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Defining conservation targets for fish and molluscs in the Port Stephens estuary, Australia using species-area relationships

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Abstract

Effective planning for marine protected areas should be based on conservation targets that are representative of underlying habitats and species distributions. Here, we present the results of an investigation into using species-area relationships (SARs) to define habitat conservation targets for two dominant taxonomic groups (fish and molluscs) using data from the Port Stephens estuary in New South Wales, Australia. Results demonstrated that planning conducted using variable habitat targets, based on SARs, provided significant improvements in representation of habitats and species, compared to planning using uniform (fixed percentage) habitat targets. Planning based on SARs was also found to provide significant improvements in species protection for fish and molluscs when compared with planning implemented without the benefit of detailed biodiversity information. However, SAR targets were found to be sensitive to the function type chosen to represent species distributions (i.e. power-law and exponential), and to the method used for estimation of species richness. Therefore, where SARs are used to set targets in conservation planning, it is important to ensure that they are representative of underlying species distributions. Overall, the improved performance of conservation planning based on SARs indicates the potential for broader application of this technique in planning marine protected areas.

Keywords

Species accumulation curve; Power-law; Marxan; marine protected area

1. Introduction

Effective conservation planning in marine protected areas (MPAs) involves systematic scientific investigations and consultation with stakeholders (Airamé et al., 2003; Fernandes et al., 2005). Given important MPA features are not readily apparent from the surface, planning for MPAs therefore needs to be based on accurate information, and robust methodology (Fernandes et al., 2005; Stewart et al., 2003). Despite this, MPA planning decisions are often made on an *ad hoc* basis, or with incomplete information, leading to inefficient, or inadequate design (Pressey, 1994; Stewart et al., 2003).

Marine conservation planning is implemented to accomplish a range of objectives including achieving social and economic goals (Ban et al., 2011; Stewart and Possingham, 2005), protecting rare and threatened species (Leslie, 2005; Powles et al., 2000) and conservation of biodiversity (Agardy et al., 2003; Leslie, 2005). Within this broader management framework, planning to protect biodiversity is frequently conducted using uniform conservation targets for habitats or regions, with a 10% target specified for marine areas in Convention on Biological Diversity Aichi Target 11, and 20% targets widely applied in marine protected area planning (Fernandes et al., 2005; Green et al., 2009). The use of uniform targets has, however, been criticised because they imply that all regions or habitats are adequately protected by the same criteria, which ignores biological variations across regions and habitats (Agardy et al., 2003; Pressey et al., 2003). Alternatives to uniform targets are therefore needed (Pressey et al., 2007; Svancara et al., 2005) and conservation targets based on species-area relationships (SARs) are increasingly being used for this purpose in marine conservation planning (Ashworth et al., 2010; Foster et al., 2013; Metcalfe et al., 2013).

The species-area relationship is one of the most widely recognised patterns in ecology (Connor and McCoy, 1979), with the number of species in a taxonomic group increasing with total area (Arrhenius, 1921). It therefore follows that the number of species protected will rise as the size of an effective protected area increases, and that SARs can therefore be used to calculate targets aimed at protecting a specified proportion of local species richness (Desmet and Cowling, 2004). This conservation approach provides a scientific basis for quantitatively setting non-uniform targets for habitats to protect the species they shelter (Metcalfe et al., 2013), and has been identified as being especially useful where protection of a broad range of species is required (Neigel, 2003).

Habitat targets for species protection defined based on SARs (SAR habitat targets) depend on the taxonomic group (Holt et al., 1999), the type of SAR function (Connor and McCoy, 1979), and the methodology used to derive functions from measured species data (Metcalfe et al., 2013). Multiple functions are available to represent SARs (Connor and McCoy, 1979), with power-law functions generally having the broadest applicability (Connor and McCoy, 1979; Williamson et al., 2001). However exponential functions are also widely applicable (Tittensor et al., 2007; Williamson et al., 2001) and other types of functions have been derived (Smith, 2010; Tjørve, 2003). Previous studies examining the use of SARs to set conservation targets for MPAs have generally been based on benthic fauna (Foster et al., 2013; Metcalfe et al., 2013; Rondinini, 2011), and have often selected power-law functions *a priori* to represent SARs (Metcalfe et al., 2013; Rondinini, 2011). However, the influence of taxonomic group and type of SAR function on SAR habitat targets has not been fully examined.

Given the complexity associated with defining SAR habitat targets, it is important to demonstrate that this methodology offers benefits, in terms of species protection, compared with using simpler uniform habitat targets, or conservation planning without detailed biodiversity data. Here, we investigate using SARs to set habitat conservation targets for two taxonomic groups (fish and molluscs) for the Port Stephens estuary, New South Wales, Australia, using data gathered over a 15 month period (Davis et al., 2016a). We further examine the impact on SAR derived conservation targets for habitats (SAR habitat targets) of using different SAR functions (power-law and exponential), and different algorithms for estimating species richness, with the objective of determining the sensitivity of targets to SAR modelling assumptions. We test the hypothesis that SAR habitat targets provide improved protection for fish and mollusc species, compared to uniform habitat targets. Finally given the Port Stephens estuary is within a large multi-use marine park, we examine the potential for implementing SAR habitat targets within the estuary using Marxan conservation planning software (Ball et al., 2009). The study aims to provide marine park management agencies with new approaches to use in conservation planning for protection of sub-tidal estuarine habitats and species.

2. Material and methods

2.1 Study site

The study was conducted using data from the Port Stephens estuary (Figure 1) which lies within the existing Port Stephens-Great Lakes Marine Park (PSGLMP), managed by the New South Wales (NSW) Marine Estate Management Authority. The PSGLMP is the largest marine park in NSW and was zoned into NSW protection-level categories, including no-take marine sanctuaries, in 2007 (NSWMPA, 2007). The Port Stephens estuary is a tide-dominated drowned river valley (Roy et al., 2001), which contains a diverse range of estuarine and marine habitats (Davis et al., 2016b). The estuary is of importance in NSW as it contains extensive areas of the threatened seagrass *Posidonia australis* (Creese et al., 2009), is the only known location where the soft coral *Dendronephthya australis* occurs in abundance (Poulos et al., 2013) and is important for threatened and protected species (Harasti et al., 2014a; Wiszniewski et al., 2009).

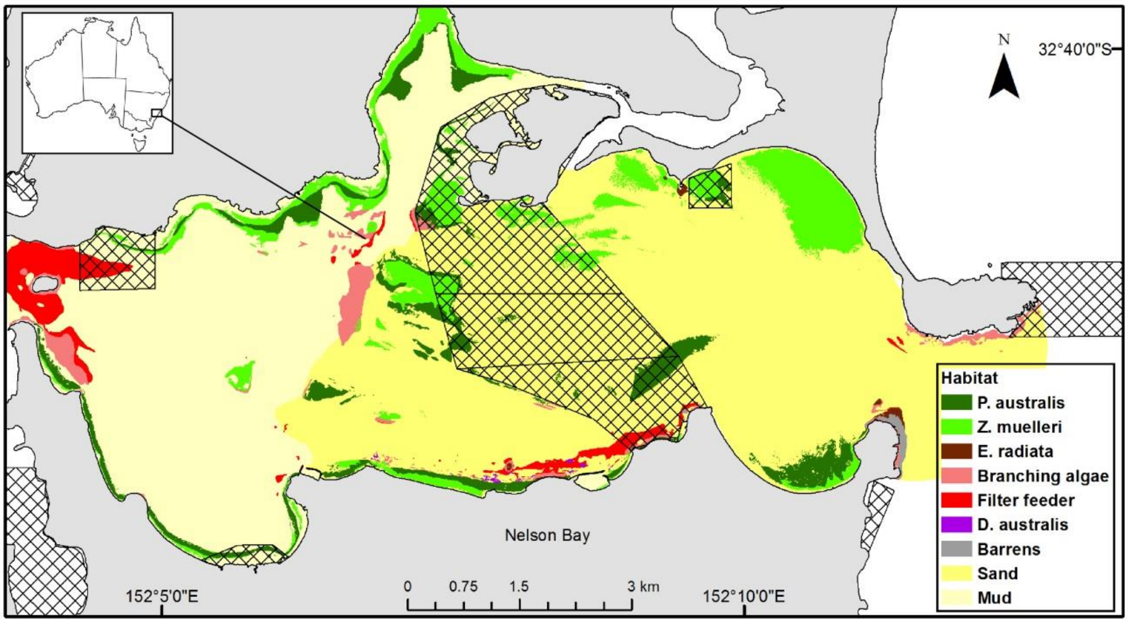

Figure 1: The Port Stephens estuary, New South Wales, Australia with existing no-take areas (hatched areas), and habitat types as described in Table 1.

2.2 Assessment of biological assemblages

Within the Port Stephen estuary, habitats were classified into eight major categories (Table 1) by Davis et al. (2016b) using the Australian CATAMI system for classifying underwater imagery (CATAMI, 2013). Biodiversity data were gathered in each habitat type, every three months from June 2014–August 2015, for fish (Davis et al., 2016a) and molluscs, giving twelve randomly situated replicate underwater visual census (UVC) belt transects (25×5 m) in each habitat, with methods adapted from Smith et al. (2008). These taxonomic groups were selected as they have been shown to provide useful surrogates for other phyla in marine assemblages (fish (Ward et al., 1999), and molluscs (Smith, 2005)). As biodiversity measures for habitats should be based on resident species, and exclude accidental or temporary immigrants, non-resident species (e.g. tropical and pelagic species) were excluded from all calculations. Tropical species typically occur in the study area only for brief periods (Booth et al., 2007), and pelagic species are highly variable at small spatial scales (McClanahan et al., 2007).

Table 1: Sub-tidal habitat types in the Port Stephens estuary. Habitat types classified by dominant biotic cover as defined by (Davis et al., 2016b)

Habitat type	Description
Barrens	Areas of rocky boulders dominated by encrusting coralline algae, with high abundances of the urchin *Centrostephanus rodgersii*
Branching algae	Areas dominated by mixed branching and filamentous macroalgal species, with filter feeders present in lower abundance
D. australis	Areas dominated by the soft coral *Dendronephthya australis*, with other filter feeders and macroalgae present in lower abundance
E. radiata	Areas dominated by the macroalgae *Ecklonia radiata* (i.e. kelp)
Filter feeder	Areas dominated by filter feeders (i.e. sponges, ascidians, hydroids, bryozoans, and corals) with macroalgae present in lower abundance
P. australis	Areas dominated by the seagrass *Posidonia australis*
Sand/Mud	Sand or mud substrate with minimal biotic cover (i.e. <10%)
Z. mulleri	Areas dominated by intermingled seagrasses *Zostera muelleri* ssp. *Capricorni* and/or *Halophila ovalis*

The ability of power-law functions (Eq. 1) and exponential functions (Eq. 2) to represent fish and mollusc SARs was evaluated by fitting both types of functions to species accumulation curves generated for fish and mollusc data (Figure 2),

$$S = c\,A^{z} \qquad (1)$$

$$S = d + e\log(A) \qquad (2)$$

(S = species, A = area, z = slope in log-log space, e = slope in log-linear space, c, d = constants dependent on function and region)

Species accumulation curves were generated by averaging across 100 random transect sequences, using EstimateS (Colwell, 2013), for the 96 transects conducted (i.e. twelve replicate transects in eight habitats). The accuracy of SAR function fit to measured species accumulation curves was assessed for both power-law and exponential functions using least-squares error estimates. Exponential functions (fish, $R^2 = 0.998$ and molluscs, $R^2 = 0.982$) provided a superior fit to observed distributions, compared with power-law functions (fish, $R^2 = 0.928$ and molluscs $R^2 = 0.963$, Figure 2), indicating that exponential functions provide more accurate representation of SARs for fish and molluscs within the study area.

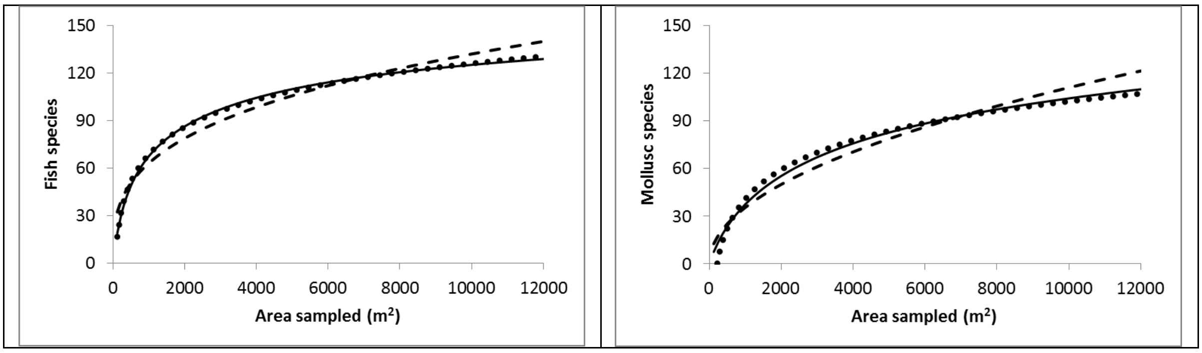

Figure 2: Species accumulation curves (solid lines) across all subtidal habitats in the Port Stephens estuary for fish and molluscs, and species-area relationship curves for exponential functions (dotted lines), and power-law functions (dashed lines).

2.3 Evaluation of conservation target sensitivity to SAR modelling assumptions

To evaluate sensitivity of SAR habitat targets to SAR modelling assumptions, targets were calculated for two taxonomic groups (fish and molluscs), for two different SAR function types (power-law and exponential), and two different algorithms for estimating species richness (Bootstrap and Jackknife 2). SAR habitat targets were calculated to protect 80% of the selected taxonomic group within each habitat, with the species protection level set at 80% as recommended by the Joint Nature Conservation Committee for conservation of marine species (Ashworth et al., 2010). Comparisons among SAR habitat targets for alternate methods were conducted using two-tailed paired Student's *t*-tests.

Species-area relationships were derived for each habitat, taxonomic group, function type, and species richness estimation technique, using the methodology proposed by Desmet and Cowling (2004), with functions fitted through (S_h, A_h), where S_h = the average species richness per transect in habitat-h, and A_h = habitat transect area (0.015 ha), and (S_{Th}, A_{Th}), where S_{Th} = the estimated total species richness in habitat-h, and A_{Th} = total area of habitat-h in the study region. From these, the slope (z) of the power-law function in log-log space (Eq. 3), and the slope (e) of the exponential function in log-linear space (Eq. 4) were calculated. Species-area relationship habitat targets (A’) were then calculated to provide specified species protection levels (S’) using equations derived for power-law functions (Eq. 5), and logarithmic functions (Eq. 6, ref. supplementary Appendix S1 for derivations).

$$z = (\log(S_{Th}) - \log(S_h)) / (\log(A_{Th}) - \log(A_h)) \qquad (3)$$

$$e = (S_{Th} - S_h) / (\log(A_{Th}) - \log(A_h)) \qquad (4)$$

$$A' = \sqrt[z]{S'} \qquad (5)$$

$$A' = 10^{\left((S'-1)S_{Th}/e\right)} \qquad (6)$$

Values for S_h and A_h were obtained from sampling data for each taxonomic group, values for A_{Th} were calculated using ArcMap (http://www.esri.com/, accessed 17 April 2015) using habitat maps of the Port Stephens estuary (Davis et al., 2015), and values for S_{Th} were estimated for each taxonomic group using either Bootstrap or Jackknife 2 species richness estimation techniques in EstimateS (Colwell, 2013). Estimated values for S_{Th} were calculated based on 100 random sampling sequences for each taxonomic group, across 12 transects in each habitat. The adequacy of sampling for calculation of S_{Th} was assessed by examining standard deviations between the final two estimates for S_{Th} (i.e. S_{Th} obtained from data for 11 and 12 transects), and ensuring that these were <5% of S_{Th}, as recommended by Desmet and Cowling (2004). Maximum deviations between estimates for S_{Th}, calculated from 11 and 12 transects, were 3.7% for fish and 4.3% for molluscs. Bootstrap species richness estimates were selected as these generally provided the lowest species richness estimates from the alternative options available in EstimateS (i.e. ACE, Bootstrap, Chao 1, Chao 2, ICE, Jackknife 1, Jacknife 2) and were used in the study conducted by Desmet and Cowling (2004). Jackknife 2 estimates were selected as these were generally among the highest species richness estimates for the study data, and Jackknife 2 has been shown to provide accurate estimates for species richness for small numbers of samples, as was the case for this study (Colwell and Coddington, 1994).

2.4 Conservation strategy evaluation

Protection levels for fish and mollusc species were compared among four alternate conservation strategies: (1) existing no-take areas; (2) uniform habitat targets for each habitat type; (3) SAR habitat targets for fish; and (4) SAR habitat targets for molluscs. Comparisons were conducted for the same total protected area (i.e. the area of existing no-take areas, 960 ha) determined from habitat maps of the Port Stephens estuary (Davis et al., 2015) using ArcMap . Uniform habitat targets (18.5%) were calculated from the ratio of total target area (960 ha) to total study site area (5181 ha). Habitat targets based on SARs were calculated to provide equal protection in each habitat for the selected taxonomic group. Comparisons were conducted using one-tailed, paired Student's *t*-tests for differences in average species protection among strategies, examining the hypothesis that species protection for conservation based on SAR habitat targets would be higher than for uniform habitat targets, and existing no-take areas.

For each conservation strategy, protection levels for fish and molluscs were calculated using SARs for each taxonomic group based on exponential functions and Jackknife 2 estimates for total species richness. Exponential functions were selected as they provided the most accurate representation of SARs for the study region (Figure 2), and Jackknife 2 estimates were used as these provided the most conservative (i.e. highest) estimates for total species richness.

2.5 Application of conservation targets in the Port Stephens estuary using Marxan

Marxan analyses were conducted using SAR habitat targets for fish and molluscs in the Port Stephens estuary, with a total target protected area of 960 ha. One hundred Marxan solutions were generated for each set of targets, using 614 hexagonal planning units (PUs), each with area $\leq$ 10 ha. Hexagonal PUs were selected as these provide more efficient solutions than square PUs (Nhancale and Smith, 2011). Ten-hectare PUs were used as they provide sufficient spatial resolution to distinguish among habitats across the study area, with smaller PUs shown to provide more efficient solutions in conservation planning (Pressey and Logan, 1998). A boundary length modifier (BLM) was applied to Marxan solutions to encourage compactness in conservation zones, with the BLM adding a cost penalty to solutions proportional to the free-edge length of selected PUs in solutions (Ardron et al., 2008). The magnitude of the BLM (0.02) was selected so that average values for BLM cost penalties had the same order of magnitude as PU costs, as recommended by Ardron et al. (2008). Calibrations were conducted to examine the effect of differing values for the BLM, with the selected value providing a good compromise between solution compactness and efficiency.

3. Results

3.1 Fish and mollusc species richness

Observations of fish and mollusc species across habitats identified 178 species of fish and 111 species of molluscs. Species richness in the study region was found to generally be higher for habitats with complex biotic assemblages and/or physical structures, with average species richness increasing from 6.6 ±0.5 fish/transect and 2.3 ±0.4 molluscs/transect in sand/mud, to 26.3 ±1.8 fish/transect and 12.4 ±1.1 molluscs/transect in branching algae (Table 2). Estimates of total species richness, from Bootstrap and Jackknife 2 extrapolation of species accumulation curves, also varied among habitats from 25–91 for fish, and from 10–87 for molluscs (Table 2). Jackknife 2 species richness estimates were significantly higher than Bootstrap estimates across habitats for both fish and molluscs ($P < 0.001$, both t-tests).

Table 2: Average species richness per 25×5 m transect (mean ±S.E, n=12) and Bootstrap / Jackknife 2 estimates of total species richness for fish and mollusc species in the Port Stephens estuary by habitat type (as per Table 1)

Habitat type	Average species / transect (Fish)	Bootstrap species richness (Fish)	Jackknife 2 species richness (Fish)	Average species / transect (Molluscs)	Bootstrap species richness (Molluscs)	Jackknife 2 species richness (Molluscs)
Barrens	22.2 ±1.2	61	79	5.2 ±0.6	27	40
Branching algae	26.3 ±1.8	76	91	12.4 ±1.1	58	87
D. australis	12.2 ±0.8	38	52	5.9 ±0.6	33	50
E. radiata	19.3 ±1.3	55	60	11.4 ±1.0	50	68
Filter feeder	26.1 ±2.6	73	86	10.3 ±1.3	56	76
P. australis	11.3 ±1.1	43	49	3.0 ±0.5	14	19
Sand/Mud	6.6 ±0.5	25	33	2.3 ±0.4	10	14
Z. mulleri	12.3 ±1.1	38	47	3.5 ±0.7	21	31

3.2 Influence of species-area relationships on conservation targets

Habitat targets based on SARs, to preserve 80% of species, were found to vary substantially among habitats, were highest for habitats with lowest spatial extents, and were significantly influenced by factors used to define SARs (Table 3). Average SAR habitat targets were significantly higher for molluscs (23.5 ±2.3%, mean ± S.E.) than for fish (16.0 ±1.7%, $P < 0.001$), primarily due to most molluscs being rarer and more variable than fish (Table 2). Habitat targets were also significantly influenced by the choice of SAR function, with average SAR habitat targets based on power-law functions (27.7 ±1.9%, Table 3 (1)-(2))

significantly higher than those for exponential functions (11.7 ±1.1%, Table 3 (3)-(4), $P < 0.001$). This difference resulted from SARs based on power-law functions predicting lower levels of species protection than exponential functions, for the same SAR habitat target. Therefore a greater proportion of each habitat was required in no-take areas to protect 80% of species for SARs based on power-law functions (e.g. Figure 3). Similarly, SAR habitat targets for Jackknife 2 species richness estimates (21.8 ±2.3%, Table 3) were significantly higher than those for Bootstrap estimates (17.6 ±1.9%, Table 3, $P < 0.001$) (e.g. Figure 3).

Table 3: Habitat areas and species-area relationship habitat targets (%) required to protect 80% of species (fish / mollusc) in habitats in the Port Stephens estuary for species-area relationships based on: (1) Power-law function with Bootstrap estimate of species richness; (2) Power-law function with Jackknife 2 estimate; (3) Exponential function with Bootstrap estimate; and (4) Exponential function with Jackknife 2 estimate

Habitat type	Area (ha)	(1) Power-law and Bootstrap (fish / mollusc)	(2) Power-law and Jackknife 2 (fish / mollusc)	(3) Exponential and Bootstrap (fish / mollusc)	(4) Exponential and Jackknife 2 (fish / mollusc)
Barrens	9.8	23.2 / 40.9	31.1 / 48.3	12.4 / 19.3	15.7 / 21.6
Branching algae	96.6	15.3 / 27.5	20.0 / 35.9	6.5 / 10.3	8.1 / 12.4
D. australis	3.6	32.7 / 35.4	42.1 / 45.9	18.8 / 20.0	22.9 / 24.4
E. radiata	6.4	26.4 / 38.9	29.4 / 45.9	14.6 / 19.8	15.9 / 22.4
Filter feeder	132.8	13.4 / 29.3	17.7 / 35.5	5.6 / 10.3	7.0 / 11.7
P. australis	264.4	18.7 / 23.7	22.1 / 30.2	6.6 / 7.9	7.5 / 9.4
Sand/Mud	4247.7	12.1 / 13.9	17.1 / 21.4	3.2 / 3.6	4.1 / 4.9
Z. mulleri	419.5	13.1 / 27.3	17.6 / 34.7	4.7 / 8.2	5.9 / 9.6

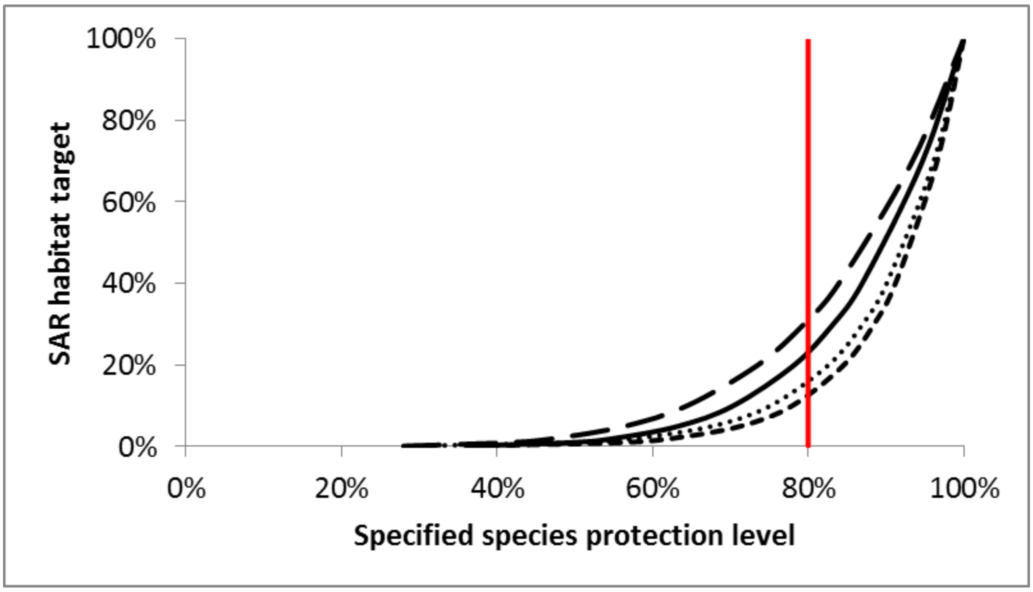

Figure 3: Species-area relationship (SAR) habitat targets, for barrens habitat, to provide specified species protection levels for fish in the Port Stephens estuary. Curves based on: Power-law function with Jackknife 2 estimate (long dashes); Power-law function with Bootstrap species richness estimate (solid line); Exponential function with Jackknife 2 estimate (dotted line); Exponential function with Bootstrap estimate (short dashes). 80% species protection target shown as vertical red line.

Overall, the greatest influence on SAR habitat targets resulted from the choice of function used to represent SARs, with choice of taxonomic group having a lesser effect, and choice of species richness estimator having the lowest effect on targets. The most conservative (i.e. highest) SAR habitat targets occurred for habitats with limited spatial extents, where SARs were generated using power-law functions, based on molluscs, with Jackknife 2 species richness estimates (Table 3).

3.3 Habitat and species protection levels for alternate conservation strategies

Comparisons among MPA conservation strategies showed substantial differences in protection levels for habitats, fish, and molluscs for alternate strategies (Table 4). Within existing no-take areas, protection for habitats varied from 0.0% for the soft-coral habitat *D. australis*, to 25.4% for the seagrass habitat *P. australis*, for fish species from 0.0–89.4%, and for mollusc species from 0.0–88.8%. The high variability in protection levels in existing no-take areas suggests that a lack of detailed biodiversity information prior to implementation in 2007, handicapped selection of representative habitat areas, especially for the least extensive habitats in the study area (i.e. barrens, *D. australis*, and *E. radiata*).

Applying uniform 18.5% habitat targets across habitats provided substantial improvement in protection levels for habitats and species, compared to existing no-take areas, with the same total protected area (960 ha, Table 4). Uniform habitat targets provided protection for equal proportions of all habitats (18.5%), and average protection levels for species across habitats were significantly higher for uniform targets (83.7 ±1.1%) than for the existing no-take areas (71.6 ±7.2%, $P = 0.040$, Table 4). Using uniform habitat targets also reduced variability in protection levels for species across habitats, with standard deviations in protection levels of 1.1% for uniform targets, compared to 7.2% for existing no-take areas.

Simulated implementation of SAR habitat targets provided further improvements in species protection levels, compared to uniform habitat targets, with significant increases in average protection levels for species ($P < 0.001$, both tests) for SARs based on fish (88.3 ±0.3%) and molluscs (89.0 ±0.2%, Table 4). These improvements were achieved through increased protection for less extensive habitats, and for habitats with higher species richness, generating increased protection for species for the same total protected area (960 ha).

Table 4: Habitat protection levels (%) and species protection levels (%) for fish and molluscs for alternate conservation strategies in the Port Stephens estuary (total protected area 960 ha); 1) Existing no-take areas; 2) conservation targets based on uniform protection for habitat; 3) species-area relationship (SAR) habitat targets for fish data; 4) SAR habitat targets for mollusc data. Species protection levels calculated using species area relationships with exponential functions and Jackknife 2 estimates of total species richness

Habitat type	1) Existing no-take areas			2) Uniform habitat targets			3) SAR habitat targets-fish			4) SAR habitat targets-molluscs		
	Habitat	Fish	Molluscs	Habitat	Fish	Molluscs	Habitat	Fish	Molluscs	Habitat	Fish	Molluscs
Barrens	10.5	75.6	70.5	18.5	81.8	77.9	36.3	89.1	87.1	40.6	90.2	88.2
Branching algae	9.3	81.1	77.2	18.5	86.6	83.8	25.2	89.1	86.6	29.2	90.4	88.2
D. australis	0.0	0.0	0.0	18.5	77.1	76.2	44.6	89.1	89.5	43.6	89.2	88.2
E. radiata	8.0	72.6	66.3	18.5	81.6	77.5	36.6	89.1	86.3	41.4	90.2	88.2
Filter feeder	19.7	87.8	84.9	18.5	87.3	84.3	23.3	89.1	86.4	28.3	90.2	88.2
P. australis	25.4	89.4	88.4	18.5	86.9	85.7	24.3	89.1	87.9	24.9	89.0	88.2
Sand/Mud	18.2	89.3	88.8	18.5	89.4	88.8	17.5	89.1	88.5	16.8	88.9	88.2
Z. mulleri	19.4	88.4	86.0	18.5	88.1	85.6	21.3	89.1	87.0	25.1	90.0	88.2
Average		73.0±10.7	70.3±10.5		84.8±1.5	82.5±1.7		89.1±0.0	87.4±0.4		89.8±0.2	88.2±0.0

3.4 Implementation of conservation strategies in the Port Stephens estuary

Marxan analyses to implement SAR habitat targets for fish and molluscs identified that multiple efficient solutions were possible for both taxonomic groups (Figure 4). Examination of the drivers behind frequently selected planning units (PUs) in Marxan solutions found that selection frequencies for PUs in localised regions were primarily driven by targets for specific habitat types (Figure 4a). Thus, targets for *E. radiata* and barrens drove selection frequency for PUs at the entrance to the estuary (region “A”, Figure 4a), and targets for *D. australis* and filter-feeder habitats drove selection frequencies along the southern shoreline of the central section of the estuary (region “B”, Figure 4a). Finally, selection frequencies in the entrance to the Myall Lakes (region “C”, Figure 4a) were to meet targets for seagrasses and branching algae, while PUs at the western end of the estuary (region “D”, Figure 4a) were selected to meet targets for filter feeders and branching algae.

Comparisons between locations of frequently selected PUs from Marxan solutions, and existing no-take areas, identified that existing no-take areas did not incorporate most of the PUs with high selection frequencies (Figure 4). The lack of overlap between existing no-take areas, and frequently selected PUs in Marxan solutions based on SARs indicates that existing no-take areas require substantial modification to improve levels of protection to those obtained in analyses using SARs.

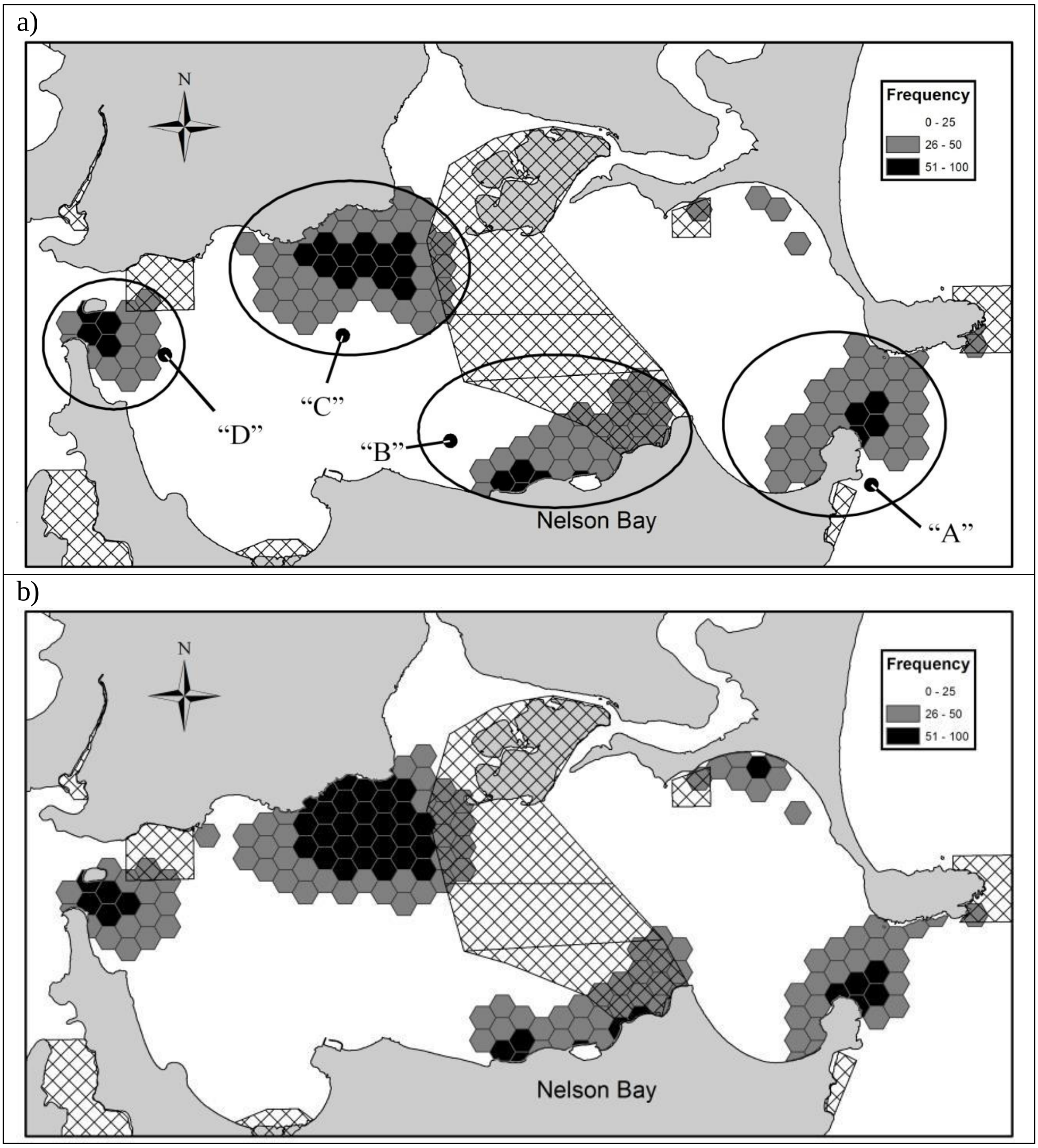

Figure 4: Marxan planning unit selection frequencies for protection of a) fish and b) molluscs in the Port Stephens estuary. Frequencies based on 100 solutions with targets for species-area relationships based on exponential functions with Jackknife 2 species richness estimates. Port-Stephens-Great Lakes Marine Park existing no-take areas shown as hatched areas. Circled regions (“A”-“D”) indicate areas where planning unit selection frequency was driven by targets for specific habitat types as discussed in the main text.

4. Discussion

Achieving efficient protection of species in conservation planning requires information on habitat and species distributions, and the use of appropriate methods for setting conservation targets (Margules and Pressey, 2000). Here, we demonstrate that significant improvements in species protection can be achieved using variable conservation targets for habitats based on SARs, compared to uniform targets. However SAR habitat targets were found to be significantly influenced by the taxonomic group used in their derivation, the type of SAR function selected, and the species richness estimates used to derive SARs. Therefore, although SAR habitat targets can provide theoretical improvements in conservation efficiency, it is important that the methodology used to define SARs is appropriate and adequately represents underlying species distributions (Connor and McCoy, 1979).

Species-area relationships often vary between taxonomic groups (Holt et al., 1999) and our results indicate that significant differences occur in targets for habitats derived using SARs from different taxonomic groups, with lower targets calculated for fish than for molluscs. These differences were primarily driven by greater spatial variability in mollusc populations among transects, necessitating protection of a larger proportion of their habitats in order to achieve the same level of protection as fish. These results indicate that the applicability of targets based on SARs across different taxonomic groups is limited, and careful consideration should be given to these limitations when SARs are used to set targets for the conservation of biodiversity across multiple taxonomic groups. Ideally, where data is available, habitat targets should be calculated across all taxonomic groups and the most conservative habitat targets used in conservation planning.

It is also important that functions used to represent SARs are only selected *a priori* where evidence exists to support use of the chosen function. If this evidence is not available, then functions need to be tested against observations, and the most appropriate function selected (Connor and McCoy, 1979; He and Legendre, 1996). We found that choice of different SAR functions resulted in significant differences in calculated conservation targets. Therefore, inappropriate *a priori* selection of a SAR function can strongly affect predicted protection levels for species, and the habitat conservation targets required to achieve these. Power-law functions, despite being widely applied (Williamson et al., 2001), are not the only type of curve that can, or should, be used to represent SARs (Connor and McCoy, 1979). Here, we identified that exponential functions more accurately represented species distributions for both fish and molluscs, with exponential functions recommended for studies where sampling occurs over small areas, as is the case in this study (He and Legendre, 1996).

Inaccuracies in habitat targets resulting from use of inappropriate SAR functions could potentially be exacerbated by poor selection of algorithms for estimation of species richness. For example, Metcalfe et al. (2013) found that choice of algorithms influenced targets based on SARs. In our study there were also significant differences between habitat targets calculated using species richness from different species richness estimation algorithms. We found that the most conservative habitat targets were provided by using the algorithm predicting the highest species richness (Jackknife 2), but importantly we found that algorithm choice had a lower effect on habitat targets than choice of SAR function and taxonomic group.

4.1 Comparison of conservation strategy performances

Although uniform targets have been widely applied in marine conservation planning (Fernandes et al., 2005; Green et al., 2009), they are no longer seen as an ideal approach due to their lack of connection to underlying biodiversity and ecological processes (Agardy et al., 2003; Pressey et al., 2003). Indeed, we found that conservation targets for habitats, based on SARs, provided significant improvements in species protection levels for fish and molluscs when compared with uniform habitat targets. Therefore, our results support the study hypothesis that habitat targets based on SARs outperform uniform habitat targets, in terms of protection for fish and molluscs species.

Within the Port Stephens estuary, planning for existing no-take areas was conducted without the detailed biodiversity information on distributions of habitats and fish and molluscs species that is now available (Davis et al., 2016a; Davis et al., 2016b). Studies in both terrestrial (Grand et al., 2007) and marine environments (Stewart et al., 2003) have identified that planning using inadequate data leads to inefficient design of terrestrial reserves and marine no-take areas. In our study, the existing no-take areas provided inadequate protection for some habitats, and the species they contain, especially *D. australis,* and *E. radiata*. These results clearly highlight the importance of having adequate biodiversity information prior to conducting systematic conservation planning.

The absence of adequate protection within existing no-take areas for the soft coral *D. australis*, is of particular concern. The Port Stephens estuary is the only location where this species is known to occur in abundance (Poulos et al., 2015), and there is evidence that the habitat is under threat (Harasti, 2016; Smith and Edgar, 2014). *D. australis* shelters a number of protected and endemic species, especially syngnathids (seahorses and pipefish, Harasti et al., 2014b), and loss of *D. australis* habitat has been linked to declines in populations of the protected seahorse *Hippocampus whitei* (Harasti, 2016). Species with limited geographic ranges are at higher risk of extinction, especially if they are subjected to disturbances (Purvis et al., 2000) and estuarine systems, such as Port Stephens, are subjected to high levels of disturbance due to their proximity to centres of human habitation (Kennish, 2002). Achieving adequate levels of protection for *D. australis* is therefore vital to prevent local extinction of this species, and the species it shelters. While increased representation of *D. australis* within no-take areas will address some of the threats faced by this habitat (i.e. those related to fishing), the habitat also faces a number of threats that are not addressed by no-take zones (e.g. entanglement by marine debris (Smith and Edgar, 2014) and mooring damage (Harasti, 2016)). An integrated management approach, addressing all threats faced by *D. australis*, is therefore required to provide adequate protection for this habitat.

In contrast, *E. radiata* (kelp) is a broad-ranging habitat-forming species, occurring throughout NSW (Coleman et al., 2011; Underwood et al., 1991) and more generally across temperate areas of the southern hemisphere (Wernberg et al., 2003). The current low level of protection for this habitat within the Port Stephens estuary should therefore be compensated for, to some extent, by protection of other areas of the habitat within marine sanctuaries across its range.

Ideally, conservation targets should be influenced by the spatial extent of habitats, and by species distributions, with increased protection for rarer and more diverse habitats, as these are at increased risk of significant species losses and extinctions (Purvis et al., 2000; Sala et al., 2002). Examination of the outcomes of using SARs to set conservation targets found that this methodology achieved these objectives, with elevated protection levels for rarer habitats, and habitats with higher species richness.

4.2 Application of conservation strategies using Marxan

Setting habitat targets is only one stage in the conservation planning process and meeting conservation objectives also requires that these theoretical targets can be achieved in practice within the areas of interest (Margules and Pressey, 2000). Here, we identified that habitat targets generated using SARs for fish and molluscs could be applied in the Port Stephens estuary, with multiple efficient solutions obtainable using Marxan. Implementation of these solutions would, however, require substantial modification of existing no-take areas to incorporate additional areas of some habitats. This could be achieved with no net increase in total conserved area by allowing small reductions in the protected area for more extensive habitats (e.g. sand or mud). The Marxan solutions provide guidance on areas that could be incorporated into existing no-take areas to achieve improvements in protection for habitats and species, and those which could be removed from existing no-take areas to offset the costs associated with the improvements, and to improve the overall efficiency of conservation planning.

While planning using conservation targets for habitats from SARs has been shown to provide efficient solutions for species protection, these solutions have substantial limitations. Habitat targets from SARs are set to protect a specified level of local species richness, based on a limited temporal snapshot of species diversity, but do not ensure that viable populations are protected (Smith, 2010), and do not provide insight into which species are protected and which are not (Desmet and Cowling, 2004; Metcalfe et al., 2013). Additional consideration therefore needs to be given in conservation planning to protecting areas that are of importance to threatened species. Conservation planning also needs to account for threats to habitats, and the risk levels associated with those threats, with increased levels of protection indicated for habitats which are at high risk from serious threats (Green et al., 2009). Habitats also need additional protections where threats are not addressed by no-take areas, such as those from pollution, climate change, coastal development, invasive marine species and increased nutrient flows (Crain et al., 2009). Finally, it should be noted that achieving conservation outcomes is only one facet of systematic conservation planning, with social and economic objectives equally important if conservation plans are to be successfully implemented and adopted by the wider community (Green et al., 2009; Stewart and Possingham, 2005).

5. Conclusions

Using SARs to systematically define conservation targets for habitats can provide significant improvements in representation of habitats and species in conservation planning. Habitat targets based on SARs were found to provide significant improvements in protection for fish and mollusc species, compared to uniform habitat targets, for the Port Stephens estuary. The methodology developed in this study, therefore, provides management agencies with the basis for more objective planning of zoning iterations for the estuarine section of the PSGLMP. The improved performance of habitat targets based on SARs, compared to uniform habitat targets, indicates potential for broader application of this technique in planning marine reserve networks where detailed biodiversity information is available. The use of SARs for these purposes, however, needs to be based on appropriate methods, with careful consideration given to choice of SAR function type, taxonomic group, and species richness estimation technique. In addition, overall planning should consider social and economic objectives, in combination with these environmental targets, and should incorporate broader assessments that examine risks and threats to habitat and species viability.

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