

Study of the coastal reef fishery pressure in a South Pacific Island (Bora-Bora, French Polynesia)

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Abstract – In the context of the general overexploitation of South Pacific reef fisheries, there is a global push to precisely define fishery parameters such as fishing effort, annual landings, and exploitation levels. In Bora-Bora, several surveys were performed to define the fishing grounds and the fishing effort of the reef fishery for the first time. Maps of the fishing grounds under different fishing pressures were created for the Bora-Bora reef fishery. The average fishing effort throughout the lagoon was 40 trips week⁻¹ km⁻². Annual landings were estimated following two different methods: school participatory surveys and landing based on the catch per unit effort. These estimations were used to determine that the maximum sustainable yield of the island's fisheries was 6.5 tons km⁻² year⁻¹, the reported annual yield in 2022 was 5.35 tons km⁻² year⁻¹, under the estimated maximum sustainable yield. The level of exploitation of the fisheries was also estimated based on the catch size composition of the ten most fished species. This revealed that fishing is responsible for more than 50% of fish mortality in six of the ten studied species, and that catch length could be increased to optimize both catches and biomass. Overall, the Bora-Bora reef fishery may be experiencing growth overfishing (i.e., the catching of fish that are too small to maximise biological sustainability and economical yield), which can endanger stock recruitment in the future if no actions are taken.

Keywords: Reef fishery / fishing effort / exploitation rate / length-based Bayesian biomass indicator / landing / maximum sustainable yield

1 Introduction

The concept of reef fisheries refers to all activities related to the exploitation of natural biological resources within a lagoon or on the outer reef slopes, down to depths of about 100 m (Morais and Bellwood, 2019). Coral reefs are among the most biodiverse ecosystems on the planet, home to some 3 million species and 25% of all marine life (Spalding et al., 2001). They also provide direct or indirect benefits to several hundred million people worldwide: coastal protection, building materials, food and income from fishing or tourism (Moberg and Folke, 1999). Unfortunately, throughout the world, the coral reefs of inhabited islands are the stage of a widespread and intensifying

exploitation of fish resources. For example, across 49 island countries, half of the reef fisheries were overexploited, with landings exceeding the maximum sustainable yield (Newton et al., 2007). Ault et al. (2019) studied the impact of fishing on the spawning potential of six commercial species in Florida and showed that 5 of the 6 studied species were overexploited. Similarly, in the South China Sea, 2 of 6 exploited species were overexploited, and 2 other species were fully exploited (Zhang et al., 2021). Overfishing often has an impact on the average trophic level of catches, the size structure of the food web, and on food availability for local inhabitants (Jackson et al., 2001). Building on these few examples, a better characterisation of the pressures exerted by fisheries on organisms living on coral reefs is necessary to estimate of the sustainability of local practices and improve the perception and knowledge of the pressure among stakeholders.

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To better understand fisheries in the frame of a socio-ecological ecosystem, the area exploited by fisheries must be described, e.g., based on field surveys to delimitate fishing areas. Furthermore, fishery pressure must be evaluated, for instance by combining a characterisation of the fishing effort with models of fish population dynamics (Gascuel, 1995). The required parameters can be difficult to assess, but the outputs can closely describe the actual pressure exerted on a given stock (Gascuel, 1995). For instance, to evaluate the fishing pressure on a fishery in the Caribbean Sea, Munro et al. (1973) calculated the nominal fishing effort with a determined unit, the number of canoes per km², combined with the average catch per canoe. However, it is often difficult to count the number of fishermen to obtain this nominal fishing effort: many do not officially declare their activity and fishing schedules can vary (Taquet, 1998). To bypass these issues, landings, which are key information to determine fishing pressure, can be estimated using participatory surveys and direct observations (Leenhardt et al., 2016). In addition, the length frequency distribution of catches can be examined (Pons et al., 2020).

In data-poor fisheries, such as many South Pacific Islands, other analysis tools have been developed to estimate fishing pressure, notably the Length Bayesian Biomass method (Froese et al., 2018). The length frequency of catches allows to obtain fitted size and age compositions using Bayesian stock assessment models. This type of analysis showed for instance that 60% of the dominantly fished species were overexploited in the Nansha islands, South China Sea (Zhang et al., 2021). A particularity of small reef fisheries is the variety in fishing gears, from fishing rods to spearguns, nets, and traps (Dalzell and Adams, 1997). Depending on the season, different types of gear allow to target specific species, which can lead to irregular landing volumes (Reynal et al., 1998). In South Pacific Islands, there is often no robust record of landings. Thus, estimating total landings and distinguishing commercial fishing from recreation or subsistence through sampling surveys are difficult (Leenhardt et al., 2016). In French Polynesia, the most recent total landing estimate of the reef fisheries was 2350 tons per year, mainly consisting of subsistence fishing (Gillet, 2016).

Overall, the fish stocks on South Pacific reefs are of crucial importance for local food security and commercial activities (Leenhardt et al., 2016). However, overfishing of the stocks has been reported in several islands by local populations (McClenachan et al., 2016). Therefore, the present study seeks firstly to define the location of the fishing grounds and the pressure exerted by fishing activities on the reefs of the South Pacific Island of Bora-Bora. Secondly, the study aims to quantify the fishing pressure of the local reef fishermen on the marine resources of the island, and to determine if these resources are being overexploited, based on multiple exploitation indicators. The use of varied exploitation indicators with different sources of data allowed to better and robustly constrain the current status of the reef fisheries of Bora-Bora.

2 Materials and methods

2.1 Study area

Bora-Bora is a 38 km² island in French Polynesia (16°29'S, 151°44'W). The lagoon, which is connected to the open ocean through a single pass on the west side of the island, has a size of

69 km². Bora-Bora is the stage of international luxury tourism, with around 100 000 tourists visiting the island every year (IEOM, 2017). Along with the development of tourism over the past decades, the island has seen its population increase from 3819 in 1990 to 10 658 in 2022 (ISPF 2022). Preliminary studies about reef fisheries have been conducted on Bora-Bora since 2020. Lecchini (2022) qualitatively determined the main types of fishing gear and the most frequently fished species around the island. Sociological studies were also performed to determine the dependence of the population on fish sales and consumption. Most of the interviewed islanders declared to have noticed changes in fish stocks over the past few years (Lecchini, 2022). Bambridge (2020) estimated that Bora-Bora has 83 professional fishermen that go fishing more than three times per week. The island also has 1224 non-for-profit fishermen, who fish one to three times per week. We performed a survey of the number of private boat gates around the island in 2022 through visual counts and observed 711 gates destined to personal use such as leisure activities and fishing. Note that a sizeable number of fishermen do not own a boat. We made the assumption that the number of fishermen on the island remained stable from 2020 (at the time of the study by Bambridge) to our study in 2022.

2.2 Spatialisation of reef fisheries at Bora-Bora

Interviews were conducted with 100 reef fishermen. Their homesteads were evenly distributed throughout Bora-Bora in accordance with housing density). The questions concerned the location of their fishing grounds, the type of gear used, the fishing period, and the frequency of outings. In addition, fourteen-year-old students from local schools that lived in households with fishermen, conducted the same survey within their households. Overall, 174 fishermen were interviewed (i.e., 13% of the total estimated number of fishermen). The fishing locations and number of visits per week during the day and at night were mapped based on the declarations of the interviewees using QGIS v3.22 to visualize fishing hotspots. The fishermen were separated into two categories: non-for-profit fishermen that fish less than three times per week vs. for-profit fishermen that fish three or more times a week (Leenhardt et al., 2016).

2.3 Estimation of the annual landing 1 based on the island-wide consumption

Within 178 random households, across two different weeks in January and February 2023, children from the local schools were taught to record the species and measure the total length of the fish that they consume over the course of a week. The total weight of weekly consumption was then determined using Le Cren's logarithmic transformed length-weight relationship (Le Cren, 1951). Furthermore, local hotels and restaurants provided the quantity of fish that they use monthly (only reporting about fish sourced in Bora-Bora). By extrapolating the household results to the 3500 households of the island, and based on the assumption that the local consumption of fish remains constant throughout the year, the island-wide annual consumption was calculated using restaurant, hotel, and household data. This provided an estimation of the annual landings based on consumption surveys.

2.4 Estimation of the annual landing 2 based on the fishing effort

The catch per unit effort (CPUE – indicator of the fish abundance) corresponds to the amount of fish caught during one trip per category of fisherman (for-profit and semi-professional) and per type of gear. The CPUE was estimated based on direct observations performed by the authors in December 2022 and January 2023. Twelve fishermen who fish with different gears in different places were also surveyed. For one trip, the total weight of the fish caught with each type of gear and by each category of fisherman was estimated by measuring the total length of each fish based on photographs (with Imagemeter 3.6.2) and by the logarithmic transformation of the length-weight relationship of [Le Cren \(1951\)](#). The fork length of each fish was also measured. The annual landing was estimated with the CPUE of each type of gear and category of fisherman, the interview results about the type and location of usage of each gear, and the estimated number of fishermen on Bora-Bora from [Bambridge \(2020\)](#). This fisherman-based annual landing was compared with the one based on the consumption surveys.

2.5 Catch size collection from roadside sales

The catch sold along the road was documented by taking pictures of “tui” (fish hanging along a rope) from October to December 2022 ([Fig. 1](#)). In French Polynesia, fishermen usually sell their catch of the day directly on the roadside, in front of their house, or near their boat, using tui (Minier et al., 2022). All pictures of tui were taken at a distance of two meters. The fish were identified at the species-level whenever possible, and the fork length of each fish was measured with ImageMeter v3.6.2.

2.6 Maximum sustainable yield estimation

The stock under study includes all commercial species in the Bora-Bora reef fishery. This assessment was based on underwater visual surveys performed in 2020 and 2022 and previously published ([Lecchini, 2022](#)). During these counts, the weight of each surveyed fish was estimated based on its species and size, using the length-weight relation developed by [Le Cren \(1951\)](#). Based on the assumption that the body length increases in accordance with the Von Bertalanffy equation (1938), the total commercial biomass per km² in the Bora-Bora lagoon was calculated. The total biomass mortality was estimated with a survival equation (Eq. (1)) under the assumption that the stock is in equilibrium (Gascuel, 2022).

$$Z_t = \ln\left(\frac{B_{t+1}}{B_t}\right) \quad (1)$$

B_t : Commercial species total biomass at the instant t (tons km⁻²) estimated from the underwater visual surveys.

Z_t : Total mortality at date t (year⁻¹) of the studied stock.

To calculate total fishing mortality (Eq. (2)), the annual yield was calculated based on the annual landings from the consumption-based survey and from the fisherman-based survey (Munro, 1985).



Fig. 1. Traditional road-side fish stall in French Polynesia, consisting of five « tui » (fish hanging along a rope). The white scale on the left has incrementations (black lines) of 5 cm. In total, the fork length of 1991 fish caught in the lagoon was calculated based on 2022 tui roadside surveys, fish caught during twelve fishing outings to follow different fishermen, as well as data from [Lecchini \(2021\)](#).

$$F_s = \frac{Y}{B} \quad (2)$$

F_s : Fishing mortality of the commercial fish stock (year⁻¹)

Y : Annual yield (tons km⁻²)

B : Mean total biomass of commercial fish (tons/km²) estimated from the underwater visual surveys ([Lecchini, 2022](#)).

The maximum sustainable yield (Y_{MSY}) across all species was then calculated with the protocol from [Leenhardt et al. \(2016\)](#) based on the estimated total landing and fishing biomass mortality (Eq. (3)).

$$Y_{MSY} = X(Y + M_s \cdot B) \quad (3)$$

Y_{MSY} : Maximal sustainable yield Annual Catch (tons km⁻² year⁻¹)

X : Corrective factor (0.3–Galzin, 1985)

M_s : Natural mortality of the stock deduced with Z_t and F_s (Eq. (6)) (year^{-1})

Y : Annual yield (tons. km^2) from the school and the CPUE surveys

B : Mean total biomass of commercial fish (tons km^{-2}) (Lecchini, 2022).

2.7 Exploitation rates determination

Fishing effort varies depending on the fish species. The fishing mortality index of the 10 most caught species (*Myripristis amaena*, *Scarus psittacus*, *Naso lituratus*, *Naso unicornis*, *Lutjanus gibbus*, *Chlorurus microrhinos*, *Chlorurus frontalis*, *Acanthurus xanthopterus*, *Acanthurus nigricauda*, *Monotaxis grandoculis*) was calculated based on the catch size database to obtain the exploitation ratio (defined as the proportion of the exploited population). This is an indicator of stock health (Fatihah et al., 2021). For this assessment, the catch length composition, growth coefficient, and asymptotic length of each studied species were used. The total mortality per species was calculated based on a formula from Beverton and Holt (1956) (Eq. (4)). This approach assumes steady-state conditions with infinite exploitable lifespans (Hicks and McClanahan, 2012). The natural mortality was assessed based on a formula from Charnov et al. (2013) (Eq. (5)) and subtracted from the total mortality to estimate fishing mortality F (Eq. (6)) and deduce the exploitation rate (Eq. (7)). This exploitation rate was compared to the optimum exploitation rate (E_{opt}) based on the assumption that E_{opt} is equal to 0.5—i.e., assuming that the sustainable yield is reached when $F=M$. If the exploitation rate E is superior to E_{opt} , the stock is considered as overfished (Hicks and McClanahan, 2012).

$$Z = K \frac{L_{\infty} - L_{av}}{L_{\infty} - L'} \quad (4)$$

Z : Total mortality of a specific species (year^{-1})

K : Growth coefficient (year^{-1})

L_{∞} : Asymptotic length of the studied species (cm)

L_{av} : Average sampling length (cm)

L' : Minimal catch size of the studied species (cm)

$$M = \left(\frac{L_{av}}{L_{\infty}} \right)^{-1.5} \cdot K \quad (5)$$

M : Natural mortality of a specific species (year^{-1})

L_{av} : Average sampling length (cm)

L_{∞} : Asymptotic length of the studied species (cm)

$$Z = F + M \quad (6)$$

F : Fishing mortality (year^{-1})

$$E = \frac{F}{Z} \quad (7)$$

Z : Total mortality for a given population (year^{-1})

E : Exploitation rate

The percentage of individuals caught below their maturity size at 50% was calculated for the 10 most caught species

(Appendices 1 and 2) to estimate the impact of fishing on the spawning biomass and on recruitment.

2.8 Length Bayesian Biomass assessment

Using the catch size database containing the data of the “tui” and the fisherman-based survey (Appendix 3), the species length frequency distribution of the four species for which more than 100 fish were sampled (893 fish in total, of the species *M. amaena*, *C. frontalis*, *C. microrhinos*, *A. xanthopterus*) was analysed with the R package Length Bayesian Biomass (LBB) (version 1.6.1). This package is based on strong assumptions such as constant recruitment and a cohort in equilibrium with a constant M/K ratio of 1.5 for each species (Froese et al., 2018). Using the field-assessed selectivity of the gear by fishermen with the first catch length (L_c) (the length at which the gear captures 50% of the individuals), and biological parameters of each species, the natural mortality rate (M) relative to somatic growth rate (M/K) and fishing mortality rate (F) relative to somatic growth rate (F/K) were calculated with the LBB package. The approximate optimal catch length ($L_{c, \text{opt}}$) (i.e., the catch length at which the stock is optimized biologically and economically) was estimated for spear gun, which was the most common type of gear in Bora-Bora. Lastly, the ratio between the fishing mortality and the natural mortality (F/M), current vs. unfished biomass (B/B_0), and current vs. maximum sustainable yield biomass (B/B_{MSY} , with $B/B_{\text{MSY}} > 1.2$: non-fully exploited fishery; 0.9–1.2: fully exploited, <0.9: overexploited – Amorim et al., 2019) were calculated. These final proxies were obtained under the assumption that the natural mortality is equal to the fishing mortality ($F=M$).

3 Results

3.1 Fisheries spatialisation

In total, 27 professional and 147 non-for-profit fishermen were interviewed (respectively 32% and 12% of the fishermen from each category on Bora-Bora – Bambridge, 2020). Among all interviewed fishermen, 39% only fished during the day, 24% only at night, and 37% did both. The average fishing effort on the reefs of Bora-Bora was estimated to be 40.3 fishing trips per week and per km^2 , with a daytime fishing hotspot in the Teavanui pass, which is the only pass of the island linking the lagoon with the open ocean (430 trips $\text{week}^{-1} \text{ km}^{-2}$; Fig. 2). The fishing effort was higher on the west side of the island in the vicinity of the more densely populated villages. Four main fishing grounds of a total area of less than 4 km^2 (6% of the lagoon area) were identified, where over 55% of the total fishing pressure was exerted (Fig. 3).

3.2 Landings and maximum sustainable yield estimation

The landings across the reefs of Bora-Bora were estimated to be 327 ± 36 tons per year ($4.8 \text{ tons km}^{-2} \text{ year}^{-1}$) based on the consumption-based survey (Tab. 1). Using a different approach (fisherman-based survey), the landings were estimated to be 410.5 tons ($5.9 \text{ tons km}^{-2} \text{ year}^{-1}$) based on

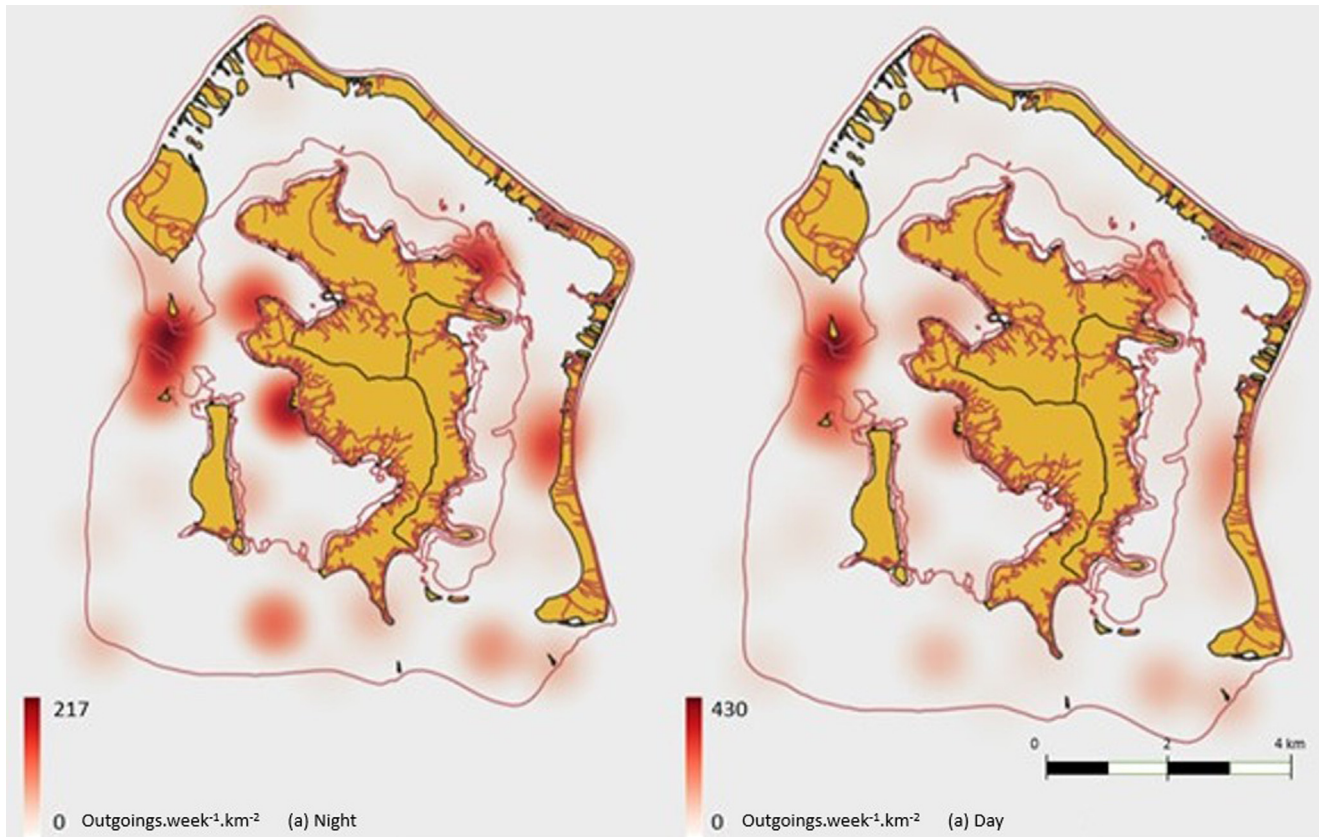


Fig. 2. Heatmap of the fishing effort distribution during the (a) night and (b) day Bora-Bora.

an average CPUE of 2.7 kg trip^{-1} (Tab. 2). Combining both sources of data, the analyses below used an average landing of 369.7 ± 40.7 tons per year, which corresponds to an average yield of $5.3 \text{ tons km}^{-2} \text{ year}^{-1}$ across the Bora-Bora reef. It was also estimated that 90.8 tons of commercial fish are landed each year within the most visited fishing ground, the 1 km^2 Teavanui pass. This represents 24.5% of the total annual landing on Bora-Bora.

On Bora-Bora, the biomass of commercial fish was estimated to be $40\text{--}83 \text{ tons km}^{-2}$ based on visual surveys performed in 2020 and 2022 respectively. Using the average of these two estimations ($61.5 \text{ tons km}^{-2}$), the average total mortality rate for all commercial species was calculated to be 0.37 per year (Eq. (1)), and the average fishing mortality was predicted to be 0.09 per year (Eq. (2)). Thus, the Maximum Sustainable Yield for all commercial species combined was estimated to be $6.5 \text{ tons km}^{-2} \text{ year}^{-1}$ (Eq. (3), Tab. 3).

3.3 Exploitation rate process

The exploitation rate of 6 of the 10 most fished commercial species (all assessed species apart from Acanthuridae) exceeded 0.5 (Eq. (7)), which indicates an overexploitation of their stocks (Tab. 4). In addition, the percentage of fish caught below the size at maturity ($L_{m(50)}$) ranged from 0 to 67%, with 6 of the 10 species above 45% (Appendices 1 and 2).

3.4 Length based Bayesian assessment

Over 100 individuals were recorded during the fisherman-based surveys as well as the roadside surveys: *Myripristis amaena*, *Chlorurus frontalis*, *Chlorurus microrhinos*, and *Acanthurus xanopterus*. All four species had current vs. maximum sustainable yield biomass ratios (B/B_{MSY}) ranging from 1.6 to 1.9 (Tab. 5). Such values correspond to a not-fully exploited status (Amorim et al., 2019). However, the most fished length class of these four species was below the optimal length at which maximal biomass would be achieved ($L_c/L_{c(\text{opt})}$) between 0.74 and 1; Tab. 5). There were only a few large individuals among the catches. This LBB assessment indicates that the fishing strategy could be optimised to increase sustainability both from an economic and ecological point of view.

4 Discussion

Coral reef fisheries are of great importance to the inhabitants of coastal tropical regions, providing around half of the protein they consume (Teh et al., 2013). But the population's dependence on this activity may come up against the problem of resource depletion, as the population continues to grow (nowadays, the population of French Polynesia is growing by 0.7% per year) (Teh et al., 2015). Unsustainable

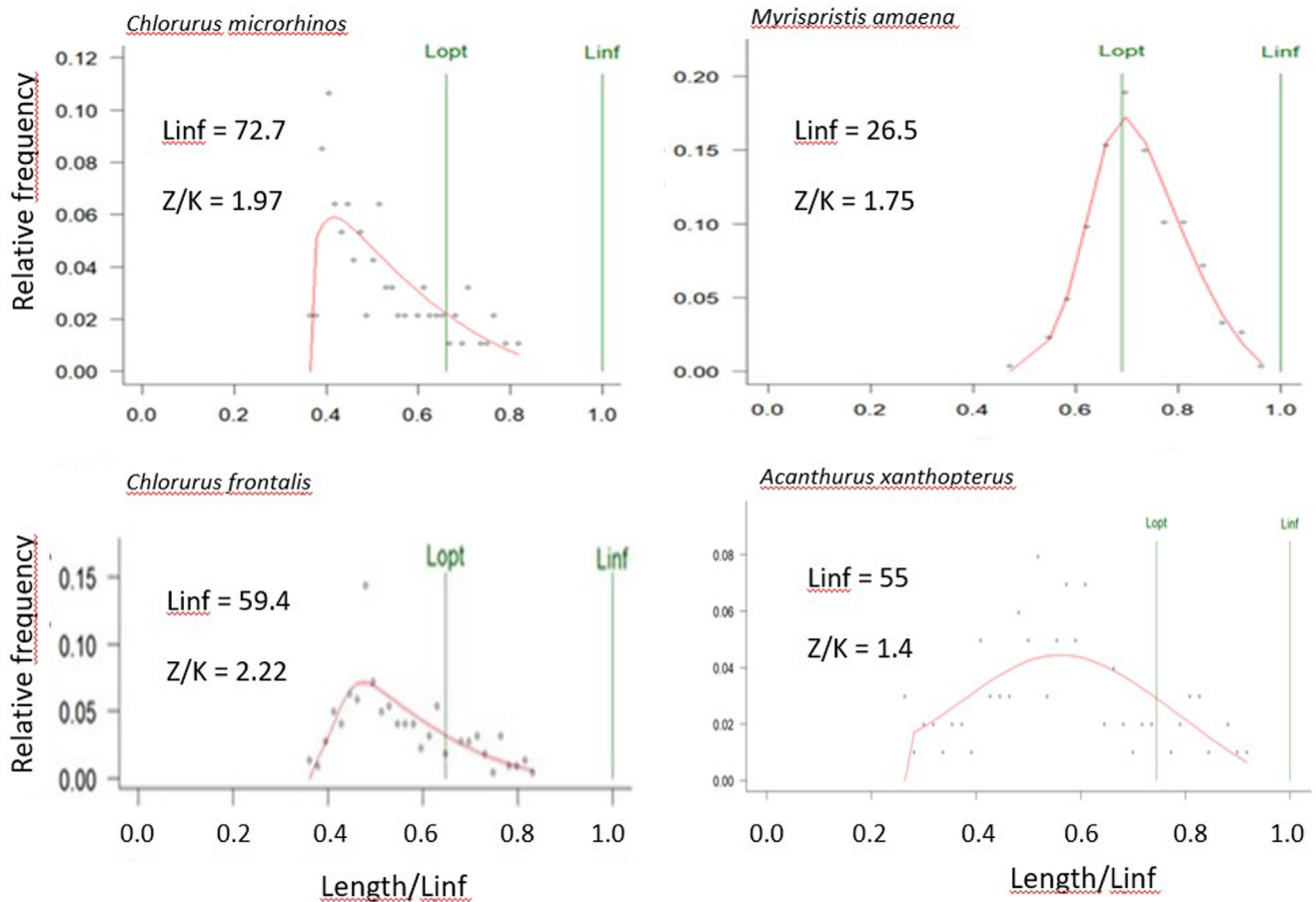


Fig. 3. Length Based Bayesian assessment for the four most commonly caught species ((a) *Chlorurus microrhinos*, (b) *Chlorurus frontalis*, (c) *Myripristis amaena*, and (d) *Acanthurus xanthopterus*). L_{opt} is the catch size that maximizes both catches and biomass, L_{inf} is the species-specific asymptotic length, and L_c is the length at which 50% of the size class is caught. Note the different scales for the y axes of each graph.

Table 1. Number of households involved in the schoolchildren-led fish consumption survey on Bora-Bora in January and February 2023.

	Week 1	Week 2
Number of questioned households	55	123
Total number of households in Bora-Bora	3045	3045
Weekly consumption for the sample (kg)	125	220
Weekly consumption for the whole island (kg)	6920	5446
Annual consumption for hotels and restaurant (tons)	5.4	5.4
Mean annual landing estimation (tons)	365.26	288.59

fishing has been identified as the most widespread local threat to coral reefs. Over 55% of the world's reefs are threatened by overfishing and/or destructive fishing (Burket et al., 2011). As suggested by Zamborain-Mason et al. (2023), sustainably managing fisheries requires regular and reliable evaluation of fish stock status, but we lack long-term research and monitoring capacity in many of the world's reef fisheries, which prevents from having reference points against which stocks can be estimated. Our study is the first assessment of exploitation indicators for the Bora-Bora reef fishery, and one of the only reports for islands across French Polynesia and the

South Pacific (Lenhardt et al., 2016). The used methodology can be readily implemented across other islands with similar socioeconomical contexts in the region to improve resource management in without the need for an extensive timeseries, which is often lacking in remote regions. It is important to note that this study makes the assumption that fishing and consumption rates remain stable through time (by combining sparse data from multiple years between 2020 and 2022). This may not be as accurate as a multi-year exhaustive dataset (Roos et al., 2015) but is the most efficient way to assess fisheries status in a data-poor context.

Table 2. Number of fishermen using rod/nylon thread, fish traps, nets, or guns among the semi-professional and non-for-profit fishermen of Bora-Bora in 2022, estimated total number of fishermen across the island (extrapolation based on Bambridge, 2020), estimated Catch Per Unit Effort (CPUE), number of fishing trips, and annual landing per type of gear and category of fisherman.

Category Gear	Semi-professional				Non-for-profit		
	Rod/nylon thread	Fish trap	Net	Spear gun	Rod/nylon thread	Net	Spear gun
Number of interviewed fishermen using each gear type	12	2	7	8	63	15	64
Estimated total number of fishermen using each gear type (extrapolation from Bambridge, 2020 and 2022 surveys)	34	6	20	23	538	134	551
Estimated CPUE based on each gear type (kg/outgoing to sea)	13.6	12	13.3	14.6	1.45	3.8	1.98
Estimated total trips at sea per year	6364	1123	3744	4305	44 761	11 148	45 843
Estimated annual landing (tons)	86.5	13.4	49.8	62.8	64.9	42.3	90.8

Table 3. Estimation of the maximum sustainable yield for Bora-Bora's reef fisheries following the Leenhardt's protocol. Visual surveys allowed us to estimate at 39.51 tons/km⁻² in 2020 and 83.25 tons/km² in 2022 yielding an average value of 58.8 tons/km² (B), assuming that the fish population evolution follows a Von Bertalanffy Growth.

Corrective factor X	0.3
B	58.7
Zt (1)	0.37
$F_s = Y/B$ (2)	0.09 ± 0.009
$M_s = Z - F$ (6)	0.28 ± 0.009
Y_{Bora} (t km ⁻² an ⁻¹)	5.3 ± 0.54
$Y_{\text{MSY}} (= X (Y + M \times B))$ (3)	6.5 ± 0.3

Our study highlighted that the fishing pressure on the reefs of Bora-Bora is not homogeneous. This may be partially linked to uneven distributions of fish across the reefs. The only pass of the island is the location of high densities of fish (notably with reproductive aggregations). It is the most visited fishing ground of the island, with over 90 tons of fish (or a quarter of all landings across the island's reefs) caught in an area of less than 1 km² annually. Fishing pressure on the reefs is also strongly related to ease of access; apart from the pass, the most intensely visited fishing grounds are close to densely populated areas. Note that the map of the fishing grounds of Bora-Bora is based on interviews – there may be inaccuracies in the reporting of the fishing location and trip frequency by the fishermen. Fishermen may be reluctant to provide this information due to their competition for limited resources (Van Campenhoudt et al., 2017). In addition, the different fishing grounds are subjected to variables such as the weather, season, and lunar cycles, leading to variability in usage that may not be captured through our interviews.

Across the island, the average fishing effort was 40.3 trips week⁻¹ km⁻². Based on direct observations by joining fishermen on their boats, the gear-specific CPUE values calculated for the fisheries of Bora-Bora were similar to those of a Great Barrier Reef fishery (Frisch et al., 2008), with

1.98 kg trip⁻¹ for spearfishers and 1.45 kg trip⁻¹ for line-fishers on Bora-Bora and 1.95 kg trip⁻¹ and 1.27 kg trip⁻¹ in Australia. The annual yields per km² calculated based on the fishermen CPUE observations and schoolchildren surveys among their families (5.9 and 4.8 ± 0.5 tons km⁻² year⁻¹) on Bora-Bora were similar in magnitude, and reconciled the use of both types of approaches (catch and consumption monitoring) on a South Pacific island. On Moorea, a nearby island with a similar sized-lagoon and slightly larger population, various surveys conducted since the end of the 1980s had led to yield estimations of approximately 1–28 tons km⁻² year⁻¹ depending on the methodology used, with underestimates linked to the lack of information from off-market sales, and overestimates due to issues in the lack of standardised reporting of consumption by households (Leenhardt et al., 2016). At a larger scale, Newton et al. (2007) reported, across 49 island nations with coral reefs, an annual yield of coral reef fisheries of 0.2–40 tons km⁻² year⁻¹ with a median of 3 tons km⁻² year⁻¹, similar to our results on Bora-Bora. Lastly, the Maximum Sustainable Yield was of 6.5 tons km⁻² year⁻¹ across the studied commercial species, which is of the same order of magnitude as the average of 5 tons km⁻² year⁻¹ from coral reef island nations (Newton et al., 2007) (Tab. 6).

Our Bora-Bora study found an average annual landing of around 370 tons of fish. Thus, each year, excluding hotel and restaurant consumption (5.4 tons), each of the 10 658 inhabitants of Bora-Bora has access to 34 kg of reef fish on average. This result can be compared to the average annual consumption of large and small pelagic and reef fish per capita in French Polynesia, which is estimated to be 70 kg (Gillet, 2016). A precautionary 10% removal of exploitable biomass has been proposed to promote long-term exploitation of stocks (Lauck et al., 1998). However, in Fiji reef fisheries, an annual removal of 5% of the existing biomass can cause significant changes in reef ecosystems (Jennings and Polunin, 1996). On Bora-Bora, the estimated commercial biomass is 58.8 tons km⁻² and the annual yield is estimated to be 5.3 tons km⁻² year⁻¹: the annual removal represents 9% of the existing biomass. From this perspective, it places the reef fisheries of Bora-Bora at the upper limit of landings hypothesised to allow for sustained exploitation when all commercial fish species are considered together, and above the threshold identified in Fiji.

Table 4. Number of caught individuals, exploitation rate, and percentage of fish below $FL_{m(50)}$ (cm) among the 10 most fished species on Bora-Bora during the study.

Species	Number of individuals	Exploitation rate	% caught below $L_{m(50)}$
<i>Myripristis amanea</i>	468	0.54	33%
<i>Scarus psittacus</i>	96	0.62	36%
<i>Naso lituratus</i>	50	0.32	0%
<i>Naso unicornis</i>	71	0.48	45%
<i>Lutjanus gibbus</i>	51	0.51	49%
<i>Chlorurus microrhinos</i>	101	0.50	57%
<i>Acanthurus xanthopterus</i>	100	0.19	54%
<i>Chlorurus frontalis</i>	223	0.52	48%
<i>Acanthurus nigricauda</i>	82	0.26	32%
<i>Monotaxis grandoculis</i>	58	0.68	67%

Table 5. Estimation of exploitation indicators for the 4 most fished stocks.

Species	L_c/L_{c_opt}	B/B_{msy}	F/M	B/B_0	Status
<i>Myripristis amaena</i>	1.0	1.9	0.3	0.7	Non-fully exploited
<i>Chlorurus frontalis</i>	0.8	1.6	0.3	0.5	Non fully exploited
<i>Chlorurus microrhinos</i>	0.7	1.6	0.3	0.6	Non fully exploited
<i>Acanthurus xanthopterus</i>	0.8	1.6	0.3	0.6	Non fully exploited

Table 6. Comparison of fisheries-related parameters between the two French Polynesia islands of Bora-Bora and Moorea. It is worth noting that the Maximum Sustainable Yield process in Moorea was carried out with the entire lagoon biomass, rather than just commercial fish biomass, which may explain the difference between the Bora-Bora results.

	Bora-Bora data	Moorea data from Brenier, 2009 and Leenhardt et al., 2012
Inhabitants	10 658	16 608
Estimated number of fishermen	1307	3773
Fishermen density	18.9 Fishermen km^{-2}	77 Fishermen km^{-2}
Average trip/week/ km^2	40.3 trips $\text{week}^{-1} \text{ km}^{-2}$	120 trips. $\text{week}^{-1} \text{ km}^{-2}$
Average catch per unit effort (CPUE)	2.7 kg trip^{-1}	1.6 kg trip^{-1}
Total annual landing	369.7 $\pm$ 40.6 t	490 t
Annual yield	5.35 t $\text{km}^{-2} \text{ year}^{-1}$	10 t $\text{km}^{-2} \text{ year}^{-1}$
Biomass estimation	58.8 t $\text{km}^{-2} \text{ year}^{-1}$	103 t $\text{km}^{-2} \text{ year}^{-1}$
Maximum Sustainable yield (MSY)	6.5 t $\text{km}^{-2} \text{ year}^{-1}$	23 t $\text{km}^{-2} \text{ year}^{-1}$
Fish landing/inhabitant/year	34.7 kg $\text{inh}^{-1} \text{ year}^{-1}$	27.98 kg $\text{inh}^{-1} \text{ year}^{-1}$

There are a few methodological limits to note about our study, with improvements possible through further investigations on Bora-Bora and in other similar island reef contexts. Firstly, we were not able to estimate all input parameters for the various equations used; some were set based on the literature (e.g., the size at first maturity of the commercial reef fish was defined based on the literature; the relative natural mortality was set to 1.5 for the Length Based Bayesian assessment). This may not be accurate for all commercial species of Bora-Bora (Hordyk et al., 2019). Secondly, we extrapolated interview results for a subset of fishermen to all fishermen on island, and we observed only 12 fishermen over two months to calculate the CPUE. Thirdly, we assumed that the fishing effort and efficiency are constant throughout the year, and that fish recruitment is stable from year to year, which may not be the case in reef fisheries (Reynal et al., 1998). Furthermore, the low landing volumes observed overall on the island can lead to high variability in the CPUE (Dalzell and Adams, 1997). Lastly, the multi-species nature of reef fisheries (with over 200 species exploited worldwide – Dalzell and Adams, 1997) can lead to issues to accurately assess fishing effort. In Bora-Bora, we estimate that at least 100 species are commercially exploited. Catches vary greatly in time across species, making it difficult to define overall and species-specific exploitation levels (Reynal et al., 1998). Nevertheless, our results echo previous findings in similar settings (notably in Moorea – Brenier, 2009; Leenhardt et al., 2016). This study makes full use of the readily available data for the Bora-Bora fisheries and sets the grounds for similar assessments in other island reef fisheries of the South Pacific.

Overall, the different indicators assessed for the reef fisheries of Bora-Bora paint a contrasted picture of the state of the fisheries. Only two stocks (*Monotaxis grandoculis* and *Chlorurus microrhinos*) exhibited a significant percentage of immature individuals in the catch. Others indicators such as the ratio between the biomass and the biomass at the maximum sustainable yield (MSY) and the exploitation rate for the major part of the 10 fish stocks highlight that overall, the state of the fisheries does not seem alarming. The Length Based Bayesian assessment indicates that the fishery is “non-fully exploited”; the Maximum Sustainable Yield has not been reached. However, older fishermen have pointed towards the fact that the fish caught were bigger before the 1980s, and there were more fish in the lagoon than nowadays. Bora-Bora is a small island with high human demand and reliability on fish resources. Yet, many fisheries assessment methods are designed for high seas and deep-sea fisheries (Appeldoorn, 2008; Bunce, 2000). Therefore, as a precautionary approach, we would recommend that steps are taken to improve the sustainability of the fisheries of Bora-Bora and avoid the overexploitation of all commercial species. To improve fishing practices, information about the size at maturity of the commercial fish species should be made available to raise awareness and empower the local fishermen to actively promote population growth and allow for increases in fish sizes (Leonchuk, 2020). Furthermore, no-take zones or periods can be put in place; in French Polynesia, traditional “rahui” are placed on certain reef areas to ban fishing for given periods. Such practices can help fish stocks recovering (McClanahan and Kaunda-Arara, 1996). To design and monitor the efficacy of such practices, it is of high importance

to use quantitative fisheries assessments. Lastly, we would recommend a re-evaluation of the reef fishery landings across all French Polynesia, which was estimated to be 2350 tons year⁻¹ (Gillet, 2016). French Polynesia has 75 inhabited islands; to date, the fisheries of three islands – Bora-Bora, Moorea, and Tikehau (representing 10% of the French Polynesia population) – have been assessed quantitatively. Combining the results, we found a total landing of 1010 tons year⁻¹ on three islands, and we thus hypothesise that the fisheries landings across all French Polynesia are currently underestimated. At the global scale, coral reefs are subjected to climate change (global warming, rising sea levels, ocean acidification). However, we must not forget to find solutions for the sustainable management of reef fisheries, so that coral reefs could continue to provide food (fish, crustaceans, molluscs) for millions of people, especially in the Pacific Islands.

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References

- Amorim P, Sousa P, Jardim E, Menezes GM. 2019. Sustainability status of data-limited fisheries: global challenges for snapper and grouper. *Front Mar Sci*. 6: 654–661.
- Appeldoorn RS. 2008. Transforming reef fisheries management: application of an ecosystem-based approach in the USA Caribbean. *Env Conserv*. 35: 232–241.
- Ault JS, Smith SG, Bohnsack JA et al. 2019. Length-based risk analysis for assessing sustainability of data-limited tropical reef fisheries. *ICES J Mar Sci*. 76: 165–180.
- Bambridge T. 2020. Rapport d’enquête, la pêche d’hier, d’aujourd’hui et de demain à Bora-Bora. *CRILOBE* (pdf available at criobe@mail.pf). p. 34.
- Beverton RJ, Holt SJ. 1956. A review of methods for estimating mortality rates in fish populations, with special reference to sources of bias in catch sampling. *Rapp Proces-verb Reun Cons Int Explor Mer* 140: 67–83.
- Brenier A. 2009. Pertinence des approches participatives pour le suivi écosystémique des pêcheries récifales, Thèse de Doctorat, Université Paris VI, p.227 (pdf available at criobe@mail.pf).
- Bunce L, Townsley P, Pollnac RB. 2000. Socioeconomic manual for coral reef management. *Global Coral Reef Monitoring Network* (pdf available on GRCMN website).
- Burke L, Reynter K, Spalding M, Perry A. 2011. Reefs at Risk Revisited, World Resources Institute (WRI), The Nature Conservancy, WorldFish Center, International Coral Reef Action Network, UNEP World Conservation Monitoring Centre and Global Coral Reef Monitoring Network, Washington, D.C., 114 p.
- Charnov EL, Gislason H, Pope JG. 2013. Evolutionary assembly rules for fish life histories. *Fish Fisher* 14: 213–224.
- Dalzell P, Adams TJH. 1997. Sustainability and management of reef fisheries in the Pacific Islands. *Proc 8th Int Coral Reef Symp* 2: 41–49.

- Fatihah I, Umari MT, Kudsiah H, et al. 2021. October. Uncontrolled fishing of dusky parrotfish *Scarus niger* (Forsskal, 1775) Spermonde Islands, *Makassar Strait, Indonesia*. *IOP Conf Ser: Earth Environ Sci* 860: 12–19.
- Frisch AJ, Baker R, Hobbs JA, Nankervis L. 2008. A quantitative comparison of recreational spearfishing and linefishing on the Great Barrier Reef: implications for management of multi-sector coral reef fisheries. *Coral Reefs* 27: 85–95.
- Froese R, Winker H, Coro G, et al. 2018. A new approach for estimating stock status from length frequency data. *ICES J Mar Sci* 76: 350–351.
- Gascuel D. 1995. Efforts et puissances de pêche : redéfinition des concepts et exemple d'application. *Les recherches françaises en évaluation quantitatives et modélisation des ressources et des systèmes halieutiques, Colloques et séminaires, Paris, Orstom* 1: 159–181.
- Gillett RD. 2016. Fisheries in the economies of pacific islands countries and territories. *South Pacific Community Report*, p. 666 (pdf available on <https://www.spc.int/>).
- Hicks CC, McClanahan TR. 2012. Assessing gear modifications needed to optimize yields in a heavily exploited, multi-species, seagrass and coral reef fishery. *PLoS One* 7: e36022.
- Hordyk AR, Prince JD, Carruthers TR, Walters CJ. 2019. Comment on “A new approach for estimating stock status from length frequency data”. *ICES J Mar Sci* 76: 457–460.
- IEOM. 2017. Rapport Annuel. In: d. E. d’Outre-Mer (Ed.). Paris, p. 59 (pdf available on [ieom-rapport_annuel_2017.pdf](https://www.ieom-rapport_annuel_2017.pdf)).
- ISPF. 2022. Bilan démographique 2022. RP Etat civil, *INSEE*, p. 26 (pdf available on <https://www.ispf.fr/>).
- Jackson JB, Kirby MX, Berger WH, et al. 2001. Historical overfishing and the recent collapse of coastal ecosystems. *Science* 293: 629–637.
- Jennings S, Polunin NVC. 1996. Effects of fishing effort and catch rate upon the structure and biomass of Fijian Reef Fish Communities. *J Appl Ecol* 33: 400–412.
- Lauck T, Clark CW, Mangel M, Munro GR. 1998. Implementing the precautionary principle in fisheries management through marine reserves. *Ecol Appl* 8: 72–78.
- Lecchini D. 2022. Acquérir les connaissances sur la biodiversité nécessaires pour une future gestion durable du lagon de Bora-Bora. *CRILOBE report*, p. 214 (pdf available on [criobe@mail.pf](https://www.criobe@mail.pf)).
- Le Cren ED. 1951. The length-weight relationship and seasonal cycle in gonad weight and condition in the perch (*Perca fluviatilis*). *J Ani Ecol* 1: 201–219.
- Leenhardt P, Lauer M, Madi Moussa R, Holbrook SJ, Rassweiler A, Schmitt RJ, Claudet J. 2016. Complexities and uncertainties in transitioning small-scale coral reef fisheries. *Front Mar Sci* 3: 60–70.
- Leonchyk Y. 2020. Length based assessment approaches LBB and LB-SPR. *BlackSea4Fish Presentation Series*, p. 17 (pdf available on [Leonchyk_LBB_LBSPR.pdf](https://www.blacksea4fish.org/)).
- McClanahan T, Polunin N, Done T. 2002. Ecological states and the resilience of coral reefs. *Conserv Ecol* 6: 11–18.
- McClenachan L, Dissanayake ST, Chen X. 2016. Fair trade fish: consumer support for broader seafood sustainability. *Fish Fish* 17: 825–838.
- Minier L, Fourrière M, Gairin E, et al. 2023. Roadside sales activities in a South Pacific Island (Bora-Bora) reveal sustainable strategies for local food supply during a pandemic. *PLoS One* 18: e0284276.
- Moberg F, Folke C. 1999. Ecological goods and services of coral reef ecosystems. *Ecol Econom* 29: 215–233.
- Morais RA, Bellwood DR. 2019. Pelagic subsidies underpin fish productivity on a degraded coral reef. *Curr Biol* 29: 1521–1527.
- Munro JL. 1973. Caribbean coral reef fishery resources. *International Centre for Living Aquatic Resources Management*, 276 pp.
- Newton K, Côté IM, Pilling GM, Jennings S, Dulvy NK. 2007. Current and future sustainability of island coral reef fisheries. *Cur Bio* 17: 655–658.
- Pons M, Cope JS, Kell LT. 2020. Comparing performance of catch-based and length-based stock assessment methods in data-limited fisheries. *Can J Fish Aquatic Sci* 77: 1026–1037.
- Reynal L, Maguer C, Taquet M. 1998. Problématique de suivi de la pêche insulaire. *Proc Gulf Caribbean Fish Inst* 50: 1065–1074.
- Roos D, Durieux M, Pothin K. 2015. Description et analyse des données de pêches traditionnelles à pied sur les platiers récifaux de la Réserve Nationale Marine de La Réunion. *Ifremer report*, 19 p. (pdf available on <https://www.ifremer.fr/fr>).
- Spalding MD, Ravilious C, Green EP. 2001. World Atlas of Coral Reefs, *University of California Press*.
- Taquet MA. 1998. Le Dispositif de Concentration de Poisson (DCP): Une Alternative à la Forte Pression de Pêche sur les Ressources Récifales de la Martinique. *Aquadoc* 1: 1–14.
- Teh LS, Teh LC, Sumaila UR, Cheung W. 2015. Time discounting and the overexploitation of coral reefs. *Environ Resour Econom* 61: 91–114.
- Teh LS, The LC, Sumaila UR. 2013. A global estimate of the number of coral reef fishers. *PLoS One* 8: 1–6.
- Van Campenhoudt L, Marquet J, Quivy R. 2017. Manuel de recherche en sciences sociales, 5^e édition, *Dunod*, p. 380.
- Von Bertalanffy L. 1938. A quantitative theory of organic growth (inquiries on growth laws. *Hum Biol* 10: 181–213.
- Zamborain-Mason J, Cinner JE, MacNeil MA, et al. 2023. Sustainable reference points for multispecies coral reef fisheries. *Nat Commun* 14: e5368.
- Zhang K, Zhang J, Shi D, Chen Z. 2021. Assessment of coral reef fish stocks from the Nansha Islands, South China Sea, using length-based Bayesian biomass estimation. *Front Mar Sci* 7: 600–610.

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Appendix 1. Size (fork length in cm) at first maturity (length at with 50% of individuals are mature) for the 10 studied species.

Family	Species	Size at first maturity ($L_{m(50)}$) (fork length)	Location of the study	Source
<i>Holocentridae</i>	<i>Myripristis amaena</i>	18 cm	Hawai	Dee et al., 1994
<i>Scaridae</i>	<i>Scarus psittacus</i>	21 cm	Hawaii	De martini et al., 2016
	<i>Chlorurus microhinos</i>	37 cm	Fidji	Prince et al., 2019
	<i>Chlorurus frontalis</i>	30 cm	New Caledonia	Prince et al., 2019
<i>Acanthuridae</i>	<i>Naso lituratus</i>	18 cm	Hawaii	Taylor et al., 2014
	<i>Naso unicornis</i>	35 cm	Hawaii	Taylor et al., 2014
	<i>Acanthurus xanthopterus</i>	31 cm	New Caledonia	Prince et al., 2019
	<i>Acanthurus nigricauda</i>	16 cm	Micronesia	Longnecker et al., 2016
<i>Lutjanidae</i>	<i>Lutjanus gibbus</i>	29 cm	Fidji	Moore et al., 2019
<i>Lethrinidae</i>	<i>Monotaxis grandoculis</i>	34 cm	Fidji	Prince et al., 2017

Appendix 2. Population parameters used for the of Length Bayesian Biomass. The size is the fork length in cm (length range) and at first maturity (length at with 50% of individuals are mature).

Species	Number of individuals	Length range	Maturity size
<i>Myripristis amaena</i>	469	11–25 cm	18 cm
<i>Chlorurus frontalis</i>	223	21–49 cm	30 cm
<i>Chlorurus microrhinos</i>	101	25–59 cm	37 cm
<i>Acanthurus xanthopterus</i>	100	16–50 cm	31 cm

Appendix 3. Overall table of all used methods and their sources.

Dataset (representativeness)	Key information	Process	Exploitation indicators
Spatialisation interviews (13% of the total estimated fishermen number)	Places of fishing, fishing gear, outings frequencies	Qgis, Extrapolation to the total fishermen number (2.2)	Fishing hotspots, Nominal effort (outings/week/km ²)
Children participatory survey (5% of the total household number)	Weekly consumption	Ricker formula, extrapolation (2.3)	Annual landing 1
Fishermen survey (0.9% of the total estimated fishermen number)	Quantity of fish caught per trip	CPUE (2.4)	CPUE, Annual landing 2
	Size composition of catches	LBB (2.8)	B/B _{MSY} ratio, L _{c_opt}
		Mortality calculation (2.6)	Exploitation rate
“tui” survey (3 months)	Size composition of catches	LBB (2.8)	B/B _{MSY} ratio, L _{c_opt}
		Mortality calculation (2.6)	Exploitation rate
Annual landings 1, 2	Average	MSY process (2.7) (Leenhardt et al., 2012)	Maximum sustainable yield landing