhui is currently serving educational purpose in Anaa Atoll, Tuamotu Archipelago (Filous et al., 2021), and the revival of ancient rāhui practices are currently being integrated in a spatial planning project in Mangareva, Gambier Archipelago, for stock replenishment of pearl oyster, at the request of farmers (André et al., 2022).

Raivavae Island (-147,67°W longitude and -23,87°S latitude) is located in the Austral Archipelago (French Polynesia), 700 km south of the main island of Tahiti (Figure 1.a). This 18 km^2 volcanic island is home to 903 inhabitants (2019) and offers a 59-km^2 lagoon and reef system, which is connected to the ocean through one main pass in the north-west and two other small passes in the north and the south. Raivavae is administratively divided into four districts, namely Rairua, Mahanatoa, Anatonu and Vaiuru (Figure 1.b).

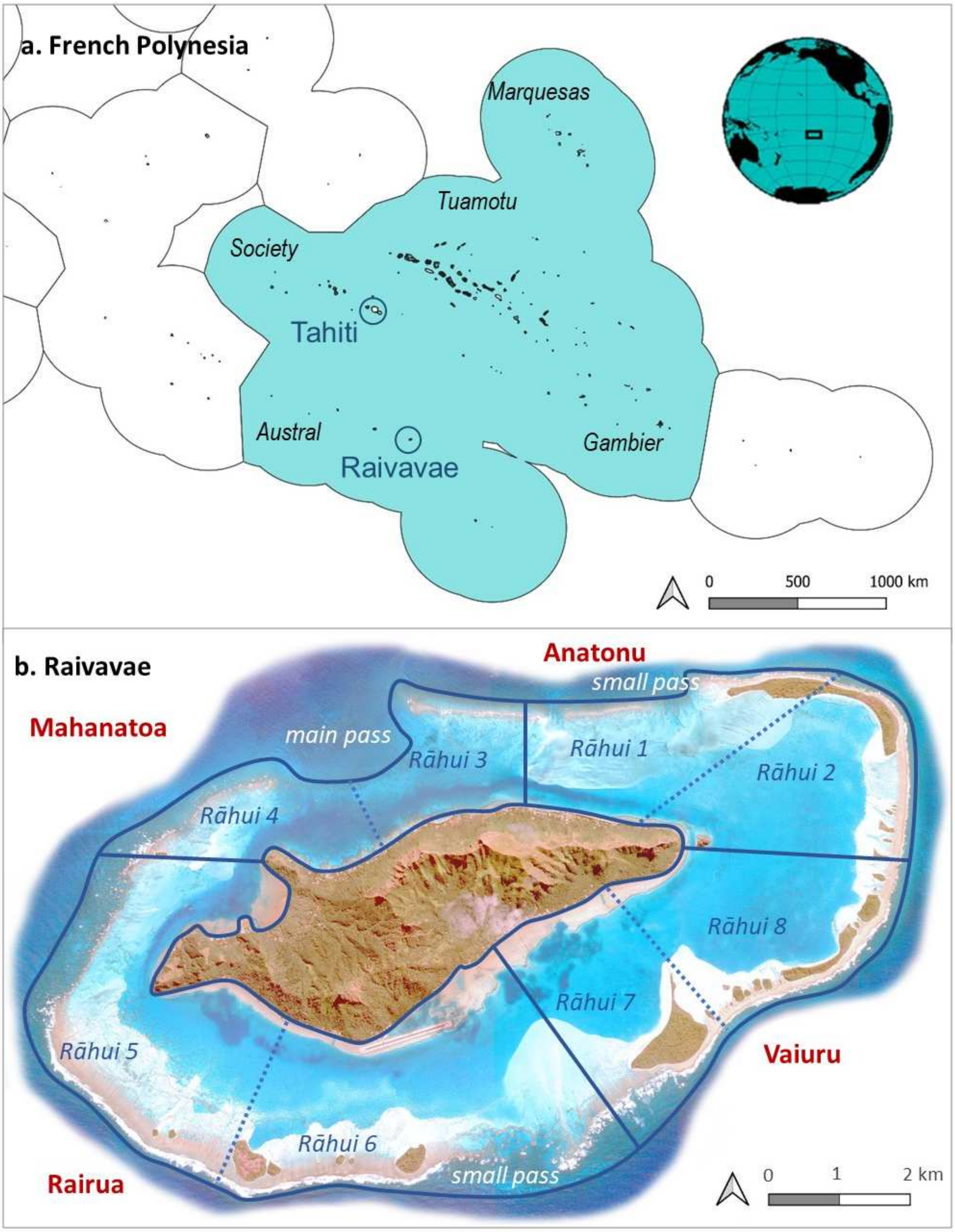

***Figure 1. Map of the study site**. (a) Location of Raivavae Island in the Austral Archipelago, French Polynesia; (b) Raivavae's four administrative districts Rairua, Mahanatoa, Anatonu and Vaiuru, and the eight rāhui zones.*

People in Raivavae rely strongly on local resources, most notably agriculture and artisanal fisheries (Kronen et al., 2009), with an estimated 1.4 $t\cdot km^{-2}\cdot y^{-1}$ marine resources annual yield on average (André et al., 2021b). The main fishing grounds are located in the south-western barrier reef and back reef zone, with the highest yields reaching 9 $t.km^{-2}\cdot y^{-1}$. A specific feature of this local fishery is its strong reliance on giant clams (*Tridacna maxima*), besides finfish (Kronen et al., 2009; Van Wynsberge et al., 2013). The giant clam fishery takes place throughout the entire lagoon (André et al., 2021b) and accounts for more than 15% of the annual catch biomass (considering the meat, without the shells) (unpublished data). An important part of this catch is exported to Tahiti as gifts for families, church fairs or for sale. In periods of high exports, the sustainability of this resource exploitation raises concerns among the population.

Raivavae is also characterised by the presence of ciguatera poisoning, as illustrated by a major poisoning outbreak in 2007 (Chinain et al., 2010). Ciguatera poisoning results from the consumption of finfish or invertebrates contaminated with neurotoxins known as ciguatoxins that are produced by benthic dinoflagellates in the genera *Gambierdiscus* and *Fukuyoa.* Since 2007, numerous cases have been repeatedly reported on the island, and fishers have developed their own strategy to avoid ciguatera-prone areas and species (André et al., 2021b). In terms of restriction of access to marine resources, ciguatera is an important constraint in Raivavae and in many islands of the Pacific region as well. In French Polynesia, where several islands are severely impacted by recurrent outbreaks (Chinain et al., 2020), ciguatera is a major threat to food security. Recently, André et al. (2021b) showed how ciguatera can be used to inform SCP scenarios and benefit the fishers in a planning process, based on the hypothesis that the foregone opportunity to fish due to a reserve implementation, or 'opportunity cost', is lower where the risk of ciguatera is high. Specifically with the SCP approach, the choice of conservation areas closed to fishing, is directed towards low cost areas, i.e. to areas presenting lower fishery catch and/or a high ciguatera risk. In Raivavae, areas with high ciguatera risk are found in the main pass, north small pass and airport strip zones (André et al., 2021b).

During the map-based interviews conducted in Raivavae in November 2019 (André et al., 2021b), the fishers expressed their concerns on their planned actions to sustainably manage the marine resources they depend on. Indeed, through an environmental association, local fishers are advocating the implementation of a traditional reserve design, called rāhui, to protect their lagoon resources. This plan has gained momentum and is strongly supported by the population, town hall authorities and church representatives. The proposed rāhui design is simple as it closes all fisheries in half the surface area of each lagoon district subdivision. More specifically, it is intended to be implemented simultaneously in each district, so that the design is equitable for the entire population around the island. To this end, the management committee proposes to split the lagoon in front of each district in two compact zones of equal surface area that extend from the shore to the barrier reef (Figure 1.b). The committee proposes to implement the fishery closure in two phases. In phase 1, rāhui would be simultaneously implemented on one half of each district lagoon area (four areas under rāhui closure, either rāhui zones 2, 3, 5 and 7 in configuration 1, or the others in configuration 2, cf. Figure 1.b), while allowing fishing in the other half of each district lagoon areas (Figure 1.b). After three years, phase 2 would start and closed *vs* open areas would switch within each district. Another remarkable feature is the emphasis on giant clam resources. It is a critical resource for the island (Andréfouët et al., 2009), and even if the rāhui should help manage all marine resources, giant clams are a prime target. The Raivavae plan is thus a true rotational scheme with predefined areas that shift their protection status through time, one area receiving protection instead of another, every three years. This is not like the aforementioned Rapa Iti or Teahupoo schemes, where, the closure is periodically harvested for a short time and the single area has never been opened to fishers thus far, respectively.

Even traditionally rooted, the rāhui design is questioned among fishers because of the closure of an arbitrary and significant 50% of the total area. There is a fear that this may actually be way too restrictive for fishers. In this context, during a meeting that took place in November 2019, the fishers association and the management committee requested scientific advices regarding their plans prior to their implementation.

To respond to the fishers' concerns, we used SCP tool to build scenarios that simulate the rāhui design in terms of objectives (protection of the giant clam stock), compactness, and equitable distribution in each subdivision, while decreasing opportunity cost to fishers. The SCP scenarios investigate how the design could be optimized by decreasing the amount of surface area in reserves and by inducing less opportunity cost to fishers, based on information on fishery catch and ciguatera risk.

2.2 Spatial data aggregation

Spatial information is required concerning each aspect of the SCP scenarios and various spatial data already available and published for Raivavae Island were used here, namely:

- (Layer 1) A map of geomorphological habitats of Raivavae lagoon. This map was used to evaluate which habitats, and how much of it, were included in the rāhui and in the SCP-derived reserves;
- (Layer 2) A map of giant clam stocks (ind.m^{-2}), produced from previous *in situ* fine scale fieldwork conducted in 2005 (Andréfouët et al., 2009) and generalised to the lagoon using the aforementioned geomorphological habitat map. The giant clam stock distribution map was updated following field investigations in 2010 (Van Wynsberge et al., 2013). As giant clams are one of the main marine resources in Raivavae (André et al., 2021b; Kronen et al., 2009), we used this map as a proxy for total marine resources;
- (Layer 3) A refined map of fishing grounds and associated catch (kg), produced from map-based surveys conducted among 59 fishers in 2019, following the methodology detailed in André et al. (2021b). In short, using a printed map of the lagoon, fishers identified their

fishing grounds, which are generally very specific to some type of fishing gears (spearguns, nets, lines, spears, etc.). Eventually, the fishing ground shapes drawn rapidly by the fishers during the interviews were spatially refined using GIS tool, to follow the outlines of the geomorphological habitats where each fishing gear can normally be used. See André et al. (2021b) for a detailed explanation. Then, for each fishing ground, an annual catch was estimated from the questionnaires.

- (Layer 4) A map of ciguatera risk, produced from local knowledge collected during the same 2019 map-based surveys. This data takes the form of a map with multiple zones and their associated coefficients of risk, depending on the nature of the risk (proven or suspected) and its date, following methodology detailed in André et al. (2021b). This layer was then used either in conjunction with the fishing ground map to build the opportunity cost map (see below), either as a standalone map to evaluate levels of ciguatera risk (see section 4 in methods below);

SCP scenarios require a grid of planning units and this set of spatial data were aggregated into a grid of polygons of hexagonal shape, generated using ESRI ArcGIS tessellation tool. Hexagon shape is efficient in creating networks with low edge to area ratio (Ardron et al., 2010). The size of hexagons was set at 100.000 m² to capture the patterns of the various input maps, to be suitable for the district sizes (≈ a minimum of 40 PU per district was targeted), and to offer flexibility between PUs when searching solution. PU were defined across the entire lagoon, hence for a total 59 km² area.

For each layer, values were aggregated for each PU, to get:

1. PU map 1 of habitat surface areas in $m^2.PU^{-1}$; from layer 1
2. PU map 2 of giant clam stocks in number of $ind.PU^{-1}$ (used as SCP target), from layer 2;
3. PU map 3 of fishery catch in $kg.PU^{-1}$, from layer 3;
4. PU map 4 of ciguatera risk in risk coefficient per PU, from layer 4;
5. PU map 5 of opportunity cost (used as SCP cost). The fishery catch and ciguatera risk values from PU maps 3 and 4 were normalized by their respective maximum value, and combined at equal relative weight to obtain the opportunity cost, following André et al. (2021b) methodology (where the impacts of different relative weights were explored).

2.3 SCP scenarios

We used ©Marxan software to run the SCP scenarios (Ball et al., 2009). In a first step, a set of scenarios were conducted at the district subdivision scale. For this, we first characterized the rāhui design by measuring the amount of giant clams that would be included in each of the 8 rāhui subdivisions, using the map of giant clam stocks and the administrative districts and their 50% subdivisions. Then a SCP scenario was designed with this exact same amount of giant clam stock set as a target. The PUs prioritized as solutions could be selected anywhere within the whole district area. This way, eight SCP scenarios were computed (two rāhui targets per district) (Scenarios 1-8).

In a second step, another set of scenarios was performed, this time considering the whole lagoon. For the two possibilities of rāhui configuration at phase 1, which closes either zones 1, 4, 6, and 8 (configuration 1), or zones 2, 3, 5, and 7 (configuration 2) to fishing activities, we calculated the total amount of giant clam stock inside all four closed areas. Two SCP scenarios (9 and 10) used these exact same amounts of giant clam stock as conservation targets and the PUs could be selected within the entire lagoon area.

For all scenarios, the cost function to minimise was the opportunity cost defined from the fishery catch and ciguatera risk combined information. Among ©Marxan settings, the Species (or conservation feature) Penalty Factor (SPF) is used to determine how much emphasis should be placed on ensuring the target is met; and the Boundary Length Modifier (BLM) aims at decreasing the summed length of overall boundaries of the selected PU network, by increasing aggregation (Game and Grantham, 2008). Calibration of both SPF and BLM was optimised for each scenario, following Ardron et al. (2010) methodology, in order to meet the target (SPF calibration) and to reach a compactness (BLM calibration) that is similar to a rāhui, or approaching it (i.e., low fragmentation of the PU network, with a maximum of one to three clusters allowed), while keeping cost as low as possible.

2.4 Comparison of SCP solutions with rāhui

SCP best solutions and the rāhui designs were compared on the basis of four criteria:
1) the surface area closed to fishing activities;
2) the opportunity cost to fishers;
3) the level of incidental ciguatera risk reached by each design in the remaining areas open for fishing. To this end, the level of risk associated with each PU was computed according to Table 1, after ranking the coefficients of risk into four classes.
4) The habitat representation, i.e. the number of habitats included in each design, which is also an incidental, indirect, benefit.

Therefore, note that the first two criteria were parameters included in the SCP optimisation function, while the two others were not.

Table 1. Levels of ciguatera risk considered in this study, and PU distribution associated to each class of risk. *The four risk classes were delimited according to the lower decile, median and upper decile of ciguatera coefficients.*

Level of risk	risk class	coefficient	number of PUs	surface area (km²)
Very high risk	4	50-764	73	5.91
High risk	3	2-49	220	17.72
Moderate risk	2	1	104	8.43
Low risk	1	0	332	26.84

3. Results

3.1 Data aggregation outputs

Fishing pressure varied between PUs throughout the lagoon. Rairua (southwest) reefs and back reefs displayed the highest levels of fishery catch per PU, including the southern small pass. PUs located in the remaining lagoon showed lower rates, except for some PU spots in the main pass, Mahanatoa fringing reef (north coast), a portion of Anatonu (eastern) barrier reef and Vaiuru (southeast) small pass (Figure 2.a).

Ciguatera risk had the highest values in Mahanatoa district near the main pass and the adjacent reefs, along with neighbouring fringing reefs. Other fringing reefs all around the island displayed medium to high values of ciguatera risk (Figure 2.d).

Overall, the total opportunity cost, resulting from fishing pressure and ciguatera risk, provided the highest cost for PUs located on Rairua reefs, including some back reef sections, the small pass and the main pass areas. The narrow margin of Vaiuru and Anatonu eastern barrier reef also displayed high costs (Figure 2.e).

The highest giant clam stocks were located on the eastern and south-western reefs and back reefs (up to 202,560 ind. for a 100,000 m^2 PU), and the northern hard bottom terrace (Figure 2.b).

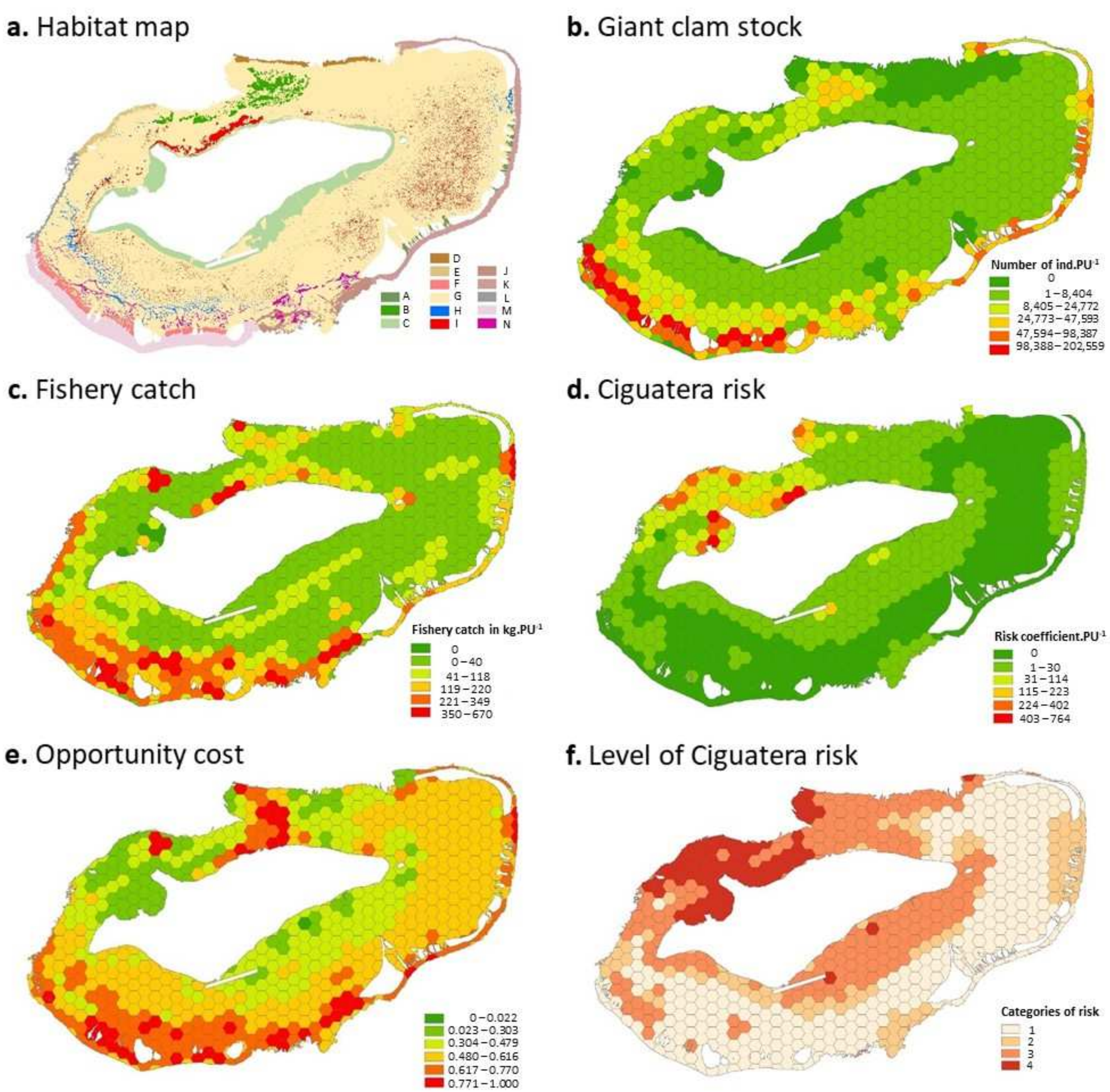

Figure 2. Ecological and socioeconomic features in Raivavae lagoon, aggregated per Planning Unit (PU). *a. Geomorphological habitat map (A: east barrier, spillway; B: north hard ground on sedimentary terrace; C: fringing reef; D: north barrier, crest; E: north-west barrier, reef flat; F: south-west back reef, reef flat, rock; G: lagoon; H: shallow lagoonal patch reef; I: deep lagoonal patch reef; J: south barrier, crest; K: east barrier, reef flat; L: west barrier, crest; M: south-west barrier, terrace, hardground; N: south-west hardground on sedimentary terrace); b. Distribution of giant clam stocks; c. Fishery catch; d. Ciguatera risk distribution e. Opportunity cost distribution, resulting from combination of c and d at equal relative weights; f. Ciguatera level of risk from 1 (low) to 4 (very high risk). Note that maps b and d were used as inputs for Systematic Conservation Planning (SCP) optimizations (to set objective and cost, respectively); and maps a and f were used to analyse the incidental effects of rāhui and SCP designs.*

3.2 Comparing SCP solutions with rāhui design

The analyses of rāhui and SCP designs were summarised in Table 2. For each rāhui, the corresponding SCP scenario could reach the same target of giant clam stock protection by closing areas 1.66 to 13.82 times smaller than the rāhui design (6.83 on average). Opportunity cost to fishers were 2.25 to 12.60 times lower for the SCP solutions than in the rāhui design (4.75 on average). This optimisation is illustrated for Rairua district (Figure 3). By contrast, and as expected considering the type of designs and the larger area in protection requested by the traditional scheme, the analysis of incidental effects showed higher habitat representation in rāhui than in SCP solutions, with a 1.20 to 3 factor (up to 9 *vs* 3 habitats for rāhui 7 *vs* Scenario 7, in Vaiuru).

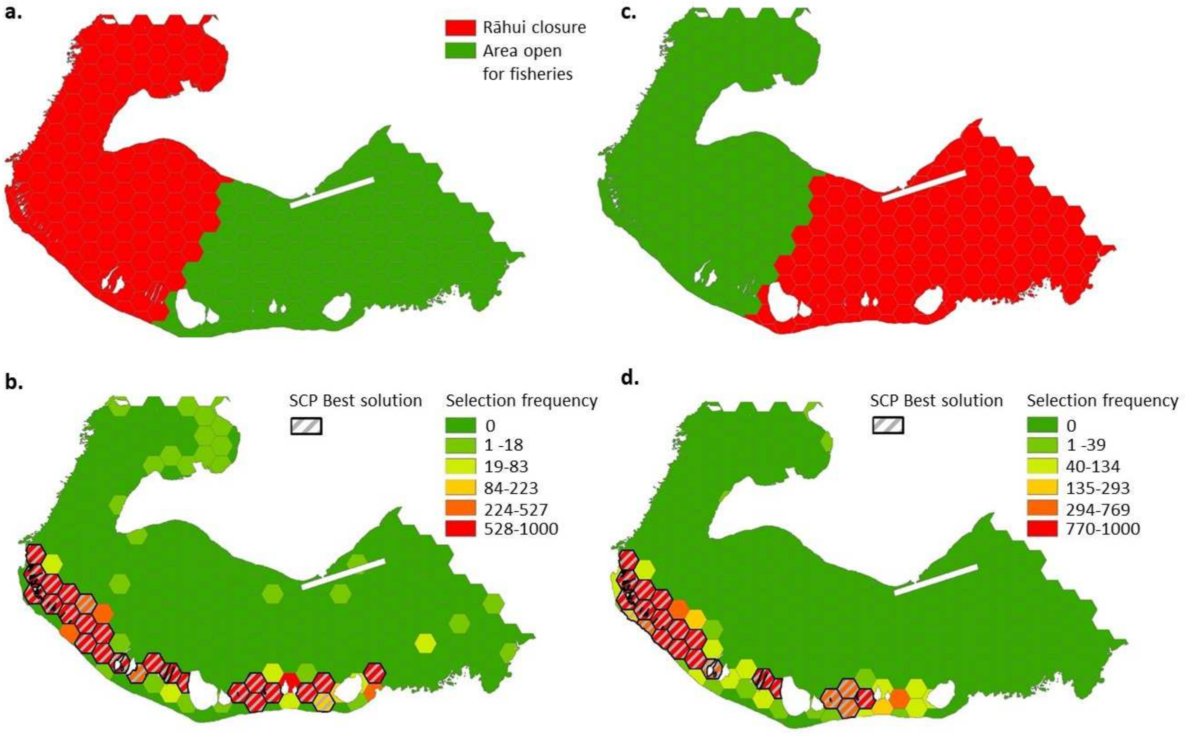

Figure 3. Map of the Rairua southwest district, under different options of management. *Top panels (a, c) display the rāhui designs, with areas closed (red) and open (green) to fisheries, respectively. Bottom panels (b, d) display the optimisation solutions, with shade colours reflecting the Planning Units (PU) selection frequency, and hatched PUs are selected for the best optimisation solution network. Panel a: rāhui 5; b: optimisation with similar conservation target as in rāhui 5; c: rāhui 6; d: optimisation with similar conservation target as in rāhui 6.*

Scenarios 9 and 10, at the scale of the whole lagoon, also showed enhancement brought by the SCP solutions. The benefit is even larger than for the district-based scenarios (Table 2). Optimised solutions required surface areas 6.01 and 8.29 times smaller than rāhui configurations 1 and 2 respectively, and opportunity costs were 4.40 and 6.70 times lower for fishers. The level of habitat representation was 1.44 times lower for both scenarios (Table 2).

Table 2. Comparison between the Rāhui designs and the optimisation scenarios*, and ratios associated to the features measured, either conducted at the scale of each district* vs *the whole lagoon. Sc: scenario; SPF: Species penalty factor; BLM: Boundary length modifier.*

Districts	Rāhui or Optimisation Scenarios (sc)	SPF (Marxan setting)	BLM (Marxan setting)	Giant clams (ind/m²): **Stock** included (rāhui) then set as a **Target** (scenario)	**Surface area** (km²)	**Total Opportunity Cost**	Number of **Habitats** included
Anatonu	Rāhui 1			312,804	6.41	37	6
	Sc 1	5	0.0001	312,801	0.46	3	3
	Ratio rāhui/sc			**1.00**	**13.82**	**12.60**	**2.00**
	Rāhui 2			744,048	7.23	49	6
	Sc 2	10	0.01	752,522	1.09	14	4
	Ratio rāhui/sc			**1.01**	**6.64**	**3.60**	**1.50**
Mahanatoa	Rāhui 3			405,908	3.50	28	5
	Sc 3	5	0.001	406,762	2.11	12	4
	Ratio rāhui/sc			**1.00**	**1.66**	**2.25**	**1.25**
	Rāhui 4			237,470	3.21	15	6
	Sc 4	5	0.001	244,338	1.04	6	4
	Ratio rāhui/sc			**1.03**	**3.09**	**2.37**	**1.50**
Rairua	Rāhui 5			3,112,274	12.18	75	9
	Sc 5	5	0.0001	3,114,631	2.35	18	6
	Ratio rāhui/sc			**1.00**	**5.17**	**4.16**	**1.50**
	Rāhui 6			2,532,236	12.18	85	8
	Sc 6	10	0.001	2,538,068	1.86	15	5
	Ratio rāhui/sc			**1.00**	**6.57**	**5.67**	**1.60**
Vaiuru	Rāhui 7			577,164	6.85	41	9
	Sc 7	10	0.001	585,708	0.61	9	3
	Ratio rāhui/sc			**1.01**	**11.30**	**4.77**	**3.00**
	Rāhui 8			1,001,423	7.32	49	6
	Sc 8	5	0.0001	1,014,838	1.15	19	5
	Ratio rāhui/sc			**1.01**	**6.36**	**2.61**	**1.20**
Whole lagoon	Rāhui 2,3,5,7			4,839,394	29.77	193	13
	Sc 2,3,5,7			4,859,623	6.17	53	11
	Ratio rāhui/sc			**1.00**	**4.83**	**3.66**	**1.18**
config. 1	Sc 9	5	0.001	4,839,135	4.96	44	9
	Ratio rāhui/sc			**1.00**	**6.01**	**4.40**	**1.44**
Whole lagoon	Rāhui 1,4,6,8			4,083,933	29.12	186	13
	Sc 1,4,6,8			4,110,045	4.51	43	11
	Ratio rāhui/sc			**0.99**	**6.46**	**4.32**	**1.18**
config. 2	Sc 10	5	0.0001	4,081,460	3.51	28	9
	Ratio rāhui/sc			**1.00**	**8.29**	**6.70**	**1.44**

Spatially, the comparison between the rāhui in configuration 1 (i.e., subdivisions 2, 3, 5 and 7 closed simultaneously in each district) (Figure 4.a), and the corresponding SCP optimisations performed at the scale either of each district (Figure 4.b), or of the whole lagoon (Figure 4.c), showed very different patterns of reserve networks (Figure 4). SCP optimisations appear to select in priority peripheral solution PUs, which is where high stocks of giant clams are found, on reefs, and those PUs then quickly satisfy the objectives. Particularly, the south-west zone condenses highly effective PUs as the majority of the PUs solution are selected in this region while planning at the scale of the whole lagoon (Figure 4.c).

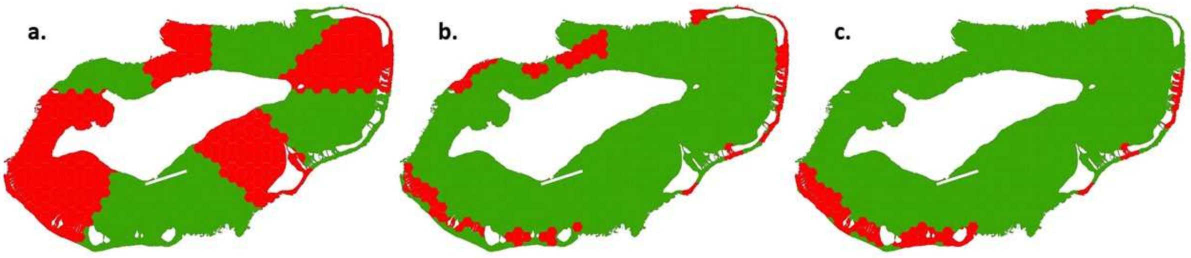

Figure 4. Example of different management options, all protecting the same stock of giant clam resource *(red for closed, green for open areas). a: rāhui 2, 3, 5 and 7 (configuration 1); b: optimisation solutions performed at the scale of each district from optimisation scenarios 2, 3, 5 and 7; c: global optimisation (scenario 9) performed at the scale of the whole lagoon.*

Finally, incidental levels of ciguatera risk in the areas that are left open (when rāhui 1 is implemented, i.e. fishing ban on rāhui 1 area, then the domain corresponding to rāhui 2 is open for fishing) were contrasted for each rāhui configuration. Some had important proportions of surface areas with high to very high level of risk (Figure 5.a, see rāhui 3 and 4), compared to others (rāhui 2 and 8) (see Supplementary material S1 for table of values). When comparing the areas that were left open for fishing, important differences appeared between rāhui designs and SCP optimisations (Figure 5.b). Particularly, SCP allowed for larger areas open to fisheries, and induced higher surface areas of low ciguatera risk for fishers, except for scenario 4, due to the high risk of ciguatera across the whole Mahanatoa district.

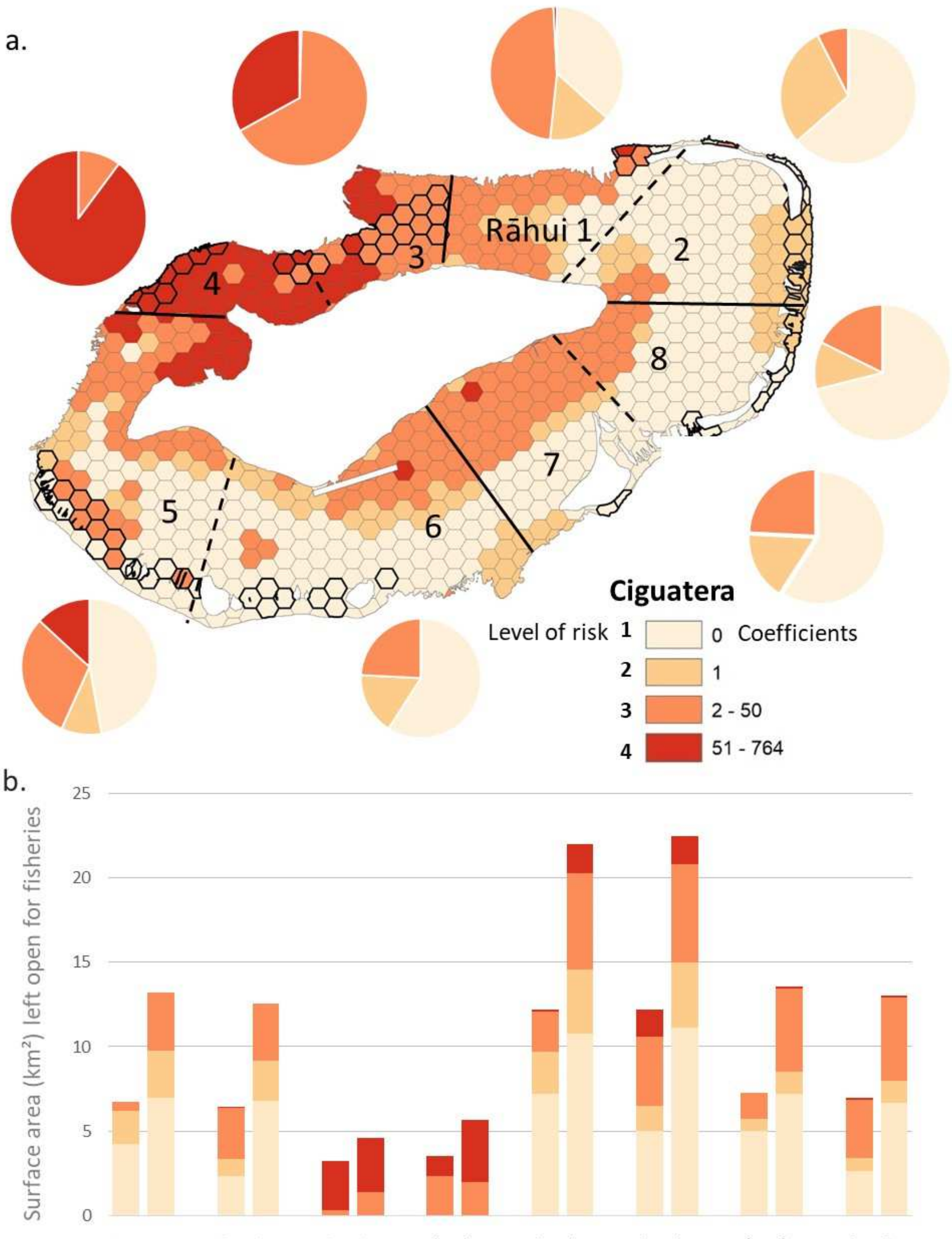

Figure 5. Incidental levels of ciguatera risk in the reserve designs. *a: map of the four levels of ciguatera risk, and pie charts for each rāhui showing the proportion of areas within each level of risk. Bold planning units show solutions for scenarios 2, 3, 5, 7. b: surface areas that are left open for fishing under each type of design and the associated distribution of ciguatera risk (remember that when rāhui 1 is implemented (situation in the first bar), the displayed surface area, open for fishing, consequently corresponds to the domain of rāhui 2).*

4. Discussion

This study stems from the context of traditional fishery management revival in a remote tropical island and the need, expressed by the resource users, to improve its original design. The general objective was to seek pathways to optimise the re-establishment of ancient practices through a collaboration with quantitative planning methods. We explored how the efficiency of a French Polynesian traditional rāhui design could benefit from insights arising from SCP spatial prioritisation tool and spatial information on (i) marine resource abundance (giant clam stock), (ii) socio-economic costs that integrate fishing pressure and ciguatera risk, (iii) incidental habitat diversity (at geomorphological level) and (vi) incidental level of ciguatera risk in areas left open to fisheries.

The SCP design either used the same district spatial limits of rāhui, or extended across the whole lagoon. SCP designs identified solutions that were less restrictive for fishers owing to the reduction of protected surface areas and socio-economic costs induced, while achieving the same rāhui's resource targets.

Several findings that could serve to evaluate other case studies in other traditional management contexts are highlighted. They include 1) the benefits that can be brought to traditional designs, 2) a critical view on the quantitative methods used to optimise the indigenous design set in a very local and specific context, and 3) the final practical recommendations.

4.1 Benefits of collaboration between SCP designs and rāhui

The analysis performed here brings key information that should raise the interest of stakeholders and particularly the local fishers, who were questioning the initial rāhui design. Results showed that SCP solutions brought substantial enhancements from the perspective of surface areas, socio-economic costs and levels of ciguatera risk. The different SCP solutions identified reserve designs 6.83 times smaller and 4.75 times less costly, on average (Table 2).

The giant clam stocks included in rāhui varied substantially between the different districts, e.g. by up to a factor of 13 in the case of rāhui 4 in Mahanatoa, *vs* rāhui 5 in Rairua (Table 2). This is explained by an uneven spatial distribution of giant clam stocks throughout the lagoon (Figure 2f). Accordingly, the SCP scenarios 9 and 10 for the whole lagoon displayed solutions that were mainly positioned on one district only, Rairua (Figure 4), which is consistent with the stock distribution.

Working at both district and lagoon scales raises the problem on deciding which scaling option would be best, as both could generate benefits and limitations regarding ecology or social dimensions (Kabbadj et al., 2018; Mills et al., 2010; Pressey and Bottril, 2009). In this study, optimisations at lagoon scale (scenarios 9 and 10) provided the most efficient networks, both smallest spatially and least costly for fishers (Table 2), but they were not equitable among the different districts since mostly Rairua was selected. Conversely, rāhui design and scenarios 1-8 were more balanced and equitable between districts, by design. This result, opposing districts *vs* whole island scenarios, was consistent with findings from previous SCP studies. A study carried out on an island in the Philippines by Weeks et al. (2010) found that while overall efficiency was twice as high and 40% larger at the island scale than considering local tenure boundaries, the latter would likely be more socio-economically viable and equitable. Another SCP study in the Tuamotu Archipelago, in French Polynesia, reached similar conclusions (Kabbadj et al., 2018), this time comparing each individual-island solution to a solution computed for the whole archipelago. Solutions for each island were less efficient overall (0.71 *vs* 0.99 level of equity expressed in relative cost for the island scale and the archipelago scale, respectively), but avoided putting all the conservation costs on the shoulders of one or two islands only. Here, the concept of spreading the cost induced by a reserve among the districts was naturally accounted for in the rāhui conception and SCP design was also able to integrate it too.

4.2 SCP approach: original contributions, nuances and limitations

SCP approaches cannot be recommended for optimization of rāhui or alternative forms of community-based management without taking some precautions.

First, SCP classically sets objectives of biodiversity, most often using some proxies or surrogates, like for instance subsets of species, habitat distribution maps, or environmental variables. Previous SCP studies in Fiji had focused on adaptive co-management of SCP with the communities (Weeks and Jupiter, 2013), or on the integration of socio-economic factors to SCP design considering multiple stakeholders (Gurney et al., 2015), which converges at some point, with this study. However, these plans were always oriented towards biodiversity conservation, targeting the representation of geomorphological habitats. Here, to obey the rāhui's objectives to preserve marine resources, the SCP scenarios were set to reach objectives of resource representation, namely giant clam stocks, which was considered as a proxy for all resources protected by the rāhui considering the importance of this fishery, widespread in Raivavae lagoon. For the present study, a complementary map of the distribution of Raivavae finfish abundance and diversity would be valuable, but was not available. For instance, the ProcFish fishery study (Kronen et al., 2009) was the last comprehensive study that censused fishes *in situ* in the lagoon, yet it did not provide enough data (insufficient station replicates per habitat) to be able to infer a reliable finfish resources map. If a new census is to be undertaken, adequate sampling efforts are advocated to allow for a spatial generalisation and mapping of this resource using habitats (Knudby et al., 2011; Van Wynsberge et al., 2012).

Second, the socio-economic costs were inferred from recent (2019) interviews of the most active fishers in the island (André at al., 2021b), who commonly target both invertebrates and finfish. It was decided for SCP scenarios to account for all fishers and fishing activities when mapping costs and not only those targeting giant clams. The consequences of this decision are beneficial since the socio-economic constraints were even greater in the scenarios, and reinforces our conclusions in terms of identifying cost-effective solutions. The inclusion in the cost function of the ciguatera risk follows the same logic.

Third, here, we emphasised ciguatera as a critical input of the SCP scenarios. In our study, SCP design potentially decreased the risk for fishers to consume ciguatoxic products by providing wider access to fishing grounds with low risk of ciguatera (Figure 5). This strategy is relevant to identify reserves for the islands that are severely impacted, like Raivavae (André et al., 2021b). This can also be useful elsewhere, as the problem is widespread at least in the Indo-Pacific and the Caribbean regions (Chinain et al., 2021). However, the ciguatera data set should be used with precaution. Indeed, ciguatera risk map was not inferred from fish toxicity survey data but from map-based interviews, i.e. it relied mainly on the population's local knowledge and perception of ciguatera risk, which is difficult to assess. However, this knowledge was shown to be quite accurate, as is also the case in other islands in French Polynesia (Chinain et al., 2010; Morin et al., 2016). Further, the map of ciguatera risk we used was generic and not species-specific, but actually, within a given area, it is well established that not all species are susceptible to cause ciguatera poisoning (Chinain et al., 2010; Morin et al., 2016). Thus, nuance is required as zones with 'high ciguatera risk' could still be fished provided only low risk species are targeted, as shown by the PU maps of fishery catch and ciguatera risk, where high values from both actually superimpose in the main pass zone and along the northwest shore.

Precaution must also be taken when putting ciguatera in perspective with conservation. Indeed, implementing reserves/rāhui does not prevent ciguateric micro-algae development, as evidenced by the severe mass-poisoning event in Rapa iti in 2009-2010, which primarily occurred in a periodically harvested rāhui zone (Chinain et al., 2020). Given that ciguatera risk is known to vary in time and space (Bienfang et al., 2008), it raises the point that when an area is under fishing ban for a while, fishers lose or cannot update their knowledge on ciguatera risk.

Fourth, the temporal dimension that was envisaged in the rāhui with rotating closures could not be integrated to the study conducted here. Indeed, at the current level of development, modelling temporal aspects in SCP is challenging as these tools implicitly tackle static conservation planning problems (Possingham et al., 2009). A few SCP studies were able to consider temporal dynamics by conducting iterative SCP exercises and using successively a series of data sets from the same type as input data, such as sea surface temperature time series (Makino et al., 2014) or monthly fishery bycatch data (Grantham et al., 2008). In that perspective, a SCP integrating rotating closures such as rāhui does, would ideally require additional consecutive data sets.

To go further, any data driven planning (not only SCP) would ideally require to model several cycles of opening/closing to fishery, to assess the full impact and value of such a rotating closure, as carried out for sea cucumbers in Australia (Plagányi et al., 2015), or abalones in New Zealand (Gnanalingam et al., 2021). In other places, some key biological and ecological parameters of invertebrate species targeted by artisanal fisheries have been specifically studied to inform management strategies (Cumplido et al., 2022; Martino et al., 2021). In the case of Raivavae, conducting this step would require knowledge on the giant clam local population dynamic factors (growth, natural mortality, fertility, reproduction and recruitment success, etc., which are currently not available) to run a realistic model (Van Wynsberge et al., 2017 and as attempted for other locations by Van Wynsberge et al., 2013). Indeed, other islands where giant clams were monitored (i.e. Raivavae and Tubuai Island), showed a variety of trajectories of the stock status from field studies (Van Wynsgerge et al., 2013) that models had missed because they assumed mortality rate to be uniform throughout the lagoon. It is then recommended to monitor local population dynamic factors not only regularly (twice a year) but also spatially, by habitat type, since the different environmental conditions may shape different demographic processes. Moreover, additional important factors would be necessary, such as the dynamic of the fishing effort, its spatial reallocation, catch levels and consequences on the stocks. For instance, Halpern et al. (2004) demonstrated that protecting 50% of the surface area of a site, which is similar to this rāhui design, leads to a theoretical fishing pressure twice as large in the open area, but it would allow for a three-fold compensation factor in resource production and export production from the reserve. This advocates for regular data collection to monitor the changes.

We acknowledge that, despite our attempt to incorporate as much as possible the rāhui principles, the temporal dimension is missing from the present assessment, due to technical incapacity and lack of the necessary information to make robust simulations on the stock evolution. Nevertheless, the initial phase is critical and brings useful information, to optimise the lagoon exploitation and conservation. This first step of implementation is an important starting point to set the course of the trajectory of the reserve performances. More generally, this rāhui temporality was not questioned in this study, and the local management committee seemed to have set the 3-year period also rather arbitrarily. Periodically harvested closures and their ability to maintain sustainable fisheries are questioned in the literature and some complementary measures that could apply here are advocated, such as longer closure periods combined with full protection of vulnerable species (Carvalho et al., 2019; Goetze et al., 2016; 2018; Jupiter et al., 2012). Some of these references (Carvalho et al., 2019; Goetze et al., 2016; 2018) are based on models but we also emphasize they are lacking temporal validation data. The temporal aspect is at the core of the validation of rotational closure schemes, but predicting its effect is difficult. Only time, and adequate surveys, will locally provide the data to estimate the rāhui effects on the long term.

4.3 Positive perspectives from collaboration of traditional management and SCP

Overall, other aspects that interplay in a rāhui building process were obviously not captured by SCP, and reinforce the value of mixing both approaches. For a population, the interest but also the challenge of building and managing contemporary rāhui projects also lie in multifaceted social dimensions such as federating a community (Govan, 2009), or experimenting multi-actors hybrid governance, based on cultural roots and both local traditional management and formal administration, such as for Teahupo'o rāhui (Fabre et al., 2022). Beyond fisheries management, these local, bottom-up initiatives often help strengthen social networks, raise awareness on the environment and ecological considerations through resource stewardship, and the feeling of responsibility for sustaining resources for next generations.

Conservation system is sometimes conducted in parallel to the local communities and does not integrate the stakeholders needs (Pilbeam et al., 2019), which can be different from strict biodiversity conservation *per se* (Gurney et al. 2021). Moreover, the stakeholder's needs and conception of the closure can be different from one locality to another, even when claimed under the same rāhui appellation for instance, as in French Polynesia where rāhui schemes are diverse (Fabre et al., 2021). Here, we advocate that SCP can precisely constitute a step to offer important points for traditional fisheries management such as rāhui and also other forms, including *taboos* and *buls*. In such contexts where the stakeholders are open to discussion and in demand for information and optimisation, essentially, SCP can be tailored to each case to adapt to the local vision and support decision-making by informing the deliberations. This type of case study with cooperation of knowledge sources and designs can greatly improve planning process, both for the relevance of SCP solutions to local needs, and for the incidental improvement of local stakeholder's ecological knowledge and commitment in decision-making processes, such as underlined in Fijian case-studies by (Mills et al., 2012; Wendt et al., 2016).

Additional positive outcomes can result from collaborations between approaches, iterative discussions and knowledge sharing among stakeholders and with scientists. Positive outcomes include incidental increased sensitivity of the population to ecological processes, knowledge on species resource life traits, and empowerment regarding questions of management such as setting clear objectives and constraints, as witnessed by Trouillet et al. (2019). Ensuring that stakeholders are up to date with information on basic ecology, status of fisheries and management tools, are among the objectives of the Pacific framework for Action on scaling up community-based fisheries management (SPC, 2021). Further, this type of co-design situation can naturally lead to some form of co-management of local fisheries, which are largely recommended worldwide (Cohen et al., 2021; Lehodey et al., 2018; O'Leary et al., 2020; Pita et al., 2016). Building on the flexibility of Pacific islanders to a changing environment (McMillen et al., 2014; Nunn et al., 2017), on the ground local enhancement and regular *in situ* monitoring can help commit to adaptive co-management and allow reviewing the design periodically, to adjust to new challenges (Ban et al., 2011; Weeks and Jupiter, 2013) and mitigate impacts from global origin.

4.4 Practical recommendations

Despite room for improvements, a number of pragmatic advices emerge from this study to strengthen traditional management, which can be generalised to other contexts with a reef fishery component. We suggest to:

1. Consider a SCP step to explore how to improve traditional designs, with local communities support, by decreasing (or increasing, depending on the case) the spatial extent of closures and the opportunity costs to fishers in terms of fishing ground access;
2. Integrate exposure to ciguatera risks if relevant, collect data on ciguatera poisoning cases continuously and systematically, including their spatial occurrences, as ciguatera risk varies in time and space. A tool allowing the on-line report of poisoning cases is already in place in French Polynesia (https://ciguawatch.ilm.pf), but could be strengthened if the population perceive direct interest in sharing this information for their lagoon management and design of the next phase of rāhui rotation. An additional precious source of reliable information could be toxicity tests conducted on randomly-caught fish, but these are very costly;
3. Monitor the marine resources on a regular basis (as in Gnanalingam et al., 2021) to assess its status and to allow for potential adaptive planning. The Raivavae population expressed interest in assessing the impacts of rāhui implementation on the stocks/abundance of resources on a regular basis, so as to understand its impact. This encouraging intention will benefit from technical support by local authorities for impact monitoring following the reserve creation and the reallocation of fishing grounds (Smallhorn-West et al., 2020b). In return, a community-based participatory approach could help produce valuable spatialized and quantified long-term datasets for further management and adaptive conservation spatial planning. The acquired data could help implementing enhanced management measures to keep improving the rāhui and SCP designs. Acquired in a participatory approach, such data could also be used to implement non-spatial complementary measures, such as quotas or size limits, in this co-management context.

5. Conclusion

In the present study we demonstrated the interest of SCP contribution to optimise traditional reserve designs for sustained fisheries, as occurring in French Polynesia and further in the Pacific Ocean, as well as globally in many indigenous communities from the poles to the equator. The Raivavae Island and French Polynesian rāhui case study provides one example of possible collaboration between traditional management practices and scientific, data-driven, approaches. Considering the benefits of social cohesion brought by a rāhui, SCP prioritisation and planning should be seen, as usual, as one useful step in a suite of design and management process towards implementation in coordination with indigenous communities (Game et al., 2011; Watson et al. 2021; Wendt et al. 2016). In our case study, the benefits are unequivocal in terms of resource representation *versus* cost ratio. Consequently, we strongly recommend for the benefits of all, to be cautious when putting forward traditional practices without recommending in the same time possible pathways for objective diagnostics and optimisation, including through the collection of relevant data when it is imperative to use a sound, accurate and updated baseline, for instance in terms of stock levels. In the same time, it is necessary to remain aware of the limitations of a quantitative data-driven approach.

Basically, the work performed here prior to the re-establishment of traditional practices can be recommended in any locations where local indigenous traditions remain strong. Despite the broad potential, geographically speaking, of this simple advice, the assessment, test and implementation phases of similar work are necessarily very local in scope. Besides, while a suite of SCP spatial tools were applied in this case study, alternative optimisation pathways exist if available data or management traditions are not spatially explicit and area-based. The collaboration between the approaches is a sound way to reinforce the interest put into revived traditional approaches.

Authors' contributions / Credit Roles

Laure Vaitiare André: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing - original draft, Writing - review & editing. **Simon Van Wynsberge**: Conceptualization, Methodology, Validation, Writing - review & editing. **Mireille Chinain**: Funding acquisition, Investigation, Project administration, Resources, Writing - review & editing. **Serge Andréfouët**: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing - review & editing.

Data availability

Data are available on request.

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Competing interest statement

The Authors declare no competing interests

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Supplementary material S1

Table S1. Surface areas (km²) under the different levels of risk in each rāhui (complementary information to Figure 5.a).

	Level of risk			
	1	**2**	**3**	**4**
Rahui 1	4.26	1.95	0.50	0.00
Rahui 2	2.35	0.96	3.05	0.05
Rahui 3	0.02	0.00	2.33	1.16
Rahui 4	0.00	0.00	0.32	2.88
Rahui 5	3.11	0.63	1.99	0.86
Rahui 6	3.84	1.09	1.57	0.00
Rahui 7	3.84	1.09	1.57	0.00
Rahui 8	4.74	0.75	1.18	0.00