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A FRAMEWORK FOR SYSTEMATIC MARINE RESERVE DESIGN IN SOUTH AUSTRALIA: A CASE STUDY

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Abstract

Ad hoc reserve design has been shown to produce inefficient reserve systems in terrestrial environments, limiting opportunities to achieve conservation goals. In this paper, we devise a framework for systematic marine reserve design using South Australia as a case study. The framework consists of the reservation goals, a database of conservation features, a method for identifying conservation priorities and measures to evaluate the performance of alternative marine reserve systems. MARXAN, a reserve selection algorithm, was used to identify marine reserve systems for three different scenarios. In the first scenario, MARXAN was free to either ignore or incorporate South Australia's existing marine reserves. The second scenario was required to identify marine reserve systems that built on South Australia's existing marine reserves, whilst the third scenario gave preference to sites adjacent to South Australia existing coastal and island reserves. Expanding on the existing marine reserves led to significantly larger marine reserve systems, reflecting the inefficiency of *ad hoc* marine reserve design decisions in South Australia. Using area to perimeter ratio as a measure of efficiency, we then explore the consequences of spatial clustering in alternative marine reserve systems.

Keywords
Systematic marine reserve design; marine reserves; conservation planning; optimisation; efficiency; South Australia

1 INTRODUCTION

Efficiency is an important consideration for *in situ* biodiversity conservation, due to the limited availability of resources to achieve reservation goals (Pressey and Nicholls, 1989, Freitag et al., 1996, Rodrigues et al., 1999, Araujo, 1999, Pressey, 1994, Bedward et al., 1992, McDonnell et al., 2002, Pressey et al., 1999, Pressey et al., 1993). It refers to the ability of a reserve design process to represent regional biodiversity in the least number of available sites (Freitag et al., 1996, Pressey and Nicholls, 1989, Pressey and Cowling, 2001, Underhill, 1994, Camm et al., 1996). This particular expression of the reserve design problem was first described by Kirkpatrick (1983) as the minimum representation problem. It is derived from the idea that whilst biodiversity conservation objectives may wish to maximize the area within the reserve system, they must compete against social, economic and management constraints (Possingham et al., 2000). Being efficient ensures flexibility in the future and provides the opportunity to negotiate acceptable outcomes.

Since Kirkpatrick's publication of the first reserve selection algorithm, the use of iterative algorithms to identify the minimum (or near-minimum) representation solution has been successfully applied to reserve design in terrestrial systems (McDonnell et al., 2002, Bedward et al., 1992, Williams et al., 1996, Margules and Nicholls, 1988, Kirkpatrick, 1983). Despite considerable interest, reserve selection algorithms have only recently been applied to marine reserve planning (Leslie et al., in press, Beck and Odaya, 2001, Ball and Possingham, 2001, Ward et al., 1999, Ardron et al., 2001). Our aim is to show how mathematical methods can be applied to identify efficient marine reserve systems. In particular, we investigate the utility of mathematical algorithms as a flexible decision support tool to investigate options for marine reserve design specifically, and more broadly for regional marine planning.

As efficiency of sampling and performance of marine reserve systems in general, is largely determined by how the reserve design problem is framed, we begin with the development of a systematic marine reserve design framework, using South Australia as our case study. The framework consists of reservation goals, a database of conservation features, a method for identifying conservation priorities and measures to evaluate the performance of alternative marine reserve systems. We show how alternative marine reserve systems can be generated under different circumstances by applying the reserve design framework to three scenarios. The first scenario ignores the status of South Australia's existing marine reserves; the second scenario locks-in South Australia's existing marine reserves for the design of all marine reserve systems, and the third scenario preferentially selects sites adjacent to existing coastal national parks or offshore island reserves).

We consider how the efficiency of the marine reserve systems is influenced by the constraints of each scenario and particularly, how efficiency is affected when the existing reserves are retained. We also evaluate the performance of marine reserve systems against secondary goals such as size and shape. To provide a context for the application of a marine reserve design in South Australia, we commence with a brief overview of the status of marine reserve planning in South Australia.

1.1 Status of South Australia's Marine Reserve System

South Australia is located on the temperate coast of Australia in a region that has been geographically and climatically isolated for around 65 million years. It features some of the highest levels of marine endemism in Australia and the world, with 90-95% of known species endemic or of restricted range (Edyvane, 1999a, IMCRA Technical Group, 1997). The general consensus is that marine reserve planning has been *ad hoc* and is inadequate to meet current conservation objectives (Government of South Australia, 1998). A recent report listed 15 marine protected areas amounting to almost 60,000 hectares (Edyvane, 1999a). This represents 0.9% of the state waters and a contribution of less than 0.2% to the national total. Since then, the establishment of the Great Australian Bight Marine Park has increased this value to around 4.5% of state waters, however a considerably lesser amount is dedicated to no-take areas.

In recognizing the inadequacies of the existing system, the South Australian government has announced its intention to establish a system of multiple-use Marine Protected Areas. Their proposed goal is "to maintain the long term ecological viability and processes of marine and estuarine systems, and contribute to ecologically sustainable development" (MES). In addition, they carry a responsibility to contribute to the primary goal of the National Representative System of Marine Protected Areas, "...to establish and manage a comprehensive, adequate and representative system of MPAs…" (marine protected areas) (ANZECC, 1999).

2 METHODS FOR ESTABLISHING A MARINE RESERVE DESIGN FRAMEWORK FOR SOUTH AUSTRALIA

2.1 System Goals and Objectives

Mathematical approaches require a clear statement of the conservation objective in order to inform how reservation will proceed. For example, a marine reserve system that emphasizes the protection of charismatic, rare and threatened species will differ from a reserve system that aims to maximize representation of marine biodiversity. In this paper, our goal is to identify marine reserve systems that are as representative of biodiversity as possible (ANZECC, 1999, Pressey and Cowling, 2001, Kelleher, 1997, Agardy, 1994, Ballantine, 1991).

As biodiversity is still a vague concept for which there is no simple, comprehensive and fully operation definition (Noss, 1990), our first task is to establish operational definitions for biodiversity. For both marine and terrestrial systems this is hampered by limited information and poor understanding of ecological processes (Pressey and McNeill, 1996). As many aspects of reserve design are subject to uncertainty, existing scientific information has been considered to identify some general reserve design principles (Pressey et al., 1993, Ballantine, 1991, Salm, 1984). Adopting a systems-based approach with replication and preferably, larger rather than smaller reserves are typical goals that can be implemented. Ideally, sites would be situated at 'source' locations in an arrangement that supports positive ecosystem linkages (Pulliam and Danielson, 1991). Reserve size would take into consideration the long-term viability of populations and communities, with provision for catastrophes (Allison et al., in press).

The objective and goal for our analyses is to design marine reserve systems that are representative of our surrogates for biodiversity, but use the least number of sites. We set proportional representation targets at 10% for all conservation features but ignore explicit rules for replication.

2.2 Database

The lesson for marine reserve planning is not to be constrained by single indices for which data are available, but where possible to recognize and provide for the inherent complexities of marine systems and their functions by representing as many features as possible. This is feasible when using reserve selection algorithms, which guarantee that representation targets will be met. The critical issue then is whether the biodiversity surrogates used to identify representative marine reserve systems can ensure that systems are comprehensive as well. This calls for the identification of surrogates at an appropriate level of organization (Noss, 1990) and quite possibly, at multiple levels of organization.

To capture patterns of biodiversity, we proceeded with a hierarchical approach which focused on providing a consistent framework for conservation planning (Pressey et al., 2000, Noss, 1990). Using this method, the basic unit of biodiversity (species) is generalized into more heterogeneous classes such as ecological communities or species assemblages (Margules and Usher, 1981). However, the more generalized classes become, the less confidant we can be that reserve systems are comprehensive, for the variability within a class is ignored. We can counter the size of this effect by increasing the level of representation for each conservation feature (i.e. total amount) and replication (i.e. multiple occurrences).

We outline the conservation features used as biodiversity surrogates for the design of representative marine reserve systems for South Australian state waters. Conservation features were identified from 6 data layers obtained from state government agencies: the Department for Environment and Heritage, and the Department for Primary Industries, South Australia. An additional feature class was delineated to represent the status of South Australia's existing reserves.

2.2.1 Biogeographic regions (meso-scale 100-1000s of km)

Biogeographic regions have been identified at the national level using a marine ecosystem-based classification scheme, known as the Interim Marine and Coastal Regionalisation of Australia (IMCRA). The classification provides a scientific basis for reporting on the adequacy of marine ecosystem representation in the national system of marine reserves. It was derived using a combination of expert field ecological knowledge and interpretation of existing regionalisations (IMCRA Technical Group, 1997). These include sea floor topography, sea floor sediments, physical oceanographic water column, coastal zone geomorphology and pelagic and demersal fish regionalisations. Each bioregion comprises a cluster of interacting ecosystems that are repeated in similar form throughout. There are 60 bioregions delineated for the Australian coastal and offshore waters and 8 of these occur wholly or partly within South Australian state waters.

2.2.2 Biounits (micro-scale 10-100s of km)

At this micro-scale level, distinct regional and local variations in habitat and biodiversity occur. These variations are classified on the basis of local-scale ecological units (i.e. rocky shores, shoals or reef systems) and information on the spatial extent of these units. South Australia's micro-scale biounits were defined primarily on the basis of coastal physiography, topography and major marine physical habitat or seascape features, as well as habitat distribution (Edyvane, 1999b). A total of 35 biounits have been identified and comprise 30 coastal biounits and 5 offshore units (Edyvane, 1999b). Seaward boundaries of the coastal biounits were defined using the 30 m bathymetric contour. For the offshore biounits boundaries were drawn at the 50 m depth contour. Because biounits are not always nested within the meso-scale bioregions, each data layer represented a unique conservation feature class.

2.2.3 Marine benthic habitat maps

The idea of habitat representation is based on the notion that by conserving all habitats, the maximum number of species will be represented, including species not used to define the habitats (Margules and Nicholls 1989). Ward et al. (1999) concluded that habitat level surrogates can be used effectively to delineate reserves for conserving marine biodiversity.

Benthic habitat coverage has been mapped for coastal and gulf waters of the state. Habitats were identified by tracing of discernible underwater features on satellite images. Aerial photographs were used for 'truthing'. The resulting dataset uses biological data for classification of seagrass densities and geomorphological descriptions for reefs. As a benthic classification scheme has not yet been developed for South Australia, habitat type is classified at a broad level (i.e. seagrass, platform reef, sand) and does not incorporate information on the dominant species assemblages. We identified 6 unique conservation features in this feature class.

2.2.4 Coastal saltmarsh and mangrove habitats

Intertidal vegetation of the coastal regions of South Australia has been identified from digitised 1:40000, 1:15000 and 1:10000 non-rectified aerial photography. Habitats were classified and coded using landform, life form and condition categories. Classification was based on aerial photo interpretation, survey data, ground truthing and expert knowledge. In total, 65 habitat classes were identified with 11 of these relating to intertidal or tidal areas. To approximate a similar scale of resolution to that of the marine benthic habitat categories identified above, these classes were collapsed into the more generalised categories of intertidal/tidal marine algae; intertidal and tidal bare sand; intertidal/tidal seagrass, mangroves and saltmarsh. This classification provided a further 5 unique conservation features.

2.2.5 Species occurrence

Species occurrence data were incorporated where coverage extended across the study area and occurrence records were of sufficient quality. On these grounds, we identified 3 conservation features from the data layers available for South Australian distributions of seabirds, Australian sea lions and New Zealand fur seals.

Seabirds of South Australia – This dataset describes population and breeding seasons, including mainland and offshore island sites. The dataset is suitable for the identification of significant seabird habitat communities within South Australia.

Australians sea lions and New Zealand fur seals within South Australian waters- sea lion and fur seal locations are identified, with population, breeding season and breeding and haulout sites for both the mainland and island locations. The dataset is suitable to identify significant breeding and haul out sites for habitat conservation purposes.

2.2.6 Bathymetry

This dataset is a compilation of water depths for the offshore waters of South Australia, with depth values representing depths to the seabed. Data were collected as part of the National Mapping Bathymetric Program, which was designed to provide generalized detail of the seabed of the Continental Shelf. Depth values were delineated into 5 categories, 0-10 m, 10-20m; 20-30 m; 30-40 m and 50 m +. By seeking proportional representation of each depth category, we aim to achieve representation of offshore environments, where biological data are often limited. We therefore devised a constraint requiring representation of each depth category within each of the 8 bioregions. This provided an additional 40 conservation features.

2.2.7 Protected areas

This data layer provides an accurate location for the legal boundaries of both terrestrial and marine reserves and is used to formulate marine reserve design scenarios. In South Australia, different legislation can be used to designate marine protected areas (marine reserves) and the level of protection afforded to a reserve can vary widely (i.e. netting closures, marine sanctuaries and multiple use marine parks). We generated a user defined marine reserve theme as a subset of protected areas derived from the Australian Collaborative Protected Area Database. It includes areas recognized as marine reserves, as well as coastal/offshore island reserves with significant marine components. Rock lobster sanctuaries and netting closures were not included. Consequently, in this paper South Australia's existing marine reserves comprised 21 marine reserves with a total area of approximately 2880 km^2.

2.2.8 Conservation features

The conservation features are what our reserve system will attempt to cover. They are recorded as either distributions (i.e. coverage) or abundance (i.e. species abundance). Our database encompassed 97 conservation features identified from the 6 biophysical data layers described above.

The database was formatted for conservation evaluation, using a series of geographical information system (GIS) processing steps to define the planning units (i.e. the basic selection units) and create suitable data files. For the analyses, we created a grid extending west to east from the Western Australia boarder to the Victorian border and north to south encompassing all South Australian state waters. This process delineated 3119 planning units, with each planning unit a 5 km X 5 km cell. Due to the irregular shape of the study area, a number of these were truncated at the coastline and offshore islands, and so provided some size variation across the study area. Each planning unit then contains information on the amount of each conservation feature within. The amount of each conservation feature *j* in each planning unit *i* formed the basic data matrix a_{ij}. With 97 conservation features and 3119 planning units, 19597 occurrences were recorded in all.

2.3 Using Mathematical Reserve Selection Methods for Conservation Evaluation

Reserve selection algorithms differ from traditional marine reserve selection methods in how they define the reserve selection problem. At the core of the problem is the goal of minimizing the area encompassed in the reserve network, described by Kirkpatrick (1983) as the minimum representation problem and formulated by Possingham et al. (2000) as a non-linear integer programming problem:

Minimize the objective function:

$$\sum_{i=1}^{M} c_i x_i + BLM\left(\sum_{i=1}^{M} x_i l_i - 0.5\sum_{i=1}^{M} x_i \sum_{k=1}^{M} x_k b_{ik}\right) \qquad (1)$$

subject to the constraints:

$$\sum_{i=1}^{M} a_{ij} x_i \geq t_j \sum_{i=1}^{M} a_{ij} \quad \text{for all } j = 1..N,$$

$$x_i \in \{0,1\} \quad \text{for all } i = 1..M, \qquad (2)$$

where x_i are the control variables such that if x_i=1 then site i is selected for the reserve system and if x_i=0 then site *i* is not in the reserve system, c_i is the "cost" of site *i*. l_i is the perimeter or boundary length of site *i*, b_{ik} is the common boundary length of sites *i* and *k*. BLM is the boundary length modifier variable that controls the weight given to the boundary length. It allows spatial design requirements to be incorporated by determining the relative importance placed on minimizing the boundary length relative to minimizing area. When BLM is very small then the algorithm will concentrate on minimizing area, while if BLM is relatively large then there is greater emphasis on minimizing the boundary length and more spatially compact reserve systems are configured.

Equation 1 is our objective: minimize a linear combination of site costs and reserve system boundary length (the length of the boarder between selected and unselected planning units). in this paper, costs are expressed as the number of planning units in the marine reserve system. Equation 2 is a set of constraints that ensures the target for each conservation feature is met where a_{ij} is the abundance of the feature type j in site i and t_j sets the target fraction for each feature (in this paper we assume $t_j = 10\%$ for all j). There are N different conservation features spread across M different sites. A feasible solution is one, which selects a set of sites (using the control variables x_i), whilst ensuring that the specified level of representation for each conservation feature is met.

2.3.1 MARXAN-Reserve Selection Algorithm

MARXAN – a tool for Marine Reserve Design, was designed by Ian Ball and Hugh Possingham (Ball, 2000, Ball and Possingham, 2000) and is based on terrestrial reserve design software by the same authors. The software is freely available and can be downloaded from www.ecology.uq.edu.au.

Because our reserve design problem is large (2^{3119} possible marine reserve systems), it is virtually impossible to find an optimal solution in reasonable time. MARXAN provides an alternative method, using optimisation methods to identify reasonably good solutions by selecting a set of sites to achieve the best objective function score. In this paper, we use simulated annealing with iterative improvement to select planning units that satisfy a set target of ecological, spatial, social and economic criteria. A planning unit is randomly added to the reserve system and the change to the system is evaluated. The planning unit is then added or removed, depending on the evaluation. This process continues for a set number of iterations and has the advantage of allowing the reserve system to move temporarily through sub-optimal solutions space, increasing the number of routes by which the global minimum might be reached (Possingham et al., 2000). This method generates marine reserve systems that can have identical or very similar objective function scores but with different configurations. By repeating the selection process (simulation), MARXAN can identify a range of reasonably good solutions to the same problem.

2.4 Generating Alternative Marine Reserve System Solutions

Our analyses consider the effect of two variable factors: the reserve design scenario constraints (*No Reserves*; *Reserves Fixed; Reserves Free*) and the boundary length modifier (set at values of 0, 0.1, 0.5 and 1.0). In total, this provided 12 different marine reserve system design problems. For each problem 10 replicate simulations were performed, with each simulation comprising 1000 runs. Thus, generating 10,000 alternative marine reserve systems for each reserve design problem.

2.4.1 Reserve Design Scenarios

We devised three scenarios for the design of marine reserve systems in South Australia, with each formulated in mathematical terms using equation (1) and (2) described above.

The "No Reserves" scenario, follows the problem defined by equations (1) and (2). The number of conservation features *N* is 97, the number of sites *M* is 3119. As we ignore the status of South Australia's existing marine reserves, our control variable x_i can assume a value of either 0 or 1 for all 3119 planning units. If x_i =1 then that planning unit forms part of the reserve system and if x_i =0, planning unit *i* is excluded from the reserve system. We set the cost variable c_i to 1, which means every site has equal cost. The parameter l_i is the boundary length (km) of planning unit i and b_{ik} is the common boundary length (km) of planning unit *i* and *k*. This delivers a benefit to planning units that share a common boundary. Conservation feature targets are set to a target fraction of their regional coverage t_i in this case at 0.1 (10%). Lastly, the abundance of the conservation feature type j in planning unit i is depicted by the variable a_{ij} .

A "Reserves Fixed" scenario alters the 'status' of individual planning units by locking in the sample of planning units that represent South Australia's existing reserves. We revisit equations (1) and (2) to formulate the problem, where we maximize the objective function and constraints as before but with $x_i = 1$ for all sites that are in the existing reserves. This amounts to 288 planning units that represent South Australia's existing reserves. We adopt the matrix defined for the *no reserves* scenario with minor amendment, as there are now fewer sites available for selection (the existing reserves are all locked-in). Accordingly, our control variable x_i now assumes a value of either 0 or 1 for only 2831 planning units. The problem is to add to the existing reserves until the conservation targets are met.

A "*Reserves Free"* scenario, uses the same matrix as defined for the *No reserves* scenario, except that information on adjacent land types is incorporated to modify boundary length cost. So where planning unit *i* is adjacent to an existing coastal or marine reserve, the boundary length parameter l_i (km) of planning unit *i* is set to 0. This scenario assumes that the adjacent land type makes some contribution towards the reserve system goals such as reduced management costs, which may be the case when marine reserves abut coastal reserves.

2.5 Performance Measures

For each marine reserve system generated, MARXAN generates summary data, which includes the objective function score, the number of planning units and the total boundary length. The best (near-minimum) marine reserve system configuration is identified as the one with the lowest objective function score (from a total of 10,000 alternative solutions). These are then mapped in a geographical information system (GIS) platform and the number of individual reserves and total area of the best marine reserve system calculated. Because solutions with the lowest objective function score may not always be the preferred marine reserve system when other constraints are considered, we employ alternative measures to evaluate differences between marine reserve systems generated for our reserve design problems.

To assess how efficiently representation targets are being met, we use Pressey's (Pressey and Nicholls, 1989) measure of *efficiency*. It varies from 0 to 1, with 1 being the most efficient solution.

$$E = 1 - X/T \tag{3}$$

Where E is efficiency, X is the number of planning units needed to meet the constraints, and T is the total number of planning units.

As we are also interested in the spatial configuration of the reserve system, we provide *compactness* as a measure of the ratio of the reserve system boundary length to the circumference of a circle with the same area (the theoretical minimum). As values near 0 the solution becomes more compact and as values increase, solutions become more fragmented.

$$\text{Ratio} = \frac{\text{Boundary Length}}{2\sqrt{\pi \times \text{Area}}} \tag{4}$$

The effect of spatial clustering on the marine reserve system perimeter, area, compactness and marine reserve system combination size (number of planning units in a solution) was examined by varying BLM. Analyses were performed on the best marine reserve system for each different reserve design problem.

As there are many possible marine reserve systems, it is useful to know something about the relative importance of individual planning units for conservation planning. We use selection frequency counts, otherwise referred to as 'summed irreplaceability' to provide a measure of the contribution of any one planning unit to the reservation goals (Ball and Possingham, 2001, Pressey et al., 1994, Leslie et al., in press). It assumes that the relative value of a planning unit increases the more times it is selected. In this paper, we use an approach defined by Stewart et al. (Stewart et al., in press.) that uses the mean combination size (Ferrier et al., 2000) to determine the probability, p, that any site is chosen by random. This allows us to determine whether or not a site is selected by MARXAN more than randomly, by comparing selection frequencies to that expected for a binomial distribution with probability, p, of success over 10000 trials. We then compare individual planning unit selection frequency counts with the 95% confidence interval for predicted selection frequency distributions, to determine whether planning units are selected more than could be expected from chance alone.

3 RESULTS AND DISCUSSION

3.1 No Spatial Clustering

Setting the BLM to 0 is equivalent to having no spatial clustering effect. Marine reserve systems configured under these circumstances scored the lowest objective function (Table 1) within their respective reserve design scenarios and delivered the most efficient solutions. In contrast, the compactness of these marine reserve systems was very poor, and comprised a large number of small individual reserves. The type of configuration observed for the marine reserve systems when there is no emphasis on spatial clustering is shown in Figure 1. The feasibility of such a system from a management perspective is questionable and cautions against selecting marine reserve systems on the grounds of efficiency of sampling alone.

We observed a difference between the *Reserves Fixed* and the *No Reserves* and *Reserves Free* solutions, when there was emphasis on spatial clustering (BLM= 0). Results indicate that nearly twice the number of planning units are required in the *Reserves Fixed* scenario to meet the same representation targets as for the *No Reserves* and *Reserves Free* solutions. We discuss reasons for the inefficiency of the *Reserves Fixed* design scenario when we consider the effect of the design scenarios below.

3.2 Spatial Clustering

Emphasis on spatial clustering results in less efficient marine reserve systems due to an increase in the number of planning units (Table 1). As the number of planning units increase, the overall perimeter of the marine reserve system decreases and solutions become more compact. This highlights the trade-off between marine reserve system area and perimeter, and between efficiency and compactness, when representation targets remain the same.

Figure 1 illustrates the influence of the BLM on the *Reserves Free* scenario. Results show that with increasing changes to the BLM value, marine reserve systems comprise fewer individual reserves. Arguably, the small gain in area (approximately 7%) that results when the BLM is changed from 0 to 1 is an acceptable trade-off for fewer, larger and possibly more viable marine reserves.

3.3 Design Scenarios

Inspection of the summary data (Table 1) and the reserve system combination size in particular, suggests that the performance of the best marine reserve systems are influenced by factors other than the BLM values. Results indicate that this difference is due to the unique constraints of our three reserve design scenarios. We performed single factor analysis of variance to assert that there is a significant difference between the mean combination size ($p<0.05$) and multiple comparison procedures to conclude that in all cases, the observed difference was between the *Reserves Fixed* and the *No Reserves/Free Reserves* scenarios. Clearly, this provides evidence that constraints of the reserve design scenarios have a variable effect on the number of planning units and therefore the efficiency of the marine reserve system solutions. This in turn influences the size, shape and connectivity between alternative marine reserve systems.

We found that the marine reserve systems identified for the *No Reserves* and *Reserves Free* scenarios were always more efficient then the *Reserves Fixed* reserve system at the corresponding BLM value. Indeed, the *No Reserve* marine reserve systems achieved the same representation targets in approximately 66% of the area required by *Reserve Fixed* systems. For the *Free Reserves* scenario, this value varies between 55% and 60% of the overall area of the *Reserves Fixed* systems. If instead, our representation goal were to maximize the representation target within a given amount of area, then the *No Reserves* and *Reserves Free* scenarios would be the more effective marine reserve systems. As it is, they achieve the same representation targets at a much-reduced cost. We conclude that the existing marine reserve system does not efficiently contribute to the reservation goals identified here. This perhaps, is not so surprising, given that South Australia's existing marine reserve system has been driven by objectives other than representativeness and comprehensiveness. Locking in these areas exerts a significant constraint on expansion of the system, as areas are added in a way that best complements the existing values.

Next we examined the *Reserves Free* scenario with emphasis on spatial clustering (BLM is set to a value greater than 0). We observed a difference in the number of individual reserves and an increase in the overall perimeter of the marine reserve system, compared to systems identified under the *No Reserves* scenario (Table 1). This is reflected in compactness measures that are typical of a moderately fragmented system. Despite the larger overall perimeter and number of individual reserves, the best marine reserve systems identified for the *Reserves Free* reported a similar score and contained a similar number of planning units, compared with the best systems identified for *No Reserves* scenario. This suggests that a proportion of the planning units in the *Reserves Free* marine reserve system were located adjacent to an existing coastal/marine reserve. We recall that adjacent planning units received a benefit, in the form of a free boundary length. Thus, the increased overall perimeter of the system is countered by a cost savings derived by the selection of planning units that do not have a boundary length cost for the shared boundary. Whilst these solutions are not as compact as marine reserve systems generated in the *No Reserves* scenario, they do provide feasible alternatives at a minimum cost. We conclude that compactness may not be a good measure of the marine reserve system performance in this planning scenario as is does not account for benefits that arise from the spatial arrangement of marine reserves adjacent to coastal reserves. With approximately one third of the South Australian coast under some form of protected area management, these solutions suggest that there is sufficient flexibility to create efficient marine reserve systems that are located adjacent to SA's existing coastal reserves.

3.4 Summed Irreplaceability – Identifying Conservation Priorities

We have shown how mathematical methods can be used as a flexible tool to explore the consequences of alternative reserve design problems. Here, we focus on their role as a tool for identifying conservation priorities. The non-unique occurrence of many indices of biodiversity means there is often more than one way to achieve our goals (Possingham et al., 2000). However, it follows that some planning units are likely to make a more valuable contribution than others and so the options for replacing it with an alternative site are much reduced (Pressey, 1993).

Using selection frequency counts and comparing these with the 95% confidence interval of our predicted probability distributions, the relative conservation value of planning units under the *No Reserves* and *Reserves Fixed* scenarios was determined. For our analyses, the BLM was set at 0.5. Figure 4 presents these results and indicates areas of high conservation priority. Conservation classes are established to identify planning units selected less than could be expected from chance (no colour), those selected as often as could be expected by chance (light pink), planning units that were selected more than could be expected by chance (red). Of this last category, the top 100 planning units are coloured dark red. Using this technique, we assign a measure to planning units according to how often they are selected in a marine reserve system. This is clearly a useful measure to assist identify core areas that attain some critical value for marine reserve system design and for regional planning at a broader scale.

4 CONCLUSION

We have shown how a properly posed marine reserve system design problem and mathematical methods can be used to investigate the implications of alternative planning scenarios. In particular, we show how reserve design tools can be used to evaluate alternative options in a way that can demonstrate the trade-offs that result from different constraints. Using South Australia's existing marine reserve system, we illustrated how selecting reserves in an *ad hoc* manner can have significant implications for the design of representative marine reserve systems. We found that establishing reserve systems around these areas is comparatively inefficient, than if they were ignored. Whilst we don't expect reserve planners to abandon existing marine reserves on the basis of results shown here, we do wish to emphasise that past and present decisions yield great effect on the design of marine reserve systems. Overall, mathematical algorithms provide a means to consider different variations to the reserve design problem and have an important role in supporting informed marine reserve design decisions.

Table 1. Alternative marine reserve systems for South Australia

We generated marine reserve systems for the *No Reserves*, *Reserves Fixed*, and *Reserves Free* scenarios. For each planning scenario we performed 10 simulations of 1000 runs each. For each simulation, the best marine reserve system was identified as the system with the lowest objective function score. The best of these was taken and analysed using the performance measures identified below. The number of planning units in the best marine reserve system identified for each simulation in each scenario (n=10) was then averaged, to determine the mean combination size.

The influence of the boundary length modifier variable was examined when BLM was set to 0, 0.1, 0.5 and 1.0. Compactness is determined as the ratio of the perimeter of the reserve system to the perimeter of a circle of the same area. Efficiency of sampling is measured using the formula defined by Pressey (1989), where Efficiency = 1- (No. sites selected/total number or area of sites).

***No Reserves* scenario for Marine Reserve System Design**

BLM	Score	No Planning Units	Perimeter (km)	Area (km^2)	No. Individual Reserves	Compactness	Efficiency	Mean Combination Size +/- SE
0	276.1	273	5120	6767	233	17.56	0.912	273.9 +/- 0.32
0.1	519.1	284	2263	6922	48	7.67	0.909	283.3 +/- 1.16
0.5	1246.7	307	1823	7302	30	6.02	0.902	306.7+/- 5.12
1	2128.8	322	1800	7518	32	5.86	0.897	317.6 +/- 6.60

***Reserves Fixed* scenario for Marine Reserve System Design**

BLM	Score	No Planning Units	Perimeter (km)	Area (km^2)	No. Individual Reserves	Compactness	Efficiency	Mean Combination Size
0	497.0	497	6192	10568	192	16.99	0.841	497.8 +/- 0.63
0.1	970.2	504	4545	10689	165	12.40	0.838	504.9 +/- 3.11
0.5	2443.0	524	3725	11089	44	9.98	0.832	524.4 +/- 4.40
1	4274.0	536	3628	11357	39	9.60	0.828	541 +/- 6.94

***Reserves Free* scenario for Marine Reserve System Design**

BLM	Score	No Planning Units	Perimeter (km)	Area (km^2)	No. Individual Reserves	Compactness	Efficiency	Mean Combination Size
0	275.8	274	5127	6784	235	17.6	0.912	273.9 +/- 0.88
0.1	451.2	286	2742	6867	73	9.3	0.908	286.9 +/- 2.13
0.5	934.5	317	2721	7251	67	9.0	0.898	310.8 +/- 5.31
1	1529.0	314	2596	7314	65	8.6	0.899	322.8 +/- 7.16

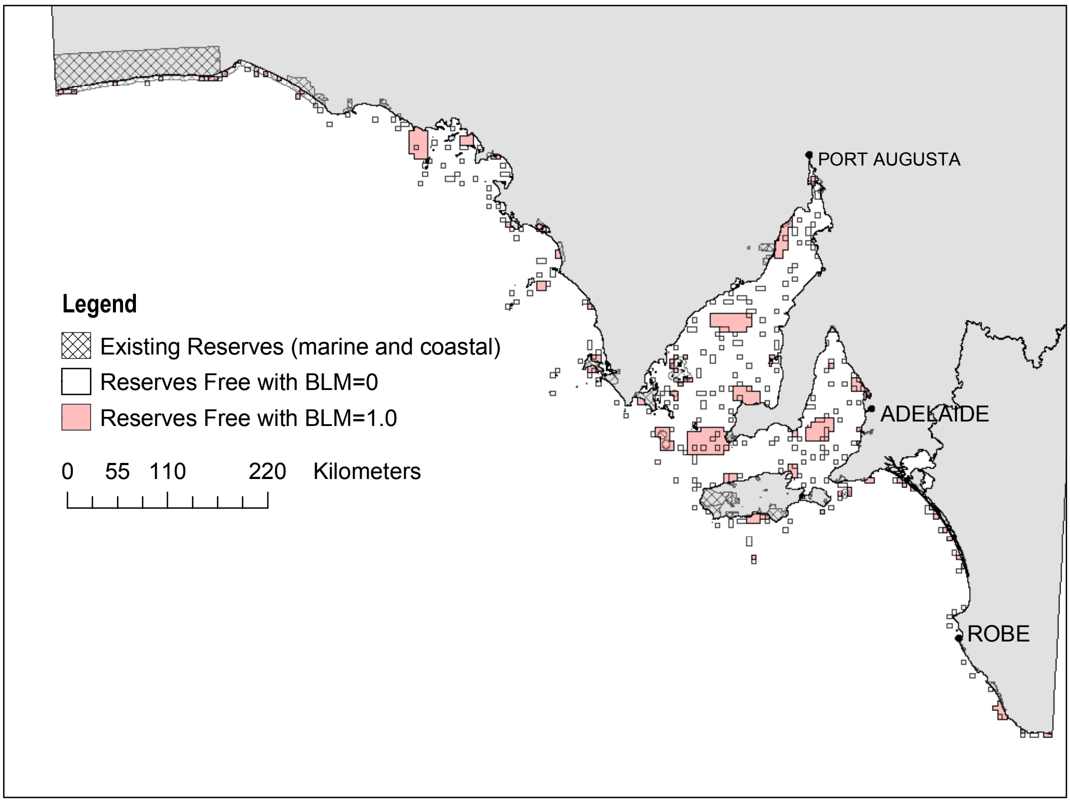
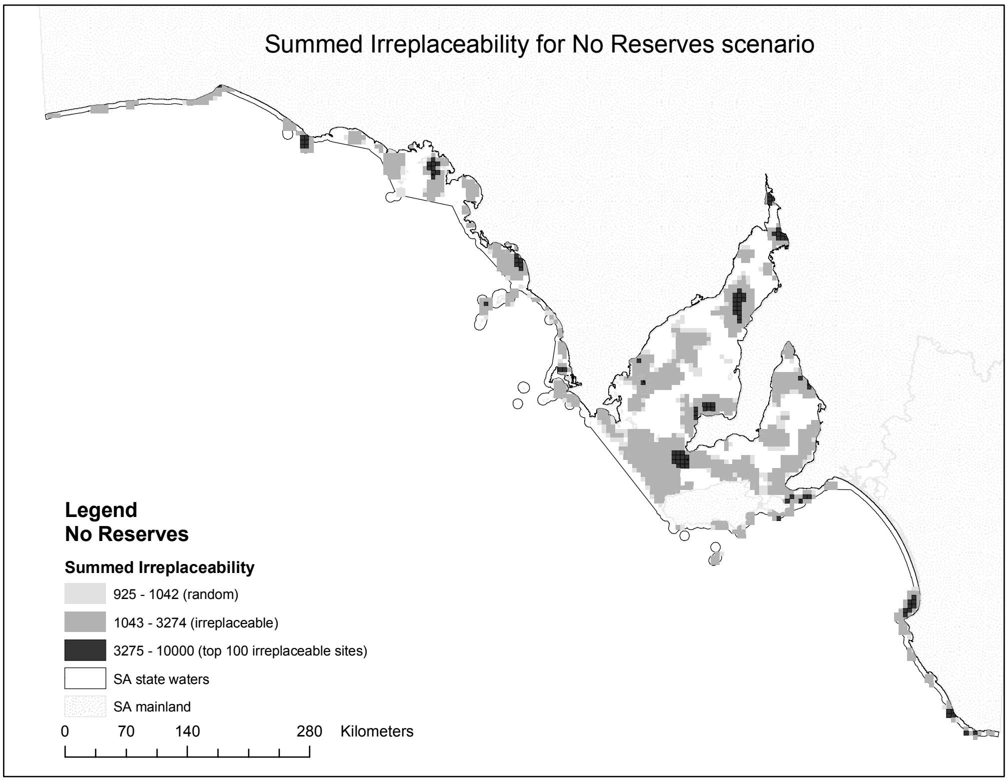


Figure 1 – Effect of Spatial Constraints in Marine Reserve Design

The effect of the boundary length modifier (BLM) is shown when set to 0 (hollow) and 1 (solid) for two alternative marine reserve systems with the same reservation goals. It acts to provide a control on the level of fragmentation in the marine reserve system. Our marine reserve systems are generated for the *Reserves Free* scenario, which provides an additional benefit to reserves located adjacent to South Australia's existing reserves (shown in green).



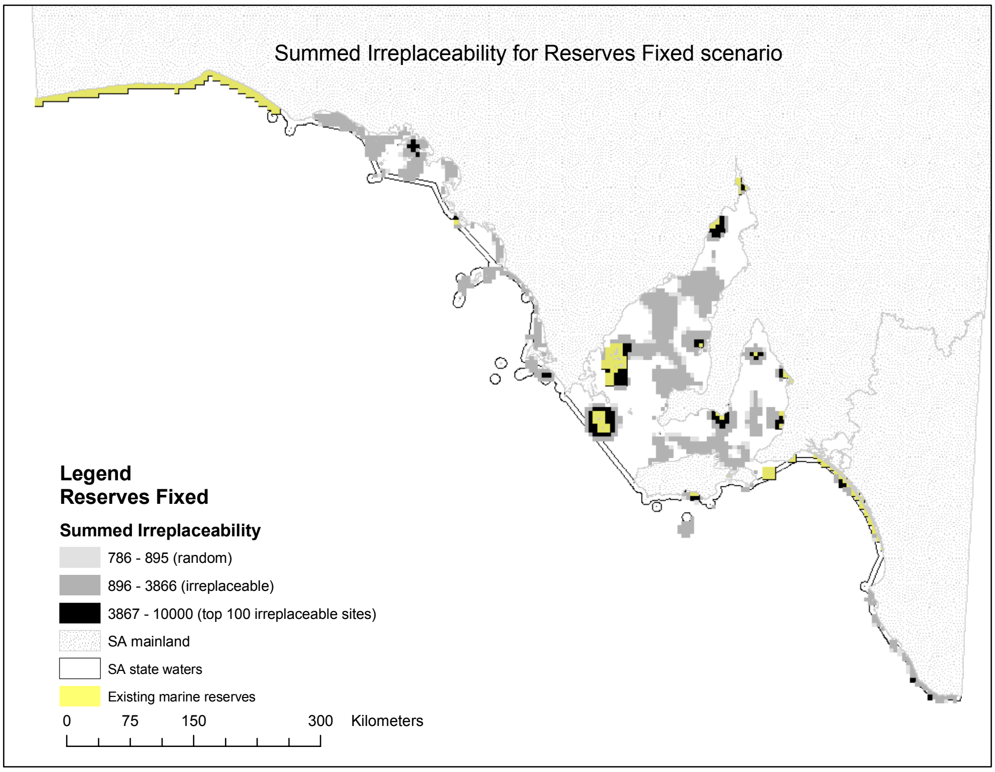


Figure 2 – Summed Irreplaceability for Marine Reserve Systems under different reserve design constraints

The contribution of an individual planning unit to marine reserve system goals is measured using a summed irreplaceability value, derived from selection frequency counts. It assumes that the more times a site is selected, the more valuable it is for reserve planning. We identify planning units that are selected more than could be expected from random sampling (shaded) for the *No Reserves* and *Reserves Fixed* scenarios with the boundary length modifier set to 0.5. The more irreplaceable planning units are shown in the darker shades.

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