Assessing Key Fish Stocks of Seychelles' Artisanal Trap and Line Fishery

Project Name/ID: Third South West Indian Ocean Fisheries Governance and Shared Growth Project (SWIOFish3) / P155642

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Executive Summary

Catch assessment surveys, vessel monitoring data, and biological information were used to assess the stock status of key species in Seychelles' artisanal fisheries. Trap gears, used primarily in coastal habitats, increased in catch rate, total effort, and total catch since 1990, though catch rates of key species groups (Siganidae and mixed reef species) have recently declined. Increasing effort reflects high fishing pressure on Seychelles' coastal ecosystems, which have also been heavily impacted by climate-driven coral mortality. Total catch of resilient Siganidae (cordonier) species has been sustained over two decades, suggesting that trap fisheries will continue to support high fishing pressure. However, declining catch rates of individual species groups and uncertainty in mixed species groups demand further attention. Demersal and pelagic fisheries (handlines) accounted for most of the landed artisanal catch in Seychelles, primarily from whaler-type vessels that target the Mahé plateau. Many of these species have declined in catch rate, reducing total landed catches, but key stocks of Carangidae (carangues), *L. sebae* (bourgeois) and jobfish are showing signs of recovery, possibly due to reductions in effort by whaler-type vessels. In contrast, outboard vessels target similar pelagic and demersal species in inshore fishing grounds and have experienced sustained catch declines since 2010.

Catch-based stock assessments suggest that most artisanal stocks are at or above sustainable limits. Siganidae have not been overfished over 2000-2019, but mixed reef species (other trap fish) are now experiencing overfishing. Most pelagic and demersal species were overfished between 2005-2015, but key stocks are now at or above their maximum sustainable yield. Given uncertainty in catch-based stock asssessments, particularly for mixed species groups, and limited catch contrast over 2000-2016, collection and analysis of additional biological data would help to inform management strategies. For example, age and size data collected for *Lutjanus sebae* suggest that targeting of a strong juvenile cohort (and/or high catchability) led to significant changes in catch rates over 2003-2010, and that this stock has recently recovered to within sustainable limits. With stocks close to fishing limits and most artisanal fishing effort unregulated, implementation of harvest controls would help to protect long-term yields for these fisheries. I recommend that SFA develop management plans for four key artisanal fisheries (Carangidae, *L. sebae*, and jobfish caught with handlines, Siganidae caught with traps). Management should be appropriate for species' life history strategies, such as protecting growth overfishing in slow-growing species and spawning habitat of aggregating species. Collection and analysis of additional biological data, such as age, size and key spawning habitats, would help to inform these strategies. The CAS system is a rich data source for quantifying artisanal fishing patterns and continues to improve with greater species resolution. Enhanced support for data collection and analysis could provide targeted, real-time information on stock status that would help to track the effectiveness of harvest controls and to detect future fishing impacts. The code and methodology provided with this report can be used a basis for conducting routine, reproducible stock assessments.

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1. Introduction

1.1 Project objectives

This assessment is intended to provide key inputs for the monitoring and evaluation of the Third South West Indian Ocean Fisheries Governance and Shared Growth Project (SWIOFish3). One of the SWIOFish3 Project Development Objective Indicator (PDOI_2) is '*Share of key demersal indicator species stable or rebuilding in the Mahé Plateau fisheries'*, which will be used to understand and improve the improvement of the health of the main artisanal fisheries of the Mahé Plateau.

The objectives of this report are to:

1. Derive abundance indices for key species or species groups through standardisation of CPUE data
2. Determine the status of stocks for key species or species groups using applicable stock assessment methods
3. Determine the status of *Lutjanus sebae* through an age-structured stock assessment model
4. Identify further research and data collection needs which would be required for improved stock assessments

These objectives will be completed by analysis of datasets collected by Seychelles Fishing Authority (SFA), namely:

- catch and effort data from Catch Assessment Surveys (CAS)
- estimates of total catch and effort from CAS (i.e. raised catches)
- fishing location data collected from boats installed with a Vessel Monitoring System (VMS)
- size-based data on *Lutjanus sebae*, a key stock targeted by handlines across the Mahé Plateau

1.2 Context

Seychelles' artisanal fisheries target over 100 species across pelagic, demersal, and coral reef habitats habitats on the Mahé Plateau. These fisheries are major contributors to employment, income, trade, and food supply in Seychelles. The artisanal fleet is composed of ~140 whaler-type vessels and schooners and ~300 outboard vessels that catch ~ 4,250 tonnes per year (Seychelles Fishing Authority 2016), most of which is consumed domestically (Le Manach et al. 2015). Most catch is landed by handlines that target semi-pelagic (Carangidae species and jobfish) and demersal species (snappers in Lutjanidae, groupers in Serranidae), including whaler-type and schooner vessels that can fish for several days, as well as smaller inshore outboard vessels. Trap gears are also used by outboard vessels in coastal habitats to target reef-associated fishes (Siganidae, Scaridae, Mullidae) (Seychelles Fishing Authority 2016). Catch, effort and capacity are known to be underestimated, with catch reconstructions suggesting that total catch reached 11,200 t in 2017 (Christ et al. 2020). From the 1950s to 2017, these reconstructions also suggest that artisanal catch has increased by 500% (1,900 t to 11,200 t per year) as fishing capacity has increased 158-fold (21,500 kWdays to 3.4 million kWdays) (Christ et al. 2020).

These artisanal fisheries are open-access with no catch limits, though vessels must register with SFA, follow gear restrictions (e.g. mesh limit on traps), and use VMS systems above a certain vessel size. Industrial vessels are prohibited in shallow areas (<200 m), and both demersal trawling and spearfishing are prohibited throughout Seychelles' EEZ (Le Manach et al. 2015). However, Seychelles is committed to developing fisheries management to achieve long-term sustainable exploitation of marine resources. To this end, data-limited stock assessments have been conducted on key artisanal stocks, particularly *Lutjanus sebae* which is highly valued for food and trade. The most recent assessment suggested that the catch rates had declined over 2006-2013 while total fishing effort doubled (Gutiérrez 2015). Independent analysis confirmed that species-level declines were particularly pronounced for whaler-type vessels fishing on the Mahé Plateau, and have occurred from 1990 to 2016 (Robinson et al. 2020). Catch rates for reef trap fisheries have increased or remained stable over the same time period, despite large-scale loss of corals and regime shifts to macroalgal habitat (Robinson et al. 2019). *L. sebae* has been a particular focus of stock assessments, and was estimated to be overfished in the early 2000s. Age and size data indicated that targeting of juvenile fishes in 2004-2005 likely caused a sustained decline in total catch (Grandcourt et al. 2008; Gutiérrez 2015).

Data are now available for 1990-2019, presenting an opportunity to update these assessments of artisanal fishery status. The assessments in this report are also intended to support development and implementation of the Mahé Plateau Trap and Line Fishery Co-management Plan.

2. Methods

2.1 Data summary

This report defines a fishery as a unique combination of gear and vessel type, focusing on trap and handline gears used by artisanal vessel types (defined in Catch Assessment Surveys, CAS). There were two trap gears (static and active traps, deployed by outboard vessels) and four handline vessel types (outboard, lekonomi, lavenir and whaler vessels). These six gear-vessel types targeted 27 species groups. Catch and effort data were extracted for 1990 to 2019, comprising 230,788 records from 84,854 fishing trips. Here, catch records were aggregated into 23 species groups that have been recorded in CAS since 1990 (Table 1), mostly combining related species together (e.g. Carangidae species), though key single-species stocks, such as *Lutjanus sebae*, were recorded individually. Outboard vessels had the highest number of catch records and have increased to over 3,000 per year since 2011, whereas offshore vessel types each had 50-200 records per year (Fig. 1). The improved CAS system (2016-present) records catches at species level, but these were combined into the original species groups to facilitate time-series analysis.

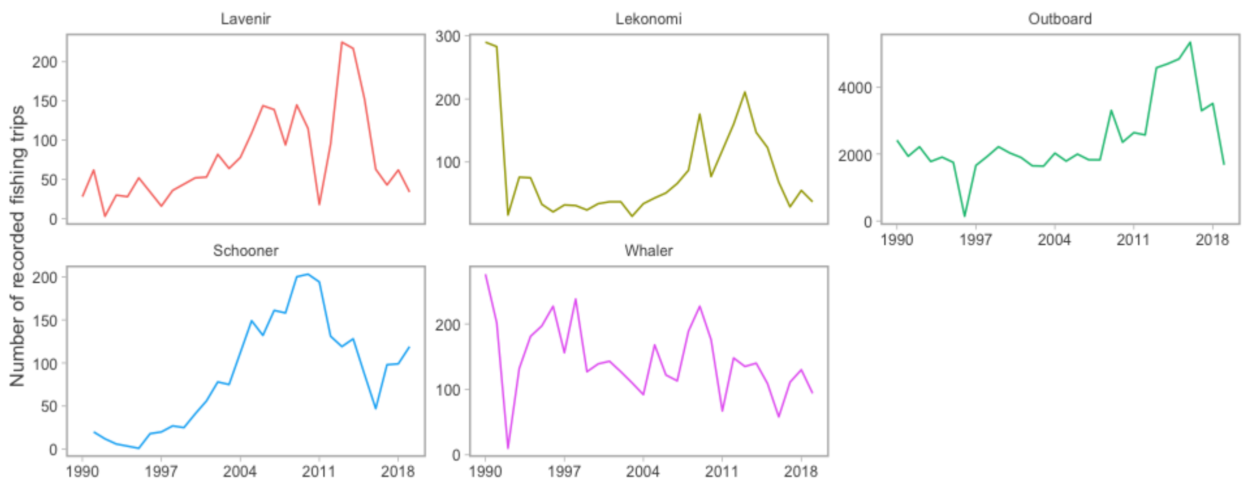

Figure 1 | Total number of surveyed catch records from 1990 to present, for each of the 5 fleets analysed in this stock assessment. Catch records without effort data are excluded.

2.2 Abundance indicators: catch-per-unit-effort analysis

Catch-per-unit-effort (CPUE) was standardised across gears and fleets to kg per trap (static traps, FIXS), kg per trap per hour (active traps, FIXA), and kg per man per hour (handlines, LHP). Daily CPUE was averaged for each species group, gear and fleet in each month and landings site, and $\log_{10}$ transformed. Generalised additive models (GAM) (Pedersen et al. 2019) were fitted to these CPUE estimates, with smoothers (*f*) for time (month-year), calendar month (cyclic, 1-12), two oceanographic covariates (BEST ENSO, www.esrl.noaa.gov/psd/people/cathy.smith/best/ and Indian Dipole Mode (DMI), psl.noaa.gov/gcos_wgsp/Timeseries/DMI/) (Saji et al. 1999), and two total effort metrics (fishing days, number of fishers) (Eq. 1).

$$CPUE_i = f\left(month_{year_i}\right) + f(month_i) + f(ENSO_i) + f(DMI_i) + f(fishing\_days_i) + f(n\_fishers_i) + \zeta_{site} + \zeta_{island} + \epsilon_i \quad (1)$$

Landing site and island were fitted as random varying intercepts (ζ), and model with Gaussian errors (ϵ_i). Models were fitted for each gear-fleet (i.e. FIXS-Outboard, LHP-Whaler), either for total CPUE or for key species groups (Table 1). Species-level CPUE analyses were conducted only on species groups that were frequently targeted by each fishery, defined as those representing over 75% of total catch records per gear, and were recorded in at least 23 years over 1990-2019 (Table 1). Species-level models were the same structure as total CPUE model but with the time smoother fitted separately to each species. Catch rates of rarely caught species were not analysed, owing to model fitting issues. Temporal trends in CPUE were examined by predicting CPUE over time, excluding all other modelled effects (month, oceanography, landings site, fishing days). Note that all CPUE models measured catch rates of landed species and thus do not account for changes in catch success (i.e. frequency of 0 catches over time).

2.3 Vessel Monitoring Data for whaler-type vessels

Vessel monitoring data were collected for 117 vessels from 2005-2019. All vessels were in the lavenir, lekonomi and traditional whaler fleets, and thus primarily fished using handlines in offshore fishing grounds. We extracted the location (latitude, longitude), speed, and vessel identity of all VMS records. VMS positions were filtered to retain records within Seychelles' EEZ, and we excluded any positions that were at steaming speeds (> 2 knots, i.e. transiting not fishing) or within 1km of any coastline (e.g. at port) (Lee et al. 2010). The remaining VMS positions thus represent the potential fishing footprint of the artisanal handline fleets that target demersal and pelagic species (Robinson et al. 2020). It was not possible to match vessel positions to CAS catch records.

VMS records were aggregated to visualize the potential fishing intensity across Seychelles' EEZ. All fishing areas further than 1 km of any coastline were divided into a grid of 1' resolution (342 km^2 per grid cell). VMS records were then summed within each cell and divided by the total number of VMS records, giving the percentage of potential fishing intensity per grid cell. This analysis was conducted for all years and fleets, for each year, and for each fleet. We also estimated the size and position of the fishing grounds, defined as the grid cells containing all VMS records, for a given year and fleet. Fishing ground area was the total area of fishing grid cells and fishing ground position was the median longitude and latitude of fishing grid cells.

2.4 Stock assessment of raised catch and effort data

The CAS system provided estimates of total monthly catch by species group, fleet and region, based on average CPUE and total estimated effort (number of traps or number of man hours). We summed total catches for each species group across all fleets and regions in each year. Although larger fishing vessels target distant fishing grounds (e.g. whalers, schooners) and outboard vessels primarily target nearshore habitats, data linking fleet distribution to catch composition are lacking. We therefore assumed that the total catch of each species group represents a single stock. As species-specific catch data were only collected from 2017, most stocks were also composed of multiple related species (Table 1).

We conducted catch-only stock assessments of 11 species groups, representing ~3,170 tonnes average catch per year. We used a method based on the Schaefer production model that uses time-series catch data and simple biological information to estimate fisheries reference points (Froese et al. 2017). We used prior information on initial biomass (*B_0_*) and historical catches to reconstruct stock trajectories from plausible combinations of carrying capacity (*k*) and maximum population growth rate (*r*). Species' resilience classifications from Fishbase were used to inform likely values of *r* (Martell and Froese 2013). For each species group, we assigned a resilience (very low, low, medium, high) and corresponding range of *r* values (Froese et al. 2017), based on the species and families that are expected to comprise the majority of catches in each group. Models were implemented using the R package *datalimited2* (Free 2018). We extracted estimates of maximum sustainable yield (MSY), spawning biomass (B), spawning biomass at MSY (B_{MSY}), B_0 (unfished biomass), fishing mortality (F) and fishing mortality at MSY (F_{MSY}). Note that although the previous stock assessment also fitted catch-based assessment models (Gutiérrez 2015), these were fitted to the sum of sampled catch records per year, rather than the sampled catch data raised by effort to total catch that are used here, and so are not comparable.

To aid with interpretation of catch trends, we also analyzed temporal trends in raised effort values. For each fleet (outboard, schooner, whaler-type vessels) and gear (handlines, static traps, active traps), we extracted the total men days (for handlines) and total number of traps deployed in each year. We identified temporal trends by fitting a GAM smoother.

2.5 *Lutjanus sebae*: size-based indicators

Data on *Lutjanus sebae* body sizes (fork length, cm) were collected by sampling the commercial catches at the Victoria Port or at fish processing plants. Fish were selected at random for sampling. We examined temporal changes in length frequencies and median size of targeted fish from 1989-2020. Using an estimated size at maturity of 62 cm for individuals in Seychelles (Grandcourt et al. 2008), we examined the relative proportion of immature (< 62 cm) and mature (≥ 62 cm) individuals in the population to assess the risk of growth overfishing.

Next, using age estimates from otoliths collected in 2000, we created an age table based on the age and size of individuals, then fitted a multinomial model to predict age according to length (1 cm bins) (Ogle 2018). This model was used to predict the age of each individual sampled from 1989-2020, and to examine the median age-at-capture, and proportion of juvenile fishes targeted, where age at maturity was 9 years. Note that these data are fishery-dependent (i.e. from catches) and can not provide standardized metrics of fishery status, as fishers may move fishing grounds over time, with such varying effort and selectivity influencing the size distribution of captured individuals.

2.6 Data and code availability

All data were provided by Seychelles Fishing Authority. The raw data files can be accessed upon request. The aggregated and cleaned datasets analyzed in this report are available at github.com/jpwrobinson/SeychellesStocks. All R code required to clean data, fit GAMs, run catch-based stock assessments and create figures are provided in this repository.

Fishery group SFA	Definition	Species	Artfish code (& FAO)	Trap	Handline	Total	Primary gear	Resilience
Other trap fish	Reef fish	*Species of Scaridae, Mullidae, Acanthuridae, Labridae*	**OTF**, AJS, BMK, PWT, USY, HJH, UVE, USX2, JBK, HIF, HUU, DGP, NAS, VRL, VRA, BWH, HVM, CJC, IHA, LOV, ORF, PKF, GQV, PRC, RPX, RPX2, QZH, RPH, RPB, RFP, RPY, AXQ, AQI, AXQ3, AXQ4, DGW, AXQ2, GMR, JLR	34,807	1,650	**36,457**	Trap	Medium
Capitaine	Emperors	*Lethrinidae sp, lethrinus mahsena, lethrinus crocineus*	**EMP**, JBO, LEN, LHN, LHV, LHO, LTK, LTS, LWO, LTQ	35,375	313	**35,688**	Handline	Medium
Cordonier	Rabbitfish	*Siganidae sp., siganus sutor, siganus argenteus*	**SPI**, IUU, IUT, IGA, IGR	11,868	22,501	**34,369**	Trap	High
Carangues	Carangidae	*Carangidae sp., carangoides fulvoguttatus, carangoides gymnostethus*	**CGX**, CXS, GLT, NGS, NGU, NGY, NXM	375	27,612	**27,987**	Handline	Medium
Job	Jobfish	*Aprion virescens, pristipomoides filamentosus, aphareus rutilans*	**LWX**, AVR, ARQ, PFM	376	17,767	**18,143**	Handline	Medium
Bourgeois	*Lutjanus sebae*	*Lutjanus sebae*	**LUB**	2,222	12,553	**14,775**	Handline	Medium
Other vieille	Groupers	*Serranidae sp.*	**GPX**, EMN, EML, EEP, EEA, EFT, AYG, GPX, EHG, EWF, EEN, CFF, EWC, EEK, EEV, EWU, EWW, EWV, EWL, EWP, EEk2, CFI, EZ	2,437	10,932	**13,369**	Handline	Low
Bonite	Bonito	*Sarda orientalis,Scombrinae*	**BZX**, BIP	66	10,760	**10,826**	Handline	Medium
Becune	Barracuda	*Sphyraena sp, sphyraena jello*	**BAR**, BAC, BAN, GBA, YRB	26	9,743	**9,769**	Handline	Low
Maconde	*Epinephelus chlorostigma*	*Epinephelus chlorostigma*	**EFH**	697	6,254	**6,951**	Handline	Low
Red Snapper	*Red snapper sp.*	*Lutjanus bohar, Lutjanus gibbus*	**LJB, LZJ**	41	6,831	**6,872**	Handline	Medium
Other snappers	Snappers	*Lutjanidae sp., etelis coruscans*	**SNA**, LUV, RES, QIT, LVK, LJL, LJF	832	2,052	**2,884**	Handline	-
Other tuna	Tunas	*Thunnini sp., scombroidei sp., gymnosarda unicolor, thunnus albacares, thunnus obesus,*	**TUN**, KAW, BET, DOT, SKJ, YFT	15	2,273	**2,288**	Handline	-
Sharks & Rays	Sharks & Rays	*Elasmobranch sp.*	**SKH**, NGA, DHV, MAE, AML, CCE, OCS, SPL, CCB, ALS, SKX	179	1,946	**2,125**	Handline	-

Table 1 | Species groups analysed in CPUE and effort models and catch-based stock assessments. Groups ordered by total number of catch records in the CAS datasets from 1990-2019. Records without effort data were excluded. Resilience categories from Fishbase (Froese and Pauly 2021) were used in catch-based stock assessments.

3. Results

3.1 Abundance index: catch-per-unit-effort from 1990 - 2019

3.1.1 Trap fisheries

Traps were used primarily by outboard vessels, targeting coastal habitats and reef-associated species. Active traps (FIXA) are deployed for multiple hours and had catch rates of ~1 kg trap^{-1} hour^{-1} between 1990-2010. FIXA catch rates almost doubled over 2015-2019, reaching ~2 kg trap^{-1} hour^{-1} (Fig. 2A). Static traps (FIXS) are deployed for one or more days and had catch rates that increased steadily from ~3.5 kg trap^{-1} between 1990-2000 to ~4 kg trap^{-1} by 2015-2019 (Fig. 2A). Both trap gear types targeted similar species groups, dominated by cordonier (50% of FIXA catches and 30% of FIXS catches) and other trap fish (20% and 30% respectively) (Fig. 3A). These species are primarily reef-associated, reflecting targeting of shallow and coastal habitats by trap fishers. Higher trophic level species, such as groupers (other vieille, maconde) were also caught in traps but only rarely. Trip fishing effort had a negative effect on CPUE, with both FIXS and FIXA catch rates declining steeply from 1-4 traps (FIXS) and 1-10 traps (FIXA) (Fig. S1A).

Despite increases in average catch, the catch rate of species groups declined from 2010-2019 for both static and active traps (Fig. 3B). This suggests that traps are increasingly being used to target multiple species groups, maximizing total catch as the catch of species groups declines. This pattern is corroborated by trends in catch diversity, which increased fourfold from 1990-2019, particularly coinciding with recent declines in species-level catch rates (Fig. S2A). Trap catches landed on average 1.5 species groups per trip over 1990-2013, before increasing rapidly to 3-4 species groups by 2019 (Fig. S2B).

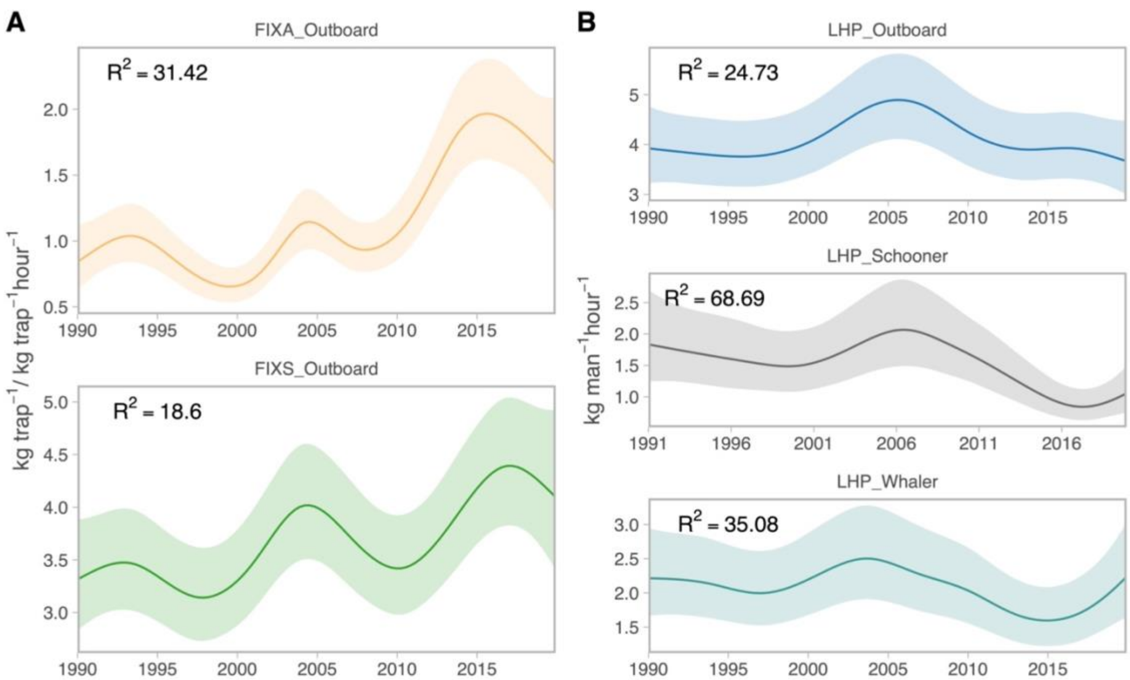

Figure 2 | CPUE for trap (A) and handline (B) gears over 1990-2019. Panels show different fleets, where lines are predicted CPUE (from GAMs), controlling for month, oceanography, location, and average fishing trip effort. Shaded areas are approximate 95% confidence intervals.

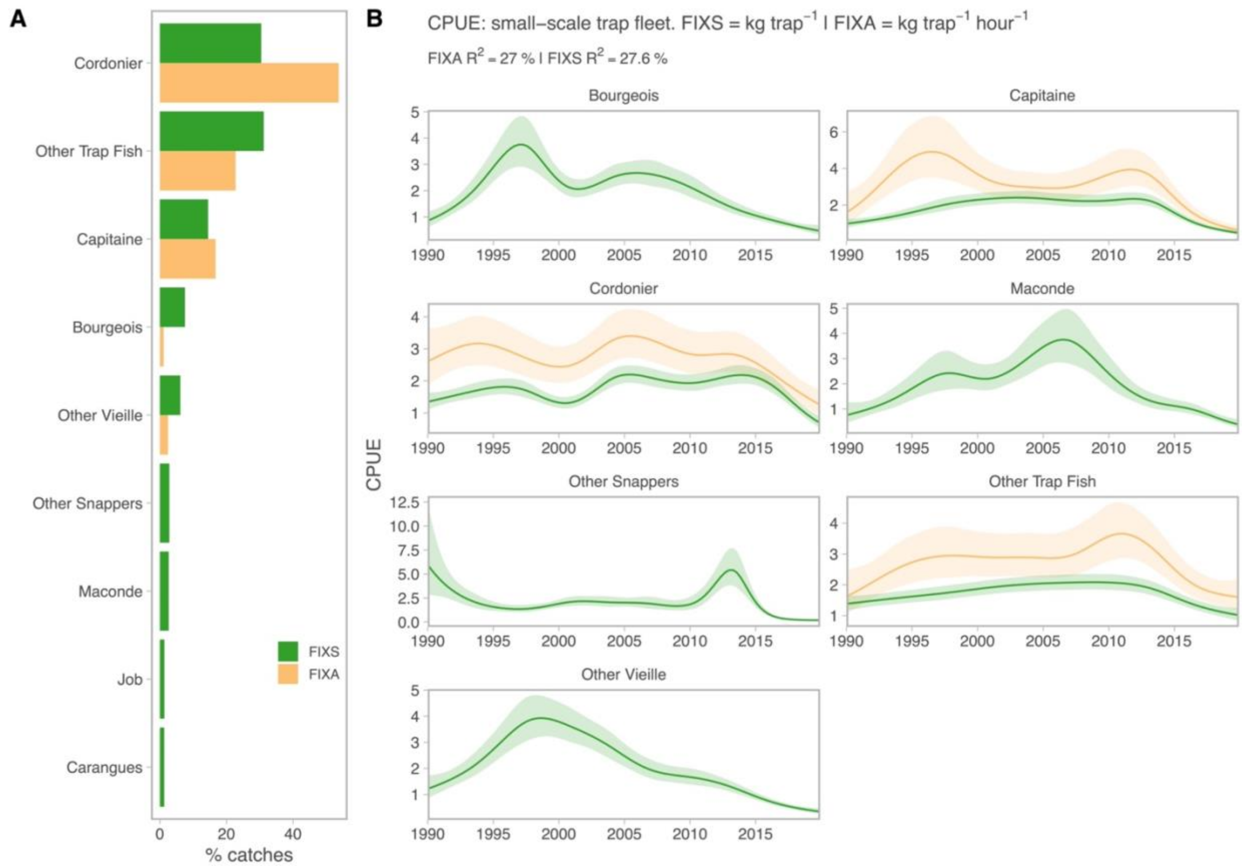

Figure 3 | Trap CPUE over 1990-2019 for key species groups A) The proportion of catches of each species group over the time-series, for static traps (FIXS, green) and active traps (FIXA, yellow). **B**) Smoothed CPUE trends for each species group and trap gear. Lines are predictions from general additive models, controlling for month, oceanography, location, and total effort. Shaded areas are approximate 95% confidence intervals.

3.1.2 Handline fisheries

Handlines were used by outboard, schooner and whaler fleets, comprising ~51% of artisanal catch records in the CAS. Mean CPUE in handline varied among fleets, with highest catch rates from outboard vessels followed by schooner and whaler vessels (Fig. 2B). Higher CPUE for outboard vessels is likely due to their lower effort (hours fishing) compared to offshore fleets, which use larger boats and fish for multiple days. Outboard CPUE remained at ~4 kg man^{-1} hour^{-1} from 1990-2000, before increasing to a maximum 5 kg man^{-1} hour^{-1} from 2000-2005 (Fig. 2B). CPUE has declined since 2005, reaching a minimum of 3.5 kg man^{-1} hour^{-1} in the most recent survey years. Though the outboard handline model had overall low variance explained (R^2 = 25%), recent declines had the greatest certainty, suggesting low CPUE has occurred across landings sites. Outboard catches were dominated by carangues, capitaine, job and bonite (each >10% of catches), though 12 species groups were landed (Fig. 4A). Species groups followed similar CPUE trends, increasing from 1990-2005, before declining to their lowest levels in recent years (Fig. 4B). Species-level CPUE trends largely corresponded with overall trend in CPUE, which has declined since 2005 to reach its minimum by 2019. This suggests that outboard handline catches are decreasing in weight landed (per hour), driven by declining catch of all targeted species groups.

Whaler fleets, defined as lekonomi, lavenir and traditional whalers, primarily targeted job, bourgeois, carangues and capitaine, with similar catch composition between whaler boat types (Fig. 5A). Total CPUE was ~2 kg man^{-1} hour^{-1} from 1990 – 2010 and declined to a minimum of 1.5 kg man^{-1} hour^{-1} in 2014, before recovering to 2-2.5 kg man^{-1} hour^{-1} by 2019 (Fig. 2B). However, total CPUE trends had large uncertainty intervals because CPUE varied with species targeted and vessel type. Becune, capitane and red snapper CPUE declined from 1990-2019, whereas bonite, bourgeois, other pelagics and other tuna have overall increased CPUE from 1990-2019 (Fig. 5B). Several species groups had maximum CPUE between 2000-2010 (bourgeois, job, carangues, other vielle) followed by declines and recovery to average CPUE levels by 2019. It is not clear if high CPUE levels were due to biological factors (e.g. strong age class) or increased targeting of these groups, but recovery to average CPUE levels suggest these four species groups are not currently being overfished.

Schooner catch rates have declined in total CPUE from ~1.75 kg man^{-1} hour^{-1} in 2000 to ~1 kg man^{-1} hour^{-1} by 2016-2019 (Fig. 2B). Schooners targeted similar species to other whaler-type vessels. Temporal trends in bourgeois and red snapper catch rates were similar to whaler-type vessels, suggesting these fleets target the same stocks (Fig. 6B). However, for schooners, catch rate for carangues increased from 0.1-0.3 kg man^{-1} hour^{-1} over 1991-2012, remaining at 0.15 kg man^{-1} hour^{-1} by 2019, while job catch rates have remained at ~0.15 kg man^{-1} hour^{-1} from 2001-2019. For these species, schooners did not experience the catch declines seen in whaler-type vessels (Fig. 5B), suggesting that schooners may be targeting different fishing grounds or fishing methods.

Across all fleets, trip fishing effort had a negative effect on CPUE, with handline catch rates declining steeply as the trip fishing hours increased (Fig. S1B).

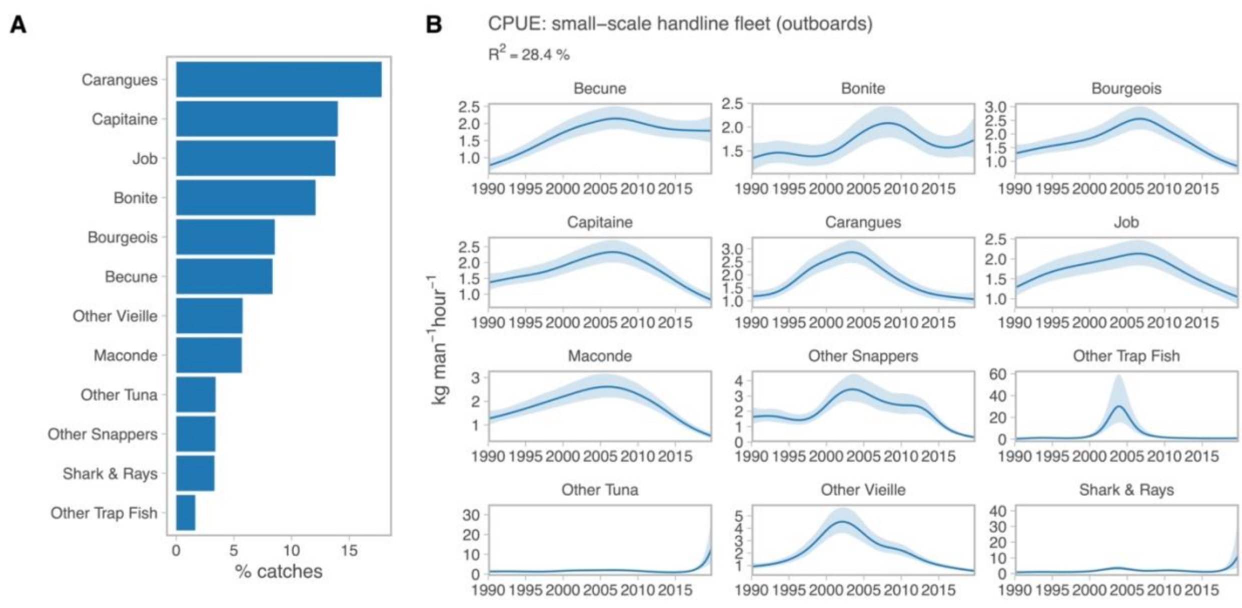

Figure 4 | Handline CPUE of outboard vessels over 1990-2019 for key species groups. A. The proportion of catches of each species group over the time-series. B. Smoothed CPUE trends for each species group and trap gear. Lines are predictions from general additive models, controlling for month, oceanography, location, and total effort. Shaded areas are approximate 95% confidence intervals.

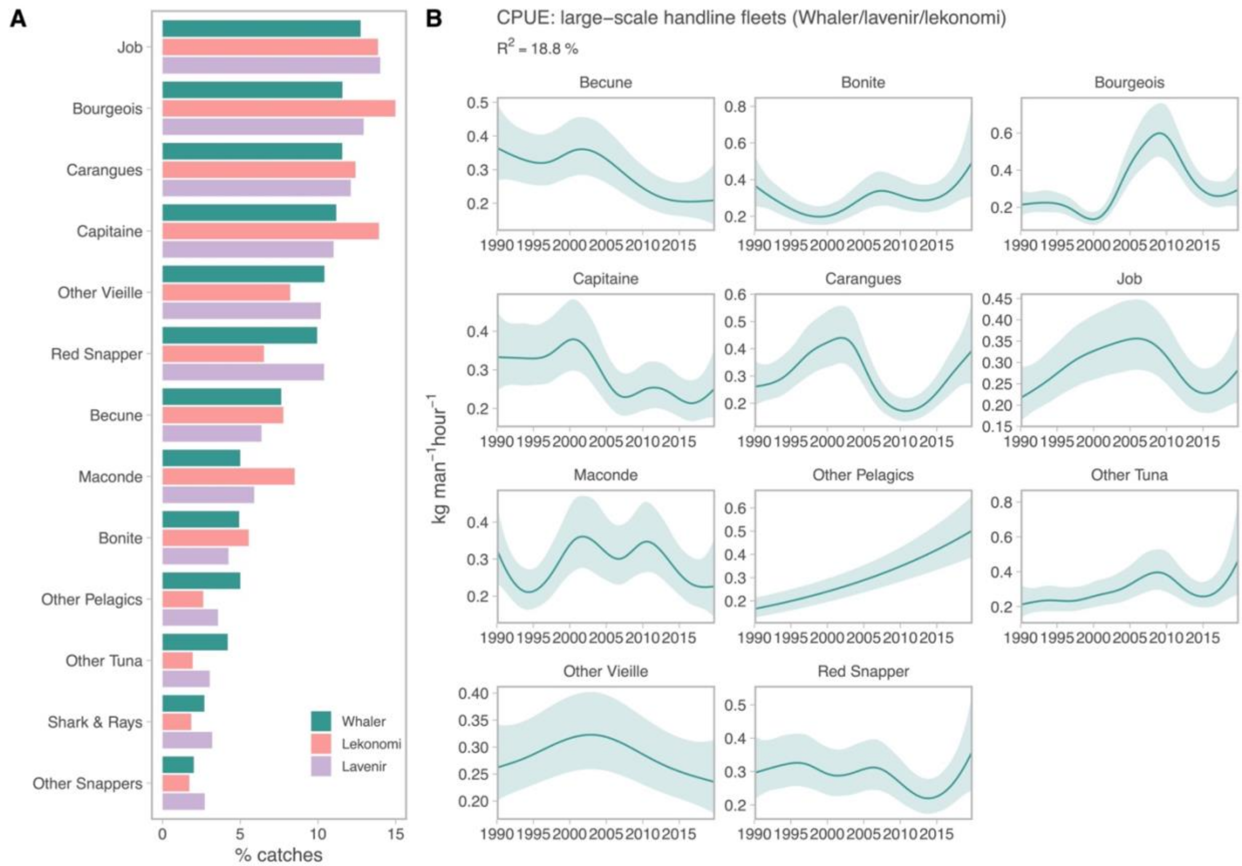

Figure 5 | Handline CPUE of whaler vessels over 1990-2019 for key species groups. A) The proportion of catches of each species group over the time-series, for lavenir (purple), lekonomi (pink) and whaler (green) vessels. **B**) Smoothed CPUE trends for each species group. Lines are predictions from general additive models, controlling for month, oceanography, location, and total effort. Shaded areas are approximate 95% confidence intervals.

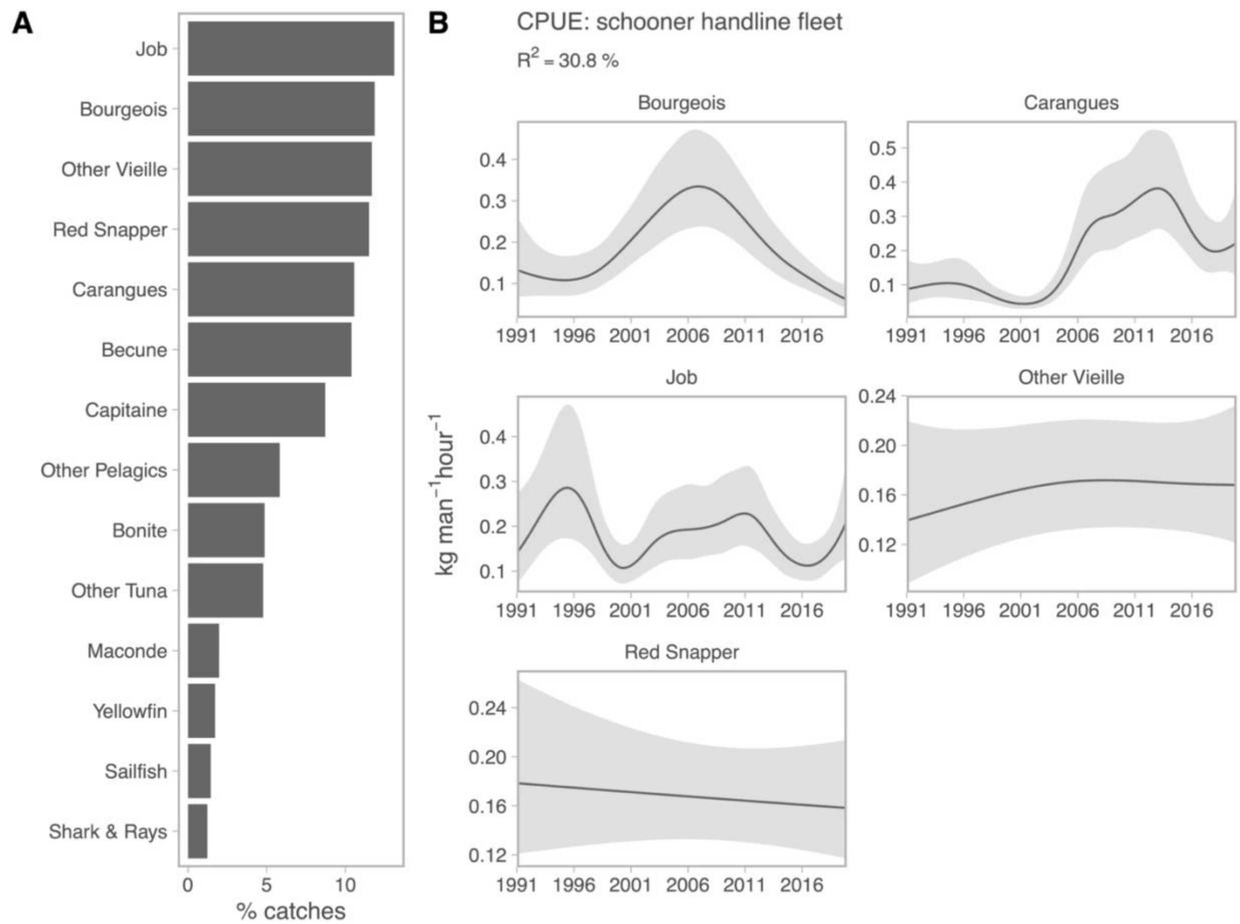

Figure 6 | Handline CPUE of schooner vessels over 1990-2019 for key species groups. A) The proportion of catches of each species group over the time-series. **B**) Smoothed CPUE trends for each species group. Lines are predictions from general additive models, controlling for month, oceanography, location, and total effort. Shaded areas are approximate 95% confidence intervals.

3.1.3 Fishing effort (per fishing trip)

Static trap fishers used more gears on average (6-10 traps trip^{-1}) than active trap fisheries (4-6 traps trip^{-1}) (Fig. 7A). For both gear types, trap effort increased from 1990-2015 before declining slightly over 2016-2019. Outboard vessel fishing effort also increased from ~6-7 hours trip^{-1} over 1990-2010 to 7-8 hours trip^{-1} from 2015-2019 (Fig. 7B). For whaler-type vessels, effort per fishing trip remained steady at ~50 hours trip^{-1} over 1990-2015, before declining to 25 hours trip^{-1} by 2019 (Fig. 7C). Fishing trip effort was similar among whaler-type vessels, despite differences in size and power. Schooner trip effort declined moderately from 80 hours trip^{-1} in 1991 to ~65 hours trip^{-1} in 2019, with high uncertainty across years, suggesting schooner trip effort is highly variable (Fig. 7D).

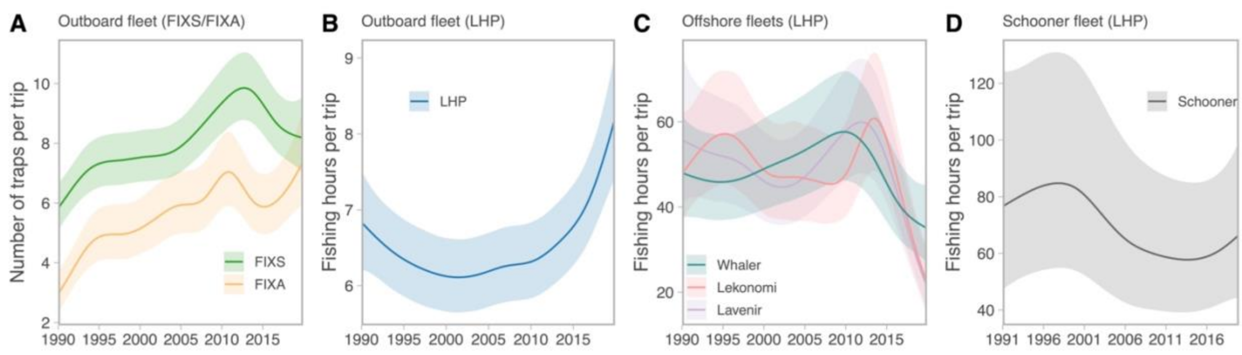

Figure 7 | Fishing effort per fishing trip from 1990-2019. A. The predicted number of traps per trip for outboard vessels using static traps (FIXS, green), active traps (FIXA, yellow). B, C, D. The predicted mean fishing hours per trip for handlines in outboard (blue), lavenir (purple), lekonomi (red), whaler (green) and schooner (grey) vessels. Lines are GAM predictions shaded with 95% confidence intervals.

3.2 Fishing distribution from VMS data

The number of vessels fitted with VMS increased from 37 in 2006 to a maximum 75 in 2014, and down to 66 in 2019 (Fig. 8A). Most VMS-installed vessels were schooners (n = 16-38), followed by whalers (13-21), lavenir (4-12), and lekonomi (4-11). Note that these VMS analyses are biased to a subset of handline vessels that target offshore pelagic and demersal fisheries, and thus are an incomplete view of these fisheries. Across all years and fleets, VMS-installed vessels targeted the entire Mahé plateau and extended to the Amirantes island group, Alphonse, Plate, and Coetivy (Fig. 8B). Most grid cells had 0-1% of total fishing activity, indicating that relative fishing activity was low and vessels were highly dispersed across Seychelles' EEZ. Most vessels fished primarily on the plateau, and thus targeted habitats less than 200m depth. Though effort was widely dispersed across the plateau, fishing hotspots with >1% fishing activity were identified at the North East edge of the plateau, SW of Mahé, and around Frigate island.

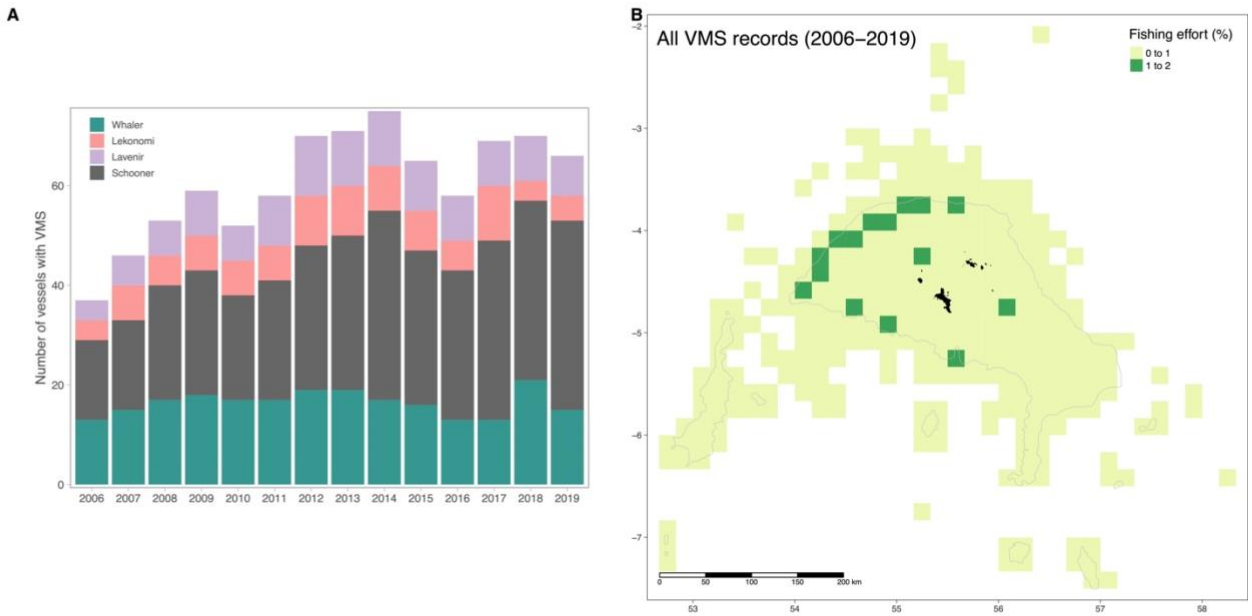

Figure 8 | Number of VMS vessels and time-averaged fishing grounds from 2005-2019. A) Number of VMS-installed vessels recorded in each year. Bars are filled according to fleet (lavenir, lekonomi, whaler, schooner). **B)** The average fishing ground extent of all VMS-installed vessels in lavenir, lekonomi whaler and schooner fleets from 2006-2019. Fishing grounds are divided into 342 km^2 grid cells and coloured by their relative fishing intensity (%), using the total number of VMS tracks as a proxy for fishing intensity. Islands are filled black and the Mahe plateau boundary in black outline.

Fishing hotspots varied among fleets. Schooners and whalers were most widely dispersed, targeting the entire Mahé plateau and all islands, with minimal evidence of fishing hotspots. Lavenir vessels primarily targeted areas on the plateau boundary that were due North of Mahé, whereas lekonomi vessels remained closer to Mahé and Praslin, particularly fishing areas near Frigate island (Fig. 9). Dividing VMS records by year revealed temporal changes in fishing ground location, with VMS records covering the smallest area between 2006-2011 and some areas of the Mahé plateau and Amirantes group not recorded as fished (Fig. S3). However, this may be due to fewer vessels having VMS in these years (Fig. 8A). By 2009, most of the plateau was fished, and vessels had extended to target the entire Amirantes group, which were all targeted from 2009-2019

Maps of VMS tracks in grid cells were used to quantify the potential fishing footprint of VMS-installed vessels across years and fleets. The total fishing ground area covered by all vessels increased from ~60,000 km^2 to ~75,000 km^2 from 2006-2019, which was driven mostly by expansion of schooner, lavenir, and lekonomi fleets (Fig. 10). Fleets also differed in their fishing ground area, with schooners covering the largest fishing ground, followed by whalers, lavenir, then lekonomi vessels. Traditional whaler vessels did not increase fishing ground area from 2006-2019.

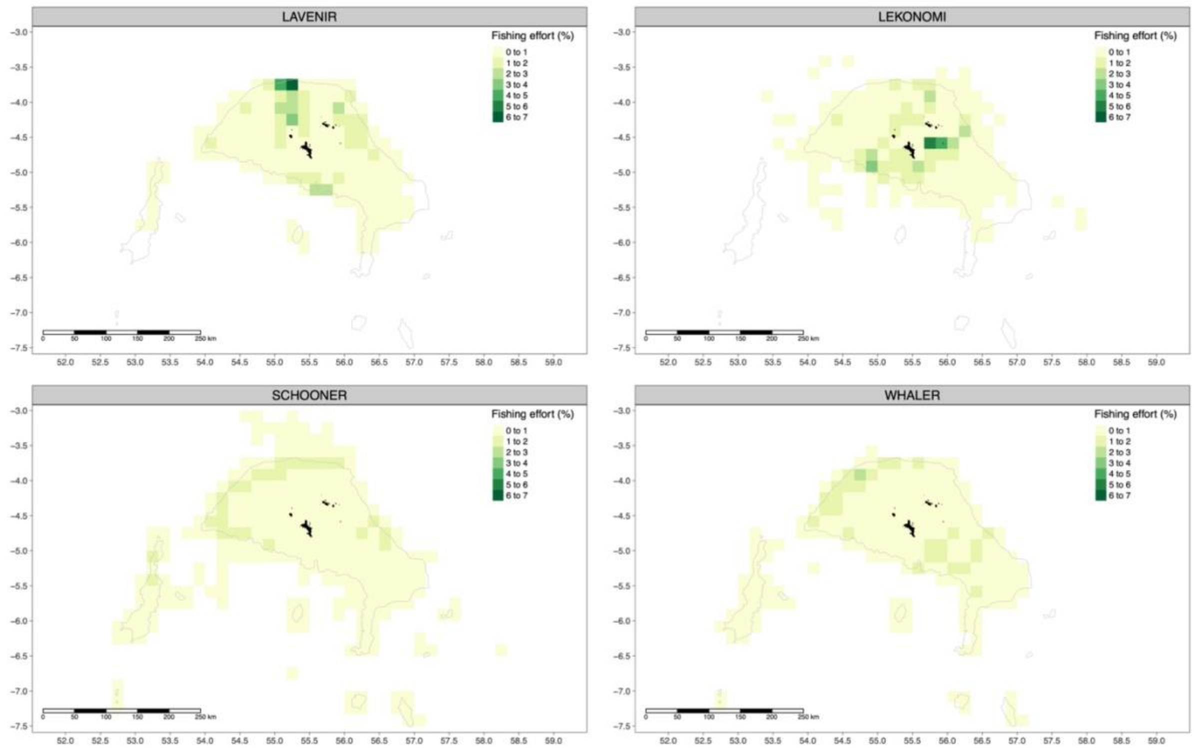

Figure 9 | Variation in fishing grounds among fleets, averaged over 2006-2019. Fishing grounds of lavenir, lekonomi, schooner, and whaler fleets are divided into 342 km^2 cells and coloured by their relative fishing intensity (%). Islands are filled black and the Mahe plateau boundary is in black outline.

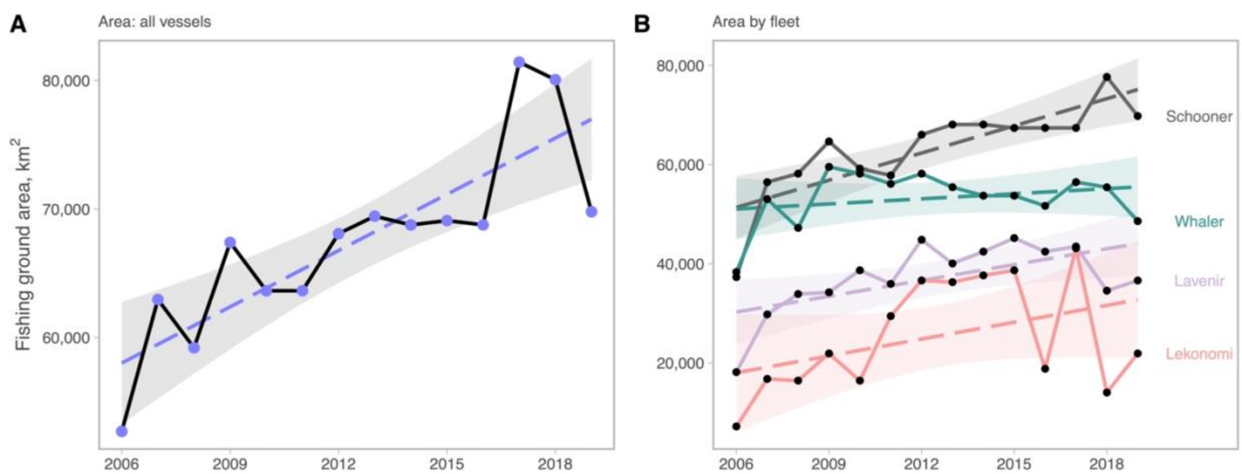

Figure 10 | Change in fishing ground area from 2006-2019 by fleet. Total fishing ground area estimated for all vessels (**A**) and each fleet (**B**). Dashed lines are linear regression fits with shaded 95% confidence intervals.

3.3 Catch-based stock assessments (single-species or family groups)

3.3.1 Becune (Sphyraenidae)

Becune catches declined from a peak of ~300 t in 2002 to a low of ~50 t in 2010, before recovering to ~180 tonnes in 2019 (Fig. 11). Based on these catch levels, for Sphraenidae species that have low resilience to fishing pressure, the catch-based model predicted an MSY of 194 tonnes year^{-1} (110-201 t). Fishable biomass was below B_{MSY} in most years, recovering to 90% by 2019, while catches currently exceed MSY and fishing pressure currently exceeds F_{MSY}. High catch contrast and similarity of species in terms of life history in this catch group lend confidence to this stock assessment.

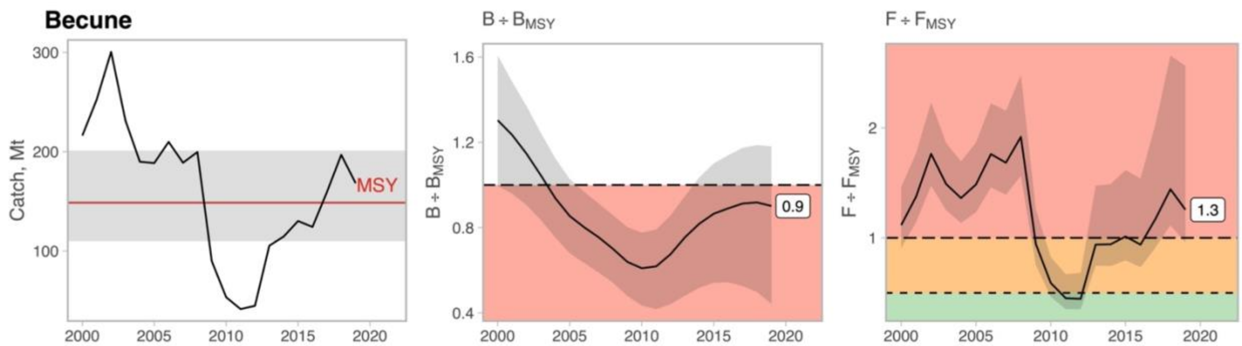

Figure 11 | Catch-based stock assessment for becune (Sphyraena species). Left panel is the catch time series, with MSY catch level in red (95% confidence intervals in grey). Middle panel is the spawning biomass relative to biomass at MSY, where values < 1 indicate stock depletion (shaded red). Right panel is the fishing mortality relative to fishing mortality at MSY, where values > 1 cause depletion (red), values between 0.5 - 1 are below MSY but risk depletion (orange), and values < 0.5 do not risk overfishing (green).

3.3.2 Bonite (*Sarda orientalis* and other bonito species)

Catches of bonite were highly variable from 2000-2019, suggesting CPUE has strong inter-annual fluctuations (Fig. 12). This variability led to a highly uncertain MSY estimate of 142 t (84-237 t), with a range that included most of the historical annual catch values. However, sustained high catch levels (2008, 2009, 2013, 2017) and medium resilience to fishing of *S. orientalis* mean that fishing levels were predicted to have always remained below F_{MSY}, with high certainty.

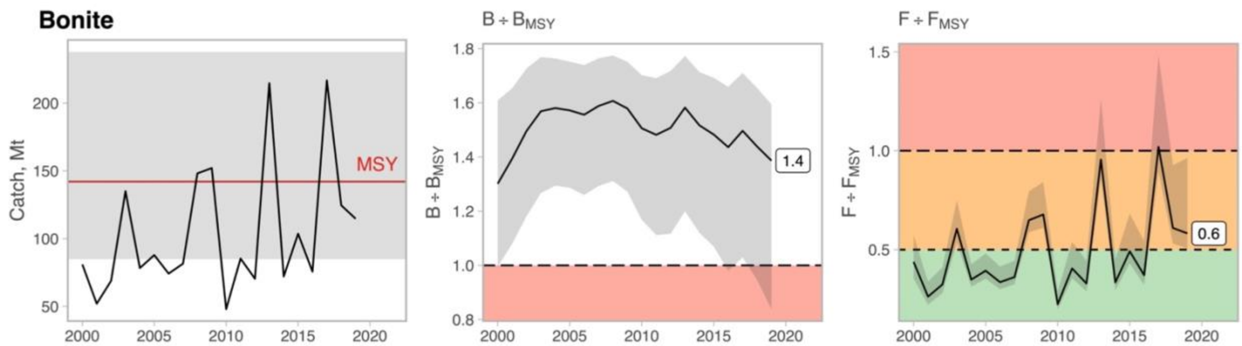

Figure 12 | Catch-based stock assessment for bonite (bonito species, tribe Sardini). Left panel is the catch time series, with MSY catch level in red (95% confidence intervals in grey). Middle panel is the spawning biomass relative to biomass at MSY, where values < 1 indicate stock depletion (shaded red). Right panel is the fishing mortality relative to fishing mortality at MSY, where values > 1 cause depletion (red), values between 0.5 - 1 are below MSY but risk depletion (orange), and values < 0.5 do not risk overfishing (green).

3.3.3 Bourgeois (*Lutjanus sebae*)

Bourgeois is a single-species stock with high productivity and medium resilience to fishing, contributing between 200-1,078 t annual catch (Fig. 13). High CPUE in 2005-2008 caused estimated catches to peak at 1,078 t, before declining to a low in 2012. Recent increases in catch, consistent with improving CPUE (Fig 5B), suggest this stock is returning to MSY levels. Predicted MSY was 501 t (427-587 t), with fishing levels falling below F_{MSY} since 2015. High contrast in this stock, with 5x difference between maximum and minimum catch levels, lend confidence to catch-based MSY estimates.

Across 2000-2019, fishing mortality on *L. sebae* was estimated to be 2-3x higher than in Grandcourt et al. (2008), though that analysis was for 1989-2006 and used a yield-per-recruit model that may not have accounted for the medium resilience of *L. sebae* to fishing mortality. Grandcourt et al. (2008) also noted that their fishing mortality estimates during 2003-2005 (high catches) were likely underestimates due to the lagged effect of overfishing juvenile age classes, whereas the catch-based method used here draws on information from both the high catch period (2005-2008) and subsequent period of low catches (2009-2017).

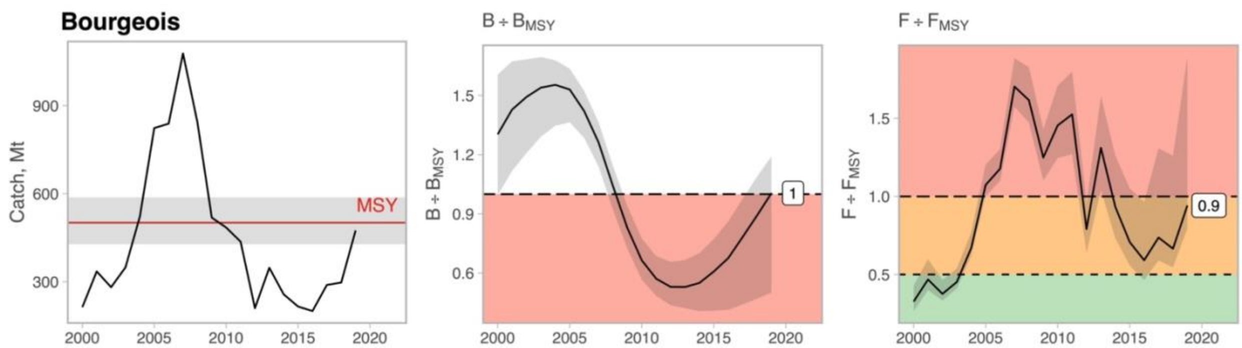

Figure 13 | Catch-based stock assessment for bourgeois (*Lutjanus sebae*). Left panel is the catch time series, with MSY catch level in red (95% confidence intervals in grey). Middle panel is the spawning biomass relative to biomass at MSY, where values < 1 indicate stock depletion (shaded red). Right panel is the fishing mortality relative to fishing mortality at MSY, where values > 1 cause depletion (red), values between 0.5 - 1 are below MSY but risk depletion (orange), and values < 0.5 do not risk overfishing (green).

3.3.4 Carangues (Carangidae species)

Carangues are the largest contributor to total catch, providing 538-2,040 t per year (Fig. 14). Maximum catches were reached in 2002, declining to 500-800 t over 2009-2012, and recovering to ~1100 t by 2017. Catches from 2017-2019 are estimated to be within the MSY of 1106 t (932-1311 t), though biomass is at B_{MSY} and highly uncertain. Fishing mortality has also fluctuated around F_{MSY} in most years, with high uncertainty. Despite recent increase in catch levels, the overall high pressure on carangues (targeting by both outboard and offshore vessels), high uncertainty in stock trends, and current fishing mortality close to F_{MSY} together suggest that this mixed-species stock remains at risk of overfishing.

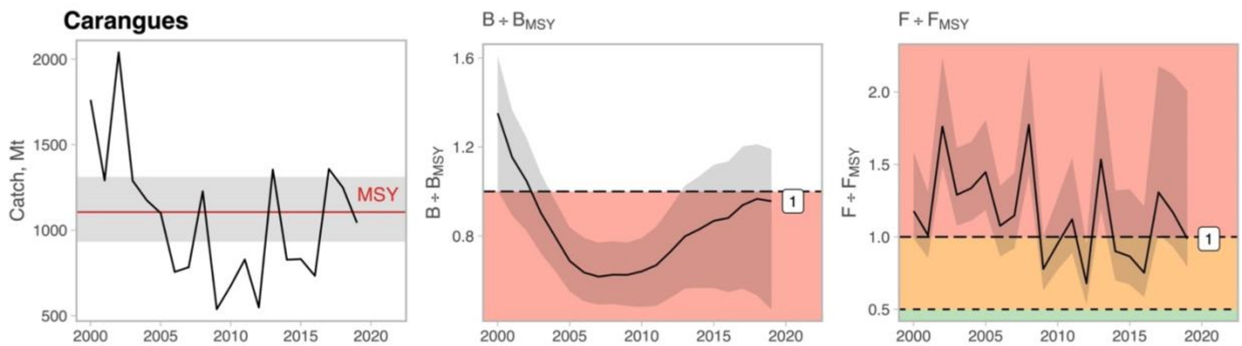

Figure 14 | Catch-based stock assessment for carangues (Carangidae species). Left panel is the catch time series, with MSY catch level in red (95% confidence intervals in grey). Middle panel is the spawning biomass relative to biomass at MSY, where values < 1 indicate stock depletion (shaded red). Right panel is the fishing mortality relative to fishing mortality at MSY, where values > 1 cause depletion (red), values between 0.5 - 1 are below MSY but risk depletion (orange), and values < 0.5 do not risk overfishing (green).

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3.3.5 Cordonier (Siganidae species)

Cordonier are targeted by trap gears and are the most landed species group in those fisheries. Catches have remained constant at 200-300 t per year (Fig. 15). Such low contrast in catch records limits insights from catch-based models, as maximum catches and levels of stock depletion are unknown. MSY estimates were highly variable (329 t, range = 200-538 t), and above current catch levels, indicating that fishable biomass and fishing mortality are both below MSY. Cordonier have high resilience to fishing, and catch rates have remained steady or increased since 1990.

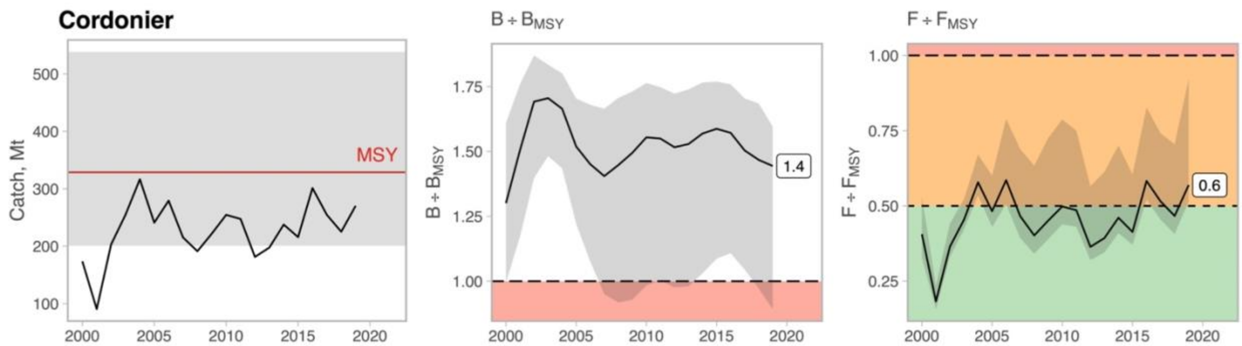

Figure 15 | Catch-based stock assessment for cordonier (Siganidae species). Left panel is the catch time series, with MSY catch level in red (95% confidence intervals in grey). Middle panel is the spawning biomass relative to biomass at MSY, where values < 1 indicate stock depletion (shaded red). Right panel is the fishing mortality relative to fishing mortality at MSY, where values > 1 cause depletion (red), values between 0.5 - 1 are below MSY but risk depletion (orange), and values < 0.5 do not risk overfishing (green).

3.3.6 Job (*Aprion virescens, aphareus rutilans* and other jobfish)

Job contributed the second highest average catch of all species groups, and were targeted by all handline vessels. Catches remained between 500-700 t from 2000-2009, before declining to 200-400 t from 2010-2016 (Fig. 16). Recent years suggest this mixed-species stock has recovered to MSY levels of 496 t (427-576 t), though fishable biomass and fishing mortality are at or above MSY, with high uncertainty.

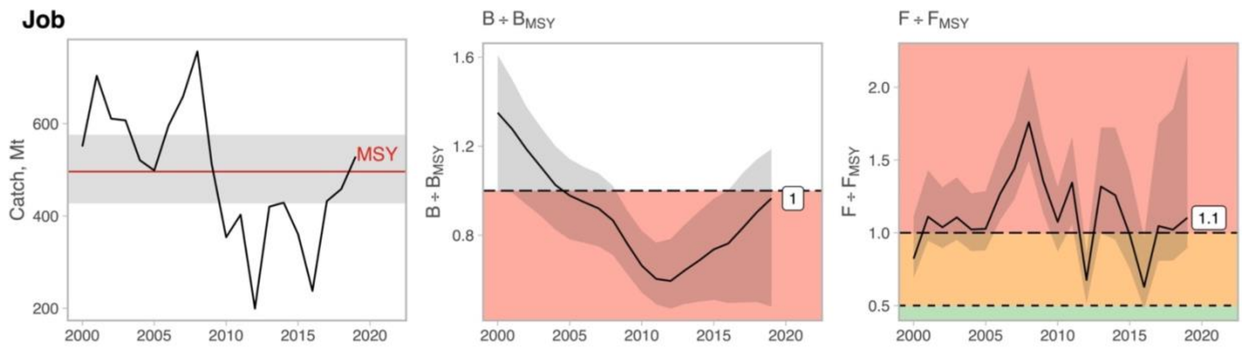

Figure 16 | Catch-based stock assessment for job (jobfish species, family Lutjanidae). Left panel is the catch time series, with MSY catch level in red (95% confidence intervals in grey). Middle panel is the spawning biomass relative to biomass at MSY, where values < 1 indicate stock depletion (shaded red). Right panel is the fishing mortality relative to fishing mortality at MSY, where values > 1 cause depletion (red), values between 0.5 - 1 are below MSY but risk depletion (orange), and values < 0.5 do not risk overfishing (green).

3.3.7 Maconde (*Epinephelus chlorostigma*)

Maconde catches remained around 30-50 tonnes from 2000-2016, before increasing rapidly to over 100 t (Fig. 17). This limited catch contrast limited certainty of the stock assessment, MSY of 57 tonnes predicted with high uncertainty (32 – 99t). The most recent catches of 95 t (2018) and 117 t (2019) suggest stock productivity has at least doubled relative to 2000-2017. Such large catches may indicate that fishers have identified new fishing grounds, increased gear effectiveness, and/or have increased targeting of maconde. Relatively lower historic levels suggest that these high yields are unlikely to be sustained. This stock should be carefully monitored, and further examination of the high raised catch estimates that occurred in the updated CAS system (2017-2019).

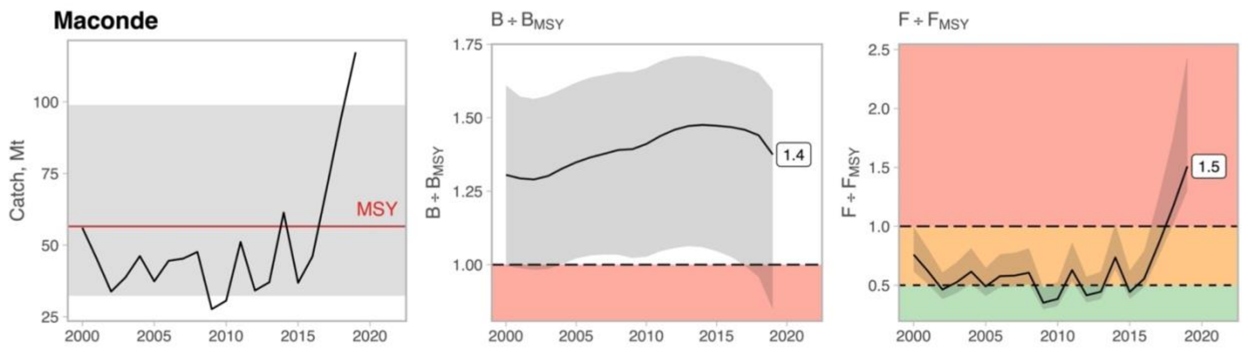

Figure 17 | Catch-based stock assessment for maconde (*Epinephelus chlorostigma*). Left panel is the catch time series, with MSY catch level in red (95% confidence intervals in grey). Middle panel is the spawning biomass relative to biomass at MSY, where values < 1 indicate stock depletion (shaded red). Right panel is the fishing mortality relative to fishing mortality at MSY, where values > 1 cause depletion (red), values between 0.5 - 1 are below MSY but risk depletion (orange), and values < 0.5 do not risk overfishing (green).

3.3.8 Red snapper (*L. bohar, L. gibbus*)

Red snapper catches were between 150-200 t over 2000-2008, before falling to 50-100 t from 2009-2012 (Fig. 18). Since 2017, catches have returned to 145-179 t, which is close to the estimated MSY (148 t, 95% CI = 124-176) and similar to historic high levels. These catch trends suggest that stocks were overfished and depleted between 2005-2010, with fishing pressure reducing from 2010 to reach sustainable limits from 2015-2019.

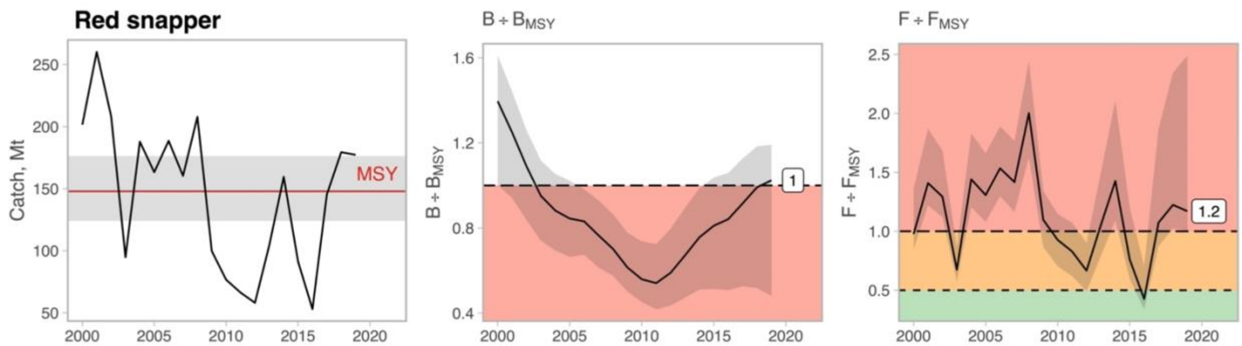

Figure 18 | Catch-based stock assessment for red snapper (*L. bohar, L. gibbus*). Left panel is the catch time series, with MSY catch level in red (95% confidence intervals in grey). Middle panel is the spawning biomass relative to biomass at MSY, where values < 1 indicate stock depletion (shaded red). Right panel is the fishing mortality relative to fishing mortality at MSY, where values > 1 cause depletion (red), values between 0.5 - 1 are below MSY but risk depletion (orange), and values < 0.5 do not risk overfishing (green).

3.4 Catch-based stock assessments (mixed species groups)

3.4.1 Capitaine (Lethrinidae species)

Capitaine are targeted by all vessels and gears, and are characterized by a diverse group of Lethrinidae species. Most species occupy multiple habitats, and thus may be targeted by different gears at different life stages, though have medium resilience to fishing. Annual catch has declined from a maximum 479 t in 2001 to 97 t in 2010, before recovering to ~270 t by 2018 (Fig. 19). Current catch levels are within the estimated MSY of 252 t (213-298 t), though fishable biomass and fishing levels are at MSY. Given high uncertainty in biomass and F values, diversity of species group, and high number of supported fisheries, capitaine appear at risk of overexploitation.

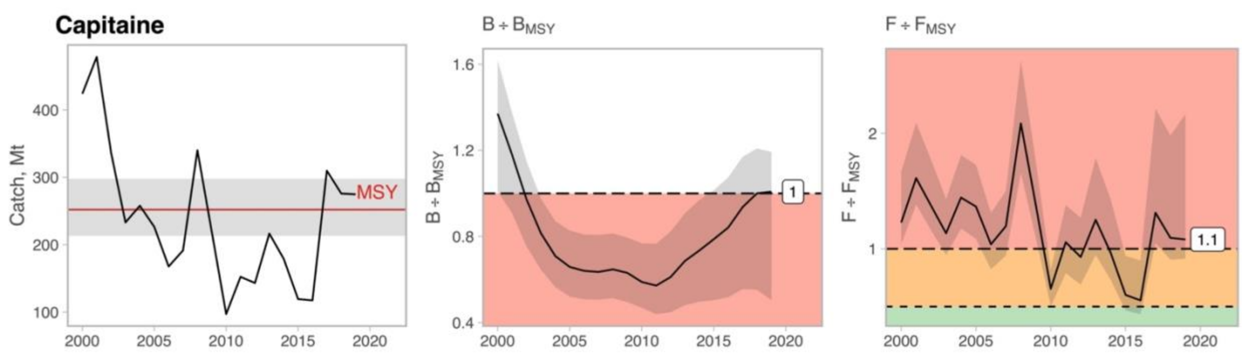

Figure 19 | Catch-based stock assessment for capitaine (Lethrinidae species). Left panel is the catch time series, with MSY catch level in red (95% confidence intervals in grey). Middle panel is the spawning biomass relative to biomass at MSY, where values < 1 indicate stock depletion (shaded red). Right panel is the fishing mortality relative to fishing mortality at MSY, where values > 1 cause depletion (red), values between 0.5 - 1 are below MSY but risk depletion (orange), and values < 0.5 do not risk overfishing (green).

3.4.2 Other trap fish (mixed reef fish species)

Other trap fish are the most speciose group, containing over 30 species of reef-associated fish, including species of parrotfish, goatfish and wrasse families. These species have different life histories, growth rates, and resilience to fishing, meaning catch-based assessments have limited power. Catches have declined from ~200 t in 2000 to fluctuate around 125-160 t from 2001-2014, before increasing to their highest level of 251 t by 2019 (Fig. 20). Biomass and fishing mortality are predicted to be above MSY, though the confounding aspect of multiple species with difference resilience levels make this reference point less reliable. Stock assessments for this group would be greatly improved by generating raised catch estimates for specific families that are likely to share life history traits. This will soon be possible using the new CAS that records single species catches from traps. The simplest, standardized method of doing this would be to divide species into family groups, and estimation of raised catches prioritized for the families that contribute to ~80% of the proportion of catch in CAS. These groups could be identified from 2017-2019 data using the new species-level catch information (e.g. Scaridae, Mullidae and Labridae codes in Table 1).

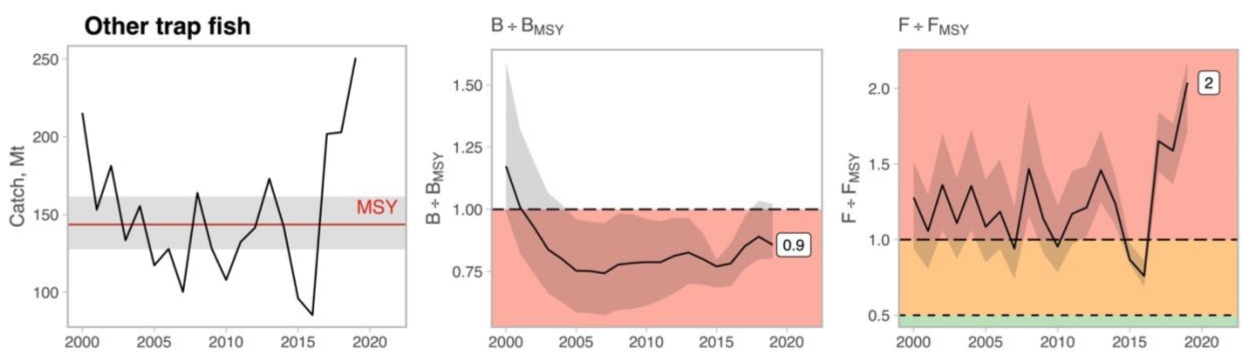

Figure 20 | Catch-based stock assessment for trap fish (mixed reef fish group) Left panel is the catch time series, with MSY catch level in red (95% confidence intervals in grey). Middle panel is the spawning biomass relative to biomass at MSY, where values < 1 indicate stock depletion (shaded red). Right panel is the fishing mortality relative to fishing mortality at MSY, where values > 1 cause depletion (red), values between 0.5 - 1 are below MSY but risk depletion (orange), and values < 0.5 do not risk overfishing (green).

3.4.3 Other vielle (Serranidae species, groupers)

Groupers were caught by trap and handlines, in both inshore and offshore fleets, and this catch group contains multiple species. Though Serranidae species share life history traits, it is likely that different gears and fleets target different age classes, which may confound stock assessments based on raised catch across fleets. Catch fluctuated between 50 and 100 t between 2000-2013, before reaching mostly high catches over 100 t (2014, 2015, 2017, 2018, 2019), though 2016 had very low catches (Fig. 21). MSY was estimated at 93 t, with large uncertainty (53-162 t).

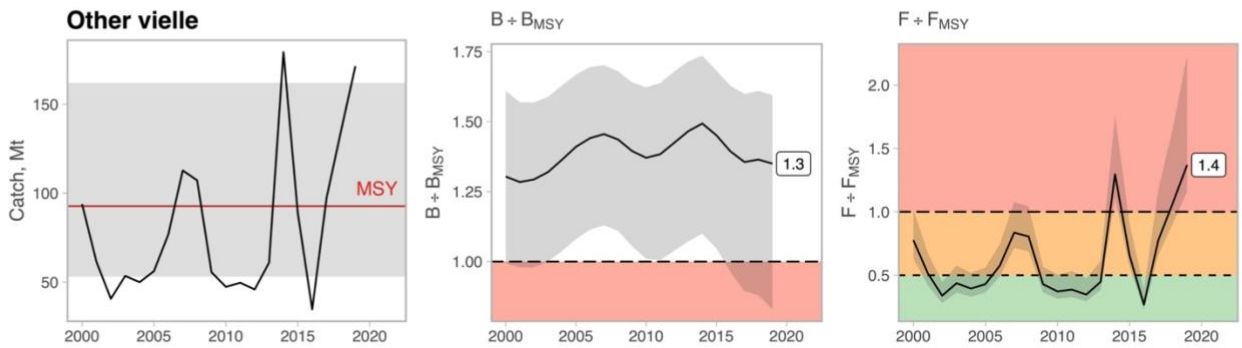

Figure 21 | Catch-based stock assessment for other vielle (family Serranidae, groupers). Left panel is the catch time series, with MSY catch level in red (95% confidence intervals in grey). Middle panel is the spawning biomass relative to biomass at MSY, where values < 1 indicate stock depletion (shaded red). Right panel is the fishing mortality relative to fishing mortality at MSY, where values > 1 cause depletion (red), values between 0.5 - 1 are below MSY but risk depletion (orange), and values < 0.5 do not risk overfishing (green).

3.5 Total effort for fleets and gears

Raised catch estimates are based on the raised effort and catch-per-unit-effort of each species, gear type and fleet. Raised effort trends can therefore be used to contextualize the stock assessment results. Outboard vessels using handlines decreased total fishing effort (men days) from 2000-2012, before increasing and returning to ~2000 levels by 2016 (Fig. 21A). Schooners increased fishing effort until 2012, before declining to ~2000 levels by 2016. However, whaler-type vessels (i.e. lekonomi, lavenir, traditional whalers) declined in total men days, from ~40,000 in 2000 to ~20,000 by 2016. The total number of traps deployed by outboard vessels was variable over time, but with no predictable trend, remaining at ~16,000 active traps and ~58,000 static traps deployed per year (Fig. 22B). Combined across fleets, these raised effort trends indicate an overall decrease in handline effort, with men days decreasing from ~50,000 in 2000 to ~25,000 by 2016 (Fig. 23B). The total number of traps deployed (static and active) remained at an average ~75,000 traps per year (Fig. 23C).

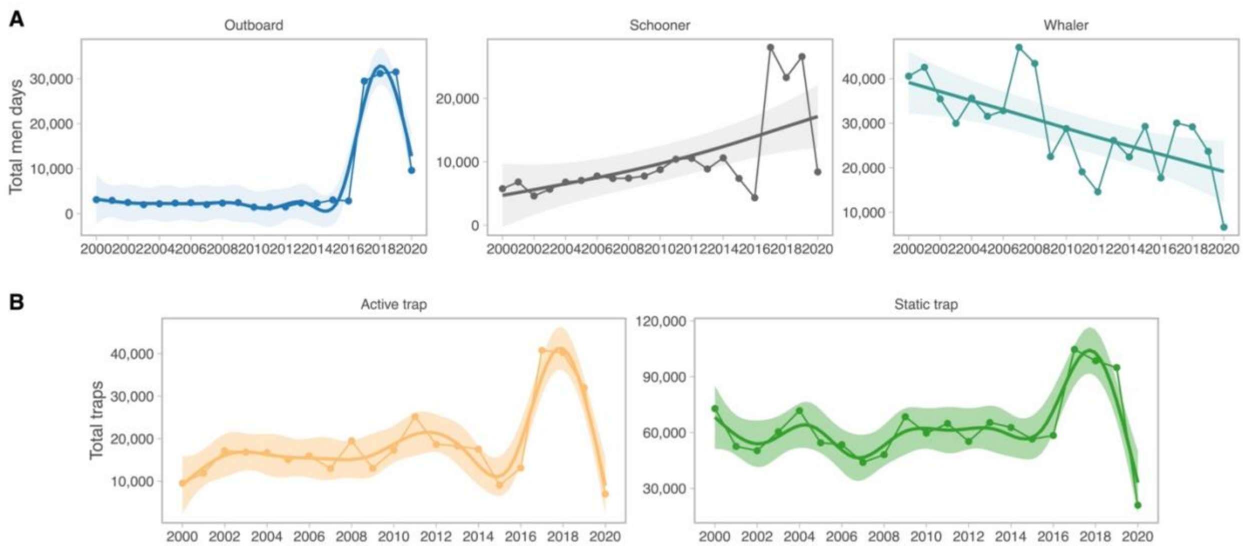

Figure 22 | Total men days and traps deployed from 2000-2016. Annual estimates of raised effort are shown for handlines (A) and traps (B), separated by fleets. Points are annual estimates, with fitted GAM smoothers and 95% confidence intervals. Note raised effort data for 2017-2019 were unavailable.

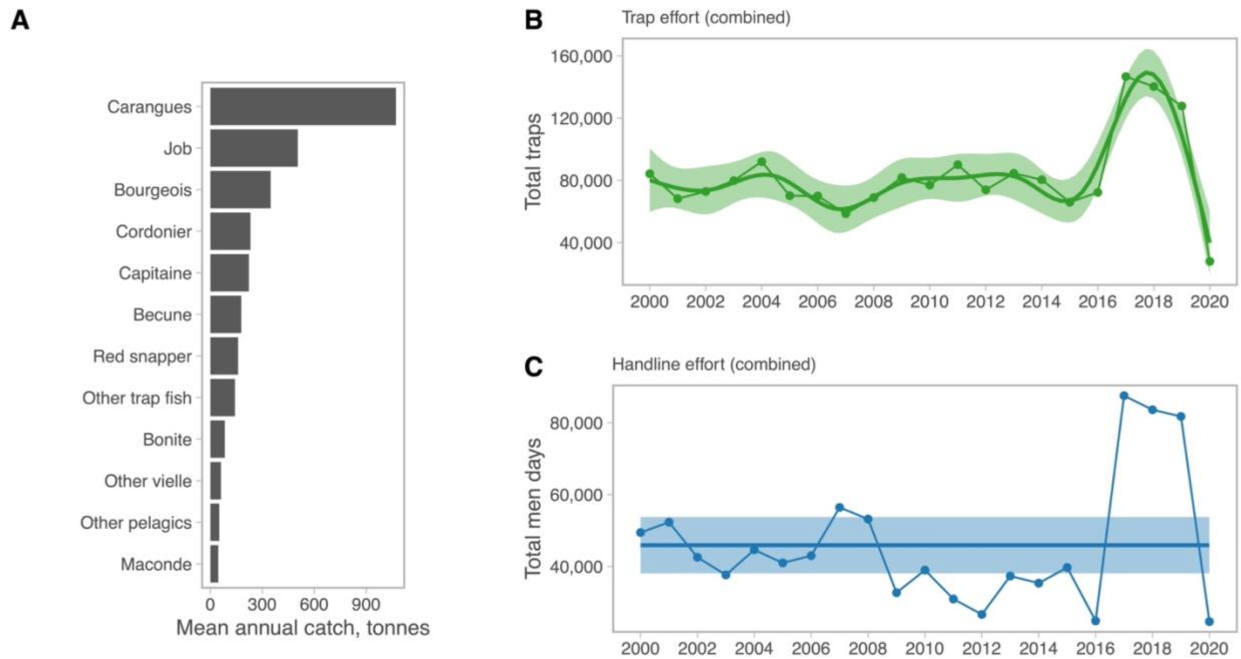

Figure 23 | Average total catch composition, and total effort across all fleets from 2000-2016. A) Barplots show the mean total landed weight of each species group analyzed in stock assessments. Total effort is shown for handlines (B) and traps (C), combined across fleets. Static and active traps are also combined. Points are annual estimates, with fitted GAM smoothers and 95% confidence intervals. Note raised effort were not available for 2017-2019.

	r (growth rate)			k (carrying capacity)			MSY			F_{MSY}			B_{MSY}		
	Estimate	Lower	Upper	Estimate	Lower	Upper	Estimate	Lower	Upper	Estimate	Lower	Upper	Estimate	Lower	Upper
Carangues	0.553	0.393	0.777	7998.48	5320.95	12023.35	1105.68	932.38	1311.18	0.276	0.197	0.389	3999.24	2660.48	6011.68
Bonite	0.566	0.407	0.785	1005.03	556.82	1813.99	142.09	84.90	237.82	0.283	0.204	0.392	502.51	278.41	907.00
Becune	0.282	0.163	0.487	2106.28	1045.39	4243.79	148.62	109.84	201.10	0.141	0.082	0.244	1053.14	522.69	2121.90
Cordonier	1.191	0.957	1.482	1103.97	689.93	1766.48	328.77	200.79	538.33	0.596	0.479	0.741	551.98	344.96	883.24
Other trap fish	0.566	0.407	0.785	1015.41	688.84	1496.79	143.56	127.56	161.57	0.283	0.204	0.392	507.70	344.42	748.40
Red snapper	0.541	0.383	0.762	1094.09	731.04	1637.43	147.88	124.03	176.30	0.270	0.192	0.381	547.04	365.52	818.72
Bourgeois	0.557	0.395	0.785	3599.95	2403.77	5391.39	501.39	427.88	587.52	0.279	0.198	0.393	1799.98	1201.89	2695.70
Job	0.561	0.405	0.777	3534.88	2365.80	5281.66	496.03	427.23	575.92	0.281	0.203	0.389	1767.44	1182.90	2640.83
Maconde	0.282	0.163	0.487	801.21	348.82	1840.30	56.53	32.32	98.89	0.141	0.082	0.244	400.60	174.41	920.15
Other vielle	0.282	0.163	0.487	1313.96	572.27	3016.90	92.71	53.04	162.06	0.141	0.082	0.244	656.98	286.14	1508.45
Capitaine	0.529	0.370	0.755	1906.93	1288.85	2821.41	252.01	213.18	297.90	0.264	0.185	0.377	953.46	644.43	1410.70

Table 2 | MSY reference points for species groups analyzed in catch-based stock assessments. r (growth rate) and k (carrying capacity) were estimated based on the species group resilience to fishing, and historic catch trends. These values then inform the MSY catch level and the fishing mortality (F_{MSY}) and spawning biomass (B_{MSY}) at MSY.

3.6 Length-frequency data: *Lutjanus sebae* (Bourgeois)

Length frequency distributions indicate that the median captured fish over 1989-2020 ranged from 54-66.5 cm (Fig. 24). The median landed fork length was also similar to the *L. sebae* length at maturity (62 cm, Grandcourt et al. 2008) (Fig. 24B), meaning that a large proportion of immature individuals were targeted (20-75%) (Fig. 24C). However, there were subtle shifts in age and size-at-capture over time. The median fork length of captured fish increased from ~60 cm between 1989-2005 to 63 cm from 2007-2020. The fork length of mature fish was constant over time (~67 cm), indicating that these long-term changes in size frequency distributions were driven by slight increases in the size of captured immature fish. Decreases in median fork length corresponded with a slight increase in the proportion of juvenile fish in catch, from ~50% between 1989-2001 to >50% from 2003-2005 (Fig. 24C). Since 2005, targeted *L. sebae* are older (median age ≥ 10) and larger (median fork length ≥ 62 cm) than 1989-2004, with the smallest proportion of juvenile fishes in catch (<50%). The slight increase in median age and size and decrease in proportion of immature fish suggest the risk of growth overfishing has reduced over time, though targeting of juveniles is likely to impact future stock health.

Figure 24 | Age and size structure of targeted *Lutjanus sebae* from 1989-2020. A) Median age of targeted fishes, based on an age-length key and model from 2000. **B)** Median fork length of captured fish (cm). Lines indicate the median age and length for all fish (black), immature (red) and mature (grey) fish, assuming length of maturity is 62 cm and age at maturity is 9 years. **C)** The proportion of juvenile fish (%), where age at maturity is 9 years. Annual age and size distributions are shown in Figs. S4 and S5.

4. Stock status & management recommendations

4.1 Stock status

I next interpret the MSY, CPUE and effort trends for each species group. All stocks except *L. sebae* lack data on population size structure and fishing selectivity, meaning it was not possible to confidently identify the likely drivers of stock status. Comparing the above MSY estimates with Gutiérrez (2015) is not possible, as that analysis was based on daily catch surveys and did not account for total effort in the fishery (i.e. the raised catch).

4.1.1 Handline fisheries

Whaler-type and schooner vessels (i.e. large-scale) exerted the most fishing pressure on Seychelles' handline fishery. These fleets thus accounted for the majority of landed catch, with this high fishing effort likely driving most CPUE patterns across the Mahé plateau. These vessels targeted demersal and pelagic species groups (Fig. 4A), most of which were estimated to have fishing mortality close to MSY between 2016-2019 (Fig. 25A). Recent catch levels and fishing mortality are therefore likely to be sustainable, if fishing pressure does not increase substantially. However, with recent declines in total fishing effort, current catch levels of most species groups have recovered from a period of stock depletion. This occurred for most species groups over 2005-2015 (Fig. 25B), including becune, bourgeois, capitaine, carangues, job, and red snapper. These groups therefore have the potential for stock recovery despite overfishing, and without harvest or effort controls being applied. For most groups, stock recovery, rising catches, and decrease in fishing effort in recent years has occurred as CPUE has increased and handline effort has decreased (Fig. 23). VMS data also indicate an expansion of fishing grounds by whalers and schooners (Fig. 10). Together, these effort metrics suggest that recent periods of catch declines have caused fishers to reduce fishing activity, while those vessels that remain must fish further and longer to maintain catches. The reasons for declining effort are unclear, though likely include economic factors such as market price for catch, fuel and maintenance costs, and crew availability. I next assess the fishery status of each species group in turn, ranked in order of total catches (Fig. 23A).

Carangues and job were the top two landed species groups across all artisanal fisheries. These species groups were assessed at close to their MSY limits, with both fishing mortality and spawning biomass close to MSY (Fig. 25A). Though current fishing levels may sustain catch levels into the future, both groups were depleted in 2008 and had low spawning biomass from 2010-2015 (Fig. 25B), suggesting that high fishing pressure can quickly deplete these stocks. For the large-scale fleet, carangues and job had similar CPUE trends, increasing from 1990-2000 before declining to 2010 (carangues) and 2015 (job), and increasing by 2019. Carangidae and job are semi-pelagic fishes with resilience to fishing of ~0.5 (Table 2) and similar maturation ages (1.3 and 2.2, respectively), and thus may be expected to have experienced similar fishing mortality. These two species were targeted by whaler-type vessels and schooners, but fleets had contrasting temporal patterns in catch rate (Figs. 5, 6) whereby schooners sustained a constant long-term CPUE while whaler-type vessels experienced CPUE declines. This may be explained by the greater fishing ground area of schooners (Fig. 10), suggesting that pelagic stocks may be more depleted nearer to Mahé and Praslin. Inshore fishing effort is likely to be higher, with smaller vessels clustered within smaller fishing grounds. Outboard and small whaler-type vessels may therefore be targeting overlapping stocks, causing a competitive lowering of CPUE, whereas larger whalers and schooners can fish over larger areas with less competition.

For bourgeois (*L. sebae*), the third most landed species, catch rates for the large-scale fleet increased 4x from 1990-2000, producing a substantial increase in total catch. These catch patterns were driven by whaler-type vessels that accounted for the majority of bourgeois total catch, and likely due to increased targeting of juvenile fish between 2001-2004 (>50% of individuals, Fig 24C). Increased targeting of juveniles (Fig. 24C) also suggests that the *L. sebae* stock had a strong juvenile cohort over 2001-2004, which may have supported high catch rates over 2007-2008. High catchability and increased fishing effort in this period likely contributed to the subsequent stock depletion and low catches over 2010-2015. Recent increases in CPUE suggest the stock has recovered spawning biomass and catches have returned within sustainable limits. The average age and size of fish is now slightly higher than the 2001-2004 catch period, and juvenile fish comprise <50% of individuals, suggesting that growth overfishing is no longer occurring.

Other handline targets were more sustainable, with bonite, maconde and other vielle generally having fishing mortality below F_{MSY} and sustainable levels of spawning biomass. Of these groups, large-scale catch rates of demersal species were highly variable but did not decline from 1990-2019 (maconde, other vielle), and catch rates of pelagic bonite steadily increased from 2000-2019 (Fig. 4B). These species groups have the lowest total catch of any fishery analyzed in these stock assessments, suggesting these stocks are less productive than other pelagic and demersal species and so are not preferentially targeted by fishers. For these groups, lighter fishing pressure, relative to carangues, job, and bourgeois, likely has helped to keep spawning biomass within sustainable limits. As with other pelagic and demersal stocks, it was not possible to identify shifts in the age and size structure of these populations.

Catch rates of the remaining large-scale handline species groups have either declined (becune, red snapper) or steadily increased (other pelagics, other tuna). Both becune and red snapper were estimated to be in stock depletion from 2004-2019 (Fig. 25A), suggesting that these stocks were unable to sustain the current level of fishing pressure on the Mahé Plateau. Catches of mixed pelagics and tuna species were not sufficient for a catch-based stock assessment, though the steady increase in catch rates (Fig. 4B) suggest these species may become more important in the artisanal sector.

The outboard handline fisheries (i.e. small-scale) targeted the same species groups as large-scale vessels but had contrasting catch rates. For all species groups, catch rates peaked around 2005 and were at their lowest levels by 2019 (Fig. 3B). These trends, across diverse species from pelagic and demersal habitats, suggest that the stocks available to outboard vessels have become depleted. Such patterns might be expected because the outboard vessels have a far smaller fishing range than whalers and schooners, and thus their fishing effort is concentrated on inshore fishing grounds. However, spatial information on outboard fishing grounds, and size and age composition of outboard catches, is needed to confirm stock status.

4.1.2 Trap fisheries

Trap fisheries were less important by weight than handline fisheries, but the outboard fleet is considerably larger than whaler-type vessel fleet, underlining the importance of trap fisheries for employment and livelihoods in Seychelles. Cordonier are only targeted by traps and were the 4th most landed species group (Fig. 23A), reflecting their high cultural importance and long-term contribution to domestic seafood supply (Robinson et al. 2007, 2011). This group is represented by macroalgal-feeding Siganidae species, primarily *Siganus sutor* (Robinson et al. 2011). Fishery-independent diver survey data suggests these species have increased in biomass in the last 20 years, owing to their fast growth rates (Table 3) and positive response to increased macroalgal cover in shallow reef habitat (Robinson et al. 2019). Diver survey data also indicated that Siganidae size structure has not been negatively impacted by coral decline or fishing pressure, with high abundance of small body sizes in 2011 and 2014. Though diver surveys were only conducted every three years between 2005-2017, the increased biomass, positive association with macroalgal cover, and intact size distributions suggest that cordonier can sustain high fishing pressure despite coral loss and are likely to remain an important target species group in the future. The stock assessments presented here suggest that cordonier have been fished within sustainable limits from

2000-2019 (Fig. 25), which is consistent with previous assessments that Siganidae species have not been overfished in Seychelles (Robinson et al. 2011).

In contrast, two reef-associated groups (other trap fish and capitaine) contain many species that are known to rely on habitat structure provided by corals. Diver survey data also suggest that biomass of these species have increased in biomass since mass bleaching, particularly parrotfish which have likely benefited from increased algal availability and the return of branching coral habitat over 2005-2014 (Robinson et al. 2019). However, these reefs bleached again in 2016 and 2017, resulting in mass coral mortality and loss of habitat structure (Wilson et al. 2019), which may have impacted reef fish populations. For the other trap fish group, fishing mortality reached its highest levels in 2017-2019. Given the high importance of Scaridae, Labridae, and Lethrinidae to outboard catches, and likely impact of recent coral declines, monitoring of catch composition would help to assess whether bleaching-induced coral declines have caused shifts in fish community composition.

For both fixed and active traps the overall fishing trip catch rate increased steadily from 2010-2017, and yet catch rates have declined for all trap species groups. This suggests fishers are maintaining catch rates by catching multiple species groups, which has caused a corresponding 2-4x increase in catch diversity (Fig. S2A). Declining species-level catch trends was therefore obscured by increases in trip-level CPUE. Declining species catch and increase overall catch is also indicative of growing catch instability in trap fisheries (i.e. higher variability), that has previously been linked to climate-driven shifts in benthic and fish composition on shallow reef habitat (Robinson et al. 2019). Further investigation into these trends would benefit from monitoring of fishing ground location and interviews of fisher behaviour (e.g. targeting of single or multiple species). Given the rapid and ongoing impacts of climate change (particularly marine heatwaves and coral bleaching) in reef systems in Seychelles, further analysis of species-level trends for reef-associated fishes is urgently needed.

Figure 25 | MSY reference points for all species groups from 2000-2019. A) Fishing mortality (F) relative to F_{MSY}, where green colours indicate fishing mortality below F_{MSY} and red colours indicate fishing mortality above F_{MSY}. Fishing mortality close to F_{MSY} is yellow. B) Spawning biomass (B) relative to biomass at MSY (B_{MSY}), where red colours indicate depleted biomass (below B_{MSY}) and green colours indicate sustainable biomass levels (above B_{MSY}). Reference point values are provided in Table 2.

4.2 Management options

Seychelles' artisanal fleets have always operated in open-access fisheries, presenting difficulties for introducing formal harvest controls. However, the Mahé Plateau Trap and Line Fishery Co-management Plan was recently designed to improve the sustainability of Seychelles' artisanal fisheries, based on the results of an earlier stock assessment (Gutiérrez 2015). There are opportunities to develop co-management practices, whereby fishery resources are owned by fishers with engagement and advice from SFA. I consider co-management options for regulating fishing of key stocks and fishing grounds, such as carangues, *L. sebae*, jobfish, and Siganidae. These four groups are represented by one or more species with similar life history, are major contributors to total catch, and represent the most frequently caught species in three fisheries types (handline-pelagic, handline-demersal, trap-coastal).

4.2.1 Semi-pelagics (Carangidae and jobfish)

Carangidae and jobfish are semi-pelagic species groups. Fishers targeting these species may have large fishing grounds but there is little information on spatial variability in catch rates, and on the age and size composition of populations. Mobility of these species is also likely to confound analyses of spatial patterns in catch rates. As with most stocks that were depleted over 2005-2009, the return to historic catch levels suggests that these species can recover from overfishing. However, it is not possible to identify if stocks were depleted due to overfishing (e.g. growth or recruitment), or a combination of fishing pressure and adverse environmental conditions. Indeed, declining catch rates in both whaler-type vessels and outboard vessels suggests that populations may be depleted in inland locations.

Given that these species groups contribute ~50% of total artisanal catch, data collection of size and age composition, and fishing ground location should be prioritized. These data can be used to improve understanding of fishery dynamics. If VMS data can be linked with existing CAS surveys, this would be an effective way of identifying temporal patterns in species-specific fishing grounds (for example, identifying if schooners, whalers and outboards target semi-pelagic species in different areas). If monitoring data indicated risk of overfishing, life history information should be used to inform harvest controls, for example ensuring juveniles are not targeted by setting a minimum catch size of 23 cm (Carangidae) and 35 cm (job) (Table 3).

4.2.2 Cordonier (Siganidae)

In contrast, Siganidae species form spawning aggregations that are often targeted by fishers. Though the stock is within sustainable limits, precautionary protection of spawning sites would require data to be collected on fishing ground locations. Spatial catch data would help to identify locations where spawning aggregations are known to form, building on extensive research on Siganidae spawning behaviour (Robinson et al. 2007, 2011; Bijoux et al. 2013). Indeed, trap fisher associations on Mahé and Praslin have recently begun to implement local fishery closures of nursery habitat, aimed at minimizing overfishing of Siganidae. Such spatial protection may be effective in protecting fishable biomass if spawning aggregations are relatively transient and thus move in and out of protected areas. Studies of Siganidae spawning behaviour in Seychelles do indicate that spawning site fidelity is high (Bijoux et al. 2013), such that co-management and local fishery closures to protect aggregations may be the most effective management strategy for this fishery.

4.2.3 Bourgeois (*L. sebae*)

L. sebae also form resident spawning aggregations, but our understanding of key fishing grounds is less developed, particularly lacking evidence on where fishers may target these aggregations. Given that this stock is targeted across most of the Mahé Plateau, it may not be possible to survey most *L. sebae* aggregation sites with sufficient accuracy. Area closures in key spawning sites may help to minimize growth overfishing, as stock depletion of *L. sebae* was linked to changes in population size structure, targeting of juveniles, and subsequent exhaustion of a strong cohort. Analyzing size-frequency annually also would help to inform fishery managers of the current risk of growth overfishing and thus inform the timing and extent of area closures. Alternatively, harvest control options for this fishery would involve setting limits of minimum landed size, for example requiring fishers to only catch mature individuals (≥ 62 cm), but this risks mortality from barotrauma and is unlikely to be effective (Grandcourt et al. 2008).

Species group	Species name	Family	Age at maturity (years)	Length at maturity (cm)	Natural mortality (yr^{-1})	Maximum length (cm)	Maximum age (years)
Becune	Mixed	Sphyraenidae	2.4	25.9	0.5	49.1	9.7
Bonite	*Sarda orientalis*	Scombridae	3.1	62.5	0.4	132.4	9.3
Bourgeois	*Lutjanus sebae*	Lutjanidae	4.4	45.3	0.2	89.7	24.2
Capitaine	Mixed	Lethrinidae	2.6	23.3	0.5	41.4	12.0
Cordonier	*Siganus sutor*	Siganidae	2.2	25.7	0.8	37.1	8.8
Carangues	Mixed	Carangidae	1.3	22.7	1.0	43.7	6.2
Job	*Aprion virescens*	Lutjanidae	2.2	35.4	0.5	79.6	8.8
Maconde	*Epinephelus chlorostigma*	Serranidae	5.5	37.4	0.3	73.1	15.8
Red snapper	*Lutjanus bohar, Lutjanus gibbus*	Lutjanidae	2.8	33.4	0.3	66.6	13.2
Other trap fish	Mixed	Scaridae	2.2	22.6	0.4	39.4	11.0
Other tuna	Mixed	Scombridae	2.0	40.2	0.7	74.8	7.2
Other vielle	Mixed	Serranidae	4.4	25.8	0.4	46.1	13.2

Table 3 | Key demographic parameters of target species groups. Age and length at maturity, maximum age and maximum length, and natural mortality extracted from Fishlife (Thorson et al. 2017), either for single species or average family values for mixed species groups. Note that estimates for *L. sebae* exist for Seychelles which indicate individuals are longer-lived than the values shown here (age at maturity = 9 years, length at maturity = 62 cm, natural mortality = 0.12) (Grandcourt et al. 2008).

4.3 Data quality and monitoring

The CAS system has impressive scope for monitoring fisheries, and is well-suited for estimation of abundance indices (e.g. CPUE), effort patterns, and total catch. However, catch surveys are an incomplete picture and total catch estimates have uncertainty (Christ et al. 2020). This introduces uncertainty in CPUE trends and stock assessments. Coordinated collection of additional data on key stocks, and expertise to analyse those data, would considerably improve the understanding of stock status in Seychelles' artisanal fisheries. This report has identified several areas where SFA could further enhance fisheries monitoring.

First, routine data collection of the size and age composition of key target species would add considerable information on stock status. Data collection could follow protocols already implemented for *L. sebae*, and focus on improving understanding of Carangidae, jobfish, and Siganidae, given their high contribution to total catches.

Second, for whaler-type vessels, much data exists on catch and vessel movement. Efforts to link VMS records to catch records could be used to identify fishing grounds of key species, rather than just total fishing effort (e.g. Fig. 9). VMS-linked catch data could be used to measure variability in catch rate among species and locations, and thus identify the most productive fishing grounds for certain stocks. This resource would be particularly useful for future management of offshore stocks where, for example, if catch and size composition data identified risk of overfishing, then fishing ground maps would help to identify fishing hotspots where effort could be most effectively regulated. Given declines in outboard handline species and large catch contribution from this fleet, spatial information on outboard fishing grounds and size and age composition of outboard catches would aid future assessments.

Third, catch-based stock assessments for data-limited fisheries perform best when catch time-series contain periods of both high catches and stock depletion (i.e. catch contrast). Therefore, incorporating pre-2000 raised catch data in stock assessments would likely improve MSY estimates, as these will contain the highest historic catch levels. These data (raised catch 1990-1999) are available in published reports but not in digital format.

Finally, the species-level CAS system implemented in 2017 is an opportunity to estimate species-specific abundance indices for mixed species groups (e.g. other trap fish) and to investigate spatial and temporal variability in catch composition that might indicate changes in resource availability. However, the two CAS versions have not been merged, which led to data quality issues during data analysis for this report. To improve integration of CAS systems, Table 4 lists the data issues encountered, with potential solutions. Funding of additional fisheries science expertise within SFA to routinely analyse both CAS and the biological monitoring datasets would allow stock assessments to be conducted in real-time, and thus support adaptive management of the key artisanal fisheries.

	Data issue	Example	Limitation	Solution
1	Raised catch and effort files have different formats between 2000-2016 and 2017-2019	SIH_Processed data_2017_2019.xlsx does not have a total 'man days' variable	Cannot combine raised catch and effort time-series	Ensure CAS is raised using the same process for all years, and thus produces one output file.
2	CAS categories are inconsistent among years	Updated CAS collects species-level information, but CAS pre-2016 uses coarser species groups.	Cannot combine species-level CPUE estimates across years	Provide CAS file with species-level catches also matched to the pre-2016 groups, so both coarse and fine-scale species analyses can be computed in the same file
3	Multiple fishing effort variables	Fishing effort is recorded using five variables P03_OBSDEB_OPERATION.csv (t_peche_navire, t_peche_engin) and P03_OBSDEB_MAREE.csv (duree_maree_jour, duree_maree_heure, time_fishing)	Unclear which fishing effort variable should be used for each gear-fleet	Identify duplication in _OPERATION and _MAREE datasets and simplify to only two effort variables (gear time and total trip time)
4	Fishing effort variables are imputed	In 2017-2019, t_peche_engin and time_fishing have >10,000 Nas, but these variables appear more reliable than these vars are more reliable than duree_maree_heure and t_peche_navire, which appear imputed (e.g. 24 hours)	Imputed effort values are not reliable and indicate increased effort	Remove all imputed effort values
5	High number of NA records after matching catch and effort tables	93,750 catch records were NA due to missing or unusual (e.g. negative) effort values	Fewer catch records for stock assessments, and not clear if NA values are biased to certain gears, species or locations	Ensure tables are matched efficiently and NA values are limited in data entry.

Table 4 | Data issues encountered during stock assessment analyses.

5. Conclusions

- Trap fisheries have increased average catch rate (CPUE) since 2010 but individual species groups are declining. This coincided with increased targeting of multiple species groups, suggesting that fishing pressure is becoming more balanced over multiple stocks, but that individual species may be experiencing overfishing. Fast-growing Siganidae species are likely being fished below sustainable limits, but high species diversity of 'other trap fish' limits understanding of catch limits for multiple reef-associated species. Given substantial coral mortality and changes to reef ecosystems in Seychelles, investigation into species-level catch trends using the updated CAS dataset (2017-2019) should be prioritized. Outboard handline catch rates declined as effort has increased, suggesting that inshore stocks are depleted.

- Whaler-type vessels accounted for most of the total catch and effort in artisanal fisheries, and thus likely were the primary contributors to fishing impacts on pelagic and demersal populations. Though many species have experienced overfishing between 2003-2015, catch rates have recently increased, leading to increases in total landed catch. Drivers of catch trends were not clear, owing to limited biological information on key stocks such as job and carangidae species. Similarly, total effort and average fishing trip effort by whaler-type vessels has decreased steadily, but the reasons for decline are not clear.

- Most data were collected on *Lutjanus sebae*, providing greater understanding of changes to catch rates and total landed catch. This stock appears to have recovered from low catch rates that followed a period of high catch and effort over 2004-2007, which may have been due to targeting of a strong juvenile age class in that period. Routine analysis of age and length data for *L. sebae* should be continued, and data collection implemented for other key whaler targets (Carangidae and jobfish).

- CAS conducted over 1990-2019 provide a robust and consistent source of catch and effort data. The R code and methodology provided by this assessment should be adapted to conduct routine stock assessments on key fisheries, if SFA have funding and support. These stock assessments could integrate CAS and biological datasets (e.g. size, length) to provide real-time estimates of fishing pressure and stock status.

- Implementation of harvest controls and/or habitat protection of key artisanal stocks would help to protect long-term catches of species that are major contributors to domestic seafood supply in Seychelles. This report identified carangues (handlines), bourgeois (handline), jobfish (handline), and cordonier (trap) as key fishing stocks, based on their total (raised) catch and targeting by trap and handline fleets. Harvest controls must be designed with consideration of the species' life history and fishery dynamics, which should be based on routine analysis of CAS and biological datasets.

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7. Appendix

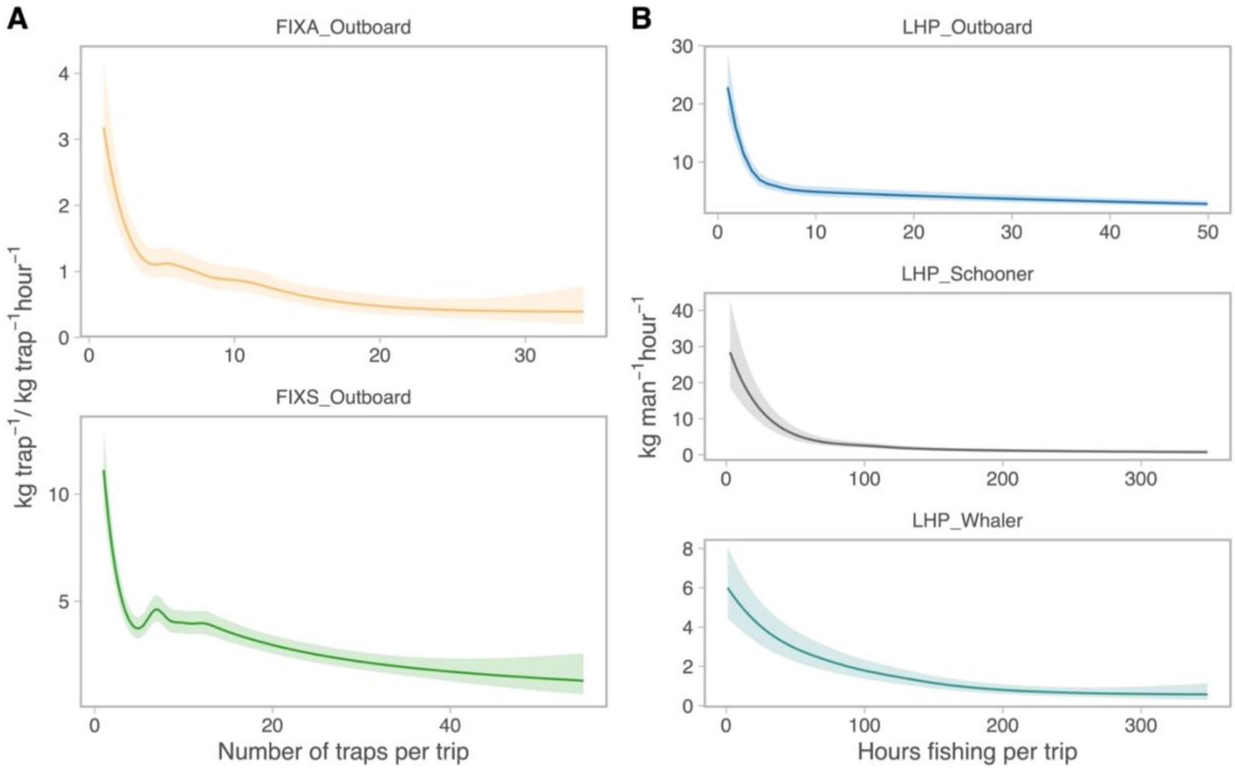

Figure S1 | Effect of trip effort on CPUE, for trap gears (**A**, number of traps) and handline fleets (**B**, fishing hours). Lines are model predictions holding all other covariates to their mean, shaded ± 2 standard errors.

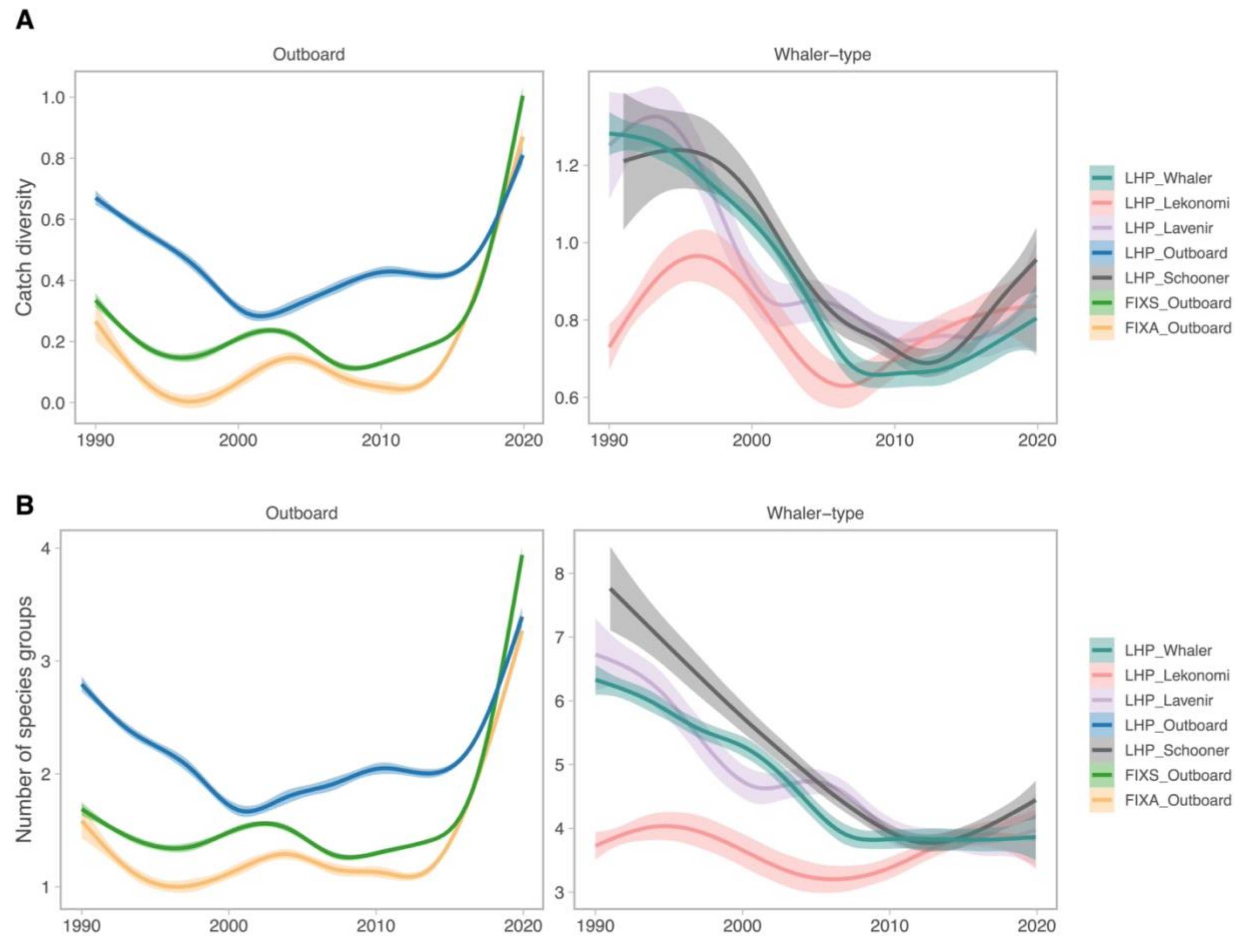

Figure S2 | Catch composition of artisanal fleets. A) Catch diversity of each fleet, where high values indicate catches of many species in similar amounts and low values indicate catches of few species in uneven amounts. **B**) Mean number of species groups caught by each fleet. Lines are fitted GAM smoothers with 95% confidence intervals.

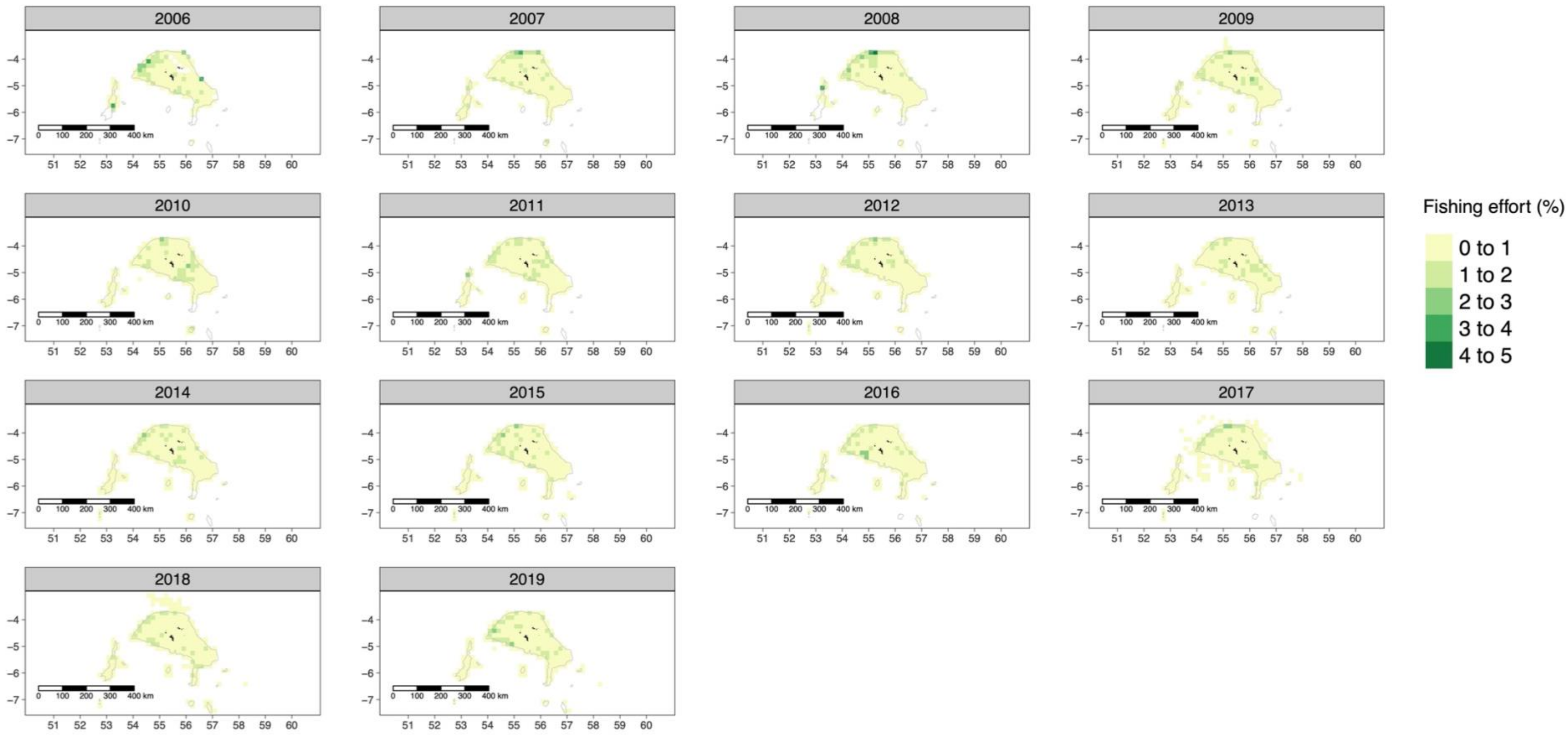

Figure S3 | Variation in fishing grounds among years between 2006-2019, averaged over fleets. Fishing grounds are divided into 342 km^2 cells and coloured by their relative fishing intensity (%). Islands are filled black and the Mahe plateau boundary in black outline.

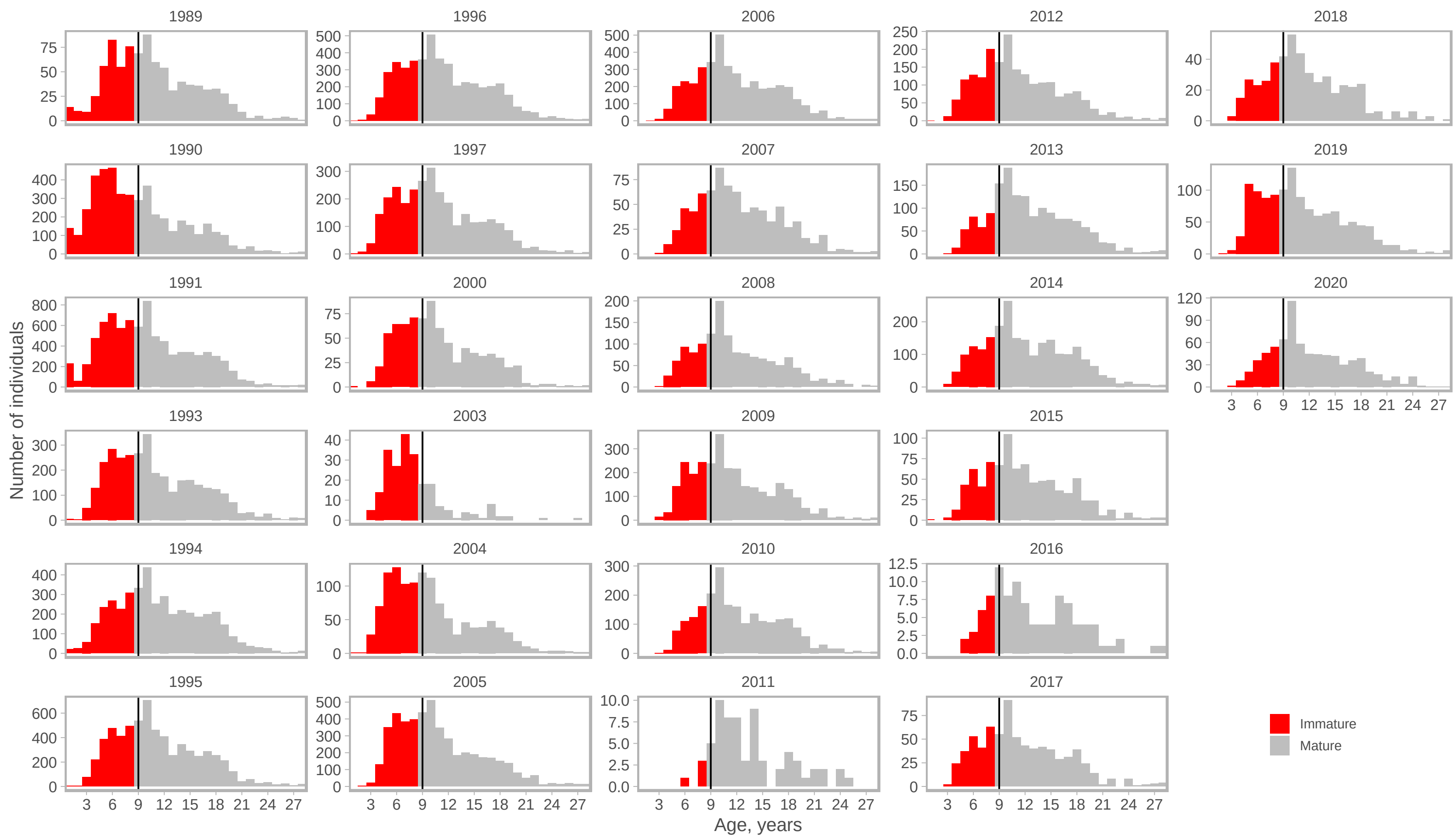

Figure S4 | Age frequency distribution for *Lutjanus sebae* from 1989-2017. Age estimated from length based on otolith data collected in 2000. Immature individuals (< 9 years) are highlighted red.

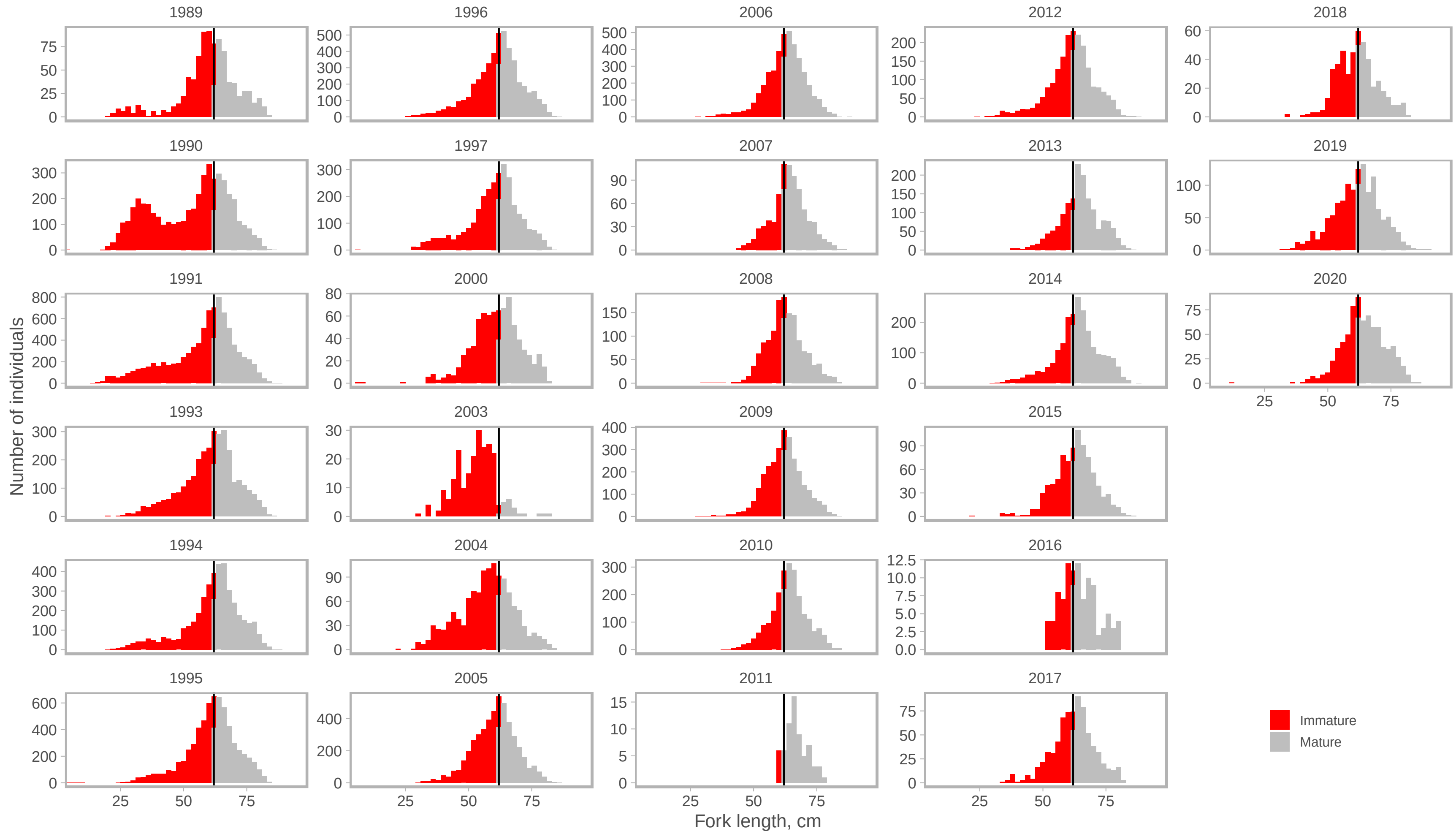

Figure S5 | Length frequency distribution for *Lutjanus sebae* from 1989-2017. Immature individuals (< 62 cm) are highlighted red.