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Predicting impact to assess the efficacy of community-based marine reserve design

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Abstract
During the planning phase the efficacy of different strategies to manage marine resources should ultimately be assessed by their potential impact, or ability to make a difference to ecological and social outcomes. While community-based and systematic approaches to establishing marine protected areas have their strengths and weaknesses, comparisons of their effectiveness often fail to explicitly address potential impact. Here, we predict conservation impact to compare recently implemented community-based marine reserves in Tonga to a systematic configuration specifically aimed at maximizing impact. Boosted regression tree outputs indicated that fishing pressure accounted for ~24% of variation in target species biomass. We estimate that the community-based approach provides 84% of the recovery potential of the configuration with the greatest potential impact. This high potential impact results from community-based reserves being located close to villages, where fishing pressure is greatest. These results provide strong support for community-based marine management, with short-term benefits likely to accrue even where there is little scope for systematic reserve design.

KEYWORDS
boosted regression trees, community-based management, conservation biology, fishing pressure, marine protected area, predictive impact, spatial planning, Tonga

1 | INTRODUCTION

The prevailing combination of ongoing ecosystem exploitation and limited conservation resources highlights the critical need to develop rapid, cost-effective management actions. No-take marine protected areas (MPAs) are a key tool used in marine conservation and are suggested to enhance ecosystem resilience and reduce the decline of fisheries resources (Gaines, White, Carr, & Palumbi, 2010; Halpern & Warner, 2002; Mellin, Aaron Macneil, Cheal, Emslie, & Julian Caley, 2016). The objectives for MPA implementation are also broad

(Govan & Jupiter, 2013; Jupiter, Cohen, Weeks, Tawake, & Govan, 2014), targeting both general (e.g., increasing biodiversity) and local (e.g., maintaining fish stocks) conservation priorities. In some cases, reserve systems have been systematically designed to meet particular objectives of species inclusion, based on the best available knowledge of ecosystems and species distributions (Pressey & Bottrill, 2009). In other cases, reserves have been established at ad hoc locations by local communities (Mills, Adams, Pressey, Ban, & Jupiter, 2012). While each approach has its strengths and weaknesses, the degree to which the two differ in effectiveness depends upon

their likely impact. The conservation impact of a reserve is the difference it makes to one or more intended or unintended outcomes relative to no intervention or a different intervention (Pressey, Visconti, & Ferraro, 2015; Pressey, Weeks, & Gurney, 2017).

Community-based approaches to MPA management are common in developing nations and tend to involve the opportunistic establishment of reserves where there is a willingness of local resource owners to participate in marine management (Gaymer et al., 2014; Horigue et al., 2015; Mills et al., 2012). Here, we define community-based conservation as natural resource or biodiversity protection by, for, and with the local community (Western & Wright, 1994). This governance approach generally prioritizes the goals of local communities, such as maintaining target fisheries, and responds to local constraints and opportunities (Ban et al., 2011), but does not focus explicitly on goals such as biodiversity conservation *per se*. Local engagement results in greater compliance, participation in enforcement and other management activities (Gurney et al., 2016), with a longer-term commitment to reserves (Gaymer et al., 2014). Community-based reserves can also be implemented effectively even without the coordination and logistic support from a centralized government (Cox, Arnold, & Villamayor, 2010). However, conservation efforts implemented opportunistically and focused on local priorities might not meet biodiversity conservation objectives (Horigue et al., 2015).

Other approaches to reserve design include top-down central management, which we define as natural resource and biodiversity protection by a central governing authority. Central management can incorporate systematic conservation planning, which is characterized by explicit objectives and considerations of spatial context to guide the selection and management of conservation areas (Pressey & Bottrill, 2009). The systematic approach theoretically has the capacity to target conservation actions in a way which maximizes impact, thereby being more effective at achieving national and international conservation objectives (Hansen et al., 2011; Mills et al., 2012). However, globally it is now well established that many protected areas are residual, in locations that are less than likely to be affected by extractive activities (Devillers et al., 2015; Joppa & Pfaff, 2011). Residual MPAs might be more likely to arise from central management, with political agendas minimizing conflict with extractive uses while maximizing perceived gains for conservation, with gains often gauged by misleading measures such as MPA extent (Pressey et al., 2017).

While both central and systematic MPA planning can incorporate the interests of communities to varying degrees, the conservation actions they suggest are frequently at odds with the interests of communities, and often face strong opposition from stakeholders (Bennett & Dearden, 2014). Local communities might not feel involved in these processes, so compliance can be low (Gaymer et al., 2014). While, in theory, the ability of these top-down approaches to achieve target objectives will generally be greater than ad hoc community-based management, they often fall short in practice (Ban et al., 2011; Gaymer et al., 2014).

The most common method used to compare systematic and community-based conservation planning has been to rate their abilities to reach habitat representation targets (e.g., Ban et al., 2011; Bode et al., 2016; Hansen et al., 2011; Horigue et al., 2015; Mills et al., 2012). Generally, this approach suggests that community-based MPA designs either fail to reach national conservation targets for habitat representation or fall well below the systematic approach. However, the pervasive use of habitat representation as the sole basis for identifying conservation priorities risks failure to achieve impact (Pressey et al., 2017). Despite extensive literature on the relative pros and cons of community-based and systematic MPA design, the effectiveness of both methods in terms of conservation impact is unknown. Furthermore, while there is now an extensive body of literature measuring ecological outcomes of MPAs, few tools exist to predict the relative impact of alternative reserve designs during the planning phase.

Here, we predict the potential conservation impact, measured as the recovery of target species biomass, of alternative configurations of no-take MPAs in the Vava'u island group of Tonga. Tonga has recently expanded its marine conservation program to incorporate the widespread use of community-managed MPAs, of which 13 were implemented in Vava'u in 2016-2017. In this program, the size and location of MPAs are determined by local communities rather than systematically by the government based on ecological and/or social factors. We set out to answer two main questions: (1) How much of the predicted optimal impact is achieved by community-based MPAs? (2) What is the potential impact of a secondary, theoretical configuration of MPAs designed to balance both impact and maximum total potential biomass in MPAs?

2 | METHODS

Potential impact was calculated using a two-step process incorporating both social and ecological data. First, social data on fishing effort across Tonga were obtained from questions regarding fishing practices in the 2016 Tongan National Census (Statistics Department of Tonga, 2017) and key informant interviews (Figure S1). To quantify the relationship between fishing pressure and target species biomass, a continuous spatial layer of fishing pressure derived from the social data set and ground-truthed during key informant interviews was included as a predictor variable (Harborne, 2016; Harborne et al., 2018). Fishing pressure was calculated as the weighted abundance of fishers in each village overlaid on the fishing grounds of Vava'u using separate decay
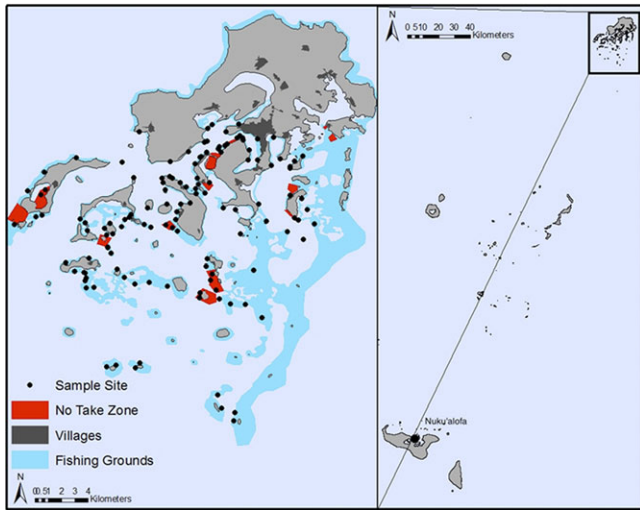
FIGURE 1 Map of Vava'u, Tonga, depicting the sample sites and new no-take reserves. Fishing grounds are defined as reef and patch reef environments at depths shallower than 10 m. Right-hand map shows the location of the Vava'u island group in the Tongan archipelago. Dark areas on land represent the outlines of villages

kernels for subsistence and commercial practices, derived from the key informant interviews (Figure S2; Thiault, Collin, Chlous, Gelcich, & Claudet, 2017). Fisher abundance was weighted by district-level data on fishing practices (commercial or subsistence), gear type (spear and handline), and frequency of fishing activities. This fishing pressure metric assumes that, all else being equal, fishers preferentially select sites closer to home and move further out as closer sites become exhausted or closed to fishing. While the model might therefore be decoupled from current fishing effort, it is nonetheless useful in constituting the long-term effects of fishing on fish assemblages throughout the island group.

Second, ecological surveys of coral reef fish community composition and biomass were conducted at 129 sites in Vava'u in 2016 to 2017 (Figure 1, Figure S3). At each site, the abundance and size of all target fish species was recorded in four 30 m x 5 m belt transects. Key target species were identified from survey questions in a baseline socioeconomic report for the new management areas (Parks & Specialist, 2017). The length and abundance of reef fish was converted to biomass following published length-weight relationships for each species (Kulbicki, Guillemot, & Amand, 2005). We then used Boosted Regression Trees (Elith, Leathwick, & Hastie, 2008) and eight predictor variables (fishing pressure, habitat, wave energy, rugosity, slope, historic management status, district, surveyor; Figure S4 Table S1, S2) to create a spatial predictive of the current biomass of target fish species across all reefs in the Vava'u group (Harborne, 2016; Harborne et al., 2018). A random number variable was included and any predictor variables that explained less variability in the data than random were removed. Boosted Regression

Trees are an additive regression model in which individual terms are simple trees, fitted in a forward, stagewise fashion (Elith et al., 2008;). The model parameters (learning rate and tree complexity) were calculated across a series of values and the values that gave the best explanatory power were included in the final model. Confidence intervals were estimated around these fitted functions by taking 1,000 bootstrap samples, to which we fitted the model. We used these samples to make separate predictions for the spatial data. All models were run using the "gbm" package in R 3.X.

To assess the potential impact of the recently implemented no-take marine reserves in terms of recovery of target fish biomass, we re-inputted the data into the model with the same environmental variables, but with all fishing pressure values set to zero. Potential impact was calculated by subtracting, for each 50 m grid cell, current biomass from the potential biomass. The result was a layer continuous across the island group predicting the recovery of target species biomass for each 50 m grid cell.

The predicted impact of the current community-based configuration was then compared to two alternative systematic configurations with the same total area (8.8 km^2). The first comparison was made with the configuration that systematically protected an area equal to the community-based approach, but was configured to have the greatest impact. Impact is a measure of change and could therefore be equal in areas of both high and low predicted current biomass. Consequently, multiple configurations might exist with comparable impact, but with large differences in maximum recovered biomass. The community-based configuration was therefore also compared to a second systematic configuration, which aimed to maximize both potential impact and total biomass following recovery. This was done by preferentially selecting grid cells with high predicted biomass under no fishing when differences in impact between candidate cells were minimal.

A caveat to our estimation of impact is that it aimed to maximize the short-term benefit inside reserves only, without accounting for increased fishing pressure in nonreserve areas. However, because the relocated fishing pressure is spread over a large area, the fisheries squeeze effect is likely to be small. In addition, by maximizing the impact inside reserves, the recruitment subsidies from reserves will be greater than if reserves were situated in unfished areas.

3 | RESULTS

The predictor variables in the current biomass model explained 69% of the total variation in target fish biomass across Vava'u (Figure 2). The boosted regression tree learning rate was set to 0.001 and the interaction depth to 5, which resulted in a best iteration of 1,720 trees. The greatest
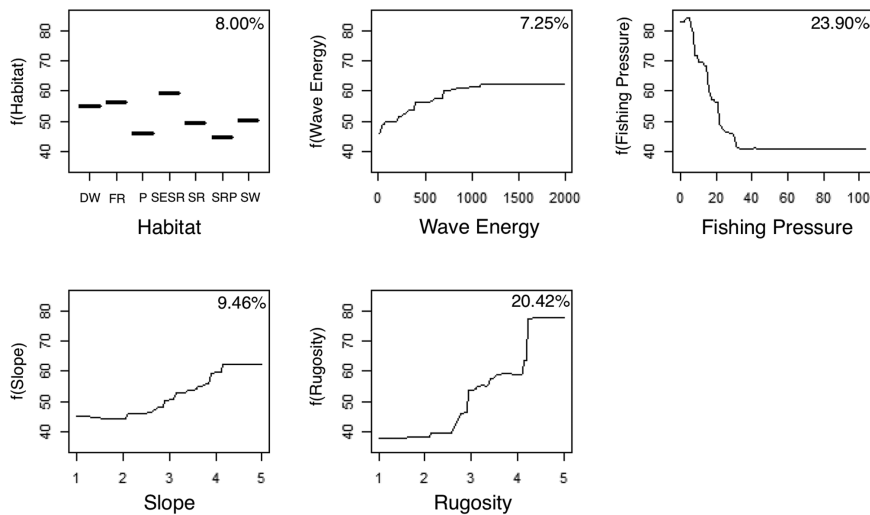
FIGURE 2 Boosted regression tree outputs. Relationships between each significant predictor variable and target species biomass (y-axes) after accounting for the average effects of all other variables in the model. Percent values represent how much of the deviance was explained by each variable. Habitat labels are: DW – deep wall, FR – exposed forereef, P – bare pavement, SESR – semiexposed sloping reef, SR – sheltered reef, SRP – sandy rubble with patches, SW – shallow wall. Wave energy was calculated as joules per square meter. Fishing pressure is the abundance of fishers per grid cell fishing every 2 weeks or more frequently using a spear or handline. Slope and rugosity were both recorded on a five-point scale (Figure S3 Table S1)
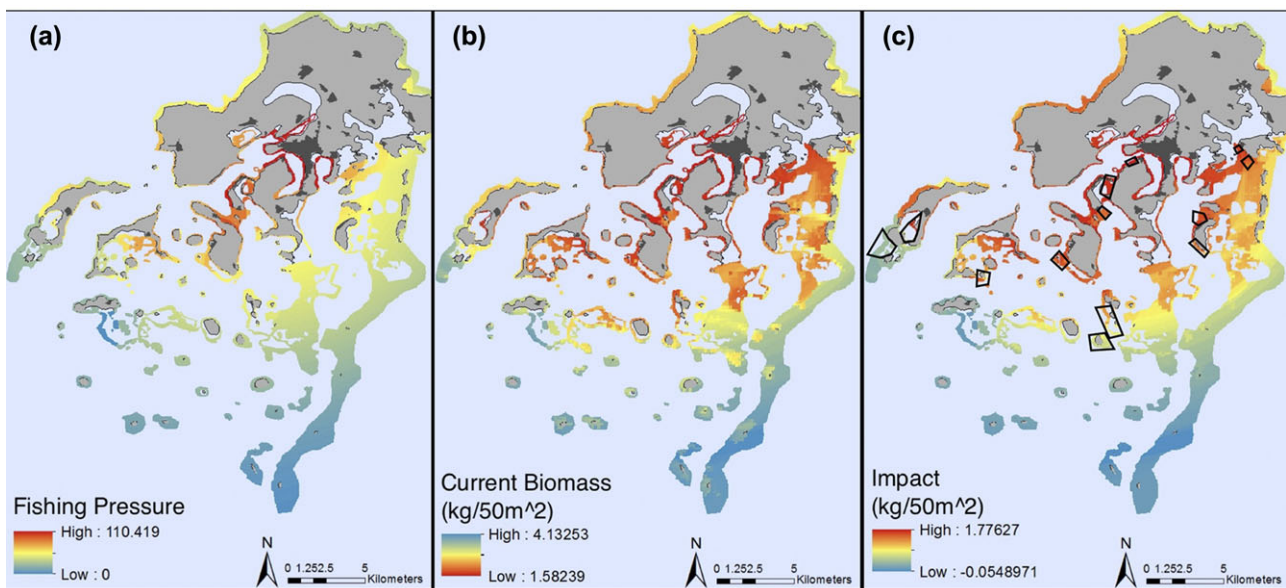
FIGURE 3 Vava'u fishing pressure, predicted current biomass, and potential impact (a) fishing pressure in Vava'u defined as the number of fishers capable of fishing an area fortnightly or more frequently (b) predicted current biomass of target species per 50 m grid cell (c) potential impact, or change in target species biomass per 50 m cell, following the implementation of a no-take MPA. The black lines indicate the configuration of the 13 recently implemented MPAs

proportion of deviance (23.9%) was explained by fishing pressure (Figure 3a), with target species biomass declining rapidly as fishing pressure increased. However, the predictive power of fishing pressure decreased as fishing pressure increased, and this variable was unable to predict variation in target fish biomass at locations with values beyond ~40 fishers. The boosted regression tree models indicated that fish biomass increased rapidly with increasing distance from land (and decreasing population pressure), with biomass at the southernmost islands 2.5 times greater than around the inner islands (Figure 3b). The predictor variables district, historic management status and surveyor all explained less variability in the data than the random variable and were therefore removed.

The predicted total recovery of target species biomass (Figure 3c) across the 13 community-based MPAs was 84% of the systematic configuration with the greatest recovery potential (Figure 4). The second systematic configuration, which preferentially selected grid cells with high total biomass when differences in impact were minimal, achieved 8.8% greater total biomass than the first systematic configuration while only reducing predicted recovery by 2.3%. The systematic approach targeting high-impact areas focused protection on the central region of Vava'u where fishing pressure was highest (Figure 5a). The plateau of fishing pressure's effect on biomass corresponded spatially to the inner island group of Vava'u (Figure 5b). Within this region, the second systematic configuration targeted areas with high-quality habitat and
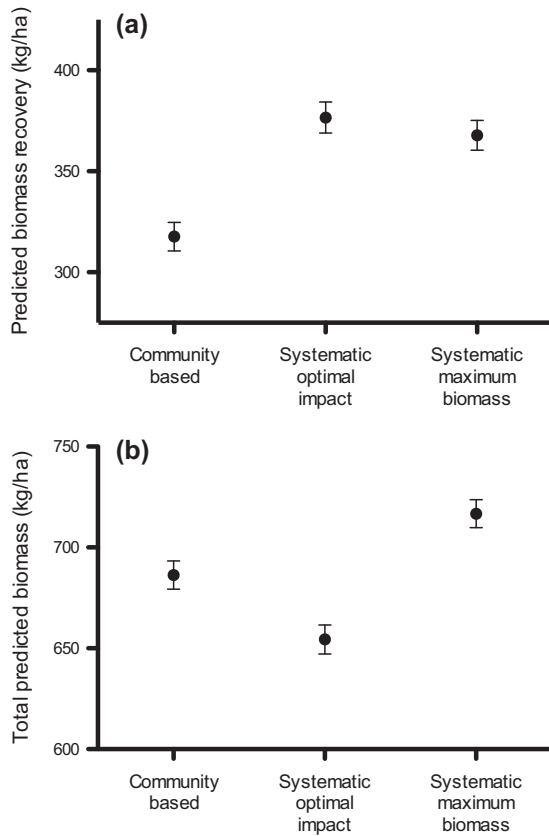
FIGURE 4 Numerical comparisons of a community-based and two systematic MPA configurations (a) predicted impact as recovery of biomass (b) total predicted biomass. Error bars represent the 95% confidence intervals estimated from taking 1,000 bootstrap samples of the input data, but selected randomly with replacement, and repeating the analysis for each sample

greater wave energy, and not those with the greatest fishing pressure (Figure 5c).

4 | DISCUSSION

Our results indicate that local fishing pressure is reducing the biomass of target species close to villages, with fishing pressure accounting for ∼24% of the variation in fish biomass. This suggests that community-managed no-take MPAs could have positive impacts on fish stocks, particularly in areas of high fishing pressure. The predicted impact of the community-based configuration of no-take reserves was 84% of the impact of the best-case systematic configuration. This result is important because it suggests that close-to-ideal benefits of MPAs can be achieved in situations where there is relatively little data for systematic placement of reserves or social/political constraints on applying systematic approaches.

This study confirms that fishing pressure can be a strong predictor of target species biomass. Other ecological metrics such as size distributions and community structure have
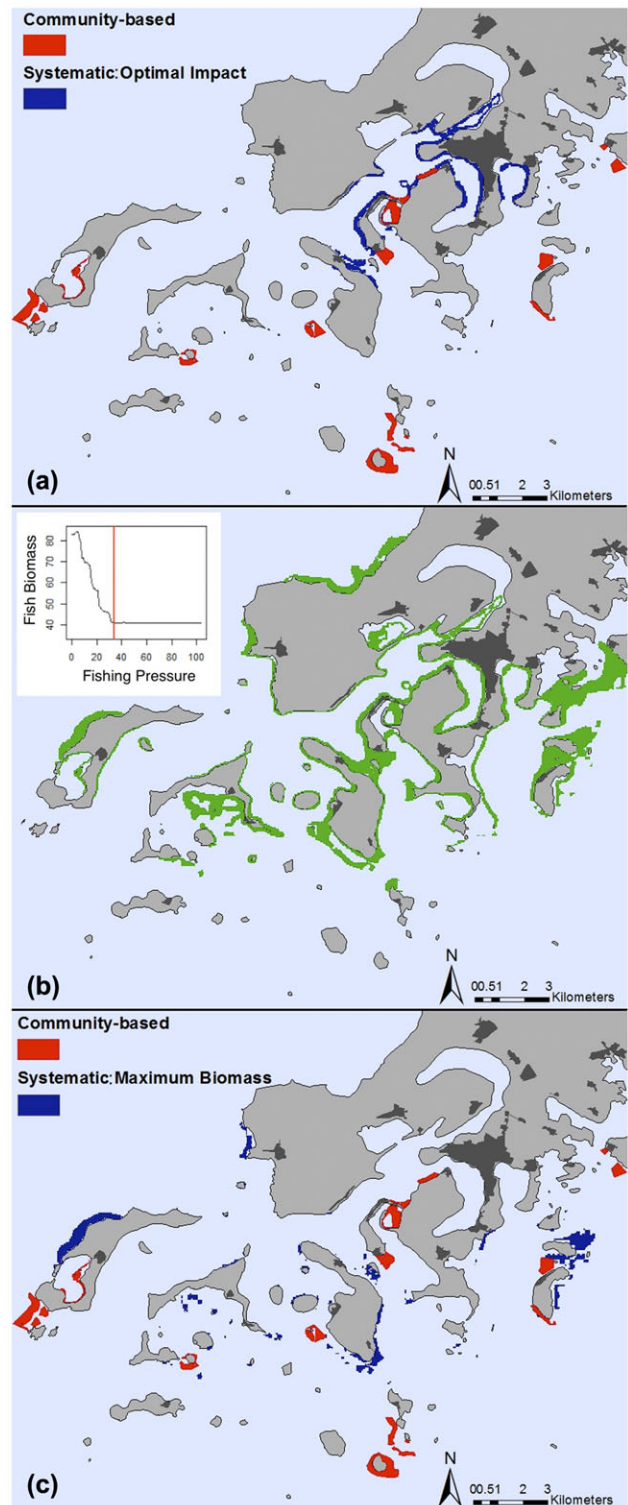
FIGURE 5 Spatial comparison of community-based and alternative configurations of no-take MPAs (a) the current community-based configuration compared to a systematic configuration aimed at maximizing potential impact (b) the region in which fishing pressure's effect on fish biomass plateaus; within this region, alternative reserve configurations would have marginal differences in predicted recovery (c) the current community-based configuration compared to a second systematic configuration that maximizes total biomass when differences to potential impact are minimal

also been demonstrated to vary along gradients of fishing pressure (Graham, Dulvy, Jennings, & Polunin, 2005; Wilson et al., 2010). However, despite the high variance explained by fishing pressure, the model's predictive power decreased in areas of high fishing pressure. This result is indicative of the potential depletion or collapse of the inshore reef fishery in Vava'u. This is further corroborated by the ecological surveys, in which we observed that most of the inner island sites had small sizes and low abundances of reef fish.

Studies assessing the community-based approach to establishing MPAs have generally used habitat representation, and generally concluded that the resulting configurations of MPAs failed to reach 50% of their total capacity (Hansen et al., 2011; Horigue et al., 2015; Mills et al., 2012). However, by using predicted impact on target species as a metric of potential success, our results indicate the benefits could be much greater. The high impact predicted by our results is attributable to community-based MPAs generally being established close to villages where fishing pressure is likely to have been high. In contrast, systematic designs based on habitat representation are likely to include areas that are subject to little or no fishing pressure.

MPAs are often situated next to villages for social reasons, as a way to support local enforcement and maximize compliance (Cinner & Aswani, 2007). While social and ecological strategies are not always aligned (Gaymer et al., 2014), the high potential impact of implementing reserves near villages in this study illustrates how ecological benefits can be achieved by emphasizing social priorities. The systematic approach to reserve design is also not always feasible, especially in resource-limited nations, and a community-driven approach can therefore often be the most viable solution for marine management in the absence of well-supported centralized management (Ban et al., 2011). High compliance and marine stewardship by local communities are also critical to the success of MPAs (Mascia, Claus, & Naidoo, 2010), and the greater support of community-driven projects could potentially offset the difference in predicted impact between the systematic and community approach. Furthermore, in practice, centralized planning is frequently not systematic, often resulting in residual MPAs situated to have minimum conflict with human activities and therefore low impact (Devillers et al., 2015).

The similarity in potential impact between alternate MPA configurations suggests that within this system there can be flexibility when selecting areas using the predictive impact approach. Although the systematic configuration suggested placing reserves around the most populated part of the region, this might not be practical because compliance and enforcement around urban centres could be difficult. Our results demonstrate that alternative configurations can maintain high impact while also maximizing total biomass. This flexibility enables this approach to be incorporated into future manage-ment decisions both in Tonga and other small-island developing nations.

Given Tonga's remoteness, the net rate of stock depletion will likely remain constant following reserve establishment, potentially resulting in a fishery squeeze effect whereby fishing pressure is displaced rather than reduced (Agardy, di Sciara, & Christie, 2011; Halpern & Warner, 2002). Although this study did not explicitly examine the potential loss of biomass in the absence of protection, this limitation was partially offset by factoring maximum biomass into the configuration as well as impact. Depletion of fish stocks might be exacerbated initially as fishers move to less harvested areas, with long-term benefits accruing only when MPAs build up standing populations of large, spawning fish (Agardy et al., 2011; Hopf, Jones, Williamson, & Connolly, 2016). In addition, changes in fish biomass are not always predictable and the impact of no-take reserves on fish stocks can be limited by large-scale chronic impacts such as habitat degradation, pollution, and climate change (Green et al., 2014). However, many of these caveats are not isolated to our predictive method, but are limitations of MPA design in general. Various additional management strategies such as size limits and gear restrictions can be employed to help mitigate these impacts outside of existing MPAs (Lundquist & Granek, 2005; Weeks, Green, Joseph, Peterson, & Terk, 2016).

Our model allowed us to estimate, based on local environmental parameters and changes to fishing pressure, a hypothetical carrying capacity representing the biomass an area might reach with the implementation of a well-managed no-take reserve after sufficient time has passed for fish stocks to recover. The time required for the biomass ceiling to be reached is beyond the scope of this study, encompassing many aspects of reef ecology. There is also a myriad of additional ecological factors that will affect the carrying capacity of a site, so our results are only indicative of which sites could have the greatest potential impact. Other factors such as coral cover, frequency of disturbances, and larval transport will also be important in establishing the final carrying capacity of each site (Hopf et al., 2016; Jones, McCormick, Srinivasan, & Eagle, 2004). In addition, other conservation targets such as fisheries yield are also important for fisheries management and could also be incorporated into estimates of the efficacy of alternative management strategies (McClanahan, 2018)

There are various other approaches to the design and implementation of MPAs, each with their own merits and shortcomings (Botsford, Micheli, & Hastings, 2003; Gaines et al., 2010). Our technique can be added to the existing toolset of marine conservation planners to highlight regions in which efforts should be focused and additional methods employed. While habitat representation is not a panacea to reserve design (Pressey et al., 2017), there are still significant ecological benefits to be accrued by protecting a range of habitats and conservation targets (Airame et al., 2003; Ward,

Vanderklift, Nicholls, & Kenchington, 1999). Importantly, these two approaches are not mutually exclusive, and future management should aim to incorporate both in conjunction when formulating decisions.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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