The Design of Marine Protected Areas: Adapting Terrestrial Techniques

I.R Ball[a] and H.P. Possingham[b]

[a] *Antarctic Marine Living Resources Group, Australian Antarctic Division, Kingston, Tasmania 7050, Australia (ian.ball@antdiv.gov.au)*

[b] *The Ecology Centre, University of Queensland, St Lucia, QLD 4072, Australia (hpossingham@zen.uq.edu.au)*

Abstract There is a growing interest, both in Australia and overseas, in the problem of optimally siting marine protected areas. Operations research methods have been successfully applied to terrestrial reserve design problems and they are promising methods for marine problems. The marine setting requires a greater emphasis on connectedness within the marine protected areas but the underlying methods of optimisation remain the same. This paper outlines the basic method and introduces new concepts of robustness such as selection frequency and replaceability which strengthen the use of computer designed marine protected areas as tools of negotiation.

Keywords: Marine Protected Areas; Operations Research; Irreplaceability

1. INTRODUCTION

The design of marine protected areas is an area of much current research [eg Leslie et al., 2001; Agardy, 1994; Car, 2000] and there are many countries initiating marine strategies which include marine protected area [eg ANZECC, 1998; NOAA, 1999; DFO, 2000]. A great deal of work has been done on the theory of optimum reserve siting for terrestrial nature reserves [see for example McDonnell et al., in press; Possingham et al., 2000 and Pressey et al., 1993]. The marine environment is different from the terrestrial environment in a number of ways. For example, the way in which different locations are connected biologically depends greatly on current flows in the marine environment. The level of information available to the marine protected area designer also tends to be different to that available to a terrestrial reserve planner. However, much of the terrestrial work is based on fundamental operations research methods which translate readily over to the marine setting.

This paper introduces Marxan, a marine reserve planning tool which is derived from terrestrial reserve siting programs. Marxan defines an objective function which can give a relative value on the quality of different potential marine protected areas in terms of their size and cost and ability to meet biodiversity representation requirements. Given the objective function and a set of candidate areas which could be included in the protected area, optimisation methods are then applied to automatically generate systems of protected areas. This software has already been used in the planning of reserves in US waters [Satie Airame pers. comm.] and is currently being used to aid in the design of the great barrier reef's marine protected areas.

Automatically designed systems of protected areas can be used as the basis for negotiation with stakeholders over the final design of a system of marine protected areas. Because the software can generate solutions relatively quickly it can be used to explore a wide variety of scenarios with different representation requirements, different formulations of the objective function and different costs and restrictions placed on the selection of candidate areas.

The use of an objective function requires the planner to be able to explicitly state the representation requirements for the protected areas. The process of turning an understanding of the marine ecology of an area into explicit targets and delimited conservation features is itself a very important step, although not always a simple one. Candidate areas also need to be given an explicit value such as the value of the candidate area for all of the stakeholders. With such values given explicitly and unambiguously there is then a simple measure in the objective function which can rate the value of one potential set of protected areas against another.

Where there is a paucity of data on the distribution and composition of biodiversity within an area, as there is in many marine locations, these methods can still be used. Here habitat types, or environment types [Belbin, 1993] can be used as the primary feature for protection. It is possible to integrate many different levels of information and features of species for conservation with very different requirements, within the same framework.

This paper will describe how Marxan works as well as giving an example of the results that it can generate. The paper will also introduce two new ideas for measuring the importance of candidate areas for a system of protected areas. These are the simple but novel concepts of selection frequency and replaceability. A terrestrial system is used in the example due to the availability of a suitable data set.

2. MARXAN

Marxan is an optimisation program designed for marine protected area site selection. It is an extended version of a family of software including Spexan, SITES and Simann.

The region under consideration is divided up into a number of planning units which might be included in a marine protected area system. The system would consist of one or more discrete protected areas. There are a number of discrete conservation features, the distribution of which is known, which are desired to be in the marine park system. These conservation features are the elements that the protected area is set up to preserve. They might be actual species but could also be habitat or environment types. For each conservation feature there is a target level of representation to be achieved by the system. The software delivers solutions which meet the targets of the conservation features whilst minimising the cost or area of the reserve and the boundary length of the reserve. Minimising the boundary length will clump together candidate areas and promote simple contiguous shapes for marine parks.

The software combines this information into an objective function. The way in which this is done is described in detail elsewhere [Eg: McDonnell et al., in press; Ball, 2000]. The function consists of three terms: the cost or area of the marine protected system, a penalty for not achieving targets in the reserve system and a spatial configuration component. The cost of the marine protected system might simply be its area or (ideally) could be the opportunity cost of the marine protected system to stakeholders. The penalty for missing conservation features is necessary as it allows partial marine protected systems to be compared and it means that a local optima might be found even where the target representation levels for some conservation features are not achievable. In a complete marine protected system the penalty for missing conservation features will be zero. The spatial configuration component of the objective function is the boundary length or boundary cost of the reserve system. Smaller boundary lengths lead to more compact marine protected systems.

The targets for conservation features can be complex. Primarily the target is expressed in the amount of the conservation feature that is required within the system of protected areas. This could instead be given in a number of occurrences required, or possibly as a probability that the conservation feature is adequately represented in the case where there are only probabilities given for the distribution of conservation features. The target can also include a minimum patch size requirement. This guards against a conservation feature meeting its representation target in small fragments. Additionally a mutual separation target can be included to ensure that a given conservation feature is represented in locations sufficiently separated that they are unlikely to all be destroyed in the case of a localised disaster.

Marxan optimises the objective function by controlling which of the candidate areas are included in the system of protected areas. It uses either the simulated annealing algorithm or one of a number of iterative selection algorithm such as the greedy algorithm. With the greedy algorithm, at each iteration, the change that gives the greatest benefit to the objective function is enacted, either adding or removing a candidate area from the partial protected area system. It terminates when there are no more changes that it can make to improve the system. The greedy algorithm is fast and robust to the definition of the objective function but simulated annealing is the main algorithm used. It is a standard optimisation method described elsewhere [for example: Vidal, 1993].

The optimisation methods produced good and possibly optimum solutions (optimum in terms of the objective function). It can be used to explore a number of different scenarios where the targets for conservation features are varied in terms of amount and type, and also in terms of which candidate areas are locked into or out of the protected area.

As well as having a number of potential systems of protected areas there are a few useful concepts for assessing the importance of candidate areas to these systems. These include irreplaceability, selection frequency and replaceability.

3. IRREPLACEABILITY

Irreplaceability [Pressey et al., 1994] is a measure of the importance of a candidate area for meeting the conservation feature targets. It is defined in terms of the reduction in choice which would occur if the given candidate area were not available for inclusion in the protected area system. For example if a candidate area contains the only representation of a conservation feature then it is completely irreplaceable. Alternatively the loss of a candidate area might make half or three quarters of all possible systems of protected areas invalid (incapable of meeting all the targets for the conservation features).

Determining an operational measure for irreplaceability is not straight-forward. It is not in general possible to enumerate all possible systems of protected areas. Statistical methods have been explored for simple problem definitions that do not include spatial constraints or differential costing of candidate areas [Ferrier et al., 2000]. Irreplaceability has also been used as the basis for a simple index. Using this index to iteratively select candidate areas (taking the most irreplaceable candidate areas first) gives good results [Ball, 2000].

4. SELECTION FREQUENCY

A useful measure for the importance of different sites that is related to the concept of irreplaceability is the concept of selection frequency. Selection frequency can be obatined when the optimisation method used is repeated a large number of times (100 say) and the frequency with which each planning unit is included in a reserve is recorded. If a planning unit is absolutely necessary then it will appear in one hundred percent of the solutions. If it is one of many alternatives then it will have a lower frequency.

This measure is easy to understand and not hard to generate. For it to be useful the selection method by the optimisation method needs to be unbiased. Unlike the greedy algorithm which selects the most conservation feature rich candidate areas first, the simulated annealing algorithm is superb for generating selection frequency maps.

The selection frequency map can contain a large amount of information, but needs to be read with some care (some appear in the test case below). A candidate area that is irepplaceable will appear in 100% of the solution, but even 50% can be a high-rating for a candidate area. If one of two locations were absolutely necessary then they are obviously important, they might have a value of 50% or so.

The concentration and location of clumps of high frequency planning units will indicate where careful planning needs to be applied, just as the spread of low frequency planning units can indicate areas which can be decided upon at a later stage. Where there is a conflict of interest with stakeholders it could be of extreme value to see the areas which are likely to cause the most conflict early on in the process as well as seeing which areas are easily replaced.

One of the strengths of the Marxan package is its use of an objective function. This can be quite complicated, including spatial restrictions. It means that frequency can give information that would be hard to create using irreplaceability itself. A site might appear frequently not because of what it contains but because of its spatial relationship with other sites.

5. REPLACEABILITY

Replaceability is a measure of how easily replaceable a candidate area is if it were lost to a protected area system. Unlike selection frequency the replacement value for a candidate area only makes sense in the context of a given protected area system. Replaceability is generated by taking a generated solution and locking out each candidate area of the solution in turn and then finding a new solution. The replaceability measure is then the difference in the objective function value between the two solutions. A low replaceability cost means that the candidate area could easily be replaced.

This analysis could be done with the replaceability cost broken down into different components corresponding to the different components of the objective function.

6. TEST CASE

These ideas are demonstrated using data from the Northern Territory. Terrestrial data are used because of availability. The conservation features are vegetation types. The territory has been divided into 1,958 squares and there are 112 different vegetation types. The target for each vegetation type in the reserve system is n%.

As well, the boundary length is included in the system with a multiplicative factor of 4 relating the value of the boundary to the value of the area. Results with and without the boundary length modifier are taken. The target has been set to give relatively large reserve systems and the boundary length modifier, when used, is set high enough that a larger degree of clumping is achieved.

The cost term is equivalent to the number of squares which are required to meet the representation targets of the conservation features. This means that squares have equal cost. The boundary between any two cells in the system is the same. Boundaries between the land and the ocean are 'free' boundaries – there is no cost associated with them.

The target in each case is to ensure that 10% of the total distribution of each vegetation type is represented in the protected area system.

7. RESULTS AND DISCUSSION

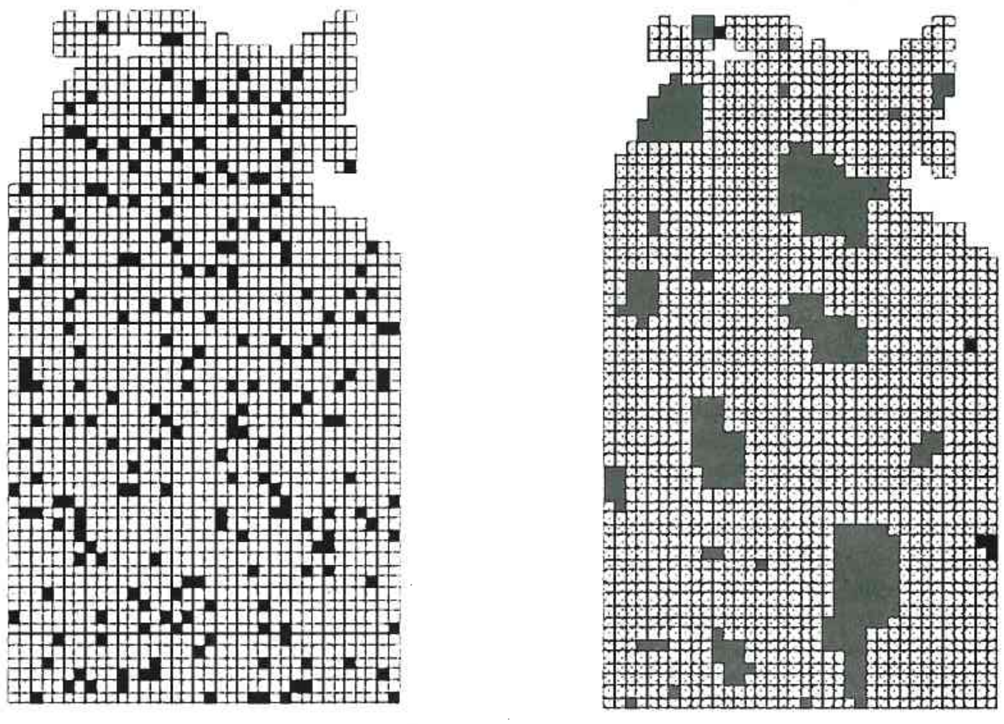

Figure 1. Two solutions for the 10% representation problem. The black areas are the squares in the reserve and the grey areas are those which could have been selected. Figure 1a is the case where there is no boundary length multiplier and consists of 207 candidate areas. Figure 1b is the case where there is a strong boundary length multiplier (4) and consists of 283 candidate area.

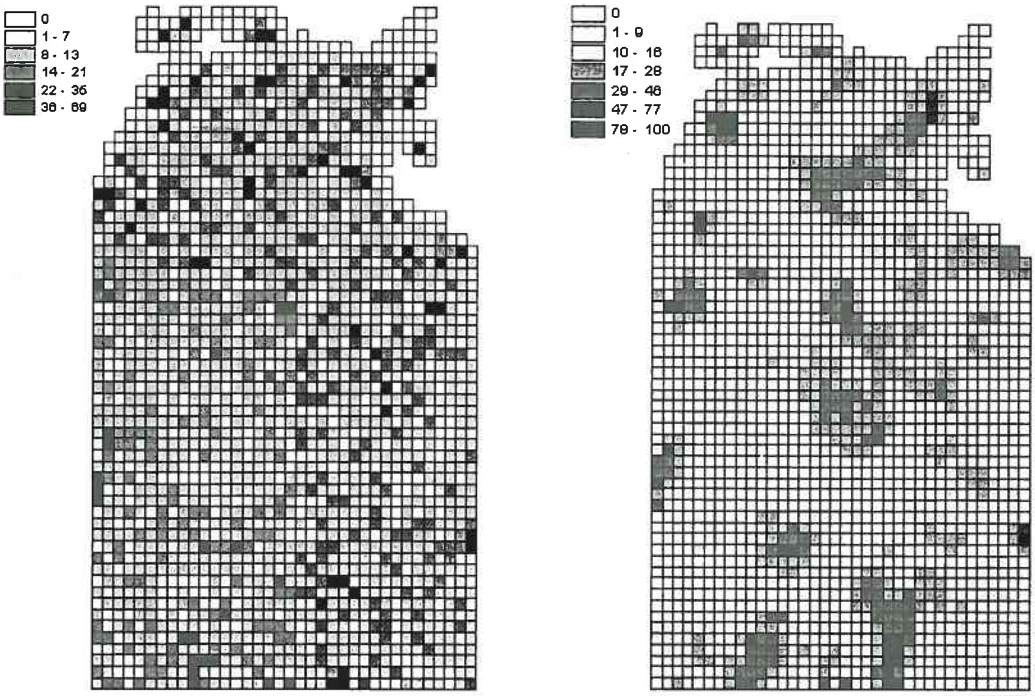

Figure 2. Two selection frequency results. In each case there are 100 runs. In neither case were candidate areas selected in more than 77 out of 100 runs. Figure 2a is the case where there is no boundary length multiplier – the only candidate areas never selected are the ones on the coast. Figure 2b is the case where there is a boundary length multiplier of 4.

Figure 1 contains two solutions derived using the simulated annealing optimisation method. They give two examples of the balance between minimum size and minimum boundary length. The first example has no boundary length modifier. Here an extreme fragmented pattern results with little compactness or contiguity among highly valued areas.. It is obviously important to include some spatial constraints.

The other case has a boundary length multiplier of 4 which is the relative weight of one boundary as compared to the value of a single candidate area. This gives a much more contiguous and compact system but the area is considerably greater and the trade off might not be worthwhile to this degree.

The second set of figures indicate the selection frequency of 100 runs of the algorithm under the two conditions.

In the selection frequency trial we can see that most of the candidate areas appeared in one or more solutions. Figure 2a is the case where there are no spatial modifiers. The distribution of selection frequency is much more even and with a few isolated exceptions most of the candidate areas appear in only a few solutions – there is a wide latitude for the design of the system of protected areas in this case.

In the case of Figure 2b, there are spatial constraints, we see that there are no cells which appear in all solutions, or there are no cells which are necessary for the reserve system. There are also few cells which do not appear in any solution, a large proportion of the land has appeared in at least one trial. This seems to indicate that there is a great latitude in placement. However there are clearly a number of regions which are quite highly constrained, and if including areas of any of these regions into a reserve system were controversial then their placement would have to be worked out as a matter of priority.

8. CONCLUSIONS

These methods of protected area selection are easily applied to marine settings. Where information is scarce, habitat types could be used in lieu of conservation features such as vegetation types. Uncertainty can be included by discounting the effective area of a habitat type within a candidate area to ensure that the total area of a nominal habitat type collected will be greater the greater the uncertainty.

The process of trying to operationalise the requirements in a marine protected area in the form needed to evaluate an objective function is important and useful because it ensures that all the parties considering the design of the area are thinking in the same terms. The ability to produce systems of protected areas automatically and relatively quickly (quicker than by hand) means that a wide variety of solutions can be considered.

The use of such measures as irreplaceability, selection frequency and replaceability enhance the information that indicates important areas, and the negotiable and non-negotiable regions in the proposed protected area.
Automatic site selection packages such as Marxan are strong tools for the design of marine protected areas, even in locations where information is scant. Their strongest use is in areas where there is a much larger amount of information than can conveniently be assimilated, or where a great number of different scenarios and assumptions are to be explored.

9. REFERENCES

ANZECC Task Force on Marine Protected Area,. *Strategic plan of action for establishing the National Representative System of marine protected areas*, Commonwealth of Australia, Canberra, Australia, 1998.

Agardy, M.T., Advances in marine conservation: The role of marine protected areas, *Trends in Ecological Evolution*, 9: 267-270, 1994.

Ball, I.R., *Mathematical applications for conservation ecology: the dynamics of tree hollows and the design of nature reserves*, Ph D. thesis, University of Adelaide, Adelaide, 2000.

Belbin, L., Environmental representativeness: Regional partitioning and reserve selection, *Biological Conservation*, **66**, 223-230, 1993.

Carr, M.H., Marine protected areas: Challenges and opportunities for understanding and conserving coastal marine ecosystems, *Environmental Conservation*, 27(2):106-109, 2000.

Department of Fisheries and Oceans, Canada (DFO). *Fisheries and Oceans 2000-2001. Estimates, Part III: Report on Plans and Priorities. Catalogue No. BT31-2/2001/III-56.* Ottawa Canada: Canadian Government Publishing (PWGSC). 73 pp, 2000.

Ferrier, S., R.L. Pressey, and T.W. Barret, A new predictor of the irreplaceability of areas for achieving a conservation goal, its application to real-world planning, and a research agenda for further refinements, *Biological Conservation* 93: 303-325, 2000.

Leslie, H., M. Ruckelshaus, I.R. Ball, S. Andelman, and H.P. Possingham, Using siting algorithms in the design of marine reserve networks, *Ecological Application*, 2001.

National Oceanic and Atmospheric Administraion (NOAA), *Turning to the sea: America's ocean future.* Washington, DC: US Department of Commerce. 64 pp, 1999.

McDonnell, M.D., H.P. Possingham, I.R. Ball, and E.A. Cousins, Mathematical methods for spatially cohesive reserve design, *Environmental Management and Assessment*, in press.

Possingham, HP, I.R. Ball, and S. Andelman, Mathematical methods for identifying representative reserve networks. Chapter 16 *in Quantitative methods in conservation biology*, S Ferson and M.A. Burgman (eds) Springer-Verlag, 2000.

Pressey, R.L., C.J. Humphries, C.R. Margules, R.I. Vane-Wright, and P.H. Williams, Beyond opportunism: Key principles for systematic reserve selection, *Trends in Ecological Evolution*, 8: 124-128, 1993.

Pressey, R.L., I.R. Johnson, and P.D. Wilson, Shades of irreplaceability towards a measure of the contribution of sites to a reservation goal, *Biodiversity and Conservation* 3: 242-262, 1994.

Vidal, R.V.V. *Applied Simulated Annealing*, Springer-Verlag: Berlin-New York, 1993.