INTEGRATING HABITAT MAPPING AND BIOTIC PATTERN IMPROVES SPATIAL PLANNING IN A MARINE PARK

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Abstract

In 1991, when the Solitary Islands Marine Park (SIMP) was established, limited knowledge of seafloor habitats and biotic patterns constrained effective conservation planning. This knowledge was improved by 2002 when the SIMP was rezoned, by mapping shallow (<25 m) sub-tidal habitats through aerial photography and single-beam sounder surveys. Since 2002, fish and benthic surveys combined with mapping have been used to produce a Habitat Classification System (HCS) integrating habitat as a surrogate for biotic pattern. This was initially undertaken for shallow-reef communities using diver surveys. However, effective conservation planning of deeper reef and non-reef communities was still constrained. An acoustic mapping program, initiated 2006, has produced high-resolution bathymetry, backscatter, and habitat maps of ~35% of the SIMP seafloor out to the SIMPs maximum depth (75 m). These have enabled targeted deployment of Baited Remote Underwater Video (BRUV) to further examine associations between fishes and abiotic habitat characteristics. Strong spatial correlations between fish assemblages and habitat characteristics served to further refine the HCS with the following categories: substratum (consolidated, unconsolidated), cross-shelf position (inshore, mid, offshore) and depth (shallow, intermediate, deep). Differentiation of unconsolidated substratum into gravel and sand habitats improves this classification. Predictive species distribution models based on BRUV data and acoustic mapping, support the importance of depth and distance from shore as drivers of the presence and abundance of fish species and groups. This combination of research approaches has improved the scientific basis for effective spatial management in the SIMP, especially when used with spatially explicit planning tools like Marxan/Marzone.

Introduction

Spatial protection is an important mechanism for managing human activities and conserving species and ecosystem functions (Laffoley *et al.* 2014). This includes spatial management through Marine Protected Areas (MPAs). Successful outcomes for desired management objectives are more-likely if protected areas are effectively planned (Cowling *et al.* 2003, Stewart *et al.* 2003, McCook *et al.* 2010). Key principles underpinning spatial conservation planning within an MPA often include efficient representation of biodiversity within highly protected areas, such as 'no take' sanctuaries (Friedlander *et al.* 2003, Stevens and Connolly 2005, Gladstone 2007), and adequacy of protection to achieve objectives. Effective planning which aspires to be 'representative' and 'adequate' requires spatial knowledge of biota, habitat, or suitable surrogates at a scale relevant to an MPA (Williams and Bax 2001, Leslie *et al.* 2003, Lombard *et al.* 2003, Roberts *et al.* 2003, Williams *et al.* 2009). A further key consideration is the effect of conservation efforts on users; effective planning and implementation of MPAs should minimise impost on user values and livelihoods (Ban *et al.* 2011, Ban *et al.* 2013, Boon and Beger 2016).

Fishes are an important biotic group in a marine park due to their high contribution to diversity and ecological, social, and economic values (Gell and Roberts 2003, Shears and Babcock 2003, Sala *et al.* 2012). Biodiversity conservation is a major objective for MPAs globally, with conservation of biota and habitats in highly-protected 'no take' sanctuaries an important mechanism for helping to achieve this objective (Worm *et al.* 2006, Claudet *et al.* 2008, Lester *et al.* 2009). Therefore, identification of representative and priority areas for fishes is often an important consideration in spatial planning of MPAs (Gladstone 2007). Although fishes are generally easy to sample relative to other taxa (Kingsford, 1998) and surveys can suggest 'hotspots' of richness or endemism (Balmford 1998, Roberts *et al.* 2002), detailed knowledge of their occurrence and abundance is often spatially constrained within a planning area (Curley *et al.* 2002, Gladstone 2007, Malcolm *et al.* 2012). Surrogacy is one approach that can lessen spatial bias associated with this constraint (Ferrier 2002, Smith 2005, Malcolm and Smith 2010, Hunter *et al.* 2016), particularly where species distribution modelling methods are used to predict the likely occurrence and abundance of biota (Moore *et al.* 2011).

There are strong relationships between habitat and biota, with habitat an important driver of biotic patterns at a range of scales (Friedlander and Parrish 1998, Curley *et al.* 2002, Gratwicke and Speight 2005, Williams *et al.* 2009, Moore *et al.* 2011). Additionally, habitats can be mapped spatially more-easily than biota, including fishes (Rees *et al.* 2013). Integrating fish assemblage patterns and seafloor habitat mapping, as a biodiversity surrogate, can improve spatial management planning in a marine park for this important group (Williams and Bax 2001, Ferrier 2002, Blamey and Branch 2009). Additionally, the surrogate may fortuitously represent other taxa with similar patterns and drivers (Bridge *et al.* 2015), as well commonly-occurring taxa with non-concordant patterns (Beger *et al.* 2007, Beger 2015).

The 720 km^2 Solitary Islands Marine Park (SIMP) in New South Wales, Australia, includes rocky reef and unconsolidated habitats that extend up to 17 km from the mainland coast to a maximum depth of 75 m. When established in 1991, there was limited knowledge of biotic patterns, seafloor habitats and habitat-biotic relationships in the SIMP, which constrained effective conservation planning in this multiple-use MPA (NSW MPA 2000). Less than 1% of the SIMP was zoned 'no take' marine sanctuary in 1991, focussing mainly around islands. The SIMP was rezoned in 2002, with ~12% of the area in sanctuary, and although understanding of habitats had increased and representation certainly improved, knowledge of fish patterns and detailed mapping of habitats was still extremely limited (NSW MPA 2000, 2009). This was especially the case in waters deeper than 30 m and on unconsolidated sediments (which comprise ~ 80% of the seafloor). This knowledge has increased dramatically since 2002, through the use of remote survey methods including acoustic swath mapping for backscatter and bathymetry of the seafloor, and Baited Remote Underwater Video (BRUVs) methods for fishes (Jordan *et al.* 2010, Malcolm *et al.* 2010b, Malcolm *et al.* 2011, Schultz 2016). Improvements in this technology, and advances in statistical approaches and software, have furthered the potential to integrate habitat and biotic pattern in the SIMP (Malcolm *et al.* 2016).

The aim of this study, which is a synthesis of various fish and habitat studies within a single MPA, is to demonstrate how improved habitat mapping and knowledge of fish diversity and assemblage patterns in the SIMP, and their integration, has subsequently improved the capacity for effective spatial management planning in a multiple use marine park.

Methods

Study location and legislative background

The subtropical Solitary Islands Marine Park (SIMP) is located in a tropical-temperate transition in coastal northern New South Wales (NSW) on the east coast of Australia (Figure 1). It is positioned in a large regional embayment between Cape Byron and Smoky Cape and is influenced by the southward-flowing tropical East Australian Current (EAC), which has a stronger influence offshore (Malcolm *et al.* 2010a). The SIMP is positioned just upstream from a major separation point of the EAC from the mainland Australian Coast at Smoky Cape (Roughan and Middleton 2004).

The objectives for spatial management planning in the SIMP have changed during its 25 years, due to changes in strategic direction and legislation. The marine park was proposed in 1981 based on local support (Pollard 1981). It was initially declared in 1991 as a multiple purpose marine reserve: Solitary Islands Marine Reserve (NSW); under the NSW *Fisheries and Oyster Farms Act 1935*. This Act was replaced by the NSW *Fisheries Management Act 1994* and the reserve continued to be recognised under that Act. In 1997 the NSW *Marine Parks Act* was established and the reserve became the Solitary Islands Marine Park, initially with the same multiple use zoning arrangements. However, the objectives of these Acts differed, with the primary objectives of the Marine Parks Act being conservation of biodiversity and maintenance of ecological processes. Additionally, there were changes in some zone categories and objectives (i.e. Refuge Zone was replaced by Habitat Protection Zone). The SIMP was rezoned in 2002 (NSW MPA 2002) and that zoning is still currently in place (as at 2016). An external audit of NSW marine parks and the MPA Act (Beeton *et al.* 2012) then led to replacement of the NSW *Marine Parks Act 1997* with the NSW *Marine Estate Management Act 2014*. Under this Act, there is a focus on strategic and integrated management of the overall marine estate with a threat and risk based approach to spatial conservation.

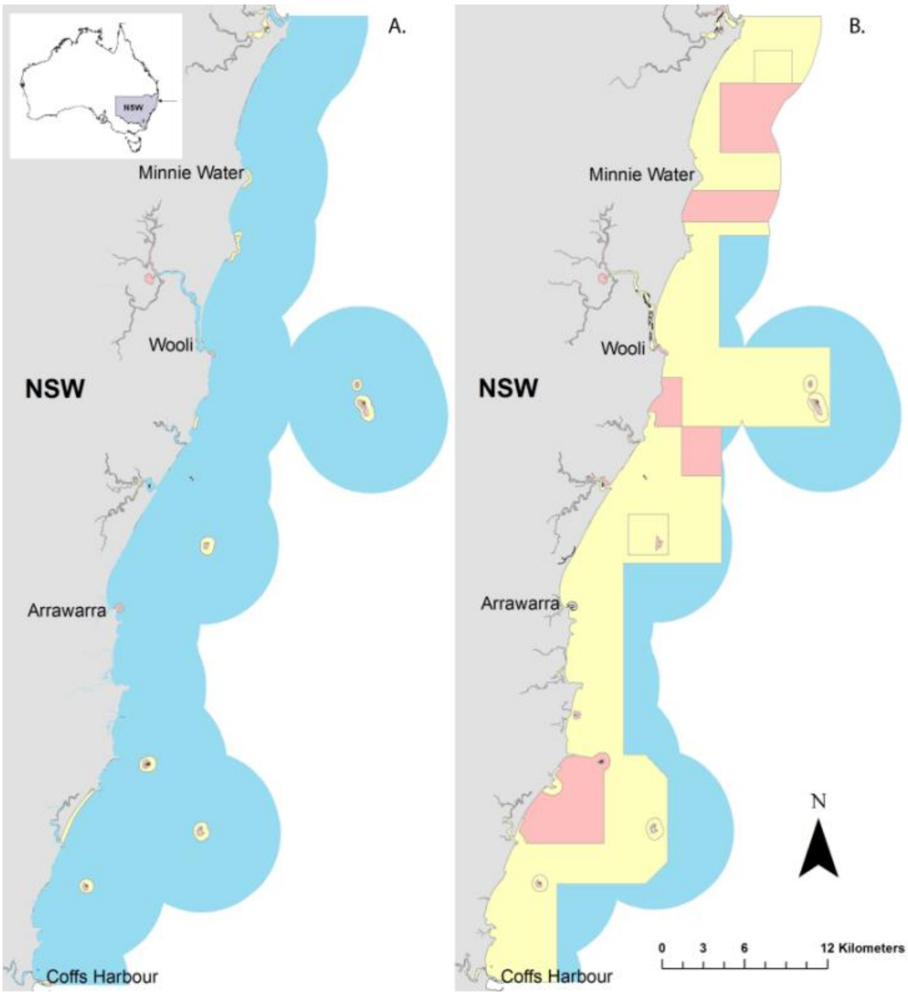

Figure 1: Map of the Solitary Islands Marine Park with initial zoning plan in 1991 and 2002 zoning plan. Pink = Sanctuary Zone; yellow (1991) = Refuge Zone; yellow (2002) = Habitat Protection Zone, blue = General Use Zone.

Habitat and fish knowledge prior to initial establishment in 1991

At the time the SIMP was established (1991), general naval bathymetric charts and sounding data were available, showing where reefs and other seafloor features were generally positioned (e.g. Figure 2: 1991). Prior to establishment, biotic information and some of the human pressures driving establishment of this MPA were focused on shallow rocky reefs around the islands of the Solitary Islands Group (Pollard 1981).

Mapping and sampling program 1991 to 2002

In the decade following establishment of the SIMP, broad areas of rocky reef habitat were mapped using a combination of aerial photography for shallow near shore reef habitats to about 15 m depth, and single-beam echo-sounder cross-shelf transects (Mau 1997, Mau *et al.* 1998, NSW MPA 2000). This was combined with bathymetric chart data to interpret and map reef habitats in GIS (ArcView). The single-beam echo-sounder survey involved 22 cross-shelf transects running from shore to the seaward extent of the SIMP (in ~75 m depth) and spread-out along the length of the SIMP (approximately 80 km). The seafloor was categorised as reef or non-reef and ground-truthing was also undertaken at sites along transects using a downward facing camera (Mau *et al.* 1998). These maps, coarse bathymetry information, and benthic biotic data were used to develop a preliminary Habitat Classification System (HCS). The map of the preliminary HCS and the spatial area within habitat categories, informed the rezoning of the SIMP in 2002. After 2002, these maps (e.g. Figure 2: 2001) were also used to facilitate site selection for broad-scale diver surveys of fishes, a key taxon for shallow (<25 m) reef communities.

Habitat mapping post 2002 - acoustic geoswath

Since 2005 swath acoustic data have been collected with a 125 kHz GeoSwath interferometric sidescan sonar, which collects geo-referenced depth and sidescan backscatter data used to generate high-resolution maps of seabed habitats. Details on acoustic parameters, data collection, and post-processing are reported in Jordan *et al*. (2010). Swath mapping has significantly improved mapping accuracy and covers ~35% of the SIMP at the time of this synthesis. This ongoing mapping program has enabled high-resolution mapping of seafloor habitats, particularly in depths >50 m (Figure 2: 2011).

Using a combination of the swath acoustic bathymetry and backscatter layers, areas of rocky reef were digitised by hand using ArcGIS at a constant scale of 1:2000. Reef was characterised by regions of high relief, greyscale heterogeneity (texture), and higher backscatter intensity. Polygon shapefiles were produced for all areas that were surveyed and aligned to the previous habitat map for the SIMP. This previous map had been digitised from existing bathymetric charts (NSW MPA 2000) and near-shore reef maps interpreted from aerial photography (Avery 2005). In areas of overlap, boundaries mapped from swath acoustic data were used preferentially. The habitat layer covering this planning area was created using a combination of these data. Differentiation of potential ‘sand’ and ‘gravel’ habitats was also possible through backscatter intensity. Ground-truthing of seabed habitats, to confirm/adjust interpretation of boundaries, has been undertaken using combinations of diver-surveys, drop video, video grabs, towed video, baited remote video field of view, and grab sampling (Mau 1997, Mau *et al.* 1998, Jordan *et al.* 2010, Malcolm *et al.* 2011, Schultz *et al*. 2015).

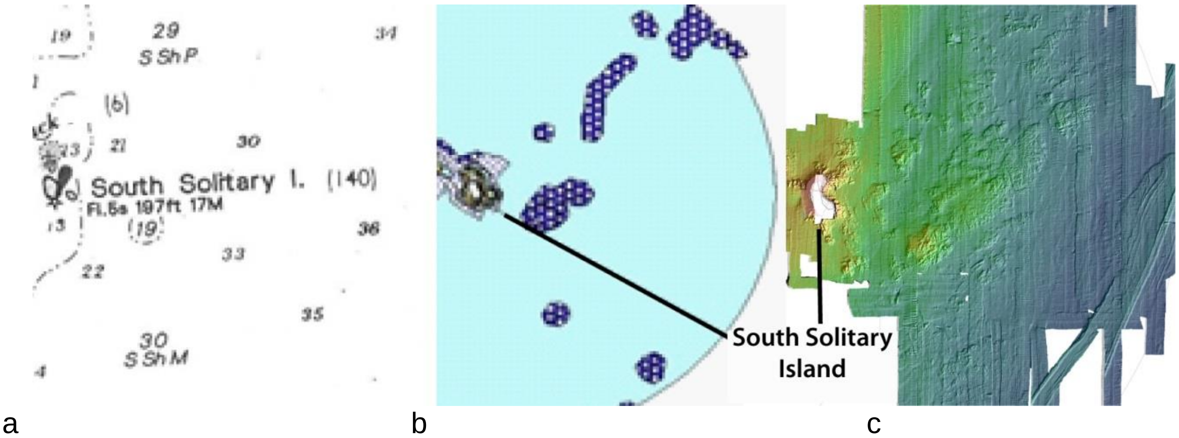

Figure 2: a) 1991; b) 2002; c) 2011. Evolution of available habitat maps from 1991 to 2011 showing the area around South Solitary Islands as an example. Purple shaded areas in 2002 indicate mapped reef. The greater extent and complexity of reef areas is visually apparent in 2011.

Diver reef fish surveys

A total of 68 shallow reef sites (in <25 m depth) were surveyed during 2002 - 2005 in areas ranging from those associated with headlands on the mainland to those adjacent to offshore islands. These covered, as broadly as possible, the geographic range of shallow reefs in the SIMP, based on the preliminary HCS map. A 30 minute roving diver count was conducted at each site to record every fish species observed, and provide a relative index of their abundance using a $\log_5$ estimate (Kingsford 1998, Malcolm *et al.* 1999). A similar area was covered during each survey, from deeper to shallower depths. A total of 18 sites have been surveyed multiple times between 2001 and 2016 to examine and confirm persistence in patterns.

BRUV reef fish surveys

Fifty six reef sites (ranging from 15 to 75 m depth range) were surveyed during the Austral winter/spring of 2007 - 2008. These sites were pre-selected in GIS (ArcMap) using bathymetry and backscatter layers from geoswath mapping to broadly cover the spatial and depth extent of reef known to be present within the SIMP, with a focus on deeper reef below 25 m. At each site, three replicate Baited Remote Underwater Videos (BRUVs) were deployed for 30 min. Replicates at a site were placed in similar depths, at least 200 m apart. Each BRUV unit consisted of a video camera with wide-angle lens in an underwater housing, an attachment frame, a bait-pole with bait, and a rope and float system linking the BRUV to the surface (Cappo *et al.* 2003, Harvey *et al.* 2012). A bait of ~1 kg of pilchard (*Sardinops neopilchardus*) was used to attract fish to a viewing area in front of each camera (Hardinge et al. 2013). Bait was contained in a plastic mesh bait bag attached to the end of a bait-pole at a distance of 1.5 m from the camera. Fish were videoed in a horizontal orientation to the benthos. From each deployment, fish were identified and the maximum number (MaxN) of individuals of each species observed in a video frame at any one point of time during the 30 minute sample, were recorded. MaxN is a comparative measure of relative abundance that removes any risk of recounting the same individual when determining abundance (Cappo *et al.* 2004, Malcolm *et al.* 2007).

BRUV unconsolidated sediment fish surveys

Fish assemblages on unconsolidated sediments were surveyed to examine patterns in relation to distance from reef (24 sites at various distances from reef), broad depth categories (24 sites spread between two broad cross-shelf areas and within depth-classes representative of the existing HCS) and ‘type’ of substrata based on backscatter intensity (12 sites spread between 4 different sediment ‘types’) (Schultz *et al.* 2012, Schultz *et al.* 2014, Schultz *et al.* 2015). Additionally, surveys were conducted behind the surf break along a number of beaches within and adjacent the SIMP to examine the influence of a range of physical variables in driving fish and mobile invertebrate assemblages. These studies were undertaken as part of a PhD study (Schultz 2016) which sought to improve spatial planning in relation to the most extensive seafloor habitat in the SIMP (~80%), which was at the time poorly described when contrasted with reef habitats and assemblages. This research sought to integrate biotic pattern with habitat and to test and potentially further refine the HCS. The same field sampling and video analyses methods as per the reef fish BRUVs study were used. Grab samples were used to ground-truth sediment type in relation to backscatter intensity and to determine sediment granulometrics for correlation with fish patterns.

Integrating fish patterns and habitat mapping

Combinations of multivariate statistical approaches in PRIMER (Clarke and Warwick 2001, Anderson *et al.* 2008) were used to integrate fish patterns and habitat mapping. Ordination patterns (HCS, nMDS) were used to visually compare fish assemblages between different habitat categories. A total of 197 BRUV deployments during 2011 were used to examine differences between reef (113 deployments) and unconsolidated substrata (84 deployments) using a Bray Curtis Dissimilarity matrix following square root transformation. Within reef habitat comparisons, likewise used this approach. Multivariate correlations (BIOENV, DistLM), and multivariate comparisons (PERMANOVA) served to compare fish assemblage patterns with various explanatory variables hypothesised to influence those patterns (e.g. distance from shore, reef type, dominant benthos, latitude, depth, depth range, sediment type, etc.). The species most responsible for driving differences in assemblage patterns were determined using SIMPER and compared between pattern groupings. Combinations of these analyses were used to determine which factors best explained biotic patterns from the different fish studies and to refine the HCS accordingly by incorporating those factors and using them to define categories.

Increased understanding of fish-habitat relationships and modelling predictions

Modelling approaches have also been used to examine fish and habitat relationships and to predict selected fish distributions in the SIMP. A suite of targeted reef fish species and fish functional groups (considered to have conservation, ecological, social and/or economic values) were modelled against a range of physical habitat variables considered likely to influence reef fish occurrence and abundance. To examine the influence of fine-scale habitat characteristics (<25m ^{2}), variables obtained using Automated Underwater Vehicle (University of Sydney's AUV Sirius) were modelled against BRUVs that were sampled within replicate AUV 25m x 25m grids.

For broader scale predictive modelling, BRUVs fish data were restricted to two areas in the SIMP where there is comprehensive swath mapping data. Habitat variables were determined in ArcGIS using various spatial analyses around each BRUVs deployment. The occurrence of each individual species was then modelled with a Generalised Linear Model with a Bernoulli distribution and log link using the MASS package (Venables and Ripley 2002). Model selection, based on AIC, was conducted using forward selection. Model adequacy was assessed by plots of the model residuals against fitted values and each predictor variable separately. Fine scale spatial autocorrelation was also considered and where evidence of spatial autocorrelation was found, models that included a random term for the survey site were considered instead. The best model for each species was then used to generate predictions of the average occurrence across each region.

Spatial planning systematic approaches – Marxan

Systematic analyses have been conducted using Marxan with the graphical interface Zonae Cogito (Ball and Possingham 2000) and with Marxan-io. Further analyses are also currently being conducted in MarZone. In the initial Marxan analyses, the SIMP was subdivided into a grid of 3712 planning units, each 500 m x 500 m square created in ArcGIS (Malcolm *et al.*

2012). The values for each planning unit used in the Marxan analyses (e.g. management status, biodiversity features, costs) were also determined in ArcGIS. A range of planning scenarios were considered based on different percentages of each planning feature to be included in sanctuary (10%, 20%, 30%) and whether the existing (2002) zoning scheme was incorporated (i.e. planning units with existing sanctuaries locked into solutions) or the marine park was a 'clean slate' (any planning unit available for selection, nothing locked in). The existing zoning plan was also considered for comparison (existing 2002 SIMP zoning scheme locked in, all other planning units unavailable for selection). The selection algorithm used simulated adaptive annealing with iterative improvement, with 1000 runs (selections of sets of areas), each with 1,000,000 iterations. Selection frequency indicated the number of times (out of 1000) each planning unit was selected, with the frequency at which a planning unit was selected indicating its' importance in meeting conservation objectives in a particular scenario. More recently, we have used Marxan-io to compare scenarios with predicted Species Distribution Models (SDMs) and scenarios with the existing HCS over a partial area of the SIMP with detailed geo-swath mapping coverage. Comparisons included both effectiveness at achieving representation and cost (i.e. area required to meet targets).

Results

Preliminary HCS

A preliminary HCS was developed in 2000 (NSW MPA 2000) and used non-systematically in spatial planning for biodiversity representation in the SIMP. This included developing a draft zoning plan in 2001 and a final plan in 2002, following a public consultation period (NSW MPA 2001b, 2002). This preliminary HCS separated habitats into reef and unconsolidated substrata, with five reef categories loosely based on depth and distance from mainland coast.

Table 1: Preliminary HCS (reef categories) developed for the 2002 SIMP rezoning

Reef type	**Characteristic**	**Depth**
Inshore reefs	Kelp dominated	Inshore reefs rising from depths <20 m
Shallow mid-shelf reefs	Coral dominated	Reefs in 20-35 m depth, rising to <15 m from surface
Deeper mid-shelf reefs	Sponge dominated	Reefs in 20 – 35 m depth, rising to >15 m from surface
Offshore reefs	Sponge dominated	>35 m
Submerged pinnacles	Steep sloping	Rising from depths > 35 m

The actual differentiation between these categories was not clearly defined spatially in relation to the SIMP. The two categories (shallow and deeper 'mid-shelf reefs') that combined depth-range (20 to 35 m) with a depth to which those reefs rose (< or > 15m) were difficult to separate and map without accurate bathymetric information. Some areas of reef were therefore mapped as 'mixed' (NSW MPA 2000). Prior to 2002, about 0.02% of the SIMP was protected in 'no take' sanctuary zone and this increased substantially to ~12% with the 2002 plan. Representation in sanctuary considerably increased for the inshore and mid-shelf reef mapped categories. Pinnacle reef was also represented in the adjacent Solitary Islands Marine Reserve (Commonwealth Waters) in the sole sanctuary in that reserve (Pimpernel Rock SZ). However, almost no reefs in the offshore category were included in sanctuary in the 2002 zoning plan, nor were deeper unconsolidated habitats.

Fish assemblage patterns

There are distinct biotic patterns in the SIMP. The fish assemblages found on reef and unconsolidated habitats strongly separate from each other, with no overlap between the two clusters (Figure 3). All the reef deployments cluster together and all the unconsolidated substrata deployments do the same. This was further evidenced by changes in fish assemblages adjacent to reef. Within about 100m from reef, the fish assemblage strongly changes from one associated with reef to one associated with sediments. There is also a 'halo' assemblage, which is a mixture of both, on unconsolidated sediments within ~50 m adjacent to a reef perimeter (Schultz *et al.* 2012).

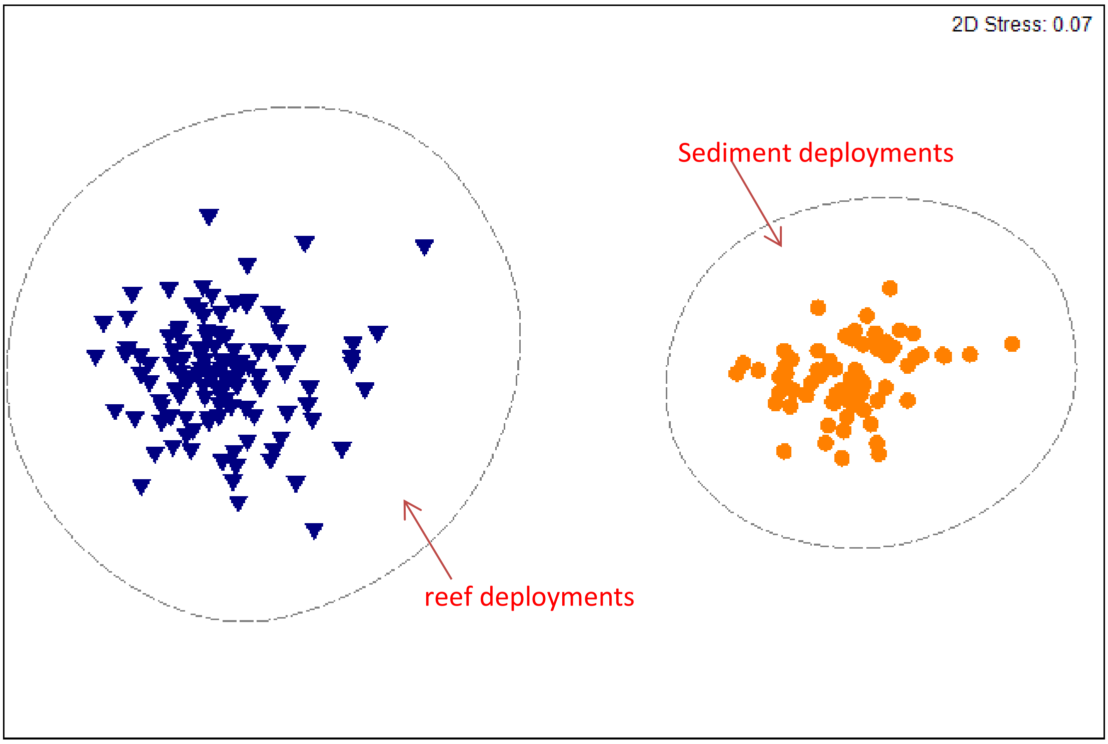

Figure 3: nMDS of deployments on reef versus unconsolidated sediments. Dark blue inverted triangles = reef deployments; orange circles = sediment deployments. N = 113 deployments on reef, 83 deployments on unconsolidated sediments (sands or gravels). 2D stress = 0.07. Dashed grey line = cluster analysis 20% dissimilarity.

Within reef fish assemblages in the SIMP, there are very strong cross-shelf (Figure 4) and depth patterns (Figure 5), which can be categorised (Malcolm *et al.* 2010b, Malcolm *et al.* 2011). Inshore areas support a higher proportion of temperate species and the highest proportion of endemics. Mid reefs support a transitional mix of temperate-subtropical-tropical species and many east coast subtropical endemics predominantly occur on these. Offshore reefs have more tropical Indo-Pacific species and the highest species richness, particularly adjacent to islands. However, this strong influence on tropical species offshore weakens with depth. Some species were only recorded in deeper waters. Visually these patterns strongly separate (Figures 4, 5).

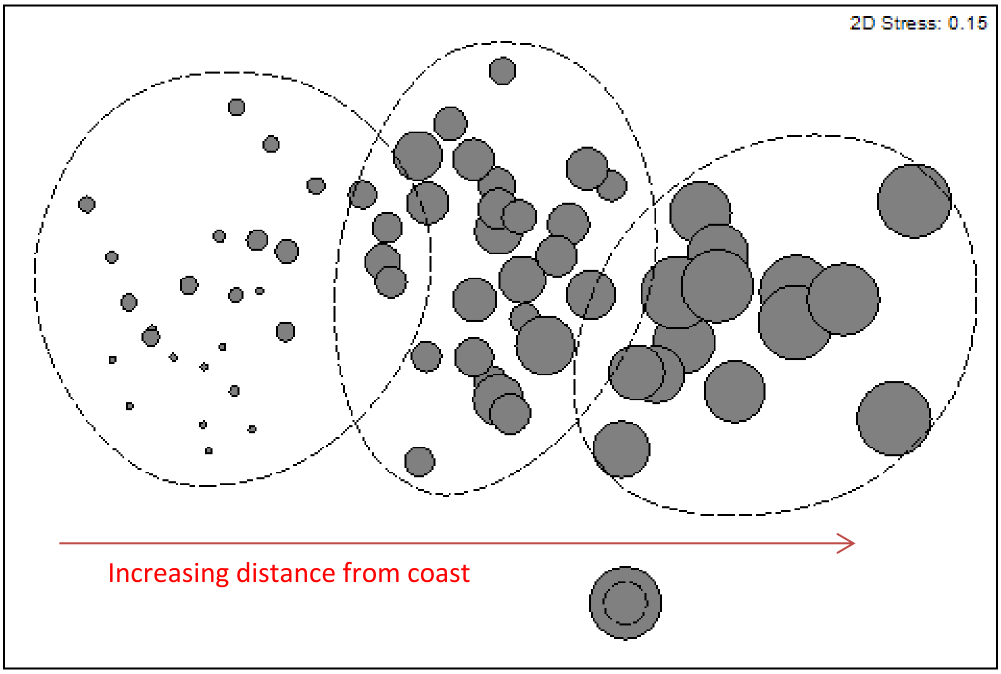

Figure 4: nMDS fish assemblage relationships showing patterns cross-shelf – where the bigger the bubble the further the site is from the coast, n = 68 roving diver sites. Dashed grey line = 50% dissimilarity

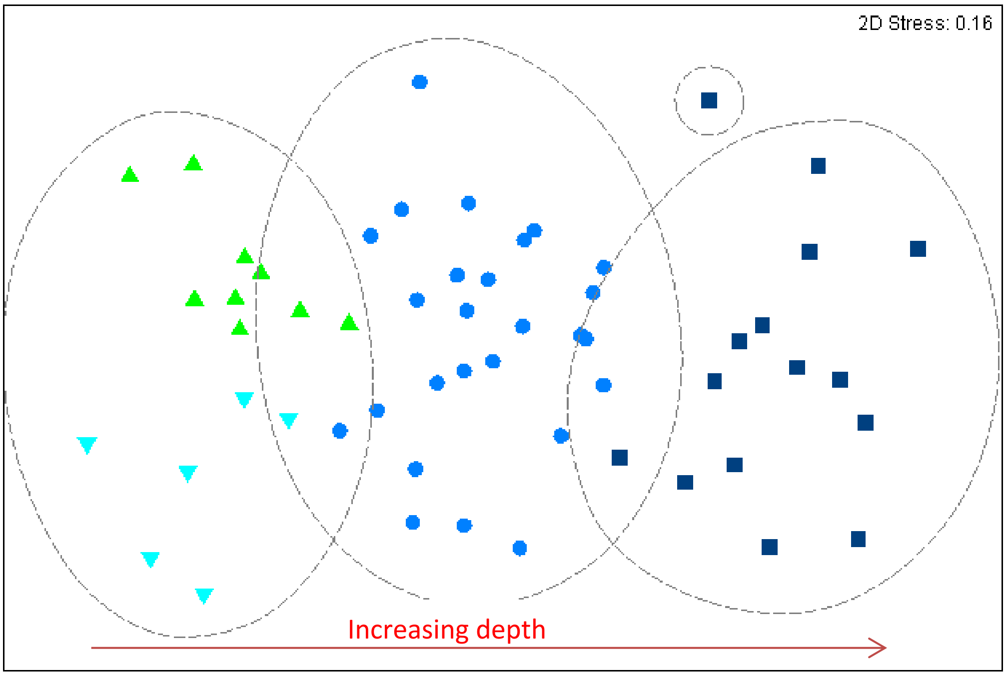

Figure 5: nMDS fish assemblage relationship showing patterns with depth from BRUVs, where: turquoise inverted triangles are <25 m depth <6 km from mainland coast; green triangles are < 25 m depth >6 km from mainland coast; mid blue circles are 25 to 50 m depth; dark blue squares are > 50 m depth, n = 56 BRUV sites. Dashed grey line = 45% dissimilarity.

Similarly, there are also depth patterns in fishes of unconsolidated substrata. Additionally, within unconsolidated substrata, there are also strong patterns associated with gravel and sand habitats (Schultz *et al.* 2014, Schultz *et al.* 2015).

Integrating Habitat and Fish: present Habitat Classification System

These strong biotic patterns, in combination with knowledge of other biotic patterns in this region, have enabled a more clearly defined HCS to be developed (Table 2).

Table 2: Present Habitat Classification System, Solitary Islands Marine Park.

Habitat	Depth	Distance offshore or sediment type	Approximate % represented in Sanctuary Zone
Reef	Shallow (<25 m deep)	Inshore	17
		Mid	19
		Offshore	35
	Intermediate (25 - 50 m)	Inshore	3
		Mid	22
		Offshore	1
	Deep (> 50 m)	Offshore	0
Unconsolidated	Shallow (<25 m deep)	Sand	19
		Gravel	
	Intermediate (25 - 50 m)	Sand	11
		Gravel	
	Deep (> 50 m)	Sand	0
		Gravel	

Inshore < 1.5 km from the mainland coast; Mid = 1.5 to 6 km from the mainland coast; Offshore > 6 km from the mainland coast. There is no deep habitat < 6 km from the coast.

Mapping to differentiate sand and gravel habitats, based on backscatter layers is still required. However, to effectively undertake and evaluate this, more-comprehensive swath mapping throughout the SIMP is still required.

Modelling fish habitat relationships and predicting distributions

Fine scale relationships over areas <25 m^2, between habitat complexity measures and fish groups, indicate that combinations of habitat with both higher and lower complexity at different scales is needed to influence the abundance of different trophic groups. Both fish community composition and abundance were strongly related to habitat complexity metrics, especially surface rugosity and its variance. Benthic biota and depth were also important predictors, although benthic biota imagery is more-expensive (to obtain and process).

Species Distribution Models (SDMs) on a range of key species and species-groups have also enabled spatial predictions to be made as to their occurrence and abundance. Modelling indicates that depth in particular is an important predictor, although a combination of multiple abiotic surrogates, especially those derived through swath mapping, will improve the predictive power. Where detailed bathymetry from swath mapping is available, a combination of geoswath derived variables, including depth, should be used to generate the

SDM's (Figure 6). However, where this is not available, the use of coarser-scale depth information, latitude, and distance from shore, still enable useful predictive maps to be generated for systematic planning purposes.

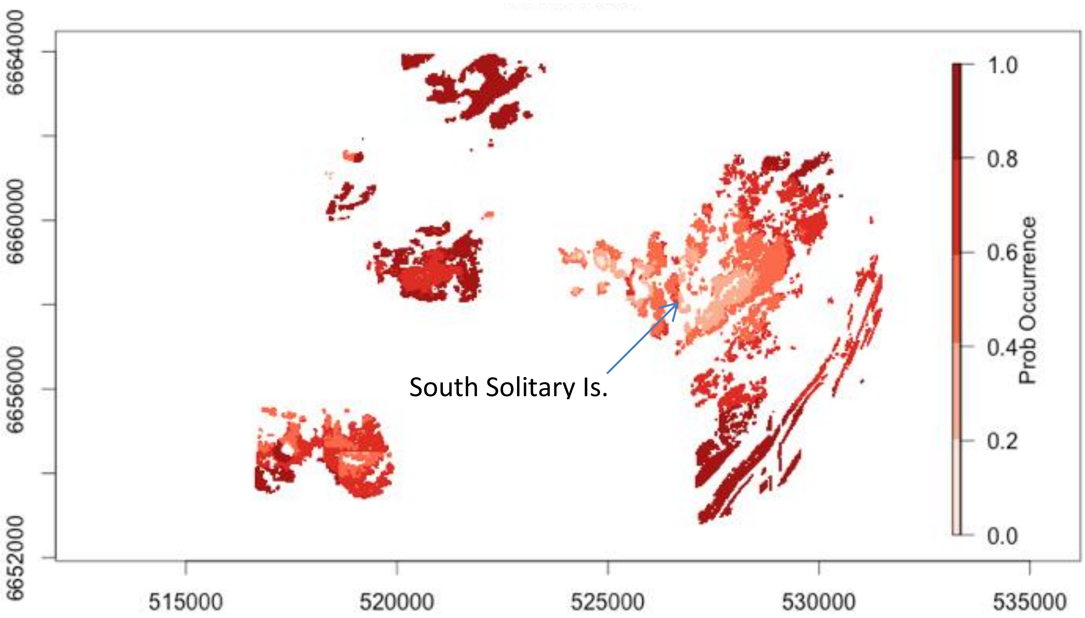

Figure 6: Example of a predictive map of snapper *Chrysophrys auratus* from the modelled relationship between occurrence and predictor variables, in the southern part of the SIMP.

Systematic planning – Marxan

The absence of deep (>50 m) habitat in sanctuary is obvious as is the lack of offshore intermediate-depth habitats represented in the SIMP (Table 2). Systematic analyses using Marxan, using HCS categories as features, emphasise that areas offshore should be included for representative targets to be met (Figure 7).

Both habitat mapping across the entire SIMP using the refined HCS, and fish data from the various reef fish surveys in this study were used in the initial Marxan analyses. The combination of habitat and fish was more effective at capturing known areas of high species richness than the habitat mapping alone in generating solutions. Fish data alone was too constrained for the purposes of systematic planning at the marine park scale. More recent Marxan / Marzone analyses have been conducted but are still in progress. These indicate that syntheses of HCS scenarios and SDM scenarios, particularly when interpreted using local knowledge, will further improve effectiveness in representation, adequacy, and cost efficiency in spatial planning.

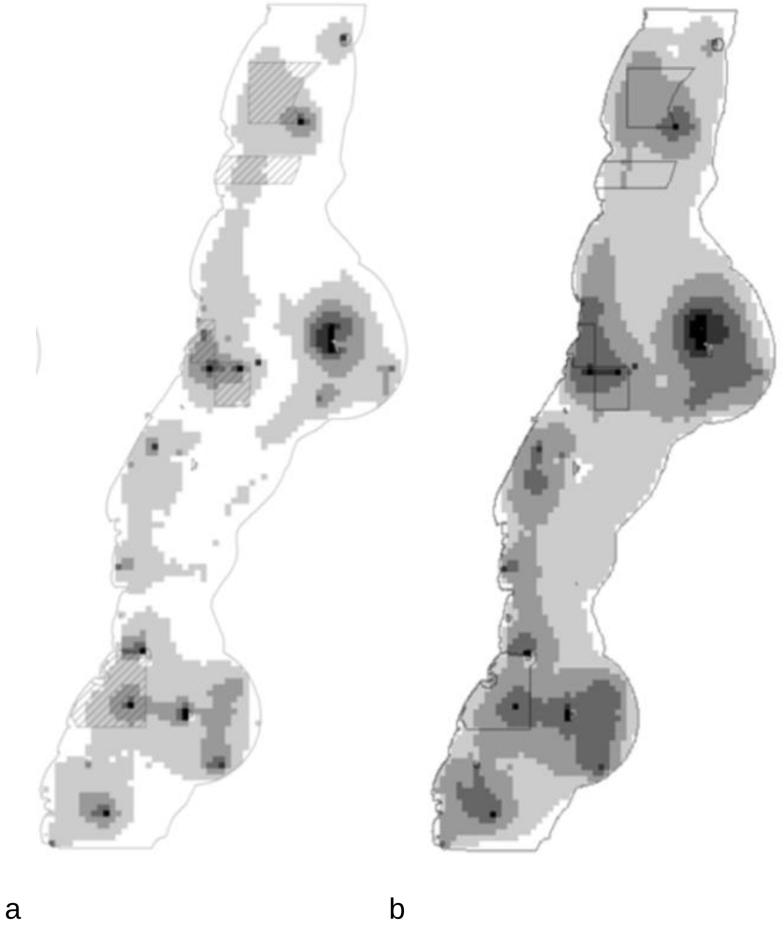

Figure 7: Frequency selection maps based on the evolving HCS but without separation between gravel and sand habitat, showing: a) 10% selection, similar to the existing percentage of SIMP in sanctuary; b) 20% selection. Darker colour = more frequently selected (therefore more irreplaceable in achieving the selection objective).

Discussion

Mapping of the seafloor has drastically improved during the 25 year history of the SIMP, and biotic patterns have been more broadly investigated at the park wide scale. This has enabled an evolving and improving integration of habitat and biotic information with increased utility for spatial management planning. Advances in seafloor mapping and modelling, combined with increased knowledge and understanding of biotic patterns in the SIMP, has greatly improved the capacity for planning using systematic approaches (Malcolm *et al.* 2016).

When the SIMP was established, seafloor mapping consisted of naval hydrographic charts, and while useful, these were primarily designed for navigation. They were too coarse-scaled and lacking in detail to enable effective spatial planning. Likewise, biotic information was spatially constrained and focused on island rocky reefs, especially from scuba diving surveys (Veron *et al.* 1974, Pollard 1981, Millar 1990). A combination of public concerns about threats (e.g. aquarium fish collecting) and known biological values of shallow rocky reefs (e.g. coral communities in a tropical-temperate transition) provided the social impetus for an

MPA in this region and strongly influenced the original placement of zones in 1991. The SIMP was established before the concept of a National Representative System of Marine Protected Areas (NRSMPA) in Australia was adopted in 1998 (ANZECC TFMPA 1998, 1999) and the original zoning plan was not designed to meet NRSMPA guiding principles of comprehensiveness, adequacy, and representativeness (CAR).

The rezoning in 2002 was undertaken with CAR as a guiding principle, and greatly benefited from improved mapping and the development of a preliminary HCS. Conservation of biodiversity and maintenance of ecological processes were primary objectives in the NSW MPA legislation at that time governing that rezoning process (NSW_Government 1997, NSW MPA 2001a). Representation of habitat categories in the preliminary HCS, as a surrogate for biodiversity, was influential in informing spatial planning but was not the only consideration. A systematic approach was not applied; instead a more ad hoc approach driven by a range of input from various stakeholder groups was adopted (NSW MPA 2009). This had variable results in terms of biodiversity representation and adequacy with some habitat types well represented and others only marginally (Malcolm *et al.* 2012). Ad hoc approaches can be ineffective in adequately selecting representative biodiversity features (Cowling *et al.* 2003, Stewart *et al.* 2003). Some fortuitous representation also occurred with unknown reef areas in sanctuaries later identified by swath mapping (Jordan *et al.* 2010, Bridge *et al.* 2015). The preliminary HCS made the initial steps in integrating biotic pattern and habitat. However, it did not effectively represent biological patterns, at least not for reef fish, as it was strongly constrained by the spatial extent of biotic data and mapping available at that time.

Geoswath mapping since 2005 has identified extensive areas of reef in deeper waters in the SIMP (Jordan *et al.* 2010). This high resolution broad scale coverage of the seafloor at the SIMP-wide scale has greatly improved the capacity for integrating biota and habitat. It has not only enabled mapping of habitats but also enabled spatial analysis of various geomorphic metrics about the seafloor complexity in relation to biotic patterns. Detailed knowledge of the seafloor facilitates the design of biotic sampling programs, which further improves this capacity.

There are very strong cross-shelf and depth patterns in this region for reef fish assemblages and biogeography (Malcolm *et al.* 2010b, Malcolm *et al.* 2011). Correspondingly, distance from the mainland coast and depth also influences the patterns of various invertebrate taxa and macroalgae in the SIMP (Harriott *et al.* 1994, Malcolm *et al.* 2010c, Harrison and Smith 2012). An important driver in these patterns is the tropical, south-flowing EAC, which has a stronger influence offshore (Malcolm *et al.* 2010a, Armbrecht *et al.* 2014, Armbrecht *et al.* 2015). Converse to this, colder counter-currents and cold water intrusions occur more frequently inshore. The EAC delivers tropical larvae, drives cross-shelf and depth patterns in phytoplankton, and creates a cross-shelf sea-temperature differential.

The fish assemblages of unconsolidated substrata strongly separate from fish assemblages on reef, and also have differing assemblage patterns associated with depth (Schultz *et al*. 2014). Fish assemblages on unconsolidated substrata are also influenced by the type of sediment present (Schultz *et al.* 2015). Gravels provide a more rugose seafloor compared to sand sediments at the centimetre scale and represent different components of biodiversity. Habitat rugosity can drive occurrence and abundance of biota (Harborne *et al.* 2011, Rees *et al.* 2013) and gravels may also provide more suitable substrata for sessile benthos to attach.

These strong patterns in fish assemblage composition in relation to particular habitat characteristics provided the basis for a refined HCS (Table 2). All the refined HCS reef categories have some unique biodiversity values in terms of representing assemblages of species, individual species, abundance of species, and biogeographic influences. Thus, this refined HCS is a tested surrogate for biotic pattern, which can usefully inform spatial management planning in the SIMP. However, it has strong limitations and should be used in conjunction with other information. For example, it cannot separate abundance patterns on reef within a category nor identify hotspots in diversity. The HCS supports findings elsewhere regarding depth as an important driver in biotic patterns (Connell and Lincoln-Smith 1999, Williams and Bax 2001, Beger and Possingham 2008, Luiz *et al.* 2015).

Predictive modelling of the relationships between habitat variables and seafloor variables further support importance of depth and distance from shore as drivers of these biotic patterns. These drivers also influence the distribution of recreationally and commercially important species. Predictive mapping of the occurrence and abundance of key targeted taxa will assist with spatial planning for ecosystem based management for important targeted species. Adequate protection of targeted species in sanctuaries will result in more and larger fish (Lester *et al.* 2009, Babcock *et al.* 2010, Malcolm *et al.* 2015), potentially assisting fisheries through increased fecundity, larval production, and spill-over (Gell and Roberts 2003, Russ *et al.* 2004). Sanctuaries can delay ecological impacts (Bates *et al.* 2014). Some habitats, in particular the offshore and deeper categories, are markedly under or unrepresented in sanctuary zones in the SIMP relative to other categories. This is likely to reduce the adequacy of the SIMP in helping to manage threats for some taxa, and needs strong consideration in future zoning arrangements.

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