PRACTITIONER'S PERSPECTIVE

Using reef fish movement to inform marine reserve design

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Introduction

A central tenet of protected area design is that conservation areas must be adequate to ensure the persistence of the features that they aim to conserve. These features might include species, populations, communities and/or environmental processes. Protected area adequacy entails both good design (e.g. size, configuration, replication) and management effectiveness (e.g. level of protection, compliance with regulations). With respect to design, guidelines recommend that protected area size be informed by species' home ranges, as individuals that move beyond protected area boundaries are exposed to threats and are thus only partially protected (Kramer & Chapman 1999). This is especially important for species that are directly exploited, as are many coral reef-associated fishes.

Information on movement patterns of coral reef fishes has only recently been summarized in the literature, along with guidelines on how this information might be used to inform the adequate design of marine protected areas (MPAs; Green *et al.* 2015). Here, we demonstrate, using an example from Micronesia, how these guidelines can be adapted and applied within a particular socio-ecological context to guide discussions with stakeholders aimed at improving the efficacy of an existing protected area network. We discuss aspects of this process that were successful and those that were challenging, and in so doing, identify areas where future ecological research effort might benefit protected area planning and design.

Guidelines for marine protected area adequacy

To achieve objectives for biodiversity conservation and/or fisheries management, MPAs must be able to sustain focal species within their boundaries throughout their juvenile and adult life-history phases, when they are most vulnerable to fishing. Thus, MPA size should be informed by focal species' home ranges (Kramer & Chapman 1999). This information can be obtained through a variety of empirical methods, including acoustic telemetry, tag–mark–recapture, satellite tracking or underwater observations (Green *et al.* 2015). However, poor availability of information on home range movements of key species has meant that practitioners have relied upon generic rules of thumb for MPA size (Moffitt, White & Botsford 2011). Despite evidence that small (e.g. <1 km^2) MPAs can be effective in increasing biomass of some targeted species (Russ *et al.* 2004), and that moderately sized MPAs might produce greater fisheries benefits (Gaines *et al.* 2010), conservation practitioners have broadly adopted a precautionary mantra that 'bigger is better' (e.g. McLeod *et al.* 2009). This is supported by theory, which contends that larger MPAs allow for more individuals of more species to spend a greater proportion of their time within MPA boundaries (Sale *et al.* 2005), and by empirical evidence, for example from a meta-analysis of European marine reserves, which found that population density of targeted species within reserves increased with reserve size (Claudet *et al.* 2008). Nevertheless, advocating for MPAs to be made as large as possible is problematic: increasing MPA size incurs socio-economic trade-offs, decision-makers can be prone to political expediency, and open-ended targets are more likely to be compromised (Devillers *et al.* 2014).

A recent review (Green *et al.* 2015) compiled hitherto inaccessible information on adult and juvenile movement patterns of coral reef fishes. Empirical measurements of reef fish movement demonstrated substantial interspecific variation in home range size: some species, such as damselfishes and butterflyfishes, move only hundreds of metres; others, including some groupers, emperors, snappers and jacks, move tens to hundreds of kilometres (Green *et al.* 2015).

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Green *et al.* (2015) recommend that marine reserves be at least twice the size of the home range of the species they aim to protect, in all directions. This will ensure that each reserve includes the entire home range of at least one individual, and likely many more where home ranges overlap (Green *et al.* 2015). Species whose home ranges cannot be encompassed within reserves will require complementary management strategies, such as size limits, catch, effort or gear restrictions. Wide-ranging species can however benefit from reserves placed in specific locations where individuals are particularly vulnerable to fishing mortality, such as spawning aggregation sites (Waldie *et al.* 2016). More generally, MPAs should be located to include the habitats utilized by focal species, and to allow for movements between them.

Context for marine protected area design in Pohnpei

Pohnpei is one of four semi-autonomous states within the Federated States of Micronesia (FSM). The state is comprised of a main island (hereafter, Pohnpei) and eight surrounding atolls distributed across c. 400 000 km^2 of the central Pacific Ocean. Approximately 96% of the state's 36 000 residents live on Pohnpei.

Pohnpei is surrounded by a well-developed barrier reef and associated lagoon, with patch reefs, seagrass beds and mangrove habitats. Household surveys indicated that 63% of households had at least one member engaged in subsistence fishing for consumption or local sale, with most fishing inside the lagoon (Hopkins & Rhodes 2010). This effort is additional to the estimated 500 MT year^{-1} of reef fish extracted by the commercial fishery (Rhodes, Tupper & Wichilmel 2008). High local demand for reef resources, relatively small reef area and high population density have led to unsustainable fishing practices (Rhodes & Tupper 2007). Further threats to nearshore habitats come from sedimentation, pollution, coral mining, dredging, deforestation and mangrove loss (Rhodes, Tupper & Wichilmel 2008).

Pohnpei is a signatory to the Micronesia Challenge, which seeks to '…effectively conserve at least 30% of the nearshore marine resources and 20% of the terrestrial resources across Micronesia by 2020' (www.micronesiachallenge.org), and includes a goal to create science-based, resilient, protected area networks. Pohnpei has 18 existing no-take MPAs on the main island and nearby Ant Atoll, with a further two proposed but yet to be formally designated. Additional fisheries management includes a seasonal sales ban on grouper species during the months of March and April (spawning season), a complete ban on the sale of bumphead parrotfish *Bolbometopon muricatum* and size restrictions in place for some species.

Pohnpei currently achieves the Micronesia Challenge targets, with 30% of marine and 25% of terrestrial habitats within the protected area network. However, marine protection is strongly biased towards the outer atolls, with only 6% of reef habitats and 5% of seagrass beds around the main island of Pohnpei within MPAs. Of further concern is the likely inadequacy of existing MPAs, attributable to both poor design (most are very small) and variable management effectiveness. At present, 25% of MPAs are smaller than 1 km^2, and 70% are smaller than 5 km^2. Though customary marine tenure and management is practised on the outer atolls, marine resources surrounding the main island are open access. State enforcement capacity is poor, and compliance with regulations is variable. In a few MPAs, there is good support for management from traditional leaders and the community, rules are locally enforced, and violations prosecuted; elsewhere, poaching is common and laws are openly disregarded (Rhodes *et al.* 2011).

Poor local support for some MPAs has been attributed to the failure of previous planning processes to incorporate local objectives for natural resource management (E. Joseph, pers. obs.); these instead focussed on biodiversity conservation objectives and achievement of international targets for such (e.g. the CBD Targets and the Micronesia Challenge). In 2014, The Nature Conservancy and the Conservation Society of Pohnpei (CSP) initiated a statewide reassessment of Pohnpei's protected area network with the aim of increasing local ownership and effectiveness in achieving both conservation and local, primarily fisheries management, objectives. This provided an opportunity to use newly accessible information on reef fish movement patterns to assess and improve the adequacy of existing MPAs.

Implementation of guidelines

The protocol we applied (adapted from Green *et al.* 2015) was as follows: (1) identify focal species for protection; (2) identify home range sizes, relevant habitats and minimum recommended MPA sizes for those species; (3) determine whether focal species are likely to be adequately protected within existing MPAs; and (4) refine MPA design or identify alternative management tools to protect species as required. This process was undertaken through two protected area network planning workshops 1 year apart (stages 1 and 4, respectively), with analyses (stages 2 and 3) undertaken by the authors in the intervening period.

Both workshops were facilitated by the authors and staff from CSP and were conducted as a series of short presentations, plenary discussions and semi-structured activities in breakout groups, focusing on both marine and terrestrial conservation areas. The first workshop was attended by nine community representatives, including traditional leaders, community conservation officers and members of Pohnpei's Marine Advisory Council (which provides recommendations to community leaders on ecologically and culturally appropriate management

innovations); eight representatives from Pohnpei State and FSM government agencies; and fourteen representatives from five NGOs based in Pohnpei and Micronesia. Stakeholders attending the second workshop included twelve community representatives, eight government and nine NGO representatives.

Focal species (Table 1) were identified by stakeholders at the first workshop held in June 2014. These include species of importance to local fisheries (groupers, rabbitfish, parrotfish, surgeonfish, snapper and trevally) and those with cultural and conservation importance (humphead wrasse and bumphead parrotfish).

Table 1. Focal fish species of interest in Pohnpei, and recommended minimum marine protected area (MPA) sizes to protect them, modified from Green *et al.* (2015)

Scientific name	English name (Pohnpeian Name)	Movement*,†	Recommended minimum MPA size*,‡
Naso unicornis	Bluespine unicornfish (pwilak)	Home ranges in Micronesia are <0·3 miles	0·6 miles
Naso lituratus	Orangespine unicornfish (pwulangkin)	Home ranges in Micronesia and Hawaii are <1·3 miles	2·6 miles
Caranx melampygus	Bluefin trevally (arong)	Home ranges in Hawaii <3·3 miles. Long-term movements may be up to 62 miles	6·6 miles. MPAs will need to be combined with other fisheries management measures to protect this species when they move outside MPAs
Plectropomus areolatus	Squaretail coralgrouper (ewen sawi)	Home ranges of adults in Pohnpei <0·6 miles. Spawning migrations are <30 km	1·2 miles. MPAs will need to be combined with other fisheries management measures to protect this species during the spawning season, for example seasonal closures
Cephalopholis argus	Peacock hind (mwoalusulus)	Home ranges in the Red Sea (only data available) <0·03 miles. Larger maximum home ranges recorded in this family	0·12 miles
Cheilinus undulatus	Humphead wrasse (merer)	Adult home ranges in Micronesia range between 1·2 and 6·2 miles	12 miles
Lutjanus gibbus	Humpback red snapper (pwahlahl)	No data are currently available. The closest proxy to use may be *L. rivulatus*, where mean long-term movement = 0·6 miles; maximum = 90 miles	3·7 miles (likely to encompass home range for most individuals)
Bolbometopon muricatum	Bumphead parrotfish (kemeik)	Mean home range in Solomon Islands <1·5 miles (range up to 4·7 miles)	9·4 miles
Hipposcarus longiceps	Pacific long-nose parrotfish (mwomw mei)	No data are currently available. The closest proxy to use may be *S. ghobban,* where home ranges are <1·2 miles; long-term movements <3·7 miles	2·4 miles. MPAs will need to be combined with other fisheries management measures to protect this species when they move outside MPAs
Siganus doliatus	Barred spinefoot (pwoarin mwomw)	Mean home range in Australia = 0·11 mile, maximum = 1·0 mile. Local knowledge suggests that this species has a restricted home range in Pohnpei. Spawning migrations are >2 km (Fox, Bellwood & Jennions 2015)	0·25 miles. MPAs will need to be combined with other fisheries management measures to protect this species during the spawning season, for example seasonal closures
Siganus punctatus	Gold-spotted rabbitfish (palapal)	No data are currently available. Until this data becomes available, home ranges for *Siganus* species (*S. lineatus, S. doliatus, S. fuscescens*) range between 0·11 and 1·24 miles	2 miles

*Linear distance in miles.
†Data from Green *et al.* (2015); where data were available from multiple sources, we preferentially used those from Micronesia or proximate regions.
‡Based on two times home range movement of species.

Movement information was sourced from the supplementary data provided in Green *et al.* (2015). Data were not available for all focal species, however. For species with no home range data available, values were substituted with those for species within the same family, of similar size, with similar behaviour (e.g. schooling), and that are found in the same part of the world (Table 1). For example, for *Hipposcarus longiceps*, we substituted movement information from another scarid of similar size with roving behaviour: *Scarus ghobban*. Additionally, where observations of species' home ranges varied substantially across studies, values from studies undertaken in Micronesia or the Pacific were given precedence (Table 1).

The minimum recommended MPA size for each species was calculated as a linear distance equal to twice the home range of that species. Importantly, this minimum size applies to the habitats that focal species use, rather than total size of the MPA *per se* (Green *et al.* 2015). Habitat maps were compiled using data from the Millennium Coral Reef Mapping Project (Andréfouët *et al.* 2006) and seagrass surveys (McKenzie & Rasheed 2015). Habitats for all focal species were assumed to be shallow geomorphic reef classes and seagrass beds, excluding areas of deep lagoon; these habitat associations should be further refined where information on benthic cover is available. Given that data on the population status of individual species were unavailable, we assumed that a sufficiently large proportion of each meta-population would be protected if 30% of fish habitat was protected within MPAs (Gaines *et al.* 2010).

To identify the 'effective size' of existing MPAs in Pohnpei, we used the ArcGIS Minimum Bounding Geometry tool to calculate the shortest distance between any two vertices of the convex hull of a polygon containing the fish habitat within each MPA. Using this information, we categorized adequacy of protection for each species within each MPA as adequate (shortest distance >2 times species home range), marginal (shortest distance within the bounds of species home range estimates) or poor (shortest distance less than species home range) (Fig. 1). Data on the spatial distribution of fishing pressure were unavailable, but would have allowed us to consider estimates of partial protection afforded to individuals whose home ranges span MPA boundaries, refining these classes.

Rather than presenting this information in the first instance, we provided workshop participants with information on focal species' home ranges and the size of each MPA to perform the analyses themselves in breakout groups. A visual depiction of the effective size of each MPA relative to the home range movements of focal
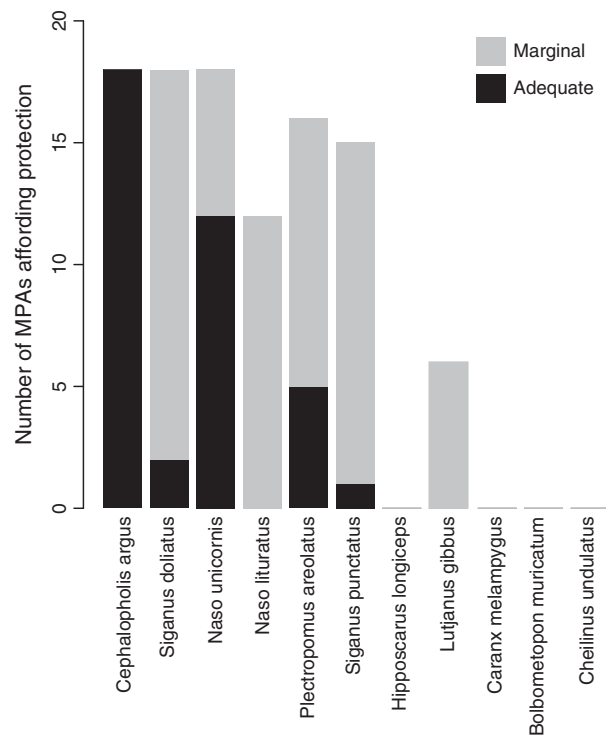

Fig. 1. Adequacy of existing marine protected areas (MPAs) in Pohnpei (*n* = 18) for key fish species. An MPA is considered adequate for a species if the shortest linear distance across the MPA is >2 times the species' home range; marginal protection is provided by MPAs with the shortest distance within the bounds of species home range estimates. Four species are not afforded protection within any of Pohnpei's existing MPAs.

species was later included on MPA-specific evaluation cards (Fig. 2), which also showed the habitat types included within each MPA and the distance to closest sea grass and mangrove habitats (a proxy for provision for ontogenetic movements between habitat types performed by some species).

These evaluation cards were used, in combination with information from management effectiveness assessments conducted at some sites, by participants at a second workshop in June 2015. Workshop participants were asked to form four breakout groups to discuss the design and management effectiveness of each of Pohnpei's MPAs. Each group used sticky notes to place each MPA along two axes ranging from poor to excellent (Fig. 3). A member of each group then presented back in plenary the rationale for their decisions. Dividing the summarized matrix into four quadrants indicated priority actions for different MPAs (Fig. 3). This exercise provided a structured focus for participant-led discussion, and allowed for stakeholder

Fig. 2. Example of an evaluation card used to facilitate discussions with stakeholders about adequate marine protected area (MPA) design. Habitat types labelled in black are present within the MPA, and those in grey are not. Distances to seagrass and mangrove habitats are included as a proxy for provision for fish species that perform ontogenetic migrations between habitats. The locations of the fish on the distance scale indicate the minimum MPA size required for that species, where an MPA is considered to provide adequate protection for a species if its shortest linear distance across is >2 times that species' home range; the dashed red box indicates the size of the focal MPA.
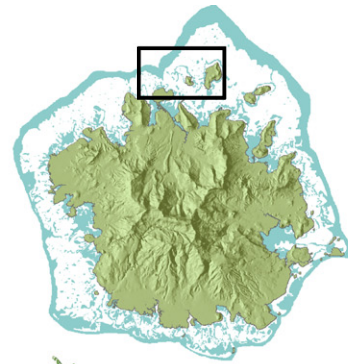
Sapwitik Marine Sanctuary

Reef Classes

- Bay exposed fringing reef
- Diffuse fringing reef
- Enclosed basin
- Forereef
- Pass
- Pinnacle
- Reef flat
- **Reticulated fringing reef**
- Shallow terrace
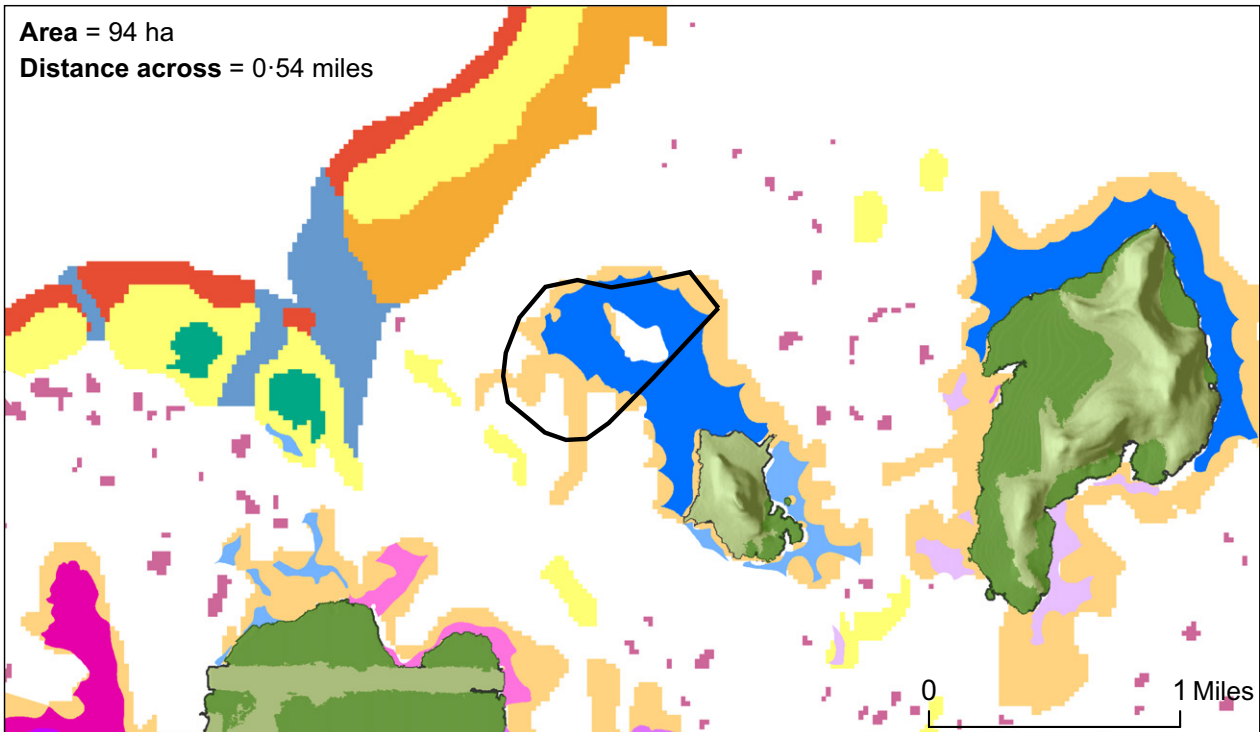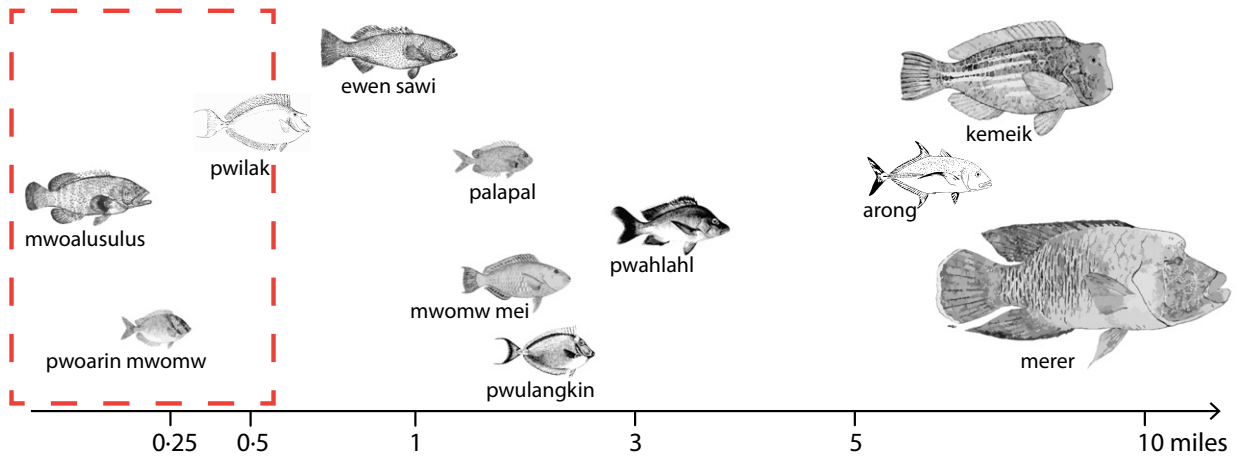
Sea grass Meadows

- C.rotundata (Continuous)
- C.rotundata (Aggregated)
- **T.hemprichii (Continuous)**
- T.hemprichii (Aggregated)
- T.hemprichii (Isolated)
- E.acoroides (Continuous)
- E.acoroides (Aggregated)
- E.acoroides (Isolated)

Distance to
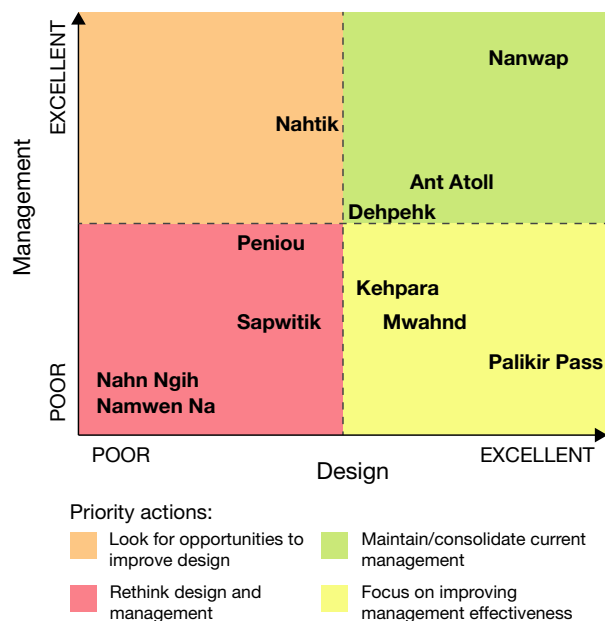seagrass = 0 miles

Distance to
mangroves = 0·65 miles

ewen sawi

pwilak

mwoalusulus

palapal

mwomw mei

pwahlahl

pwoarin mwomw

pwulangkin

kemeik

arong

merer

0·25   0·5   1   3   5   10 miles

Area = 94 ha
Distance across = 0·54 miles

0   1 Miles

Fig. 3. Workshop participants' ratings of marine protected area (MPA) design and management effectiveness can be used to inform priorities for adaptive management. MPA locations represent the midpoint from four breakout groups (three groups assessed Kehpara and Peniou, and one group assessed Ant Atoll). Note that the newly designated MPA, Palikir Pass, was considered to have excellent design but poor management, as at the time of the workshop the MPA had not been formally established and so did not have a management committee in place.

knowledge and experience to fill gaps in the management effectiveness data. The site-specific MPA evaluation cards have since been used to guide discussions with individual communities about how to improve the design of their MPA to provide adequate protection for focal species.

Successes

For adaptive management to be successful in the long term, meaningful engagement with community-level stakeholders and consensus on MPA design revisions will be required, and this takes time. However, early indications are that using reef fish movement information to inform stakeholder-led design of MPAs will lead to improved outcomes for conservation and fisheries management in Pohnpei.

The Palikir Pass marine sanctuary was formally designated in October 2015. At 12 km^2, it is the largest MPA on the reefs surrounding the main island of Pohnpei. The initial proposal for this MPA covered less than half of this area. Following discussions about MPA adequacy for focal fish species, the proposed boundaries of the MPA were changed to ensure that they encompass key habitat types utilized by many species, and a known grouper spawning aggregation (Rhodes *et al.* 2012). As the first MPA to be established following the planning process

described here, we are hopeful that this is indicative of a trend towards more adequate MPA design.

Stakeholder involvement is known to be a key element in engendering natural resource management success (Gutiérrez, Hilborn & Defeo 2011). In a 2011 survey of 647 households in Pohnpei, >97% of respondents stated that participation in management decision-making was very important and that they were more willing to assist in monitoring and enforcement when they had a role in developing management strategies (Rhodes *et al.* 2011). We found that grounding discussions in particular species and locations of interest better engaged key stakeholders in the planning process and facilitated the articulation of local objectives for the MPA network (E. Joseph & E. Terk, pers. obs.). These were absent in previous planning processes, which focussed solely on regional objectives for biodiversity conservation.

Workshop participants were better engaged during discussions about the adequacy of individual MPAs with which they were familiar, than the network as a whole. These discussions were facilitated by the availability of explicit, site-level criteria for protected area adequacy (c.f. network-level criteria, such as representativeness). When tasked with assessing the adequacy of Pohnpei's existing MPAs using information on the home range sizes of species they had identified as important, workshop participants all reported back that their MPAs were too small. This sparked discussion about how the MPA network might be redesigned far more effectively than presentations from conservation partners repeating generic 'bigger is better' guidelines. Evaluations of the design and management effectiveness of individual MPAs conducted by four breakout groups were remarkably concordant, with almost identical assessments for six MPAs, and minor disagreements for four.

Stakeholders were content for not all species to be protected within all MPAs. Though this might be desirable from a conservation perspective, workshop participants stated that the specific objectives for some MPAs were to protect *Cephalopholis argus* and *Siganus doliatus*, which have relatively small home ranges. Explicit objectives are considered an essential component of conservation planning (Margules & Pressey 2000), and focusing on locally important objectives has been recommended as an approach to create local ownership of plans (Gurney *et al.* 2015). In reality however, objective definition can be an abstract or intangible concept for local stakeholders, resulting in the predominance of broad-scale, conservation-oriented objectives in conservation plans. Here, focussing on the ecological requirements of a subset of locally important species facilitated the articulation of local objectives for the MPA network, and generated realistic expectations of what might be achieved for different focal species. Further, information on which species are likely to be afforded protection within specific MPAs can be used to refine ecological monitoring protocols.

Outstanding challenges to implementation

The realities of implementation often constrain practitioners' ability to implement scientific best practice (Pressey *et al.* 2013), and this is true in Pohnpei. Though stakeholders understood that most of Pohnpei's MPAs are presently too small to achieve local fisheries management objectives, the difficulty in altering the boundaries of MPAs that have already been legislated was identified as a major obstacle to adaptive management to improve their adequacy. This is in contrast to customary governance systems, present within other Micronesian jurisdictions (Rhodes *et al.* 2011), which can allow rapid changes to protected area rules or boundaries in response to new information (Weeks & Jupiter 2013).

With increased support from community members and contemporary traditional leaders, modifications to MPA design might be possible without changes to formal legislature, however. In addition to establishing new MPAs that afford better protection for focal species, individual communities are considering other possible mechanisms to improve the design of existing MPAs, for example by implementing larger seasonal closures that extend from the core no-take area.

Nevertheless, even where they are large enough to encompass species' home ranges, the small size of most MPAs precludes the combination of essential habitat types required by many species during ontogenetic development, and most are not located to take feeding or reproductive migrations into account. This emphasizes the importance of understanding whether and how individual MPAs are connected to allow for larval dispersal and adult and juvenile migration between them.

While workshop participants considered that MPAs did not need to protect the home ranges of bumphead parrotfish, as this species is protected through other legislative means, poor enforcement means that the effectiveness of this alternative management is questionable. Knowledge of which species are unlikely to be protected within MPAs might provide a basis for better integration of spatial and non-spatial fisheries management.

Outstanding needs for further ecological research

Our assessments of effective MPA size are based on the assumption that all species inhabit exclusive home ranges. If available, species-specific information on how individuals' home ranges are distributed relative to one another could be used to determine how many individuals an MPA of a specific size could protect. We were unable to find this information for any of the focal species in our analyses; however, it could be established through telemetry studies of individual species' movements or derived from meta-analyses of fish densities within well-designed and effectively managed marine reserves (Green *et al.* 2015).

Following the guidelines proposed in Green *et al.* (2015) led us to conclude that many MPAs in Pohnpei are too small to support fish populations that are, nevertheless, found within them. There are several possible explanations for this. First, populations might be present within MPAs due to the partial protection provided to individuals whose home range coincides with the no-take area, but in decline. Secondly, if the assumption of home range exclusivity is false, many more individuals may reside within an MPA smaller than twice their average home range size. Thirdly, home range sizes of some reef fishes are known to vary with habitat patchiness (Green *et al.* 2015). Nash *et al.* (2015) suggest that MPAs which encompass whole reefs isolated by open water may provide greater protection for fish populations than MPAs of equal size on contiguous reefs, due to the apparent reluctance of fish to cross open water. It has also been suggested that fishes may utilize smaller home ranges within MPAs.

Given that decisions regarding MPA size represent a trade-off between affording adequate protection to focal fish species and allowing for extractive activities that underpin livelihoods and food security, this uncertainty needs to be resolved. A better understanding of how home range sizes vary with habitat type, quality, fragmentation and level of protection, for all species, is required for guidelines for adequate MPA design to be refined and applied with greater precision.

Conclusions

In many contexts, social and economic considerations constrain the size at which protected areas can be implemented, making it impracticable to designate areas large enough to protect the full range of species occurring within a region. Information on how differently sized protected areas may benefit different species permits explicit evaluation of these trade-offs. Our case study demonstrates that this approach can also better engage local stakeholders in conservation planning, and influence local decision-making towards more adequate protected area design. Stakeholder-led discussions about protected area adequacy also led to more realistic expectations about what those areas can achieve, and monitoring protocols that target species predicted to respond to management.

We used available information on the home ranges of coral reef-associated fishes to inform discussions with local stakeholders about the adequacy of MPAs in Pohnpei, Micronesia. The framework that we applied is generally applicable wherever animal movement data are available, however. Our approach could be further refined with data on the territoriality (or density) of focal species, and their relative vulnerability in protected and unprotected areas.

Though adult movement is more straightforward to quantify than larval dispersal, present understanding of

movement patterns of coral reef fishes remains far from complete. Data remain unavailable for many key species; for example, no movement data are available for caesionids, which are key fisheries species in parts of South-East Asia (Russ & Alcala 1998). Further ecological research effort, for example to understand how home range size varies with life-history phase, habitat type, quality, degree of fragmentation and level of protection, will benefit efforts to improve the adequacy of marine reserves for key fishery species. This is especially critical in developing countries, where dependence upon natural resources is high, constraining the size at which protected areas can feasibly be implemented.

Acknowledgements

Data accessibility

Data have not been archived because this article does not contain data.

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Biosketch

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