Abstract

In any given region, there are multiple options for terrestrial protected area networks that achieve goals for conservation of terrestrial biodiversity and ecosystem values. When deciding on the location of terrestrial protected areas, planners typically focus only on terrestrial conservation goals, ignoring potential linked benefits to marine ecosystems. These benefits include maintenance of downstream water quality, as forest protection can prevent changes in amount and composition of river runoff that negatively impacts coral reefs. This study aims to determine the benefit of different terrestrial reserve networks to the condition of coral reefs adjacent to the main islands of Fiji to support the work of Fiji's Protected Area Committee in expanding the national protected area estate through integrated land-sea planning. Options for terrestrial protected area networks were designed using six approaches, where the primary objective of each approach was to either achieve terrestrial conservation goals (*e.g.,* represent 40% of each vegetation type) or maximize benefits to coral reefs by minimizing potential for land-based runoff. When achieving terrestrial conservation goals was the primary objective, the potential benefits to coral reef condition were 7.7-10.4% greater than benefits from the existing network of protected areas. When benefiting reefs was the primary objective, benefits to coral reefs were 1.1-2.8 times greater per unit area than networks designed to only achieve terrestrial conservation goals, but 31-44% of the terrestrial conservation goals were not achieved. These results are already being used by Fiji's Protected Area Committee to modify the boundaries of existing priority places to deliver outcomes that better meet terrestrial conservation goals while offering greater benefits to coral reef condition through prevention of run-off.

Keywords: Coral reef, integrated land-sea planning, protected areas, run-off, spatial conservation prioritization, trade-off

1.0 Introduction

Protected areas are fundamental to any conservation plan as they are one of the most effective ways at mitigating threats to species and habitats. A common goal when deciding on the location of terrestrial protected areas is to adequately represent each type of habitat or vegetation community [1]. Rarely are terrestrial protected areas placed to benefit marine ecosystems [2].

Activities on the land can influence marine ecosystems through changes in land-based runoff. The impact of these activities can vary across space depending on their intensity, geology (*e.g.*, soil type), and geography (*e.g.*, steepness of landscape). As a result, the protection of different places on the land will have differential impacts on marine ecosystems. For example, a recent analysis in Fiji found that potential benefits to coral reef condition are highly variable, depending on where forest is protected [3]. Consideration of the impacts of terrestrial activities, including protected area establishment, is important for the protection of marine biodiversity. In some cases, marine conservation efforts have little conservation benefit unless the adjacent land is also managed for conservation [4–6].

To maximize biodiversity benefits, planning for both the land and sea should be integrated. However, integrated land-sea planning is the exception in most places as governance of marine and terrestrial areas are usually done separately [2,7]. In Fiji, however, a national Protected Area Committee (henceforth 'Committee') was established to make decisions about what and where to protect to achieve the Government's goal of protecting 30% of its inshore waters and 20% of its land by 2020 [8]. Although this does not guarantee integrated planning, the Committee is composed of government and non-government representatives from terrestrial and marine sectors and is interested in ways that they can make decisions with both the land and sea in mind.

Fiji's existing terrestrial protected areas have been established on an ad hoc basis without particular attention to biodiversity values [8]. Although there is consensus that the network needs to be significantly expanded, final decisions about the location of terrestrial protected areas in Fiji have not been made, despite extensive discussions about conservation goals and priority sites. The Committee has expressed interest in designing a network that achieves terrestrial targets while maximizing benefits to downstream marine ecosystems, but an evaluation of feasible terrestrial protected area networks has not been conducted to assess this goal (S. Jupiter, personal communication). Such an assessment is urgently needed to help inform decisions about the location of marine and terrestrial protected areas in Fiji.

Here, terrestrial protected area networks were designed using six different approaches and it was determine how much each network, if implemented, would contribute towards maintaining coral reef condition and represent terrestrial vegetation communities. Systematic conservation planning was used to design four networks that achieve terrestrial conservation goals of Fiji's Committee (*e.g.,* protect 40% of each vegetation type). The four networks differ in the extent to which they emphasize clustering of sites and the transaction cost of establishing a terrestrial reserve where multiple clans would be involved in land-use decisions. Using the same transaction cost, two terrestrial networks that protect 20% of the land that most cost-effectively benefits coral reef condition were designed. The two networks differ in the extent to which they consider the importance of achieving terrestrial conservation goals. The results of the networks were compared, in terms of reef condition and representation of terrestrial vegetation communities, to the following other conservation scenarios, assuming in all cases that vegetation outside the network would be cleared for other land uses: (1) no new protected areas are added to the existing terrestrial network; (2) proposed "high priority" areas for terrestrial conservation determined by the Fiji Committee in 2010 are added to the existing network. This analysis will provide guidance to Fiji's Committee as they decide on the exact location of terrestrial protected areas, as well as inform development of integrating land-sea planning more broadly in similar tropical island ecosystems.

2.0 Material and methods

2.1 Policy Context

Less than 3% of Fiji's land is protected, covering 5.8% of remaining forests (Protected Area Committee, unpublished data). The Fijian government has set a goal of increasing the protected area estate to 20% of the land by 2020. Analyses to identify priorities for conservation of terrestrial resources have been conducted at the national scale. Olson et al. (2010) proposed a network of 40 priority forests for conservation (henceforth 'priority forests') that cover 23% of Fiji's total land area and 58% of Fiji's remaining native forest (Fig. 1). The priority forests were selected based on area requirements for some native species, habitat and species representation goals, ecological processes, as well as practical considerations associated with conservation in Fiji. In 2010, a working group of Fiji's Committee used a scoring system to rank the Olson et al. (2010) priority forests, and selected 13 as high priority sites for conservation (henceforth 'Protected Area Committee priority places'; Protected Area Committee, unpublished report) (Fig. 1). Although the approach used by the Committee is not consistent with spatial conservation prioritization principles and approaches accepted widely by the international conservation community [9], the ranking system was done specifically to give weighting to factors not easily incorporated into conservation planning software, such as feasibility of implementation and local knowledge of current financing levels at priority forest sites (Table S1). Given that exact boundaries of new terrestrial protected areas have not been formally defined and distributed throughout Government ministries, there is an opportunity to use systematic conservation planning approaches to adapt the Committee's priority places to a network that better achieves terrestrial conservation goals and benefits marine ecosystems.

2.2 Designing Terrestrial Protected Areas with Marxan

There are many ecological and socioeconomic goals of terrestrial protected areas in Fiji. Two ecological goals are consistently discussed across the various conservation efforts, including: (1) comprehensive representation of Fiji's major vegetation types; and (2) protection of endemic, threatened and culturally important species [8,10,11]. Systematic conservation planning principles were used to design networks of protected areas consistent with these goals. The study region is limited to Fiji's three largest islands, Viti

Levu, Vanua Levu, and Taveuni, because habitat data are not available for the smaller, outlying islands. The study region was divided into 1 km^2 planning units, each of which could be selected for protection, unless currently protected.

To address the goal of comprehensively representing Fiji's major vegetation types, spatial data that represents the distribution of vegetation types in Fiji were used (Fiji Department of Forestry 1996). The vegetation types include cloud/montane forest, dry forest, kaarst forest, lowland rainforest, mangroves, upland rainforest, and wetlands, as described by Muller-Dombois & Fosberg (1998). Ideally, to address the goal of protecting species, the distribution of species of interest would be targeted; however, adequate species distribution data does not exist in Fiji. The Committee is interested in addressing the goal of protecting species through the representation of 'priority forests' identified by Olson et al. (2010). Olson et al (2010) identified priority forests with consideration of areas of known importance for plants, reptiles, amphibians, freshwater fish, arthropods, and gastropods based on information from experts and existing data. Thus, each vegetation type in the priority forests were preferentially represent even though vegetation types can be imperfect surrogates for species diversity [14]. If the vegetation target, or a portion of the target, could not be met in priority forests, then it was satisfied outside priority forests.

To design terrestrial protected areas, the systematic conservation planning software Marxan [15] was used. Marxan produces spatial options for protected areas that achieve stated conservation targets for a minimum cost. Here, the target was to represent 40% of the distribution of each vegetation type on each island, unless the vegetation type does not exist on the island. The target of 40% is consistent with Fiji Department of Forestry's policy goal of protecting 40% of all extant natural forest, which roughly corresponds to 20% of original forests [10].

The conservation targets were achieved for a minimal cost. Ideally, one would know the actual management and opportunity costs of designating each planning unit as a protected area; however this information does not exist across the study region. Instead, two different surrogates for relative cost were used. The first is refered to as ‘clan cost’ and is the number of clan tenure areas intersecting each planning unit. In Fiji, indigenous Fijians have native tenure over 88% of land [16], and because implementing a protected area requires consent from the impacted clan, obtaining consent and negotiating an agreement comes at a cost to the government. Thus, ‘Clan Cost’ represents a transaction cost to conservation where the greater number of clans, the greater the transaction cost. Clan tenure boundaries have been legally mapped in Fiji by the iTaukei Land and Fisheries Commission. The second cost surrogate referred to as ‘equal cost’, where each planning unit was assigned a cost equal to the area of the planning unit.

Protected areas were designed both with and without consideration of spatial clumping. When spatial clumping was considered, the clumping value (i.e. boundary length modifier) met the following criteria: (1) produced spatially clumped solutions for a marginal cost increase; and (2) had an average size across 100 runs that was comparable to solutions produced without spatial clumping. The spatially clumped results are referred to as ‘clumped’. Existing protected areas were locked in to ensure that they contribute towards achieving the conservation targets. As the current protected area boundaries do not exactly align with the 1 km^2 planning units, a planning unit was locked in if a majority of it contained a protected area (Fig. 1). For each scenario, Marxan produced 100 near optimal ‘candidate’ protected area networks with different spatial configurations, each of which achieves stated conservation goals.

2.3 Other Terrestrial Protected Area Options

Other alternative protected area networks were considered and compared with the ones described above designed using systematic conservation planning approaches. First, a scenario developed by the Fiji Committee that includes existing protected areas and new high priority areas identified through the highest scores in the ranking exercise was considered. Second, a model developed by Klein et al. (2012) to determine where the protection of vegetation can deliver the greatest return on investment for coral reef condition without consideration of the benefit of protecting land to terrestrial biodiversity was considered (henceforth referred to as 'benefit coral reef'). Third, a scenario that protected vegetation that delivers the greatest return on investment for coral reef condition, but only if the representation goal for the vegetation feature is not achieved was considered (henceforth referred to as 'benefit coral reef and vegetation'). For the 'Benefit coral reef (and vegetation)' scenarios, the clan cost and vegetation data described above was used, which is different than in Klein et al. (2012), to determine the cost-effectiveness of protecting each planning unit. It was assumed that current protected areas will remain vegetated and were added to by allocating the most cost effective planning units until 20% of the vegetation in the study region is protected. These three scenarios were evaluated in terms of how well they represent vegetation targets and benefit coral reef condition.

2.4 Evaluation of Protected Areas

2.4.1 Coral reef condition

To assess the benefits of each terrestrial protected area network to coral reefs, a model developed by Klein et al. (2012) was used. This model estimates the relative condition, C, of each coral reef, i (i = 1,…,7759) as influenced by watershed-based pollution and fishing pressure:

$$C_i = [(e^{-\propto p_i})[(e^{-\beta f_i})(1-\delta)+\delta]], \tag{1}$$

where the first term of the equation (*i.e.,* $e^{-\propto p_i}$) represents watershed-based pollution. Watershed-based pollution is determined by the amount (p_i) and impact (here, $\alpha = 0.03$ for all analyses) of pollution of coral reefs, where

$$p_i = \sum_{l=1}^{M} V_{li}\left[\frac{\sum_{j=1}^{N_l}(1-w_j x_j)}{N_l}\right]. \tag{2}$$

The amount of pollution reaching each reef was determined using the same approach as Klein et al. (2012), where V_{li} is the amount of pollution from watershed l (l = 1, . . . , M) reaching reef i assuming all terrestrial vegetation outside of proposed protected areas has been cleared. The state value, w_j, for land planning unit, j ($j = 1, \dots N$), equals 1 if a majority of the planning unit is vegetated and is otherwise equal to 0. Different vegetation data from that used in Klein et al. (2012) were used in this study. If the planning unit is currently protected or is a protected area according to the scenarios being evaluated, x_j equals 1, otherwise equals 0. Thus, the control variable, x_j, was changed for each network of protected areas and its benefit to coral reef condition were evaluated and results were compared.

The remainder of the equation (*i.e.,* $\left[\left(e^{-\beta f_i}\right)(1-\delta)+\delta\right]$) relates to fishing pressure. The fishing pressure parameters remain the same for each scenario evaluated, which were: $B = 0.03$, $\delta = 0.1$. And f_i is spatially variable an is calculated using the data and approach described in Klein et al. (2012) for all reefs, which were assumed to be unprotected.

The benefit to coral reef condition is defined as the improvement relative to the scenario where current protected areas remain and all other vegetation is cleared, which alternatively can be viewed as the minimization of potential degradation to coral reefs from land-based pollution by protecting forests.

2.4.2 Vegetation

How well each protected area network achieves the conservation target of representing 40% of each vegetation type on each island was compared.

Insert Figure 1 about here.

3. Results

Benefits to coral reef condition of up to 10.4% would be obtained if terrestrial protected areas designed to achieve terrestrial conservation goals were implemented, in comparison to existing protected areas (Fig. 2). The range of benefits of different networks within a given Marxan scenario differed by about 1-2%, depending on the scenario (Fig. 2). The relative increase in benefits to coral reef condition were similar for all Marxan scenarios, but averaged slightly lower when a spatially variable cost (i.e., clan cost) were used (Fig. 2). In addition, all of the networks designed using Marxan will deliver 1.3-1.6 times less benefit than the Protected Area Committee priority places per unit area of terrestrial protected area. The 'benefit coral reef' and 'benefit coral reef and vegetation' scenarios deliver 2.4-2.8 times and 1.1-1.3 times more benefit, respectively, for coral reefs per unit area compared to the four Marxan scenarios where terrestrial goals were considered.

Insert Figure 2 about here.

Each scenario was compared in terms of how well they represent each terrestrial vegetation type on each island (Fig. 3). All scenarios using Marxan represent at least 40% of remaining vegetation on each island; the clan cost plus clumping scenario is shown in Fig. 3 as an example. The Protected Area Committee priority places and the 'benefit coral reef' network unevenly represent vegetation types and miss the 40% representation target for seven features. In addition, very little or, in some cases, none of some vegetation types are not represented (Fig. 3). The 'benefit coral reef and vegetation' network does not achieve the 40% representation target for five features and more evenly represents vegetation than the 'benefit coral reef' network and Protected Area Committee priority places. Taveuni is the only island that, regardless of protected area network, achieves all vegetation targets as the vegetation is currently well represented in a protected area (forest reserve) that has already been established.

Insert Figure 3 about here.

4. Discussion

Although integrated planning across multiple realms is much lauded in the literature [2], there are few practical examples on the ground ([17]. The Fiji Committee is considering an integrated approach for expansion of its national protected area network, which presents an exciting opportunity to demonstrate leadership in this area to the global conservation community. Six approaches to design options for terrestrial protected area networks were used, where the primary objective of each approach was to either achieve terrestrial conservation goals (the 4 Marxan scenarios) or maximize benefits to coral reefs by minimizing potential for land-based runoff. These networks were compared with other conservation plans in terms of how well they represent terrestrial vegetation and benefit coral reef condition.

According to the model for coral reef condition, protecting any additional parcel of land containing vegetation will benefit coral reefs; thus, it is no surprise that the protected areas designed in this paper deliver benefits to coral reefs. A larger range of benefits to coral reefs from the individual protected area networks from any given Marxan scenario were expected. The representation constraints imposed when designing protected areas resulted in spatially similar protected area networks, even when different costs and clumping values were used, which explains why the variation in coral reef condition was less than 3% across 100 individual solutions in each Marxan scenario. Regardless, it is important for planners to know that, even if terrestrial representation targets are achieved, better outcomes for coral reefs are possible with slight modifications to the network. In the Marxan scenarios, the variation was lowest when a spatially variable cost (*i.e.,* clan cost) was used as this further constrained the problem. Eliminating the vegetation representation constraints, as done in the 'benefit coral reef' scenario, resulted in networks that deliver greater benefits to coral reefs. However, there is a trade-off between benefiting coral reefs and protecting terrestrial vegetation. As eliminating vegetation representation constraints is unrealistic, numerous scenarios with relaxed representation constraints (e.g. represent less than 40% of some or all vegetation types) could be conducted and trade-offs explored. The 'benefit coral reef and vegetation' is one example of how this can be done. Knowing the nature of these trade-offs is informative to the Committee as it makes decisions about the location of terrestrial protected areas in an integrated land-sea planning context.

The result that the Protected Area Committee priority places are more beneficial to coral reefs but do a poor job at representing vegetation compared to the protected areas designed with Marxan can be explained, in part, by the prioritization approach. For example, the networks designed with Marxan explicitly aimed to represent 40% of each vegetation type whereas the Committee only considered the number of vegetation types without regard to their areal coverage. Further, the Committee gave higher scores to sites that overlapped with catchments important for land-sea connectivity (Table S1), identified by Jenkins et al. (2010), using another scoring approach that considered values for factors likely to influence run-off impact, such as catchment erosion potential, road density, creek crossings, mangrove area relative to catchment area, and coral reef area relative to catchment area. Although this may explain the slightly higher benefits to coral reefs found in the Committee's priority places, it is feasible that the result is by chance do to the scoring method used, which is not well regarded in spatial conservation prioritization [9]. Scoring-based approaches to identifying priorities for conservation lack clear objectives (e.g. represent 40% of each vegetation type for a minimum cost) and ignore the fundamental principles of spatial conservation prioritization, such as representation, adequacy, efficiency, complementarity [1,9].

The scoring approach used by the Committee, however, captures conservation values and opportunities that were not considered in the priority setting approach used in this paper. These included: (1) conservation practicality, defined at each site by expert opinion based on the number and known attitude of clans, Fiji Government development plans, land tenure, and area of significant timber production forest; (2) cultural importance, indicated by the presence of any areas of cultural and national heritage validated and mapped by the Fiji Museum within the site; and (3) economic importance, based on expert opinion (Table S1). All of the above and many other socioeconomic factors will influence conservation opportunity and subsequent management implementation [19], but are often difficult to quantify and map [17]. While some robust quantitative methods have been developed for considering conservation opportunity in terrestrial systematic conservation plans [19–21], the data are not available at the scale of the three main islands for Fiji and would be cost-prohibitive to obtain. And while key informant interviews have been used in Fiji to develop spatial layers of marine conservation opportunity using proxy variables [22], Guerrero et al. (2010) caution that predictors of conservation opportunity may not be spatially uniform, particularly across broad and heterogeneous regions.

In the absence of comprehensive data on conservation opportunity and socioeconomic cost, expert assessments and local knowledge are invaluable [24,25], particularly in countries or situations where implementation success is unlikely to be determined by the spatial efficiency of the protected area network [17,26]. In these cases, expert knowledge can be used in conjunction with spatial conservation prioritization approaches (*e.g.,* Marxan, cost-effectiveness analyses) to decide on the location of protected areas [17]. For example, in Fiji, the most feasible way forward would be to modify the Protected Area Committee priority places using outputs from a more systematic approach, like those presented here, to ensure terrestrial habitats are more evenly represented in a way that delivers the greatest benefit to coral reefs.

With the exception of the 'benefit coral reef and vegetation' scenario, the land-sea planning approach used in this paper is two-step: 1) design protected areas with objectives for the conservation of one ecosystem (land or sea); 2) evaluate how well the protected areas achieve conservation objectives of the other ecosystem. Although this is a valid strategy for making land-sea conservation decisions, it is not the most efficient strategy for protecting both ecosystems [27]. The approach in the 'benefit coral reef and vegetation' scenario considers land and sea objectives simultaneously, producing a solution that makes a reasonable compromise between the land and sea objective; however more optimal solutions are likely to exist and could be found using an optimization tool that considers land and sea objectives. Further, it was assumed that vegetation outside of protected areas is cleared for other land-uses, which may not be the case as some unprotected vegetation will remain intact or be converted to a land-use that does not negatively impact coral reefs. The impact of over 400 temporary no-take marine protected areas (Fiji Locally Marine Managed Area, unpublished data) and other gear and species-based management currently implemented by local communities in Fiji that have differential effects on coral reef condition were considered [28]. This highlights significant future research opportunities for developing an optimization approach that can accommodate terrestrial and marine conservation objectives simultaneously. Such an approach could also accommodate important aspects of integrated land-sea planning that were omitted, including protecting marine habitats and the extent and impacts of fishing pressure on marine habitats. The complexities of a fully integrated approach to land-sea planning can be overwhelming and could potentially create a barrier for adopting integrated land-sea planning in Fiji [2]. This study presents a simple and feasible approach that can be used in other places to help land and sea planning processes progress towards integration.

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Table 1. Overview of eight protected area scenarios evaluated.

Scenario name	Description
Marxan, equal cost, clumped*	In each of these four scenarios, the Marxan software was used to add protected areas to the current network so that 40% of the distribution of each vegetation type on each island. The planning unit cost was either equal to the number of clans (‘clan cost’) or area (‘equal cost’). ‘Clumped’ solutions were designed with spatial clumping of planning units considered in the design process.
Marxan, equal cost*	
Marxan, clan cost, clumped*	
Marxan, clan cost*	
Current protected areas	No new protected areas are added to the existing terrestrial network.
Protected Area Committee priority places	Proposed “high priority” areas for terrestrial conservation determined by the Fiji Protected Area Committee in 2010 are added to the existing protected area network.
Benefit coral reef*	Vegetation representation goals are ignored in favor of protecting the 20% of the land that most benefits the condition of coral reefs using an approach from [3].
Benefit coral reef and vegetation*	Protect 20% of the land that most benefits the condition of coral reefs, but only if it contributes to achieving vegetation targets (i.e. represent 40% of the distribution of each vegetation type on each island).

*The protected areas designed in this paper are indicated with an asterisk.

Figure Legends

Figure 1. Current and candidate terrestrial protected areas in Fiji: a) Distribution of vegetation (light green) and current protected areas (dark green); b) Protected Area Committee priority places (solid red) and Olson et al. 2010 priority forests (solid red and hollow red); c) Selection frequency of protected areas designed with Marxan to meet vegetation targets (Clan cost, clumped; dark blue selected >75%, light blue selected 25-75%; yellow selected <25%); d) 'Benefit coral reef' scenario: protected areas designed to maximise benefit coral reefs and protect 20% of land; e) 'Benefit coral reef and vegetation' scenario: protected areas designed to maximize benefit to coral reefs only in areas that contribute towards achieving vegetation targets and protect 20% of land.

Figure 2. Increased benefit to coral reef condition from proposed terrestrial protected area networks relative to existing protected area network under the assumption that all forest outside of protected areas is converted to other uses. For the networks designed using systematic conservation planning, dashes represent the average increase and lines represent the range of values from 100 individual networks that achieve stated planning goals. Open and closed dashes represent scenarios that do and do not consider spatial clumping, respectively.

Figure 3. Proportion of remaining vegetation represented in candidate protected area networks on Viti Levu, Vanua Levu, and Taveuni. The network designed using Marxan with clan cost and clumping is shown as an example, but all networks designed using Marxan represent at least 40% of each vegetation type. Some vegetation types are not present in the study region and, thus, cannot be protected: wetlands on Viti Levu; kaarst forest on Vanua Levu; and dry forest, kaarst forest, and mangroves on Taveuni.