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Efficiency, costs and trade-offs in marine reserve system design

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With marine biodiversity conservation the primary goal for reserve planning initiatives, a site's conservation potential is typically evaluated on the basis of the biological and physical features it contains. By comparison, socio-economic information is seldom a formal consideration of the reserve system design problem and generally limited to an assessment of threats, vulnerability or compatibility with surrounding uses. This is perhaps surprising given broad recognition that the success of reserve establishment is highly dependent on widespread stakeholder and community support. Using information on the spatial distribution and intensity of commercial rock lobster catch in South Australia, we demonstrate the capacity of mathematical reserve selection procedures to integrate socio-economic and biophysical information for marine reserve system design. Analyses of trade-offs highlight the opportunities to design representative, efficient and practical marine reserve systems that minimise potential loss to commercial users. We found that the objective of minimising the areal extent of the reserve system was barely compromised by incorporating economic design constraints. With a small increase in area (<3%) and boundary length (<10%), the economic impact of marine reserves on the commercial rock lobster fishery was reduced by more than a third. We considered also how a reserve planner might prioritise conservation areas using information on a planning units selection frequency. We found that selection frequencies alone were not a reliable guide for the selection of marine reserve systems, but could be used with approaches such as summed irreplaceability to direct conservation effort for efficient marine reserve design.

Keywords: marine reserves, decision theory, trade-offs, conservation planning, reserve selection, irreplaceability, bioeconomics

1. Introduction

All conservation problems have scientific, social and economic aspects [1], yet it is generally considered to be the socio-economic aspects that ultimately determine a reserve's success or failure, regardless of how sound it is scientifically [2–13]. Agreement on how social, economic, cultural, management and biological interests are integrated is therefore a key consideration for conservation planning, with the potential to deliver benefits such as community 'ownership,' 'stewardship,' greater acceptance of the outcome and willingness to comply with regulations. To date, assessments of socio-economic factors have mostly been conducted as a *post hoc* filter of areas selected only with regard to biological data and reserve design considerations. Socio-economic aspects have been used to evaluate marine reserve systems rather than being included in the process itself. Thus, the 'success' of reserve proposals is often weighed against socio-economic criteria not previously considered and is more likely to reflect the degree of community acceptance or economic feasibility, rather than how well a proposal contributes to biodiversity goals.

Gaining political and community acceptance is costly and time consuming and can lead to results that fail to deliver biodiversity conservation outcomes because they become lost in the bargaining process. Dispute resolution procedures that average the positions of all stakeholders tend to set limits on use based on socio-economic factors rather than biological considerations and usually result in a decline of the resource [1]. Alternatives approaches, such as the redistribution of recreational and commercial fishing effort from the reserved to the unreserved area, can potentially implicate reserve design criteria such as estimates of the minimum reserve size and so need to be addressed early in the reserve planning process. Clearly, the way that conflicts are addressed can have important implications for biodiversity conservation outcomes. So with often-competing demands for marine resources, a reserve planning framework must be prepared to address the finite number of crucial political, social and economic characteristics.

In order to understand how we might make reserves more socially desirable, we must firstly examine where the controversy lies. Reserves provide a mechanism for managing human interventions in ecosystems [14] by using spatial controls to achieve some desired outcome. The economics literature categorises benefits as either non-consumptive benefits (e.g., maintenance of more natural population and community structures [15,16], ecosystem services, increased opportunities for tourism [17,18]) or fishery productivity benefits (e.g., larger fish, increase in spawning stock biomass [19,20], protection of critical habitat [21] and reduced risk of management failure due to reduced variability in stock size [22,23]). Whether these benefits are sufficient to offset losses associated with foreclosed harvest opportunities in the reserve is the key concern for fishers [24], who are amongst the most vocal opponents to implementation of marine reserves. Economists caution that a net increase overall, and not just a gross increase in yield, is needed in the non-reserved area to make reserves worthwhile as a fisheries enhancement measure [25,26].

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Whilst theoretically, a case can be made in support of marine reserves when overfishing is high and linkages between reserves and non-reserves support a sufficiently high exchange of larvae and adults (but not so high that the reserve does not afford them protection [26]), we are still far from determining just what type of reserve system configuration is required to deliver net benefits for fisheries. Detailed knowledge of the levels of pre- and post-exploitation in the fishery, the behaviour of fishers, changes to the distribution of fish stocks and migration and dispersal pathways that follow reserve establishment are all important determinants of whether reserves generate a net increase in harvest. Furthermore, Holland and Brazee [20] highlight that even if yields do approximate pre-reserve levels after a period of equilibrium, long-term benefits are subject to economic discounting. In light of all of this, management then needs to determine sustainable harvesting policies for the exploited population [27], and fishers may still be asked to forgo harvesting rights. Not surprisingly, fishers remain sceptical about the fishery productivity benefits of marine reserves.

Whilst several researchers [18,28] quite rightly point out that the social desirability of reserves extends beyond fisheries management to encompass both non-consumptive benefits and the fishery productivity benefits (such as bet hedging), a failure to quantify the non-consumptive benefits has perhaps heightened the importance of fishery productivity benefits in the marine reserve debate. Nevertheless, if marine reserve systems are to be effective as a management tool, we need to consider where they can be situated to gain community and stakeholder acceptance, whilst still achieve conservation objectives. One approach proposed by Sanchirico and Wilen [24] is to look for double payoff circumstances that appeal to both fishers and conservationists. We envisage that this situation might arise where reserve selection seeks to achieve conservation objectives with minimal cost to foregone harvest. It is a conservative strategy in the sense that it is unlikely to dramatically change the spatial distribution of fishing activities [18].

In this paper, we extend on the work by Ando et al. [29] to show how reserve selection algorithms can be used to consider both ecological and economic factors for efficient marine reserve design. Our goal is to minimise economic losses by making trade-offs early in the design process so that conservation targets are not compromised. It is a class of problem defined by the set covering approach where the objective is to achieve some minimum representation of conservation features at the smallest possible cost [30]. Minimising the cost of the reserve system is central to the problem statement as it reflects constraints to achieve reservation goals and emphasises the importance of efficiency and complementarity as key principles for reserve selection [30–38]. We depart from previous studies that have assigned equal costs to individual planning units [39], such that the objective is to satisfy targets whilst minimising the size of the marine reserve system. Instead, we capture information on the heterogeneity of catch values distributed across the planning region by using a measure of cost that combines information on a planning unit's area and its commercial value. With commercial value derived using information on the total rock lobster catch (kg) in an individual planning unit, we assume that the reservation goal is to minimise a linear combination of the total rock lobster catch displaced by the marine reserve system and the reserve system area. We compare the performance of marine reserve systems selected using this cost objective with reserve systems that emphasise the goal of minimising the number of sites or area of the reserve system. We consider also how a reserve planner might prioritise conservation areas by examining different measures of irreplaceability [39–41] used for decision support and site selection.

2. Methods

2.1. The planning region

The planning region for the study is defined by the three-nautical-mile legal limits to South Australian state waters, located on the southern temperate coast of Australia. The region was divided into 3,119 planning units with each planning unit forming a 5 × 5 km cell. Due to the study area's irregular shape, a number of planning units were truncated at the coastline and offshore islands, providing some variation in planning unit size (area) and boundary length. Conservation features were identified from six biophysical data layers obtained from South Australian state government agencies as described in Stewart et al. [39]. They include the biogeographic regions (mesoscale, hundreds to thousands of kilometers), biounits (microscale, tens to hundreds of kilometers), marine benthic habitats, coastal saltmarsh and mangrove habitats, species occurrence (Australian sea lions *Neophoca cinerea* and New Zealand fur seals *Artocephalus forsteri*) and bathymetry (depth classes). Information on the amount of conservation features j, in each planning unit i, was then compiled and formed the basic data matrix a_{ij}. This resulted in 102 conservation features distributed across 3,119 sites, producing approximately 17,000 records.

Although some progress has been made in establishing marine reserves in South Australia, marine conservation planning has largely been *ad hoc* and is considered to be inadequate to meet current conservation objectives [42]. With approximately 4.5% of South Australian state waters already established in marine reserves, the goal is to add to these areas so that representation and design targets are efficiently met. Although earlier work by Stewart et al. [39] highlights the inefficiency of the existing reserves' contribution to reserve system goals, they are retained in this research in part to demonstrate the practical application of our approach. With these areas locked-in, the number of planning units available for selection is 2,831.

2.2. The reserve design problem

In its simplest form, the reserve planning problem focuses on the spatial allocation of sites for biodiversity conservation, so that representation and design targets are met in the least number of available sites. Advances in operations research have lead to an increasingly sophisticated reserve selection toolbox, most recently with the inclusion of features that incorporate spatially explicit design requirements that aim to mitigate the effects of local or regional disturbances and maximise population persistence [30,43–45]. These features have been incorporated into the decision support software for marine reserve design, MARXAN [46,47], as part of the formal problem statement formulated by Possingham et al. [48] and McDonnell et al. [30] as a non-linear integer programming problem:

Minimize the objective function:

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

subject to the constraints:

$$\sum_{i=1}^{M} a_{ij} x_i \geq t_j \sum_{i=1}^{M} a_{ij} \quad \text{for all} \quad j = 1, \ldots N,$$
$$x_i \in \{0,1\} \quad \text{for all} \quad i = 1, \ldots M, \quad (2)$$

where x_i is the control variable that takes on the value of 1 if site i is included in the reserve system and the value 0 otherwise. The parameter c_i is the 'cost' of site i, whilst l_i is the perimeter or boundary length of site i, and b_{ik} is the common boundary length of sites i and k. Here, a_{ij} forms the basic data matrix representing the abundance of the conservation feature type j in planning unit i, with N the set of conservation features and M the set of sites. We set the target fraction t_j to 0.2, which means that each conservation feature will be represented at 20% of their total distribution or abundance. The theory behind proportional representation of areas tacitly assumes that biological diversity will be sustained if species and habitats are protected at some specific threshold. Whilst there is no general scientific agreement on what this threshold should be [16,49], there are strong arguments for the application of conservation targets as a component of systematic conservation planning [50]. To date, estimates of the optimal marine reserve fraction required to maintain populations lie somewhere between 20 and 50% of the total area [28,51–54]. More recently, a target of 20% was proposed at the 2003 IUCN World Parks Congress as the minimum amount of each habitat to be represented in strictly protected marine reserves [55]. Though not employed in this study, the target parameter can also be used to define different spatial design requirements such as minimum patch size and minimum distance between represented features (e.g., to offset local turnover).

Equation (1) is the objective function, which minimises a linear combination of planning unit costs and reserve system boundary length, weighted by a BLM factor. Equation (2) is the set of constraints that ensures all features reach an agreed conservation target (e.g., 20% of their original extent). BLM is the boundary length modifier variable that controls the importance of minimising the reserve system boundary length relative to its cost. With a small BLM, the algorithm concentrates on minimising cost, whilst a relatively large BLM places greater emphasis on minimising the boundary length, therefore forming more spatially compact reserve systems.

We use MARXAN with the simulating annealing and iterative improvement features. This algorithm is distinct from other iterative improvement algorithms in that the acceptance of bad moves allows the system to move out of local optima, therefore increasing the efficiency of the search. It also means that the final solution can be reached via alternative pathways, generating many good reserve systems that can have identical or very similar objective function scores but with different configurations. This is a useful output as it provides a number of alternative options for marine reserve system design [30,56,57]. We run MARXAN with the adaptive annealing schedule and perform 1,000 repeat runs for each reserve design scenario using the different cost objectives described below. MARXAN then generates summary data that include the objective function score, the number of planning units and reserve system boundary length. The best (near-minimum) marine reserve system in a given scenario is identified as the solution with the lowest objective function score. The total area and boundary length are then calculated to compare the performance of individual planning scenarios.

2.3. The planning scenarios

In this paper, we devise exploratory planning scenarios to investigate options for efficient marine reserve design. Individual planning units are assigned a cost according to the objectives described below.

Objective 1 – All planning units have equal costs with c_i set to 1, such that the total reserve system cost is expressed as the number of planning units in the marine reserve system.

Objective 2 – The cost of an individual planning unit, c_i, is measured as its area; therefore, the total reserve system cost is expressed as its total area.

Objective 3 – The cost is a measure of foregone harvest. To illustrate how economic value can be integrated into the reserve design problem, we use a surrogate measure derived from the total catch of the southern rock lobster

(*Jasus edwardsii*) and reported for each individual planning unit. Rock lobster fishing occurs widely through the planning region and is a major commercial fishery in South Australia. Because the southern rock lobster fishery is largely spatial in nature, the establishment of no-take marine reserves could potentially impact on a large proportion of the total annual catch with significant economic implications [58]. The distribution of rock lobster catch was compiled across the planning region using time-series averages of catch totals over one complete cycle of temporal variation (i.e., 11 years) and data taken from a catch sampling program to estimate the proportion of lobsters taken across the planning region [58]. This information is aggregated at the level of regional fishing zones known as marine fishing areas (MFAs) and combined with estimates of the long-term mean weight of lobsters taken to estimate mean historical catch rates in each MFA. Catch rates for the MFAs (kg/km^2) were used to report on catch rates for individual planning units (kg/km^2). Data were originally compiled to assist with marine reserve planning by providing a basis for estimating the loss of rock lobster catch that would result from establishing marine reserves [58]. We note that estimates of economic loss do not incorporate any measure of benefits acquired through the establishment of marine reserves that might enhance catch from migration, spillover or indirect effects [59–62]. In this sense, it is an upper bound on the likely short-term economic cost to the commercial fishery if we assume that fishing effort is removed and not simply redistributed to the remaining area. Implicit in this assumption is that the profitability of planning units outside the reserve system remains unchanged. Whether this approach bounds the long-term costs to the fishery depends on the magnitude of spillover effects and the pre-reserve levels of exploitation outside the reserve system.

The cost of an individual planning unit is therefore a function of its area and an estimate of the expected loss of catch, defined in equation (3). A weighted variable α is included to allow the planner to prescribe the relative importance of the catch to area costs.

$$c_i = (1-\alpha)a_i + \alpha(a_i r_i) \quad (3)$$

where a_i is the area of planning unit i and r_i is the mean annual catch rate of lobsters per unit area of planning unit i [58]. We set alpha to 0.5, which gives weighting to reserve system area when minimising reserve system cost.

When different cost objectives are considered, it is important to customise the BLM factor, as this determines how the boundary length relates to the cost of the system. This can be done by identifying a BLM factor that provides the desired level of spatial clustering whilst maintaining an efficient system [30,39,45].

2.4. Identifying priority areas

Identifying the best marine reserve system provides one solution to the reserve design problem; however, it is often useful to know something about the relative importance of an individual planning unit for conservation planning. We examine two approaches used to identify priority areas and consider their role in informing the decision-making process. The first approach uses selection frequency counts generated when multiple runs of the algorithm are performed. This makes it possible to identify how many times an individual planning unit is selected out of the total number of runs and is referred to as a planning unit's selection frequency. We consider the role of selection frequencies as a guide for the identification of priority areas. Specifically, we examine whether different selection frequency thresholds (e.g., where planning units are contained in more than 50% of reserve systems) provide flexible options for efficient marine reserve design. This was achieved by locking-in planning units with selection frequencies above a certain threshold and assessing how effectively representation targets were met.

Table 1
Scenario constraints, with results for the best marine reserve systems.

Scenario	Cost objectives: Objective 1, equal				Objective 2, area				Objective 3, area and catch			
	BLM	Cost	Planning units	Available catch (tonnes)	BLM	Cost	Planning units	Available catch (tonnes)	BLM	Cost	Planning units	Available catch (tonnes)
A	0	734	734	1,027.54	0	16,346	800	1,023.16	0	105,287	814	1,126.79
B	0.01	738	738	1,013.80	1.25	16,448	772	1,033.34	2.50	106,290	782	1,124.98
C	0.1	745	745	1,004.17	2.50	16,496	763	1,028.00	5.0	106,153	783	1,125.38
D	0.2	752	752	1,043.55	5.0	16,679	769	1,050.60	6.25	107,630	786	1,122.51
E	0.3	758	758	1,042.23	6.25	16,670	763	1,022.70	7.50	106,330	795	1,125.25
F	0.5	755	755	1,013.49	7.0	17,006	781	1,000.75	12.50	106,511	790	1,124.88
G	1.0	786	786	1,041.47	12.5	17,200	792	972.95	25	108,848	789	1,120.41
H	5	917	917	1,041.92	125	23,678	1,048	1,004.92	125	129,344	1,055	1,086.06

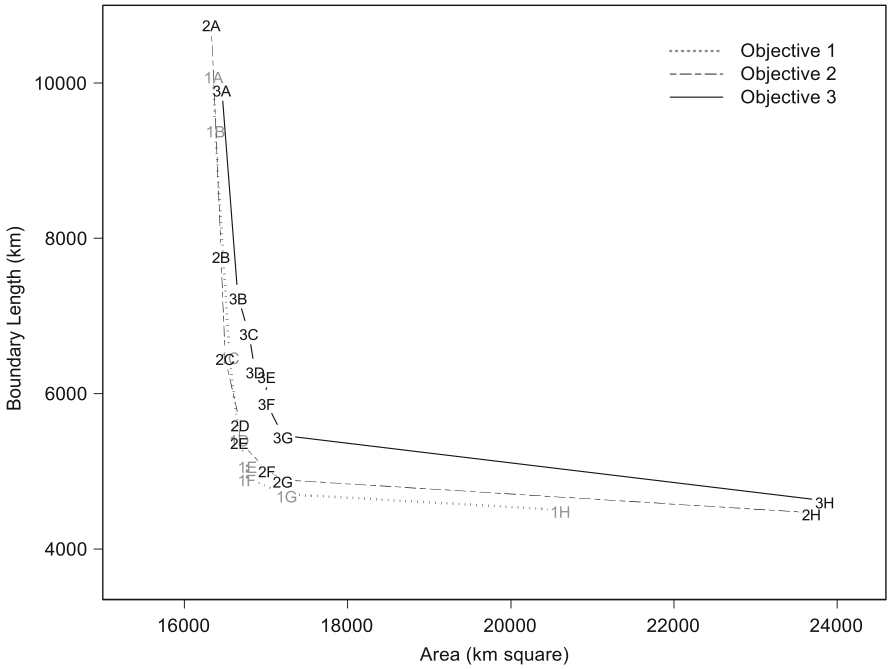

Figure 1. Trade-offs in marine reserve design. Exploratory marine reserve design scenarios are used to examine alternative BLM values for the selection of compact and efficient marine reserve systems when different cost objectives are used. The trade-off between minimising boundary length and minimising area is *highlighted*, and marine reserve systems that achieve an acceptable trade-off were identified. We regard the best marine reserve system identified using objective 1 to be the *1F* scenario, when BLM was set to 0.5. The best marine reserve system identified using objective 2 was the *2F* scenario with BLM set to 7. The best marine reserve system identified using objective 3 was the *3G* scenario with BLM set to 25. BLM values for all scenarios are reported in table 1.

An alternative method is to use information on a planning unit's selection frequency to assign irreplaceability values. This is achieved by determining whether a planning unit is selected more than could be expected from random sampling alone. Assuming that every planning unit has an equal probability, p, of success of being selected [63], then:

$$p = (C - R)/(T - R) \tag{4}$$

where C is the mean combination size [40] defined as the average number of planning units contained in the reserve systems over a given number of runs. T is the total number of planning units (n = 3,119), and R is the number of planning units excluded from selection (planning units may be locked-out or locked-in), so with the existing marine reserves locked-in, R is fixed at 288. The number of times a planning unit with probability p of being selected appears in 1,000 repeat runs will have a binomial distribution if selection is purely random. Under this assumption, Tukey's 95% confidence limits on the predicted selection frequency can be determined. Planning units with selection frequency counts greater than the upper 95% confidence limit are regarded as irreplaceable as they were unlikely to be selected in the reserve system due to random sampling alone. Planning units that perform no better than random are described as *ad hoc* [64].

By comparing these approaches with the best marine reserve system identified in previous scenarios, we can consider how efficiently prioritisation methods contribute to reserve system targets. Analyses are performed to identify the number of missing features where targets are not met.

3. Results

3.1. Effect of the cost objective

Spatial design requirements are examined for marine reserve systems using exploratory planning scenarios, with boundary length modifier (BLM) values described in table 1. Our goal is to configure reserve systems that achieve a desired level of spatial clustering, without compromising the efficiency of reserve systems selected. Table 1 reports on the reserve system cost, number of planning units and available catch[1] for the single best marine reserve systems selected. Because each cost objective uses a different definition of efficiency to minimise reserve system cost, the relative importance of the BLM varies accordingly. This must be considered when determining spatial requirements as the BLM controls the importance of minimising boundary length relative to cost. Adopting a single BLM value for reserve design planning scenarios would result in

[1] This is what we want to maximise in order to minimise economic losses. It corresponds to the estimated catch that would be available for harvest outside the reserve system.

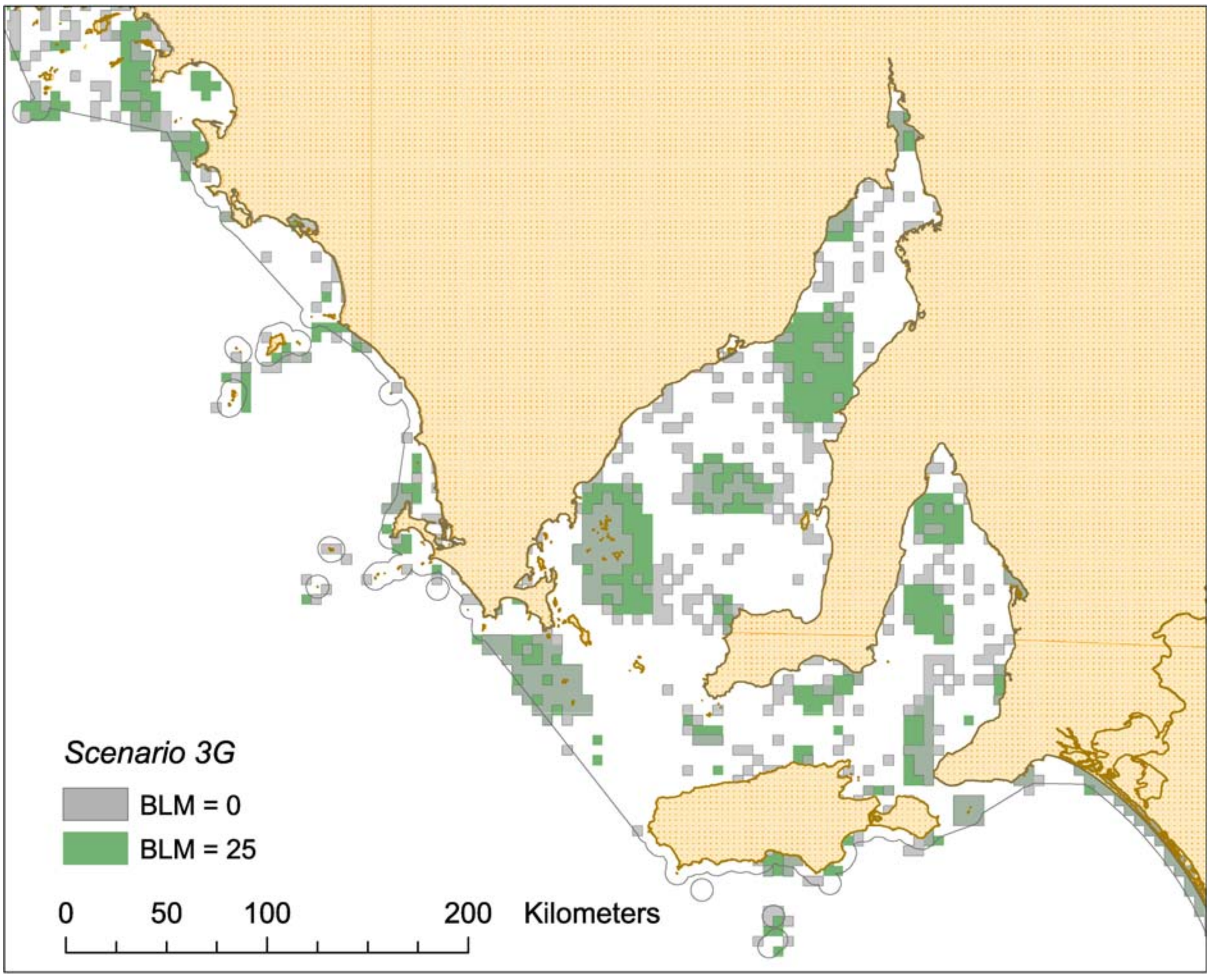

Figure 2. The effect of the boundary length modifier on spatial clustering. Two alternative marine reserve systems configurations are shown to illustrate the effect of spatial design constraints. Reserve systems configured when there are no spatial design constraints results in many individually small reserves, whilst increasing the BLM results in larger, more compact marine reserve systems. Here, cost is a function of a planning unit's area and the commercial rock lobster catch (*objective 3*). The full extent of the planning region is not shown.

quite different levels of spatial clustering across the three cost treatments.

To determine an appropriate BLM value that achieves the desired level of spatial compactness, we must first consider the effect of increasing the boundary length modifier and minimising boundary length on the total reserve system area. Figure 1 highlights the design trade-off where spatial compactness is achieved at some cost to the reserve system area when different cost objectives are used. We are willing to trade off area and boundary length to achieve efficient, yet reasonably compact reserve systems. This is done by accepting minimal increases in area for large gains in spatial clustering (minimising boundary length), which result as the BLM is increased. The effect of the BLM is shown in figure 2 for marine reserve system configurations with and without spatial clustering.

Marine reserve systems that achieve the desired level of spatial compactness are identified in table 2. The performance of individual reserve systems is assessed in terms of the number of planning units, the boundary length, reserve system area and foregone catch (i.e., the amount of catch contained within the reserve system). We found that cost objective 3 was the most effective strategy for minimising economic losses as the amount of catch contained within the reserve system was reduced by more than a third compared with objectives 1 and 2. This result was achieved with only minor trade-offs to area (less than 3%) and boundary length (approximately 10%). Because we expect that it will be more difficult to establish reserves in areas where fishers suffer large losses, reserve systems identified under cost objective 3 are considered to be more acceptable.

Even when different spatial requirements are incorporated, our findings suggest that clear economic benefits can be achieved. As figure 3 illustrates, the estimated amount of catch that is available for harvest outside the reserve system is always greatest under cost objective 3, although reserve systems may vary in size and compactness. By comparison, reserve systems configured under cost objec-

Table 2
Assessing trade-offs for the best reserve design scenarios.

Scenario	Cost objective	BLM	Planning units	Combination size (n = 1,000)	Boundary length (km)	Area (km^2)	Foregone catch (tonnes)
1F	1	0.5	755	771.8	4,913	16,764	307.42
2F	2	7.0	781	777.7	5,021	17,007	320.15
3G	3	25	789	812.4	5,461	17,204	200.49

tive 1 (i.e., minimise number of sites) and objective 2 (i.e., minimise area) resulted in lower catches, which means greater economic losses for fishers. These findings demonstrate that economic gains do not result in larger reserve systems; rather, the increased size reflects the requirement for reserves to be spatially compact and occurs regardless of which cost objective is used. Furthermore, with reserve systems of similar size producing different levels of catch depending on the cost objective, we conclude that size alone is not a good indication of how socially or politically desirable a reserve system will be.

3.2. Identifying priority areas

Figure 4 identifies 'priority' areas selected using the summed irreplaceability method. Results show options for marine reserve design using objective 3, with estimates of the mean combination size as reported in table 1 (*Scenario 3G*). Priority areas are identified as irreplaceable planning units, depending on how often they appear in good marine reserve systems. Planning units selected more than could be expected from random sampling are categorised as 'irreplaceable' (>95% UCL) or '100% irreplaceable' (required in every solution). In this example, 858 planning units were found to have some irreplaceability value (note that this value is assigned to planning units available for selection; therefore, existing marine reserves are excluded). Locking-in the irreplaceable subset of planning units together with the existing reserves would result in one target not being met.

If instead we use selection frequencies to identify priority areas, where any planning unit above a fixed selection frequency is considered to have conservation value, it is interesting to consider options that provide for efficient marine reserve design. We examined thresholds ranging from 0% (which defines priority areas as planning units selected at least once) to 100% (planning units must appear in every reserve system). Results are reported as the number of planning units and the number of targets not met as a function of the selection frequency thresholds (figure 5). A low threshold increased the likelihood of meeting all targets, but with more than half the planning region identified. As the threshold increases, the number of planning units decreases, yet the number of missing values increases. To ensure that all targets are met, the selection frequency threshold must be approximately 10%, whereby

Figure 3. An estimate of the rock lobster catch available outside the reserve system as a percentage of pre-reserve levels (i.e., total catch). The estimated proportion of commercial rock lobster catch available outside the marine reserve systems as a percentage of the total available catch (i.e., pre-reserve levels). Available catch is reported as a function of the overall reserve system area. *Symbols* correspond to the cost objective and spatial constraints described in table 1.

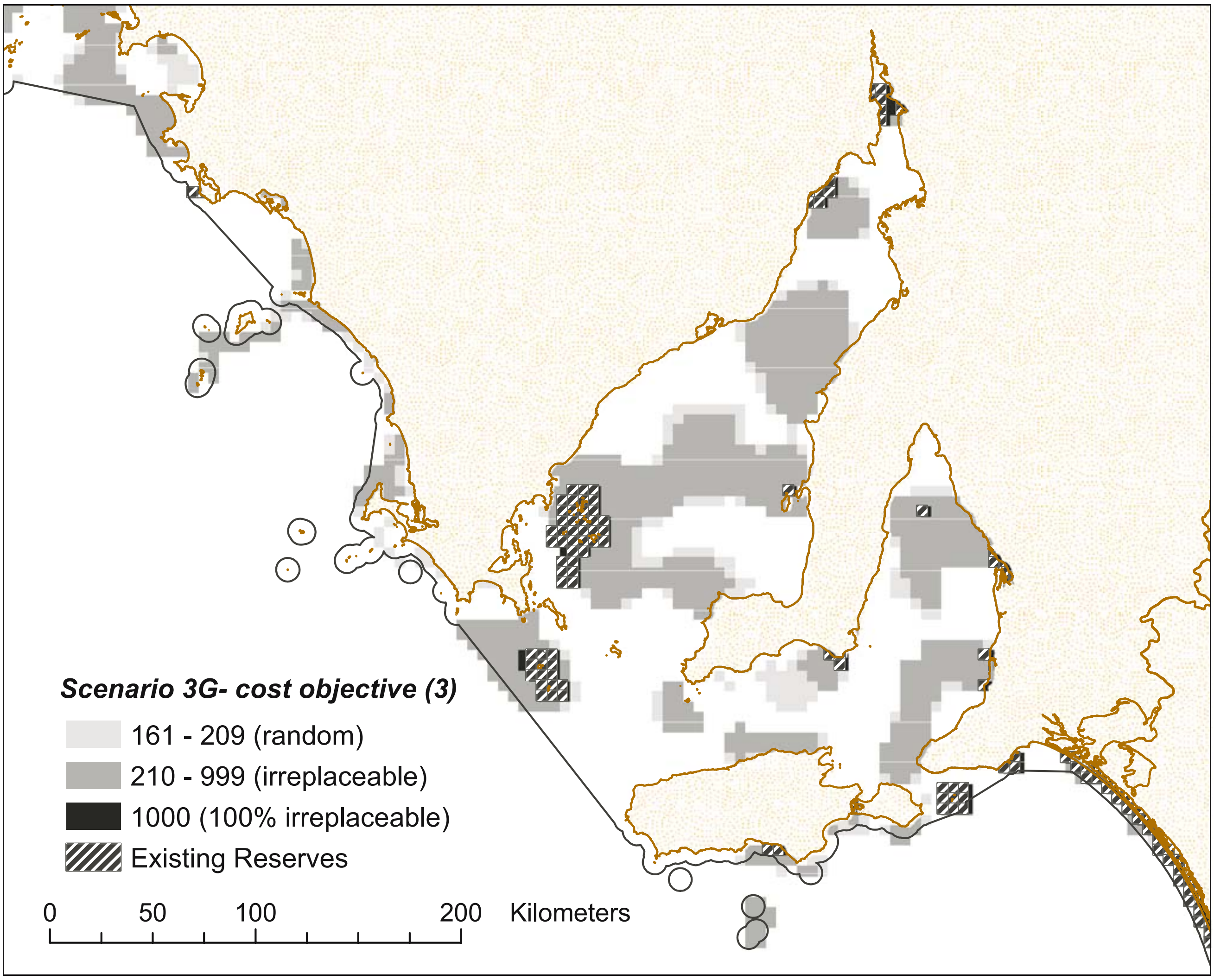

Figure 4. Identifying priority areas using summed irreplaceability. Priority areas are identified using summed irreplaceability values for the reserve system design scenario *3G* (BLM value of 25, 1,000 repeat runs and cost objective 3). The mean number of planning units reported for reserve systems identified in this scenario is 812 (mean combination size; table 2). The probability that a planning unit will be selected by random is 0.185 with the 95% confidence limits for selection frequencies reported as 161 (LCL) and 209 (UCL). Planning units selected more than 209 times out of 1,000 runs are identified as irreplaceable, as they are selected more than could be expected from random sampling alone. Planning units with irreplaceable value are coloured *dark grey* and *black*. Planning units with selection frequencies within the confidence limits are identified as random (*light grey*). South Australia's existing marine reserves are shown as *hatched areas*. Planning units selected fewer times than random are left blank.

planning units with a selection frequency of 10% or above are regarded as priority areas, an amount totalling 1,500 planning units. If we proceeded to identify priority areas using a selection frequency threshold of 50%, as many as 67 targets would not be met, yet far fewer planning units are identified (approximately 350 planning units). Selection frequencies of between 20 and 30% contribute to fewer planning units being identified, yet minimise the number of targets that are unmet.

4. Discussion

Using the reserve selection software MARXAN, we have demonstrated how biophysical and economic information can be integrated to deliver marine reserve systems that achieve better economic outcomes for commercial users, with minimal consequences for other reserve design constraints. We have used a measure of cost that combines information on the commercial value of rock lobster catch in a planning unit with its area. We found this to be an effective way to integrate economic goals, without compromising conservation goals or spatial design requirements, such as minimising the area or boundary length. Our comparison of the different cost objectives provides compelling evidence to support the engagement of stakeholders and incorporate their aspirations early in the reserve design process. In doing so, marine reserve systems may be more likely to be accepted by the stakeholders and the community.

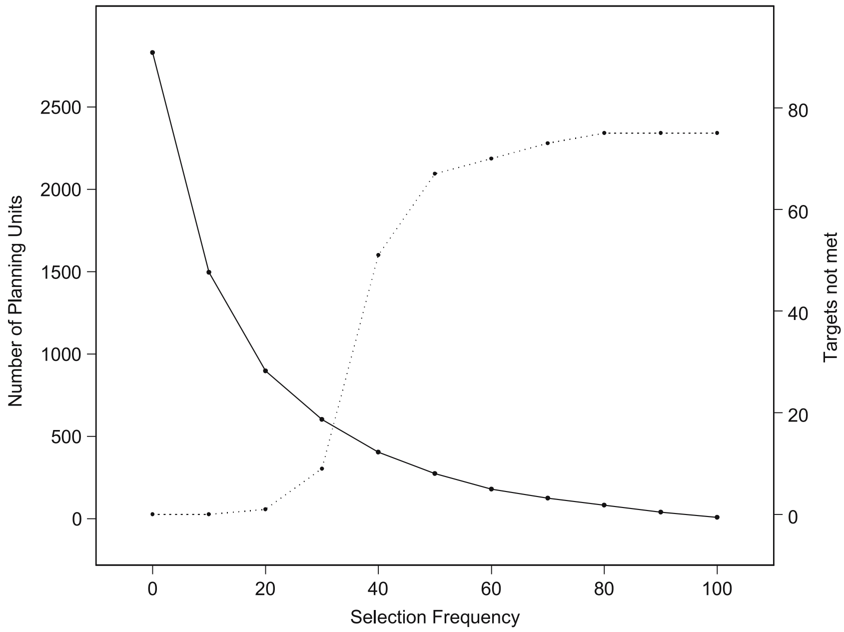

Figure 5. Identifying priority areas using selection frequencies. The number of planning units selected in marine reserve systems more times than a given selection frequency (shown on the *x*-axis) is reported for scenario 3G (*solid line*). As the selection frequency counts for all planning units range between 0% (all planning units are priority areas) and 100% (only eight planning units are priority areas), the number of missing values can be plotted as a function of the selection frequency solution (*dotted line*). For example, 81 planning units have a selection frequency of 80% or more, which means that they were identified in the best marine reserve systems at least 800 out of a possible 1,000 times. A reserve system configured using just these planning units would fail to meet targets for 75 conservation features. By comparison, priority areas identified using a 20% selection frequency threshold consist of 898 planning units. A marine reserve system containing these planning units would result in one unmet target.

Exploratory scenarios such as these can make a valuable contribution to the reserve design process through definition of the solution space (i.e., best- and worst-case scenario), which then serves to better define the reserve design problem. If some economic losses are inevitable, then the focus can shift towards identifying acceptable limits that the reserve selection process should operate within or locking out certain locations that have significant economic consequences. Analysis of the trade-offs may demonstrate support for the design of larger reserve systems if both conservation and economic goals are met. More importantly, we found that the effect of different constraints on biodiversity outcomes can be easily determined and need not result in conservation objectives being lost in the bargaining process. We believe that these outcomes will lend greater support for mathematical reserve selection tools that can integrate socio-economic and biophysical data from the outset. Exploratory reserve design scenarios then assist with definition and ongoing refinement of the reserve design problem.

Although we have demonstrated the application of this approach using a single economic constraint, multiple social and economic constraints can be integrated into a planning unit's cost quite simply as the sum of all values contained within. Alternative approaches, which distinguish between different social and economic activities, would be a useful tool for conflict resolution as the interests of different stakeholder groups could be dealt with independently from one another, rather than being lumped together. With each activity identifying explicit targets, the reserve design problem would be to identify marine reserve systems that do not impact on more than some proportion of its total value. Such approaches will no doubt be limited in the short term by the lack of information on the social and economic uses and an understanding of conditions for both economic and ecological sustainability, but clearly have an important role in supporting conservation planning within an ecosystem-based management framework.

Because reserve establishment is likely to proceed sequentially, rather than through the establishment of entire networks, the identification of priority areas is likely to emerge as a key area for decision support. We illustrated two methods that can be used to identify priority areas on the basis of their selection frequency (i.e., the number of times a planning unit is selected). Summed irreplaceability proved to be a quick and effective way to identify candidate sites, allowing for both flexibility and redundancy in the marine reserve system. Redundancy is likely to be desirable in the event that certain options are foreclosed. By comparison, setting a selection frequency threshold produced results that warrant some consideration for how they are applied. Most surprising perhaps was that 67 targets would not be met if we reserved planning units that were selected in half of the best marine reserve systems generated. As these findings are closely related to the underlying dataset and the distribution of conservation features, we would be cautious in using selection frequencies at a fixed threshold as a reliable guide for prioritising effort for marine reserve system design. However, the results from summed irreplaceability appear more robust, providing that assumptions of the predicted frequency distribution hold true.

Lastly, we wish to point out that high-priority areas are not necessarily the same as high conservation areas, rather they are priority areas for a given set of conditions, which are defined by the reserve design problem. Consequently, planning units that are 100% irreplaceable, as defined by their selection frequency, make a valuable contribution to the scenario goals, yet are not necessarily 100% irreplaceable as defined by Ferrier et al. [40] and Pressey et al. [41], for deletion of planning units does not mean that conservation targets cannot be met. Rather, deleting those sites may have consequences for some other design constraint (i.e. cost, efficiency, spatial clustering). This reflects the expanding nature of the reserve design problem and the fact that multiple objectives require complex trade-offs.

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