Integrated planning for land-sea ecosystem connectivity to protect coral reefs

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Abstract

Coral reefs are threatened by human activities both on the land and in the sea. However, standard approaches for prioritizing locations for marine and terrestrial reserves neglect to consider connections between ecosystems. We demonstrate an integrated approach for coral reef conservation with the objective of prioritizing marine reserves close to catchment with high forest cover in order to facilitate ecological processes that rely upon intact land-sea protected area connections and minimize negative impact of land-based runoff on coral reefs. Our aims are to 1) develop and apply simple models of connections between ecosystems that require little data, and 2) incorporate different types of connectivity models into spatial conservation prioritization. We compared how, if at all, the locations and attributes (e.g., costs) of priorities differ from an approach that ignores connections. We analyzed spatial prioritization plans that allow for no connectivity, adjacent connectivity in the sea, symmetric and asymmetric land-sea connectivity, and the combination of adjacent connectivity in the sea and asymmetric land-sea connectivity. The overall reserve system costs were similar for all scenarios. We discovered that integrated planning delivered substantially different spatial priorities compared to the approach that ignored connections. Only 11-40% of sites that were high priority for conservation were similar between scenarios with and without connectivity. Many coral reefs that were a high priority when we considered adjacent connectivity in the sea and ignored land-sea connectivity became low priorities when symmetric land-sea connectivity was included, and vice versa. Our approach can be applied to incorporate connections between ecosystems.

Key words

land-sea connectivity, coral reefs, marine protected area, Marxan, conservation planning, integrated planning

1. Introduction

Coral reefs are the world’s most diverse marine ecosystem, supporting the livelihoods of millions of people (Burke et al. 2011). At the same time, they are facing escalating threats from land- and sea- based human activities (e.g., agriculture, deforestation, overfishing) (Carpenter et al. 2008; Hughes et al. 2010). There are many conservation initiatives around the globe aimed at protecting coral reefs (e.g., the Convention on Biological Diversity aims to effectively protect at least 10% of each of the world’s marine and coastal ecological regions, while the Coral Triangle Initiative has regional action plans and targets for coral reef protection through the implementation of marine protected areas). Marine protected areas (MPAs) that place restrictions on fishing and other extractive and non-extractive activities within a bound spatial area are the most common form of coral reef management. Yet, MPAs are affected by threats originating outside their boundaries (Boersma and Parrish 1999), as many of them lie in coastal waters which are vulnerable to terrestrial runoff and impacts from coastal development (Allison et al. 1998; Wood et al. 2008).

In MPAs, local land-based activities, as well as other global and regional stressors, can cause declines in the condition of coral reef systems regardless of whether sea-based activities (e.g., fishing) are prohibited (Jameson et al. 2002; Jones et al. 2004). Increased levels of sedimentation, nutrients, and other pollutants are some of the most important causes of coastal coral reef degradation (Halpern et al. 2007). Amounts of runoff are strongly influenced by land uses such as logging and agriculture (Bouwman et al. 2005). Eroded sediments carried from the land to the sea through rivers are deposited within a few kilometers from the river mouth and can smother corals or reduce the available light for the photosynthetic coral symbionts by increasing turbidity (Fabricius 2005; Rogers 1990). In such cases, land-based management, such as restrictions on logging, agriculture and development by requiring buffer areas, controlling drainage and regulating the use of chemicals and fertilizers, can protect coral reefs from negative direct and indirect impacts of terrestrial runoff (Davies and Nelson 1994; Weijters et al. 2009).

Another conservation strategy would be to place MPAs where there are fewer threats from the land (e.g., placing MPAs close to vegetated and protected catchments). Protection of intact terrestrial and freshwater ecosystems can prevent negative impacts on downstream habitats and species from land-based runoff, while at the same time preserving important cross-realm ecological processes. For example, many freshwater fish, crustaceans and mollusks found on tropical high islands are diadromous, meaning they migrate across multiple habitats throughout their life cycles (McDowall 2007). Their migration across habitat boundaries is affected by human disturbance causing habitat destruction and changes to hydrologic flow (Jenkins et al. 2010; Weijters et al. 2009). Thus, to preserve positive cross-realm processes and avoid negative consequences of habitat degradation, there is a strong need for integrated plans that account for linkages between terrestrial and marine ecosystems (Cicin-Sain and Belfiore 2005), though benefits of integrated planning are rarely quantified (but see Klein et al. 2012).

Systematic conservation planning is becoming the preferred approach used to inform decisions about the location of protected areas (Pressey and Bottrill 2009). With few exceptions (see Tallis et al. 2008, Hazlitt et al. 2010, Klein et al 2012), the standard approach of systematic conservation planning has usually focused on choosing the best conservation actions in just one realm (terrestrial, freshwater or marine) and does not consider the connections between ecosystems (Álvarez-Romero et al. 2011; Beger et al. 2010a; Stoms et al. 2005). The lack of information regarding the relationships between terrestrial, freshwater and marine ecosystems has presented a barrier to integrated prioritization (Pressey et al. 2007). In addition, there are political, administrative, institutional and cultural difficulties in implementing multiple-realm plans (Beger et al. 2010b) and planners and scientists face the challenge of incorporating land-sea connections into conservation plans (Green et al. 2009). Furthermore, the cost of applying integrated planning solutions compared to basic conservation planning, where connections are ignored, is largely unknown.

Although significant strides have been made towards integrated land-sea planning (Game et al. 2011; Hazlitt et al. 2010; Klein et al. 2012; Lombard et al. 2007; Tallis et al. 2008), significant research gaps remain. For example, no one has compared the spatial and cost differences of incorporating different types of land-sea connections. Further, there are no simple models to represent land-sea connections in data limited regions. In this paper, we demonstrate a theoretical approach to integrated land-sea planning using the systematic conservation planning tool Marxan (Ball et al. 2009). Our aim is to prioritize areas that contain coral reefs adjacent to forested catchments for protection to facilitate cross-realm processes and minimize negative impact of land-based runoff on coral reefs. We develop simple models to represent land-sea connections to reflect the lack of data in many places interested in land-sea planning. We integrate these models into a conservation planning framework and explore how the spatial configurations and attributes (e.g., costs, size, land-sea connections) of conservation priorities differ when we incorporate different types of connectivity. This study can help facilitate the widespread use of integrated planning by showing the impact of incorporating different types of connectivity when identifying spatial priorities.

2. Material and methods

2.1 Planning for connectivity in Marxan

To identify priorities for conservation, we used one of the systematic conservation planning tools, Marxan (Ball et al. 2009). Marxan minimizes an objective function that is the sum score of the total “cost” of selected sites, the total connectivity penalty for not selecting sites that are connected to selected sites, and penalties for not meeting target amounts of conservation features (Equation (1)(2))(Ball et al. 2009). Marxan finds near optimal solutions for protected area networks that achieve conservation targets with minimized cost and spatially allocated with consideration of connections of planning units. The problem Marxan solves is to

minimize

$$\sum_{i=1}^{m} c_i x_i + CSM \sum_{i1=1}^{m} \sum_{i2=1}^{m} x_{i1}(1 - x_{i2})\, CV_{i1,i2} \quad (1)$$

subject to

$$\sum_{i=1}^{m} a_{ij} x_i \geq t_j \;, \text{for } j = 1, \ldots, n, \qquad (2)$$

where *m* is total number of planning units and c_i is the cost of selecting planning unit *i*. If planning unit *i* is selected for conservation, x_i= 1 and if not x_i= 0. The strength of connectivity penalty is defined by the connectivity value matrix, *CV*, which is equivalent to the "total boundary length" in the original version of Marxan. The CV_{i1i2} reflects the strength of connection from planning unit i = 1 to i = 2 (Beger et al. 2010b). *CV* is scaled by the connectivity strength modifier (*CSM*), which is equivalent to the boundary length modifier (*BLM*), to adjust the importance of connectivity in priority area selection, relative to independent planning unit costs and penalties for not meeting conservation targets (Watts et al. 2009). In equation (2), t_j is the target amount for feature *j* (*j*=1, …, *n*) and a_{ij} is the amount of each feature *j* in planning unit *i*.

2.2 Data

Our data covers the catchments and coral reefs of Vanua Levu, Fiji (Fig. 1), an area where comprehensive models of land-sea processes do not exist. We chose this region as we wanted to demonstrate our methods in a region that has limited land-sea process data, which is typical of places interested in integrated land-sea planning. Our analysis is not intended to influence conservation decisions in the region. We divided the region into planning units, each of which could be selected as a priority area for conservation.

The planning units on the land (n = 110) were the river catchments described in Jenkins et al. (2010). Catchments with less than 50% cover were excluded from the planning region. This was based on the management recommendation to protect forests at or above 50% of catchment area as loss in forest cover has been associated with a significant reduction in freshwater fish species, an important indicator of water quality and catchment health (Jenkins et al. 2010). We used land cover classifications from Klein et al. (2012), which were derived from Landsat 5 Thematic Mapper images captured between 2000 and 2002. We divided land areas that met these forest calculation requirements into catchment polygons using the tool tabulate area in ArcGIS (spatial analyst extension) with processing cell size of 1. We divided marine areas into hexagonal 1 km^2 planning units (n = 2861) and included places up to a distance of 30 km from the coastline.

2.3 Prioritization objectives

The conservation feature on the land was dense forest and conservation features in the sea were fringing reefs and non-fringing reefs. We aimed to identify priority areas for conservation that include 20% of total forest cover and 30% of both types of coral reef, to be consistent with Fiji Government targets (Jupiter et al. 2011).

2.4 Definition of different types of connections and scenarios

We defined five different types of connectivity between planning units to assign connectivity values to each planning unit (Table 1). The first two scenarios reflect what is commonly done in marine conservation planning and are useful for comparison to scenarios 3-5 that reflect new methods for considering land-sea connectivity.

In the “no connectivity” scenario (scenario 1), connections between planning units were ignored and we assumed that none of planning units were connected to any other planning units. The connectivity value matrix was zero in this case.

Second, we considered adjacent connections in the sea in “adjacent reef connectivity” scenario (scenario 2) to represent ecological processes such as movement of adult reef fish, short distance dispersal of fish, and invertebrate larvae. This type of connection is commonly considered in marine conservation planning. Only the connections among adjacent reef planning units were considered, and connections to the terrestrial catchments were ignored. We illustrate this connection in Fig. 2a with three reef planning units as an example. The reef planning units *i* = 1 and *i* = 2, as well as reef planning units *i* = 2 and *i* = 3 share boundaries (connected), whereas reef planning units *i* = 1 and *i* = 3 are not adjacent (not connected) (Fig. 2a). The connectivity value for connected reef planning units, $CV_{i=1,i=2}$ is equal to the outside boundary length of reef planning unit *i* = 1 and *i* = 2 (the shared boundary is not counted). The connectivity value for unconnected reef planning units (*i* = 1 and *i* = 3), CV_{i1i3} is the sum of the outside boundary length of reef planning unit *i* = 1 and *i* = 3. The connectivity value CV_{i1i3} is larger than CV_{i1i2} because reef planning unit *i* = 1 and *i* = 3 do not share boundaries. This means connections between adjacent reef planning units are favored, which is a commonly used approach to design spatially compact conservation areas (Linke et al. 2011; Stewart and Possingham 2005).

Third, we defined “symmetric land-sea connectivity” (scenario 3), where connections between catchments and reef planning units were considered to be equally important in both directions, representing movements of anadromous, catadromous and amphidromous animals downstream and upstream between catchments and reefs (Fig. 2b). The *CV* is explained below.

Fourth, we analyzed a scenario called “asymmetric land-sea connectivity” (scenario 4). In contrast to the “symmetric land-sea connectivity” (scenario 3), directional connections between catchments and reef planning units were considered (Fig. 2b). For example, if a reef is prioritized, the closest catchment is more likely to be prioritized, whereas if a catchment is selected, it will not impact the selection of nearby reefs. Considering this direction is useful when the conservation objectives are to avoid negative runoff from the land. The *CV* of this scenario is explained below.

To calculate the connectivity values of scenario 3 (symmetric land-sea connectivity) and scenario 4 (asymmetric land-sea connectivity), we used the distance from the closest river mouth to each reef planning unit. This approach preferentially prioritizes reefs for conservation that are closest to the terrestrial catchments with high forest cover to facilitate the ecological processes between ecosystems and to avoid negative runoff from the deforested land areas. The connectivity value, CV_{ik}, of reef planning unit *i* and catchment *k* is calculated with the following equation:

$$CV_{ik} = f_k \times d_{ik}^{-1} \qquad (3)$$

where f_k is the forest area of catchment *k*, and $d_{ik} > 0$ and is the distance between the center point of reef planning unit *i* to the closest river mouth of catchment k. We assumed that the dispersal of river discharge declines linearly with the distance. Scenario 3 (symmetric land-sea connections) is non-directional ($CV_{ik} = CV_{ki}$), while in scenario 4 (asymmetric land-sea connections) connections are represented by an asymmetric connectivity matrix CV_{ik} with $CV_{ki} = 0$.

Fifth, we defined a scenario that incorporates two types of connections called “adjacent reef and asymmetric connectivity” (scenario 5). We sum the connectivity values of the adjacent reef and asymmetric land-sea connectivity models (i.e., scenario 2 plus 4). This scenario considered the conservation objectives described in scenario 2 and 4.

Connectivity values used in each scenario are summarized in Table 1. We calibrated the connectivity strength modifier (*CSM*) value in Marxan (Appendix A) using a method developed by Stewart and Possingham (2005). For scenario 1, *CSM* was zero as no connectivity was considered. In scenario 2, we used the range of 0.001 to 10 of the *CSM* and the *CSM* was chosen that had the similar opportunity cost to the base scenario 1 but also gave reasonable spatial compactness. In scenario 3 to 5, a *CSM* was chosen that had the similar opportunity cost to the base scenario 1.

2.5 Costs

For terrestrial areas, we used rent data from existing logging concessions in Fiji as the cost of land, representing the potential opportunity cost to landholders (Klein et al. 2012). The maximum opportunity cost of logging was FJD\$2 231.00 km^{-2}. This maximum value was multiplied by forest area in each terrestrial planning unit and assigned as logging opportunity cost for the planning unit on the land (total range of FJD\$47.80 to FJD\$2 194.00). For the marine areas, we used a maximum value of fishing opportunity costs, developed from a model estimating foregone revenue from fishing due to establishment of MPAs in one district (Kubulau) in Fiji (Adams et al. 2011). The functions of this model were food fish abundance and probability of catch based on fishing gear type and market value of species. We used the maximum value of predicted spatial data of opportunity costs on fringing reefs and non-fringing reefs. The maximum opportunity cost of not fishing a fringing reef was FJD\$4 762.00 km^{-2} and a non-fringing reef was FJD\$1 649.00 km^{-2}, respectively. These maximum values were multiplied by the area of fringing reefs and non-fringing reefs in each reef planning unit and assigned as fishing opportunity cost for the planning unit in the sea (total range of FJD\$0.02 to FJD\$4 763.00). We assumed each conservation feature has the same per area cost, however, we acknowledge that in practice foregone income would depend on species distributions and spatial distribution of fishing effort which can vary with access to transport, gear and markets (Naidoo et al. 2006).

2.6 Marxan analyses

For each scenario we produced 100 different solutions using simulated annealing in Marxan. To compare the differences between scenarios, we used the solution with the minimum total score of 100 Marxan solutions (i.e., best solution) and the planning unit selection frequencies of 100 Marxan solutions. We evaluated the priority differences by comparing the selection frequency of each planning unit across scenario solutions. To measure the differences that were driven by incorporating land-sea connectivity, we explored the percentage of pairs of prioritized catchments and their recipient reefs in best solutions between scenarios. Other attributes (e.g., the number of selected planning units, perimeter of marine priority areas, and the similarity of selected reef planning units) of conservation priorities were compared using the best solutions across all scenarios.

3. Results

The locations of spatial priorities (i.e., selection frequency) differed substantially between each scenario (Fig. 3). As expected, the selected reef planning units in scenario 1 (no connectivity) were scattered throughout the planning region (Fig. 3.1). Reef planning units were clumped regardless of where selected catchments were in scenario 2 (adjacent reef connectivity) (Fig. 3.2), whereas selected reef planning units were congregated close to catchments with high forest cover in scenario 3 (symmetric land-sea connectivity) (Fig. 3.3). On the other hand, selected reef planning units in scenario 4 (asymmetric land-sea connectivity) were scattered the same as scenario 1 which resulted in more priority catchments (Fig. 3.4). The selected reef planning units were clumped between reefs and congregated their closest catchments in scenario 5 (adjacent reef and asymmetric land-sea connectivity) (Fig. 3.5). These patterns can also be seen by looking at the perimeter of marine priority areas and the number of selected reef planning units (Table 2). For example, a large perimeter for marine priority areas indicates that they are not well connected and scattered across the region.

When we compared the selection frequency of each planning unit across all scenarios, we found that reef planning units that were a high priority (selection frequency >90) in one scenario became low priorities (selection frequency <10) in another scenarios, and vice versa (Table 3 and 4). There were large differences in priority selection between scenarios using adjacent reef connectivity (scenario 2) and symmetric land-sea connectivity (scenario 3); 86% of the high priority reef planning units in scenario 2 were not a high priority in scenario 3. Furthermore, 72% of high priory reef planning units of scenario 3 became a low priority in scenario 2 (Table 4). From 87% (scenario 2 and 3), 98% (scenario 4), up to 99% (scenario 2) of high priority reef planning units of scenario 5 did not become a low priority in other scenarios (Table 4).

From the best solution results, we found that in scenario 1 (no connectivity), 82% of selected reef planning units were connected to selected catchments, however only 68% were connected in scenario 2 (adjacent reef connectivity). In scenarios 3 to 5, when any type of land-sea connectivity was considered, 100%, 100%, and 95% of selected reef planning units, respectively, were connected to selected catchments.

We evaluated the similarity of selected reef planning units in the best solutions between scenarios (Table 5). The highest percentage of selected reef planning units shared was between scenarios 2 (adjacent reef connectivity) and 5 (adjacent reef and asymmetric land-sea connectivity), where 60% of selected reef planning units in scenario 2 were also selected in scenario 5 (Table 5). Selected reef planning units in scenario 1 (no connectivity) shared from only 11% of units (with scenario 2) to a maximum of 40% units shared (with scenario 4; Table 5).

Finally, we found that the considerable spatial variability in solutions exists despite minimal differences in opportunity costs. When costs of scenarios 2 through 5 were compared to the baseline scenario (scenario 1), the differences in the opportunity costs among best solutions as well as in the average opportunity costs among 100 solutions across all scenario varied less than 2% (Table 2).

4. Discussion

Integrated biodiversity conservation is required to address the problem of biodiversity loss both on land and in the sea (Rands et al. 2010). Our approach demonstrates that integrated planning that considers simple models of both land-sea connectivity and adjacent reef connectivity (scenario 2 to 5) can be facilitated with very little difference in overall reserve system costs to a scenario that ignored any connections and were less effective. There were, however, substantial differences in the spatial allocation of conservation priorities when connectivity was included. Our consideration of land-sea connectivity ensured that priority areas for marine conservation were spatially connected and geographically placed close to catchments with high forest cover to allow for ecological processes and avoid negative runoff from the land (Rouget et al. 2003).

In addition, our methods (scenario 3 and 5) ensured that marine priorities were spatially clumped, a feature that would reduce the perimeter of MPAs, making it generally easier for management enforcement than scattered MPAs with less controlling and costs (Ban et al. 2011). In some places, the tight spatial clustering using both land-sea and sea-only connections are preferred as management costs are minimized (Clarke and Jupiter 2010). However, clustered and large MPAs are not always ideal in regions where local tenure units are divided across smaller spatial scales than relevant ecological processes, as is the case in the Philippines (Weeks et al. 2010). In such cases, one of our methods (scenario 4) considering only asymmetric land-sea connectivity would be useful.

Our results show that higher number of pairs of linked catchment and reefs were selected in the “no connectivity” scenario (scenario 1) than in the “reef adjacent connectivity” scenario (scenario 2). This suggests the importance of accounting for the processes that link the land and the sea simultaneously (scenario 3-5) as well as considering the connectivity in the sea (scenario 2) in conjunction with stakeholder input (Pomeroy and Douvere 2008), when developing conservation plans. Management solutions applying different types of connectivity produced substantially different solutions, suggesting the importance of the decision to incorporate the correct type of connectivity when identifying conservation priorities. Managers may wish to choose one scenario over another depending on management objectives that may be constrained by ecosystem condition and government policy. Our objective was to prioritize cost-efficient marine reserves that are spatially connected to adjacent catchments with high forest cover to facilitate the cross-realm processes and to avoid negative runoff from the land. On the other hand, if the aim is to protect reefs only from the negative impacts of land-based runoff (Halpern et al. 2009), it is advised to place marine reserves away from the mouths of degraded rivers (Klein et al. 2012 and Tallis et al. 2008).

We showed how to develop integrated planning when small amounts of data on land-sea ecological processes and cross system threats are available. Additional data would improve our ability to assess the validity and quality of our modeled connections. We used only three conservation features and their connections: forest to represent terrestrial ecosystems, and fringing reefs and non-fringing reefs to represent marine ecosystems. However, we acknowledge that more features are necessary to represent the biodiversity patterns and processes in a region (Cowling et al. 1999). Moreover, the connections between conservation features in one or multiple ecosystem(s) will depend on the ecology of the features, thus the definition of connections would be different from this study when more, or different, conservation features are considered (Kinlan and Gaines 2003). Using the same conservation features with improved ecological data and at different scales would produce different outcomes. Also, the result that the high priority reef planning units in scenario 3 became low priorities in scenario 2 because of the connectivity value matrix. However, even using the different connectivity value matrix, scenario 5 shared from 87% up to 99% of high priorities with other scenarios. Results will likely be different if the definition of connections and their calculation differ. We have shown that integrated planning was not necessarily more expensive than planning that ignored connections, which is yet another reason why multiple ecosystems planning should be done. This may not always be the case, however, if opportunity costs and land-sea connectivity are positively correlated. Conservation planners should be aware of the limitations of our methods, decide what types of connections to consider and how to define connections based on their unique objectives.

Although our models were not comprehensive enough to represent the actual land-sea connectivity, using the best approximation available can be an important precautionary approach to activate discussions among scientists, managers and stakeholders (Ban et al. 2010). We used the distance from the closest river mouth to each reef planning unit and forest area of terrestrial catchment to represent the land-sea connections, we acknowledge that reefs are typically influenced by multiple rivers, and other factors such as wind and tidal-driven currents affect flood plume dispersion (e.g., Wolanski 1994). Further research is required to refine these land-sea relationships (e.g., more detailed quantification of runoff, ocean currents, and faunal connections). Scaling down of catchment planning units coupled with improved sediment delivery models would advance the analysis and potentially enable identification of specific areas within catchment to target for remediation (Beger et al. 2010a). On the other hand, investments in data collection to evaluate connections might not be the most immediate priority for coral reef conservation. In many places, the majority of marine managed areas are established by communities to meet local objectives of short-term food security and income for cultural practice as opposed to longer-term objectives for reef persistence and biodiversity conservation (Foale et al. 2011). These conditions suggest that investing in collecting more data on connections will deliver little benefit (Grantham et al. 2008; Hansen et al. 2011).

Systematic conservation planning has the advantages of transparency, repeatability, and practicality for decision makers (Watson et al. 2011). We demonstrated how to incorporate different types of connectivity in systematic conservation planning while keeping the costs constant with a basic approach. Our approach can accommodate different types of cross-realm processes including sedimentation, larval dispersal, and species movements across ecosystems. Furthermore, this method can be applied to design protected area networks across any environmental realms by incorporating the different kinds of connections between realms (i.e., terrestrial, freshwater and marine).

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References

Adams, V.M., Mills, M., Jupiter, S.D., Pressey, R.L., 2011. Improving social acceptability of marine protected area networks: A method for estimating opportunity costs to multiple gear types in both fished and currently unfished areas. Biological Conservation 144, 350-361.

Allison, G.W., Lubchenco, J., Carr, M.H., 1998. Marine reserves are necessary but not sufficient for marine conservation. Ecological Applications 8, S79-S92.

Álvarez-Romero, J.G., Pressey, R.L., Ban, N.C., Vance-Borland, K., Willer, C., Klein, C.J., Gaines, S.D., 2011. Integrated Land-Sea Conservation Planning: The Missing Links. Annual Review of Ecology, Evolution, and Systematics 42, 381-409.

Ball, I.R., Possingham, H.P., Watts, M., 2009. Marxan and relatives: software for spatial conservation prioritisation, In Spatial conservation prioritisation: quantitative methods and computational tools. eds A. Moilanen, K.A. Wilson, H. Possingham, pp. 185-195. Oxford University Press, Oxford, UK.

Ban, N.C., Adams, V., Pressey, R.L., Hicks, J., 2011. Promise and problems for estimating management costs of marine protected areas. Conservation Letters 4, 241-252.

Ban, N.C., Alidina, H.M., Ardron, J.A., 2010. Cumulative impact mapping: Advances, relevance and limitations to marine management and conservation, using Canada's Pacific waters as a case study. Marine Policy 34, 876-886.

Beger, M., Grantham, H.S., Pressey, R.L., Wilson, K.A., Peterson, E.L., Dorfman, D., Mumby, P.J., Lourival, R., Brumbaugh, D.R., Possingham, H.P., 2010a. Conservation planning for connectivity across marine, freshwater, and terrestrial realms. Biological Conservation 143, 565-575.

Beger, M., Linke, S., Watts, M., Game, E., Treml, E., Ball, I., Possingham, H.P., 2010b. Incorporating asymmetric connectivity into spatial decision making for conservation. Conservation Letters 3, 359-368.

Boersma, P.D., Parrish, J.K., 1999. Limiting abuse: marine protected areas, a limited solution. Ecological Economics 31, 287-304.

Bouwman, A.F., Van Drecht, G., Knoop, J.M., Beusen, A.H.W., Meinardi, C.R., 2005. Exploring changes in river nitrogen export to the world's oceans. Global Biogeochem. Cycles 19, GB1002.

Burke, L., Reytar, K., Spalding, M., Perry, A., (eds), 2011. Reefs at Risk Revisited. World Resources Institute, Washington, D. C.

Carpenter, K.E., Abrar, M., Aeby, G., Aronson, R.B., Banks, S., Bruckner, A., Chiriboga, A., Cortés, J., Delbeek, J.C., DeVantier, L., Edgar, G.J., Edwards, A.J., Fenner, D., Guzmán, H.M., Hoeksema, B.W., Hodgson, G., Johan, O., Licuanan, W.Y., Livingstone, S.R., Lovell, E.R., Moore, J.A., Obura, D.O., Ochavillo, D., Polidoro, B.A., Precht, W.F., Quibilan, M.C., Reboton, C., Richards, Z.T., Rogers, A.D., Sanciangco, J., Sheppard, A., Sheppard, C., Smith, J., Stuart, S., Turak, E., Veron, J.E.N., Wallace, C., Weil, E., Wood, E., 2008. One-Third of Reef-Building Corals Face Elevated Extinction Risk from Climate Change and Local Impacts. Science 321, 560-563.

Cicin-Sain, B., Belfiore, S., 2005. Linking marine protected areas to integrated coastal and ocean management: A review of theory and practice. Ocean and Coastal Management 48, 847-868.

Clarke, P., Jupiter, S.D., 2010. Law, custom and community-based natural resource management in Kubulau District (Fiji). Environmental Conservation, 98-106.

Cowling, R.M., Pressey, R.L., Lombard, A.T., Desmet, P.G., Ellis, A.G., 1999. From representation to persistence: requirements for a sustainable system of conservation areas in the species-rich mediterranean-climate desert of southern Africa. Diversity and Distributions 5, 51-71.

Davies, P., Nelson, M., 1994. Relationships between riparian buffer widths and the effects of logging on stream habitat, invertebrate community composition and fish abundance. Marine and Freshwater Research 45, 1289-1305.

Fabricius, K.E., 2005. Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. Marine Pollution Bulletin 50, 125-146.

Foale, S., Cohen, P., Januchowski-Hartley, S., Wenger, A., Macintyre, M., 2011. Tenure and taboos: origins and implications for fisheries in the Pacific. Fish and Fisheries 12, 357-369.

Game, E.T., Lipsett-Moore, G., Hamilton, R., Peterson, N., Kereseka, J., Atu, W., Watts, M., Possingham, H., 2011. Informed opportunism for conservation planning in the Solomon Islands. Conservation Letters 4, 38-46.

Grantham, H.S., Moilanen, A., Wilson, K.A., Pressey, R.L., Rebelo, T.G., Possingham, H.P., 2008. Diminishing return on investment for biodiversity data in conservation planning. Conservation Letters 1, 190-198.

Green, A., Smith, S.E., Lipsett-Moore, G., Groves, C., Peterson, N., Sheppard, S., Lokani, P., Hamilton, R., Almany, J., Aitsi, J., Bualia, L., 2009. Designing a resilient network of marine protected areas for Kimbe Bay, Papua New Guinea. Oryx 43, 488-498.

Halpern, B.S., Ebert, C.M., Kappel, C.V., Madin, E.M.P., Micheli, F., Perry, M., Selkoe, K.A., Walbridge, S., 2009. Global priority areas for incorporating land–sea connections in marine conservation. Conservation Letters 2, 189-196.

Halpern, B.S., Selkoe, K.A., Micheli, F., Kappel, C.V., 2007. Evaluating and Ranking the Vulnerability of Global Marine Ecosystems to Anthropogenic Threats. Conservation Biology 21, 1301-1315.

Hansen, G.J.A., Ban, N.C., Jones, M.L., Kaufman, L., Panes, H.M., Yasué, M., Vincent, A.C.J., 2011. Hindsight in marine protected area selection: A comparison of ecological representation arising from opportunistic and systematic approaches. Biological Conservation 144, 1866-1875.

Hazlitt, S.L., Martin, T.G., Sampson, L., Arcese, P., 2010. The effects of including marine ecological values in terrestrial reserve planning for a forest-nesting seabird. Biological Conservation 143, 1299-1303.

Hughes, T.P., Graham, N.A.J., Jackson, J.B.C., Mumby, P.J., Steneck, R.S., 2010. Rising to the challenge of sustaining coral reef resilience. Trends in Ecology & Evolution 25, 633-642.

Jameson, S.C., Tupper, M.H., Ridley, J.M., 2002. The three screen doors: can marine “protected” areas be effective? Marine Pollution Bulletin 44, 1177-1183.

Jenkins, A., Jupiter, S., Qauqau, I., Atherton, J., 2010. The importance of ecosystem-based management for conserving aquatic migratory pathways on tropical high islands: a case study from Fiji. Aquatic Conservation: Marine and Freshwater Ecosystems 20, 224-238.

Jones, G.P., McCormick, M.I., Srinivasan, M., Eagle, J.V., 2004. Coral decline threatens fish biodiversity in marine reserves. Proceedings of the National Academy of Sciences of the United States of America 101, 8251-8253.

Jupiter, S., Tora, K., Mills, M., Weeks, R., Adams, V., Qauqau, I., Nakeke, A., Tui, T., Nand, Y., Yakub, N., 2011. Filling the gaps: identifying candidate sites to expand Fiji's national protected area network. Outcomes report from provincial planning meeting, 20-21 September 2010, p. 65 pp, Wildlife Conservation Society, Suva, Fiji.

Kinlan, B.P., Gaines, S.D., 2003. Propagule dispersal in marine and terrestrial environments: a community perspective. Ecology 84, 2007-2020.

Klein, C.J., Jupiter, S.D., Selig, E.R., Watts, M.E., Halpern, B.S., Kamal, M., Roelfsema, C., Possingham, H.P., 2012. Forest conservation delivers highly variable coral reef conservation outcomes. Ecological Applications 22, 1246-1256.

Linke, S., Turak, E., Nel, J., 2011. Freshwater conservation planning: the case for systematic approaches. Freshwater Biology 56, 6-20.

Lombard, A.T., Reyers, B., Schonegevel, L.Y., Cooper, J., Smith-Adao, L.B., Nel, D.C., Froneman, P.W., Ansorge, I.J., Bester, M.N., Tosh, C.A., Strauss, T., Akkers, T., Gon, O., Leslie, R.W., Chown, S.L., 2007. Conserving pattern and process in the Southern Ocean: designing a Marine Protected Area for the Prince Edward Islands. Antarctic Science 19, 39-54.

McDowall, R.M., 2007. On amphidromy, a distinct form of diadromy in aquatic organisms. Fish and Fisheries 8, 1-13.

Naidoo, R., Balmford, A., Ferraro, P.J., Polasky, S., Ricketts, T.H., Rouget, M., 2006. Integrating economic costs into conservation planning. Trends in Ecology & Evolution 21, 681-687.

Pomeroy, R., Douvere, F., 2008. The engagement of stakeholders in the marine spatial planning process. Marine Policy 32, 816-822.

Pressey, R.L., Bottrill, M.C., 2009. Approaches to landscape- and seascape-scale conservation planning: convergence, contrasts and challenges. Oryx 43, 464-475.

Pressey, R.L., Cabeza, M., Watts, M.E., Cowling, R.M., Wilson, K.A., 2007. Conservation planning in a changing world. Trends in Ecology & Evolution 22, 583-592.

Rands, M.R.W., Adams, W.M., Bennun, L., Butchart, S.H.M., Clements, A., Coomes, D., Entwistle, A., Hodge, I., Kapos, V., Scharlemann, J.P.W., Sutherland, W.J., Vira, B., 2010. Biodiversity Conservation: Challenges Beyond 2010. Science 329, 1298-1303.

Rogers, C.S., 1990. Responses of coral reefs and reef organisms to sedimentation. Marine Ecology Progress Series 62, 185-202.

Rouget, M., Cowling, R.M., Pressey, R.L., Richardson, D.M., 2003. Identifying spatial components of ecological and evolutionary processes for regional conservation planning in the Cape Floristic Region, South Africa. Diversity and Distributions 9, 191-210.

Stewart, R., Possingham, H., 2005. Efficiency, costs and trade-offs in marine reserve system design. Environmental Modeling and Assessment 10, 203-213.

Stoms, D.M., Davis, F.W., Andelman, S.J., Carr, M.H., Gaines, S.D., Halpern, B.S., Hoenicke, R., Leibowitz, S.G., Leydecker, A., Madin, E.M., Tallis, H., Warner, R.R., 2005. Integrated coastal reserve planning: making the land–sea connection. Frontiers in Ecology and the Environment 3, 429-436.

Tallis, H., FerdaÑA, Z., Gray, E., 2008. Linking Terrestrial and Marine Conservation Planning and Threats Analysis. Conservation Biology 22, 120-130.

Watson, J.E.M., Grantham, H.S., Wilson, K.A., Possingham, H.P., 2011. Systematic Conservation Planning: Past, Present and Future, In Conservation Biogeography. pp. 136-160. John Wiley & Sons, Ltd.

Watts, M.E., Ball, I.R., Stewart, R.S., Klein, C.J., Wilson, K., Steinback, C., Lourival, R., Kircher, L., Possingham, H.P., 2009. Marxan with Zones: Software for optimal conservation based land- and sea-use zoning. Environmental Modelling & Software 24, 1513-1521.

Weeks, R., Russ, G.R., Bucol, A.A., Alcala, A.C., 2010. Incorporating local tenure in the systematic design of marine protected area networks. Conservation Letters 3, 445-453.

Weijters, M.J., Janse, J.H., Alkemade, R., Verhoeven, J.T.A., 2009. Quantifying the effect of catchment land use and water nutrient concentrations on freshwater river and stream biodiversity. Aquatic Conservation: Marine and Freshwater Ecosystems 19, 104-112.

Wolanski, E., 1994. Physical Oceanographic Processes of the Great Barrier Reef. CRC Press, Boca Raton, FL, USA.

Wood, L.J., Fish, L., Laughren, J., Pauly, D., 2008. Assessing progress towards global marine protection targets: shortfalls in information and action. Oryx 42, 340-351.

Figure captions

Figure 1. Catchments, forest cover, rivers, river mouths, and coral reefs of study region across Vanua Levu, Fiji.

Figure 2. Example of connections in the sea as well as between the land and the sea for scenario 2-5. This diagram shows connections (a) between reefs planning units i = 1, 2, 3 (scenario 2 and 5), and (b) between linked reef planning unit i and catchment k (scenario 3-5). The solid line represents the connection from reef planning unit i to catchment k. The dotted line represents the connection from catchment k to reef planning unit i.

Figure 3. Selection frequency of planning units in scenarios 1-5. 1) scenario 1 “ no connectivity”; 2) scenario 2 “adjacent reef connectivity”; 3) scenario 3 “symmetric land-sea connectivity”; 4) scenario 4 “asymmetric land-sea connectivity”; and 5) scenario 5 “adjacent reef and asymmetric connectivity”. Selection frequency maps represent the number of times a planning unit was selected across 100 near optimal solutions to each scenario.

Tables

Table 1. Summary of different types of connections used to define the connectivity value *CV*. Where f_k is the forest area of catchment *k*, and d_{ik} is the distance between the centre point of reef *i* to the river mouth of the closest catchment *k*.

Type of connectivity	Connectivity value (*CV*)
No connectivity	$CV_{i1i2} = CV_{i2i1} = 0$
Adjacent reef connectivity	$CV_{i1i2} = CV_{i2i1} = \text{Boundary length}_{i1i2} = \text{Boundary length}_{i2i1}$
Symmetric land-sea connectivity	$CV_{ik} = CV_{ki} = f_k \times d_{ik}^{-1}$
Asymmetric land-sea connectivity	$CV_{ik} = f_k \times d_{ik}^{-1}$, $CV_{ki} = 0$

Table 2. Comparison of attributes (i.e., overall reserve system costs, fishing opportunity cost, numbers of selected planning units as well as selected reef planning units, and perimeter of marine priority areas) of each scenario using best solutions.

Scenario	Total opportunity cost (FJD$)	Fishing opportunity cost (FJD$)	Number of selected planning units	Number of selected reef planning units	Perimeter of marine priority areas (km)
1: No connectivity	1 308 485	1 021 410	1 110	1 087	2 756
2: Adjacent reef connectivity	1 308 513	1 021 490	482	462	369
3: Symmetric land-sea connectivity	1 310 736	1 021 419	922	903	1 154
4: Asymmetric land-sea connectivity	1 308 483	1 021 474	1 102	1 073	2 760
5: Adjacent reef and asymmetric land-sea connectivity	1 308 612	1 021 402	625	606	458

Table 3. The number of high and low priority reef planning units (n=2861) selected in each scenario. High and low priority reef planning units are those that were selected more than 90% and less than 10% of the time across 100 solutions to the problem.

Scenario	Number of high priority reef planning units	Number of low priority reef planning units	Percentage of high priority reef planning units that are a low priority in other scenarios	Percentage of low priority reef planning units that are a high priority in other scenarios
1: No connectivity	0	5	0%	80%
2: Adjacent reef connectivity	253	2067	39%	7%
3: Symmetric land-sea connectivity	202	943	73%	8%
4: Asymmetric land-sea connectivity	0	30	0%	43%
5: Adjacent reef and asymmetric land-sea connectivity	144	1733	28%	7%

Table 4. Pairwise comparisons of high priority reef planning units (selection frequency >90) in a scenario in row that became a low priority (selection frequency <10) in another scenario in column. For example, 72% of high priority reef planning units in scenario 3 became a low priority in scenario 2, whereas no high priority reef planning units in scenario 3 became a low priority in scenario 1.

Scenario	1	2	3	4	5
1: No connectivity	-	-	-	-	-
2: Adjacent reef connectivity	2%	-	30%	1%	8%
3: Symmetric land-sea connectivity	0%	72%	-	5%	48%
4: Asymmetric land-sea connectivity	-	-	-	-	-
5: Adjacent reef and asymmetric land-sea connectivity	1%	13%	13%	2%	-

Table 5. Pairwise comparisons of selected reef planning units in best solutions. Percentage represents the selected reef planning units in a scenario in row that were also selected in another scenario in column. For example, 60% of selected reef planning units in scenario 2 were also selected in scenario 5, whereas 46% of selected reef planning units in scenario 5 were also selected in scenario 2.

Scenario	1	2	3	4	5
1: No connectivity	-	11%	30%	40%	18%
2: Adjacent reef connectivity	27%	-	30%	29%	60%
3: Symmetric land-sea connectivity	36%	15%	-	38%	36%
4: Asymmetric land-sea connectivity	40%	12%	32%	-	19%
5: Adjacent reef and asymmetric land-sea connectivity	33%	46%	54%	34%	-