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An Ecoregional Plan for Puerto Rico: Portfolio Design

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by

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Greater Caribbean Ecoregional Plan

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The Nature Conservancy
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EXECUTIVE SUMMARY

Known best for its white-sand beaches, the Caribbean is actually one of the earth's greatest centers of biodiversity, and one of the earth's most imperiled regions. Human impacts are often intense -- and because island species are already naturally vulnerable to extinction, the Caribbean has had more recorded extinctions of mammals than the continents of Africa and Asia combined. Extinction threat is further exacerbated by political complexity – the region contains over 30 countries, each with a unique history and culture. To create a science-based conservation vision that matches the region's scale and complexity, the Nature Conservancy has undertaken an intensive two-year study of the Greater Caribbean Basin, including detailed examination of both the biology and the socioeconomics of the region. At the core of this effort is "Conservation by Design", the Conservancy's science-based planning process which identifies the landscapes and seascapes that, if conserved, promise to ensure biodiversity over the long term.

We are now assembling, into a standard and seamless GIS database, the biological and socio-economic data necessary for basin-wide analysis. As a key part of this process, we used Puerto Rico as a case study for more intensive analysis. Here we report our results including the mapping of Puerto Rico's freshwater, terrestrial and marine biodiversity and analysis of human impacts that influence the persistence of these targets. Much of this work resulted from input from local experts during workshops held in June 2003 and March 2004 in San Juan, Puerto Rico.

We developed a set of spatial tools to quantitatively evaluate all significant and restorable biodiversity. This report presents a preliminary ecoregional plan for Puerto Rico and its archipelago that includes terrestrial, freshwater and marine components. We acknowledge that the results presented here should be considered preliminary and subject to further investigation, as science-based planning is a dynamic process of data gathering, evaluation and decision-making.

Analysis of Puerto Rico, including the main island, Vieques, Culebra, and Mona, was done using a spatially explicit annealing program called Marxan. We used Marxan to identify and map an efficient portfolio of conservation areas based on representation

of a suite of conservation targets for terrestrial, marine and freshwater biodiversity. We found a minimum portfolio consisted of 868 planning units (225,680 ha) could be assembled to meet all conservation goals for freshwater and terrestrial targets. In addition, an efficient portfolio consisting of 412 planning units, or a total area of 107,120 hectares that contained enough of the distribution of all the marine targets to fully meet their representation goals. In addition to producing the optimal solution, Marxan also generates a value equivalent to the irreplaceability of each planning unit. Irreplaceability measures the importance of a planning unit to achieving the target goals efficiently, because the biodiversity captured in that planning unit is unlikely to be captured elsewhere. Because it is unlikely that comprehensive implementation of conservation areas could happen at once, measures of irreplacability can guide and prioritize where actions should occur first and identify areas of relatively higher biological value, based on targets abundance, condition and spatial configuration.

Another key element of our approach is *open-architecture design.* Biological and socio-economic information will be assembled into a database which will be made freely available to interested stakeholders via the internet (with the exception of sensitive and propriety information). The information will be organized in a manner where new information can be easily incorporated and housed and maintained in a central location by The Nature Conservancy.

Continued advancement of systematic, science-based planning approaches will help ensure proper management for the long-term viability and robustness of the ecological systems of Puerto Rico. Methods and tools developed using Puerto Rico as a pilot study will be extended to encompass the entire Caribbean Basin and will identify the best remaining and potentially viable habitat areas. We make several recommendations for the advancement and improvement of the Puerto Rico Ecoregional Plan. These include improving the baseline data systems and information sources and, most importantly, establishing a technical training process that will promote sound, data-driven decision-making by agencies and local NGOs.

INTRODUCTION

Known mostly as a vacation destination with serene seascapes and white-sand beaches, the Caribbean is actually one of the earth's greatest centers of biodiversity and endemism. The Caribbean Archipelago was once part of a chain of islands that bridged North and South America in the region that became Central America, well back in the time of Pangea and Gondwanaland. As the Caribbean plate moved east it carried with it land fragments and in the late Cretaceous separate tectonic episodes created more land. The Greater Antilles was formed first, generally through uplift and accretion; later the Lesser Antilles was formed largely through volcanic activity along the subduction zone. The Greater and Lesser Antilles together form what is known historically as the West Indies (see Stehli and Webb (1985) and Woods (1989) for extensive reviews). Evolution in isolation resulted many large species radiations, particularly in the terrestrial and freshwater environments of the Greater Antilles. Estimates suggest that about 40% of the Caribbean's plant life and terrestrial vertebrates are endemic and the total number of species is comparable to the entire continental US.

The same biogeographic and evolutionary forces that have shaped this extraordinary array of biodiversity found throughout the Caribbean have also resulted in vulnerability to extinction. Island species evolving in the absence of top predators and competition are notoriously easy for humans to exploit. There have already been more recorded extinctions of mammals in the Caribbean than on the continents of Africa and Asia combined. Extinction threat is exacerbated by political complexity – the region contains over 30 countries, each with a unique history and culture, resulting in a mix of social, economic and conservation problems. The result is that the Caribbean is on of the most impacted places on earth -- less than 10 percent of the region's original vegetation remains intact, many of its species are currently threatened or endangered and most countries lack capacity and infrastructure to deal with conservation issues. Yet what remains are often the last examples of species or ecosystems.

Puerto Rico is the smallest and most easterly island of the Greater Antilles. With its archipelago—Vieques, Culebra, Mona, Monita, and Desecho— the Commonwealth of Puerto Rico has a total land area of ca. 8,900 (8898) km^2. Though small in size, Puerto Rico, like the other islands of the Greater Antilles, is characterized by species endemism and is one of the world's most threatened places. Here we assess the state of the islands biota and provide analytical tools and maps that can be used to complete the following objectives:

1) Determine and prioritize areas of conservation importance that contain multiple and viable examples of all native and endemic plants, animals, as well as ecological communities and systems in Puerto Rico.
2) Identify functional areas in which the ecological processes may be sustainable over a long period of time to safeguard the diversity of life.
3) Develop strategies for the conservation, sustainable use and management of the island's biodiversity resources.

Terrestrial Biodiversity

Puerto Rico harbors a diverse flora and fauna with a high level of endemism at multiple scales -- some species are endemic to the West Indies in general, to the main island, to individual islands of the archipelago, and to isolated areas within each island. There are 30 major vegetation systems, 2891 vascular plant species, and 206 vertebrate species--106 species of resident birds, 21 species of mammals, 79 species of reptiles and amphibians--in the Commonwealth of Puerto Rico. Of this rich terrestrial biota, 46% of herpetofauna and 8% of plant species are endemic to Puerto Rico (**Table 1**). Moreover, Puerto Rico has the highest species density of herpetofauna per area among the islands of the Greater Antiles (Duellman, 1999). Figueroa-Colon (1996) examined the native flora of Puerto Rico and found that the mountain habitats harbor the highest number of endemic tree species within the Commonwealth. The trends of endemic tree species richness follow the humidity gradient from wet to dry areas.

While there is no known loss of native plant species (Figueroa-Colon, pers. com., March 2003), a number of faunal species have suffered extinction in the recent past (Rivero, 1998). Extinction of any faunal species in a small island ecosystem is of great concern because there is little species redundancy allowing readjustment or replacement of the lost ecological functions of the extinct species.

To map Puerto Rico's terrestrial biodiversity, Holdridge identified 6 Life Zones—climatic zones which allow specific vegetation types to develop. The Cordillera

Central, an east/west oriented inactive volcanic mountain chain, straddles the central part of the island and reaches 1388 m at its highest point. Other major mountain ranges are Sierra de Luquillo in the NE and Cordillera Jaicoa in the NW. The moisture-laden NE trade winds modified by aspects and elevation of mountain ranges create precipitation gradients along the NE/SW direction. The moist or wet vegetation occurs in the north and NE of the island; whereas the dry vegetation is found in the rain shadow of the Cordillera Central, notably in the south and SW of the island. The varied topography and complex geology result in 28 geoclimatic zones in which vegetation and species have evolved and diversified (**Table 2**).

Freshwater Biodiversity

The Freshwater System in Puerto Rico, which harbors 2% of native fish species and 12% of aquatic insects in the Caribbean, is composed of surface running water, ground water, wetlands, coastal lagoons, a few natural ponds and geothermal springs. Also there are artificial reservoirs, channels for agricultural irrigation and cattle ponds. Most of the wetlands are in the lower watersheds and there is one natural lake (lake Cartagena). All headwaters are below 1,350 meters elevation (4,455 feet) as the highest peaks of the island barely approach such an altitude. As usually occurs in the Caribbean islands, stream flows in Puerto Rico vary widely because of a rainfall pattern influenced by windward / leeward and orographic effects, as well as the impact of seasonal storms and hurricanes.

Freshwater biodiversity patterns respond to the same geoclimatic conditions (Table 2) as terrestrial biodiversity, although at a different spatial scale. According to Bogart et al. (1964) the chemical composition of stream water in Puerto Rico reflects the island's geology. This is particularly true with respect to the concentrations of calcium and bicarbonate and Bogart and colleagues propose six stream groups based on the concentration of these ions. In contrast, water temperature is reported to have no significant variation across the island, ranging from 70°F to 90°F. This is different from islands such as Hispaniola and Cuba, where water temperature varies widely, and is a consequence of the island's generally low elevation. Turbidity due to sedimentation is a distinctive characteristic of the island's aquatic systems because of steep topography, heavy rainfall and erodable soils. Turbidity has been accentuated by human activities, such as urban development and agriculture. Lower reaches of watersheds and lake Cartegena are degraded by unnaturally high levels and sedimentation.

According to Bogart et al. (1964) there are 17 major watersheds in the island. In a later revision, the Department of Natural Resources divided the system in 33 watersheds and sub-watersheds. The largest, measured by drainage area, are: Grande de Loiza (774.6 km2), La Plata (652.2 km2), Grande de Arecibo (505.0 km2), Grande de Añasco (495.8 km2), Caliza de Arecibo (491.9 km2), Guayanilla (466.0 km2) and Guajataca (461.1 km2).

For planning purposes, we grouped watersheds with similar topographic patterns, drainage density, hydrologic characteristics, and connectivity, the freshwater assessment team, in consultation with Puerto Rican experts, and mapped five ecological drainage units (EDU) in the Commonwealth of Puerto Rico (**Map 1**). The South EDU is flat and drier than the rest of the country. Its watersheds are very small, usually with low flows, but subject to occasional flash flooding. The South EDU includes the rivers Guamaní, Seco, Salinas, Coamo, Jacaguas, Tallaboa, Guayanilla, and Yauco. The West EDU includes few but relatively large watersheds. There are three major rivers in the West EDU, the Grande de Añasco, Guanajibo and Culebrinas. The Northeast EDU is a complex of watersheds in the northeast corner of Puerto Rico. This EDU has the highest drainage density but the watersheds are relatively small except for Loiza. Other rivers in the Northeast EDU are the Espíritu Santo, Mameyes, Fajardo, Blanco, Humacao, Guayanés, Maunabo and Grande de Patillas. The Northwest EDU includes Puerto Rico's karst region. Much of the drainage is underground. Surface freshwater systems in the Northwest EDU are sparse but there are some large rivers, the Guajataca, Camuy, Grande de Arecibo, Grande de Manatí, Cibuco, La Plata, and Bayamón. The EDU of the archipelago includes the islands of Vieques and Culebra. These islands do not have any large streams. They exhibit similar drainage characteristics as the islands of the Lesser Antilles. Catchments areas for these rivers are small and generally in flat areas.

Human Impacts and Opportunities

The vegetation cover of Puerto Rico has undergone significant changes in recent times. In the 1940s, deforestation was the most intense, leaving only 6% forested land. Economic changes lessened agricultural activities, and by 1987, forests regenerated on abandoned agricultural fields, covering 35% of the island (Thomas, 1999). The recent Land Cover map, based on 1991 Landsat TM imagery, shows that now at least 41.6% of the main island is covered by forest (Helmer, et al., 2002). This positive development is not reflected in the population of fauna. Modifications in the environment have been considered the prime culprit for faunal species decline. Other causes such as the introduced Indian mongoose (Herpestes javanicus) are believed to be responsible for the extinction of several species of lizards and snakes (Henderson 1992). Evidence also points to feral cats, dogs, pigs, and goats, which can damage the native flora and fauna significantly (Rivero, 1998). A preliminary analysis of the distribution of ecosystems and critical elements (rare or threatened plant and animal species) in Puerto Rico has confirmed the importance of the Forest Reserve network, in which 70% of the ecosystems (geoclimatic regions), and 87% and 48% of the critical plant and animal species occur respectively (Figueroa-Colon, 2003d). Approximately only 5% of forested areas in Puerto Rico are now under protection. Setting aside more land areas based on the occurrences of representative vegetation and faunal communities within distinct geoclimatic regions has been one of the most important tasks of the Ecoregional Planning project.

In order to systematically analyze conservation values , address threats to biodiversity, promote conservation action at-scale and to provide needed decision-making tools we have initiated an ecoregional plan for Puerto Rico. This effort includes detailed examination of both the biology and the socioeconomics of the island archipelago. At the core of this effort is "Conservation by Design", the Conservancy's science-based planning process which identifies the landscapes and seascapes that, if conserved, promise to ensure biodiversity over the long term. This report provides an overview of science-based methods and preliminary results of the ecoregional plan for Puerto Rico.

Conservation Approach: Puerto Rico

Puerto Rico's context is similar to that of the entire Caribbean – it is a critically important place for biodiversity that exists in a difficult, and ever-changing political backdrop. Through the process of ecoregional assessment, a number of high-leverage objectives are beginning to emerge that can broadly promote conservation at both national and region-wide scales. These high leverage objectives include:

- broadening a wide-range of conservation efforts to include consideration of representation and protection of a full range of terrestrial, freshwater and marine biodiversity and systematic assessment of threats,
- enhancing existing conservation efforts by providing technical and scientific assistance and collaboration opportunities, and
- further developing methodologies for identifying and abating threats to existing protected areas and other critical areas for conservation at-scale

We suggest that the process of assessment can provide leverage and enhance existing conservation efforts by embedding scientific planning tools into decision-making forums and by facilitating coordinated conservation activities by bringing together multiple constituencies. This approach has great potential because the conservation landscape throughout the region is highly fragmented and multiple parties -- NGOs, government agencies and universities – often duplicate efforts or fight for the same resources. Access to information and funding is often disorganized and poorly-defined responsibilities within government agencies compound the challenges faced by conservation institutions. Through completing the Caribbean Basin Ecoregional Assessment, we hope to transcend local politics between institutions. We believe the Conservancy is uniquely positioned to have strong and positive impact and play an lead role in facilitating science-based management and decision making. We suggest that our ability to rally conservation groups and harness their capabilities and provide science-based decision tools that will ultimately lead to sound management and improved conservation decision-making. We hope to continue to play this role as efforts progress from planning to action, with specific focus on analytical training and local partnerships.

Scientific Background

Responding to a growing consensus in the scientific communities and to practitioners frustrated by the incremental progress being made to stem the tide of biodiversity loss, The Nature Conservancy and its partners developed a systematic approach to conservation planning and action. Outlined in Conservation by Design: A Framework for Mission Success (TNC, 1996), the overall goal of conservation planning has become:

> *"The long term survival of all viable, native species and community types, through the design and conservation of portfolios of sites within ecoregions"*

This approach draws on a developing field of conservation science called reserve design where, over the past 30 years, biologists have developed a number of principles and tools to aid in systematic selection of conservation areas, with the overall goal of biodiversity conservation (MacArthur and Wilson 1967; Diamond 1976; Diamond and May 1976; Diamond 1986; Noss and Cooperider 1994; Noss 1996; Soulé and Terborgh 1999; Margules and Pressey 2000). An ecoregional plan applies well-accepted principles of conservation biology and thus provides a science-based framework for identifying and prioritizing areas for conservation, based upon biological values, predicted viability, human threats, and opportunities for implementation.

One advantage of regional scale systematic approaches, is that they move away from insular and fragmented conservation planning efforts that prevail in many locations (Schwartz 1999; Soulé and Terborgh 1999). An ERP should incorporate the best existing knowledge and planning for a region, including an emphasis on landscape and biological integrity, connectivity, long-term viability and the precautionary principle.

A fundamental basis for the Caribbean Basin Ecoregional Plan is the utilization of analytical models for mapping biodiversity targets, and the quantification of expert opinion using a viability modeling approach. These models involve the mapping of biodiversity surrogates for efficiency, which involves identification and mapping of ecological processes, states and gradients that combine to result in on the ground biodiversity. Representation analyses and connectivity assessments are two additional tools used in ERP development. These ensure that all ecological communities have received appropriate conservation consideration and protection.

Our overall objectives are, therefore, to delineate and prioritize areas for protection and develop sound conservation strategies for these areas, based on current scientific knowledge, the tenets of conservation biology, and the precautionary principle. History has shown that without such a plan, the Caribbean basin biodiversity and ecosystem functioning will continue to be eroded by human impacts until species and ecosystems are irreversibly lost. Here we describe results from the study of the island of Puerto Rico. We report initial portfolio design methods and results for terrestrial, freshwater and marine components. These data and tools will form the foundation of scienc-based actions for Puerto Rico and will also serve to inform the ecoregional plan for the entire Caribbean basin. The report is based on work leading up to and resulting from a series of workshops held in San Juan, in March 2004.

METHODS

General Approach

We developed a set of spatial tools to quantitatively evaluate all significant and restorable biodiversity. The terrestrial and freshwater teams agreed to adhere to the same general approach, which is outlined below, to assemble their specific portfolios. The marine team used a similar approach that was modified to suit the marine environment. The purpose of this report is to integrate the portfolios in order to present a framework for a unified ecoregional plan for Puerto Rico and its archipelago. All work is ongoing and done in collaboration with local experts.

Planning sequence:

1) Selection and mapping of conservation targets that represent the full range of terrestrial and freshwater biodiversity. Coarse-scale conservation targets—ecological systems or communities—were identified and mapped with the help of spatial data sets of key environmental parameters that define the distribution of targets. Fine-scale conservation targets—species groups or species—were singled out by examining a variety of species-occurrence databases. Both coarse and fine scale conservation targets were subsequently reviewed and their distribution verified in a series of experts' workshops.

2) Viability analysis of conservation targets at individual target occurrences based on quantifying experts' estimates of the current status of key ecological factors. Key ecological factors are the ecological processes, habitat states or environmental gradients, whose functional integrity is necessary to maintain the target's biological health. Virtually all key factors critical to these species, communities, and ecological systems vary over time in natural conditions. The displacements of the key factors from their natural range of variability allow us to estimate the current target health at specific target locations.

3) Assembling a portfolio of conservation areas with deliberate conservation goals for individual targets using Marxan. Typically, the target conservation goals

include quantity, such as the size of proposed conservation areas for a specific target, and quality, such as conditions of target occurrences.

4) Incorporating impacts of human activities as "cost of biodiversity conservation" in the respective terrestrial/freshwater portfolios. This involves generating a value that would essentially reflect the relative intensity of the human footprint per unit area. The higher the density or accumulation of human activities within a given area, the more difficult the long term conservation of biodiversity within that area can be.

Methods and results for mapping conservation targets and viability analysis were documented in a earlier report (An Ecoregional Plan for Puerto Rico: Preliminary Results; July 2003). Here we describe methods and results related to portfolio assembly and conservation cost modeling (#3 and #4 above). Preliminary Marine methods and results will also be briefly described but will be further detailed in future scientific publications in collaboration with University of Puerto Rico.

Portfolio Assembly

Early conservation assessments depended on manual mapping to delineate sites and were often totally reliant on expert opinion and sharpie markers to delineate and prioritize conservation sites. The large number of conservation targets and the large size and diverse types of data sets describing the targets in this study required the use of a more systematic and efficient site selection procedure. We used MARXAN, software that implements a site optimization algorithm, developed by Dr Hugh Possingham, University of Queensland, and Dr Ian Ball, now at Australian Antarctic Division in Tasmania. MARXAN comes from a lineage of successful selection algorithms, beginning with SIMAN, SPEXAN, and SITES. MARXAN was developed from SPEXAN and SITES in part to aid in work on the Great Barrier Reef Marine Park In order to design an optimal reserve network, MARXAN examines each individual planning unit for the values it contains. They then select a collection of these units to meet the conservation targets that have been assigned. The algorithm will add and remove planning units in an attempt to improve the efficiency of the reserves. What makes these algorithms different from other iterative approaches is that there is a random element programmed into them such that early on in the process the algorithm is quite irrational in what it chooses to keep or discard, often breaking the rules of what makes a good selection. This random factor allows the algorithm to choose less than optimal planning units earlier that may allow for better choices later. As the program progresses, the computer behaves more predictably –but not entirely. The process continues, with the criteria for a good selection getting progressively stricter, until finally the reserve network is built. Given a sufficiently diverse set of features, it follows that because of the random element, no two runs are likely to produce exactly the same results. Some may be much less desirable than others. Still, if enough runs are undertaken, a subset of superior solutions can be created. Furthermore, the results from all runs may be added together to discern general trends in the selection process.

MARXAN and other similar software programs (e.g. SITES, SIMAN, SPEXAN) have been or are being used as an aid for designing and analyzing alternative portfolios in a number of TNC ecoregional plans, including the Northern Gulf of Mexico (Beck et al. 2000), Cook Inlet, Klamath Mountains, Sierra Nevada, Middle Rocky Mountains-Blue Mountains, and Southern Rocky Mountains ecoregions. MARXAN utilizes an algorithm called "simulated annealing with iterative improvement" as a heuristic method for efficiently selecting regionally representative sets of areas for biodiversity conservation (Pressey et al. 1996, Csuti et al. 1997, Possingham et al. 1999). It is not guaranteed to find an optimal solution, which is prohibitive in computer time for large, complex data sets such as ours. Rather, the algorithm attempts to minimize portfolio "cost" while maximizing attainment of conservation goals in a compact set of sites. This set of objectives constitutes the "Objective Cost function:"

Cost = Area + Species Penalty + Boundary Length

where Cost is the objective (to be minimized), Area is the number of hectares in all planning units selected for the portfolio, Species Penalty is a cost imposed for failing to meet target goals, and Boundary Length is a cost determined by the total boundary length of the portfolio.

MARXAN attempts to minimize total portfolio cost by selecting the fewest planning units and smallest overall area needed to meet as many target goals as possible, and by selecting planning units that are clustered together rather than dispersed (thus reducing boundary length). MARXAN accomplishes this task by changing the planning units selected and re-evaluating the Cost function through multiple iterations. We had MARXAN perform 1,000,000 iterative attempts to find the minimum cost solution per simulated annealing run and perform 200 such runs for each alternative conservation scenario we explored. Alternative scenarios were evaluated by varying the inputs to the Cost function. For example, the Boundary Length cost factor can be increased or decreased depending on the assumed importance of a spatially compact portfolio of sites, and a range of goals can be used. Varying the inputs to MARXAN in order to assess the outcome, in terms of the planning units selected, allows portfolio design to be tailored to expert opinion, while quantifying the effects of such subjective decisions.

We used numerous MARXAN runs to determine alternative portfolios which met stated goals for protection of the target groups, in terrestrial, freshwater and marine realms. Our ultimate objective was to find the portfolio that met stated goals for all target groups in an efficient manner, while also meeting the general criteria of reserve design (e.g., connectivity, minimal fragmentation).

Parameters

Several factors besides the number and type of targets used influence MARXAN outcomes. These include type of planning units, protection status of planning units, planning unit cost measure, penalty applied for failure to meet target goals ('species penalty factor'), penalty applied for dispersed rather than clustered planning units in results ('boundary length modifier'), the number of repeat runs of the algorithm (and number of iterations within each run) to include in summing results from several scenarios, and goal level for each target.

Planning Units

Planning units can be any shape or size, but appropriate units should be designed according to the available target data and to best facilitate conservation efforts in the priority sites identified. Planning units can be natural, administrative or arbitrary sub divisions of the land and seascape. The units size is chosen to reflect differences between fragmented and non-fragmented habitats or distributions and the quantitative differences between units. Data on distributions within very small units becomes presence / absence information and does not reflect differences regarding the size of patches or the co-existence of biodiversity targets between the units. We used 260 hectare hexagons (1km on a side). This not only allows consistency across terrestrial, freshwater and marine analysis, but using uniform sized planning units also avoids the area-related bias that can occur the planning unit selection process when differently-sized planning units with irregular boundaries, such as watersheds, are used.

Species Penalty Factor

These values determine the importance of representation of individual biodiversity targets in the analysis, and so how likely they were to meet the goal representation. It was decided that it was preferable for all biodiversity targets to meet the goals set. We used the a high penalty factor (100,000) for all targets. We ran a series of experimental runs to determine that this was a sufficiently large penalty factor to force Marxan to meet all goals.

Spatial Clustering

Using a measure called the boundary length modifier, the influence of the boundary length in the calculation of total portfolio cost can be increased. This has the effect of increasing the clustering of planning units together into sites in the portfolio. We used boundary length modifier of 0.0005 to determine clump size.

Repeat Runs

We made 200 repeat runs (each comprised of 1,000,000 iterations of planning unit selection) for each of the terrestrial, freshwater and marine runs. Hexagons chosen frequently represent places more necessary (i.e. more irreplaceable) for biodiversity conservation, while those chosen few times represent locations where similar biodiversity is found many other places or where human impacts are significant. Separate analyses were done for freshwater, terrestrial and marine data. The portfolios were then overlaid to produce a combined result. Marxan can be used to generate an integrated analysis of data from more than one realm. However, conservation targets in the three realms are impacted differently by human activities. For example, while dams have significant direct impacts on freshwater targets, their impact on terrestrial or marine conservation targets is less clear. Thus, in order to capture the differential impacts of human activities to each of the three realms, realm-specific marxan runs were done.

Human Impacts – Conservation Cost Surface

Planning units with lower levels of human impacts should be chosen over those with higher levels of impacts, when other factors are equal. This cumulative intensity index (cost index) is assumed to be a surrogate for the cost of doing conservation in a given planning unit. The cost index is a number that Marxan strives to minimize, so when faced with a choice between two planning units of comparable ecological value Marxan will tend to choose the one with lowest cost. The index and the cost of conservation are proportional so that the higher the index, the higher the cost of reducing the intensity. The site selection algorithm will tend to avoid areas that have high cost in favor of lower cost areas of comparable ecological value. This general approach should lead to selection of areas that are more likely to contain viable examples of species and ecological systems. Thus, rather than simply using the number of hectares in each planning unit for the Area component of our MARXAN analyses, we developed a cost model, based on relative levels and intensity of human impacts, specific to terrestrial, freshwater and marine targets.

We grouped human activities into three classes—protected areas that favor biodiversity conservation, and urban and agricultural areas that demand more serious conservation efforts. Urban areas include areas with infrastructure (e.g., dams, canals, wastewater treatment plants, and industries) or paved-over areas, such as roads. Agricultural areas involve areas, where the natural environment has been modified and is being actively managed to produce crops for human consumption. The intensity of urban and agricultural activities was assessed during the June 2003 experts' workshop. The data layers of human activities specific to terrestrial/freshwater areas were overlaid with the corresponding terrestrial/freshwater portfolios to estimate the degree of impact of human activities on individual conservation targets and the cost to capture significant and restorable biodiversity (**Table 3**).

To quantify the intensity of urban and agricultural activities and determine cost for terrestrial planning units, we assumed that urban intensity is reflected in population density and that agricultural intensity is reflected in kilo calories (kcals) of inputs required for the production of different types of crops. Taking into account the idea that the cumulative intensity of human activities is not a linear function, the team used a curve (**Figure 1 a & b**) to generate a function to facilitate the adding of the urban and agricultural costs to achieve a unified cost value per unit area, such as the planning unit defined in the Marxan program. Using the following two functions, Urban function ($y = -0.0157x^3 + 0.1145x^2 + 0.0108x + 0.02$) and Agricultural function ($y = 0.0042x^3 + 0.0179x^2 + 0.0744x + .0007$), the team classified the intensity level into 6 classes for urban activities and 5 classes for agricultural activities, with the higher class number indicating an increment score of intensity level. Terrestrial cost surface is shown by **Map 2**.

A similar approach was used to develop a freshwater cost surface. This was based on a downstream flow accumulation model of human activities that impact freshwater systems, including agriculture intensity, urban area and the presence or absence of dams. The freshwater cost surface is shown by **Map 3**.

Marine cost was derived in a similar manner. A workshop was conducted at the University of Puerto Rico in March '04 to get a better understanding of the degree of influence of key threats (socio economic activities) on each marine target in Puerto Rico. Four major threats were identified: fishing, pollution, urban development and tourism. In order to incorporate this information into our portfolio design we built a cost surface that reflects the cumulative intensity of these four socio-economic activities in marine areas. Conservation of targets within a planning unit that is totally or partially within an existing protected area should be less costly than for those outside of protected areas. Thus, the marine protected areas information was used to lower the cost index for planning units that are partially or totally within protected areas. It follows that planning units within Marine protected areas will be more attractive to the algorithm, everything else being equal. Therefore, although the marine team did not lock in the protected areas, they were incorporated in the analysis and influenced the final marine portfolio through consideration in the cost surface. Marine threat (i.e. cost) surface is shown by **Map 4**.

Terrestrial Conservation Targets and Goals

The occurrence map of 30 coarse-filter conservation targets for Puerto Rico, reviewed by experts during a workshop held in San Juan on June 10-12, 2003, serves as the building blocks for assembling a portfolio of conservation areas. On the basis of current land cover maps of Puerto Rico, including the main island and archipelago (Culebra, Vieques, Mona, Monita and Desecho), Helmer's article (Helmer et al., 2002) on mapping and image interpretation, and advice by Olga Ramos of IITF, we have been able to distinguish the general vegetation condition in its entire distribution range. We ranked the vegetation condition according to the degree of disturbance, using **1** to indicate primary vegetation, **2** to indicate secondary vegetation, and **3** to indicate abandoned pasture lands with vegetation in recovery (**Table 4**).

For the area goals to input into Marxan, mangrove and wetland, the terrestrial team followed the decision of the marine team and freshwater team respectively--65% of the current extent for mangrove and 25% for wetland. For all other terrestrial vegetation targets except for Dry Alluvial and Moist Alluvial, we set the goal of conserving 10 % of the *original extent* of each vegetation type (target) in accordance with TNC's institutional mandate. *Original extent* here refers to the hypothetical vegetation area predicted by geoclimatic model. Geoclimatic regions therefore suggest the potential extent of individual vegetation types defined by climate, geology and unaffected by human interference. For example, conservation and restoration of the Dry Alluvial and Moist Alluvial vegetation types, now existing in scattered fragments, present a formidable challenge. We set 30 % of their current extent as our conservation goals. The Marxan program is set up to select individual vegetation targets, with primary vegetation indicated by "1," secondary vegetation by 2, and abandoned land areas by 3. For example, to reach the conservation goal of 1,000 ha of "Moist Forest", Marxan will first select primary vegetation. If the area of primary vegetation is less than 1,000 ha, the program will add secondary vegetation. If necessary, the Marxan program will add abandoned land areas until the area goal of 1,000 ha is met.

We assumed that most of the species-level biodiversity is captured through vegetation targets. We first ran Marxan using the coarse-filter targets (vegetation) data set. Furthermore the team considered three types of fine filter targets: (1) **nationally rare or threatened species** identified by The Natural Heritage Division of the Department of Natural and Environmental Resources (DNER); (2) **cave communities** (e.g. cave-dwelling bats, amphibians, invertebrates and detritivores) that occur in non-vegetated habitats; and (3) **species groups** (e.g. waterfowl, shorebirds or migratory birds) that depend on ecological processes not covered by vegetation targets. The occurrence map of fine filter targets in addition to the map of coarse filter targets constituted another input data set for a separate Marxan run. Our conservation goal is 10 occurrences for plant targets and 20 occurrences for animal targets. The targets include both critically imperiled and imperiled species with urgent conservation needs, as recognized by IUCN and TNC. Results of the two Marxan runs—one with coarse filter targets and the other with both coarse and fine filter targets—allow us to test the efficiency of conservation areas designed on the basis of coarse filter targets exclusively. It will show us to what degree fine filter targets have been captured.

The input data sets for the Marxan runs including area amount of 30 vegetation targets with condition status (**Table 4**), the number of occurrences of 195 rare or threatened plant species (**Table 5**), 19 bat-dwelling cave communities, 55 rare or threatened animal species (**Table 6**), and the conservation goals of individual targets. For descriptions of individual targets presented in the Marxan portfolio, please see previous report (An Ecoregional Plan for Puerto Rico: Preliminary Results; July 2003) for more details on target mapping and key ecological factor assessment.

Freshwater Conservation Targets and Goals

We used two different types of freshwater targets: 1) Aquatic Ecological Systems (coarse-filter) which are spatial units that ensures the conservation of rare and endemic species as well as those common and widespread and 2) species level (fine filter target), which are represented by single species or species assemblages.
Different habitat types represent "coarse filter targets" as they should capture the range of biological diversity and systems, as well as the natural processes that sustain them. A detailed analysis of all potential aquatic habitats allowed the elaboration of a list with

those relevant and distinctive habitats for Freshwater Biodiversity (**Table 7**). Although some of them may be divisible in smaller units, because of their physical and/or chemical characteristics, they may not represent real pattern of natural stratification of the biota. For a detailed analysis at the species or species assemblage level is necessary to developed the appropriate data that allow an inform decision to group or separate them. Species distribution is now under study base on Museums records and expert opinion. A detailed map of fishes and some key macro-invertebrates present in each watershed will provide the relevant information to review some of the coarse filter targets and provide the scientific rationale that will support future changes.

Experts selected the freshwater conservation targets in a two-day workshop held in Puerto Rico. The experts received a list of potential conservation targets present in the Caribbean Ecoregions and selected those in the EDUs described for Puerto Rico (**Map 1**). In addition, experts reviewed a list of key ecological factors, chose those relevant to the selected conservation targets and ranked them for their importance in maintaining functional ecological health. Experts also helped with a spatial definition of each conservation target enabling a map of target occurrences to be prepared. For descriptions of individual targets presented in the Marxan portfolio, please see previous report (An Ecoregional Plan for Puerto Rico: Preliminary Results; July 2003) for more details on target mapping and key ecological factor assessment.

The freshwater team developed and mapped five ecological drainage units (EDU) to capture geographic scale spatial variation in the freshwater biodiversity of Puerto Rico (**Map 1**). An EDU is a group of watersheds with similar biogeographic histories, topographic patterns, drainage density, hydrologic characteristics, and connectivity. Because of these similarities EDUs are likely to have a set of freshwater communities and habitats distinct from other EDUs. Stratifying the choice of conservation targets by EDUs captures geographic variation in freshwater biodiversity. Using the EDU map, the team identified a comprehensive suite of freshwater biodiversity conservation targets during a two-day workshop (San Juan, Puerto Rico 11-12 June 2003). Within each EDU, different habitat types are identified and selected as conservation targets by the group of experts and the freshwater team. The different habitat types represent coarse-filter targets (**Table 7**) because their scales are expected to capture the range of biological diversity and systems, as well as the natural processes that sustain them.

Marine Conservation Targets and Goals

Because of differing ecological factors and available data sets, marine conservation goals were set using different criteria. In the absence of historical distribution information of conservation targets the marine team defined a range of conservation goals from 30% to 100% of their current distribution. Participants at the Vth IUCN World Parks Congress in Durban South Africa (2003) called on the international community as a whole to include 20 to 30% of each habitat in strictly protected areas. Although no assumptions have been made regarding the choice of protection strategy that will be advocated for the portfolio sites, the Puerto Rico planning effort adopted the upper end of the range, 30%, as the minimum level of representation for marine targets in this ecoregional plan. The decision to assign conservation goals to specific targets was based on scoring the ranks of 5 criteria that reflect important ecological characteristics of the conservation targets:

1. **Source** – whether or not the target is a source of larvae that can seed other areas. Source areas are extremely important and usually refer to whether the target represents a critical life stage of one or more organisms. In the case of Puerto Rico, nesting and roosting areas for Pelicans; spawning aggregations; manatee calf areas and Fringing Mangroves all represent key areas for spawning and/or nursery grounds. Independent of any other consideration Source areas should be represented at a high level in the Portfolio, and therefore conservation targets considered sources received a score of '3', while the remainder received a score of '1'.
2. **Rare** – whether or not the target is rare for Puerto Rico. Independent of all other consideration rare targets should be represented at a high level within the portfolios. Each target was ranked in relation to whether it was Rare or not. If it was considered rare it would receive a score of 3. If it was not rare it would receive a score of 1.

3. **Coarse filter** – whether or not the target represents a number of different species and ecosystem processes. Independent of everything else a coarse filter target has greater ecological value than a single species or taxa. Thus a coarse filter target would receive a score of 3, while a fine filter target would receive a score of 1.
4. **Vulnerability** – How vulnerable is the target to socio economic activities. This information was derived from expert opinion (see assessing threats section). We made the judgment that independent of everything else, a highly vulnerable target should be represented at a higher level. (Resilience principle)
5. **Current Status** - Experts produced a ranking of the overall current status of the key ecological factors for all conservation targets at the Puerto Rico scale. This was based on a scale from Very good, good, fair and poor (see Viability section). Expert opinion on the current status includes perception of how much a given target has deteriorated in relation to historical abundance. Independent of everything else a target that is in worse condition requires extra conservation help. Thus a poor ranking would get a score of 3, a fair gets a score of 2 while a good/very good ranking would get a score of 1. We grouped very good and good into one category for purposes of maintaining a consistent scale among goal selection criteria.

A frequency distribution analysis suggests divisions in the range of scores (**Figure 2**). Anything below the median (score 6 and lower) would be assigned the lowest representation goal of 30%. All conservation targets that scored 7, 8 or 9 warranted higher representation but not necessarily total representation. 100% representation goals were assigned to targets that scored 10 and 11, which were sources, rare, vulnerable, and fair or poor current condition. Resulting conservation goal assignments are illustrated in **table 8**.

RESULTS

The portfolio for Puerto Rico, including the main island, Vieques, Culebra, and Mona, was assembled using Marxan (Ball and Possingham, 2000). Marxan allowed us to enter information, based on planning units, about the distribution of our targets, the location of protected areas, and the location of various human activities. Using this information and the representation goals for all the conservation targets outlined by the freshwater, terrestrial, and marine teams, Marxan computes the optimal portfolio design by selecting the necessary hexagons to meet our goals using the least cost and number of planning units possible.

The optimal portfolio for freshwater conservation locked in protected areas and used a clustering factor (boundary length modifier of 0.0005) to encourage the clumping of conservation areas. The cost surface incorporated the impacts of agriculture, agriculture intensity, urban areas, roads, population density, and industry, and accumulated these costs based on a flow accumulation model, such that downstream areas accumulated the impact of upstream areas. This cost surface also gave dams a relatively high weight. The best solution incorporates 442 planning units (114,920 ha total) into the freshwater portfolio. The optimal terrestrial portfolio also locked in the current protected area system, used a clustering factor (boundary length modifier of 0.0005) and used a cost surface, but did not incorporate dams and did not use the flow accumulation model. The optimal portfolio included 651 planning units (169,260 ha). When we overlaid the two portfolios there were 225 planning units that were selected for both realms, so the final portfolio resulted in 868 planning units (225,680 ha).

The optimal portfolio for marine conservation was built with slightly different parameters for the freshwater and terrestrial realms. The large extent of the existing Marine Protected Areas can exert an inordinate influence on the portfolio if they are locked into the analysis. Following expert advice, the marine team did not lock-in the protected areas opting to include the protected area information in a cost surface along with the human activities. The final portfolio consisted of 412 planning units, or a total area of 107,120 hectares that contained enough of the distribution of all the marine targets to fully meet their representation goals.

In addition to producing the optimal solution, Marxan also generates a value equivalent to the irreplaceability of each planning unit. Irreplaceability measures the importance of a planning unit to achieving the target goals efficiently, because the biodiversity captured in that planning unit is unlikely to be captured elsewhere (Margules and Pressey, 2000). To derive the optimal solution for a given set of parameters, we had Marxan do 200 runs for a given scenario. The optimal solution is the set of planning units that is the least cost. However, the program also calculates the number of times that a planning unit was selected in each of the 200 runs, which became our measure of irreplaceability (this is similar in concept, but different in calculation to Margueles and Pressey, 2000). If a planning unit was selected during all 200 runs, then it contains biodiversity that cannot be found elsewhere (or, in the case of protected areas, the planning unit was locked in). Map 5 - 7 shows the irreplaceability results for the terrestrial, freshwater, and combined portfolio, and Map 8 shows irrepleceability for the marine portfolio.

DISCUSSION

Despite the few remaining intact habitats, intensive urban development, rivers canalization, damming, industrial scale tourism and agricultural development, there remains a positive future for conservation of biodiversity in Puerto Rico. We identify here a suite of remaining biodiversity targets and provide a quantitative method assembling these targets into conservation portfolios and provide tools to assess the relative human impacts throughout the island. Data and tools yielded during this research support the development of a state-of-the-art conservation blueprint, enabling sound, pragmatic conservation decisions.

Emerging from this analysis will be strategies for conservation and restoration; for example, we have begun to identify some freshwater systems that remain relatively intact and places where river connectivity may be restored, particularly in the headwaters. Further socio-economic analyses and interactions with local agencies and conservation organizations will enhance this kind of insight into conservation opportunities.

In addition, the completed database will be an impartial source of information that can be used by disparate stakeholders for conflict resolution and collaboration conservation work depending on user needs and values. In this way, the study will also support the development of strategic partnerships with local organizations — a key to achieving lasting results. Future work needed includes training and technical follow-up with local agencies and organizations.

We hope this effort will be a significant contribution towards protecting the region's irreplaceable terrestrial, freshwater, coastal and marine biodiversity and we believe that we have provided many of the technical tools and data necessary to achieve a long-term and sustainable future for Puerto Rico's biota.

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