Coral Reefs (2022) 41:1449–1464
https://doi.org/10.1007/s00338-022-02294-z

REPORT

Ten years of dynamic co-management of a multi-species reef fishery

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Received: 11 November 2021 / Accepted: 15 July 2022 / Published online: 9 August 2022

Abstract Co-management, a governance process whereby management responsibility is shared between resource users and other collaborators, is a mainstream approach for governing social and ecological aspects of small-scale fisheries. While many assessments of co-management are available for single time periods, assessments across longer time-scales are rare–meaning the dynamic nature, and long-term outcomes, of co-management are insufficiently understood. In this study we analyse ten-years of catch and effort data from a co-managed, multi-species reef fishery in Solomon Islands. To further understand social, ecological and management dynamics we also draw on interviews with fishers and managers that had been conducted throughout the same decade. We aimed to answer (1) what are the temporal trends in fishing effort, harvesting efficiency, and catch composition within and beyond a periodically-harvested closure (i.e. a principal and preferred management tool in Pacific island reef fisheries), and, (2) what are the internal and external drivers that acted upon the fishery, and its management. Despite high fishing effort within the periodically-harvested closure, catch per unit effort remained stable throughout the ten years. Yet the taxonomic composition of catch changed substantially as species targeted early in the decade became locally depleted. These observations indicate that both the frequency of harvesting and the volumes harvested may have outpaced the turnover rates of target species. We argue that this reflects a form of hyperstability whereby declining abundance is not apparent through catch per unit effort since it is masked by a shift to alternate species. While the community sustained and adapted their management arrangements over the decade as a response to internal pressures and some signs of resource changes, some external social and ecological drivers were beyond their capabilities to govern. We argue the collaborative, knowledge exchange, and learning aspects of adaptive co-management may need even more attention to deal with this complexity, particularly as local and distal pressures on multi-species fisheries and community governance intensify.

Topic Editor Alastair Harborne

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00338-022-02294-z.

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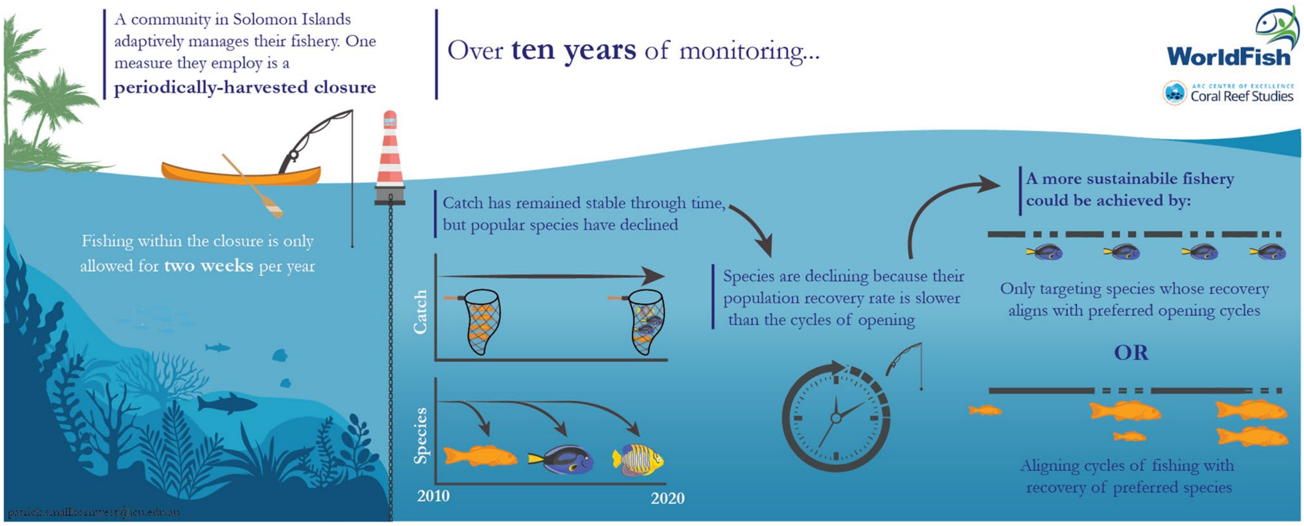
Graphical abstract



Keywords Community-based fisheries management · Coral reef · Marine protected area · Small-scale fisheries · Periodically-harvested closure · Locally-managed marine areas

Introduction

By 2020, the global community committed to conserve and sustainably use the oceans, seas and marine resources (Nilsson et al. 2016). The United Nations Sustainable Development Goals (UN 2015) included an explicit target (i.e. SDG 14.2) to; "*sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans*". Many strategies, across sectors and all levels of governance, have been proposed to progress this target (Recuero Virto 2018). Dominant amongst these are collaborative forms of fisheries management, henceforth co-management, that draw together and give credence to a range of institutions, knowledge sources and management measures (FAO 2015a). Adaptive co-management (sensu Armitage et al. 2008, co-governance (sensu Chuenpagdee and Jentoft 2018), and community-based co-management (sensu Gutiérrez et al. 2011) supports social and environmental outcomes (including, but not limited to, SDG14) whilst retaining degrees of flexibility to specific places and adaptability to social or ecological system changes (Olsson and Folke 2004).

There are many cases where small-scale fisheries that supply domestic markets and consumption predominantly fall under co-management arrangements where government and/or non-governmental organizations work alongside community groups to design, implement and adjust management strategies (Govan 2009a, b; Jentoft 2013; Jupiter et al. 2014). Institutional support for fisheries co-management is bolstered by policy and funding commitments at global (FAO 2015a; Jentoft 2014), regional (FAO 2015b; Song et al. 2019), and national levels (Schwarz et al. 2017; FAO and WorldFish 2021). Implementation of co-management arrangements for marine and coastal fisheries and ecosystems appear to be proliferating (Govan 2009a, b; Mills et al. 2019; Smallhorn-West et al. 2020a, b). Yet, the progress these efforts have made toward the sustainable management of complex social-ecological systems and multi-species fisheries remain relatively poorly understood. A global meta-analysis of 29 cases found that co-management generally brings improvements for fishing communities, but that outcomes vary hugely between cases, and the management costs and fisheries benefits are experienced unequally between different parts of society (Evans et al. 2011). Analysis of 130 cases of co-management found fisheries focussed on benthic and demersal species tended to benefit, but co-management was less successful, or benefits were not evident, for multispecies fisheries (Gutiérrez et al. 2011). In a review of 42 cases, mixed-species biomass was found to be higher in co-managed areas than in areas that had no local or co-management arrangements (Cinner et al. 2012). An analysis of 52 cases found there to be proportionally greater impacts for socio-economic outcomes (72%), relative to ecological outcomes (42%), but that very few evaluations of co-management efficacy had employed robust impact evaluation techniques (Smallhorn-West et al. 2020a).

Adaptive management is an iterative process of changing management practices based on new experiences and insights (Cinner et al. 2019), and in so doing recognizes the dynamic and often unpredictable nature of social-ecological systems (Gunderson and Light 2006). The adaptive element acknowledges deep uncertainty inherent in natural resource management and attempts to deal with the unknown by deliberately considering management actions as experiments to test policy (Walters, 1986). Adaptation emphasizes the importance of learning (experiential and experimental) and collaboration to draw together different ways of knowing to improve collective understandings of, and ability to respond to, complex social-ecological systems (Armitage et al. 2008). Adaptive *co*-management results in a flexible system of resource management, tailored to specific places and situations, supported by, and working in conjunction with, various actors at different scales (Armitage et al. 2008; Buck et al. 2001; Olsson and Folke 2004). A critical component of adaptive co-management is feedback from ongoing assessments and reflections, and may include the provision of monitoring tools and training provided by government or non-governmental collaborators (Armitage et al. 2008) in order to complement the local and traditional knowledge of resource custodians (Folke 2004). Monitoring and evaluation in this form are fiscal and human resource intense, and few long-term assessments combining data sources have been published (but see Cinner et al. 2019).

Adaptive fisheries co-management frequently includes a range of management strategies to address locally or nationally identified resource concerns (Jupiter et al. 2014). In many community-based forms of co-management, local ecological knowledge and customary management practices are integral and integrated into these contemporary arrangements. A dominant, and now well-documented, feature of co-management across Asia and the Pacific is small permanent and non-permanent marine area closures (Jupiter et al. 2014). In these contexts, closures are commonly applied over coastal areas that fall within customary or local tenure regimes. Access and use within these areas are restricted, and areas can be periodically opened to harvesting; known both as area taboos (Foale et al. 2011) or periodically-harvested closures (PHCs) (Cohen and Foale 2013).

Although the historical origins, use, and management of PHCs are based on managing social relations and events (Foale et al. 2011), they are commonly adjusted and employed to achieve contemporary fisheries objectives (e.g. Bartlett et al. 2018; Cohen and Steenbergen 2015). However, there is mixed evidence on the efficacy of PHCs as an adaptive and temporal fisheries management tool. Periodically-harvested closures have been shown to increase target species biomass and abundance prior to harvesting events, but these benefits are rarely observed post-harvest (Goetze et al. 2017; Smallhorn-West et al. 2020a). Even following recovery periods of up to 12 months positive impacts can be limited, and are often only seen for low and moderately vulnerable fish species (Smallhorn-West et al. 2020a). The benefits of PHCs are most pronounced for short-lived, fast growing taxa in low fishing pressure situations (Cohen and Foale 2013; Cohen and Alexander 2013). Fishing effort when PHCs are opened can be intense (e.g. Jupiter et al. 2012), with one example illustrating greater fishing effort with a PHC during its short opening than was observed across an entire year in nearby fishing grounds (Cohen et al. 2013). The cessation of fishing activity when PHCs are closed can also change patterns of fish behaviour so that they are more approachable and therefore more readily caught (Januchowski-hartley et al. 2014). While this has clear short-term benefits for catch efficiency, it may also lead to issues of hyperstability, where patterns of catch remain stable while masking underlying stock decline. Despite these insights into specific instances of change from management implementation, few studies have examined the long-term efficacy of adaptive fisheries co-management arrangements, that is, beyond the impacts of single openings and/or closures (though see Cinner et al. 2019).

The timing and duration of PHC open and/or closed periods, while often controlled for social reasons (Cohen and Steenbergen 2015), are a key way in which fisheries co-management can be adaptive. However, PHCs, and fisheries co-management in general, are only one part of how diverse social-ecological systems are managed, and many factors influence patterns of resource use and sustainability. There are therefore a range of impacts that are inevitably beyond the control of local adaptive management measures. Understanding both the internal (e.g. deliberate responses in management to change) and external (e.g. dynamics peripheral to the fishery and its management) drivers that these institutional arrangements can and cannot manage for, is critical to understanding their utility, and thus also to understanding when other measures may prove more successful.

In this paper, we draw on ten years of quantitative and qualitative data to describe the dynamics of, and long-term outcomes associated with, the community-based co-management of a multi-species coastal fishery in Solomon Islands. Whilst we look across the whole management scheme and fishery, we apply a strong focus on adaptive co-management and outcomes associated with PHCs, as this was the prominent management measure receiving the community's fishing and management attention (Cohen and Alexander 2013). We address the following questions: (1) Are there signs of stability or change in the fishery through time with respect to a) fishing effort, b) efficiency (catch per unit effort), and c) catch composition?; and, (2) What were the major internal and/or external drivers or triggers that acted upon the fishery and/or the management or governance arrangements of the fishery? In discussing our results we explore where

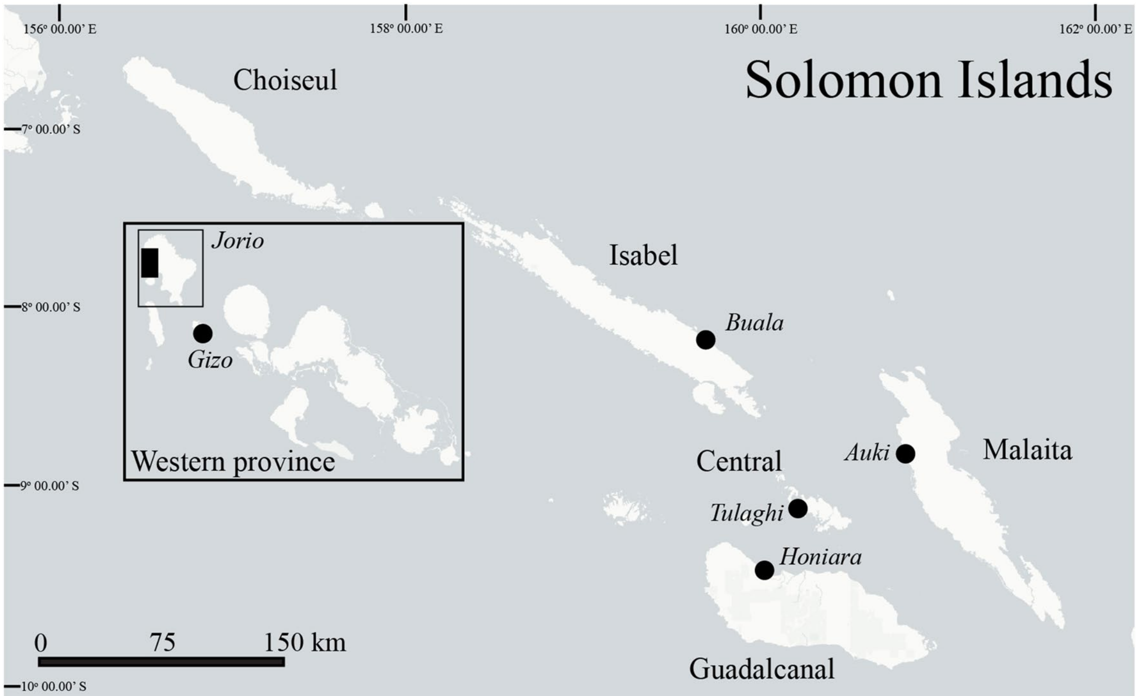


Fig. 1 Map of the Solomon Islands, indicating Western Province and the provincial capital of Gizo. The communities included in this study are located in the Jorio region marked. Specific village names are not included due to confidentiality agreements

shifts in management were likely to have impacted upon, or were in response to (i.e. adaptive management), changes in fishing patterns (i.e. gear use, effort distribution through time and space, etc.), or fisheries trends (i.e. catch volumes, composition or rates). We further discuss where changes were instead the result of factors or drivers beyond the scope of the fishery and its management (i.e. external drivers, shocks, ungovernable change). Ultimately, we aim to bring new insights into how adaptive fisheries co-management drives progress to "*sustainably manage and protect marine and coastal ecosystems… to achieve healthy and productive oceans*" (SDG14 – life below water). We do this using a case in Solomon Islands—a Large Ocean State—where healthy and productive oceans are a foundation of culture, food and nutrition security, and livelihoods of communities.

Methods

Ethics

Research clearance, which included ethics clearance, was provided by the Minister for Education and Human Resource Development, Solomon Islands, and by James Cook University, Australia under ethics approval number H3337 and University of Wollongong ethics approval number 2017/565. Interviewees gave their verbal consent to participate in the study and consent was noted on the data form, if verbal consent was not given the survey, interview or focus group did not proceed. The ethics committees (James Cook University and University of Wollongong) accepted verbal consent as being appropriate for this research.

Study location

In 2008, with support from WorldFish (an international research organization) and the Provincial Government, five adjacent communities in the Jorio region of Western Province (Fig. 1), Solomon Islands commenced a more formal and collaborative form of management that included co-development of resource-use regulations and education, and compliance and monitoring strategies (Schwarz et al. 2017). In subsequent years co-management in three communities ceased due to weak governance (Abernethy et al. 2014); this study focused on the two communities who persisted over the ten-year study period. A range of management measures were applied within a broader region of management including two PHCs and one no-take reserve where all fishing activities were prohibited. Management also included restrictions on the size and use of nets, and restrictions on spear fishing at night which applied at various times to all areas in the broader managed area (i.e. PHC and areas continuously open to fishing). Both the PHCs and no-take reserve were situated within the fishing grounds of

Table 1 Number of trips per year between management zones and whether trips were conducted while the PHC area was opened or closed

Year	Period—Open		Period—Closed		Sampling days (n)
	Open	PHC	Open	Total	
2010	197	236	103	536	38
2011			86	86	7
2013	106	210	203	519	35
2014	169	209	159	537	30
2019	166	44	94	304	16
2020	0	114	86	200	12
Total	638	813	731	2182	138

PHC periodically-harvested closure

these communities and were separated by several kilometres. The approximate area of coastal waters under management by the two communities was eight km^2. Within those coastal waters, approximately 1.2 km^2 (i.e. approximately 15% of the total managed area) were managed as PHCs. At the beginning of the program PHCs were opened for most of December, but opening frequency and durations were gradually reduced so that by 2020 the opening time was three days once per year. Compliance over the ten years of management was commonly perceived by community members and manager as being high (see Cohen and Steenbergen 2015).

Patterns of fishing and catch

We collected fishing trip and catch data in six sampling periods over 10 years, commencing in November 2010 and ending in March 2021, all centred around PHC opening periods. In all sampling periods (which lasted between two weeks and three months) we attempted to record the details of all fishing trips undertaken by women, men, and children living in the communities. When periodically-harvested closures (PHCs) were opened for fishing we continued to sample all fishing, i.e. fishing being undertaken in these newly opened areas and in fishing grounds continuously open to fishing. Inevitably, some fishing trips were not recorded. Through both direct observation (i.e. counts of boats and people out fishing, compared to those recorded) and informal discussion with fishers and managers, we estimated that we recorded approximately 80–90% of all trips undertaken during the sampling periods. The number of trips recorded in each of the six sampling periods ranged from 86 to 537 (Table 1).

Sampling and data collection are as described by Cohen and Alexander (2013) and Cohen et al. (2013) who analysed data from more communities in the region, but only during two sampling periods across 12 months. In sum, at least one trained observer (either WorldFish staff or trained community members, including authors PJC, EK, AR, SR, FS, ST, and RT) was posted at each landing site (approximately six) on each day and night of sampling periods. As soon as fishers returned to shore they were asked to recount details of their fishing trip, which included: time of departure and return, number and gender of fishers on the trip, gear(s) used (gleaning, line, net, spear, trolling or a mixture of methods), fishing location (i.e. identified by location name and clarified using a map), and management zone (i.e. a fishing ground continuously open to fishing, or a PHC that had been opened). The total wet weight (kg) of the catch was measured using hanging fishing scales and the number of individuals caught from each taxonomic grouping was also recorded. Fishing trips included both those targeting finfish and those targeting invertebrates. The local nomenclature system was used to categorize finfish and invertebrates for counting and recording purposes (Cohen et al. 2014), which were then converted to family level taxonomic groupings. If fishers were not encountered at landing locations upon return a "recall" method was used where catch composition and weight were reconstructed through interview (Cohen et al. 2013) ($n = 324$ trips). Over the six time intervals we recorded a total of 2182 fishing trips (813 within PHCs and 1369 in open areas) which accounted for a total of 11,970 fisher hours, and a cumulative catch weight of 11,238 kg of finfish and invertebrates.

Analysis

To examine the fishing pressure being exerted on fishing grounds, we calculated the cumulative effort (fisher hours) and cumulative yield (kg) per square kilometre of fishing ground each day, for each time point in both management zones, calculated using the total area of fishing ground on open and PHC reefs. The total area of fishing grounds was calculated based on the areas fishers recorded visiting during sampled trips. Daily values were calculated as the mean hours fished (effort), or kg of catch (yield), exerted by fishers on PHCs or open areas in each day. Average effort applied to continuously open fishing grounds (henceforth 'open') was calculated separately for the two different sampling periods (i.e. when PHCs were closed, and when PHCs were open) given the substantial variation between these two periods reported previously (Cohen et al. 2013).

We then disaggregated data by fishing method and management to compare patterns of catch by fishing methods between management zones. Mixed effects models were used to examine overall differences in patterns of catch per unit effort (CPUE) (kg per fisher hour) between fishing method and management (PHC or Open), with year included as a random factor. Generalized additive models (GAMs) were then used to assess temporal trends in CPUE as a product of management for each fishing method. In each of the six GAMs, fixed effects included management and data collection method (standard or recall), and splines were fit for management. Up to four knots were allowed to be fit within the spline, but less if it resulted in a better model fit. Models were fit using log(x + 1), lognormal, gamma and negative binomial distributions, and final model selection based on the lowest Akaike Information Criterion (AIC) score. Model fit was assessed by examining residual histograms, fitted values vs. residuals and tests for over dispersion, which in all cases suggested model fits were acceptable. All analysis was conducted in R version 3.6.2 (R Core Team 2016).

To examine the overall taxonomic composition of fish and invertebrate catch, we calculated the percent of annual catch from each family between management zones. These analyses were conducted on the number of individuals caught (*n*) per trip from each family rather than weight (kg), as only the total weight of the entire catch was recorded during sampling. To examine temporal trends in catch rates of key families as a function of management and time, subsequent GAMs were fit for the ten most common finfish and eight most common invertebrate families following the same methodology as above but on the number of individuals caught from each management area. Data in most cases were heavily skewed towards zero, with many trips not catching any individual of some families, and therefore negative binomial models were fit for all families.

Management dynamics

We used ten years of trip reports (i.e. written accounts of trips taken by field staff from the WorldFish Center to Jorio to facilitate research or management processes), semi-structured interviews, focus group discussions, and informal interviews to reconstruct the dynamics of fisheries co-management in the participating communities. During the decade of monitoring and engagement, fishers, researchers, and community managers (i.e. local fishers and non-fishing community members who had been delegated with responsibilities to make, or facilitate, community decisions about management arrangements and enforcement measures) recalled changes that impacted on the communities' fishery or fisheries management activities. These were recorded in field trip reports following each sampling event ($n = 6$), informal interviews with fishers and managers ($n = 20$), household surveys ($n = 1$ of multiple households), quotes collected during management plan reviews ($n = 2$ review sessions), and extensive additional notes and reflections by WorldFish staff during and following monitoring trips. In reading and reviewing qualitative data we categorized changes as being either: (i) deliberate responses to change in management or fishing that we considered adaptive (henceforth 'internal drivers'), or (ii) dynamics peripheral to the fishery and its

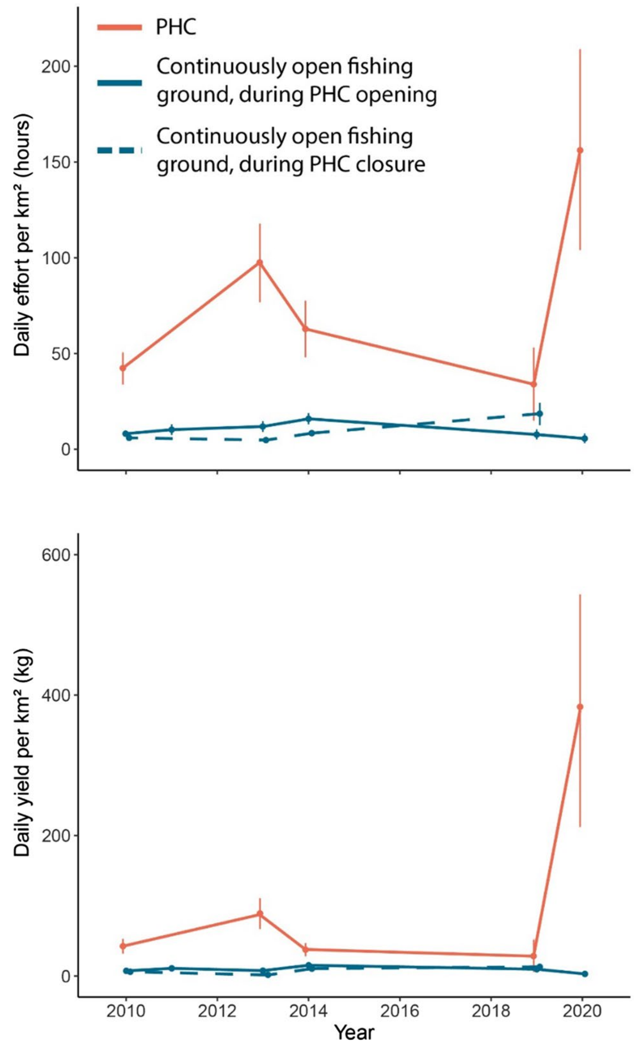


Fig. 2 Mean (± SE) daily effort (hours) (top) and yield (kg) (bottom) per km^2 of fishing ground under different forms of management during the sampling period. Red represents periodically harvested closures (PHCs) and blue open fishing grounds. Solid lines represent pressure at time points when PHCs were open to harvest and dashed lines when they were closed

Table 2 Number of trips per fishing method by gender and management. Differences in the total number of trips between Table 1 and 2 are due to instances of missing or incomplete data. PHC = periodically harvested closure

Method	Female		Male		
	Open	PHC	Open	PHC	Total
Gleaning	166	155	95	92	508
Line	167	102	450	99	818
Mix	8	44	51	83	186
Net	4		59		63
Spear	1	4	92	189	286
Trolling	7		235		242
Total	353	305	982	463	2103

management (henceforth 'external drivers') that may have had flow on effects on the fishery or its management.

Caveats

As with many natural experiments and studies of multispecies fisheries, there are several limitations on the interpretations we can draw from this case study. First, patterns of change through time between PHCs and continuously open fishing grounds were not directly comparable – that is open areas were not an accurate counterfactual of PHC areas due to differences in habitat – and thus the true impact of management could not be fully assessed. Continuously fished areas contained mangroves and pelagic zones where net fishing and trolling was possible, which were not available to fishers within the PHC. Continuously opened fishing grounds were, by definition, available to be fished all year-round, and we were only able to assess patterns of catch at specific time intervals, whereas we captured all fishing within PHCs during their major openings in given years. Whilst acknowledging these caveats, the observed patterns of catch and the management timeline both provide key data

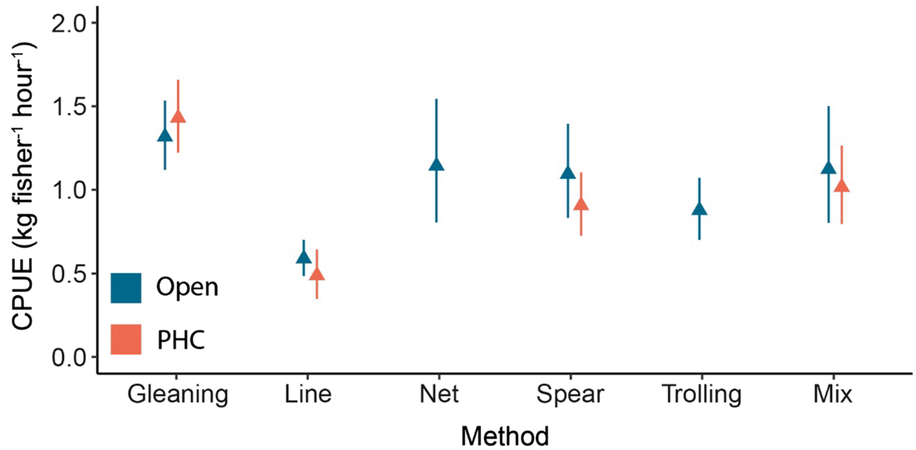


Fig. 3 Overall differences in catch per unit effort (kg per fisher hour) between fishing methods and management zones. Summary statistics and contrasts are available in the supplementary materials

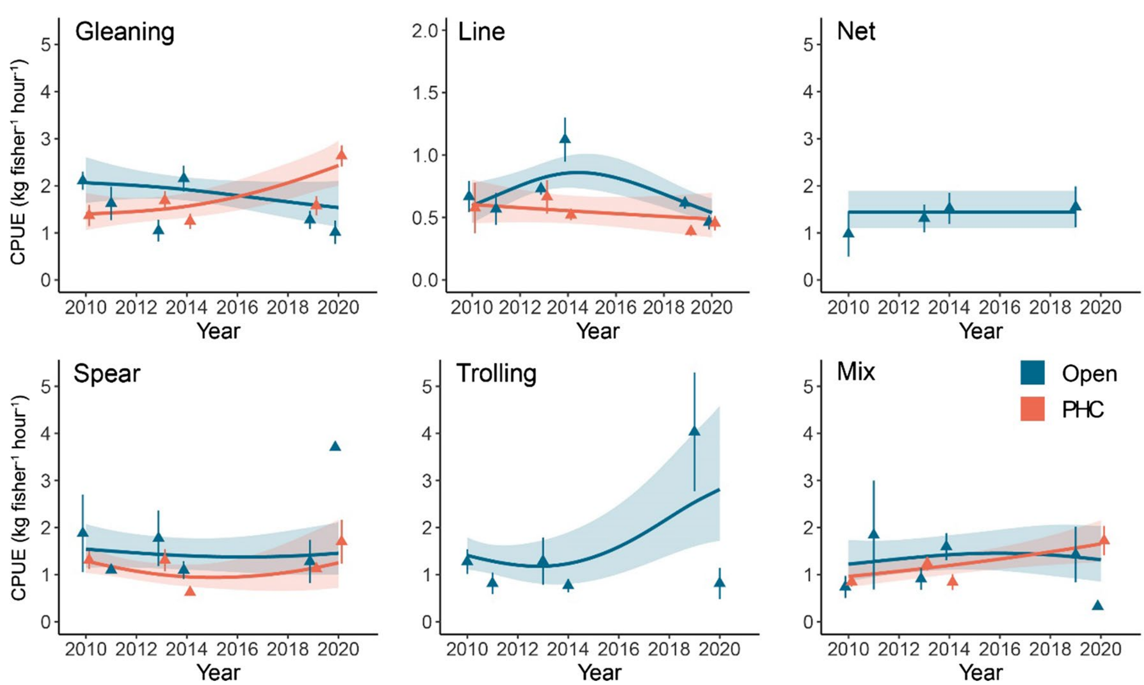


Fig. 4 Temporal fishing dynamics in multi-method fishery between open and periodically harvested fishing grounds. Red indicates periodically harvested closures (PHC) and blue fishing grounds open year round. Points represent mean ± SE values of all data from each year on PHC and open fishing areas. Splines represent GAM model predictions ± 95% confidence intervals. Where one spline falls within the error envelope of another, there is no significant difference in mean measurements between those splines for that time period. Note the difference in y-axis scale for line fishing

on how different harvesting and management regimes will lead to medium-term fisheries, and/or longer-term sustainability effects for the managing communities.

Results

Patterns of fishing effort, efficiency, and composition

During openings, daily fishing effort and yield were far greater in PHCs than areas open to fishing throughout the year, indicating a concentration of effort within the PHCs during opening periods (Fig. 2). Pressure in fishing grounds continuously open to fishing was consistently lower than PHCs regardless of whether fishing occurred when PHCs were open or closed. There was also substantial variation through time, and effort during the three days of PHC opening in 2020 was 39 and 125 times greater than in open fishing grounds for hours and yield respectively.

The dominant forms of fishing recorded were gleaning and line fishing (Table 2). Overall, fishing methods used by women did not differ substantially between management zones, and they almost exclusively employed gleaning or line fishing methods, which target invertebrates and finfish respectively. Gleaning methods were dominated by women, who conducted 63% of all recorded trips using this method. Conversely, men's fishing patterns were both more diverse and differed with management strategy, with spearfishing the dominant fishing method employed within PHC areas, and line fishing the dominant fishing method

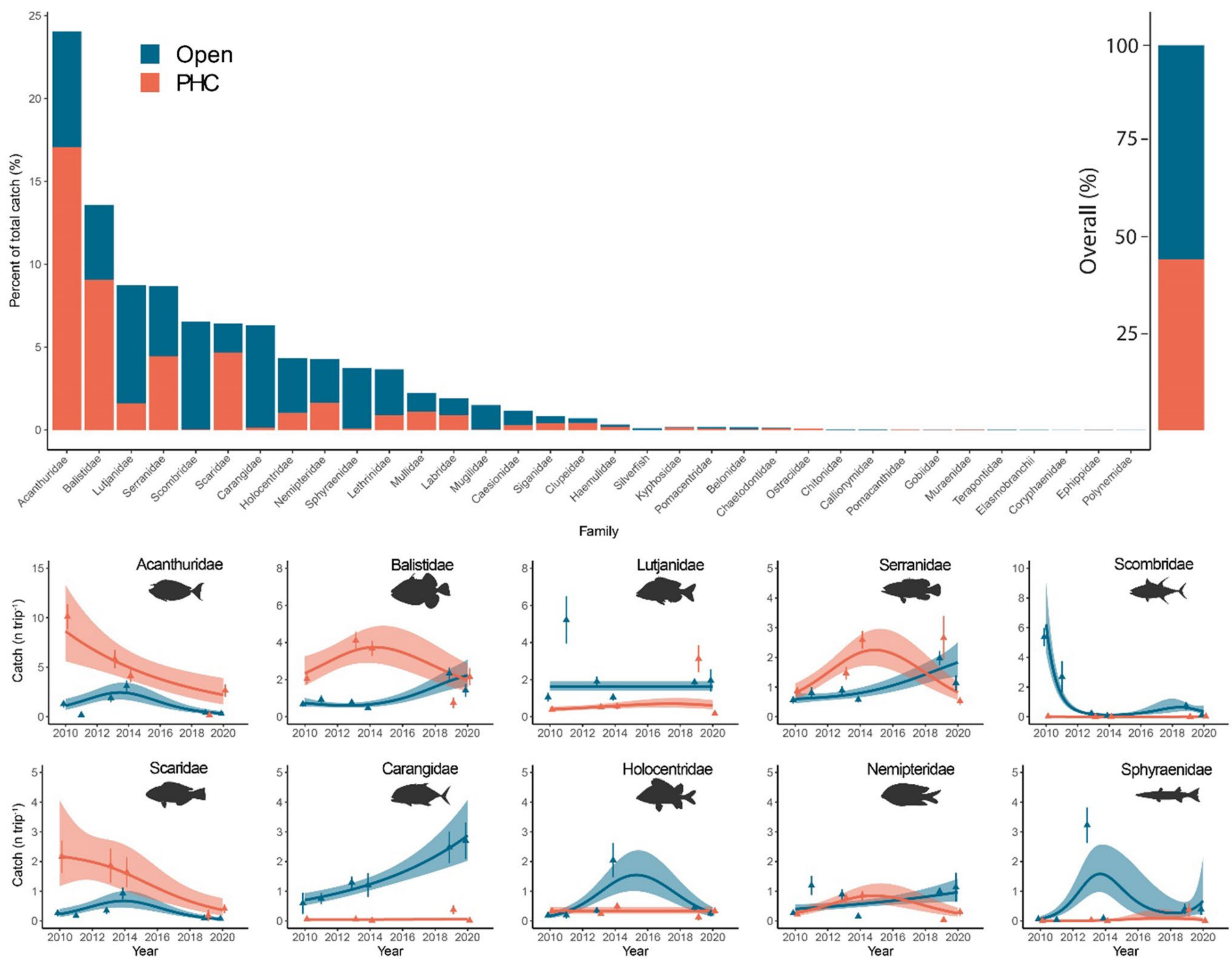


Fig. 5 Temporal patterns in finfish catch between periodically harvested closures (PHCs) and open fishing grounds. Top: Proportion of total reported catch (number of individuals) between management zones from each fish family across the entire sampling period. Bottom: Temporal trends in the number of individuals caught per trip between management zones for the 10 most common finfish families. Points represent mean ± SE values for each year in PHC and open fishing grounds. Splines represent GAM model predictions ± 95% confidence intervals. Where one spline falls within the error envelope of another, there is no significant difference in mean measurements between those splines for that time period. Note the difference in y-axis scales

in open areas. While there were significant differences in CPUE between fishing methods, only for gleaning was there a significant interaction effect between method and management, and then only marginal (Fig. 3) (Table S1). For gleaning, CPUE within PHCs was 0.11 (0.00–0.23) kg fisher^{-1} h^{-1} greater than in areas open to fishing year-round. Catch per unit effort was also significantly lower for line fishing than for all other types of fishing.

With the exception of trolling, patterns of fishing by method were fairly consistent through time (Fig. 4)

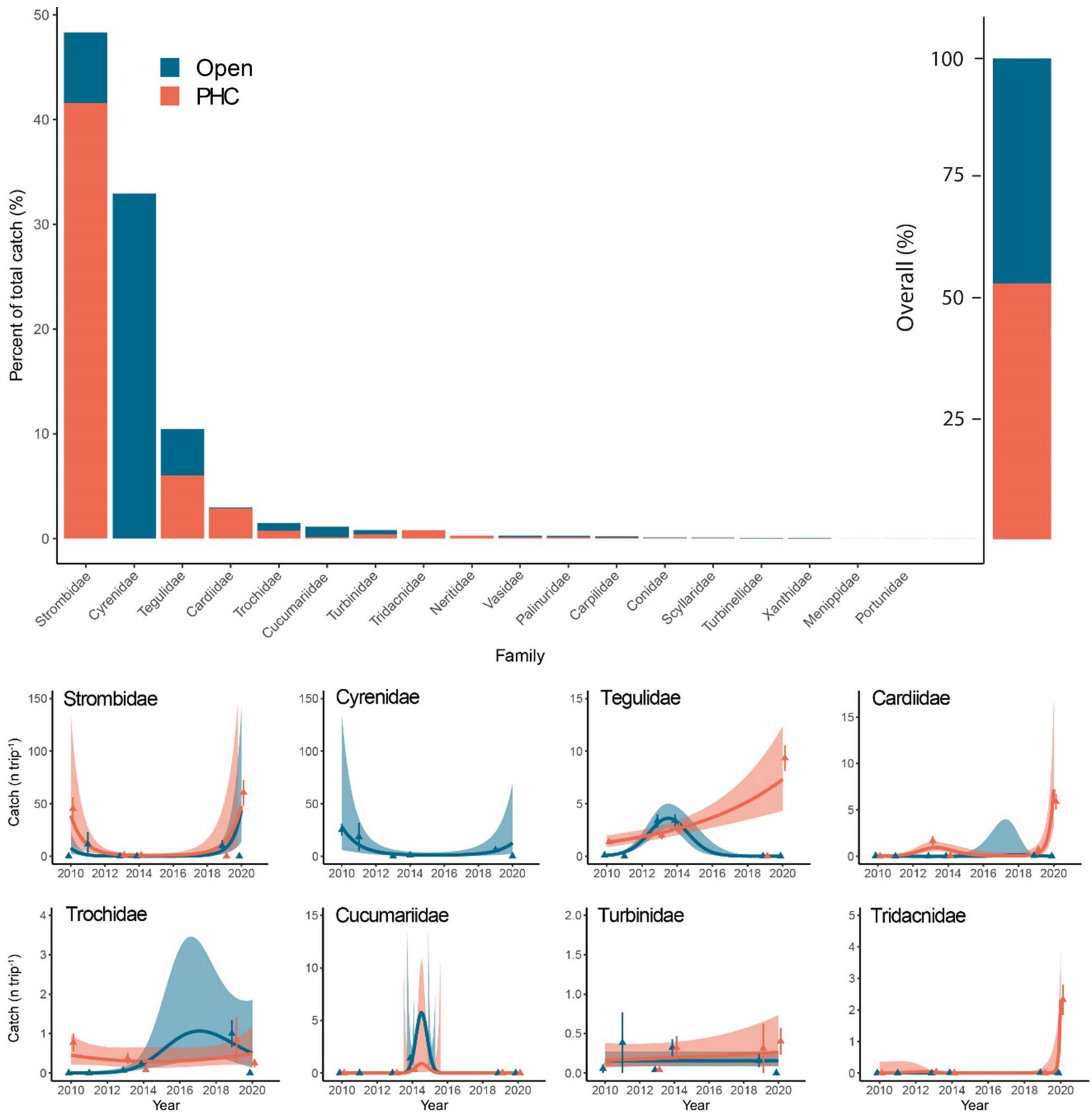


Fig. 6 Temporal patterns in invertebrate catch between periodically-harvested closures (PHCs) and open fishing grounds. Top: Proportion of total reported catch (number of individuals) between management zones from each invertebrate family across the entire sampling period. Bottom: Temporal trends in the number of individuals caught per trip between management zones for the eight most common invertebrate families. Points represent mean ± SE values for each year in PHC and open fishing grounds. Splines represent GAM model predictions ± 95% confidence intervals. Where one spline falls within the error envelope of another, there is no significant difference in mean measurements between those splines for that time period. Note the difference in y-axis scales

(Table S2). The greatest temporal difference between open and PHC areas was for gleaning, which increased marginally in PHC areas in 2020, and decreased marginally in continuously open areas. CPUE for line fishing was always low. Net and spearfishing both appear stable, and for spearfishing both within and beyond the PHCs. While there was a substantial increase in trolling CPUE in 2019, in 2020 this returned to levels that had been observed from 2010 to 2014.

The most commonly caught fish taxa per trip were acanthurids, and the 10 most common finfish families accounted for 90% of all individuals caught (Fig. 5) (Table S3). Within these 10 families there was substantial variation in catch per trip through time as a product of management. The greatest consistent changes through time within the PHC were for catches of acanthurids and scarids. At the beginning of sampling, catches per trip of acanthurids and scarids were 7.9 and 8.3 times greater on average in PHC areas than in open fishing grounds, respectively. However, catches per trip declined by 74% (Acanthuridae) and 81% (Scaridae) across the ten years in PHCs but did not follow a consistent trend in open areas so that by 2020 catch rates were comparable between management zones for both families. Carangidae catch per trip increased 4.5-fold in continuously open areas over the ten year period, but there were consistently low catches within PHCs where their primary habitat was not present. Likewise, catches per trip of Lutjanidae and Scombridae were also substantially greater in continuously open fishing grounds than in PHCs due to differences in habitat between open fishing grounds and PHCs, but Scombridae catch per trip was 18.6 and 9.4 times greater in 2010 and 2011, respectively than during the rest of the sampling period, respectively. Within PHC fishing grounds catch per trip of Serranidae increased from 2010 to 2019 by a factor of three, but this trend was not evident in 2020. With the exception of 2019, mean catch per trip of Balistidae was also greater in PHCs across all sampling periods.

Total numbers of invertebrates were dominated by two families: Strombidae and Tegulidae, which comprised 80% (by number) of individuals caught per trip (Fig. 6) (Table S4). Overall temporal trends for invertebrates were less consistent than for finfish, with more occasions of both very high and very low catches. The most consistent trend was a 6.9-fold increase in catch per trip of Tegulidae within PHCs across the ten years, although none were recorded in catches from 2019. Lastly, the only substantial harvest of giant clams (family Tridacnidae) throughout the entire sampling period was in 2020 within the PHCs.

Management dynamics

Internal drivers were those instigated based on the needs, demands, or observations of the community in ways that saw the community management committee make deliberate deviations from originally intended management plans and arrangements.

One form of adjustment that was made was the opening of PHC areas outside pre-established cycles. These minor openings typically occurred several times a year, for reasons including church fundraising, such as a one-day trochus harvest in 2013 in order to raise funds for a minister's ordination (Fig. 7). Formalization of minor opening was also enacted in 2013 due to the perceived difficulty of denying people entry into the PHC if they required income. During the 2019 management plan review this was again raised as a key point:

> "At the moment generating cash is hard, and the only way of finding money is to dive for fish or trochus."

Removal of other management rules, such as the ban on sea cucumbers in 2014, also occurred due to increased demands for funds, resulting in substantially increased harvest of these taxa at these times. Demographic changes associated with declines in resources or catch due to population growth were also commonly cited as an internal driver of changes in the fishery. In 2011, due to fisher observations and data feedback from WorldFish demonstrating very high effort by fishers within PHCs, opening cycles were reduced from one month to two weeks, and trochus harvesting was only allowed within the first three days of each opening. In 2012, the harvest of *Strombus luhuanus* and all species of giant clam was also banned within PHCs due to fishers experiencing low catches in the previous year and observing low abundance when inspecting the area prior to opening. A formal management plan review in 2013 subsequently banned all net fishing and nighttime spearfishing within PHCs, and placed further restrictions on the harvest of all species of giant clam, green snail (*Turbo marmoratus*) and crayfish. Due to difficulties of enforcement, a ban on nighttime spearfishing in open fishing grounds was dropped at this time.

External drivers were those we considered to be beyond the scope of the fishery and its management to deal with, such as external shocks and ungovernable change. For example, political changes throughout this period included a reduction in the number of communities involved in the management process. When the management plan was first developed in 2008 it incorporated five communities, and their different fishing grounds, within the Jorio region, but by 2010 three communities ceased co-management, and WorldFish collaboration continued with the two remaining communities (whose fishing grounds constitute those in this study). Contested ownership of one of the reefs managed as a periodically harvested closure meant that efforts to manage that reef via a PHC ceased and this reef was not included in the current study. An additional external political driver was the occurrence of an election during sampling in March

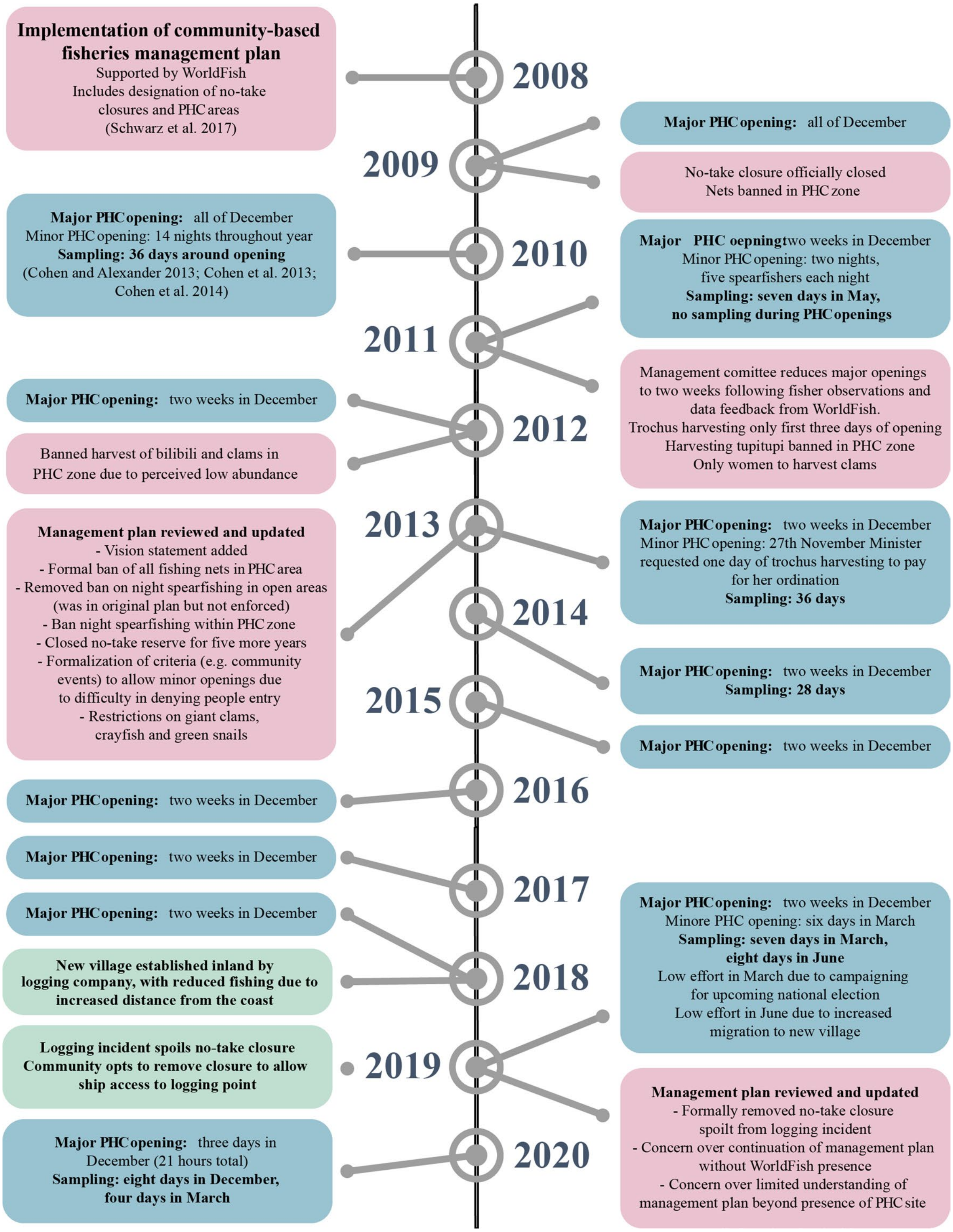


Fig. 7 Timeline of co-management throughout the decade of community partnership with WorldFish. Blue boxes represent periodically-harvested closure (PHC) openings and/or sampling events. Pink boxes represent significant management events driven primarily by the internal dynamics of the community. Green boxes represent substantial external drivers of change for the fishery or its management

2019, and the corresponding low fishing effort due to campaigning for the national election. It was also only following several years of engagement that committee members perceived full agency as managers, including the agency to change and adapt management plans as the community saw fit. In June 2012 a committee member made the comment:

> "I only just now realize what WorldFish meant when they said this was our management plan and we could change it if we wanted to."

The arrival of new economic ventures in the village also changed patterns of fishing and management. Most notably, a logging agreement implemented in 2017 meant that people who would otherwise have been fishing intensively were largely occupied in paid employment. Associated with the logging agreement was the negotiation by the land-owning tribe for more permanent housing to be constructed in a new settlement area that was at greater elevation (to be protected from tsunamis) and hence, further from the sea. In 2019, women explained that this new village site was simply too far from their fishing grounds, and people were fishing less often as a result:

> "When we were living down there [in the old, coastal settlement] activities to do with the sea were easy, but going to the bush and to the garden were hard. Now [since relocation] things in the bush and garden are easy, but activities associated with the sea are difficult. Overall, living here [in the new settlement location] is nice."
> "It's a bit of a way between our house and the sea. We don't have a torch, so getting down and back to the canoe is harder as we are worried we might run into things. There also isn't anywhere secure on the coast to store our canoe."

In 2019, the commencement of logging operations and the establishment of a coastal log pond (i.e. area where logs are stored before being transferred to ships) and transfer point was linked to reef damage in what had previously been designated as a no-take closure. Managers felt there was no point in closing the reef if these impacts of logging were to continue and so the protection status was removed. Given that the logging company wishes to return to log the same area again, and ship access to the log point is what damaged the reef, it is likely that future damage will also occur. In response to a committee member indicating the logging company wishes to return:

> "It's no good to put back management, since then the company will just spoil it more."

Discussion

Management of multi-species fisheries is inherently difficult due to the different vulnerabilities amongst species to fishing pressure, and the inordinate number of factors acting upon their exploitation and response. In examining 10 years of adaptive co-management of a local multi-species fishery we found that patterns of resource use have changed due to i) changes in the fishery; ii) changes in how the fishery has been managed; and, iii) external shocks beyond the control of fisheries management. First, the stable CPUE we observed within the PHC through time has masked a distinct shift in the taxonomic composition of catch. This is likely driven by intensified fishing effort within PHCs when they become open, and misalignment between closure durations and the life-history of target species. Second, specific changes to the rules and regulations of PHC harvesting have occurred based on the needs, demands, and observations of the community, such as the ban on night-time spearfishing. Third, major demographic and physical changes have taken place in the local community that are beyond the scope of adaptive fisheries co-management, but nonetheless have had major repercussions for how, and how many, people fish. In the section that follows we discuss the implications of these findings for the broader practice of adaptive fisheries co-management, as well as the specific implications of these findings for these communities.

Catch per unit effort (CPUE) is a standard measure of extraction efficiency, and is commonly used as an indicator of stock status and the sustainability of a fishery (Petrere and Giacomini 2010; Radovich, 1976). Yet, CPUE has multiple limitations as an indicator and can be a crude, and even misleading measure, in isolation. In this case we observed stable CPUE within PHC boundaries over a decade of observation. Within the same region as this study, CPUE commonly falls between 0.5 and 2 kg/fisher hour (Roeger et al. 2016); which were consistent with our observations through time, between methods, and between management zones. Only when we examined the composition of catches more closely did substantial patterns emerge. The steady and substantial decline in acanthurid and scarid yields within PHCs suggests that two of the most harvested species within the PHC are being harvested unsustainably, and catch patterns (e.g. what species are being targeted) may be shifting to accommodate this change. It is unlikely that this change is due to the 2013 ban on night-time spearfishing within the PHC because i) we observed the decline prior to this ban, ii) the relative frequency of day-time to night-time spearfishing did not substantially change through time (Table S5), and iii) spearfishing in general remained relatively rare compared to more dominant fishing methods (e.g. line and gleaning). In sum, if fishers or evaluators assessed management performance or fishery health based on the observation of stable CPUE, management responses could become inappropriate or even maladaptive.

Hyperstability is a fisheries concept whereby yield and abundance become decoupled, so that catch can remain stable even while populations decline (Erisman et al. 2011; Hamilton et al. 2016; Maggs et al. 2016). This concept is normally associated with aggregating species and single species fisheries, such as the North Atlantic cod; a fishery that collapsed as a result of managers assuming stable catches indicated a stable population (Rose and Kulka, 1999). However, in the current study a similar situation has arisen due to the multi-species nature of the fishery, so that as some species decline others are targeted more heavily. This outcome is likely a result of a misalignment between the rules and regulations of management, and the life-history characteristics of the targeted species. There are three parts to this decoupling: first, the high effort within PHCs during opening events led to catches that were too high to be sustainable for populations of most species, and were in fact higher than the annual cumulative effort on nearby fishing grounds that are continuously open to fishing (Cohen et al. 2013). Second, the duration of PHC closures (~ 11-12 months) is shorter than the time required for the populations of many targeted species to recover (Abesamis et al. 2014). Third, the duration of PHC closures is also sufficiently long enough to accrue behavioural changes in the naïveté or "tameness", and hence catchability, of these same target species (Januchowski-hartley et al. 2013, 2014; Smallhorn-West et al. 2022). In the short term, shifting to other species has alleviated declines in catch from species with populations in decline. In the long-term, this combination of high effort and misalignment between opening events, life-history characteristics, and fish behaviour are a substantial threat to the sustainability of these communities fishery.

Despite these pressures, the strength of adaptive co-management is that rules and regulations can be changed based on new experiences and learning. This has occurred in these communities on numerous occasions, based on previous feedback from monitoring, and has included reductions in the length of PHC opening periods, and limits on mid-year openings. If the current management practices are not further adjusted, in the short-term there is likely to be a continued shift to other species, which may continue to maintain high levels of effort and stable CPUE. However, in the long-term this is likely to lead to the serial depletion of taxa until the multi-species fishery is largely depleted. In this case adapting the current management will entail aligning effort, periodicity and duration of PHC openings with the life-history characteristics of target species. This could be done in two ways: first, if socio-cultural norms prohibit substantially altering harvest cycles and effort (e.g. Foale et al. 2011), then limiting harvest to specific taxa that are sustainable under this harvest regime would be more likely to increase the longevity of the fishery. Alternatively, if specific species are preferred, then adapting the opening periods and effort to align with the life-history of these species would be required to maintain the fishery. Regardless of the preferred option, stability of the fishery would likely benefit from integrating the life-history of target species into the management plan, in addition to the rules currently implemented.

Few studies of adaptive co-management span multiple sampling periods (though see Cinner et al. 2019; Hamilton et al. 2019), meaning longer term analysis of the conditions co-management generates, and in fact responds to, are rare (Keith et al. 2011). The decade-long observation period we present here illuminates the dynamic nature of adaptive co-management, and the diversity and scale of social and ecological changes that management must respond to. These included the changes in gear (e.g. net banning in 2009; re-instating night spearfishing in 2013 in openly fished areas), and species (e.g. banning harvest of clams in 2012) regulations within the PHC, changes to opening and closure cycles of the PHC (e.g. one month to two weeks to three days) as well as formalizing criteria for minor openings, and the implementation and subsequent removal of a no-take reserve. Feedback of research findings to the communities (for example the evaluations done by Cohen et al. 2013; 2014) stimulated conversations with managers, and where their observations aligned with the quantitative findings changes to management were made. Management changes were made by the community-based management committee, based on the needs and demands of the broader community (particularly the reef-owning tribe), and observations of community members, fishers and designated community managers (who were both fishers and community members).

Several incidents over the ten years of observation, discussion and quantitative monitoring highlight the impact major external drivers can have on local management, and how it is a practice that occurs within, and is not isolated from, larger societal, demographic and economic influences. For example, the change in participation from other communities was beyond the control of focal communities to deal with, yet affected their ability to engage in collective management at a higher level. Likewise, the logging agreement provided the opportunity to change village location to be resilient to potential tsunamis, yet also caused direct damage to managed reefs. Rather than constrain logging, the management committee instead felt it was in the best interest of the community to alter the management plan by removing the no-take reserve that had been impacted by logging activities. While it is possible for management practices to respond to these events, such as by moving (or in this instance removing) spatial closures, they cannot easily be mitigated. Linking co-management and community agency between and across levels of government is thus a key pathway for local actors and issues to be represented at sub-national, national, and regional levels (Cohen et al. 2012).

Our findings raise two additional points for consideration in the context of adaptive fisheries co-management. First, patterns of fishing were much more diverse for men than for women, who specialized almost exclusively in gleaning and line fishing. It is possible, therefore, that women's fishing activities may be less resilient to shocks and changes than men's, since there are fewer ways (as dictated by social and cultural norms) in which women can adapt if parts of the fishery change (Grantham et al. 2020). Second, social obligations within kin, tribe or community, can mean requests to access and use fishing grounds to meet financial or social needs can be difficult for managers to deny (Cohen and Steenbergen 2015). The flexible nature of adaptive co-management in these instances is critical to meet social and cultural obligations, and economic and subsistence needs, as they arise, but also what can lead to inefficiencies at achieving ecological objectives.

Conclusion

Adaptive fisheries co-management is a dynamic, continuous, and inevitably messy process. It also occurs within a larger societal framework exposed to external shocks and broader socio-economic changes. Adaptive co-management, particularly where risk and responsibility fall so heavily on local managers, cannot therefore be a panacea for achieving sustainable resource use (Ruddle and Hickey 2008; Foale 2021). Nonetheless, it is still a valuable approach to help ensure multi-species fisheries continue to meet community livelihood, cultural, and food needs. In a rare long-term time series of data, our analysis has demonstrated that in these communities local fishers are experiencing stable catch efficiency, but that through time this stability is masking substantial ecological change. Increased attention to the different life-history characteristics of target species will be necessary to ensure longer-term sustainable fisheries. Ultimately, fisheries co-management therefore does have value in progressing SDG target 14.2 – sustainably managed, healthy, and productive oceans, but this value needs to be understood within the context of broad societal change.

Acknowledgements We would like to thank the Government and People of Solomon Islands for their support of, and engagement with, this work. We acknowledge the primary funders of this research; the Australian Research Council, the Australian Postgraduate Awards, the Australian Government and the Australian Centre for International Agricultural Research (Projects FIS/2012/056 and FIS/2016/300). This work was undertaken as part of the CGIAR Research Program on Fish Agri-Food Systems (FISH) led by WorldFish. The program is supported by contributors to the CGIAR Trust Fund. Special thanks to the invaluable research assistance provided by S. Bitia, W. Lea'amana, W. Zeke, E. Maelulu, D. Evan, C. Daokalia, T. Inipitu, and P. Koso.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions.

Declarations

Conflict of interest The authors declare no conflict of interest.

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