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A comparison of zoning analyses to inform the planning of a marine protected area network in Raja Ampat, Indonesia

Hedley S. Grantham [a,b,*], Vera N. Agostini [c], Joanne Wilson [d], Sangeeta Mangubhai [d], Nur Hidayat [e], Andreas Muljadi [d], Muhajir [d], Chris Rotinsulu [f], Meity Mongdong [f], Michael W. Beck [g], Hugh P. Possingham [a]

[a] The University of Queensland, Centre for Applied Environmental Decision and Analysis, St Lucia, Queensland 4072, Australia
[b] Conservation International, 2011 Crystal Drive, Suite 500, Arlington, VA 22202, USA
[c] The Nature Conservancy, Global Marine Team, 255 Alhambra Circle, Miami, FL 33134, USA
[d] The Nature Conservancy, Indonesia Marine Program, Jl. Pengembak 2, Sanur 80228, Bali, Indonesia
[e] Conservation International, Jl. Kedondong, Puncak Vihara, Klademak, Sorong 98414, Papua Barat, Indonesia
[f] Conservation International, Jl Dr. Muwardi 17, Renon, Denpasar, Bali, Indonesia
[g] The Nature Conservancy, 100 Shaffer Road, University of California, Santa Cruz, CA 95062, USA

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ABSTRACT

Marine protected areas (MPAs) are often managed using several management zones, each of which allows different human-uses. Decision support tools can be applied to provide advice on potential zoning configurations. However, few studies used decision support tools to systematically determine good locations for different types of zones that accommodate multiple and often conflicting objectives. Previous studies have mostly used scores to integrate multiple objectives and identify different zoning configurations or explored priority areas for each zone separately. Neither of these approaches ensure that solutions meet both biodiversity and human-use objectives. Nor do they deal with the fact that in zoning plans the whole is not the same as the sum of the parts, the importance of a site depends on how the rest of the sites are managed. The aim of this study was to identify different zoning configurations for the Raja Ampat MPA network in Eastern Indonesia that address biodiversity, sustainable fisheries and community resource access objectives. Identifying zoning configurations is particularly difficult here given the importance of protecting high biodiversity reefs and other conservation values, and the high reliance of local communities on their marine resources. Potential areas for no-take zones were identified that have a small and equitable impact across the fishing grounds of different fishing communities whilst ensuring each community has access to a 'sustainable fishing zone'. Access to fishing grounds for each community is complicated due to marine tenure restricting where individuals can fish and reliance on traditional types of fishing vessels that restrict long distance travel. This approach for zoning was compared to three others. The first focused on identifying areas only for the no-take zone, a traditional systematic planning approach, and the second on both zones without explicitly accounting for the issue of resource access for each community. The solutions unfairly impacted particular communities. Finally, it is demonstrated how a pre-existing zoning proposal, driven by negotiation can be integrated into systematic planning.

1. Introduction

Marine ecosystems are facing mounting pressures worldwide and conflict between and among user groups characterize a great portion of the world's oceans [1]. Marine protected areas (MPAs) are helping address these pressures by providing effective area based protection necessary to maintain ecosystem health and productivity, while safeguarding social and economic development [2]. Many MPAs are often managed through the establishment of different zones that regulate human activities in different ways. Given how complex it is to decide which zone to place where, having access to tools that can support the decision-making processes (decision support tools) by providing potential zoning configurations that accommodate competing objectives is useful, and can be a starting point for a negotiation. An analysis of the trade-offs between multiple and often conflicting objectives can help minimize potential conflicts between stakeholders and/or resources users [2,3].

* Corresponding author at: Conservation International, 2011 Crystal Drive, Suite 500, Arlington, VA 22202, USA. Tel.: +1 7033412430.
E-mail address: h.grantham@conservation.org (H.S. Grantham).

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Previous approaches to zoning analysis have mostly used multi-criteria decision analysis frameworks e.g. [4,5]. Multi-criteria decision analysis can be used to explore a number of zoning scenarios by combining information from several different criteria to form a single index of evaluation for each site. Values for each criterion are given a score. For example, Brown et al. [3] individually scored water quality, productivity, coral reef health and mangrove habitat as ecological criteria, then combined these scores to evaluate management options for an MPA in Tobago. Scoring methods however, do not usually solve a well defined problem in conservation planning and cannot accommodate the notion of complementarity [6]. For example, scoring methods are mostly ineffective at identifying representative areas of different biodiversity [7], which is often an important objective in MPA planning [8]. Also, scoring methods value sites individually rather than collectively and thus do not account for the relationships between sites [6,9].

'Spatial conservation prioritization' is a field of conservation science that focuses on identifying locations that are either representative of biodiversity for minimum socio-economic cost, or maximize benefits to biodiversity given socio-economic constraints [6]. Socio-economic costs can vary and can include economic costs (e.g. fisheries effort and catch data), preferences away or toward particular human-uses and threats (e.g. aquaculture sites), and social preferences (e.g. willingness of people to be involved in a protected area) [10]. For example, to help inform the rezoning process of the Great Barrier Reef Marine Park in Australia, the conservation planning software Marxan was used to help prioritize locations for no-take zones that would achieve equitable representation of different types of ecosystems while minimizing a number of social and economic costs [8]. This type of decision support tool has not been widely applied for multi-objective zoning as, until recently, readily available conservation planning software could only identify locations for a single zone. Recent advances in the software Marxan (Marxan with Zones) allow the user to identify locations for multiple zones simultaneously and address multiple objectives [11]. For example, Klein et al. [12] identified areas for multiple types of fishing and conservation zones in California using Marxan with Zones.

When planning MPAs, there are usually many different stakeholders and their interests need to be taken into consideration. Current conservation planning frameworks identify the need to set targets for different conservation features and avoid socio-economic costs where possible but often fail to discuss the need to set targets for different stakeholder groups e.g. [13,14]. Typically, to avoid different socioeconomic costs, important areas are summarized by combining information into a single cost layer or metric e.g. [15]. How information is aggregated will impact the location of areas being avoided, and aggregating information into a cost metric does not guarantee that stakeholder objectives and targets are accounted for in the zoning solutions [16]. One way to address this issue in zoning analysis is to set targets for different stakeholders [12]. For example, Weeks et al. [16] identified locations for MPAs in the Philippines and ensured that a significant amount of each community tenure was not within the MPA network by setting targets for each tenure explicitly. For multi-objective problems that have competing objectives and targets, there is a need to explore the trade-offs between objectives as there are rarely win–win situations [12].

Here a critical problem faced when zoning MPAs is assessed, and one that has received little attention in the literature: identifying configurations of zones that achieve multiple objectives and allow specific stakeholder group's interests to be explicitly addressed. The Raja Ampat region is used to illustrate the approach. The aim of this study was to facilitate consideration of biodiversity conservation and fisheries needs for all communities in the Raja Ampat MPA network. While information was collected that will help address other objectives (e.g. tourism) in the zoning process, it was not explicitly addressed in this analysis because it was biodiversity and fisheries which posed the greatest challenges to the zoning process. The tools and approaches developed here are designed to help decision makers in Raja Ampat with their MPA network zoning efforts, as well as serve as a template for other areas engaging in multi-objective zoning efforts.

Located on the north-western tip of Papua, eastern Indonesia, Raja Ampat consists of nearly 1500 islands and encompasses an area of over 4.5 million hectares (Fig. 1). Sitting in the epicenter of the Coral Triangle, Raja Ampat contains the world's most biodiverse coral reefs [17] and is a global priority for conservation [18]. Ecological surveys in the Raja Ampat archipelago have recorded 1320 species of coral reef fish [19] and 553 species of scleractinian corals which is around 75% of the world's total [20]. The region is also important for many species of marine megafauna including 16 species of cetacean, dugong, and three species of turtles [21].

Raja Ampat has a rich and diverse cultural heritage that ranges from indigenous Melanesians to settlers from as far as the Middle East that arrived during the spice trade era [22,23]. A more recent trend is government-initiated transmigration of people, particularly from Java [24]. Raja Ampat's rich marine resources make it a target for economic development including commercial fisheries, tourism, mariculture, oil and gas, mineral, mining and logging [25]. Fish stocks are generally in decline [26] and there are issues with illegal, unreported and unregulated fisheries [27]. With a growing economy that relies on healthy ecosystems for fishing, tourism and mariculture, and globally significant biodiversity, there is a need for ecosystem-based management for the coastal and marine resources in Raja Ampat. In response, the Raja Ampat regency government has declared a network of six multiple use MPAs, in addition to the existing MPA to create a network of seven MPAs that cover 1,185,940 ha.

In addition to the national, provincial and district governance systems, there is a traditional and complex customary system, which include land and marine tenure and traditional natural resource management, such as, prohibitions on harvesting species during particular times and locations, called *sasi* [28]. Many people in Raja Ampat rely on small-scale commercial and subsistence fishing for their livelihoods [29]. The location of community fishing grounds is spatially constrained by a marine tenure system and the fact that most communities are using traditional types of fishing vessels that can only travel so far [30,31]. The zoning of the Raja Ampat MPA network must account for the fishing grounds of numerous communities when identifying potential no-take zones.

The following describes several approaches for considering multiple objectives within an integrated zoning analysis across a network of MPAs and compare them. Two types of zones were considered that contribute to meeting these biodiversity and fisheries objectives, a no-take zone and a sustainable fishing zone respectively. There will be other types of zones in the management of the Raja Ampat MPA network but it is these two types of zones that will form the foundation of the zoning plan, will cover the greatest area and are the most complicated to identify.

2. Methods

A database was compiled on the distribution of ecosystems, species, human-uses and threats to underpin the zoning process and to enable us to apply decision support tools. A range of data sources were used (Table S1). This included field observations,

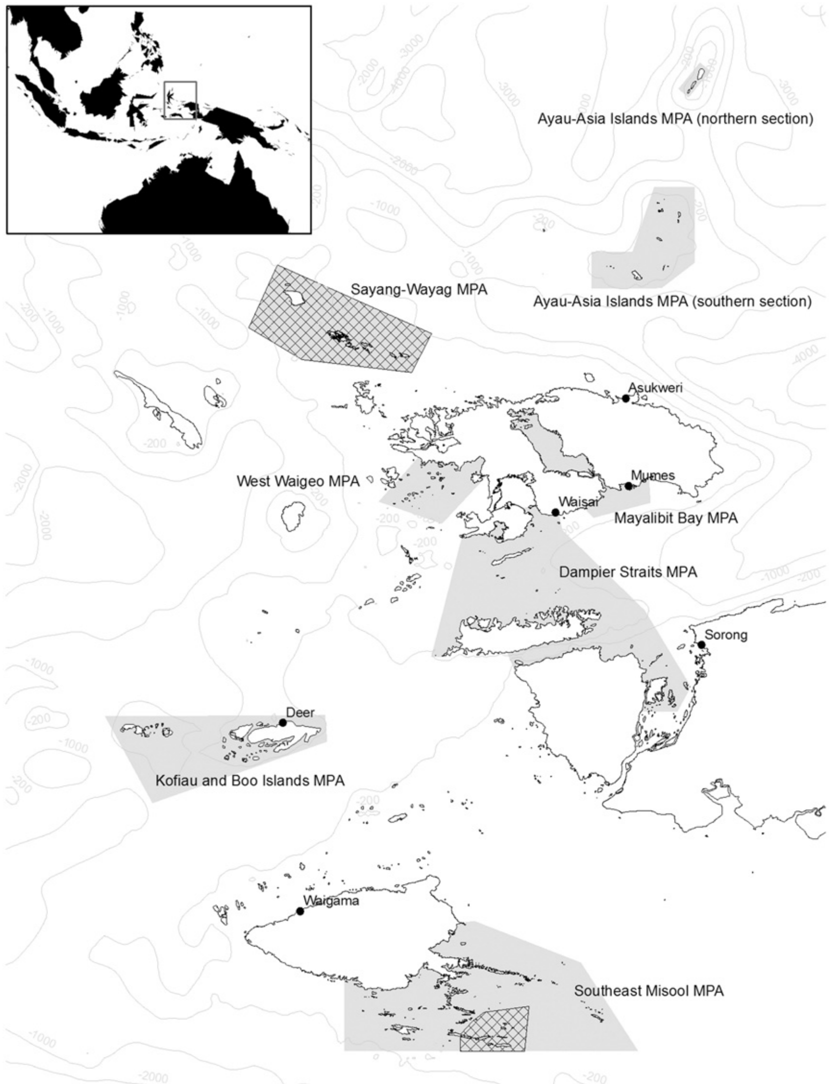

Fig. 1. Location of the Raja Ampat. There are seven marine protected areas Ayau-Asia, Teluk Mayalibit, West Waigeo, Sayang Wayag, Dampier Straits, Kofiau and Boo Islands and Southeast Misool. Hashed areas are existing no-take areas.

satellite imagery and expert information. The following describes the data sets gathered and methods deployed for the zoning analysis.

2.1. Data

2.1.1. Ecosystems

Various sources of data were used to map the extent of different ecosystem types in Raja Ampat (Table S1). None of the ecosystem types were divided into different classes except for coral reefs due to limited data available. Coral reefs were classified based on De Vantier et al. [32] who developed a hierarchical classification based on oceanography, bathymetry, physico-chemical parameters, coral communities, reef fish occurrences and expert opinion. These were modified slightly by combining some of the coral reef classes that were known to be relatively homogenous. A finer level of classification was also applied to Southeast Misool MPA. Both this and the MPA network classifications were used to examine zoning scenarios.

Coral reef condition data, collected through manta tow surveys [33] were available for all six of the MPAs (Conservation International (CI) and The Nature Conservancy (TNC) unpublished data). Reef health surveys recorded percentage cover of hard corals, soft corals, algae, rock and rubble. The percentage of a reef that is damaged was the sum of the percentage that is dead and the percentage of rubble.

2.1.2. Species data

The location of important species and critical habitats such as nesting beaches and spawning grounds was mapped (Table S1). Manta ray (*Manta birostris*) aggregations were mapped sites from aerial surveys [34] and participatory expert mapping. For the aerial survey locations, a location with more than two manta rays was assumed to be an aggregation site. Turtle nesting locations were identified for Wayag-Sayang, Ayau-Asia and Kofiau and Boo Islands and Southeast Misool MPAs (TNC, Yayasan Penyu Papua and WWF unpublished data). Separate conservation targets were used for the northern (Wayag-Sayang and Ayau-Asia), and southern MPAs (Kofiau and Boo Islands and Southeast Misool) to ensure representation across the MPA network.

Areas used by dolphins, whales and dugongs were mapped using a combination of the results of participatory expert-mapping workshops, opportunistic observations, ecosystem maps and aerial survey points (TNC and CI unpublished data). In Ayau-Asia MPA, shark locations were mapped using the outline of the atolls reefs where there were many shark records from the aerial survey. In addition a 1 km buffer around other shark observations was included as shark habitat.

2.1.3. Fisheries and mariculture data

In Southeast Misool and Kofiau and Boo Islands MPAs, local communities or *karamba* (fish cage) owners have identified potential or historical fish spawning aggregations (TNC unpublished data), but none of the monitoring to date have confirmed these to be active sites. Regardless, these potential or historical spawning aggregation sites were included as an important feature that may recover if adequate protection was in place. Important fish spawning aggregations were identified at an expert mapping workshop. Targets were set separately in Kofiau and Boo Islands and Southeast Misool MPAs to ensure historic fish spawning aggregations were represented within both of the MPAs.

Access to community fishing grounds is important to local communities and these were digitized spatially the locations of 126 community fishing grounds, from a range of information sources including community and expert interviews, resource use monitoring programs across the network (this included interviewing fishers on the water, to obtain information on their fishing activities, including type of boat, gear and composition of catch) and monitoring surveys. For Ayau-Asia, West Waigeo, Mayalibit Bay and Dampier Straits MPAs fishing grounds were mapped by a combination of point data from surveys (resource use and aerial surveys that identify locations for either canoes or traditional boats with small motors (*ketinting*)) and data derived from experts. For Kofiau and Boo Islands and Southeast Misool MPAs participatory community mapping was done to identify the key commercial species that local communities harvested (including *Trochus*, grouper, green snail, sea-cucumbers, lobsters,) as well as key fishing grounds (Table S1; TNC unpublished data). Data generated via community mapping efforts were verified against resource use data collected in the MPA as Kofiau and Boo Island and Southeast Misool MPAs. For Ayau-Asia, West Waigeo and Dampier Straits MPAs fishing grounds were identified for the majority of communities (Table S1). For Mayalibit Bay, Kofiau and Boo Islands and Southeast Misool MPAs, fishing grounds for specific species were also identified (Table S1). GPS coordinates for mariculture sites were obtained directly from commercial operators, or from data collected during resource use monitoring. The main mariculture in Raja Ampat is pearl farming, which is foreign-owned but with a large percentage of employees hired locally from communities.

2.1.4. Threats data

Potential sediment plumes were identified by assuming that if any significant clearing had occurred, or is occurring within a catchment this would likely lead to a sediment plume at the river mouth. To identify areas of significant clearing expert mapping data was used on the location of mineral, and oil and gas mining, data on road development in south West Waigeo (CI unpublished data), and visual interpretation of a landsat image. Catchments were based on rivers using data from the Raja Ampat Atlas [35]. For any catchment with significant clearing a 2 km radius plume from the river outlet was mapped based on advice from a local expert on the typical extent of sediment plumes.

2.2. Analysis

For each zoning analysis 'Marxan with zones' spatial planning software was used. Marxan with Zones allows the user to identify solutions for the location of multiple and different types of zones simultaneously that minimize the cost of the entire system subject to the constraints that zone-specific targets are achieved [11]. The software uses an algorithm, simulated annealing, to identify zoning configurations. This algorithm has a randomization component and therefore usually generates a different solution during each run. Marxan with Zones was run to produce 100 solutions that attempt to satisfy the objectives and constraints of each scenario. The results of the 100 runs are typically presented as either the best solution across these runs, and the "selection frequency", which represents the frequency a particular planning unit was selected for a zone across the 100 runs. Some areas were not allocated to a zone and these areas were identified as a third zone called 'unallocated'. A new method of classifying a planning unit on the frequency it was selected for each zone was developed. The classification was the following: 'mostly unallocated' (selection frequency = 80–100% for unallocated zone), 'most frequently no-take' (selection frequency = 80–100% for no-take zone), 'frequently no-take' (selection frequency = 60–79% for no-take zone), 'most frequently sustainable fishing' (selection frequency = 80–100% for sustainable fishing zone), 'frequently sustainable fishing' (selection frequency = 60–79% for sustainable fishing zone) and 'flexible' (the rest of the planning units selected).

The details of how targets were set are in Grantham and Possingham [36]. A target of 30% was used for each habitat type across the MPA network, as it is specified in the design criteria developed for the Raja Ampat MPA network (TNC unpublished data). All areas important for species life history stages and specific important locations had a 75% target given their importance for species persistence and their small distributions. Known functional reef fish spawning aggregations were given a target of 100% due to their rarity and importance [34]. For areas with inactive coral reef fish spawning a 50% target was used. For most species distributions a target of 30% was used as the data source was participatory expert mapping which made them less reliable observations due to likely errors in mapping compared to field observations. The exceptions to this were crocodiles, white dolphin, sharks and the dugong hotspots, which had a 50% target due their importance in the region. A 75% target was used for each community fishing ground to be represented in the sustainable fishing zone to ensure that communities would have access to their primary fishing grounds by including a substantial proportion of each fishing ground in the fishing zone.

A cost layer was developed for each zone (except for the planning units designated as 'unallocated') that considered the relative socio-economic costs of implementing that zone in each planning unit. This determines the relative preference for where targets should be achieved. For example, all else being equal, Marxan with Zones will try to avoid placing any planning unit in the higher cost zone. Each planning unit has a cost for being assigned to each of the zones. All values in each planning unit was standardized first for each cost feature by dividing the value in the planning unit by the total across all planning units for each feature of interest (e.g. reef condition, distance to community). This ensures the relative abundance or intensity of each feature is maintained. This was done for both continuous values and for presence/absence of a feature. The cost of placing a planning unit in a no-take zone, Cnt, is

$$\text{Cnt} = r + m + f + c + s + 100 \quad (1)$$

where r is a measure of reef condition, m is the occurrence of mariculture (seaweed farming + pearl farming/2), f is the occurrence of fishing structures (FADs + fishing cages + fishing shelters + sero traps/4), c is a measure of the cost of a site in terms of its use for community fishing grounds (sum of all fishing grounds/127 (which is the number of total fishing grounds)) and s is the occurrence of a sediment plume.

The sustainable fishing zone cost value for each planning unit was the distance from that planning unit to the nearest community with planning units closer to a community cheaper than those further away. This was chosen because fishing grounds closer to communities are easier for that community to access. The cost of placing a planning unit in the sustainable fishing zone, Csf, is

$$\text{Csf} = d \quad (2)$$

where d is the distance to the nearest community.

Planning units are discrete areas used as potential candidate areas for a no-take or sustainable fishing zone. In addition to achieving targets and minimizing the total cost, Marxan with Zones also tries to cluster planning units assigned to the same zone for ease of practical implementation. To do this, the user indicates the relative importance reducing fragmentation by minimizing the boundary of the selected areas within a zone relative to their planning unit cost by adjusting a parameter called the zone boundary cost. This was explored by varying the weighting to determine an appropriate value that ensured solutions were clustered.

To explore trade-offs between no-take zone and sustainable fishing zone targets, a weighting value is specified for each target for each zone to control its importance relative to other targets. When a solution cannot be found that achieves all targets, this weighting will determine which targets are more important. This weighting was varied until all the sustainable fishing zone targets were achieved in preference to the no-take zone targets given this will result in a solution that local communities are more likely to implement.

The study area includes 11,480 planning units in total: 1119 in Ayau-Asia, 3416 in Dampier Straits, 1816 in Kofiau and Boo Islands, 3786 in Southeast Misool, 677 in Mayalibit Bay and 665 in West Waigeo MPA. The planning units were mostly marine areas but also included some areas on land that contain mangroves and turtle nesting beaches. The distribution/abundance of each feature and each cost layer measured for each planning unit.

Two areas were already zoned and thus were assigned to a pre-determined status. The first was the entire Sayang-Wayag MPA where there is already an agreement with the custodians of this region for the entire MPA to be a special no-take zone. The other area is a no-take zone already implemented in Southeast Misool MPA, where there is a 25-year marine conservation agreement with custodians of the area and Misool Ecoresort. There are other areas that are being negotiated with communities for zoning and others types of existing management (e.g. *sasi* areas which are temporal closures, usually for invertebrates) but were not included in the analysis as the information was not available at the time of this study and it was not known the extent to which they were enforced.

2.3. Comparison of scenarios

A number of scenarios were run to reflect different zoning analysis (Table 1). Scenario one was the baseline scenario that identified locations for both the no-take and the sustainable fishing zones. This was compared to scenario two, which only identified areas only for the no-take zone to investigate what happens when areas are not also selected for the sustainable fishing zone and how this affects access to community fishing grounds. If a large proportion of a community fishing grounds is selected for the no-take zone, this would reduce access for that community. The impact of the two scenarios on each community fishing ground was measured by calculating the proportion selected as no-take based on the "best solution" for each scenario. The "selection frequency", between these scenarios was also compared. This was because the selection frequency is often used to guide spatial planning as it enables a consideration of several options for planning. To compare selection frequencies a spearman rank correlation coefficient was applied to compare the relative ranks of selection frequencies for each planning unit and tested the significance of correlations with randomization.

The second comparison was between scenarios one and three (Table 1). Scenario one was the baseline and scenario three was similar to this, except for how Southeast Misool MPA was treated. At that site for this scenario, fishing grounds in the sustainable fishing zone were defined only based on each fisheries species and did not include information on which community fished there. Targets were set to include 75% of each fishery extent into the sustainable fishing zone (e.g. 75% of where grouper are caught). This was to measure the impact on each community's access to fisheries of the areas identified for the no-take zone in the analysis when information on each community is not included. To compare these two scenarios the amount of each community fishing ground (as defined in scenario one) was measured in Southeast Misool MPA inside the sustainable fishing zone "best solution".

The final comparison was between scenario ones and four (Table 1). For scenario four a new approach to identify potential zoning configurations is introduced that integrates information from an expert derived zoning proposal. This proposal was generated by asking practitioners at a workshop to identify areas where they thought no-take zones would be most appropriate based on their knowledge of zoning issues and through working with communities likely to be impacted by the design of the zoning plan. Workshop participants included some government representatives and non-governmental organizations. At the workshop the results from initial Marxan with Zones analyses was showed to participants, and it was asked for them to modify the results given their knowledge of the area and an understanding of the needs of local communities. For the expert derived no-take proposal the representation of each ecosystem and amount of each community fishing ground inside the no-take zone proposal was measured. The expert derived zoning proposal was then used as a target for the no-take zone, varying the target between 0% and 100%. A target of zero was the same as scenario one (i.e. ignored the proposal), a target of 100% meant that all of the expert proposed no-take areas had to be included in the no-take zone. Targeting different proportions of the expert derived

Table 1
Four scenarios compared in this study.

	Zones	Features used to guide selection
Scenario 1	No-take	Ecosystems and species
	Sustainable fishing	Community fishing grounds and catch species (where possible)
Scenario 2	No-take	Ecosystems and species
Scenario 3	No-take	Ecosystems and species
	Sustainable fishing	Community fishing grounds (except Southeast Misool MPA) and catch species (where possible)
Scenario 4	No-take	Ecosystems, species and no-take zone proposal
	Sustainable fishing	Community fishing grounds and catch species (where possible)

zoning proposal in the zoning analysis was explored in two ways. First the proportion of the no-take zone cost metric that was inside the best solution for the no-take zone was measured. Then the number of community fishing grounds that did not achieve their target was measured.

3. Results

Scenario one was the baseline scenario (Table 1). For this scenario it was possible to find zoning configurations that achieved nearly all targets for both the sustainable fishing and no-take zones. For example, for the best solution (Fig. 2i), it was found this scenario meets all but three biodiversity (Fig. 3a) and three sustainable fishing zone targets (Fig. 3b). The failure to meet three biodiversity targets is a result of the high penalties assigned when fishing ground targets are not met. The failure to meet sustainable fishing zone targets despite the high penalties assigned for not meeting the targets is a result of a high overlap in the location of some sustainable fishing ground with the location of Misool Eco Resort marine conservation agreement area (no-take area); this overlap made the targets unachievable.

Scenario one (baseline) and two (identified locations for no-take zone only) were compared by measuring the proportion of each community fishing ground in the no-take zone using the best solutions for each scenario (results shown in Fig. 2ii). For scenario one it was found that four community fishing grounds had over 25% of their fishing grounds selected as no-take zones (Fig. 4). In comparison, for scenario two, 33 out of 127 community fishing grounds had over 25% of their fishing ground selected as no-take zones (Fig. 4). This included one community fishing ground in Southeast Misool MPA with 100% of its grounds in the no-take zone. The spatial correlation of priorities between the scenarios was compared by measuring the percentage difference in the selection frequencies (Fig. 5i–iii). The differences were generally small and major differences were predominantly found in the northeast of West Waigeo MPA, western part of Dampier Straits MPA, western part of Kofiau and Boo Islands MPA and various spatially confined locations throughout Southeast Misool MPA. The selection frequencies of no-take zones were found to be significantly correlated ($rho = 0.842$, $p < 0.001$) between scenarios one and two.

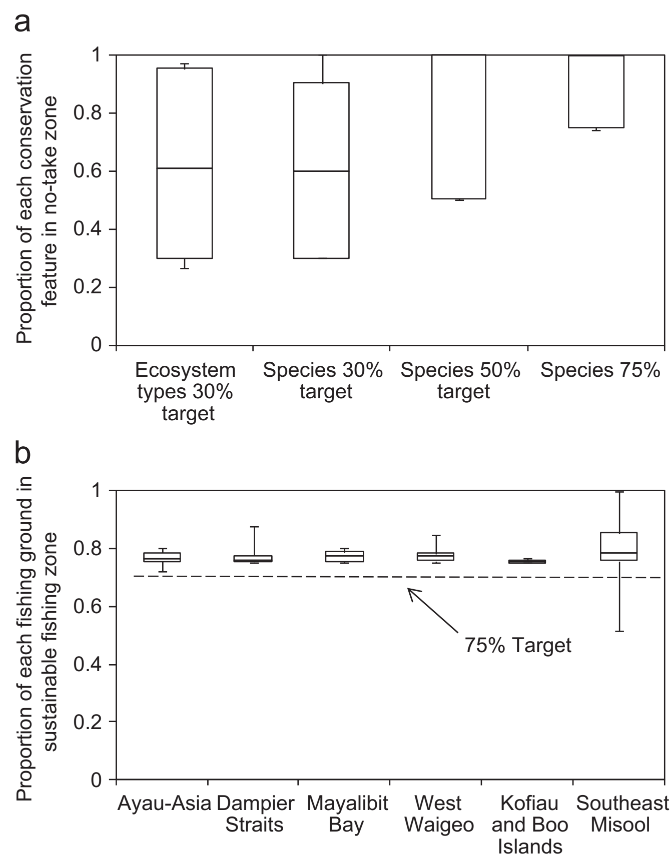

Fig. 3. The proportion of features selected for each zone for scenario one, (a) ecosystems and species, and (b) community fishing grounds.

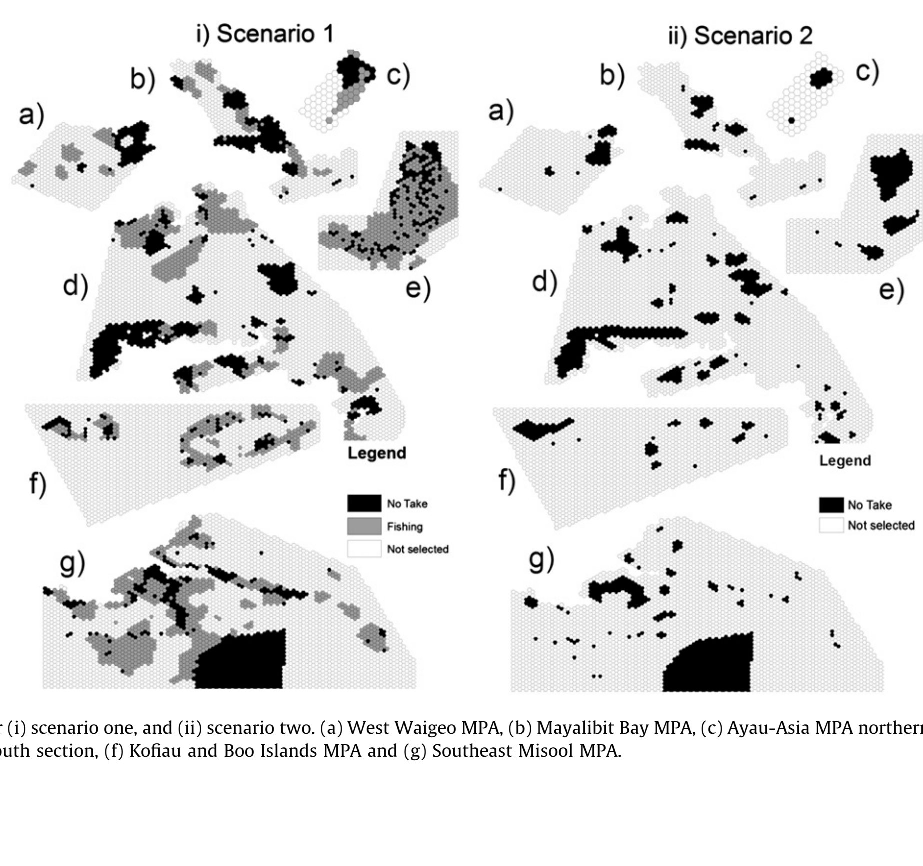

Fig. 2. The best solution for (i) scenario one, and (ii) scenario two. (a) West Waigeo MPA, (b) Mayalibit Bay MPA, (c) Ayau-Asia MPA northern section, (d), Dampier Straits MPA, (e) Ayau-Asia MPA south section, (f) Kofiau and Boo Islands MPA and (g) Southeast Misool MPA.

Results from scenario one (baseline) and three (Southeast Misool MPA fishing grounds defined only by species and not community) were compared, and there were differences in the proportion of each community fishing grounds contained in the sustainable fishing zone for the two scenarios (Fig. 6). For scenario one, all but 4 community fishing grounds had reached its target of 75% of their grounds in the sustainable fishing zone because targets were set for them. Those that had less were due to a significant overlap with Misool Eco Resort making the targets unachievable. For scenario three many community fishing grounds did not achieved their target. There were 18 community fishing grounds below the 75% target level, and the proportion of a communities fishing area for each species varied from 10% to 100%.

For the expert derived zoning proposal developed by workshop participants for the no-take zone (shown in Fig. 7i), ecosystems were unevenly represented, ranging from 0% to 100%, with most having around 20% of their distribution within the proposal (Fig. 8a). For the community fishing grounds, there was variability in the proportion within the proposal, with some community fishing grounds largely covered by no-take zones (Fig. 8b). There was variation between the MPAs.

Targeting different proportions of the expert derived no-take zone proposal in the zoning analysis influenced the results and the trade-offs were measured in two ways. The first was measuring the proportion of no-take zone cost metric selected by the best solution. The total cost of the best solution was unaffected by the proportion of expert derived no-take zone proposal included in the no-take zone proposal when that proportion is less than 40% (Fig. 9a). Once more than 40% of the expert derived no-take zone proposal must be in the result, the cost increases. The second method of measuring the trade-off was based on the number of community fishing grounds targets not met. There was little change in the measurement until 80% of the expert derived no-take zone proposal was targeted (Fig. 9b). The results of this

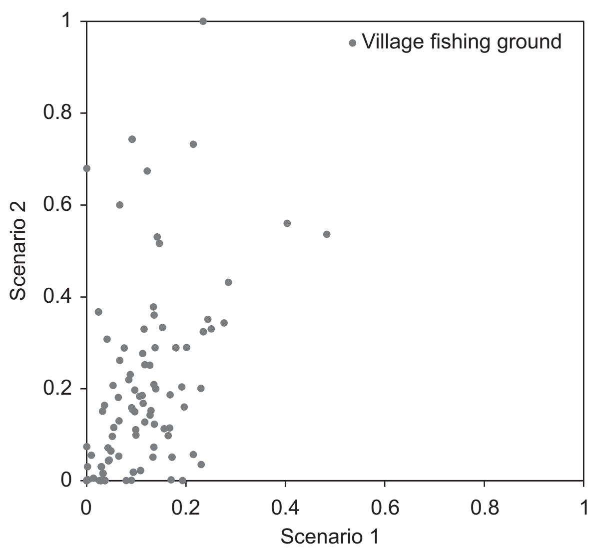

Fig. 4. Proportion of fishing ground in the no-take zone comparing scenarios one and two. Hashed line represents the maximum proportion a fishing ground should be in the no-take zone to ensure sustainable fishing zone targets could be achieved.

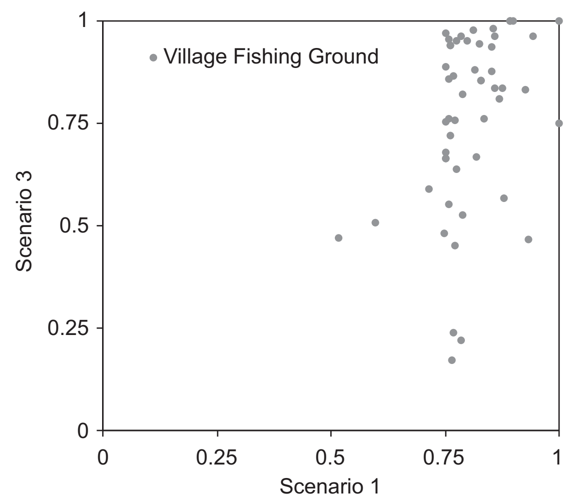

Fig. 6. Proportion of each community fishing grounds in the sustainable fishing zone for each fishing grounds in Southeast Misool MPA comparing scenarios one and three.

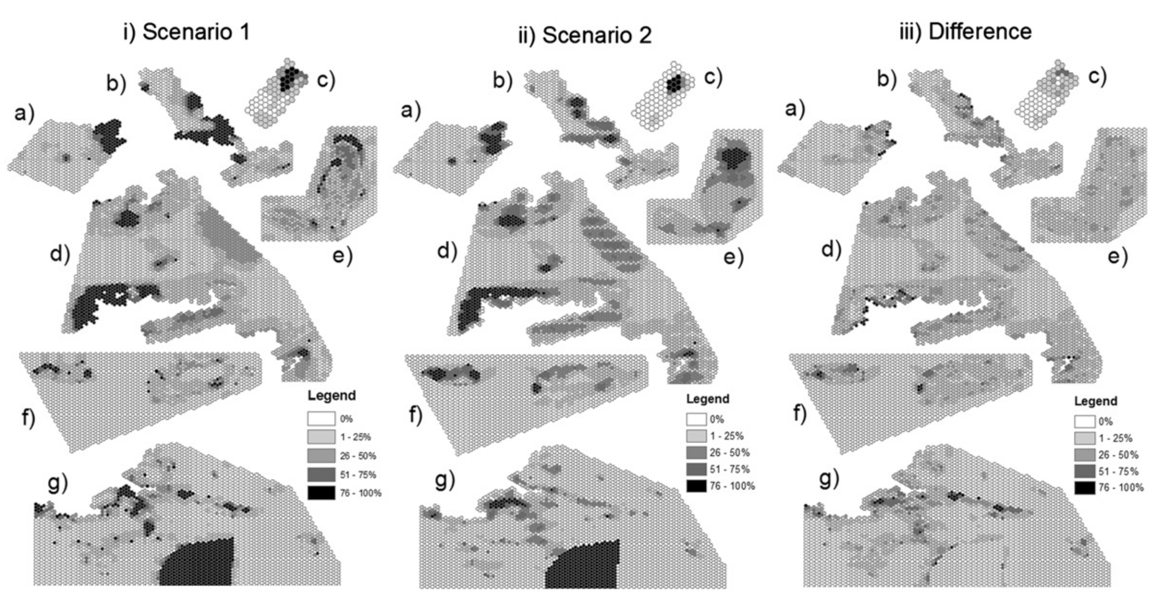

Fig. 5. Selection frequency for no-take zone for (i) scenario one, (ii) scenario two, and (iii) percentage difference for no-take zone selection frequencies between scenarios one and two. (a) West Waigeo MPA, (b) Mayalibit Bay MPA, (c) Ayau-Asia MPA northern section, (d), Dampier Straits MPA, (e) Ayau-Asia MPA south section, (f) Kofiau and Book Islands MPA and (g) Southeast Misool MPA.

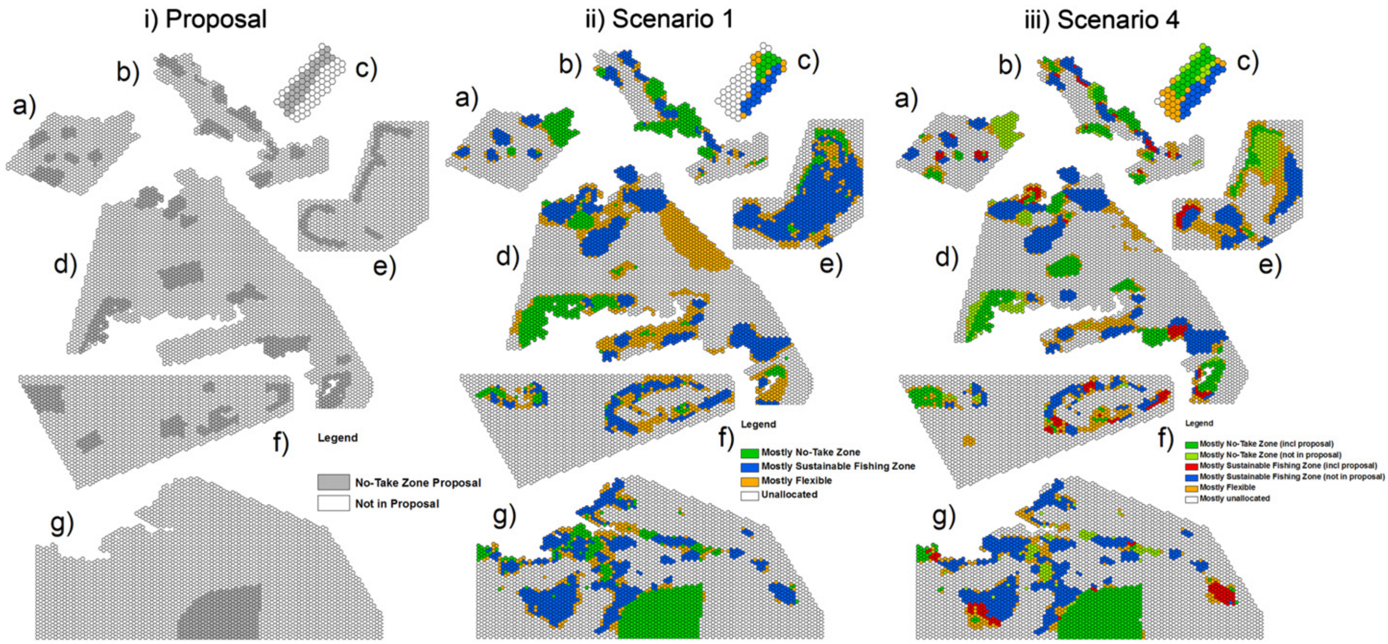

Fig. 7. Comparing scenarios one and four. (i) Expert derived no-take zone proposal resulting from participants at a workshop. (ii) and (iii) show classified solutions for scenarios one and four. The selection frequency was used to classify each planning unit into 'mostly no-take' (selection frequency=60–100% for no-take zone), 'mostly sustainable fishing' (selection frequency=60–100% for sustainable fishing zone), 'mostly unallocated' (selection frequency=60–100% for unallocated zone), and 'flexible' (the rest of the planning units selected). (a) West Waigeo MPA, (b) Mayalibit Bay MPA, (c) Ayau-Asia MPA northern section, (d), Dampier Straits MPA, (e) Ayau-Asia MPA south section, (f) Kofiau and Boo Islands MPA and (g) Southeast Misool MPA.

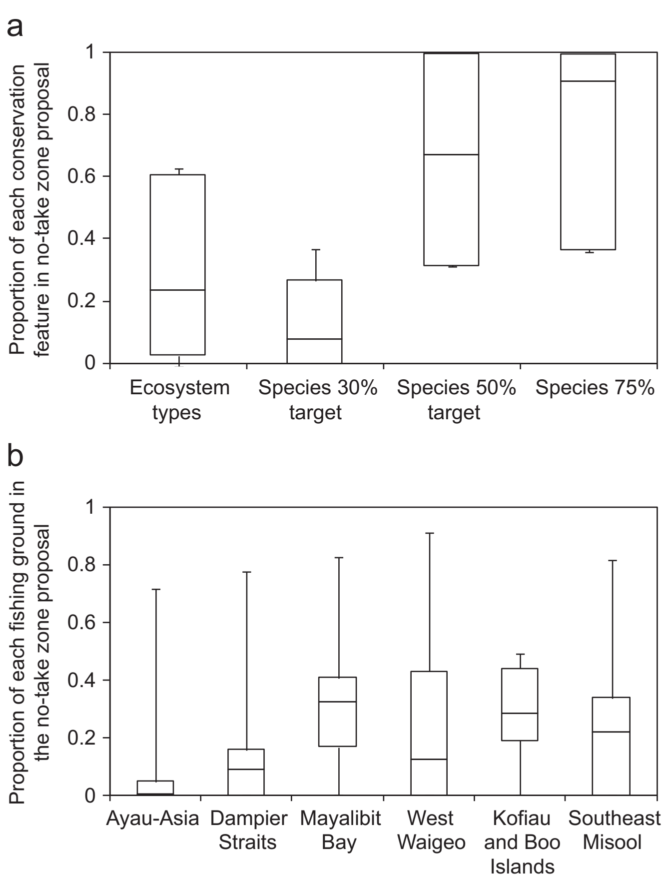

Fig. 8. The proportion of each feature with a no-take zone proposal in scenario four showing (a) ecosystems and species, and (b) community fishing grounds. The boxplot shows the range, upper and lower quartiles and median values.

scenario with a 60% target of the expert derived no-take zone proposal were compared with scenario one, based on classifying each planning on how frequently it was selected for either zone (Fig. 7iii). It was found that there were some differences between the two scenarios spatially.

4. Discussion

The ability to balance access to fisheries, biodiversity conservation and other human demands is important in many regions globally. A major advance in providing support to multi-objective MPA zoning is the ability to satisfy the interests of multiple stakeholders [11]. This study shows that Marxan with Zones can be a powerful decision support tool to help with this process. This type of analysis is especially important for planning in Raja Ampat as zoning needs to ensure that all of the numerous communities have access to marine resources for subsistence within their traditional marine tenure systems [29,37,38].

This study focused on two types of objectives: biodiversity (representation of ecosystems and protection of species of conservation concern) and fisheries (sustainability and access to fisheries). Despite the competing uses that conservation and fishing activities represent, zoning configurations that achieved nearly all the targets considered were found. The occasional inability to achieve all objectives was mainly a result of conflict between different objectives, as well as the need to include past decisions (for example, established areas such as the Misool Eco Resort).

Locations important for conservation zones are often planned without simultaneously planning for other types of zones and considering trade-offs that between alternative management scenarios. Taking this route can lead to inequitable impact for particular communities (25% in this case) as demonstrated by

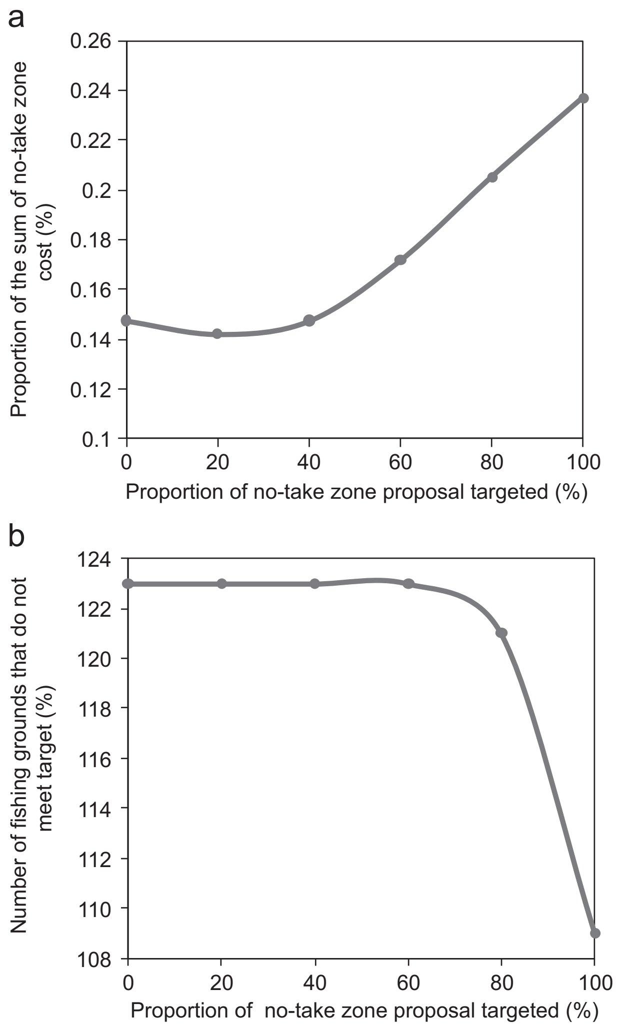

Fig. 9. The trade-offs when increasing the amount of the expert derived no-take zone proposal as a target for the no-take zone. Different percentages of the expert derived proposal were targeted to be included in the no-take zone ranging from 0% (none of it targeted) to 100% (all of it targeted). Measuring (a) proportion of no-take zone cost metric, and (b) number of community fishing grounds that did not reach their target.

scenario two. A similar finding was made by Weeks et al. [16] and Klein [12] but for the boundaries of MPAs rather than zone boundaries within an MPA network. In addition, when solely focusing on distribution of catch species and not community fishing grounds, this also generated inequitable impacts on communities (scenario 3). These results point to the importance of setting targets to represent stakeholders' needs in multi-objective zoning. Too often targets are solely based on ecological data, potentially leading to inequitable impacts on communities and low support for the MPA and compliance with its regulations.

A limitation of any zoning approach is the existence of relatively even data to comprehensively represent each planning objective. If one competing objective or region (e.g. an MPA) has more comprehensive data than another, it might skew the identification of zones. To try and overcome this issue participatory expert mapping was needed to fill in key knowledge gaps. The experts interviewed were a combination of staff from organizations working in the region, community groups and government representatives. This method was used to help map ecosystems, specific locations important for species, and to improve the knowledge of the locations where communities fish. This was a rapid and cost-effective method of developing spatial data. There are however, likely prejudice toward particular types of information and spatial biases in participants knowledge [39] and where possible these were crossed checked with field observations.

This analysis could be improved with more data on biodiversity. Seagrass and mangroves distributions were fairly coarsely mapped and could be improved through remote sensing and field sampling techniques [40]. It would also be useful to classify both of these ecosystems into different types based on differences in their species composition, so the variation could be captured in planning no-take zones. Many ecosystems were not mapped due to time constraints and further mapping could focus on other types of ecosystems such as offshore benthic habitat mapping and identification of pelagic ecosystems [41] that might allow for taking a stronger ecosystem approach to management.

The fishing information also presented some limitations. Attributes were not identified like which areas within the fishing grounds were the most productive or otherwise important to the community, which reefs were currently being fished versus those that were historically used, grounds specific to reef versus those specific to non-reef fisheries, which species were more important compared to others. These issues should all be considered for future planning efforts. In addition, there are a number of ways the fishing target could have been developed. A fixed level of 75% target was chosen for each fishing ground. For example, the target could be adjusted depending on the size and importance of the ground or through specific negotiations with the community.

Social, economic and political factors will have a very large influence on where no-take zones can be implemented. This influence is loosely represented through the data on fisheries examined, a major consideration for the MPA zoning process. To improve this, a novel method of incorporating an expert derived no-take zoning proposal into the analysis was included that was developed with people who are working with communities in developing the zoning plan (scenario four). This allowed indirectly incorporate social, economic and political considerations. The expert driven proposal represents a more feasible solution based on knowledge of these communities but it still had biases in their knowledge about the region. According to the data, the proposal would unfairly impact some communities more than others and it did not evenly represent all the ecosystem types assuming the conservation of ecosystems is an important objective for the MPA network. The results from scenario four can be used as a method of integrating local knowledge with a systematic zoning analysis.

A major objective of MPA network was ensuring zoning contributed toward sustainable fisheries. What makes a sustainable fishery is a complex matter [42,43] and representing this in a systematic planning platform difficult. The approach to dealing with fisheries in this study was static and quite simple. Targets for different types of coral reefs and fishing grounds were included. There is evidence to suggest closures can improve fisheries due to the increased probability of increasing fish abundance and catch [44] and protection of a proportion of each ecosystem can increase fisheries catch outside of those areas [45]. More sophisticated approaches to determining the costs and benefits of zoning for sustainable fisheries and fishery access are needed for small-scale fisheries and MPA zoning, although transparency and ability to implement in tropical countries should be considered. These approaches are likely to require a lot more data (e.g. spatial fish and fisheries dynamics), which might not be readily available in many tropical countries. Other less data intensive approaches could include ensuring key species and interactions within the ecosystem are included within a no-take zone [46], further protection of key life history stages areas of fisheries species (e.g. spawning and nursery grounds), and addressing trophic "gate keepers" such as small pelagic fish [47–49].

A visual representation of zoning solutions from the analyses in this study is a powerful tool to help the decision makers decide on zoning configurations. There are a number of spatial representations produced in this project that can be used to facilitate those discussions. For example, the maps that present the frequency a particular planning unit selected for a specific zone (e.g. Fig. 5i and ii) illustrate the best options for achieving targets while also considering other objectives for both zones. The areas identified in these maps could be used to guide future location of final zones, with the areas that are most frequently selected to be included in a particular zone type likely to be critical areas. The map showing which zone was most frequently selected is also useful as it summarizes the whole analysis for a scenario on a single map and makes it visually easier to interpret e.g. (Fig 7ii and iii). The maps that present a single solution are the probably the least useful because they only show one configuration of zones out of potentially many (e.g. Fig. 2). They do, however, indicate what a solution that achieves most of the targets looks like. Finally the map that incorporates the original expert derived zoning proposal is very useful as it shows within the proposal which areas have agreement for the zone in the proposal, which areas do not and finally, other areas to consider for that zone e.g. (Fig. 7iii).

Identifying the most socially-acceptable locations particularly for no-take zones is a difficult process. The analysis presented here can help inform potential locations and is part of a much wider process that includes extensive community consultation. The results from this study have provided scenarios and options to government, NGO and communities, working towards developing zoning plans for a network of MPAs within the Raja Ampat Regency.

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Appendix A. Supplementary information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.marpol.2012.05.035.

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