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Periodically harvested closures require full protection of vulnerable species and longer closure periods

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ABSTRACT

Periodically harvested closures (PHCs) are small fisheries closures with objectives such as sustaining fisheries and conserving biodiversity and have become one of the most common forms of nearshore marine management in the Western Pacific. Although PHCs can provide both short-term conservation and fisheries benefits, their potential as a long-term management strategy remains unclear. Through empirical assessment of a single harvest event in each of five PHCs, we determined whether targeted fishes that differ in their vulnerability to fishing recovered to pre-harvest conditions (the state prior to last harvest) and demonstrated post-harvest recovery benefits after 1 year of re-closure. For low and moderately vulnerable species, two PHCs provided significant pre-harvest benefits and one provided significant post-harvest recovery benefits, suggesting a contribution to longer-term sustainability. PHCs with a combination of high compliance and longer closing times are more likely to provide fisheries benefits and recover from harvest events, however, no benefits were observed across any PHCs for highly vulnerable species. We recommend PHCs have longer closure periods before being harvested and species that are highly vulnerable to fishing (e.g. large species of; grouper, wrasse and parrotfish) are avoided during harvests to avoid overexploitation and increase the sustainability of small-scale fisheries.

1. Introduction

In an attempt to recover fisheries resources and provide food security to communities in the Western Pacific, locally-managed marine areas have been widely promoted (Govan, 2009; Jupiter et al., 2014). Periodically harvested closures (PHCs) have become one of the most common forms of fisheries management used in locally-managed marine areas, with over 1000 closures estimated across the Western Pacific (H. Govan, pers. comm.). PHCs are generally small fisheries closures (e.g., median area of 1 km^2 in Melanesia; Govan et al., 2009), with periodic harvest regimes that make them functionally similar to rotational closures (Cohen and Foale, 2013). Historically they have been applied in Pacific coastal communities to increase catch efficiency and provide for socioeconomic and cultural needs, while objectives such as sustaining small-scale fisheries and conservation of biodiversity have been proposed more recently (Cohen and Foale, 2013; Jupiter et al., 2014, 2012). The widespread use of PHCs in a region where small-scale fisheries are essential for food security (Bell et al., 2009), highlights the importance of understanding the best practice and trade-offs of PHCs for fisheries management and conservation strategies.

PHCs vary markedly in the way they are managed, in particular the time they are closed versus open to fishing, which has resulted in variation in their ability to increase the abundance, size or biomass of targeted species (Bartlett et al., 2009; Cinner et al., 2006; Goetze et al., 2015; Jupiter et al., 2012). However, a recent meta-analysis found that PHCs across Melanesia were capable of providing pre-harvest protection benefits through increased abundance and biomass of targeted species, which translated into harvest benefits when opened to fishing (Goetze, 2016). The meta-analysis found that these benefits are greater in PHCs that are large, have high compliance and are closed to fishing for long periods. However, variation in these factors within Fijian PHCs has resulted in inconsistent outcomes for the abundance, size and biomass

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of targeted species (Goetze et al., in review). While there is some evidence for well-managed and designed PHCs providing short-term fisheries benefits prior to harvesting, a large proportion of the biomass of targeted species is usually removed during harvest events (Goetze, 2016). The ability of PHCs to recover from high levels of harvesting and their role in sustaining fisheries has not been explored empirically.

Similar to no-take marine reserves (hereafter referred to as marine reserves), recovery of targeted biomass within a PHC is expected to occur through multiple mechanisms, the importance of which will vary depending on the length of time that the area is protected (Russ and Alcala, 2003). Recruitment, the addition of juveniles, growth of the existing population and migration/movement across PHC boundaries are some of these mechanisms. The rapid changes in fishing pressure associated with opening and closing PHCs makes it particularly important to account for migration/movement across PHC boundaries. For example, "spill-in" of targeted species into protected areas can occur when fishing pressure outside is high (Eggleston and Parsons, 2008) or a "bail-out" effect can occur when there is a sudden increase in fishing pressure within PHC boundaries (Jupiter et al., 2012). This highlights the importance of monitoring both PHCs and sites open to fishing across the entire harvesting regime when investigating recovery dynamics.

Assessing the implications of PHCs for long-term fisheries management and conservation requires understanding how species that vary in their vulnerability to fishing are affected by harvest regimes. Long term studies using marine reserves have been used to assess how coral reef fish recover from the effects of fishing and suggest that decadal time scales may be required for the full recovery of fish assemblages in heavily fished areas (McClanahan et al., 2007; McClanahan and Graham, 2015; Russ and Alcala, 2004). In addition, coral reef fishes have a broad range of life history traits that influence their vulnerability to overfishing including: maximum size; growth rate; maximum age; age of sexual maturity; and rates of mortality (Abesamis et al., 2014; Cheung et al., 2005; Jennings et al., 1999; Russ and Alcala, 1998). Recovery trajectories will thus not only depend on the local fishing intensity, but also on the life history traits and vulnerabilities of targeted fish species, with higher vulnerabilities generally resulting in slower recovery (Abesamis et al., 2014; Claudet et al., 2010; McClanahan and Humphries, 2012). For example, Abesamis et al. (2014) use marine reserves to show that the full recovery of large predators in overfished regions may take between 20 and 40 years, while smaller-bodied herbivores may recover within 10 years.

The recovery trajectories of coral reef fishes observed in marine reserves is applicable to PHCs during the no-take closure periods. Abesamis et al. (2014) related the recovery trajectories observed in marine reserves to the management of PHCs and estimated that a 10% removal of stock will require several years of recovery for less vulnerable species (e.g., small parrotfish), while moderately to highly vulnerable species (e.g., large groupers) may take more than a decade. This suggests that certain species will be better suited to the strategy of periodic harvesting and collecting data on the recovery trajectories of target species across different levels of vulnerability will be essential to ensure the long-term sustainability of the harvesting regime within PHCs. We estimated the biomass of targeted species immediately (1–2 days) before, after and 1 year after a harvest event, inside and outside of five PHCs across Fiji with varying management strategies. We aimed to determine if targeted fish biomass within PHCs would recover to pre-harvest conditions and provide post-harvest protection benefits after 1 year of re-closure, a common closure time across Melanesia (Goetze, 2016). Additionally, we assessed how targeted species with low, moderate and high vulnerabilities to fishing were impacted and whether they recovered from harvest events. We hypothesised that species with high vulnerability were likely to benefit least from PHCs, and that magnitude of recovery would decrease with increasing vulnerability.

2. Methods

2.1. Study area

Surveys were carried out on reefs adjacent to five villages on Koro (Nakodu, Tuatua), Ovalau (Nauouo, Natokalau) and Vanua Levu (Kiobo) islands in Fiji in 2013 and 2014 (Appendix A). PHCs had been established for 3–8 years prior to surveys, though the frequency at which they had been previously harvested and level of compliance with management varied (Table 1). Each PHC was established by the local community in conjunction with a non-government organization. Surveys were carried out 1–2 days before, 1–2 days after and approximately 1 year after harvests, which lasted between 1 and 7 days and involved line fishing, spear fishing and/or fish drives into gill nets. Key informants reported that historical harvest events were of similar intensity to those presented here, although this could not be verified empirically. For clarity we refer to the PHCs by their associated village (Nakodu, Tuatua, Natokalau, Nauouo and Kiobo; Table 1, Appendix A).

2.2. PHC and harvest information

Most PHCs were relatively large (0.73–3.14 km^2) compared to the median for Melanesia (1 km^2; Govan et al., 2009) and varied in habitat and depth (Table 1). No significant differences in the benthic strata (measured through underwater visual census) were observed between PHC and open areas (Jupiter et al., in review). Compliance levels were based on surveys with village spokespersons, who were asked to rate compliance as low (frequent breaches of management rules), moderate (occasional breaches of management rules) or high (infrequent offenses of management rules), based on their direct observations within each village. To estimate fishing pressure during harvest events (harvest intensity), we recorded the gear, area, time, number of fishers and their catch (species, abundance and length) during the harvest of each PHC. Harvest intensity was then calculated as the total number of fisher hours per km^2 of PHC.

2.3. Sampling design

We sampled between 2 and 5 sites inside each of the five PHCs (depending on PHC size), and 4 to 6 sites outside PHCs in areas open to regular fishing (depending on comparable available habitat; Appendix A). Sites open to regular fishing were distributed on either side of each PHC in areas within the local community's fishing ground. At each site, the fish community was sampled by conducting stereo diver operated video (stereo-DOV) surveys along six replicate 5 × 50 m transects separated by 10 m, following Shedrawi et al. (2014). Sampling was conducted 1–2 days before the opening of each PHC, 1–2 days after the harvest and approximately 1 year after the harvest. All five PHCs were closed to fishing for the entire year following the monitored harvest.

2.4. Sampling technique and video analysis

Stereo-DOVs can provide highly accurate estimates of fish length and position relative to the camera system (Harvey et al., 2004) and are one of the most effective methods for detecting harvest impacts on targeted species within PHCs (Goetze et al., 2015). Stereo-DOVs were used to collect length estimates and biomass was calculated using the standard length-weight equations and values from FishBase (Froese and Pauly, 2015), preferentially selected from sites closest to Fiji (Jupiter and Egli, 2011). System design and procedures for video analysis followed Goetze et al. (2015), and data were extracted from EventMeasure software and checked following Langlois et al. (2015).

Table 1
PHC contextual information and percent of catch during harvests in each vulnerability category.

PHC (Village)	Size (km^2)	Habitat (depth)	Year est.	Compliance	Historical harvest regime	Harvest duration (days)	Harvest intensity (hrs/km^2)	Harvest efficiency (fish person $hour^{-1}$)	Time closed prior to harvest (years)	% of catch in vulnerability category		
										Low	Moderate	High
Kiobo	2.07	Reef slope (5–8 m)	2009	Moderate	Once every year	7	65.7	1.95	1	21	69	10
Nakodu	0.73	Lagoon (1–3 m)	2010	High	None since creation	4	1271.6	3.7	3	47	47	6
Tuatua	1.34	Reef slope (5–8 m)	2005	High	Every 3 months	1	50.1	2.93	0.25	75	22	3
Natokalau	2.17	Lagoon (1–3 m)	2006	High	Once in 2011 and 2012	2	94.3	3.38	1	26	71	3
Nauouo	3.69	Back reef slope (5–8 m)	2010	Low	Once in 2011 and 2013	3	39.9	2.44	0.08	57	32	11

2.5. Vulnerability and species selection and

We used intrinsic vulnerability levels that integrate life history and ecological characteristics of fishes, using a fuzzy expert system developed by Cheung et al. (2005) and extracted from FishBase (Froese and Pauly, 2015). Due to a paucity of species in the high or very high vulnerability categories (species with a score of >65), we categorized our species into three levels with different vulnerability ranges: Low (10–25); Moderate (25–50); and High (50–90) (Appendix B). Targeted species were defined as those caught during each harvest, which varied between villages. Catch from each harvest was used for subsistence purposes, which resulted in a broad range of targeted species (Appendix C).

2.6. Data analysis

In order to assess recovery, we followed the analytical framework presented in Goetze (2016), which defines the hypotheses, mechanisms and effect sizes required to assess the multiple potential protection and harvest benefits from PHCs. Here we assessed: (1) the ability of a PHC to provide increased biomass of fishes before the harvest when compared to open areas, the *pre-harvest protection benefit*; (2) the proportion of biomass removed from the PHC during harvest, the *harvest benefit*; (3) the ability of a PHC to provide an increased biomass when compared to open areas after 1 year of recovery, the *post-harvest recovery benefit*; and (4) the level of biomass in the PHC after 1 year of recovery compared to the pre-harvest level, the *recovery of pre-harvest protection benefits*. A large positive effect size for the *pre-harvest protection benefit* and the *post-harvest recovery benefit* would represent a greater biomass within PHCs compared to open areas. In contrast, a large negative effect size for the *harvest benefit* would represent a greater proportion of biomass removed from PHCs compared to open areas and therefore a benefit to fishers. An effect size of zero for the *recovery of pre-harvest protection benefits* would represent full recovery from the impact of harvests after 1 year. We used the mean biomass per transect from surveys done before, immediately after and 1 year after the harvests for all targeted species and species in the low, moderate and high vulnerability categories to allow comparisons across villages.

2.7. Effect sizes

For each PHC i, the effectiveness of a PHC to deliver a *pre-harvest protection benefit* $E_{b,i}$, was calculated as the log-ratio of the mean biomass per replicate in the *PHC Before*, $\overline{X}_{Pb,i}$, and the *Open Before*, $\overline{X}_{Ob,i}$ (Fig. 1):

$$E_{b,i} = \ln\left(\frac{\overline{X}_{Pb,i}}{\overline{X}_{Ob,i}}\right)$$

The variances $v_{E_{b,i}}$ associated with the effect sizes $E_{b,i}$ were calculated as:

$$v_{E_{b,i}} = \frac{\sigma^2_{Pb,i}}{n_{Pb,i} \times \overline{X}^2_{Pb,i}} + \frac{\sigma^2_{Ob,i}}{n_{Ob,i} \times \overline{X}^2_{Ob,i}}$$

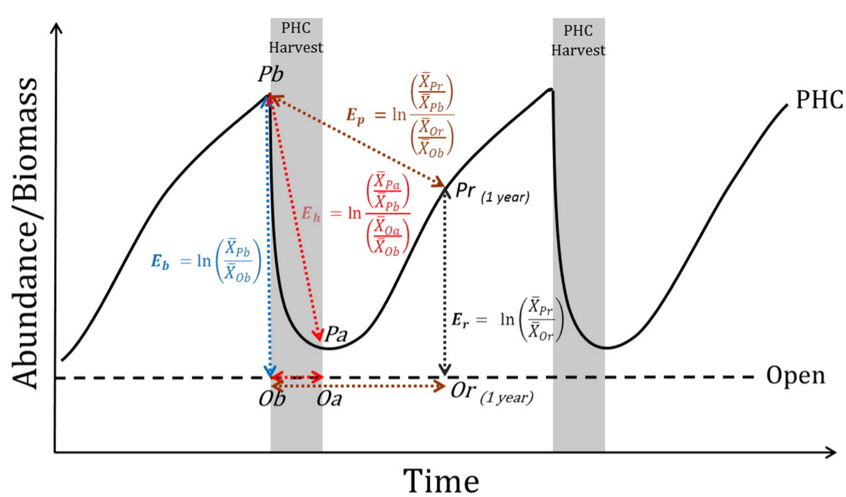

Fig. 1. Conceptual diagram of an optimal harvest regime within PHC (P) and Open areas (O) before (b) and after (a) harvest events, with recovery (r) indicated in the PHC 1 year after a harvest event. Effect sizes (E) are shown in blue for *pre-harvest protection benefits* (E_b), red for *harvest benefits* (E_h), black for *post-harvest recovery benefits* (E_r) and brown for *recovery of pre-harvest benefits* (E_p). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

where $\sigma_{Pb,I}$ and $\sigma_{Ob,i}$ are the standard deviations associated with the means $\overline{X}_{Pb,i}$ and $\overline{X}_{Ob,i}$, respectively, and $n_{Pb,i}$ and $n_{Ob,i}$, are the number of replicates used to calculate each mean.

For each PHC *i*, the *harvest benefit* $E_{h,i}$ was defined as the relative difference in the mean biomass per replicate between the *PHC after* ($\overline{X}_{Pa,i}$) and before ($\overline{X}_{Pb,i}$) the harvest, whilst controlling for differences between open areas after ($\overline{X}_{Oa,i}$) and before ($\overline{X}_{Ob,i}$) the harvest (Fig. 1):

$$E_{h,i} = \ln \frac{\left(\overline{X}_{Pa,i}/\overline{X}_{Pb,i}\right)}{\left(\overline{X}_{Oa,i}/\overline{X}_{Ob,i}\right)}$$

The variances $v_{E_{h,i}}$ associated with the effect sizes $E_{h,i}$ were calculated as:

$$v_{E_{h,i}} = \frac{\sigma^2_{Pa,i}}{n_{Pa,i} \times \overline{X}^2_{Pa,i}} + \frac{\sigma^2_{Pb,i}}{n_{Pb,i} \times \overline{X}^2_{Pb,i}} + \frac{\sigma^2_{Oa,i}}{n_{Oa,i} \times \overline{X}^2_{Oa,i}} + \frac{\sigma^2_{Ob,i}}{n_{Ob,i} \times \overline{X}^2_{Ob,i}}$$

where $\sigma_{Pa,i}$, $\sigma_{Pb,i}$, $\sigma_{Oa,i}$ and $\sigma_{Ob,i}$ are the standard deviations associated with the means $\overline{X}_{Pa,i}$, $\overline{X}_{Pb,i}$, $\overline{X}_{Oa,i}$ and $\overline{X}_{Ob,i}$, respectively, and $n_{Pa,i}$, $n_{Pb,i}$, $n_{Oa,i}$ and $n_{Ob,i}$, are the number of replicates used to calculate each mean.

For each PHC *i*, the effectiveness of the PHC to deliver a *post-harvest recovery benefit* $E_{r,i}$ was defined as the log-ratio of the mean biomass per replicate after 1 year of recovery inside the PHC ($\overline{X}_{Pr,i}$) to the open areas ($\overline{X}_{Or,i}$) (Fig. 1):

$$\frac{E_{r,i} = \ln (\overline{X}_{Pr,i}}{\overline{X}_{Or,i})}$$

The variances $v_{E_{b,i}}$ associated with the effect sizes $E_{r,i}$ were calculated as:

$$v_{E_{r,i}} = \frac{\sigma^2_{Pr,i}}{n_{Pr,i} \times \overline{X}^2_{Pr,i}} + \frac{\sigma^2_{Or,i}}{n_{Or,i} \times \overline{X}^2_{Or,i}}$$

where $\sigma_{Pr,I}$ and $\sigma_{Or,i}$ are the standard deviations associated with the means $\overline{X}_{Pr,i}$ and $\overline{X}_{Or,i}$, respectively, and $n_{Pr,i}$ and $n_{Or,i}$, are the number of replicates used to calculate each mean.

For each PHC *i*, the *recovery of pre-harvest protection benefits Ep,i*, was defined as the relative difference in the mean biomass per replicate 1 year after the harvest ($\overline{X}_{Pr,i}$) to the pre-harvest levels ($\overline{X}_{Pb,i}$), whilst controlling for relative differences between open ($\overline{X}_{Or,i}$) and pre-harvest ($\overline{X}_{Ob,i}$) conditions after 1 year (Fig. 1):

$$E_{p,i} = \ln \frac{\left(\overline{X}_{Pr,i}/\overline{X}_{Pb,i}\right)}{\left(\overline{X}_{Or,i}/\overline{X}_{Ob,i}\right)}$$

The variances $v_{E_{p,i}}$ associated with effect sizes $E_{p,i}$ were calculated as:

$$v_{E_{p,i}} = \frac{\sigma^2_{Pr,i}}{n_{Pr,i} \times \overline{X}^2_{Pr,i}} + \frac{\sigma^2_{Pb,i}}{n_{Pb,i} \times \overline{X}^2_{Pb,i}} + \frac{\sigma^2_{Or,i}}{n_{Or,i} \times v^2_{Or,i}} + \frac{\sigma^2_{Ob,i}}{n_{Ob,i} \times \overline{X}^2_{Ob,i}}$$

where $\sigma_{Pr,i}$, $\sigma_{Pb,i}$, $\sigma_{Or,i}$ and $\sigma_{Ob,i}$ are the standard deviations associated with the means $\overline{X}_{Pr,i}$, $\overline{X}_{Pb,i}$, $\overline{X}_{Or,i}$ and $\overline{X}_{Ob,i}$, respectively, and $n_{Pr,i}$, $n_{Pb,i}$, $n_{Or,i}$ and $n_{Ob,i}$, are the number of replicates used to calculate each mean.

2.8. Meta-analysis framework

We used a random effects model meta-analysis framework, with a restricted maximum-likelihood estimator to assess the *pre-harvest protection, harvest, post-harvest recovery* and *recovery to pre-harvest protection* benefits. Meta-analyses were done using the package metafor (Viechtbauer, 2010) in the R language for statistical computing (R Development Core Team, 2015).

3. Results

3.1. Targeted species and vulnerability categories

In total 164 different species were caught during harvests across the five PHCs. Stereo-DOV surveys observed 245 species, of which 98 were recorded in the catch (hereafter referred to as targeted species, Appendix C). Of the 245 species observed during stereo-DOV surveys, 97 species belonged to the low vulnerability category, 115 to moderate and 33 to high (Appendix C). The villages Kiobo, Nakodu and Tuatua had greater levels of targeted biomass per transect both inside and outside of their PHCs compared to Natokalau and Nauouo (Fig. 2). Low levels of biomass were recorded for species with a high vulnerability to fishing across all villages when compared to the low and moderate categories (Fig. 2). This was also reflected in the catch data from all five harvests, with high vulnerability species ranging from 3 to 11% of the total catch, moderate 22 to 71%, and low 21 to 75% (Table 1).

3.2. PHC benefits for all targeted species

On average PHCs provided little *pre-harvest protection benefits* (E_b) for targeted species, with a 43% greater biomass inside PHCs compared to open areas prior to harvests. This result was heterogeneous suggesting variation across PHCs (Fig. 3). The Nakodu and Kiobo PHCs provided *pre-harvest protection benefits* with a 202% and 220% greater biomass of targeted species compared to open areas, while targeted biomass within the Nauouo PHC was 42% lower than open areas. Overall, PHCs provided significant *harvest benefits* (E_h) with on average a 38% greater removal of targeted biomass within PHCs compared to open areas during harvest events. PHCs provided little *post-harvest recovery benefits* (E_r) after 1 year of re-closure, with an overall 7% greater biomass of targeted species when compared to open areas. This result was heterogeneous and mostly driven by the Nakodu PHC, which had 102% greater biomass when compared to open areas. In contrast, targeted biomass was 51% lower within the Nauouo PHC when compared to open areas. 1 year was insufficient for *recovery of pre-harvest protection benefits* (E_p). Benefits after 1 year of recovery were on average 29% lower than pre-harvest.

3.3. PHC benefits across vulnerability categories

PHCs did not provide *pre-harvest protection*, *harvest*, or *post-harvest recovery benefits* for highly vulnerable species (Fig. 4). However, significant heterogeneity was recorded with *post-harvest recovery benefits*. The Natokalau PHC provided *post-harvest recovery benefits* for highly vulnerable species, while a lower biomass of highly vulnerable species was observed in the Kiobo PHC when compared to open areas after 1 year of re-closure. The *recovery of pre-harvest benefits* was not assessed due to a lack of *pre-harvest protection* or *harvest benefits* for highly vulnerable species. On average, PHCs provided little *pre-harvest protection benefits* for low or moderately vulnerable species, however these results were heterogeneous (Fig. 4). The Kiobo and Nakodu PHCs provided *pre-harvest protection benefits* for low and moderately vulnerable species, while the Nauouo PHC had a lower biomass of low vulnerability species compared to open areas. Overall, PHCs provided *harvest benefits* for low and moderately vulnerable species with a 31% and 54% greater biomass removed from PHCs compared to open areas during harvests.

PHCs did not provide *post-harvest recovery benefits* for low or moderately vulnerable species after 1 year of re-closure, however these results were also heterogeneous. The Nakodu PHC provided *post-harvest protection benefits* for low and moderately vulnerable species. In contrast, there was a lower biomass of moderately vulnerable species within the Kiobo PHC and low and moderately vulnerable species within the Nauouo PHC following harvests compared to open areas. 1 year was insufficient for the *recovery of pre-harvest protection benefits* for low vulnerability species, where benefits after 1 year of recovery were 27%

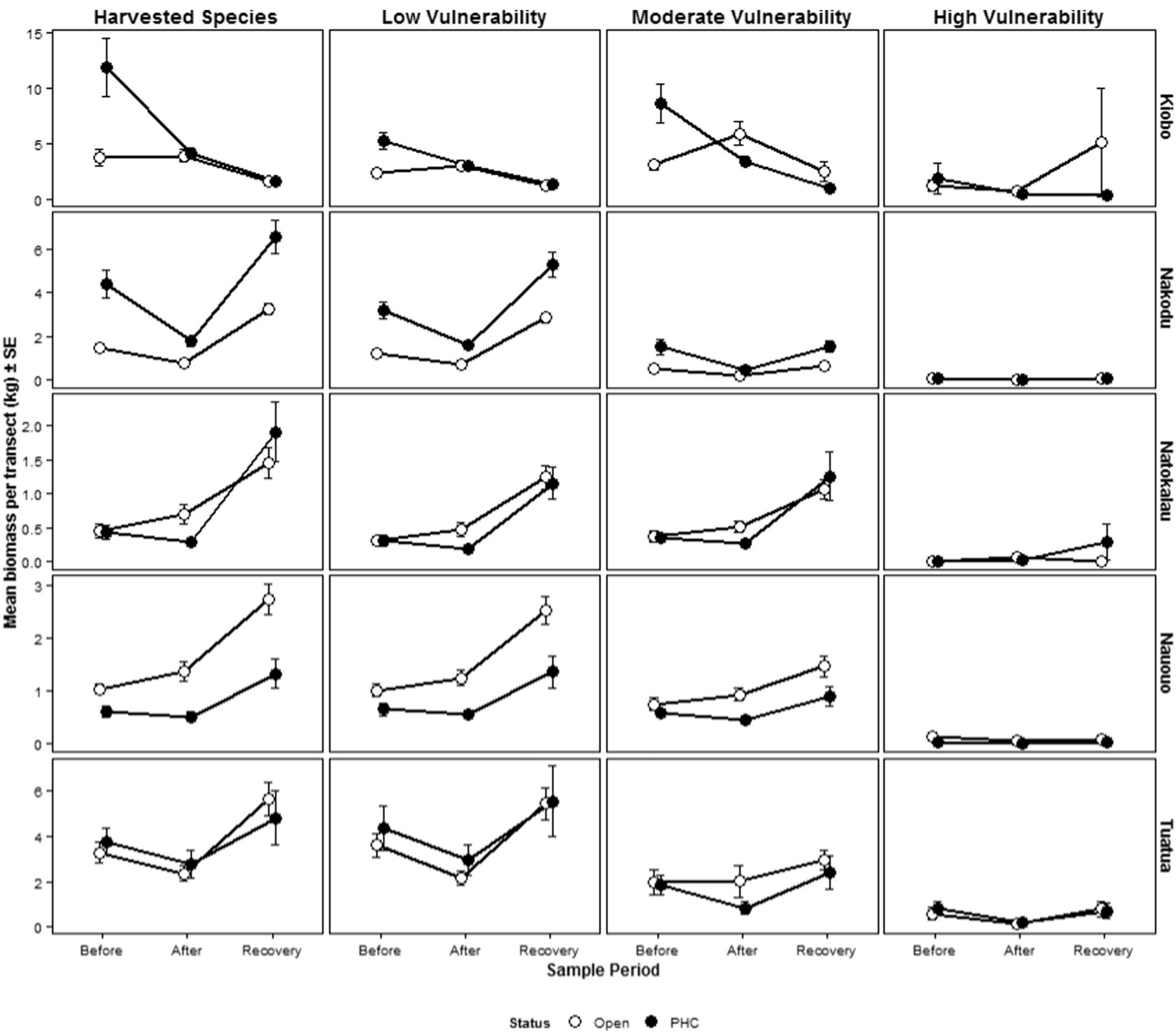

Fig. 2. Mean biomass of harvested species and vulnerability categories (low, moderate and high) before, after and with 1 year recovery from the harvest, across the five villages inside and outside of each PHC.

lower than pre-harvest. On average, the protection benefits after 1 year of recovery were 37% lower than pre-harvest for moderately vulnerable species, although this result was heterogeneous. In the Kiobo PHC, protection benefits were lower than pre-harvest after 1 year of recovery for moderately vulnerable species.

4. Discussion

With a decline in the resources that support small-scale inshore fisheries (Mora et al., 2009; Newton et al., 2007), food security in areas such as the Western Pacific has become a major concern (Andrew et al., 2007; Bell et al., 2009). To improve the status of small-scale fisheries resources, many non-government agencies have promoted the use of locally-managed marine areas, within which PHCs are the most common and often primary management strategy (Govan, 2009; Jupiter et al., 2014). Although PHCs have been widely promoted as a management tool, there is very little empirical evidence to support their ability to provide long-term fisheries benefits (Bartlett et al., 2009; Cinner et al., 2006; Goetze et al., 2015; Jupiter et al., 2012). The widespread use and reliance on PHCs as a management strategy to improve fisheries resources, that are essential to the food security of millions of people, highlights the importance of understanding the functioning of PHCs and providing advice on their management.

PHCs in Fiji had variable pre-harvest protection benefits, with on average a 43% greater biomass of targeted species that translated into harvest benefits with 38% of the biomass removed from PHCs during harvests. This is below the average for PHCs across the Western Pacific, where pre-harvest benefits of 92% and harvest benefits of 50% were observed (Goetze, 2016). This is likely due to a combination of shorter periods of closure and lower compliance observed in a number of these Fijian PHCs, which affects the ability of PHCs to provide pre-harvest and harvest benefits (Goetze, 2016). On average, PHCs in Fiji provided little or no post-harvest recovery benefits after 1 year of re-closure, which was also insufficient for the recovery of pre-harvest benefits. This suggests that harvesting PHCs annually will decrease the long term sustainability of target populations and therefore fail to meet a

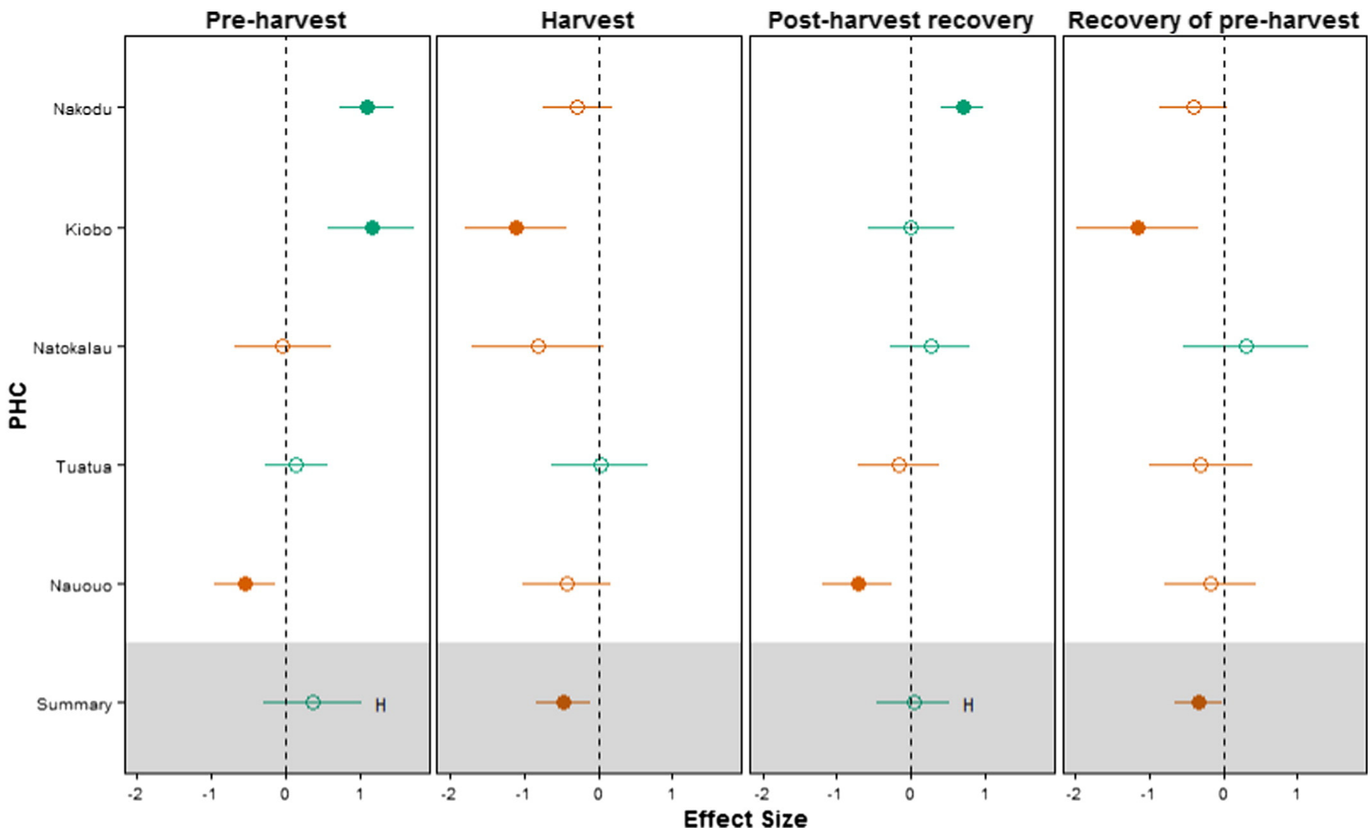

Fig. 3. Effect sizes for the pre-harvest protection, harvest, post-harvest recovery and recovery of pre-harvest protection benefits in terms of mean biomass of targeted species for the five individual PHCs and the summary of all PHCs (shaded grey). Red dots represent negative effects sizes and green dots positive effects sizes, while closed dots represent results where the 95% confidence interval of the effect size does not overlap zero. The superscript H indicates that significant heterogeneity ($H < 0.05$) was associated with the overall effect size. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

major objective in PHC implementation of maintaining fish for the future (Cohen and Foale, 2013; Jupiter et al., 2014). These results are likely transferable across the Western Pacific, particularly where a greater proportion of target biomass is typically removed during harvests (Goetze, 2016), suggesting longer closure times are necessary. Longer closure periods are unlikely to have extensive socioeconomic impacts on any of the communities studied given that recent surveys in 2015 documented that 91% of households from Kiobo and 100% of households in Nakodu, Nauouo, and Tuatua earn income from other sectors besides fisheries (e.g., farming, salaried employment, remittances; Jupiter et al., in review).

Pre-harvest benefits were observed in two PHCs (Kiobo and Nakodu) and post-harvest recovery benefits in one PHC (Nakodu). Greater benefits in terms of increased abundance and biomass prior to harvesting are observed as the size, time of closure and compliance with PHC closures increases (Goetze, 2016). Both Kiobo and Nakodu had relatively good compliance and Nakodu had a pre-harvest closure time of 3 years compared to a study average of 1.65 years, which has likely resulted in greater pre-harvest benefits compared to other PHCs. The increased resilience to the impacts of harvesting observed in the Nakodu PHC is likely due to a combination of high compliance and 3 years of closure to fishing prior to the harvest, which resulted in a 200% greater biomass when compared to open areas. These results suggest that under certain management regimes, PHCs are capable of achieving objectives such as increasing targeted fish biomass and show potential for the sustainable harvesting of PHCs under extended closure regimes (Bartlett et al., 2009; Jupiter et al., 2012; Jupiter and Egli, 2011). The Nakodu outcomes are consistent with results found in marine reserves where older and more highly enforced areas gave better conservation benefits (Claudet et al., 2008; Edgar et al., 2014; Vandeperre et al., 2011). However, the post-harvest recovery benefits observed in Nakodu after 1 year of re-closure did not match pre-harvest benefits, indicating an annual harvest regime of the same magnitude would not be sustainable in the long term. In order to provide long-term increases in target species biomass, it is likely that PHCs will need at least the 3 years of closure observed pre-harvest in Nakodu and/or reductions in harvest intensity.

The pre-harvest benefits observed in two PHCs (Kiobo and Nakodu), and harvest benefits across all PHCs and post-harvest recovery benefits in one PHC, were primarily observed for species with low and moderate vulnerabilities to fishing. This is consistent with the results of Abesamis et al. (2014), who found that low to moderately vulnerable species respond to protection from fishing and recover at faster rates. Overall, we found no evidence of pre-harvest protection or harvest benefits for highly vulnerable species, suggesting they will not benefit from PHC management under current harvest regimes. However, post-harvest recovery benefits for highly vulnerable species were observed in one PHC, with further investigation revealing this was primarily due to an increase in one species of tang, *Zebrasoma scopas*. This species' life history traits make it highly vulnerable to fishing (primarily due to a slow growth rate; Froese and Pauly, 2015), however, it is not preferentially targeted in Fiji due to its small body size, suggesting this result may have been due to spill-in of small roving herbivores such as *Zebrasoma scopas,* as observed in Jupiter et al. (2012). Further research that incorporates local context within the vulnerability estimates may improve the applicability of this tool.

We recorded low levels of biomass for highly vulnerable species across all of the villages fishing grounds, suggesting these species have already been depleted due to overfishing in the region (Goetze et al., 2011; Jennings and Polunin, 1997, 1996). Low levels of biomass and a

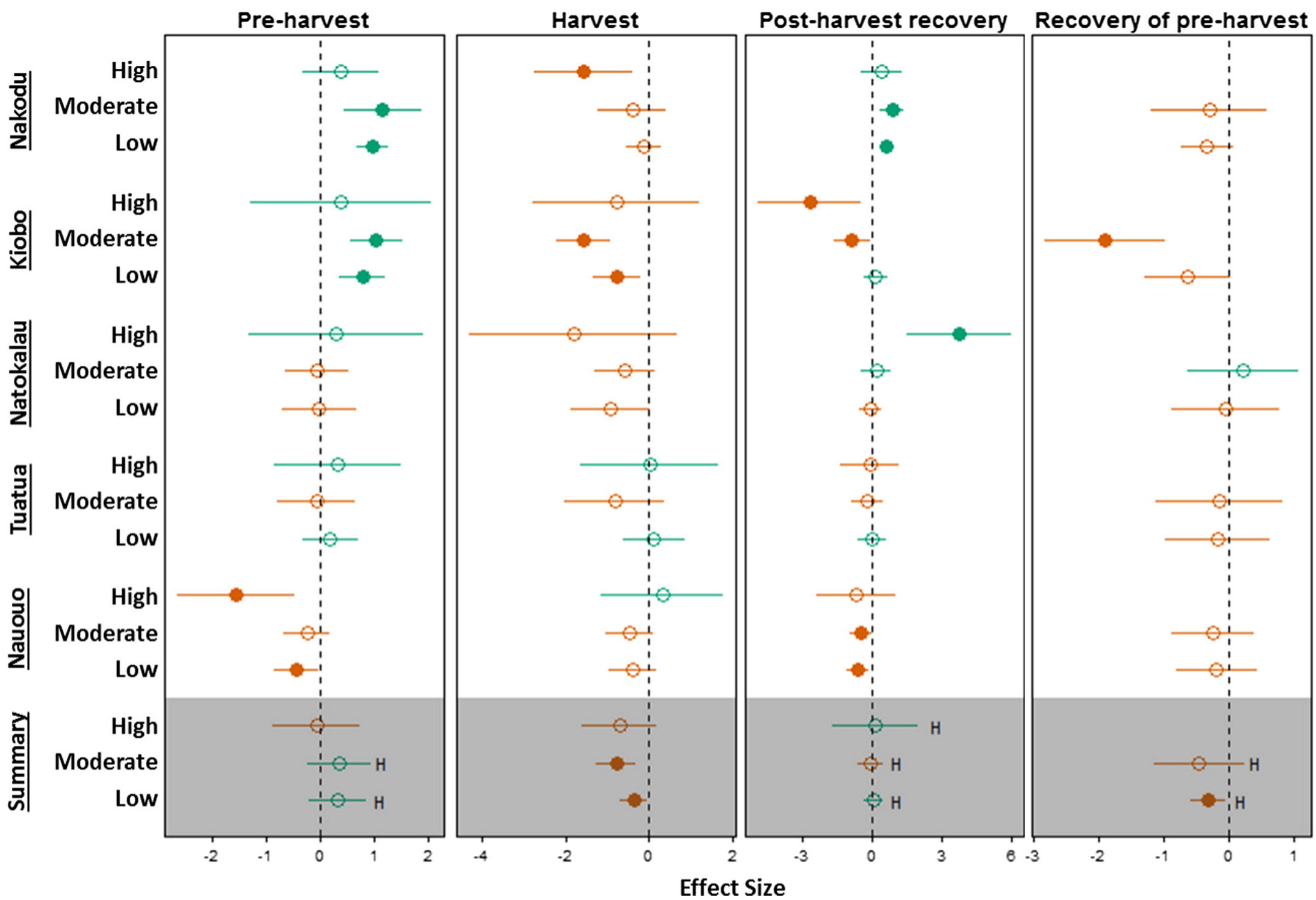

Fig. 4. Effect sizes for the pre-harvest benefit, harvest, post-harvest recovery and recovery of pre-harvest benefits in terms of mean biomass of low, moderate and highly vulnerable species for the five individual PHCs and the summary of all PHCs (shaded grey). Red dots represent negative effects sizes and green dots positive effects sizes, while closed dots represent results where the 95% confidence interval of the effect size does not overlap zero. The superscript H indicates that significant heterogeneity (H < 0.05) was associated with the overall effect size. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

lack of build-up of these highly vulnerable species within PHCs suggests that species such as large groupers, wrasse and parrotfish should be avoided when harvesting (see Appendix C for a full list of species). Ideally we would recommend no-take marine reserves to promote the recovery of such species (Costello and Ballantine, 2015; McClanahan and Graham, 2015; McClanahan and Humphries, 2012). However, in areas where the implementation of marine reserves is difficult (Cohen and Foale, 2013; Jupiter and Egli, 2011), bans on catching these species during harvests of PHCs may also promote recovery.

Despite positive results across a number of PHCs, we consistently observed a significantly lower biomass of targeted species within the Nauouo PHC compared to open areas. This result is primarily due to a short closure time of 1 month prior to pre-harvest surveys and low compliance (Goetze, 2016). In addition, the PHC boundaries were poorly defined (i.e. did not follow identifiable channels in the reef or landmarks), with awareness of these boundaries varying between local fishers, and unlike other sites, there were no trained, local fish wardens to carry out surveillance for poachers from outside the community (Jupiter et al., in review). We recommend that PHC boundaries follow clearly identifiable features of the reef or landmarks (Edgar et al., 2014) so that fishers can easily identify boundaries. Similar problems were observed in the Kiobo PHC, where despite recording pre-harvest benefits, a significantly lower biomass of moderate and highly vulnerable species were recorded in the PHC after 1 year of recovery. This suggests that compliance with the PHC restriction may have broken down post-harvest or the community failed to shut down the harvest once objectives were achieved, as observed in other Fijian PHCs (Jupiter et al., 2012).

4.1. Conclusions

PHCs in Fiji are capable of providing pre-harvest and harvest benefits primarily for low to moderately vulnerable species. However, closing PHCs for just 1 year in most cases will provide little long-term benefit to fishers and is not sufficient for the recovery of pre-harvest benefits required for sustainability of the harvest regime. Identification of the precise harvest regimes for sustainability of the PHC strategy will require studies over large temporal scales (i.e. decades) that integrated variable harvesting regimes, as seen with long-term studies of marine reserves (McClanahan and Humphries, 2012; Russ and Alcala, 2004, 2003). However, PHCs are already extant across the Western Pacific, where small-scale fisheries are often essential for food security and livelihood, meaning these communities cannot afford such delays in management advice to help sustain these fisheries. Alternative methods such as population modelling that uses the empirical data currently available may provide further insight into the management of PHCs. While continued studies are important, we recommend that PHCs are closed to fishing for greater than 1 year, with a strong recommendation for 3 years or more to increase the potential for short-term ecological benefits and long-term sustainability of small-scale fisheries, and that highly vulnerable species are protected from harvests. It is also important that PHCs are used in conjunction with conventional fisheries management strategies, which will promote the recovery of coral reef fisheries (MacNeil et al., 2015). Similarly, we recommend that permanent, no-take marine reserves are used for conservation of biodiversity (Costello and Ballantine, 2015), given that PHCs are unlikely to provide long-term conservation benefits.

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