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Research

Quantitative decision support tools facilitate social-ecological alignment in community-based marine protected area design

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ABSTRACT. Marine protected areas (MPAs) are increasingly used to support both biodiversity conservation and fisheries management. However, MPA performance is likely to be compromised if people who depend on fishing are excluded from MPA design decision making. Participatory MPA design helps to address this problem by engaging local stakeholders in all critical decisions, including the total coverage, placement, and local size of no-take marine reserves. Here, we report the findings from a participatory MPA design project on Selayar Island, Indonesia, in which a community initiated collaborations with scientists to access modern quantitative tools for community-led MPA scenario testing. The outcomes highlight a local disagreement between ecologically and socially desirable MPA designs. Focused on social considerations, the initial community-supported MPA design consisted of four small reserves (0.5–1 km wide) in predominately southern community waters, where they were intended to restrict external fishers. Ecologically optimal MPA designs, in contrast, consisted of one or two large reserves (4–6 km wide) in northern community waters, where they were expected to restrict primarily local fishers but better support the rebuilding of fish populations and fisheries. However, ecologically optimal MPA designs were socially infeasible. Using quantitative MPA performance assessments, the community negotiated an alternative MPA design consisting of two 1.5–2 km wide reserves at socially and ecologically favorable locations. Compared to the initial proposal, this revised MPA design was estimated (1) to protect three to four times more individuals of key fishery species within reserve boundaries and (2) to double local fishery catches. We conclude that even simple MPA design tools, which quantify and visualize local conservation and fishery outcomes under alternative MPA scenarios, add value to participatory decision making and likely MPA performance.

Key Words: *comanagement; conservation; fisheries management; marine reserve network; marine reserves; MPA; participatory MPA design; social-ecological systems; trade-offs*

INTRODUCTION

Marine protected areas (MPAs) are an important tool for biodiversity conservation and fisheries management, especially in tropical developing countries where heavy overfishing is commonplace and the capacity to regulate fisheries by other means is limited (Hilborn et al. 2004, Gaines et al. 2010, White et al. 2014). However, MPAs can fail to deliver expected conservation and fishery benefits if their effectiveness is compromised (Agardy et al. 2003, Sale et al. 2005, Mora and Sale 2011, Edgar et al. 2014, Gill et al. 2017). One key factor suspected to impair MPA performance is that critical decisions on the total coverage, placement, and local size of protected areas are often centralized, and therefore, decoupled from local knowledge, local values, local objectives, and the socioeconomic impacts on people where MPAs are implemented (Ban et al. 2009, Charles and Wilson 2009, Ferse et al. 2010, Pollnac et al. 2010, Christie et al. 2017). Fishers in those areas are less likely to support and comply with MPAs (Arias et al. 2015, Turner et al. 2016). To tackle this challenge, the concept of participatory MPA design approaches was established. Participatory MPA design aims to capture both social and ecological objectives by fostering the engagement of local communities and stakeholders in a systematic decision-making process (Mascia 2003, Ban et al. 2013, Lopes et al. 2013).

Participatory MPA design and local stakeholder support are likely to be critical in many regions worldwide, given that capacity shortfalls hinder top-down enforcement and MPA performance globally (Gill et al. 2017). However, participatory MPA design is often small in scale and tends to lack the scientific capacity and quantitative decision support tools available to centralized (i.e., large scale and government coordinated) MPA design projects. In consequence, many local MPA designs resulting from a community-based decision-making process could fail to achieve sufficient conservation and fishery benefits, even though local support and compliance is initially high.

Here, we explore the likely benefits of an MPA design decision-making process that amalgamates participatory and centralized approaches by making a comprehensive selection of quantitative decision support tools available to a small island community for MPA design scenario testing. Our MPA design toolkit included general guidelines (Roberts et al. 2003, Gaines et al. 2010, Green et al. 2015, Krueck et al. 2017*b*), standard MPA placement optimization software (Ball et al. 2009), spatial fishery models (Krueck et al. 2017*b*), and novel methods to reconcile conservation and fishery objectives of MPAs (Krueck et al. 2017*a,* 2018). Our primary aim was to support a community's aspiration to assess local MPA performance by specifying possible conservation and fishery outcomes under initially qualitative and various alternative MPA designs. Second, we aimed to quantify the potential benefits for science–community collaborations in MPA design, identifying the key strengths of MPA design decision support tools for similar applications in the future.

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METHODS

The study was conducted in Bungaiya, Indonesia, which is a small community with approximately 1700 residents (~500 households) who are distributed over six settlements across the northern end of Selayar Island, South Sulawesi (Fig. 1). Most of Selayar's population lives on the coast and depends on coral reefs and nearshore fisheries for food and income. In Bungaiya, all households rely on fishing as their main occupation (~150), second occupation, or to supplement family food supply. Community fisheries are small scale, with the fishing fleet dominated by small boats without engines or with small outboard motors. Dominant fishing gear includes hook and line, raft lift nets, gillnets, and fish traps. According to local informants, the annual rate of fish consumption has risen with an increasing population. Some of Selayar's coral reefs, including those in Bungaiya, have deteriorated because of destructive fishing methods, including blast (bomb) and cyanide fishing, whereas others are in good condition.

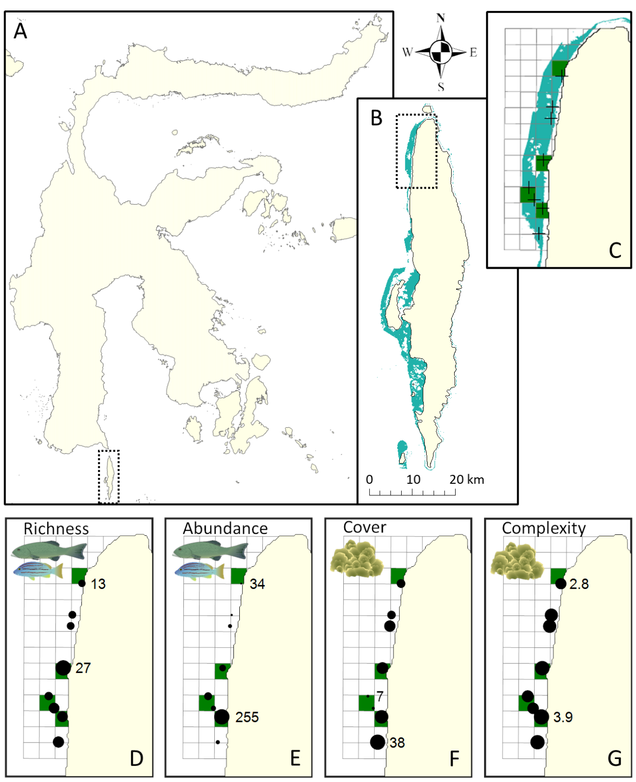


Fig. 1. Maps of the study area, field survey sites, and field survey outcomes. (A) Sulawesi, Indonesia, highlighting Selayar Island in the dashed box. (B) Selayar Island and surrounding coral reefs, highlighting the study area in western Bungaiya in the dashed box. (C) Coral reef habitat in western Bungaiya. Subplots in the lower panel show observed fishery species richness (D), fishery species abundance (E), live coral cover (F), and reef habitat complexity (G). Green cells = proposed reserve locations. Black symbols = field survey sites. Circle sizes scale to magnitude, with numbers highlighting minima and maxima next to respective sites.

Bungaiya is particularly active among the communities of Selayar in promoting traditional culture and traditional fishing methods, which they believe to be the most sustainable and fairest use of coastal resources. Bungaiya has a rich tradition around fishing practices, including customary rules for 11 different types of fishing gear, some of which are documented in ancient Makassan and Dutch documents. Prior to our study, the community had established one small no-take marine reserve, intending to prohibit all fishing within its boundaries, which was encouraged by the Coral Reef Rehabilitation and Management Program (COREMAP) program of the Coral Triangle Initiative (CTI). This small reserve was formally declared under village regulations but was not rigorously enforced once local support through the COREMAP project ended. The community aimed to improve this situation by initiating a rigorous surveillance and enforcement program for a total of four no-take reserves, comprising the one already established and three additional ones. The configuration (location, number, and size) of no-take reserves in community waters is what we aimed to help optimize through systematic MPA design decision making. One of the main incentives of the community for expanding from a single reserve to a reserve network (hereafter referred to as MPA) was to strengthen its position in combatting destructive fishing practices by outside fishers. The community also perceived that additional no-take reserves would benefit local fish abundance, although this assumption had never been tested. The community's goals in entering the science–community participatory MPA design approach reported here were: (1) to analyze whether their intended MPA design could be improved, and (2) to make use of scientific assessments to leverage stronger support from government for their marine management plans.

The collaboration reported here was part of a year-long participatory diagnosis to support multiple communities in Selayar, including Bungaiya, in working with government toward effective marine and coastal management (Ross et al. 2018). The collaboration was funded and implemented in the larger context of the five-year research and development program "Capturing Coral Reefs and Related Ecosystem Services" (CCRES; https://ccres.net/). Overall, the team of authors conducted six dedicated field visits in Bungaiya, each involving two to three community meetings and discussions. Additionally, we conducted an initial scoping visit over 7 days and an additional 25 days of community meetings and participant observation (conducted by three of the Indonesian team members) before and after the MPA design project. The MPA design project involved three community workshops and three days of joint marine fieldwork activities with the community conducted over a period of approximately two weeks. Each of the three workshops was attended by approximately 50 community members and used open discussions for formal data collection. Approximately one-half of the attendees at each workshop practiced fishing as their primary occupation, but all attendees were active fishers. Among the attendees of all three workshops were the elected leaders of each settlement (subvillages), which jointly form a community governance system, with the power (under Indonesia's national governance system) to make regulations that can be ratified by the district and provincial governments to attain the force of law. This body of settlement leaders elects one of their own as Chair, who acts as the "Head of the Village Legislature". Further, the entire village elects a Head of Village, who was informed about and supportive of all MPA design workshops and associated outcomes, but did not personally attend. The Bungaiya community is empowered to form, and does form, committees as required. One of these committees is the "Coastal Protection Committee", whose Chair and members were very prominent during workshop discussions and the associated decision making process reported here.

To prepare for the MPA design project in Bungaiya, we generated maps of the coastline and local coral reef habitat. We then overlaid the full extent of coral reef habitat with a 1 × 1 km planning grid for quantitative MPA design optimization, a resolution previously agreed upon and used for all field survey and spatial planning projects under the CCRES program. We highlighted all grid cells covering the four community-proposed reserve locations. Following initial preparations of the modeling environment, the community convened a planning workshop, during which we discussed state-of-the-art MPA design approaches as part of an interactive presentation. The discussion was focused on quantitative decision support tools and how such tools can be used to support effective biodiversity conservation and fisheries management decisions. We asked the community which management objectives they expected to achieve by enforcing reserves. The unanimous answer was that reserves are intended to benefit both biodiversity conservation and fisheries productivity, considering that both species and catches were assumed to be threatened. Using our grid, we then invited the community to map local fishing grounds, explain their fishing activities, list primary target species, specify how primary target species are caught, and specify how overfished each species is likely to be. Fishing grounds were recorded by assigning a simple score between values of 1 for low fishing intensity and 3 for high fishing intensity to each cell in the planning grid. The same simple score was also used to assign overfishing intensities to their most important fishery target species, with minimum values of 1 indicating low overfishing intensity and maximum values of 3 indicating heavy overfishing. All estimates of overfishing intensity were nonspatial, representing the assumed status of each target species across the planning region. Finally, we asked community members to flag any cells in the planning grid where ecosystems are known to be threatened or habitats are known to be damaged, for example, by bomb and cyanide fishing, pollution, coral bleaching, or cyclones, all of which could fundamentally undermine MPA performance. However, the community was uncertain about the location, scale, and severity of local threats, so we could not consider them in planning.

Our initial workshop clarified that the Bungaiya community was concerned primarily with MPA designation in community waters on the western side of Selayar Island, between latitudes 5.90° and 5.77° S. The longer, western coastline comprises most community settlements and harbors the most important fishing grounds, which are fished intensively over an extended period of 6–9 mo/yr over the East monsoon season. In contrast, the eastern side of the island is less populated and can be fished only 4–5 mo/yr during the West monsoon season. We therefore narrowed down our planning region exclusively to western community waters, which contained all four existing or intended reserve locations of primary interest to the community. Two of these four reserves were located in southwestern waters (R-South1 and R-South2) because of the assumptions that: (1) they can help maintain the currently healthy fish populations, (2) they protect a potential fish spawning aggregation, and (3) they reduce overall fishing pressure and undesirable fishing methods (specifically night spearfishing) by external fishers (up to 40 fishers/day), who are not associated with the Bungaiya community and are assumed to enter primarily from neighboring villages in the south. One area in central community waters (R-Central) represented the reserve that had already been established in consultation with COREMAP staff. The main reason for selecting this central reserve location was its proximity to the settlement that was most closely engaged in CTI marine conservation initiatives, which was expected to facilitate surveillance and enforcement. Another reason for choosing the central reserve location was that fish were assumed to be abundant. The same reason was also given by the community for selecting the intended reserve location in northwestern community waters (R-North), i.e., fish abundance was assumed to be high.

Fishery species of primary interest to the Bungaiya community were identified as: (1) groupers (Serranidae), (2) snappers (Lutjanidae), and (3) emperors (Lethrinidae). The level of overfishing intensity was assumed to be high for groupers and snappers and low to medium for emperors. To estimate the distribution and biomass depletion of these and other fished species in community waters, we concluded the initial meeting by establishing a field survey team consisting of community members as well as local and external researchers. The field team conducted rapid ecological surveys at eight sites in and around each of the four reserve locations (Fig. 1C). Field surveys were aimed at assessing fish assemblages and spatial variation in habitat quality. At each site, surveys were implemented via scuba diving using three 50-m belt transects laid out approximately 10 m apart along the reef at 8–12 m depth. Habitat quality was assessed by estimating live coral cover and habitat complexity within approximately 5 × 5 m squares every 10 m along each transect, resulting in a total of five squares starting at 0, 10, 20, 30, and 40 m. Live coral cover was estimated as a percentage of the total area. Habitat complexity was assigned using a simple score ranging between 1 for featureless and 5 for highly complex (Polunin and Roberts 1993, Wilson et al. 2007). The abundance of locally fished species was recorded across a 2.5-m extent on each side of the belt transect, covering a total area of 250 m² (N = 3) at each survey site. Sizes of individual fish were estimated visually to the nearest centimeter.

To narrow down depletion levels of the major families of locally important food fishes and estimate the status of associated fisheries, we used two different approaches. The first approach was based on a simulation of likely length frequency distributions in community waters compared to a hypothetical unfished system. The second approach was based on field estimates of fish biomass in community waters compared to protected locations further south on Selayar Island and to low and high fish density sites on largely unfished reefs in Raja Ampat, Indonesia. For length-frequency based estimates of depletion, we started by calculating maximum lengths of all species of groupers and snappers observed in the field. We then extracted theoretically expected maximum lengths of all of these species published in FishBase (Froese and Pauly 2019). Maximum expected lengths were then used as benchmarks for creating length frequency distributions of hypothetical unfished populations. To create these distributions, we sampled 1000 individual lengths per species from the negative binomial distribution, achieving good fits to prespecified maximum unfished lengths when setting the mean unfished length to one-third of the maximum unfished length. The standard deviation was fixed to one-half the mean unfished length. We then simulated population depletions by killing off individuals of fixed minimum fishable length > 5 cm (estimated based on community discussions). The probability of fishing mortality of individuals was assigned relative to their lengths, with the biggest individuals most likely to be caught, and mortality events were continued until maximum lengths in hypothetical populations matched those of fished populations observed in the field. Using species-specific length-weight coefficients (Froese and Pauly 2019), we then estimated population biomass in the hypothetical unfished system vs. the current fished system. Our results indicated family-level depletions in biomass of 94% for groupers and 99% for snappers (Appendix 1). Estimates of population depletions based on field-based measurements of fish biomass alone were similar. Compared to the fish biomass in effective no-take reserves in Raja Ampat (World Wildlife Fund, *unpublished data*), groupers and snappers in Bungaiya community waters were likely to be depleted by 92–98% and > 98%, respectively (Appendix 1).

Analyzing the combined information available from the community meeting and field surveys, we then convened another meeting with the community to develop scenarios for the application of decision support tools. We aimed to help answer three key MPA design questions: (1) How much coral reef habitat should be protected? (2) Where should reserves best be placed? And (3) How large should local reserves be?

How much to protect?

The first question aimed to help the community identify a percentage of all coral reef habitat in their community waters to be closed to fishing. In agreement with stated MPA design objectives, we aimed for this target to contribute to species protection while at the same time ensuring that the productivity of local fisheries improves. A generic no-take reserve target for this purpose under limited information on the status of local fisheries is to cover 20–30% of all fished habitat (Krueck et al. 2017*b*). However, fishery simulations were used to fine-tune this generic guideline according to local conditions using spatial fisheries modeling software (based on methods detailed by Krueck et al 2017*b*). Briefly, fishery simulations were based on a biomass production model, which captured annual dynamics in fish biomass and catch according to natural adult mortality, growth, adult movements, larval dispersal, recruitment, and fishing mortality in each cell of the 1 × 1 km spatial planning grid. As requested by the Bungaiya community, simulations were aimed at representing the local coral trout (*Plectropomus leopardus*) fishery. To parameterize the fishery model, empirical estimates of natural annual mortality and growth of *P. leopardus* were sourced from FishBase (Froese and Pauly 2019). Field measurements of the scales of adult movements (Green et al. 2015) and dispersal of fish larvae (Williamson et al. 2016) were used to calculate exchange through fish movements among all cells in the planning region. Recruitment was calculated according to the Beverton-Holt function by assuming post-settlement density dependence typical of most fishery species (Myers et al. 1999; see Appendix 2 for a summary of key parameter values). The amount of coral reef habitat in each cell was quantified based on high-resolution Landsat imagery (Roelfsema et al. 2013), with coral trout population biomass per cell distributed in proportion to coral reef habitat area, implicitly assuming that habitat quality is spatially uniform. Fishing effort in different cells represented community-specified scores of fishing intensities between values of 1 (low) and 3 (high). Following reserve enforcement in any given simulation, total fishing pressure was concentrated (i.e., all fishers kept fishing) while maintaining the initial distribution of relative fishing pressure as specified during the initial community meeting. Fishing pressure was parameterized according to simulation- and field-based estimates of fish biomass depletion (Appendices 1 and 2), which were very closely aligned with community-estimated levels of high overfishing intensity (3 out of 3). All modeling procedures and assumptions were otherwise as specified under “spatially-explicit scenarios” in Krueck et al (2017*b*).

In the first set of scenarios, we used coral trout fishery simulations to quantify the effect of the initial community-proposed MPA on long-term fish population biomass and catch. We then contrasted associated findings to a scenario that optimized the configuration of reserves for fishery rebuilding (maximum catch). Lastly, we quantified the effects of alternative MPA design proposals considered by the community. In all presented scenarios, we incorporated the effect of directional transport of fish larvae by predominately southward-flowing ocean currents, as observed in the field and confirmed by the community. For this transport, we made conservative estimates of local ocean current flow (1 km/day), mean pelagic larval duration (20 days), and the associated southward displacement of dispersal probabilities (approximately 20 km).

Where to protect?

Fishery simulations provided first information on the effects of reserve placement decisions under directional (southward) transport of fish larvae. However, fishery simulations did not capture all social considerations about reserve placement, nor did they incorporate field survey results. Standard protected area placement optimization software such as Marxan and Zonation (Ball et al. 2009, Lehtomäki and Moilanen 2013) could have helped run additional spatial prioritization scenarios for this purpose but was challenged by the nature and availability of data. That is, social considerations were categorical in nature and difficult to map for spatial prioritization, and field survey data were patchy and could not be interpolated meaningfully across the planning area. In consequence, we developed a simple scoring system based upon which all four supported reserve locations were ranked according to three social and ecological criteria of primary interest to the Bungaiya community. Scores were based on a Likert scale with values of −2 (highly undesirable), −1 (undesirable), 0 (uncertain), 1 (desirable), and 2 (highly desirable). The three social considerations were: feasibility, which represented the proximity of locations to settlements where community members could easily observe and enforce compliance; acceptance, which represented local knowledge and support of each reserve; and impacts on fishers, which represented the value of local fishing grounds at reserve locations to both community members (high value/strong impact undesirable) and external fishers (high value/strong impact desirable). The three ecological considerations were: fishery benefits, which

Table 1. Outcomes from field surveys covering eight sites in and around community-proposed reserve (R) locations. Results are means of richness, abundance, and length of fished species, as well as cover and complexity of coral reefs.

Location (north to south)	Species richness (species/100 m²)	Abundance (individuals/100 m²)	Length (cm)	Live coral (%)	Complexity (scale of 1–5)
R-North	2	5	14	22	3
South of R-North	2	5	15	22	3
North of R-Central	2	9	12	29	3
R-Central	4	15	12	29	4
R-South-offshore	2	18	14	7	3
R-South	3	12	14	8	3
South of R-Central.	3	34	9	34	4
South of R-South	3	9	13	38	4

represented the likelihood of adult spillover and larval dispersal from reserves to surrounding fishing grounds; species richness, which was quantified according to the presence of local fishery species; and habitat quality, which was quantified according to measured coral cover and habitat complexity.

How large should local protected areas be?

Fishery simulations also provided some information on the desirable sizes of local reserves. However, the modeling resolution of 1 km was too coarse to capture the smaller scale of adult movements of local fishery species for accurate predictions of reserve size effectiveness. For this reason, we used no-take reserve size optimization software, which quantifies reserve effectiveness for species protection (and spillover to fishing grounds) according to data on species home range, density, or maximum length (Krueck et al. 2018). The software and associated user manual are available for free download at https://ccres.net/index.php?/resources/ccres-tool/mpa-size-optimization-tool. We used the software to calculate no-take reserve sizes required to achieve the protection of at least 50% of unfished fish densities, ensuring a notable conservation benefit while mitigating any short-term catch declines and allowing for long-term fishery benefits through adult spillover from reserves to fishing grounds. Reserve size protection assessments were completed for all observed members of key fishery families (species of groupers and snappers). In addition, we illustrated reserve size effects on the protection of eight key fishery species of grouper, which we did not observe in community waters, but for which we had robust empirical data on home ranges, densities, and schooling behavior (Krueck et al. 2018). The community used these predictions of ecological effectiveness and perceived social impact on fishers to reconsider current and intended reserve sizes of approximately 0.5–1 km along the reef.

RESULTS

Field surveys

Field surveys confirmed that fished groupers and snappers were present throughout western community waters and that members of both families are likely to be heavily overfished (Appendix 1). Emperors, as the third most important family of fishery species, were not encountered during any survey (see Appendix 3 for a list of all 46 observed fishery species, including their abundance and mean length).

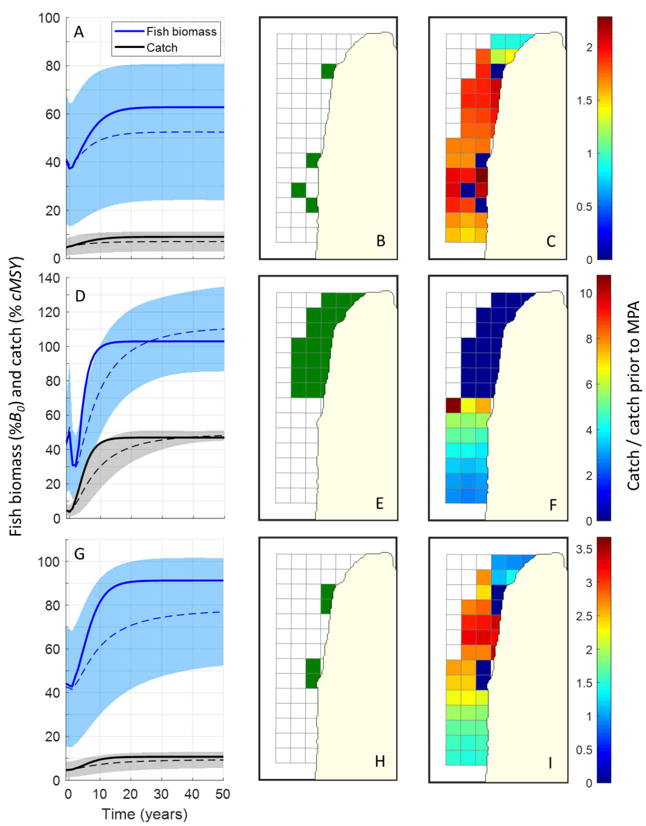
Spatial variation in habitat quality and fish assemblages did not appear to be pronounced, but our surveys highlighted several notable differences. Mean cover of live coral on inshore reefs (within 1 km of the shore), for example, was estimated to increase from approximately 22% in northern community waters to approximately 38% close to community boundaries in the south. Mean coral cover on more distant reefs (> 1 km offshore) was strikingly lower (~7%; Table 1). In contrast, coral reefs in all areas showed comparably complex structures, revealing complexity scores between means of 2.8 and 3.9 throughout the planning area, but lacking obvious latitudinal trends (Appendix 4). Habitat complexity showed a generally positive correlation with both fished species richness and abundance and a clear negative correlation with mean fished species size. No such trends appeared to be evident for live coral cover.

Maximum richness of fishery species (4 species/100 m²) was observed at the primary reserve candidate site in central community waters. Maximum abundance of fishery species (34 individuals/100 m²) was observed at an inshore survey site south of the central reserve candidate location. At that survey site, the mean size of fished species was lowest (9 cm), whereas the mean habitat complexity was highest (score of 3.9). The lowest overall fished species richness (2 species/100 m²) and abundance (5 individuals/100 m²) was observed at the reserve candidate site in northern community waters (Table 1, Fig. 1).

How much to protect?

The initial community-proposed network of reserves covered 11.7% of local coral reef habitat. Spatial fisheries modeling showed that this initial MPA design could help rebuild coral trout population biomass from 5% back to 9% of unfished levels (mean = 7% ± 4%). Coral trout catch was estimated to recover from ~40% back to 63% of the maximum sustainable level (mean = 52% ± 28%; Figs. 2A–C and 3). In contrast, the MPA design optimized for fishery rebuilding covered a much larger area of connected cells in reserves, usually consisting of a single large reserve in northern community waters, which contained up to 50% of coral reef habitat. A single large reserve in northern community waters was predicted to rebuild coral trout populations back to 47% of their unfished biomass (mean = 48% ± 3%) and increase catch to 103% of the estimated maximum in an openly fished system (mean = 110% ± 25%; Figs. 2D–F and 3). Thus, ambitious no-take reserve coverage targets for species conservation did not

Fig. 2. Coral trout fish population biomass and catch predicted for alternative marine protected area (MPA) designs. (A–C) Initial community-proposed MPA design. (D–F) Theoretically optimal MPA design. (G–I) Community-revised MPA design. Leftmost panels (A, D, G) show temporal trends following MPA enforcement, with solid lines representing best estimes and dashed lines and shaded areas representing means and associated standard deviations across simulated parameter ranges. Center panels (B, E, H) highlight the placement of individual no-take reserves. Rightmost panels (C, F, I) show the distribution of projected catch relative to catch before MPA enforcement, with values > 1 highlighted in warm colours, indicating local fishery benefits. Abbreviations: B_0, unfished biomass; cMSY, community maximum sustainable yield.



appear to diminish long-term fisheries productivity, providing for the flexibility to achieve strict coral reef protection targets of up to 50%, but at the cost of higher initial catch declines.

Where to protect?

Using a simple Likert scale to capture key social and ecological considerations for reserve placement, the existing central reserve location was found to score highest (Table 2). From a social perspective, this location was highly feasible because it was within eyesight of a settlement committed to strict surveillance and enforcement (see a list of all social and ecological objectives in Table 3). Additionally, it was the only established reserve location that was known by the local fishing community, including fishers from neighboring villages, even though its enforcement has been

Fig. 3. Coral trout fish population biomass (A) and fishery catch (B) predicted for alternative marine protected area (MPA) designs. Within panels, bars represent the initial community-proposed (Proposed), theoretically optimal (Optimal), and community-revised (Revised) MPA designs (see also Fig. 2).

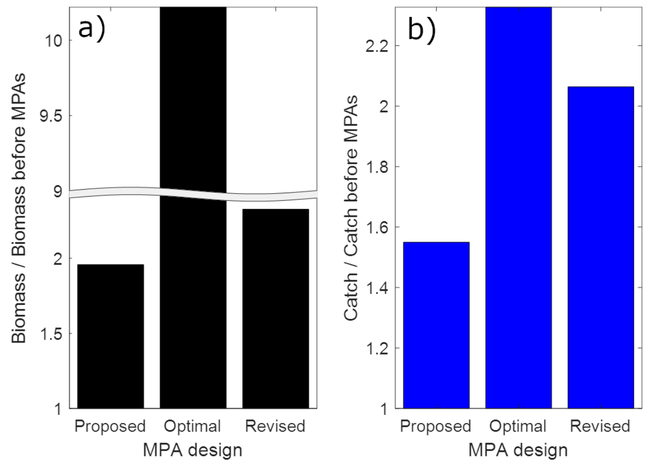


Table 2. Scores for social and ecological considerations at all community-proposed reserve locations. The order of reserves is based on total scores across all considerations. Abbreviations: R = reserve, C = central, N = north, S = south.

System aspect	Consideration	R-C	R-N	R-S2	R-S1
Social	Feasibility	2	0	0	−1
	Acceptance	2	1	1	1
	Fisher impacts	−1	−1	0	1
Ecological	Fishery benefits	1	2	0	0
	Species richness	2	0	1	0
	Habitat quality	2	0	−1	−1
Total score		8	2	1	0

dormant since support from COREMAP stopped. Ecologically, the central reserve was characterized by the highest observed richness of fishery species and by high-quality habitat (Table 1, Fig. 1). The second highest score was evident for the intended reserve location in northern community waters, primarily because this location was expected to be of highest potential fishery value. That is, fish population recovery at this location was most likely to result in the export of fish larvae to important fishing grounds, given that ocean current flow in western community waters was predominately southward. Both southern reserve locations, in contrast to northern and central areas, were more likely to export fish larvae and associated fishery benefits to neighboring communities. However, the main incentive for Bungaiya community members to enforce southern reserves was social and not ecological because spatial closures in the south were assumed to help restrict fishing activities by neighboring community members. Specifically, Bungaiya people aimed to control negative effects of nighttime spearfishing in the south, even though large parts of the area close to both southern reserve sites were undesirable in terms of feasibility and likely ecological effectiveness.

Table 3. Ecological and social objectives for community-based marine protected area (MPA) design in Bungaiya, Indonesia.

MPA design question	Ecological objective (quantitative assessment)	Social objective (qualitative assessment)
How much to protect? Where to protect?	Ensure biodiversity protection and fisheries rebuilding while avoiding declines in the productivity of fishery target species	Ensure access to most highly fished areas, potentially increasing number and size of reserves once fishery benefits materialize
	Fisheries: Prioritize upstream locations in northern community waters, where reserves can help rebuild populations that seed fishing grounds through the southward dispersal of fish larvae by ocean currents	Enforcement: Practicality of surveillance and enforcement depends on accessibility, which means that reserves need to be close to community settlements so they can be easily watched and reached
	Effectiveness: Prioritize high fish population recovery potential by protecting places that are fished but where the habitat is still intact and where target species are still diverse	Management: Prioritize reserves close to a neighboring village to reduce total fishing pressure caused by outsiders and to monitor fishing practices that Bungaiya community has banned (e.g., nighttime spearfishing) Impact: Avoid many reserves in areas where Bungaiya people fish most often (central and northern waters), minimizing harmful impacts on fisheries productivity Impact: Avoid conflicts with traditional stake nets (*seros*), which are stationary fish traps of high local importance Social: Prioritize multiple small reserves near each settlement because local reserves are a source of pride and social identity
How big should local reserves be?	Conservation: Ensure local reserves are large enough to facilitate population recovery by protecting fishery target species effectively Fisheries: Ensure local reserves are small enough so that recovered fish populations export both adults and larvae to adjacent fishing grounds	Impact: Prioritize small reserves at popular fishing grounds (central and northern waters) and large reserves near neighboring village (south)

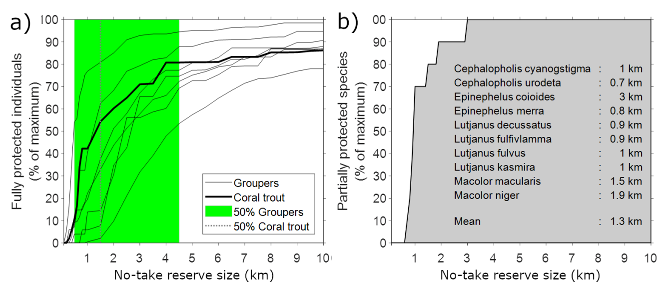
How large should protected areas be?

The initial plan of the Bungaiya community was to enforce generally small no-take reserves that extended between approximately 500 m and 1 km along local fringing reefs. However, quantitative assessments revealed that reserves of this size were unlikely to offer sufficient protection to any well-researched species of groupers that were of primary fishery and conservation concern to the community (Fig. 4A). Similarly, none of the locally observed fishery species of groupers and snappers were found to experience minimum recommendable protection in 0.5–1 km wide reserves, given that, on average, 1.3 km (700 m to 3 km) of protection was required to ensure that at least 50% of local individuals were likely to range within reserve boundaries (Fig. 4B). For well-researched grouper species, reserves needed to be on average 1.5 km wide (500 m to 4.5 km) to provide for that level of protection.

Revised marine protected area design proposal

Following assessments and discussions of all findings during a final (third) meeting, Bungaiya community members decided to prioritize the enforcement of no-take reserves that extended 1.5–2 km along inshore fringing reefs, ensuring the effective protection of > 50% of individuals of most locally observed fishery species. However, similar to initial plans, total initial reserve coverage was not supposed to exceed 10% of local coral reefs, given that higher reserve coverage might cause unacceptable short-term declines in catch (Fig. 2D). In consequence, the community negotiated a revised MPA design proposal. Instead of the initial plan to establish four small reserves, the community decided to prioritize the establishment of two larger reserves at the highest priority locations in central and northern areas, together covering approximately 9% of all local coral reef habitat (Fig. 2H). According to fishery simulations, the revised MPA design was estimated to rebuild coral trout populations from 5% back to 11% of unfished biomass (mean = 9% ± 4%), representing a 2.3-fold increase compared to an openly fished system. Catches more than doubled, recovering from ~40% back to 91% of the sustainable maximum (mean = 77% ± 25%). Compared to the initially proposed MPA, these outcomes represented a 1.4-fold increase in recovered fish biomass and a 1.9-fold increase in fishery catch (Fig. 3). Following full enforcement and the monitoring of both conservation and fishery impacts associated with the revised MPA design, the community planned to add one more reserve in southern community waters. This southern reserve was planned to extend over a larger area, including both initially proposed reserves (R-S1 and R-S2) and a presumed spawning aggregation

Fig. 4. Fish protection effectiveness in no-take reserves of increasing size. (A) Simulated protection of eight species of well-researched grouper. (B) Regression-based estimate of reserve sizes needed for the partial protection of fished grouper and snapper species observed in Bungaiya, Indonesia. Partial protection means that at least 50% of local individuals range within reserve boundaries.



site for groupers nearby, achieving a total no-take area coverage of 16% of all local coral reef habitat.

DISCUSSION

Multiple studies have stressed the importance of the involvement of stakeholders in MPA design decision making (Pollnac et al. 2010, Ban et al. 2011, 2013, Lopes et al. 2013, Christie et al. 2017), which is often a government-coordinated (top-down) process. Our study is an example of a bottom-up process in which a community initiated collaborations with MPA design experts as equal partners interested in testing and improving the current management arrangements. The results show that modern quantitative tools can support community decision making by specifying likely MPA performance from the perspective of both fish and fishers and subject to the constraints of social considerations, the latter of which is likely to be critical for the sustained local support of MPAs.

Community-based MPA design decisions in Bungaiya were driven by considerations of local feasibility of MPA surveillance and enforcement as well as MPA impacts on local vs. external fishers. These considerations differ from those driving many centralized MPA design projects, which are focused on economic costs of enforcement and environmental targets set out by marine conservation agreements (Parson et al. 1992, Fernandes et al. 2005, Maes 2008). Widely applied protected area placement decision support software such as Marxan and Zonation (Ball et al. 2009, Lehtomäki and Moilanen 2013) has been developed in support of such centralized MPA design projects, helping to identify priority sites across vast ocean areas where protected areas are most likely to capture unique or many conservation features at a minimum economic cost (Possingham et al. 2000, Ball et al. 2009). Spatial prioritization software such as Marxan is highly flexible (e.g., Halpern et al. 2013, Krueck et al. 2017*a*), but the conditions in Bungaiya offered little scope for quantitative reserve placement optimization. First, the planning region covered only 38 km^2 of ocean along a 14-km stretch of coastline. And over this small scale, we found little evidence for gradients in habitat quality, fish abundance, or environmental stress that would warrant biophysical prioritizations in the light of key social constraints such as the feasibility of local surveillance and enforcement. Second, most social considerations, such as the intended use of reserves to regulate external fishers, were of a qualitative nature, complicating the use of any currently available decision support tool to help optimize for environmental, economic, and social outcomes simultaneously (Plagányi et al. 2013).

However, fishery simulations highlighted a local disagreement between ecologically and socially desirable MPA designs. Incorporating information on fishing grounds, coral reef habitat, ocean current flow, and the biological characteristics of key fishery species (Krueck et al. 2017*b*), fishery simulations consistently identified large no-take reserves in northern community waters as the most effective means to rebuild both fish population biomass and catches. From a social perspective, in contrast, the community aimed to establish the largest reserves in southern community waters, where they were expected to restrict fishers from neighboring communities while having a low impact on local fishers. Subsequent MPA design negotiations were focused largely on this apparent conflict. Clearly, even generic MPA design guidelines (Roberts et al. 2003, Gaines et al. 2010, Green et al. 2014, 2015, Krueck et al. 2017*b*) could have helped to identify the nature of conflicts among socially and ecologically optimal MPA designs in Bungaiya. However, the main benefit of quantitative tools such as fishery simulations and explicit predictions of reserve size effectiveness (Krueck et al. 2018) was that they specified and visualized expected conservation and fishery effects associated with alternative community decisions. In consequence, likely MPA performance was substantially improved.

The original MPA design by the Bungaiya community included four small no-take reserves, two of which were located in southern community waters primarily to restrict external fishers. This socially favorable MPA design jeopardized the recovery of both fish populations and fisheries because individual reserves were too small relative to known scales of adult reef fish movements to expect effective protection and because most fish larvae produced in reserves were likely to be carried southward beyond community waters by local ocean currents. The revised MPA design, in contrast, included only two but comparatively large reserves in northern and central community waters, together covering approximately 9% of local coral reef habitat (similar to the initial proposal). Under the revised proposal, individual reserves were likely to protect three to four times more individuals of key fishery species within their boundaries and to retain more locally produced larvae of these species in community waters, thereby supporting future fisheries productivity.

CONCLUSION

The reported collaboration of a community with scientists demonstrates the potential impact of participatory and bottom-up management decision making. Participatory management approaches, while highly valuable, often continue an imbalanced power relationship between government and scientists and those they choose to invite into the process (Lynch 2017). We believe that the approach documented here was fundamentally supported by the following factors: (1) a year-long engagement of social scientists in community discussions of local marine management issues; (2) the inspiring role of local champions for marine and fisheries conservation; (3) participatory field work; and (4) a series of participatory community meetings, which involved (5) continued guidance on MPA design scenarios and (6) a progressive decision-making process based on the review of interim assessments, modeling outcomes, and field survey results. An important step in fostering informed bottom-up MPA design is the continued development of decision support tools, which can be used by communities to quantify and visualize predicted and observed MPA performance.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/11209

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Appendix 1. Key data, sources and outcomes from estimates of biomass depletion for groupers and snappers

Please click here to download file 'appendix1.xlsx'.

Appendix 2. Key life history and fishing parameter values used in the coral trout fishery model.

Please click here to download file 'appendix2.xlsx'.

Appendix 3. List of the names, numbers and mean total lengths of fished species observed during field surveys in western Bungaiya

Please click here to download file 'appendix3.xlsx'.

Appendix 4. List of sampling dates, geographic coordinates, transect numbers and associated data on live coral cover and habitat complexity recorded during field surveys in western Bungaiya

Please click here to download file 'appendix4.xlsx'.