Including Ecological Function into Habitat Networks Using Numerical Modeling: Assessing Performance and Cost

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ABSTRACT

Numerical models are tools used to identify areas of complex biodiversity or potential hotspots of fisheries production that then can be targeted for priority protection. On a larger scale these can be linked to form potentially self-sustaining habitat networks. Traditionally, models have used habitat as a surrogate for species or community representation, but have not addressed the more difficult task of ensuring that ecological function is incorporated into model results. We have identified an approach to structuring habitat data that facilitates the incorporation of ecological function into model outputs, as well as developing connectivity-based guidelines for assessing results. These were applied to data from Puerto Rico using Marxan. Model runs were made under two levels of clustering, with the "conservation target" arbitrarily set at 30 %. Results showed that only with higher clustering did priority areas meet the connectivity criteria, but at the cost of requiring about 50% more area to be selected. To further assess results, we constructed a "null" model composed of the four basic habitats (reef, sand, SAV, mangrove), which assumes that all patches within habitat type are equal. Results show little correlation between priority areas chosen by the two models, and patterns of frequency count, indicated that significant adjustments in area selection were made to incorporate ecological function. Again, additional costs were evident. Compared to the null model, the resulting number of planning units selected under the ecological function approach increased by 30%, regardless of the degree of clustering. The benefits are worth such costs.

KEY WORDS: Marxan, habitat, ecosystem-based management, coral reef ecosystems, MPAs

Incluyendo las Funciones Ecológicas en las Redes de Hábitats Utilizando Modelos Numericos: Determinación de su Resultados y Costo

Los modelos numéricos son herramientas utilizadas para identificar áreas de alta diversidad o localidades de alto potencial pesquero que luego pueden ser objeto de protección prioritaria. En gran escala estas areas pueden conectarse para formar redes de hábitats con auto-mantenimiento. Tradicionalmente, los modelos han utilizado hábitat como variable que representa a las especies o comunidades, pero no han considerado el trabajo de asegurar que las funciones ecológicas sean incorporadas en los resultados de dichos modelos. En esta trabajo hemos identificado una forma de arreglar los datos de hábitat de forma que incluyan la función ecológica en los resultados de los modelos, así como desarrollar guías de cómo interpretar los resultados considerando la conectividad. Esta aproximación fue aplicada a datos de Puerto Rico utilizando Marxan, las corridas de los modelos utilizaron dos niveles de agrupación, con un objetivo de conservación arbitrario de 30%. Los resultados muestran que los criterios de conectividad solo fueron alcanzados bajo un alto agrupamiento, con un costo en el tamaño del área seleccionada de un 50% mayor. Al expandir el estudio con un modelo base compuesto de cuatro hábitats básicos (arrecife, arena, hierbas marinas y mangles), que asume que los parchos dentro de cada hábitat son iguales. A su vez los resultados muestran poca correlación entre las áreas seleccionadas por los dos modelos y los patrones de frecuencia, sugiriendo que cambios significativos en la selección de las áreas fueron realizados para poder incorporar las funciones ecológicas. Nuevamente los costos adicionales fueron evidentes, comaraciones contra el modelo base reflejan que el número de unidades de área seleccionadas fueron un 30% mayor sin importar el nivel de agrupación. Los beneficios obtenidos al introducir las funciones ecológicas valen dichos costos.

PALABRAS CLAVE: Marxan, habitat, manejo basado en ecosistemas, ecosistemas de arrecife de coral, MPAs

Incluant les Fonctions Écologiques dans les Réseaux D'Habitats en Utilisant des Modèles Numériques: Détermination son Résultats et de Coût

MOTS CLÉS: Marxan, habitat, fonctions écologiques, modèles numériques

INTRODUCTION

The state of coral reef ecosystems, and the fisheries they support, has declined markedly throughout much of the Caribbean region, and this requires new approaches if these systems are to be restored. Ecosystem-based management (EBM), where the emphasis is on maintaining ecosystem health and productivity, represents a paradigm shift in fisheries management with a potential for reversing current trends (Appeldoorn 2008, 2011). Nevertheless, while the objectives of EBM may be clear, ways to implement these objectives are not always straightforward. For example, while protection of habitat and biodiversity are among the key objectives under EBM, how does one determine what and where are the priority areas needing protection? Cerveny (2006) and Cerveny et al. (2011) argue that essential fish habitat should be viewed on a multispecies, multihabitat basis, and suggest that special attention be given to those areas with high habitat diversity. Similarly, the basic biological principles of marine reserve design (Ballantine 1997a, 1997b), i.e., representation, replication and self-sustaining network design, suggest that the areas identified for high priority protection are those with high diversity. This still leaves the questions as to how to identify these areas and how to maximize the probability that these will maintain necessary ecological functions across spatial scales. As argued by Appeldoorn et al. (2011), the most efficient approach to network design is to use habitats as a proxy for species distributions, and they lay out a two part process for using these data for identifying high priority areas for protection. The first was to subdivide habitats to reflect differences in represented fauna, with a particular emphasis on differential habitat use across both species and ontogenic stages within species. This at least requires that all the habitats needed, especially those to support ontogenetic habitat shifts, will be represented, while assuming that the minimization function within any model will work to include all these habitats in near proximity, particularly if some degree of clustering is specified, and that this spatial proximity will enhance the probability of connectivity at the local scale.. The second was to define known limits of connectivity, in terms of distance or locations. These limits could then be used to assess the suitability of results and perhaps suggest that analysis be redone with additional constraints, such as stratifying areas or specifying maximum separation distances to produce a sufficient number and spacing of reserves to ensure larval connectivity. They further illustrate this process using existing data from Puerto Rico, developing both a specific habitat classification system that should enhance ecological function and a set of specific criteria for assessing results. Our objectives in this study are:

i) Apply these habitats and criteria as developed for Puerto Rico, incorporating them into the Marxan multivariate numerical model (Possingham et al. 2000), and
ii) To develop a null model to assess how the habitat classification system alters Marxan results as a response to adding ecological function.

METHODS

Input data used were those identified in Appeldoorn et al. (2011). The marine environment around Puerto Rico was divided into a grid of planning units, with each unit being a hexagon 1 km on a side (~2.6 km^2). Only those units for with underlying habitat distribution data were available were used in the analyses. Marxan runs were repeated for two levels of clustering, low and high (cl = 0.0005 and 0.005, respectively); higher clustering forces the model to group selected planning units into larger "reserves". The conservation target (proportion of each habitat/species to protect) was equal for all habitats/species and was arbitrarily set at 30%. The number of trials for each run was 200, with the best result saved. The cost for all planning units was equal, so that the "best" result is the one that minimizes the number of planning units required to meet the conservation targets. For each run, results were exported to ArcView GIS and maps prepared showing the planning units selected from the best run and the number of times each planning unit was selected during the 200 trials. Results were compared to the ecological criteria in Table 1 to assess their compliance with the goal for retaining ecological function.

Under the null model for Marxan, habitats were grouped only in the basic units of hardbottom, unconsolidated sediment, mangrove and submerged aquatic vegetation. This corresponds to the assumption that all patches within habitat type are equal. If the detailed subdividing of habitat used in our analysis is effective in creating ecologically meaningful connectivity, significantly different results should occur suggesting that the way in which the model selects planning units has been fundamentally altered. To assess this, emphasis was placed on the frequency count (= number of times a given planning unit was selected within the 200 iterations), and the correlation of the frequency counts of each hexagon under the two models was tested. Also, compared were the total area selected to achieve the overall goal of 30% inclusion.

RESULTS

Under low clustering, results should reflect the intrinsic value of each planning unit. Here, a few discrete areas are shown to be of particular importance, especially the areas of off La Parguera, Guanica, eastern and western

Table 1. Criteria for assessing if area selections retain ecological function. (from Appeldoorn et al. 2011)

Criterion	Metric
Maximum spacing among reserves	40 km
Habitats included within area	All
Habitat dispersal within area	Coastline to Shelfedge
Habitat separation	$10^2 – 10^3$ m

Vieques, Culebra, the San Jose lagoonal system of San Juan and off Dorado further to the west. The resulting pattern of selected areas (Figure 1a) reflects these, yielding a number of larger sites at these areas and a scattering of other sites around the island, including Mona. Most of the larger sites encompass sufficient area to contain the desired habitat connectivity, but even some of these do not consist of the full range of necessary habitats from the shoreline to the shelf edge. Higher clustering (Figure 1b) resulted in three very large selected areas off La Parguera, Culebra, and the entire east coast stretching to western Vieques, plus several areas along the north coast, Desacheo and Mona that are proportionally small due to the narrow expanse of the insular shelf. All of these contain the full array of cross-shelf habitats. Comparison of the high and low clustering results show that high clustering resulted, in some cases, in a shift away from otherwise important areas (*e.g.*, north and east Vieques) to areas of seemingly lesser importance (*e.g*. northeast Puerto Rico) with the result that more planning units must be included under higher clustering to meet conservation targets. In both scenarios there are broad areas of the southern and western coasts that are poorly represented.

Model results showed that only at the higher clustering value did selected areas meet the criteria of encompassing all habitats and extending from shoreline to shelf edge. However, the better performance under the higher clustering value came with the cost of requiring about 50% more planning units to be designated for protection. Spacing between some areas was greater than 40 km, and thus not fully meeting the criteria for larval dispersal.

Regardless of the degree of clustering, results show little correlation between the areas chosen by the two models (Figure 2), and patterns of frequency count are significantly different, indicating that significant adjustments in area selection were made. These results suggest that given the available data in the appropriate format, Marxan can be used to identify areas maximizing biodiversity conservation while maintaining basic design princi-

Table 2. Comparison of the total number of planning units selected to achieve 30% inclusion using the Null Model and Functional Habitat Model under Marxan.

Marxan Run	Planning Units Selected	% Area	% Above Null
Low Cluster			
Null Model	230	17.00	
Functional Habitat Model	299	22.10	30.00
High Cluster			
Null Model	346	25.57	
Functional Habitat Model	455	33.63	31.50

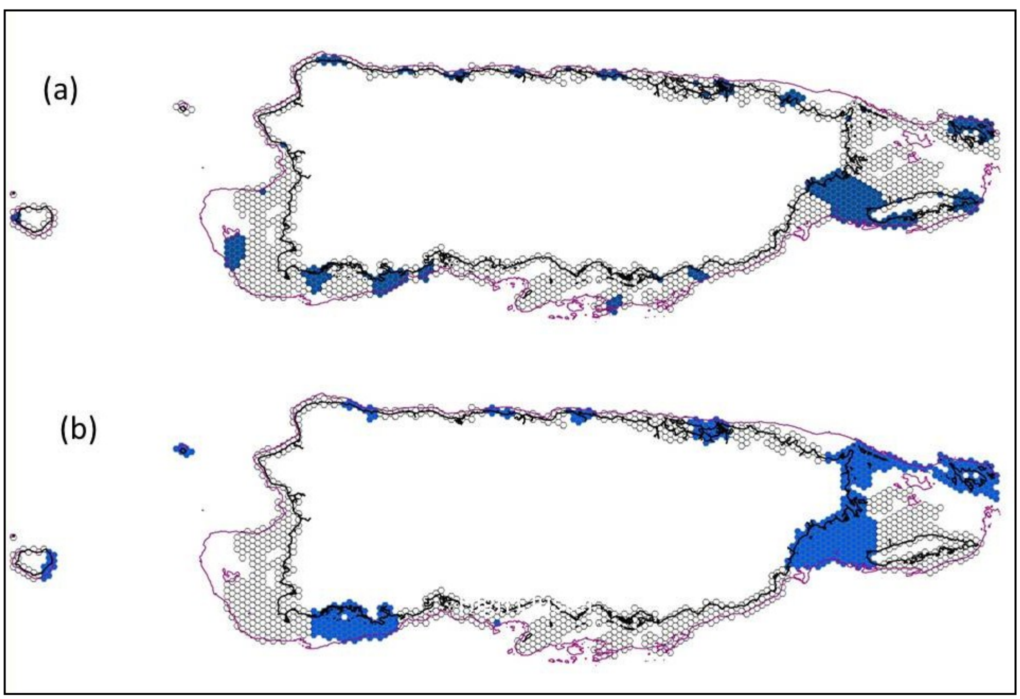

Figure 1. Results of Marxan analysis, with target selection set at 30%. (a) Best result (blue), low cluster. (b) Best result, high cluster. Red line represents the edge of the insular shelf (30-m depth contour).

ples. However, the adjustments made to meet design principles come with significant cost (Table 2). Not only does more area need to be protected under high cluster scenario that best meet connectivity criteria, the resulting number of planning units targeted for conservation under the functional habitat model relative to the null model increased by 30%, regardless of the degree of clustering.

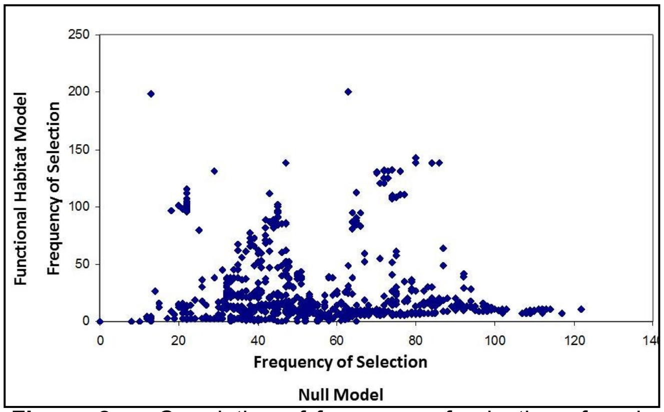

Figure 2. Correlation of frequency of selection of each hexagonal planning unit between the Null and Funcitional Habitat Models run in Marxan under high cluster.

DISCUSSION

Results, particularly under the high-clustering constraint, produced a number of areas where the full range of habitats from shoreline to shelf edge was represented, thus protecting fishes and large invertebrates (conch, spiny lobster) throughout ontogeny and over the daily wanderings of more vagile species. This was, however, more easily accomplished off the north coast or on the western islands where the extent of the shelf was small relative to the scale of individual planning units. This was more difficult to accomplish fully where the shelf was broad, such as off La Parguera or along the east coast. Practical management application of the result might suggest that, in those cases, the few planning units not selected but needed for completing the shore to shelf edge requirement would be included in the designated protected area. As recent research suggests that larger reserves may be required to stem the cascade of ecological degradation, it may, in fact, be desirable to expand potential reserve boundaries beyond those suggested by model results.

Meeting the requirement imposed by the limits of larval dispersal proved more difficult. In all runs, broad areas of the west and south coasts were poorly represented, leaving gaps larger than the estimated range of mean larval dispersal (~ 40 km). There are two solutions to this problem. One is to divide the coastline into zones and conduct separate analyses within each zone; the other is to utilize the maximum distance constraint within Marxan, which specifies that selected areas cannot be more than a specified distance apart. An additional avenue to ensure adequate larval dispersal for some of the most threaten species (e.g., snappers and groupers), not covered here, would be also to map and conserve known spawning aggregations by encompassing them in protected areas (e.g., Claro and Lindeman 2003), or by offering non-spatial protection through the use of closed seasons, as in currently done for several species in Puerto Rico.

The purpose of this study was not to specifically develop priority areas for protection in Puerto Rico. One reason for this is clearly evidenced by the relative absence of selected areas on the west coast. This results primarily from the poor habitat information for this region available in the NOS map. Nevertheless, this area represents a complex array of reef and non-reef habitats supporting important fisheries for reef fish, conch and lobster (Matos-Caraballo 2004). To incorporate this area, additional habitat information must be incorporated into the analysis. Such information is available from geological maps (*e.g.*, Morelock et al. 1994), resource surveys (e.g., Marshak et al. 2006) and ongoing habitat mapping efforts.

This study also assumed all targets have both equal weights and costs. Both of these involve societal judgments on the part of both managers and stakeholders. Additional costs may include the potential for habitat degradation from natural (Airamé et al. 2003) and anthropogenic processes (Burke and Maidens 2004), and from conflict with users such as recreational or commercial fishers, while costs may be reduced due to existing management and enforcement infrastructure and legal frameworks (Chatwin et al. 2004). Consensus on these costs will require substantial stakeholder education and involvement.

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