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Conservation planning with irreplaceability: does the method matter?

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Abstract A number of systematic conservation planning tools are available to aid in making land use decisions. Given the increasing worldwide use and application of reserve design tools, including measures of site irreplaceability, it is essential that methodological differences and their potential effect on conservation planning outcomes are understood. We compared the irreplaceability of sites for protecting ecosystems within the Brigalow Belt Bioregion, Queensland, Australia, using two alternative reserve system design tools, Marxan and C-Plan. We set Marxan to generate multiple reserve systems that met targets with minimal area; the first scenario ignored spatial objectives, while the second selected compact groups of areas. Marxan calculates the irreplaceability of each site as the proportion of solutions in which it occurs for each of these set scenarios. In contrast, C-Plan uses a statistical estimate of irreplaceability as the likelihood that each site is needed in all combinations of sites that satisfy the targets. We found that sites containing rare ecosystems are almost always irreplaceable regardless of the method. Importantly, Marxan and C-Plan gave similar outcomes when spatial objectives were ignored. Marxan

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with a compactness objective defined twice as much area as irreplaceable, including many sites with relatively common ecosystems. However, targets for all ecosystems were met using a similar amount of area in C-Plan and Marxan, even with compactness. The importance of differences in the outcomes of using the two methods will depend on the question being addressed; in general, the use of two or more complementary tools is beneficial.

Keywords Biodiversity · Conservation Planning · C-Plan · Irreplaceability · Marxan · Reserve compactness

Introduction

The importance of systematic conservation planning is becoming widely recognised, as we attempt to redress the opportunity costs and biodiversity losses incurred by previous ad hoc allocations of protected areas (Pressey and Tully 1994; Rodrigues et al. 1999; Pressey and Taffs 2001; Stewart et al. 2003). Systematic conservation planning should be supported by the identification of explicit targets for biodiversity features, to guide decisions regarding which sites in a landscape should be protected to achieve these targets (Possingham et al. 2000). The necessity for conservation planning tools has driven the development of many and varied approaches, which are used worldwide to support major decisions about the use of land and sea. It is therefore essential that we understand how much conservation planning decisions could vary if different decision support tools are applied.

Systematic reserve design involves the setting of targets for biodiversity features (such as number of populations), and the selection of sets of sites that can meet these targets. The site selection process varies between methods, but is generally based on the principle of complementarity, that is, the gain in representativeness of biodiversity, relative to targets, when a site is added to an existing set of areas (Margules et al. 1988; Vane-wright et al. 1991; Possingham et al. 2000).

A weakness of target-based reserve design arises when there are many alternative sets of sites that can meet targets, and many of these might be similarly efficient in terms of cost (such as the total area required to meet targets). Looking at a single reserve solution therefore gives no indication of the importance of each site in terms of the potential to replace it with others in the region (Pressey et al. 1994). Planners therefore cannot see if the site is unique in its contribution to targets or whether the management of specific sites is open to negotiation with other interests. The concept of 'irreplaceability' evolved from target-based solutions, and has been defined as the likelihood that a site will be required to meet a given set of targets (Pressey et al. 1994; Ferrier et al. 2000).

Irreplaceability is measured as a continuum of values between 0 and 1, where sites with values of 1 are essential for achieving one or more targets and are therefore irreplaceable. As values decrease from 1 a site has increasing numbers of potential replacements and becomes more replaceable. Hence, it might be expected that sites with rarer biodiversity features have higher irreplaceability values than sites with more common features, for which there are many conservation options in the landscape. Measures of irreplaceability can be used to determine priorities for action (Pressey 1998; Richardson and Funk 1999; Pressey et al. 2004), particularly since lack of resources and other competing land uses can prevent the achievement of all targets (Vane-wright et al. 1991; Faith and Walker 1996). Irreplaceability can also be useful for interactive building of reserve systems. The irreplaceable sites can be used to form the core of the system, and the remainder of targets can then be met by negotiation (Pressey 1998; Ferrier et al. 2000).

A number of comparisons of various reserve selection tools have been published (e.g. Csuti et al. 1997; Kelley et al. 2002). Most of these studies have compared a single solution using each tool and none have compared differences in irreplaceability values allocated to sites. This paper presents a comparison of tools for determining irreplaceability values, which provide important information for planners and have been widely used in guiding actual conservation decisions. Different tools can produce different values of irreplaceability for two reasons. First, irreplaceability can only be measured exactly for small data sets (Pressey et al. 1994) and/or simplistic targets such as one occurrence of each species or vegetation type. Large data sets typical of regional planning exercises, as well as more complex, realistic sets of targets, require irreplaceability to be estimated, and different methods for estimation are likely to produce different results. Second, tools not only vary in the way they estimate irreplaceability, but also in the problems they address, principally whether or not they account for the spatial design of conservation areas.

We compared two reserve system design tools: Marxan (Ball and Possingham 2000) and C-Plan (NSW NPWS 1999), which both calculate the irreplaceability of sites. Marxan and its predecessors have been used by The Nature Conservancy for ecoregional planning (Ferdana 2002) and for marine reserve design (GBRMPA; Stewart et al. 2003). C-Plan has been used for prioritisation and management decisions over various areas, especially in New South Wales (e.g. Finkel 1998; Pressey 1998), but also abroad (Richardson and Funk 1999; Cowling et al. 2003; Warman et al. 2004) and for a recent global assessment (Rodrigues et al. 2004).

The two tools have different objectives and operational strategies. Marxan aims to find reserve systems that meet biodiversity targets while minimising cost and addressing spatial design objectives (Ball and Possingham 2000). This is achieved by minimising the value of an objective function, which is a combination of the cost (usually area) of each potential reserve and a penalty for any unmet biodiversity targets. Marxan treats targets as objectives rather than constraints, hence the target for a feature can remain partly unmet if a large cost would be incurred to meet it completely. The emphasis on meeting targets can be adjusted with the feature penalty factor. There is also an option for including a boundary length modifier (BLM), which can be altered to control the relative importance of minimising the overall boundary length of the reserve system whilst still minimising its area, thereby maximising compactness (Ball and Possingham 2000).

Marxan finds a number of solutions, each one a set of potential new reserves, using a simulated annealing algorithm (Kirkpatrick et al. 1983; Ball and Possingham 2000). The software can then produce an irreplaceability value for each site, which is the proportion of solutions containing it (see Ball and Possingham 2000, 2002; McDonnell et al. 2002 for further details). Hence irreplaceability is calculated using an actual sample of reserve solutions, all of which are efficient relative to the design objectives. Incorporating compactness has been shown to increase the area required to meet targets (Nicholls and Margules 1993; Pressey and Taffs 2001), so more compact solutions can be less efficient than those without spatial design objectives.

In contrast, C-Plan uses a statistical approach to generate direct estimates of irreplaceability (Ferrier et al. 2000), without any considerations of spatial objectives.

The process involves the initial calculation of the ‘combination size’, which is an estimate of the number of sites needed to meet the set of targets. The irreplaceability of each site is then estimated as the extent to which options for achieving the targets, across all possible sets of sites of the combination size, are reduced if the site is made unavailable for conservation (Ferrier et al. 2000).

To determine potential reserve solutions in C-Plan, the system is used interactively (Pressey 1998; Cowling et al. 2003) and/or one of its heuristic selection algorithms is used to select sites. One of the possible rules of the selection algorithm is irreplaceability, which is then recalculated after each selection until all feature targets are met (this rule was used in the present study). Hence the site selected first has the highest irreplaceability, and the site selected second has the next highest given the contribution to targets of the first site. Ties are resolved using a series of additional rules and redundant sites are removed every 10 iterations (see NSW NPWS 1999; Ferrier et al. 2000 for further details). In this paper we address the following questions:

(1) How much do irreplaceability values vary when different reserve design tools are used and different spatial considerations are applied?
(2) To what extent is the rarity of features driving irreplaceability values? Not only is this relationship interesting in its own right, but the effect of rarity on irreplaceability values might differ between the design tools.
(3) How are irreplaceable and replaceable sites incorporated into reserve solutions by each method?
(4) What do differences between tools mean for their future use in real-world conservation planning?

Methods

(a) Data set

The study area comprises five adjacent subregions in the Brigalow Belt South bioregion, Queensland, Australia (Fig. 1). The subregions: Carnarvon, Taroom Downs, Southern Downs, Barakula, and Dulacca Downs cover a total combined area of 86,700 km^2. The region has a mean annual rainfall of approximately 650 mm and its landforms vary from hilly and rocky surfaces on sandstone to undulating plains of fine-grained sediments and clays (Sattler and Williams 1999). Approximately half of the original native vegetation in the region has been cleared (Fig. 1). Within Queensland, including the study area, ‘‘regional ecosystems’’ have been classified by association with particular combinations of geology, landform and soil (Sattler and Williams 1999). Different regional ecosystems are understood to support different species (Wessels et al. 1999), and can be used as biodiversity surrogates for conservation planning (e.g. Kirkpatrick and Brown 1994). Both Marxan and C-Plan are capable of processing various forms of data, including species data (e.g. probabilities of occurrence) but species data were scarce for the study region. Hence regional ecosystems were used as a biodiversity surrogate in determining irreplaceability values for this study.

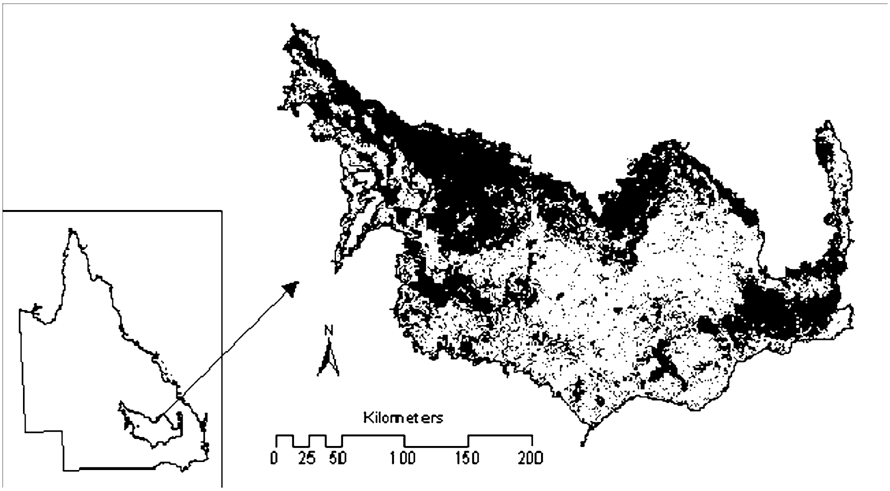

Fig. 1 The study region, part of the Brigalow Belt South bioregion, Queensland, Australia. Dark shading indicates remaining native vegetation

We obtained both remnant (Fig. 1) and estimated pre-clearing vegetation maps for the region at a scale of 1:100,000 from the Queensland Herbarium (EPA 2001). These were provided as GIS vector layers, with each polygon of remnant vegetation containing one or more regional ecosystems. We cut large polygons using an overlaid grid such that the maximum size of a subdivision was approximately 500 ha. The smaller remnants and subdivisions of larger remnants were used as sites in this study. The dataset contained 27,954 variably sized sites, and 83 regional ecosystems as biodiversity features. We set targets at 30% of the pre-clearing extent of each regional ecosystem, broadly in line with clearing policy guidelines of the *Queensland Vegetation Management Act 1999*. We set targets of total current extent for regional ecosystems that had already been cleared below 30% of their original extent. We assessed each site's irreplaceability on the basis of regional ecosystems, without the social, economic and political considerations required in a real planning task, many of which have been addressed previously by both planning tools (e.g. Pressey 1998; Cowling et al. 2003).

(b) Scenarios

We ran Marxan v1.8.3 (Ball and Possingham 2000) with an adaptive annealing schedule, producing 100 solutions for each of a range of boundary length modifiers (BLMs). We determined a good BLM for further analysis, which is found where boundary length is substantially decreased but where total area has not risen significantly (in our case a BLM of 2000). We calculated the irreplaceability of each site as the number of times, out of 100, the site was in a reserve solution for two BLM settings: (i) a BLM of zero, where the boundary length was unconstrained and the algorithm sought to minimize area only (hereafter 'Marxan with no compactness'), and (ii) a BLM of 2000 (hereafter 'Marxan with compactness'). We recorded the best reserve solution in each, which is the solution with the lowest objective function value. The penalty factor was set at 10, which ensured that all targets were satisfied by more than 99% while allowing the poorest value sites to be left out.

We also determined the irreplaceability of each site in C-Plan v3.11 (NSW NPWS 1999). We then determined a single reserve solution by running the selection algorithm based on irreplaceability (i.e. sites are selected based on irreplaceability, which is recalculated after each selection).

We generated maps showing the irreplaceability values allocated to each site by the three method variations: Marxan, with and without compactness, and C-Plan. We also recorded computational times for each step in both C-Plan and Marxan.

(c) Analysis

We initially compared the frequency histograms of irreplaceability values from the three method variations using 20 categories (0–0.05, >0.05–0.1, >0.1–0.15, etc). We did not use a significance test to compare these distributions because they do not represent samples from different distributions of values. The histograms simply provide an indication of the similarity of the distributions of irreplaceability values across the study area using different methods.

A limitation of the histogram comparisons is that they give no insight into the spatial location of the differences and similarities between irreplaceability values allocated by the method variations. We therefore compared the spatial location of irreplaceability values, firstly by measuring the proportional overlap (Prendergast 1993) in areas with irreplaceability values of 1.0 between each pair of methods. The proportional overlap method normalizes the measure of overlap by the maximum possible overlap, which is in this case the lesser of the two total areas of irreplaceable sites in the scenarios being compared.

We also looked spatially at the size of the differences in irreplaceability values assigned by each method. To do this we subtracted C-Plan's irreplaceability value from Marxan's irreplaceability value, with and without compactness, for each site. We also subtracted Marxan's irreplaceability value without compactness from its value with compactness. Using cut-offs for differences in irreplaceability values of 0.5, 0.3 and 0.1, we mapped areas that were valued differently.

We then examined irreplaceability values of sites relative to the rarity of the features they contained. We calculated the maximum rarity of each site, which was based on the rarest regional ecosystem that the site contained. We measured rarity for each regional ecosystem as the percentage of its pre-clearing extent that remained in our dataset. Regional ecosystems with lower percentages of pre-clearing extent remaining were rarer relative to their targets because targets were based on pre-clearing extent. With all targets set at 30% of pre-clearing extent, a regional ecosystem with 60% of its pre-clearing extent remaining under native vegetation had twice the area of its target available for conservation action. A regional ecosystem with only 35% remaining had only slightly more area than its target available for conservation and a correspondingly higher rarity value. For each of the three method variations, we graphed irreplaceability values of all sites against maximum rarity values.

Finally, we compared the total area and composition of the reserve solution from each method (single solution from C-Plan, best solution from Marxan). By combining all sites with irreplaceability values of less than one and calling these 'replaceable', we found the proportions of sites in each solution made up of replaceable and irreplaceable sites. Marxan was forced to meet all targets for this part of the analysis for comparability with C-Plan.

Results

The frequency distribution of irreplaceability values generated by the three method variations were different (Fig. 2). Marxan with compactness allocated high irreplaceability values to the greatest proportion of sites. Marxan with no compactness allocated moderate values to more sites than either of the other methods. C-Plan allocated more low values than the other method variations.

C-Plan and Marxan with no compactness allocated irreplaceability values of 1.0 to a similar total area of sites, and these were almost all common to both solutions as shown by the proportional overlap value of 99.0 (Table 1, Fig. 3a–b). Marxan with compactness produced different results, identifying almost double the area as irreplaceable (Table 1, Fig. 3c). However, the high proportional overlap values (both >98.0) indicate that Marxan with compactness selects almost all of the area that C-Plan and Marxan without compactness identifies as irreplaceable. Marxan with compactness therefore adds more area as irreplaceability 1, rather than choosing different areas than are chosen by C-Plan and Marxan with no compactness.

There were small differences in irreplaceability values between C-Plan and Marxan with no compactness (Fig. 4a). Marxan with no compactness gave slightly higher irreplaceability values to extensive (pale blue) areas. C-Plan gave much higher values to small (red) areas. Marxan with compactness gave many clustered sites higher values than C-Plan and Marxan with no compactness (pale and dark blue areas) (Fig. 4b–c). In the comparison in Fig. 4c, roughly equal areas were higher in

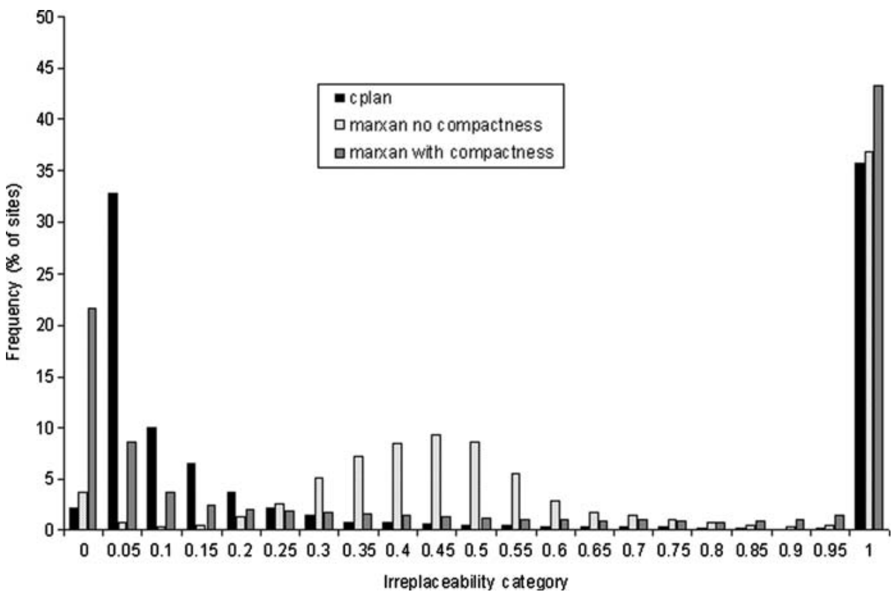

Fig. 2 Frequency distributions of irreplaceability values from each method variation using 20 categories

Table 1 Area of sites (km^2) identified as irreplaceable (with irreplaceability values of 1.0) in each method and the proportional overlap in the area of irreplaceable sites between each pair of methods. Values indicate the extent of overlap normalized by the maximum possible overlap, shown in brackets, which is the lesser of the two total areas (km^2) that were irreplaceable in the scenarios being compared

Method variation	Irreplaceable area (km^2)	Proportional overlap in irreplaceable area (maximum possible area overlap in km^2)	
		C-Plan	Marxan no compactness
C-Plan	5360		
Marxan no compactness	5444	99.0 (5360)	
Marxan with compactness	10751	98.9 (5360)	98.1 (5444)

irreplaceability from Marxan with no compactness and Marxan with compactness. Across the three comparisons, at least 27% of sites had irreplaceability differences of 0.1 or less (pale green). While the comparison between C-Plan and Marxan with no compactness had the lowest percentage in this category, it had the highest proportion of area captured within the next most similar categories.

Irreplaceability values of sites were related to their maximum rarity values (Fig. 5). The patterns from C-Plan and Marxan with no compactness are comparable (Fig. 5a, b). Sites with regional ecosystems that have been cleared below 30% of their original extent were always given irreplaceability values of 1.0 in C-Plan. Most of these sites were also irreplaceable in Marxan with no compactness for which target requirement was 99%, so a few sites containing very rare ecosystems were given irreplaceability values less than 1.0. Sites containing ecosystems that have slightly more than 30% of pre-clearing extent remaining were given a range of irreplaceability values in C-Plan and Marxan with no compactness. With increasing commonness of regional ecosystems, irreplaceability values of sites decreased for both C-Plan and Marxan with no compactness, although values in Marxan with no compactness were slightly higher overall.

The relationship between ecosystem rarity and irreplaceability in Marxan with compactness was different to the other methods (Fig. 5c). There was no obvious decline in irreplaceability values with increasing commonness of regional ecosystems; many sites with common features were given high values. Notably, more sites containing very rare ecosystems (below 30% pre-clearing extent) were given lower irreplaceability in Marxan with compactness than in Marxan with no compactness. These sites contained only very small amounts of the rare ecosystems and their omission from some solutions did not reduce targets below 99%.

Irreplaceable sites, by definition, are included in all reserve solutions but, to meet all targets, some replaceable sites are also required in any reserve solution. The solutions generated by C-Plan solution and Marxan with no compactness contained similar proportions of irreplaceable and replaceable sites (Fig. 3a, b, Table 2). Marxan with compactness had about twice the extent of irreplaceable sites in its solution and a relatively small total area of replaceable sites. As a result, reserve solutions using all method variations could meet targets with similar total areas.

Regardless of BLM setting Marxan took approximately 3 h to complete 100 runs, which includes the generation of the resultant irreplaceability value for each site. C-Plan took approximately 5 min to generate irreplaceability estimates, and a further 1 h to identify a single reserve solution using the greedy heuristic algorithm. Any subsequent reserve solutions also took 1 h to generate.

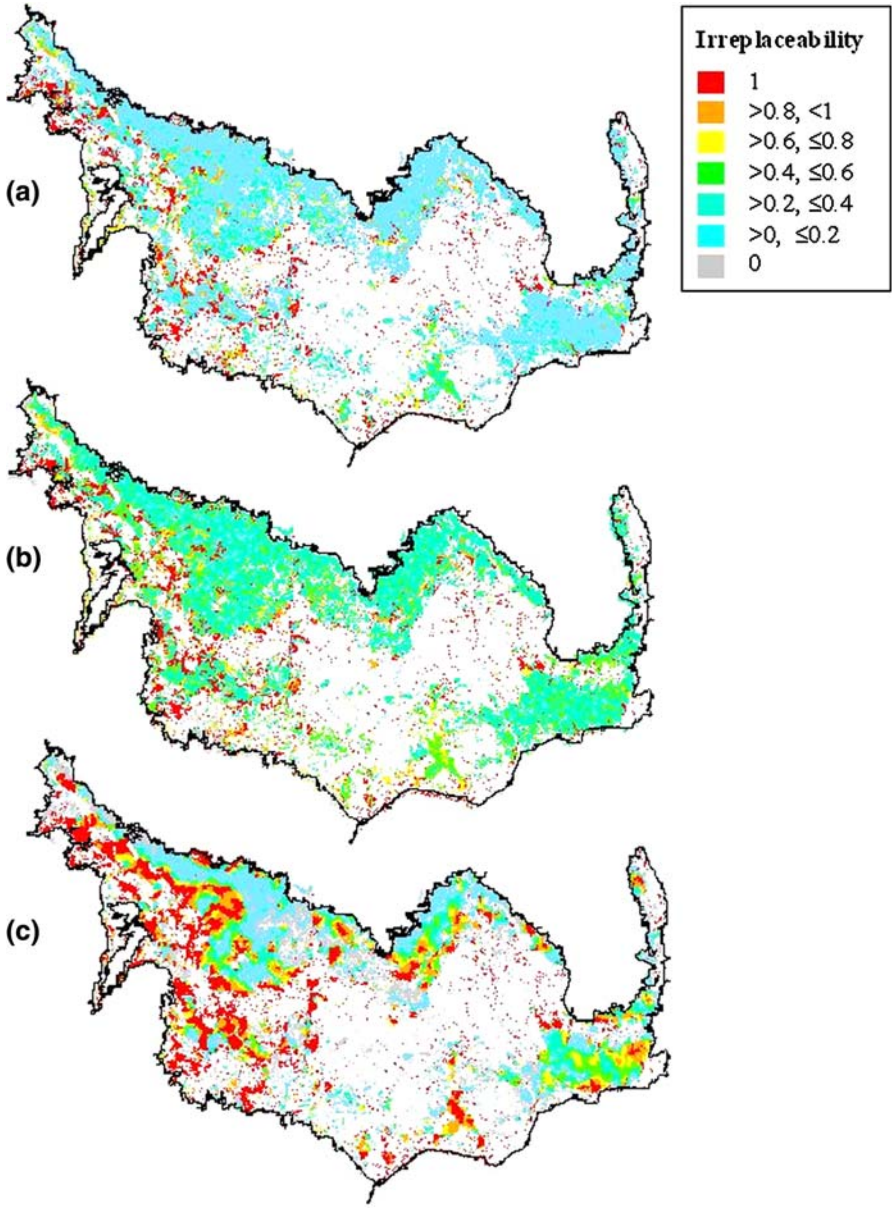

Fig. 3 Irreplaceability values allocated to sites by (a) C-Plan, (b) Marxan with no compactness, and (c) Marxan with compactness

Discussion

We found that the spatial considerations of the tool being used and the rarity of ecosystems within sites had strong effects on the distribution of irreplaceability values in our study region. We also found that a level of compactness in reserve design can be

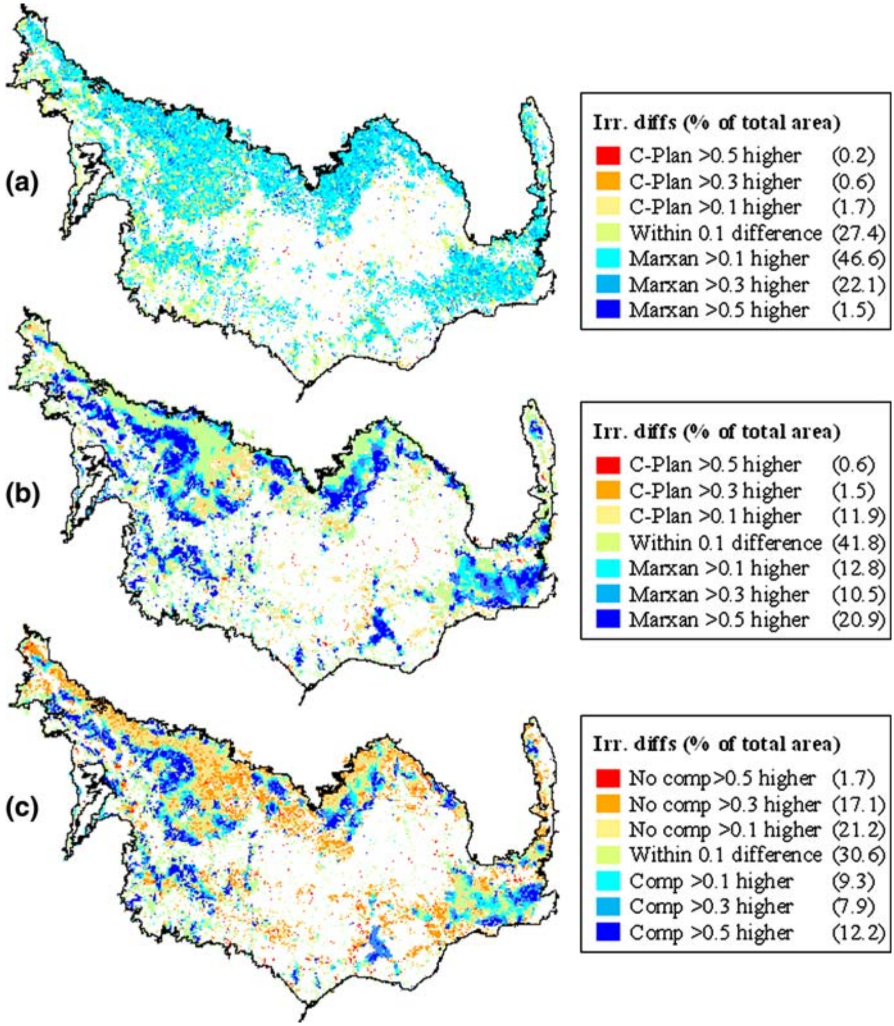

Fig. 4 Differences in irreplaceability values (Irr. diffs) and percentage of total area of sites in each difference category: (a) C-Plan compared to Marxan with no compactness; (b) C-Plan compared to Marxan with compactness; and (c) Marxan with compactness compared to Marxan without compactness (Comp and No Comp respectively)

achieved with minimal additional area cost for our dataset. We discuss these findings in the context of using Marxan and C-Plan in real world conservation planning.

Without spatial considerations, Marxan and C-Plan gave similar irreplaceability values, although Marxan allocated more sites moderate irreplaceability values than C-Plan. These areas tended to be located in extensive, unfragmented parts of the study region with low to moderate irreplaceabilities from one or both methods. These small differences are likely to be due to the different methods used to estimate irreplaceability. Marxan used 100 variably sized, optimal or near-optimal, solutions that represented a sample of all possible solutions of those sizes (but note that the number of solutions is flexible and can be much larger). C-Plan uses a statistical

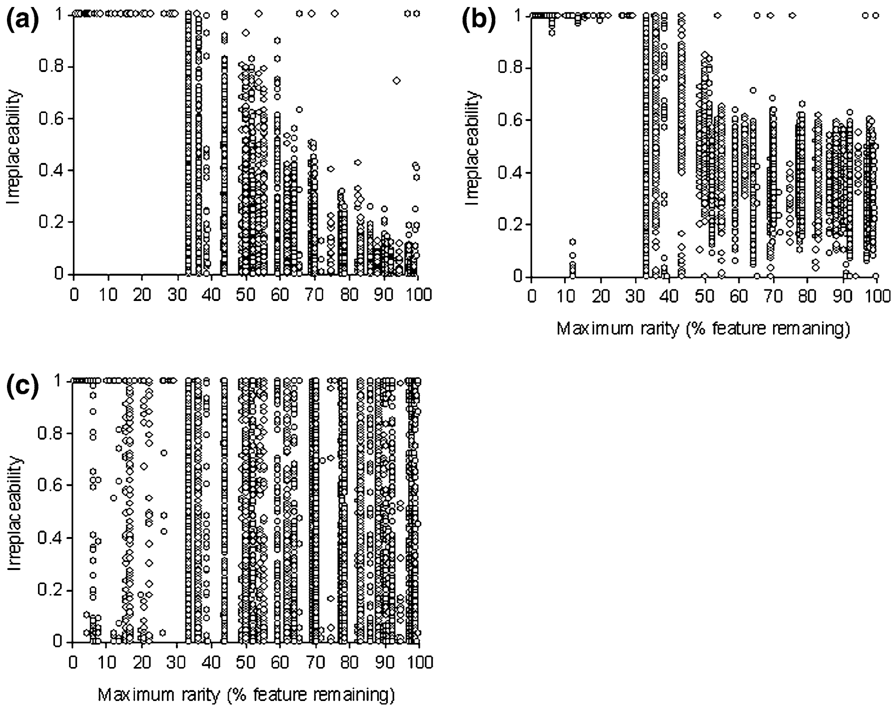

Fig. 5 Relationships between irreplaceability of sites and maximum rarity of sites based on the percentage of pre-clearing extent of ecosystems with remaining native vegetation: irreplaceability estimated by (a) C-Plan, (b) Marxan with no compactness, and (c) Marxan with compactness

Table 2 Total areas (km^2) of irreplaceable (irreplaceability = 1.0) and replaceable (irreplaceability <1.0) sites in reserve solutions from each method (values in brackets indicate these areas as percentages of the total reserve solution in each method)

Method variation	Irreplaceable area in km^2 and (as % of total solution area)	Replaceable area in km^2 and (as % of total solution area)	Total area in reserve solution in km^2
C-Plan	5360 (26.4)	14929 (73.6)	20289
Marxan no compactness	5444 (27.0)	14688 (73.0)	20132
Marxan with compactness	10751 (52.4)	9753 (47.6)	20504

estimate of irreplaceability, rather than a direct sample, based on all representative combinations of sites of a single combination size. However, despite these differences, our results suggest that the method used may not be particularly important when compactness is not used in Marxan.

Notably, maximum rarity was not the sole driver of irreplaceability values; there was much variation in irreplaceability values at a given level of rarity even without compactness. Those sites with very small areas of features with rarity values larger than 30% tended to have low irreplaceabilities because: (i) both tools recognised there were other sites that contributed to targets more substantially; and (ii) in Marxan, because target achievement was allowed to fall marginally below 100%, the small contributions of these sites to targets was not worth their cost. The irreplaceability of a site depends not only on the rarity of ecosystems or other targeted features occurring there, but on whether the site contains a small or large amount of a feature relative to its target and relative to other occurrences in the region.

Incorporating different spatial design criteria into reserve systems has been shown to significantly alter the sites that are selected (Ball and Possingham 2002; McDonnell et al. 2002; Onal and Briers 2002; Stewart et al. 2003). Our study demonstrated similarly strong effects of design on irreplaceability values. The differences in irreplaceability values given to sites in Marxan with compactness compared with C-Plan and Marxan with no compactness are partly linked with maximum rarity. Sites with rare features had high irreplaceabilities almost regardless of spatial considerations. However, many sites with common features were also given high irreplaceability values in Marxan with compactness, resulting in twice as many irreplaceable sites. This is explained by Marxan favouring examples of common features that were regular in shape and/or were in spatially preferable locations, such as beside a rare feature or filling in a gap between irreplaceable sites (McDonnell et al. 2002). These same sites were generally given low or moderate values by C-Plan and Marxan applied without compactness because they were not necessarily preferred over other sites with the same features. Our measure of feature rarity therefore determined the extent to which compactness could affect the irreplaceability values of sites.

Ecosystems with rarity values of 30% or less were almost always allocated high irreplaceability values, regardless of method, as all sites are needed to meet the targets for these features. This suggests that, in other study regions, the proportion of features that are rare relative to their targets might affect conclusions about the similarity of the results produced by the two tools. As the number of rare features increases, the similarity between the two tools is also likely to increase, even with compactness in Marxan. This points to the desirability of further comparisons between the two systems on actual and/or artificial data sets to test the effects of rarity and other aspects of data structure, as done for different selection algorithms by Pressey et al. (1999).

For this case study, we showed that it is possible to find solutions that are both reasonably efficient and compact. The similar reserve solution sizes of C-Plan and Marxan with no compactness were not unexpected, as previous studies have found iterative algorithms to be comparably efficient to simulated annealing algorithms for non-spatial problems (Csuti et al. 1997; Kelley et al. 2002). However, Marxan with compactness could also meet targets in a slightly larger area. This result is likely to depend on the nature of our data set, representation targets, and the emphasis placed on design objectives. Some previous studies have also shown that increases in adjacency and contiguity can be achieved with minimal additional cost (Lombard et al. 1997; Onal and Briers 2002). Other studies have demonstrated a trade-off between efficiency and design (Nicholls and Margules 1993; Pressey and Taffs 2001) and this is probably inevitable as emphasis on design objectives is increased. Nonetheless, even with some loss of efficiency, compactness is important in reserve design. Minimising fragmentation can be generally expected to promote the persistence of a suite of biodiversity processes, including population viability, which are essential goals of nature conservation (Soule 1986; Onal and Briers 2002; Virolainen 1999; Araujo et al. 2002). A key outcome of the present study is the ease with which spatial design and representation could be achieved simultaneously.

The importance of the differences in results between Marxan and C-Plan are specific to the context for planning. C-Plan was designed for interactive use in negotiations between interest groups for which alternative conservation scenarios needed to be explored very quickly. The system therefore uses a very fast method for estimating irreplaceability values and has extensive capabilities for interactive use. Reserve design issues can be addressed by the user as they examine different reserve options. C-Plan's automatic selection routines are iterative heuristics suitable for exploration but not for simultaneous achievement of multiple objectives. Marxan's annealing algorithm is highly suitable for identifying alternative sets of sites that achieve multiple objectives, including spatial design, which can be weighted explicitly against each other. Importantly, Marxan's ability to generate many alternative solutions allows it to estimate irreplaceability for multiple objectives, albeit less quickly than C-Plan's estimates of irreplaceability for representation targets only. Marxan also has a proven role in interactive planning. These characteristics exemplify the complementary nature of software systems for conservation planning and the advantages of using more than one. They also explain why C-Plan and Marxan have now been linked with a single graphical interface and are being used together for conservation planning in many regions.

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