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Fishing dynamics associated with periodically harvested marine closures

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ABSTRACT

Periodically-harvested fisheries closures are emerging as a socially acceptable and locally implementable way to balance concerns about conserving ecosystem function and sustaining livelihoods. Across the Indo-Pacific periodically-harvested closures are commonly employed, yet their contribution towards more sustainable fisheries remains largely untested in the social and ecological context of tropical small-scale fisheries. To address this, we use an interdisciplinary approach to examine harvesting dynamics that would affect sustainability, namely, fishing effort, yield, gear and method use, periodicity of harvesting, controls placed on harvesting and resource owners' decisions to open and close four fishing grounds in Solomon Islands. We compare these fishing patterns with those on surrounding, continuously open fishing grounds. Our study shows that total effort and total catch from periodically-harvested reef closures are low to moderate compared to reefs open to continuous fishing. When periodically-harvested closures were opened, effort in the closures was relatively intense, however, in most cases yield did not exceed annual benchmarks of sustainability described by previous studies. In some cases, harvesting during openings was restricted to a single taxon and single fishing gear and method, while in others there was unrestricted multi-species and multi-method harvesting. The duration and frequency of openings were highly variable, with open periods ranging from a single night to one month in duration, and occurring between one and 15 times per year. Fishing during openings was permitted for entire fishing communities in some cases, and only for specific rights-holding families in others. Decisions to open periodically-harvested closures tended to be based on immediate social or economic needs, and the openings provided a small boost to fish catch landed in communities. While periodically-harvested closures may alleviate fishing pressure in a small area of fishing grounds by reducing the opportunity to fish, openings of long duration or high frequency, combined with heavy or destructive exploitation, may lead to unsustainable harvesting within the area.

Small-scale fisheries support the livelihoods and food security of millions of people worldwide, and if well managed can make significant contributions to human and socio-economic development (Béné et al., 2010). However, the resources that support small-scale fisheries are in decline (McClanahan, 2002; Worm et al., 2009). Researchers and managers are searching for management strategies that can sustain livelihoods and ecosystem functions. Marine protected areas are widely applied and promoted for conservation and management, but they may not result in benefits for fisheries in small-scale fisheries dependent communities (Christie, 2004; Foale and Manele, 2004). An ongoing challenge is to identify socially acceptable and locally implementable controls on marine resource use that will result in long term and effective management of small-scale fisheries. Collaborative management partnerships between local communities, civil society, and/or governments (henceforth co-management) are increasingly emerging as a way forward to address this challenge (Evans et al., 2011; Gutierrez et al., 2011; Pomeroy, 1995).

In a centralised fisheries management context non-permanent, rotational or periodically-harvested closures are recognised for their management potential, mainly for sessile or sedentary invertebrates (Botsford et al., 1993; Nash et al., 1995; Sluczanowski, 1984). However, in open access or weak governance situations, 'pulse-fishing' can be intense when periodically-harvested closures (PHCs) are opened because fishers anticipate improved catch rates and there are few incentives to restrain

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harvest levels (Murawski et al., 2005; Russ and Alcala, 1998). The re-establishment or re-invention of customary PHCs is an increasingly common measure to regulate marine resource use in contemporary co-management initiatives across the Indo-Pacific (Johannes, 2002; McLeod et al., 2009). In co-management contexts, the dynamics of fishing (such as cycles of opening and closure and limits placed on harvests) are generally under the control of the local community or clan that holds tenure rights to the managed area (Hviding, 1996; McLeod et al., 2009).

Some ecological evaluations of PHCs have shown that they can result in higher standing stocks of fish (Bartlett et al., 2009; Cinner et al., 2005), yet whether the practice is likely to result in more sustainable fisheries depends crucially on a range of ecological conditions (e.g., pre-harvest stock levels and the demography of target species) and on the dynamics of harvesting (e.g., intensity, duration, periodicity, and harvesting methods), the latter of which are poorly understood. In this article, we contribute to better understanding the potential for PHCs to contribute to sustainability by examining associated harvesting dynamics, which have five key components: firstly, the catch yielded from areas during openings will determine the level of benefits received by fishers. The type and amount of catch extracted will also influence the potential for recovery during periods of closure, and whether fisheries are rapidly depleted or harvested sustainably (Game et al., 2009; Kaplan et al., 2010; Russ and Alcala, 1996). Secondly, controlling fishing effort is fundamental to managing fisheries, and so sustainability outcomes will be affected by the intensity of fishing during PHC open periods and the overall relief from fishing pressure due to periods of closure. Thirdly, the periodicity of opening and closure cycles is demonstrated by modelling to be critical to fisheries outcomes (Botsford et al., 1993; Game et al., 2009; Pfister and Bradbury, 1996). For example, regular openings may not allow sufficient time for populations to recover (Gerber et al., 2003) or for changes in fish behaviour to manifest and increase catchability (Feary et al., 2011). Fourth, gears and methods employed to harvest will impact conservation and fisheries outcomes, for example certain efficient gears such as small mesh nets, and non-selective and damaging gears such as dynamite, can ultimately affect the ability of ecosystems and populations to recover (Russ and Alcala, 1998). Finally, other resource-use controls that operate in conjunction with PHCs can influence fishing dynamics by restricting catch and effort levels, species harvested, and gears and methods used within PHCs and in surrounding fishing grounds.

As PHCs become increasingly implemented throughout the Pacific, critical questions remain as whether or how they can contribute towards more sustainable fisheries. As a first step in this direction, we explore the five key aspects of PHC harvesting dynamics described above. Our study has three objectives. Firstly, we aim to determine how fishing pressure, in terms of both yield and effort, compares between PHCs and reefs that are continuously open to fishing. Secondly, we aim to describe the cycles of opening and closure applied in practice, and to understand decisions driving those cycles. Finally, we seek to document the gears and methods used to exploit PHCs, and to understand how other concurrently applied management arrangements influence exploitation. We use an interdisciplinary approach to examine four periodically-harvested closures in Solomon Islands.

2. Methods

2.1. Study location

Solomon Islands is a developing Pacific Island nation situated within the global centre of marine biodiversity (Veron et al., 2009). The predominantly coastal and rural population of Solomon Islands depends on coastal fisheries as the primary source of dietary animal protein, and in many areas small-scale commercial fisheries offer one of the few viable livelihood opportunities (Bell et al., 2009). Coastal ecosystems are governed by the state through environment and fisheries legislation, but also to a large extent by communities that have traditional, and constitutionally recognised, marine tenure rights and customary governance systems (Lane, 2006). While most reef ecosystems in Solomon Islands are considered to be in relatively good condition (Green et al., 2006), communities and their partner NGOs have established over 100 co-managed marine areas in response to increasing concerns over resource sustainability. Most co-managed marine areas employ

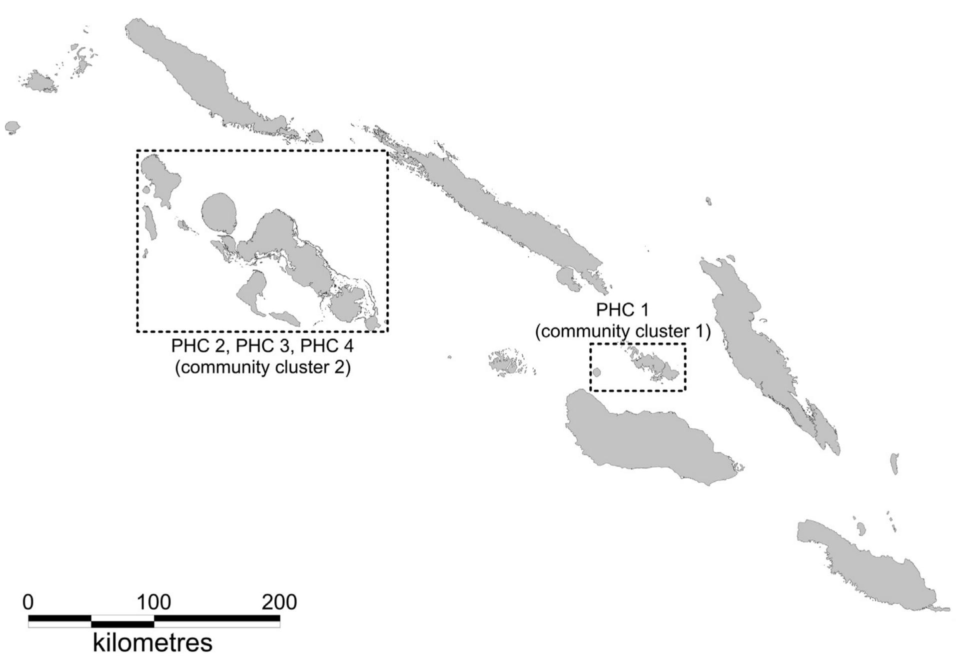

Fig. 1. Map of Solomon Islands showing the regions (demarcated boxes) in which the four periodically-harvested closures (PHC 1, PHC 2, PHC 3, and PHC 4) were situated in two community clusters.

some type of area closure which is most often periodically-harvested (Govan, 2009).

Four periodically-harvested marine closures were examined in Solomon Islands, in two locations which were each comprised of three communities (Fig. 1). Communities were selected because they were known to implement PHCs within a broader co-management framework, and communities and their partner agencies were willing to facilitate a critical appraisal of management arrangements. The first cluster of communities (community cluster one) had one PHC and community cluster two had three PHCs. In each cluster the communities were separate, but geographically proximate (i.e., within 4 and 6 km from each other, respectively). We recorded landed catch from all three communities within each cluster to account for potentially overlapping fishing grounds. Fishers from these communities had primary fishing rights to the PHCs and other nearby fishing grounds, and fishing by 'outsiders' was reported in pilot surveys to be minimal. Community names are not provided because of confidentiality arrangements.

Population density in community cluster one was moderately high (26–50 people per km^2), whereas density was low in community cluster two (less than 10 people per km^2) (Solomon Islands National Statistics Office, 1999). Food and livelihoods were supported predominantly by small-scale forestry, agriculture, remittances from relatives in urban centres, and from fishing. Commercial fisheries focussed on trochus (*Trochus niloticus*), and previously on sea cucumber (at the time of study there was a national moratorium on commercial sea cumber harvest). Communities in cluster one also sold reef fish to the national capital market. PHCs lasting around 3 months had historically been used, mainly as a mark of respect for the death of a community member or in preparation for feasting, and PHCs of varying lengths had been used to replenish and limit access to trochus stocks.

All communities were engaged in NGO-supported resource management initiatives involving the formation and commitment to management plans which incorporated resource-use rules and education, compliance and monitoring strategies. Management arrangements, including PHC 1, were established in 2005 in community cluster one, and arrangements including PHCs 2, 3 and 4 were established in 2008 in community cluster two. In each case, all extractive activities were banned when PHCs were closed.

2.2. Social data

To estimate the number of fishers in each community and the proportion of fishing trips accounted for in our sample, we conducted household surveys in 30–50% of all households in each community. We asked: (a) how many people live in this household? (b) how many people in this household go fishing? and (c) how many times do people in this household go fishing in 1 week? To understand recent site history and the co-management approach at each site, we reviewed written management plans and conducted unstructured interviews with staff of the partner NGOs. We conducted observations, informal interviews with key informants (i.e., resource owners or management committee members) and semi-structured interviews ($n = 77$), as well as focus groups ($n = 20$) with between two and six men, women or youth fishers. Interview respondents represented around 10% of the adult fishing population. We identified interview respondents through snowballing and sought equal numbers of men and women who regularly participated in fishing and were willing to be interviewed. Focus group participants were not required to be fishers but many were. We also sought people from a range of clans. Focus group and interview respondents were asked to describe the reasons for opening PHCs to harvesting, the duration and frequency of opening events over the previous 12 months, controls placed on harvesting from PHCs and other fishing grounds, and their perceptions of compliance with those controls. Interviews were conducted in Solomon Islands pijin, focus group and informal interview responses were hand written in situ. We report the responses given by over 50% of focus groups, and supported or supplemented with data provided in interviews.

2.3. Landing site sampling

Sampling coincided with community-planned openings of PHC 1 in July 2011, and PHCs 2, 3 and 4 in December 2010. We attempted to record details of all fishing trips landing at the six communities during the full period of openings, and for at least 2 weeks during closures. At least one trained observer was posted in each community on each day and night of sampling to record fishing activities. Details of the research programme had been provided in the community prior to the commencement of sampling, and community leaders also assisted in personally informing fishers of the data collection programme. Observers recorded daily observations of numbers of people sighted fishing, or leaving for fishing to allow comparison with the numbers of trips they detailed (described below).

We asked fishers to recount details of their fishing trip as soon as they returned to shore. Details included: time of departure and time of return, number of fishers on the trip, gear(s) used, name of fishing location(s), fished area description(s) (i.e., reef, mangrove, lagoon, and pelagic), and the management regime in operation (i.e., continuously open to fishing or PHC). Trips were classified into three types according to target taxa: finfish, non-finfish, or mixed (i.e., both finfish and non-finfish were targeted on the same trip). The total wet weight of the catch was measured using hanging fishing scales (either a 10 kg/5 g digital scale or 22 kg/250 g analogue scale, depending on the size of the catch) and recorded. Shell weights were included in non-finfish catch weights. Larger catches were separated for weighing and then weights summed. The local nomenclature system was used to categorise finfish and non-finfish for counting and recording purposes. Where fishers were not immediately encountered at the landing location and their catch already cooked, consumed or sold, we used a 'recall' method ($n = 207$ from the 971 fishing trips we recorded) in which the fisher was asked to provide the details of the fishing trip (as per the descriptors above), and to recall the number and lengths of finfish or non-finfish in the catch; these data were used to estimate catch weight (see Appendix 1).

We returned 6 months later in the rainy season to record fishing patterns in community cluster two to account for seasonal variation in fishing, including the relative use of coastal and pelagic areas. We were unable to return to community cluster one, however, informal interviews indicated our sampling was within the period of calmest weather and highest overall fishing activity. A total of 239 fishing trips were directly recorded from harvesting of PHCs (Table 1), and 732 trips were recorded from fishing grounds continuously open to fishing. We also documented the catch and effort of an additional 24 trips that had been recorded by community members during minor PHC opening events over the previous 12 months, and we asked key informants to describe the number of fishers, gears and methods used and/or quantities harvested, so we could reconstruct catch and effort of a further 31 trips that occurred during the other minor openings.

2.4. Characterising fishing grounds

We asked experienced fishers to name and identify reef fishing grounds on nautical charts and satellite images (Landsat 7 ETM+). The areas of fishing grounds were calculated from reef delineations derived from satellite imagery analysed by Andréfouët et al. (2006).

Table 1
Details of periodically-harvested closures (PHCs) including areas, periodic harvesting schedules applied over a 12 month period (prior to, and including, the period of study), reasons for harvesting, harvesting restrictions, access restrictions and the number of days sampled and trips recorded.

	PHC	Area (km^2)	Reason for opening	Harvest restrictions	Access restrictions	Opening duration	Proportion of period (days) sampled	# trips recorded in PHC	Total # trips continuously open areas
Community Cluster 1	1	0.044	Church fundraising	Not restricted	Family members only	12 days, June 2011	12/12 PHC open, 14/346 PHC closed	24[a]	228 (104 PHC open, 124 PHC closed)
			Family financial needs	Coral gleaning only	1–2 family members only	7 days, in 2011	–	7[c]	
Community Cluster 2	2	0.63	Scheduled in management plan	Net and clam harvest banned	Community-wide	31 days, December 2010	31/31 PHC open, 19/320 PHC closed	175[a]	504 (232 PHCs open, 281 PHCs closed)
			Birthdays, weddings	Spear fishing only	4–5 spear fishers only	14 days, in 2010	–	14[c]	
	3	0.03	Scheduled in management plan	Not restricted	Community-wide	31 days, December 2010	31/31 PHC open, 19/334 PHC closed	4[a]	
	4	0.37	Scheduled in management plan	Not restricted	Community-wide	31 days, December 2010	20/31 PHC open, 19/332 PHC closed	36[a]	
			Clinic fundraising	Trochus gleaning only	Community-wide	2 days, September 2010	–	24[b]	

[a] Trips recorded by researchers.
[b] Via community records.
[c] Reconstructed from interviews.

Where several fishing locations were identified by fishers, but indiscernible on a single reef complex, we combined data from those fishing locations and used a single area estimate. Analysis of satellite imagery (Andréfouët et al., 2006) had failed to detect two coastal reefs, and we estimated areas using a combination of raw satellite imagery, nautical charts and fisher-drawn maps. We used MapInfo 11.0 to calculate distances between each fishing ground and its respective community or communities.

2.5. Data standardisation

For comparison of annual yields between reef fishing grounds, we separated catch weights from fishing trips collecting finfish ($n = 514$) and non-finfish ($n = 144$). Where trips collected both finfish and non-finfish, we examined the composition of the catch and allocated the catch weight to finfish when there was only a small non-finfish component ($n = 36$), and to non-finfish where there was a small finfish component ($n = 12$). Finfish and non-finfish composition was more evenly distributed in a relatively small number of trips ($n = 27$) and we divided catch weights from these trips equally between finfish and non-finish catch data. To allow comparison of fishing on PHCs and continuously fished reefs, we scaled up observed daily averages of catch and effort to a year. Because we did not record 100% fishing trips within the sampling period, we used two methods to determine appropriate scaling of our catch and effort sample. Our two methods for determining the sampling rate provided slightly different results; in community cluster one household surveys indicated we had captured 10–22% of fishing trips in our sampling, whereas observation indicated we captured 40%, and in community cluster two sampling rate estimates were 33–45% from household surveys versus 60% from observations. We therefore averaged the two estimates, and used a scaling up factor of three for sampled catch and effort from community cluster one, and a factor of two for community cluster two. We standardised annual effort and catch by the area of each reef where the fishing had taken place.

In our comparison of daily fishing effort on PHCs with effort on continuously open reefs, we standardised effort by the area of each reef. Because travelling time was included in total effort (i.e., fisher hours), we limited the comparison of each PHC to reefs that were a similar distance from communities (i.e., excluding reefs further than an arbitrary 2 km from each PHC). Secondly, we compared each PHC only to reefs that were fished by the same community, or communities. We were forced to exclude from these analyses trips of unknown duration ($n = 74$), or trips to reefs of unknown or questionable area ($n = 36$).

2.6. Data analysis

We compared average daily fishing effort per km^2 among fishing grounds. Data were exceptionally non-normal due to the relatively high proportion of days with nil effort, and it was not possible to find a transformation to resolve normality. We therefore used a Kruskal–Wallis rank sum test to look for differences in daily effort per km^2 on comparable open reefs with corresponding PHCs. Due to the pairing of PHCs with a particular sub-set of open reefs for comparison, we conducted analyses of each PHC comparison separately. We used Games–Howell post hoc tests to examine where differences lay for each of the four PHCs comparisons. Daily fishing effort and catch data from all open fishing grounds (i.e., pelagic, mangrove/lagoon and reef) were square root and log transformed respectively to conform with assumptions of homogeneity of variances and normality. To determine if average daily effort or catch varied between periods when PHCs were closed versus open, we used a one way ANOVA with type three sums of squares, where closure status and community cluster were treated as fixed factors. Subsequently we examined effect size for catch and effort between open and closure periods (sensu Cohen, 1988).

3. Results

Household surveys indicated that community cluster one had a total population of approximately 1000 people, of which 460 were fishers. Community cluster two had a total population of approximately 800 people, with 266 fishers. Fishers conducted on average two fishing trips per week. Female fishers predominantly gleaned in mangrove and reef areas, whereas male fishers used line, spear or nets and fished in both reef and pelagic zones. Where fishing was conducted with a boat, dug-out canoes were used in 98% of trips and motorised boats in less than 2% of trips. Fishing activities predominantly focussed on reefs (i.e., reef fishing represented 73% of trips, mangrove/lagoon zones 8%, and pelagic zones 17%, with 2% of trips in more than one zone or in rivers). The four PHCs we examined represented at most 5% of reef area observed to be fished during sampling. There were also two indefinitely closed reserves (i.e., one in each community cluster) equivalent in size to 2% of fished reef area.

3.1. Comparison of yield

We estimated total annual yield for individual reefs, and compared these to yields suggested by other studies to be sustainable (Fig. 2a). We included all fishing trips where a reef was identified as the fishing location, and therefore loosely reef-associated or semi-pelagic finfish were included in yield estimates. We observed that 22% of reefs (including PHC 1) had higher finfish yields than the 5000 kg/km^2 maximum sustainable yield estimate presented by Newton et al. (2007), and 12% (again including PHC 1) above the range observed by Jennings and Polunin (1995) to be sustainable. Finfish catches from most reefs, including the three other PHCs, were lower than maximum sustainable yield estimates. The proportion of non-finfish (i.e., mainly molluscs, but including other invertebrates, seaweed, and turtles) in total yields varied between reefs with some reefs only being harvested for non-finfish, many for both (including PHC 1, 2 and 4) and others only finfish (including PHC 3) (Fig. 2b). Overall yields of non-finfish from PHCs were low to moderate in comparison with yields from reefs continuously open to fishing. Reconstructed catch estimates from minor opening events indicated that an additional 500 kg of finfish were taken from PHC 2 and 400 kg of non-finfish from PHC 4 throughout the year.

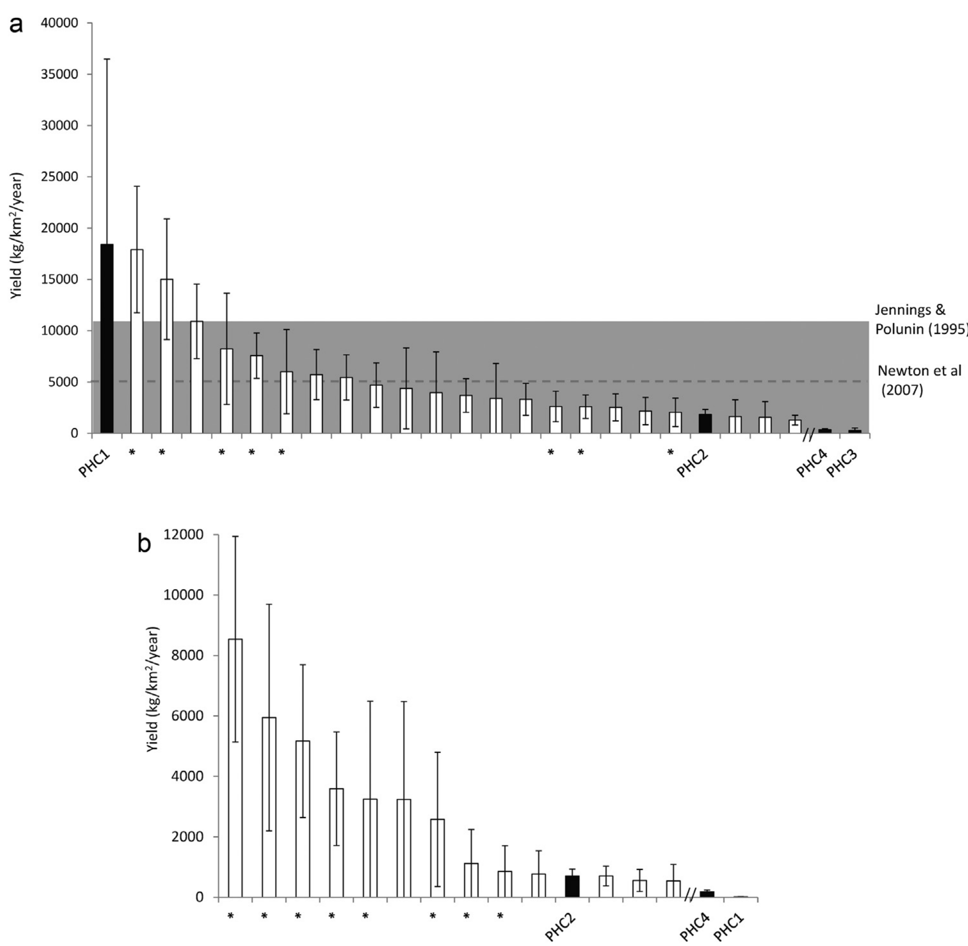

Fig. 2. (A) Estimated total annual yields (±SE) of finfish from different reefs; reefs continuously open to fishing (white bars) and observed harvests of PHCs (black bars PHC 1, PHC 2, PHC 3, and PHC 4). The dark grey shaded area indicates the range of fish yields suggested to be sustainable for tropical fisheries (Jennings and Polunin, 1995). The dashed line indicates an estimate of maximum sustainable finfish yield from reefs (Newton et al., 2007). In addition to PHC 3 and PHC 4, there were 15 other reefs with total finfish harvests of greater than zero but less than 1000 kg per km^2 year that are not presented here (i.e., to the right of the break //). *Estimates do not account for seasonal variation and therefore may provide an overestimate. (B) Estimated total annual yields (±SE) of non-finfish (inclusive of shell weights) from all reef fishing locations; reefs continuously open to fishing (white bars) and observed harvests of PHCs (black bars PHC 1, PHC 2, and PHC 4). In addition to PHC 1 and PHC 4, there were 10 reefs where total non-finfish harvests were greater than zero but less than 500 kg per km^2 per year that are not presented here (i.e., to the right of the break //). *Estimates do not account for seasonal variation and therefore may provide an overestimate.

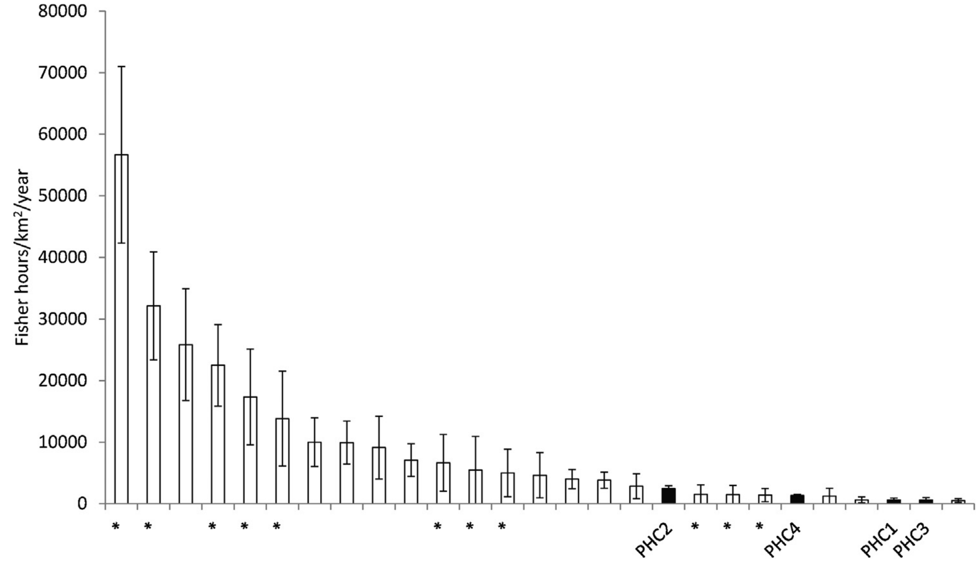

Fig. 3. Estimated total annual fishing effort (±SE) on individual continuously open reefs (white bars) within a 2 km range of PHCs (solid black bars). *Estimates do not account for seasonal variation and therefore may provide an overestimate.

3.2. Comparison of effort among fishing grounds

We scaled observed fishing effort to a full year (i.e., to account for closure periods where PHCs receive no effort yet other reefs are open to continuous fishing) and found that PHCs were fished lightly to moderately compared to reefs that were continuously opened to fishing and were a similar distance from communities as PHCs (Fig. 3). Fishing effort data that were reconstructed, through community records and interviews, indicated that effort from minor harvests within PHCs throughout the previous 12 months accounted for an additional 80% (PHC 1), 9% (PHC 2) and 20% (PHC 4) of total annual fishing effort; the remainder being accounted for by the major harvesting events we recorded directly.

While annual fishing effort on PHCs was low to moderate, on the days that PHCs were opened to fishing, effort was considerably higher, but highly variable, compared to that on reefs continuously open to fishing (Fig. 4). We found no significant difference between effort on reefs continuously open to fishing during periods when PHCs were opened or closed and the effort on PHC 1 ($\chi^2_{(2,n=220)} = 1.3$, $P = 0.523$) or PHC 4 ($\chi^2_{(2,n=46)} = 1.5$, $P = 0.461$). We did find effort was significantly higher during periodic harvests of PHCs 2 ($\chi^2_{(2,n=66)} = 12.0$, $P = 0.003$) than on open reefs in both periods. In the comparison for PHC 3 we observed significant differences in effort ($\chi^2_{(2,n=70)} = 30.6$, $P < 0.001$), but post hoc tests showed the clearest differences lay between open reefs during periods of opening (i.e., effort lower) and periods of closure (i.e., effort higher), yet not to a level of statistical significance ($P = 0.083$). Overall, we did not find consistent evidence that effort is substantially relieved or intensified on continuously open reefs due to the opening or closure of PHCs.

Daily effort and catch from all fishing grounds combined was not significantly higher when PHCs were closed compared to when they were open (Fig. 5; effort $F_{1,64} = 0.80$, $P = 0.375$, catch $F_{1,64} = 2.34$, $P = 0.131$). There was no significant interaction of effects with community cluster (effort $F_{1,63} = 0.87$, $P = 0.353$, catch $F_{1,63} = 0.62$, $P = 0.434$), and with the interaction removed from the model there was no significant effect of community cluster for effort ($F_{1,64} = 3.86$, $P = 0.054$), but there was for catch ($F_{1,64} = 5.30$,

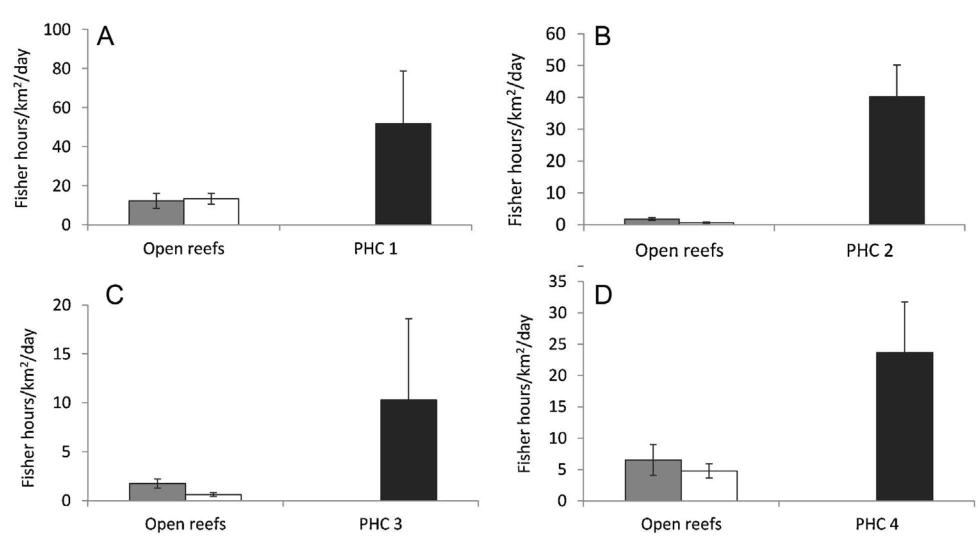

Fig. 4. Mean daily fishing effort (±SE) per km^2 of reef, for PHCs (black bars) and reefs continuously open to fishing within a 2 km range of each PHC, in periods when the PHCs remained closed (grey bars) and when they were opened (white bars): (A) PHC 1; (B) PHC 2; (C) PHC 3; and (D) PHC 4.

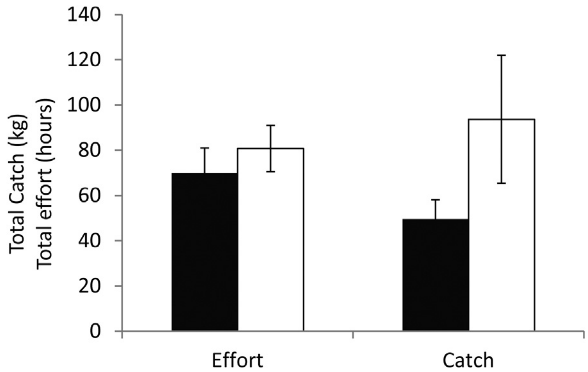

Fig. 5. Average daily fishing effort and catch (±SE) for all fishing locations (i.e., from all fishing reef, pelagic, and mangrove/lagoon fishing grounds) in periods when PHCs were open (white bars) and when PHCs were closed (black bars).

$P = 0.025$). Effect sizes were small for total effort between closed and open periods ($d = 0.22$), and were small-moderate for total catch ($d = 0.35$) (sensu Cohen, 1988).

To examine patterns of effort on PHCs more closely, we observed total effort on each day PHCs were opened, and found that effort was generally higher in the earlier stages of the opening period than the latter (Fig. 6). PHC 3 was an exception receiving only four trips relatively late in the open period, with also a very high proportion of days on which it received no effort at all. In informal interviews two reasons were cited for the low levels of fishing PHC 3 i.e., that it was a relatively poor fishing ground and that ownership was contested.

3.3. Drivers of opening and closure periodicities

Interviews suggested that across all PHCs, opening frequencies varied from once to 15 times per year (Table 1). Openings were most frequent on PHC 2 where harvest periods varied from a single major opening lasting 1 month to 14 minor events of only a single night. In the four PHCs there were three distinct harvesting patterns: (1) harvesting as needs arose, with no prescribed opening schedule (PHC 1); (2) following a prescribed opening schedule (PHC 3); and (3) following a prescribed schedule but occasionally allowing for harvests to meet social needs (PHC 2 and 4). For example, the 1 month openings on PHC 2, 3, and 4 were regular annual events scheduled for December, which was reportedly a period of high demand for cash (e.g., for school fees) and food (e.g., for Christmas). The timing of major openings had been decided, along with other management norms, by the community with the assistance of the supporting NGO, and had been committed to in the formal management plan. The more spontaneous minor openings throughout the previous 12 months were not accounted for in the management plan, but interview data showed they had occurred in response to requests to community managers and resource owners from community members to harvest for money or food for fundraising or celebrations (Table 1).

3.4. Exploitation and management

To harvest finfish and non-finfish from reefs, fishers used several types of fishing gears, which for the purpose of this study have been grouped into five main categories (Fig. 7). We observed explosives to be used only in PHC 1, and on reefs fished by communities within cluster one. Periodic harvesting was conducted mainly by spear and gleaning on PHCs 2 and 4. The opening events we observed directly were multi-gear, multi-method harvests (PHC 3 was an exception where only handlines were used), whereas spontaneous minor harvests of PHCs throughout the previous 12 months were recalled in interviews to be conducted with a single gear and method (e.g., trochus gleaning or spear fishing at night; Table 1).

In addition to the duration of openings, interviews suggested there were two forms of restrictions placed on certain harvests. Firstly, there were limitations on gears, methods and targets during the minor harvests of PHC 1 (i.e., coral harvesting by hand only), PHC 2 (i.e., spear fishing at night only) and PHC 4 (i.e., gleaning for trochus only). Secondly, access restrictions were imposed for minor openings of PHC 2, and for all harvesting of PHC 1. The authority to harvest PHC 1 was controlled by one person as the reef owner, whose extended family could harvest if they had gained his explicit permission. Interviews with fishers from community cluster 2 suggested that fishing effort, of community members who had previously fished at that location prior to PHC implementation in 2005, had been displaced to other fishing grounds.

Resource use rules in management plans entailed commitment to certain national fisheries regulations and additional community-based regulations including size limits, gear restrictions, bans on harvesting spawning aggregations and periodic closures of reef and mangroves (Table A.1). However, management plans and respondents indicated only a limited set of other fisheries restrictions actually implemented on harvesting PHCs and other fishing grounds. It was locally prohibited to harvest tridacnid clams from PHCs 2, 3 and 4, and interview and focus group data

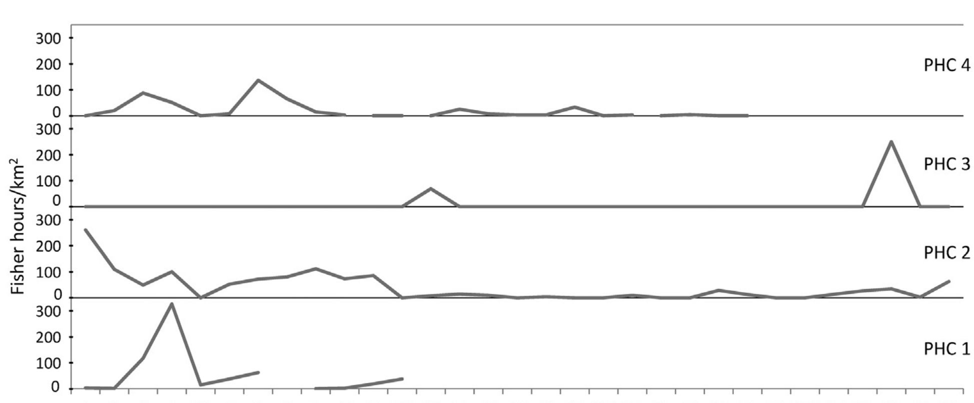

Fig. 6. Daily fishing effort (fisher hours) per km^2 throughout the opening period of each PHC (PHC 1–4). Horizontal axis indicates the day count from the first day of opening. *Indicates Sundays during openings of PHC 2, 3 and 4 where there was no fishing activity at all. PHC 1 was re-closed on day 13. Blanks during periods of opening indicate days that were not sampled.

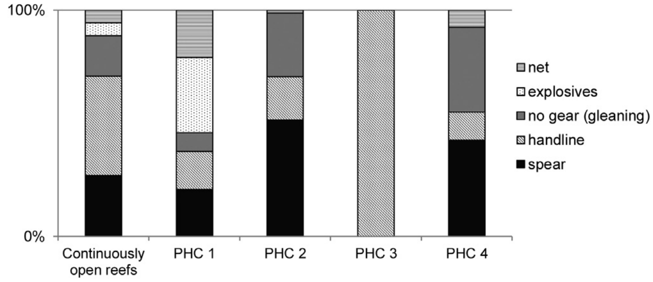

Fig. 7. Fishing gears used to harvest PHCs, and reefs continuously open to fishing. Five fishing trips that used multiple gears in a single trip are excluded from this graph.

indicated that this restriction was well complied with. Communities recognised and followed nationally legislated minimum size limits on trochus, bans on commercial harvesting of sea cucumber, and on the use of explosives (however, there were observed exceptions to this). There was a restriction in all communities on harvesting 'small fish' (specific size limits were not indicated), yet this was reportedly not well complied with. In community cluster two fishing was banned on Sundays due to Church restrictions, whereas fishing activities from communities in cluster one took place on all days of the week.

4. Discussion

Across the Indo-Pacific customary institutions form the building blocks of contemporary conservation and resource management efforts. Harvesting dynamics associated with traditionally-based periodically-harvested closures have received little research attention to date, despite the prevalence of PHCs as a fisheries co-management measure. Our study illustrates that in rural, small-scale fisheries-reliant communities, total annual fishing effort and yield on PHCs can be low to moderate compared to reefs that are continuously open to fishing. Yet, we also observed that fishing pressure can be relatively intense during periods of opening (Fig. 4) and that PHC openings can provide a small boost to catch landed in communities (Fig. 5). Harvesting frequency of PHCs is variable, but almost always flexible, and is largely driven by local social and economic needs. Patterns of harvesting, including participation and gears used, are constrained by management regulations applied to some opening events, while no constraints are placed on others.

4.1. Comparison of yields

Within co-management frameworks across the Indo-Pacific, a pressing question for managers is how much can be sustainably harvested when PHCs are opened? Confidence in estimates of sustainable yield is challenged by multiple factors, including variations in productivity between areas and the taxonomic composition of multi-species catches (Larkin, 1977; Russ, 1991). In these cases, PHCs were selected for social reasons and so a comparison of yield amongst fishing grounds is random in terms of ecological productivity. Further, in a parallel study it was found that catch characteristics were similar from PHCs and open reefs in terms of catch rates, catch composition and average size of fish (Cohen and Alexander, in press). Therefore, our estimates of yield provide a useful basis for comparison of extractive pressure. Three of the four PHCs we observed were harvested below finfish yields that previous studies have suggested might be sustainable (Jennings and Polunin, 1995; Newton et al., 2007). One PHC was harvested above measures of sustainable yield, largely due to the dominant use of efficient gears (i.e., explosives and nets) to harvest fishes that were loosely reef-associated (mostly scads and sardines) from a relatively small area of reef. Non-finfish yields from PHCs were low to moderate compared to yields from reefs continuously open to fishing, and therefore both finfish and non-finfish yields from PHCs were within the range of yields from similar reefs. We find no multi-species estimates to indicate whether the levels of non-finfish harvesting we observed might be sustainable, though a parallel study found catch rates indicated that invertebrate populations had built-up during closures, but were substantially depleted during openings (Cohen and Alexander, in press). In cases of single species harvests, such as trochus fisheries, quantitative assessments of stock condition prior to harvests have successfully informed catch limits for periodic harvests (Nash et al., 1995). However, multi-species harvests are significantly more challenging to assess, and within co-management frameworks, even single species quota determination through stock assessments is likely beyond capacity available (Johannes, 1998). In general, periodically-harvested closures would be less likely to accrue fisheries benefits when total exploitation levels are higher than, or equivalent to, levels in areas continuously open to fishing (Russ and Alcala, 2003). However, more specific guidance for community managers on harvest limits is currently lacking, but notably monitoring and controlling catch can present a substantial challenge in co-management contexts.

The sustainability of catch levels will be highly variable among target species, due to wide variation in life history traits (growth rate, longevity, fecundity, age at maturity, etc.), which confer differing levels of vulnerability to fishing (Cheung et al., 2005; Pauly et al., 1998). Similar to observations of others (e.g., Bartlett et al., 2009; Jupiter et al., 2012), the periodic harvests we observed commonly targeted a wide range of species (Cohen and Alexander, in press). Periodic harvesting strategies are, however, thought to be more suitable for short-lived and fast-growing taxa than those that are longer lived and slower growing (Foale and Manele, 2004; Jennings et al., 1999; Russ and Alcala, 1998). Surprisingly, comparisons of fish biomass inside and outside of closed areas in Vanuatu, Papua New Guinea, and Indonesia suggest that periodic closures have had benefits over strategies of continuous fishing for species deemed vulnerable to exploitation (Bartlett et al., 2009; Cinner et al., 2006). For certain species in temperate fisheries, particular cycles of closure and harvesting can in fact increase sustainable yields compared to a continuous harvesting strategies (Hart, 2003); yet for tropical species this information is not as yet available. To better understand the fisheries management efficacy of periodic harvesting strategies, more research is needed into the taxa-specific and secondary ecological responses to patterns of periodic harvesting.

4.2. Comparison of effort among fishing grounds

Implementing periods of closure reduces fishers' opportunity to harvest, and can act as an indirect measure to reduce overall fishing effort expended in a given area. Previous studies speculate that the positive fisheries effects (i.e., comparatively high density and size of standing stocks) from periodically-harvested or rotational closures may result primarily from reduced fishing pressure inside closures (Cinner et al., 2006; Kaplan et al., 2010). However, prior to our study there was no evidence that the cycles of opening and closure that were employed and controlled by communities would result in low or reduced fishing pressure. Over a 12 month period, we observed PHCs to be fished at light to moderate effort levels compared to reefs fished year-round. While there is flexibility to open PHCs more than once within a 12 month period, the major opening events accounted for the majority of effort and catch in most cases. All four PHCs were geographically closer to communities than over 50% of comparable reefs. As proximate fishing grounds tend to receive proportionally more fishing effort than those more distant (Caddy and Carocci, 1999; Daw, 2008), we might expect that if continuously open, these PHCs would be some of the most heavily fished reefs. Therefore, our comparison of effort across 12 months lends support to the hypothesis that periodically-harvested closures can receive reduced effort, but this would require pre-implementation data to confirm.

Yet, while we observed annual effort in PHCs to be relatively low, fishing effort during openings was intense (i.e., daily average effort was between four and 60 times higher on PHCs than on reefs continuously open to fishing), and effort was particularly intense early in the opening period. The phenomenon of elevated fishing intensity in 'pulse-fishing' when areas are newly opened has been observed elsewhere when fishers' anticipate higher catch rates and yields, and when social demands are high (Murawski et al., 2005; Russ and Alcala, 1998). Fishers are ostensibly benefiting from increases in growth or abundance that have accrued during closure, however intense fishing could potentially deplete stocks beyond levels of replenishment. Behavioural responses of fish such as spill-in or reduced flight initiation distance, may mean that a relatively small amount of effort is more effective at removing biomass (i.e., due to increased catchability) (Feary et al., 2011; Jupiter et al., 2012). In cases of high fishing pressure, particularly in open access fisheries, benefits of periodically-harvested closures are less evident. For example, during the first two weeks of opening a reef closure in New Caledonia, fishing catch and effort reached levels that had previously been observed over an entire year (Ferraris et al., 2005). Periodic harvests in Hawaii resulted in overall declines of target-species populations, indicating that the 1–2 year closure periods were too short for compensatory growth and reproduction (Williams et al., 2006). Similarly, unrestrained harvests of two fish reserves in the Philippines rapidly depleted finfish biomass, whereas subsequent recoveries were slow (Russ and Alcala, 2003). High ambient fishing pressures, combined with a lack of restraint during harvests, reduce the chance of realising fisheries benefits from periodic harvesting strategies. This emphasises the importance of embedding periodically-harvested closures within functional co-management frameworks, or more generally in contexts where mechanisms to limit fishing effort exist.

Implementing periodically-harvested closures shifts fishing effort in time, and potentially also in space. While periods of closure allow for closed areas to replenish, other areas can become more impacted if broader management has failed to remove net effort from the system (Hilborn et al., 2004). This will be particularly apparent in regions where fishing pressure is high, or alternative fishing grounds are minimal. Our qualitative data suggest that upon implementation of PHC 1, the fishing activities of those who had previously fished at that location were displaced to other grounds. In all cases, we found no evidence that effort is substantially shifted away from open reefs when PHCs are opened, or onto open reefs when PHCs are closed, which is likely due to the relatively small size of PHCs compared to all available fishing grounds. In locations where ambient fishing pressure is higher, or PHCs represent a greater proportion of fishing grounds, the effects of effort displacement would become more obvious.

4.3. Drivers opening and closure periodicities

The periodicity of closure and harvesting events is critical to determining the fisheries management efficacy of periodically-harvested closures (Gerber et al., 2003). In centralised management contexts optimal periods of opening and closure can be guided by modelling techniques (e.g., Botsford et al., 1993), however, in co-management contexts the factors that influence decisions to harvest, and resultant cycles of harvesting, are poorly understood. We observed planned management arrangements to vary between scheduled closures and openings, and indefinite periods of closure with the flexibility to open as needs arise; we observed areas to be opened as needs arise in three of the four cases. Decisions about when to harvest PHCs were largely based on increased economic (similar to Foale, 1998; Thorburn, 2000) or social needs (similar to Bartlett et al., 2009; Cinner et al., 2005), as opposed to ecological observations or assessments (as reported by Cinner et al., 2006; Nash et al., 1995). This flexibility to open areas fits well with meeting social objectives, but potentially increases vulnerability of fisheries to increasing demands on resources. Socially or economically driven decisions to harvest areas may not, in practice, coincide with sufficient replenishment of some species. As such, to meet longer term fisheries sustainability goals, management must seek to address the balance between social, economic and ecological indicators used to influence decisions to harvest. In scenarios of low ambient fishing pressure the need to refer to ecological indicators may not be so pressing, but in increasing or high fishing pressure scenarios the importance of resource monitoring, concurrent controls on harvesting and adaptive management institutions is elevated.

4.4. Exploitation and management

To harvest from reefs, fishers used a range of gears with different selectivity and habitat impact. In one case we observed the use of explosives; a highly non-selective and efficient gear that can cause substantial habitat damage when used directly on coral reefs (Russ and Alcala, 1998). Spears and gill nets can also damage corals directly, whereas gears such as handlines have relatively low impacts (Mangi and Roberts, 2006). Few studies have considered habitat recovery or habitat impacts of periodic harvests, however where it has been studied, species richness, live coral cover and coral diversity did not to vary significantly between PHCs and areas open year-round (Cinner et al., 2005). The concurrent use of gear and spatial fisheries controls has benefited tropical fisheries in other regions (e.g., McClanahan, 2010), yet it appears the effective implementation of gear restrictions presents a challenge in at least one case we studied (i.e., PHC 1) where compliance with existing gear controls (i.e., dynamite ban) is weak. The relative use of fishing methods and the selectivity of gears for large versus small, vulnerable versus resilient taxa will ultimately influence the sustainability of any particular level of yield. As such, in multi-species, multi-gear harvests the life history characteristics of the resultant catch will be a critical factor influencing the efficacy of PHCs for fisheries management.

Similar to many studies of periodically-harvested closures in the Indo-Pacific (Cohen and Foale, 2013), we find no limits placed on the volumes harvested during openings. We do find evidence of taxa-specific limits during minor harvests and compliance with a total ban on harvesting tridacnid clams from three PHCs. The clam ban is not accounted for in the management plan, and appears to be a useful adaption of management that accounts for relatively slow recovery rates versus closure times for that genus. Fisher participation in harvesting is limited to community residents, with more explicit limits on participation applying in certain cases. While limiting access is a fundamental mechanism to manage fisheries, restricting participation will not necessarily change the volume harvested, just who harvests it (Polunin, 1984). This distinction will become increasingly evident in scenarios of increasing or high population pressure, and commercialisation of fisheries.

In one of the four cases we find evidence of "elite capture", where direct benefits from harvesting the PHC accrued mainly to the chief and his family, whereas prior to PHC implementation that reef had been accessible to all fishers in adjacent communities. Coincidentally, this PHC happens to be the one tangible example of harvesting that may exceed sustainable levels. Elite capture refers to the disproportionate flow of benefits, often towards local powerful interests, who have exercised their existing positions or powers to secure those benefits. Many co-management initiatives aim to improve community-wide well being, however, elite capture or inequitable benefit distribution are common unintended consequences of decentralisation initiatives working within customary governance structures (Béné et al., 2009). In the case we observed, community members appear to have been only marginally disadvantaged by the implementation of the PHC due to its small area relative to other accessible fishing grounds. Yet, as competition for resources intensifies, scenarios of elite capture, or inequitable benefit distribution, will almost certainly become more common (for analogous scenarios in Philippines, see also Cabral and Alino, 2011; Fabinyi et al., 2010), and with greater implications for non-elite or marginal groups.

Despite comprehensive written management plans that included a diversity of resource-use rules, we found that locally formed and *implemented* rules were less comprehensive. There was widespread awareness and compliance with the nationally legislated trochus, sea cucumber and dynamite restrictions. However, similar to the findings of Léopold et al. (2013), other agreed-to local rules appeared less conducive to community level implementation than PHCs or small reserves. Community enthusiasm for PHCs, at least in part, arises from similarities with customary practice (Williams et al., 2006), maintaining fishers' ability to access and exploit resources in the area (Foale and Manele, 2004), observations of stock replenishment, or increased catchability after closures are lifted (Cinner et al., 2006).

In our case studies, reefs represent the dominant habitat for fishing, although fishers also utilise pelagic, lagoonal, and mangrove areas. While other resource-use rules may influence fishing in a range of habitats, most PHCs in the Indo-Pacific are placed over coral reefs (Cohen and Foale, 2013). Periodically-harvested closures and indefinitely closed reserves represented less than 7% of fished reefs, and were the most prominent form of resource-use control in the cases we studied. Closed reefs therefore represented a very small proportion of all fishing grounds and displaced effort is therefore highly dispersed amongst open fishing grounds. However, we find then that only a very small proportion of fishing grounds are influenced by any management practices at all. Long-term successful fishery management will require PHCs to be embedded within functional co-management frameworks in which a diversity of context specific, socially acceptable and fisheries appropriate management measures are implemented and adapted (Gutierrez et al., 2011). To achieve sustainable fisheries practices, attaining more comprehensive resource management within co-management frameworks presents an ongoing challenge to community managers and their support agencies.

5. Conclusion

Our research suggests that periodically-harvested closures represent a minor reduction in fishing grounds when they are closed, but when opened provide communities with an opportunity to boost fish catch to meet elevated social and economic demands. In these contexts where communities were heavily reliant on small-scale fisheries, but populations were of low to moderate density, these relatively intense pulses of fishing generally resulted in harvests that were within annual benchmarks of sustainable yields described by previous studies (Newton et al., 2007; Jennings and Polunin, 1995). In these cases we found substantial diversity in intensity of fishing during harvests, opening and closure cycles, gears and methods used to harvest, and distribution of benefits from periodically-harvested closures. Generalising about the benefits of periodically-harvested closures for managing fisheries is complicated by this variability. Our study has started the complicated task of unpacking the elements of fishing dynamics that will determine whether periodically-harvested closures can contribute towards the sustainability of reef fisheries. Examining the contexts in which periodically-harvested closures can result in enhanced and sustainable catch rates or yields is an important area of future research.

Co-management arrangements that feature periodically-harvested closures have proliferated in the Indo-Pacific region over the past decade (Bartlett et al., 2009; Jupiter et al., 2012). Yet, tropical fisheries, and their management institutions, face increasing demands from commercialisation and factors operating outside of the fisheries sector, including population growth (Bell et al., 2006; Bruno and Selig, 2007; Schwarz et al., 2011). While the flexibility to harvest closures is of social and economic importance, increasing demands may lead to increased frequency of openings and elevated intensity of harvests, resulting in net declines in stocks (Cohen and Foale, 2013). Customary management institutions (i.e., the origins of periodically-harvested closures and the foundations of many co-management initiatives in the Indo-Pacific) are not necessarily robust to factors such as population growth, export market penetration and economic modernisation (Polunin, 1984; Ruddle, 1994). However, within co-management frameworks, cross-scale institutional and knowledge exchange linkages, via partnerships with NGOs or government agencies, may guide and bolster local institutions in the face of increasing pressures (Cudney-Bueno and Basurto, 2009; Thorburn, 2000). Recognising the importance of periodically-harvested closures in the Indo-Pacific, future research should inform practical guidance to retain closures as community governed institutions that meet shorter term social and economic needs, but that also enhance progress towards longer term fisheries goals. While a suite of strategies is likely required to address contemporary fisheries concerns in the Indo-Pacific, co-managed periodically-harvested closures provide some foundations to build upon.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2013.08.010.

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