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Short communication

Marxan with Zones: Software for optimal conservation based land- and sea-use zoning

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ABSTRACT

Marxan is the most widely used conservation planning software in the world and is designed for solving complex conservation planning problems in landscapes and seascapes. In this paper we describe a substantial extension of Marxan called Marxan with Zones, a decision support tool that provides land-use zoning options in geographical regions for biodiversity conservation. We describe new functions designed to enhance the original Marxan software and expand on its utility as a decision support tool. The major new element in the decision problem is allowing any parcel of land or sea to be allocated to a specific zone, not just reserved or unreserved. Each zone then has the option of its own actions, objectives and constraints, with the flexibility to define the contribution of each zone to achieve targets for pre-specified features (e.g. species or habitats). The objective is to minimize the total cost of implementing the zoning plan while ensuring a variety of conservation and land-use objectives are achieved. We outline the capabilities, limitations and additional data requirements of this new software and perform a comparison with the original version of Marxan. We feature a number of case studies to demonstrate the functionality of the software and highlight its flexibility to address a range of complex spatial planning problems. These studies demonstrate the design of multiple-use marine parks in both Western Australia and California, and the zoning of forest use in East Kalimantan.

Software availability

Name of software: Marxan with Zones 1.0
Developers: Matthew Watts, Ian Ball, Hugh Possingham
Email: m.watts@uq.edu.au
Year first available: 2008
Program language: C++
Software required: 32 bit microsoft windows operating system or compatible emulator
Program size: 2 MB
Availability: Compiled binary available at http://www.uq.edu.au/marxan
Cost: nil

1. Introduction

Systematic conservation planning involves finding cost-efficient sets of areas to protect biodiversity. One goal of systematic conservation planning is to meet quantitative conservation objectives, such as conserving 30% of the range of each species, as cheaply as possible (Carwardine et al., 2009). This is referred to as the minimum-set problem (Possingham et al., 2006). It can be expressed as an integer linear programming problem if the cost and constraints are linear functions of the number of sites in the system (Cocks and Baird, 1989; Possingham et al., 1993; Underhill, 1994; Willis et al., 1996; McDonnell et al., 2002).

Recent research efforts have focused on developing computer software to solve the minimum-set problem (Sarkar, 2006). Numerous algorithms can find solutions to the minimum-set problem (Margules et al., 1988; Rebelo and Siegfied, 1992; Nicholls and Margules, 1993; Csuti et al., 1997; Pressey et al., 1997). The large number of feasible solutions to the minimum-set problem makes some iterative and optimizing algorithms unsuitable for large

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conservation planning problems. They often are slow to find solutions, find only inefficient solutions or find only single solutions. Marxan is the most widely used conservation planning software in the world with over 2600 individuals and 1500 organisational users in 110 countries. It uses a simulated annealing algorithm because of its ability to find many near-optimal solutions to large problems fairly quickly (Ball and Possingham, 2000; Possingham et al., 2000).

A major limitation of the approach to spatial planning employed in existing systematic conservation planning software such as Zonation, ResNet, C-Plan and Marxan, is the inability to simultaneously consider different types of zones to reflect the range of management actions or conservation activities being considered as part of a conservation plan (Moilanen et al., 2009). Indeed, in terrestrial environments, conservation practitioners implement a diversity of management actions, ranging from fire management and predator control, to restoration and reservation (Wilson et al., 2007). Furthermore, conservation activities occur in a matrix of alternative land and sea uses, many of which are contrary to conservation objectives. While the outer boundaries of protected areas are often identified using systematic conservation planning software (e.g. Fernandes et al., 2005; Airame et al., 2003), the actual process of zoning is often performed outside of a systematic framework because of software limitations.

Zoning is a common management practice to spatially and temporally designate areas for specific purposes (Anon, 1977; Korhonen, 1996; Liffmann et al., 2000; Day et al., 2002; Russ and Zeller, 2003; Airame, 2005; Foster et al., 2005). Zoning plans provide an explicit approach to resolving conflicts between activities and determining trade-offs when balancing these competing interests (Halpern et al., 2008). Zoning is implemented around the world as an approach to support the multiple objectives of marine parks (notably in Australia's Great Barrier Reef Marine Park, Fernandes et al., 2005). The purpose of zoning in a conservation context is typically to accommodate potentially conflicting activities including conservation, non-consumptive recreation (e.g. scuba), and consumptive uses (e.g. fishing) within an integrated system of management (Day, 2002).

The original Marxan software could only include or exclude a planning unit from being reserved, implicitly assuming two zones: reserved or not reserved. Furthermore all conservation features (such as vegetation types or species) are assumed to be fully protected in a reserve and all conservation features outside a reserve are lost – an assumption which does not match reality. Multiple zoning could be achieved by iterative application of the software (Loos, 2006), but that is clumsy and sub-optimal. Forest managers have used simulated annealing algorithms to harmonize site suitability for forestry regimes (Bos, 1993), and planners have internally zoned protected areas based upon spatial attributes such as compatibility and connectivity (Sabatini et al., 2007). Our zoning approach differs by explicitly targeting representation, complementarity and constraints of conflicting objectives in the problem definition (Lourival, 2008).

In this paper we introduce Marxan with Zones, an analytic tool that expands on the basic reserve design problem to allow for zones. This enables users to move from the binary decision framework of conservation planning to multi-use landscape and seascape planning by allowing for the efficient allocation of planning units (i.e. the units of land or sea available for selection) to a range of different management actions that may offer different levels of protection. We present Marxan with Zones as a tool for systematic zoning; not only to improve planning for reserve systems but also with application to a wider range of natural resource management and spatial planning problems. Two particular limitations of Marxan are overcome in Marxan with Zones: 1) the ability to spatially separate multiple and potentially conflicting activities (e.g. fishing and non-consumptive recreational activities) and 2) the ability to explicitly address multiple objectives (e.g. conservation and socioeconomic) in a systematic way. This is the first land-use zoning software with a particular focus on conservation.

First, we describe the mathematical formulation of the problem for which Marxan finds good and feasible solutions as well as the new decision problem addressed by Marxan with Zones. Next, we discuss additional data requirements and example applications that illustrate the new functions of the software. We conclude by discussing some challenges and potential applications of Marxan with Zones in conservation planning. The software should be of interest to systematic conservation planning practitioners, policy makers and natural resource managers.

2. Mathematical formulation of Marxan

The original Marxan software aims to minimize the sum of the site-specific costs and connectivity costs of the selected planning units, subject to the conservation features reaching predetermined targets in the reserve system. The Marxan minimum representation problem is:

$$\text{minimize} \quad \sum_{i=1}^{m} c_i x_i + b \sum_{i1=1}^{m} \sum_{i2=1}^{m} x_{i1}(1 - x_{i2}) cv_{i1,i2} \tag{1}$$

$$\text{subject to} \quad \sum_{i=1}^{m} a_{ij} x_i \geq t_j \quad \forall j. \tag{2}$$

where there are m planning units under consideration. The first term of equation (1) is the sum of the selected planning unit costs, where the control variable $x_i = 1$ if planning unit i is selected and 0 if planning unit i is not selected. The planning unit dependent parameter, c_i, is the cost of selecting planning unit i. The second term of equation (1) is the weighted connectivity cost of the reserve system configuration, where b is the connectivity weighting factor that controls the relative importance of connectivity in relation to the cost and target objectives and $cv_{i1,i2}$ is the connectivity cost associated with having planning unit $i1$ selected and planning unit $i2$ not selected. In other words, the connectivity cost describes the connections between planning units and a cost is paid if only one of the pair is selected, but not if both or neither is selected. This can be the monetary, distance or other value associated with a connection or adjacent boundary between a planning unit within the configuration and one without, and can also be applied to more general ideas of connectivity (Klein et al., 2008b). The parameter b is referred to as the boundary length modifier: it can be varied for more or less connected reserve systems. In equation (2), a_{ij} is the amount of each feature j held in each planning unit i, and t_j is the amount of each feature j that must be reserved.

We use a representation shortfall penalty equation to implement the target constraint in the Marxan objective function:

$$\sum_{j=1}^{n} FPF_j FR_j H(s) \left(\frac{s}{t_j}\right) \tag{3}$$

where there are n features under consideration. This penalty is zero if every feature j has met its representation target in the selected reserve system. It is greater than zero if the targets are not met, and gets larger as the gap between the target and the conserved amount increases. The terms FPF_j and FR_j are the feature penalty factor and feature representation respectively, which are the scaling factors used when a feature has not met its representation targets. FPF_j is a scaling factor which determines the relative importance of meeting the representation target for feature j. FR_j is computed as the representation cost of meeting the representation target of feature j. A zone configuration that satisfies the target for feature j only is computed, and then FR_j for feature j is set as the cost of this zone configuration. This representation cost is given in terms of the configuration cost plus the connectivity cost, and is computed for each feature by using that features representative zone configuration as the control variable x in equation (1). The shortfall s is the amount of the representation target not met and is given by $s = t_j - \sum_{i=1}^{m} a_{ij} x_i$. The Heaviside function, $H(s)$, is a step function which takes a value of zero when $s \le 0$ and 1 otherwise. The feature specific parameter t_j is the target representation for feature j. The expression (s/t_j) is the measure of the shortfall in representation for feature j. It is reported as a proportion and equals 1 when feature j is not represented within the configuration and approaches 0 as the level of representation approaches the target amounts. The Heaviside function ensures the whole equation becomes zero when the representation is greater than the target amount. We use the shortfall as a weighting factor of the total cost to meet the target, which assumes the cost associated with the shortfall is a linear proportion of the total cost to meet the target. This is a simplification as the total cost may vary non-linearly as the shortfall changes. We use the simplification because the actual cost of meeting the target for each iteration of Marxan is computationally expensive to find and provides little improvement in the final answer.

We combine equations (1) and (3) to get the overall Marxan objective function, which gives a value to any reserve system, a configuration of selected planning units. Hence, the value of the reserve system is:

$$\sum_{i=1}^{m} c_i x_i + b \sum_{i1=1}^{m} \sum_{i2=1}^{m} x_{i1}(1 - x_{i2}) cv_{i1,i2} + \sum_{j=1}^{n} FPF_j FR_j H(s) \left(\frac{s}{t_j}\right). \tag{4}$$

Marxan uses the simulated annealing algorithm (Kirkpatrick et al., 1983) to minimize the objective function score (equation (4)) by varying the control variables, x_i, which tell us which planning unit is in, or out, of the reserve system.

Marxan with Zones generalizes this approach by increasing the number of states or zones to which a planning unit can be assigned. Each term of the objective function is increased in complexity. Furthermore, two types of representation targets are allowed and consequently the representation shortfall penalty reflects two types of shortfall.

3. Mathematical formulation of Marxan with Zones

The aim of the Marxan with Zones software is to minimize the sum of costs and connectivity costs of the zone configuration of planning units, subject to meeting the representation targets and zone targets. A zone configuration is a solution and it fully specifies the type of zone in which each planning unit is placed. This is the Marxan with Zones minimum representation problem, formally defined as:

$$\text{minimize } \sum_{i=1}^{m} \sum_{k=1}^{p} c_{ik} x_{ik} + b \sum_{i1=1}^{m} \sum_{i2=1}^{m} \sum_{k1=1}^{p} \sum_{k2=1}^{p} cv_{i1,i2,k1,k2} x_{i1,k1} x_{i2,k2} \tag{5}$$

$$\text{subject to } \sum_{i=1}^{m} \sum_{k=1}^{p} a_{ij} ca_{jk} x_{ij} \ge t1_j \quad \forall j \tag{6}$$

$$\text{and subject to } \sum_{i=1}^{m} a_{ij} x_{ik} \ge t2_{jk} \quad \forall j \text{ and } \forall k. \tag{7}$$

In this case there are m planning units and p zones. The first term of equation (5) represents the sum of the costs for a configuration of planning units where each planning unit is allocated to a particular zone, and is composed of a control variable and cost matrix. The control variable $x_{ik} \in \{0, 1\}$ records which of the k zones each planning unit i is allocated to; its value is 1 if the planning unit i is allocated to zone k, and 0 if the planning unit i is not allocated to zone k. Each planning unit must only be in a single zone, so $\sum_{k=1}^{p} x_{ik} = 1 \ \forall i$. We define a cost matrix c_{ik}, which is the cost of placing each planning unit i in zone k. The second term of equation (5) represents the connectivity cost of a configuration of planning units assigned to particular zones, and is composed of a connectivity matrix recording the cost of the connections between planning units $i1$ and $i2$ if and only if $i1$ is in zone $k1$, and $i2$ is in zone $k2$.

In equation (6), a_{ij} is a feature matrix that records the amount of each feature j in each planning unit i, the parameter $t1_j$ is a representation target objective for each feature, j, that records the amount of each feature required to be protected in the zone configuration, and ca_{jk} is a contribution matrix that records the level of protection offered to each feature j by each zone k. Typically this contribution will be 1 for zones in which the feature achieves full representation, 0 for zones which do not protect the feature and an intermediate value for a zone that offers partial protection for a feature. For example, a conservation feature might enjoy full representation in a conservation zone, no representation in zones where natural resources (e.g. timber, fish etc) are extracted and partial protection where ecologically sensitive natural resource extraction is allowed.

In equation (7), $t2_{jk}$ is a zone target objective matrix that records the amount of each feature j required to be captured in a particular zone k. For example the user may specify that a particular species has at least half of its feature target conserved in full no-take reserves. If both targets $t1$ and $t2$ are used, the software attempts to satisfy their requirements simultaneously. Users should take care to enter targets that can be simultaneously achievable to avoid situations where the algorithm cannot find an answer.

We use a feature penalty equation below to implement the two target constraints in the Marxan with Zones objective function:

$$\sum_{j=1}^{n} FPF_j FR_j \left(H(s1) \left(\frac{s1}{t1_j}\right) + \sum_{k=1}^{p} H(s2) \left(\frac{s2}{t2_{jk}}\right) \right). \tag{8}$$

This is the sum of two different representation targets where there are n features under consideration. The shortfalls $s1$ and $s2$ are the amount of the two different representation targets not met and are given by $s1 = t1_j - \sum_{i=1}^{m} \sum_{k=1}^{p} a_{ij} ca_{jk} x_{ik}$ and $s2 = t2_{jk} - \sum_{i=1}^{m} a_{ij} x_{ik}$. Both shortfalls are used as weightings for the feature dependent factors of FPF_j and FR_j in the same way they were in the Marxan problem formulation.

Combining equations (5) and (8) gives the objective function for Marxan with Zones:

$$\sum_{i=1}^{m} \sum_{k=1}^{p} c_{ik} x_{ik} + b \sum_{i1=1}^{m} \sum_{i2=1}^{m} \sum_{k1=1}^{p} \sum_{k2=1}^{p} cv_{i1,i2,k1,k2} x_{i1,k1} x_{i2,k2} + \sum_{j=1}^{n} FPF_j FR_j \left(H(s1) \left(\frac{s1}{t1_j}\right) + \sum_{k=1}^{p} H(s2) \left(\frac{s2}{t2_{jk}}\right) \right). \tag{9}$$

This is identical to the Marxan objective function in equation (4) when there are two zones ($p = 2$), zone 1 is an unreserved zone with a contribution of zero for all features and zone 2 is a reserved zone with a contribution of 1 for all features ($ca = (\begin{smallmatrix} 0 & 1 \\ 1 & 0 \end{smallmatrix})$), the cost of the unreserved zone is 0 for all planning units ($c_{i1} = 0 \;\; \forall j$), and there are no zone-specific targets for all features and both zones ($t2_{jk} = 0 \;\; \forall j$ and $\forall k$).

4. Additional information requirements for Marxan with Zones

Marxan with Zones has a number of information requirements beyond those used in Marxan. Individual planning problems will determine the amount of additional information required. At a minimum, the number of zones and the costs of assigning each planning unit to each zone must be defined. In this section, we describe the additional information requirements and introduce three case studies. The case studies demonstrate how the new capabilities of Marxan with Zones can be applied to a variety of multi-zone problems. A detailed description of how to use Marxan with Zones, and the interaction between its many input parameter files, is provided in the on-line manual (Watts et al., 2008a).

4.1. Multiple zones

A list of all possible zones must be defined. These can range from high quality conservation zones (e.g. well managed national park) to extractive use zones (e.g. intensive agriculture, forestry, or fishing). The user can specify zone-specific targets to prescribe how feature targets are achieved. For example, given an overall target of 20% for each habitat type, which could be met across three different conservation zones, the user may require at least 10% of the overall target to be met in the zone offering the highest level of protection. Not specifying a zone-specific target means that the overall target for a feature can be achieved across all zones (see Case Study 1).

Furthermore, Marxan with Zones allows the user to prescribe preferred spatial relationships between zones using a zone boundary cost (Lourival, 2008). Parameters for spatial compactness and buffering of zones can be can be derived through a process of calibration, the procedure for which is described in a Marxan with Zones user guide (Watts et al., 2008b) which includes a worked example. This is useful if the user prefers two zones to be adjacent or spatially separated. For example the user may prefer national parks to be buffered by sustainable low intensity logging rather than intensive agriculture. The spatial compactness capability also exists in Marxan but the new software allows for buffering of zones.

Case Study 1. Zoning multiple-use marine parks: achieving multiple objectives and minimising conflict of use (Stewart et al., 2008)

We applied the use of Marxan with Zones to the zoning of a multiple-use marine park in Rottnest Island, Western Australia. Biodiversity and human usage data compiled for the case study was originally developed by the Department of Environment and Conservation for the Rottnest Island Authority to assist in the development of the Rottnest Island Marine Management Strategy. Coastal and marine biodiversity data included information on 28 biodiversity features, including benthic habitats, coastal landforms and marine species (such as invertebrates). We categorized human usage data as either non-extractive recreational activities (surfing, SCUBA diving, recreational boat moorings and shipwrecks), or recreational fishing activities (trolling, game fishing, and shore based fishing). The primary goal was to conserve biodiversity whilst providing for fishing and non-extractive recreational activities to the extent that they did not conflict with conservation objectives. Several potential conflicting uses within the marine park were identified:

1) Conservation and fishing (e.g. protection vs. extraction of benthic habitat)
2) Conservation and non-extractive recreational activities (e.g. coral reefs vs. SCUBA activities – Harriott et al., 1997)
3) Non-extractive recreational activities and recreational fishing (e.g. SCUBA activities vs. recreational fishing – Lynch et al., 2004).

These interactions informed the definition of a zoning framework with the flexibility to deliver across competing objectives. The three zones defined for this case study are presented in Table 1.

Marxan with Zones provides a systematic approach to the problem of managing multiple uses by allowing spatial separation of activities into zones. This reduces the potential conflict between the different uses. An additional function within Marxan with Zones is the zone boundary cost. This serves to prescribe the spatial relationship between zones and is useful to encourage further separation of conflicting uses (by setting a high zone boundary cost) or to cluster zones which share compatible management objectives (a low zone boundary cost). We set this feature so that the high protection zone is preferably buffered by partial protection zone to further reduce the potential conflict between conservation objectives and fishing activities.

To successfully manage the multiple activities within the marine park, explicit objectives must be defined that identify the target level of reservation for each activity (Table 2). These objectives can be defined broadly at the park level, or they may be more prescriptive in quantifying how much of each activity must be retained in a particular zone (or combination of zones). In this case study, we did not apply prescriptive zone targets.

Each zone makes a different contribution towards these objectives, according to whether activities are included or excluded. Table 3 defines the zones in terms of their contributions (between 0 and 100%) towards the feature targets.

Marxan with Zones generated many efficient solutions to this problem, each of which meet all of the objectives. An example map illustrating the spatial configuration of one of the solutions is shown in Fig. 1. In the example shown, Marxan with Zones retained 90% of the fishing activity, 81% of the recreational activity, and included an average of 34% of each conservation feature (with a minimum of 30%).

Marxan with Zones outperforms standard Marxan for this particular problem by delivering a zonation scheme which supports multiple objectives within an individual reserve, and configuring the zones to accommodate a range of uses that can be spatially separated. In this example these functions serve to minimize conflict of use between resource protection and resource extraction. Standard Marxan would have been limited to meeting one of the objectives (traditionally the conservation objective) and could only spatially separate two activities. Using Marxan with Zones, marine park managers can systematically approach the zoning of multiple-use marine parks, separate potentially conflicting activities, and achieve multiple objectives.

4.2. Costs

The cost of allocating each planning unit to each zone must be defined. Marxan with Zones can accommodate multiple costs for individual planning units (see Case Study 2), with the total cost of

Table 1
Zoning framework.

Zone name	Recreational fishing	Non-extractive recreation
High protection	Not allowed	Not allowed
Partial protection	Not allowed	Allowed
Multiple use	Allowed	Allowed

Table 2
Definition of multiple objectives.

Activity	Objective
Conservation	Protect minimum of 30% of defined marine biodiversity features
Non-extractive recreation	Maintain defined recreation activities at minimum 80% of current
Fishing	Maintain defined fishing activities at minimum 80% of current

Table 3
Level of contribution towards meeting objectives for each zone.

Activity objective	High protection zone	Partial protection zone	Multiple-use zone
Conservation	100%	20%	0%
Recreation	0%	100%	20%
Fishing	0%	0%	100%

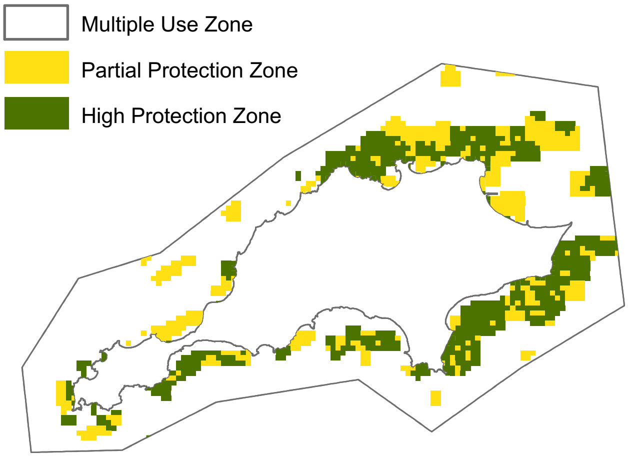

Fig. 1. Example solution for Rottnest Island Case Study.

assigning a planning unit to a particular zone measured as the sum of the individual costs. Costs can also be zone-specific. For example, there may be purchasing, opportunity, and management costs associated with designating a planning unit as a national park (Naidoo et al., 2006). A weighting factor for each cost in each zone may also be applied. All costs in a given zone will be weighted by the zone-specific multiplier, and then summed to give zone-specific costs for every planning unit.

4.3. Features

Features may be defined as elements that the user would like to occur in particular zones (Stewart et al., 2008). For example, these spatially specific elements may include, for example: habitat types, elevation gradients, soil types, and species distributions. The current use of each planning unit (e.g. protection, agriculture, recreation) may also be described as a feature and used to constrain the allocation of planning units to particular zones. For example, the user may wish to ensure that at least 20% of a landscape is

Case Study 2. Spatial marine zoning for fisheries and conservation: a case study from California (Klein et al., in review)

We applied Marxan with Zones to design a network of marine protected areas (MPAs) in Central California (Fig. 2), using the objectives and zones defined by California's Marine Life Protection Act Initiative. Our aim was to determine what socioeconomic advantages, if any, can be delivered by a tool that allows for multiple zones, Marxan with Zones, vs. a tool that can only identify one type of MPA, Marxan.

We planned for five zones, each restricted to different fisheries: 1) No-take marine reserve (all fisheries restricted); 2) Conservation area, high (7 fisheries restricted); 3) Conservation area, high/medium (4 fisheries restricted); 4) Conservation area, medium (3 fisheries restricted); 5) Commercial fishing zone (no fishing restrictions).

We used the same spatial data representing habitats, depth zones, and commercial fishing value used in the Initiative. Habitats included coastal marshes, eelgrass, estuaries, hard bottom, kelp forests, soft bottom, surfgrass, and tidal flats. We subdivided these features into three biogeographic regions (North, South, and the Farallon Islands) and three depth zones (intertidal, intertidal–30 m, 30–100 m). In all, 32 separate biodiversity features which were targeted for the inclusion in a MPA.

Spatial fishing data were derived from 174 interviews with fishermen in 2007 (Scholz et al., 2008). The surveys aimed to capture information from at least 50% of the landings and/or ex-vessel revenue from 2000 to 2006 and at least five fishermen per fishery. These data include the value in 2006 US dollars of a given planning unit to individual fishermen across eight commercial fisheries: Dungeness crab, California halibut, Chinook salmon, coastal pelagic finfish, deep nearshore rockfish, market squid, nearshore rockfish, and sea urchin.

We implemented Marxan with Zones for two different scenarios, each with different zone-specific targets. In scenario 1, represented 10% of the distribution of each biodiversity feature in a no-take reserve (zone 1) and an additional 20% in any of the four protected area zones (zone 1–4). We evaluated the results of scenario 1 to determine the proportion of lost value overall and for each of the fisheries. With the aim of more equitably affecting the fisheries, in scenario 2 we also targeted a percentage of each fisheries total value, where the fishing targets could only be achieved in zones where the given fishery was not restricted. We targeted the same proportion for each fishery and incrementally increased the target by 1% until 100% of the fishing grounds were placed in a zone without spatial fishing regulations. In addition we compare the results of our scenarios to those produced using Marxan (without zoning), where we minimized lost fishing value subject to the constraint that 30% of each biodiversity feature is protected in a no-take reserve. Given that Marxan can only select areas important for one type of protected area, we assume that selected areas are a cost to all fisheries.

We found that Marxan with Zones outperforms Marxan in two ways. First, the overall impact on the fishing industry is reduced. Second, there is a more equitable impact on different fishing sectors (Fig. 3).

Results from this application of Marxan with Zones will inform California's Marine Life Protection Act Initiative's stakeholders, staff, and scientific advisors in designing marine protected areas that efficiently achieve the biodiversity conservation and socioeconomic objectives.

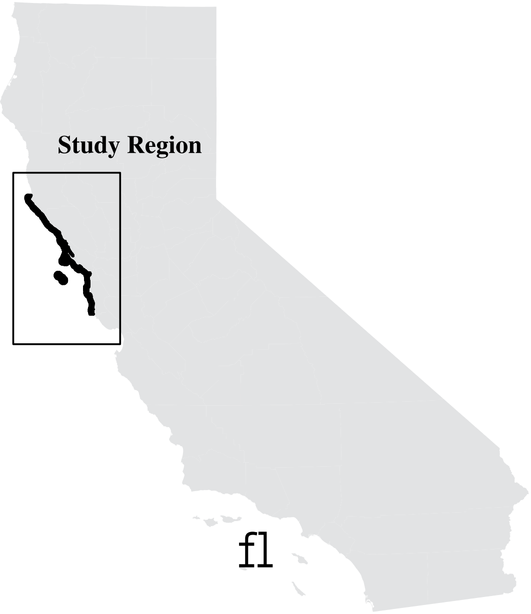

Fig. 2. Our analysis was conducted on the region defined by the 5556-m legal limits to California's state waters from Pigeon Point (lat 37.185°, long −122.39°) to Alder Creek (lat 39.005°, long −123.696°) and around the Farallon Islands (lat 37.733°, long −123.033°) but exclusive of San Francisco Bay, a total area of 1977.5 km^2.

allocated to forestry, or the expected total timber production is above a certain level.

4.4. *Relationship between zones and features*

In some cases, it may be useful to define the relationship between each zone and feature. The contribution of a zone towards achieving feature targets can be indicated by the user (see Case Studies 1 and 3). Feature targets can be achieved across a combination of zones, with the potential for some zones to contribute more than others to feature targets than others. For example, in Case Study 1, the fishing and recreational zones represent management regimes offering different levels of protection to biodiversity features. This information determines how much of each feature in each zone is needed for target achievement.

5. Software evaluation

System testing of Marxan with Zones used a staged approach. Multiple scenarios were constructed, starting with the standard Marxan dataset, and then incrementally adding new zoning and cost data structures. Using this method, we determined the influence of each new data structure on the resulting spatial configurations and summary outputs. This simplified the sensitivity analysis and identification of the cause for observed software bugs and discrepancies. The software was tested on a range of problems relating to biosphere reserves (Lourival, 2008), marine planning (see Case Studies 1 and 2), integrated natural resource management (Stewart et al., 2008), and multiple-use forestry planning (see Case Study 3). The operation of Marxan with Zones in solving realistic problems in spatial planning was verified to be mathematically correct. A user guide providing detailed examples of software validation, scenario construction and calibration is available on the Marxan website for case study 2 (Watts et al., 2008b). It includes graphs and figures that quantify the behaviour of Marxan with Zones.

The number of zones, planning units, features, and costs that can be input into Marxan with Zones is limited by the applications memory address space, which is currently 2 GB due to our use of a 32 bit computer operating system and 32 bit C compiler. A relatively simple conversion of the C code to available 64 bit operating systems and 64 bit C compilers would result in an increase of the potential memory address space to around 512 GB. A dataset with 80,000 planning units and 6000 features uses only 20% of the 32 bit application address space, and the amount of memory used scales approximately linearly with changes in the number of planning units and features. The number of zones and costs has little impact on the amount of memory used.

We developed a systematic validation software system for Marxan with Zones that reproduced every computation at each step of the algorithm in an alternative software system (Zonae Cogito). This involved implemented reporting functionality in the

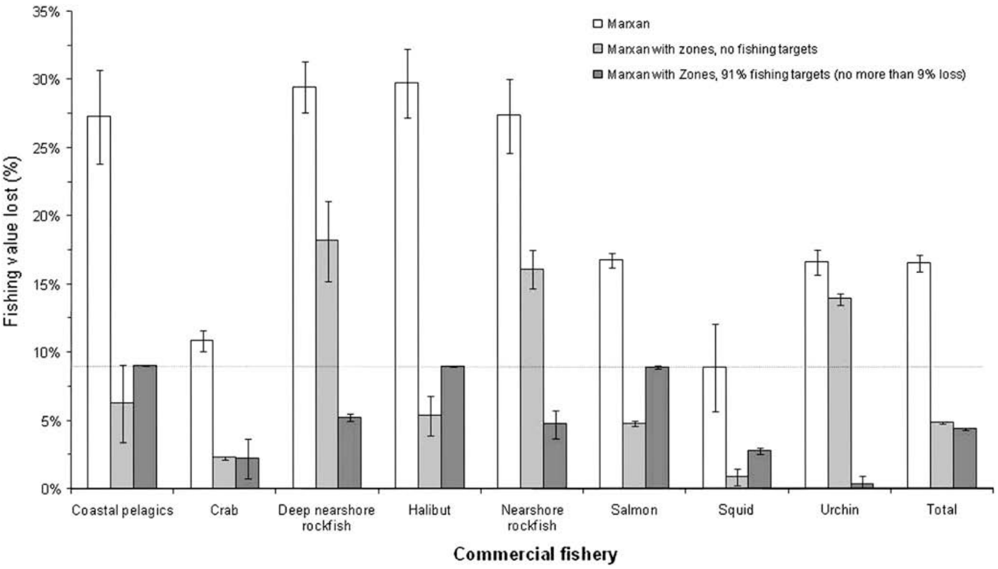

Fig. 3. Proportion of fishing value lost to each individual fishery and the commercial fishery as a whole in protected area networks designed using Marxan and Marxan with Zones (with and without fishing targets). The average (±standard deviation) value lost across 10 solutions that achieved the planning objectives for the least cost is displayed.

Case Study 3. A zoning configuration of multiple conservation strategies in East Kalimantan (Wilson et al., in review)

Tropical rainforest habitat is used for a diversity of land uses ranging from protected areas to production forests. Each alternative land use makes a different contribution to the conservation of biodiversity (Meijaard and Sheil, 2008). The degree of protection offered by different land uses varies, and a high protection status may not be necessarily synonymous with a large contribution to biodiversity conservation (Curran et al., 2004; DeFries et al., 2005). The contribution of different land uses to the conservation of species varies depending on the relative sensitivity of species to habitat modification and degradation (Nakagawa et al., 2006).

We applied Marxan with Zones to prioritize conservation investments in East Kalimantan by accounting for the relative costs and benefits of three conservation strategies across four primary land uses (Fig. 4). We obtained data on the distribution of 170 mammal species that occur in the study region and evaluated their relative sensitivity to forest conversion and degradation (Catullo et al., 2008). We assigned species-specific conservation targets and determined through expert evaluation the contribution of each land-use zone to achieving targets for each species depending on their sensitivity to forest loss and degradation. While some land uses contribute to the representation targets for all species, some land uses make no contribution to the target achievement of some species. This variable contribution was specified in the problem formulation.

We prioritized investments in each alternative strategy in a spatially explicit manner, in order to achieve the conservation targets cost-effectively. Our results revealed the potential for the costs of conservation to be grossly overestimated if we assume that conservation goals can only be met through establishing new protected areas and if we assume that the unprotected matrix makes no contribution to conserving biodiversity. If we would have accounted only for the contribution of protected areas to our conservation goals we would have overestimated the required expenditure by an order of magnitude, and the area requiring protection would have been overestimated by almost five orders of magnitude. The effective and sustainable management of the unprotected matrix is revealed to be essential in East Kalimantan in order to achieve our conservation goals.

This case study illustrates the economic and ecological imperative of considering the contribution of the unprotected matrix in planning analyses and the full suite of conservation strategies available for implementation. We found that traditional approaches deliver pessimistic estimates of the costs of achieving conservation goals, and similarly a conservative estimate of our conservation progress. By applying Marxan with Zones and making use of the expanded land-use planning functionality we have been able to evaluate not only where to act, but how to act in order to effectively and efficiently conserve biodiversity in East Kalimantan. This research provides an important step towards the development of an integrated conservation plan in East Kalimantan, and highlights the value of enhanced political and industry support for sustainable forest management, along with the need for an improved understanding of the contribution of sustainably managed forest to biodiversity conservation goals.

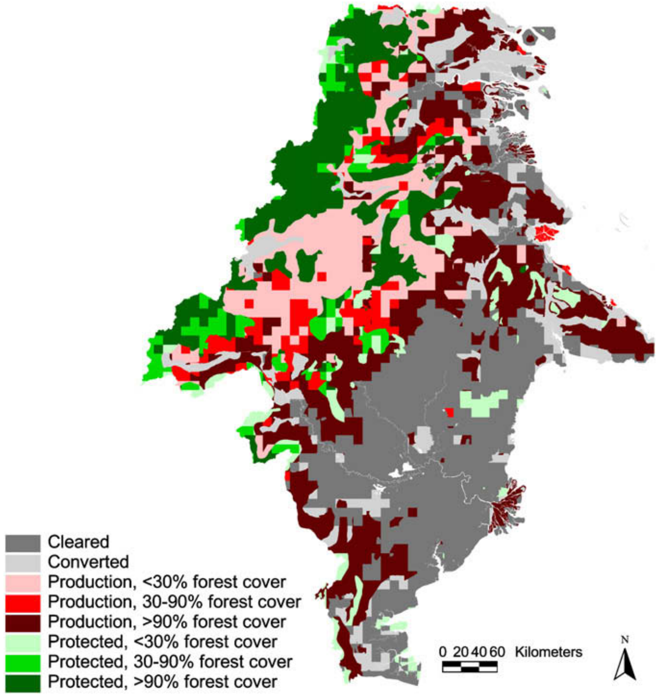

Fig. 4. Existing land uses in the Indonesian province of East Kalimantan.

Zonae Cogito decision support system (Watts et al., 2009) that automated the transfer of zoning configurations from Marxan with Zones, and generated objective function scores and other information for these zoning configurations that was used for cross validation purposes. This extremely robust validation technique gave us confidence in the reliability of Marxan with Zones.

Marxan with Zones is significantly more complicated than the original Marxan software. The software was implemented very carefully to efficiently use computing resources. As a result, the performance of Marxan with Zones at runtime is approximately equivalent to the performance of an equivalent dataset running in the original Marxan. We have found that the number of iterations used needs to be scaled according to the number of zones used for efficient operation of Marxan with Zones. For example, the original Marxan software has two zones, so if we are using six zones for a Marxan with Zones problem, we need to use three times as many iterations for equivalent efficiency, resulting in the software taking three times longer to run.

6. Discussion

Marxan with Zones offers key improvements to the Marxan software by extending the range of problems to which the software can be applied. The in-built flexibility for users to define multiple objectives, multiple zones and accept multiple costs makes the software versatile and suitable for a wide range of resource management problems. Effective conservation zoning plans must often integrate the management of multiple uses and account for the different types of interactions between and among activities. They must not only separate conflicting activities but explicitly balance competing interests in a way that delivers acceptable trade-offs. Brokering trade-offs is a challenging task and will most likely be guided by government policy. Marxan with Zones provides a systematic planning framework to evaluate the consequences and trade-offs of alternative zoning configurations, which is critical for informed decision making.

The ability to specify zone-specific planning unit costs presents a number of potential uses. It could support the design of conservation landscapes and seascapes that include both communally and privately managed areas, where the costs of conservation actions differ, but the conservation outcomes are equivalent. It also allows for complex natural resource management situations where costs and biodiversity benefits vary depending on the land and sea use or management action. For example, conservation actions such as weed control, protected area establishment, and the creation of conservation easements could be spatially assigned in a zoning configuration. Moreover, this approach could prioritize actions based on ecosystem services, where biodiversity benefits and management costs of the delivery of one ecosystem service such as carbon sequestration could differ from others such as pollination or water filtration services (Chan et al., 2006). Marxan with Zones could help identify which parts of the planning region are most suitable for providing each ecosystem service.

Marxan with Zones can support many types of conservation focused decision making including; land-use planning, marine planning, urban and regional planning, and support for group decision making in a multi-stakeholder context. More generally, the software can solve spatial resource allocation problems involving multiple actions, objectives and constraints (Wilson et al., 2009). The objectives and constraints can be based on economic, social, cultural or biological spatial features. The software is a decision support tool and is meant to support rather than replace decision making processes. The outputs can be useful in a decision making process through identification of priority areas that must be allocated to a particular zone (Klein et al., 2008a), and through the generation of alternative options for use in a negotiation setting (Airame, 2005). We hope the novel functionality of Marxan with Zones will attract wide use in a range of conservation planning problems beyond those solvable by Marxan.

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