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Cover Photograph: View from within El Yunque National Forest, one of the jewels in the network of protected areas in Puerto Rico. Photograph © Karla M. Morales.

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Characterization of the Network of Protected Areas in Puerto Rico

Jessica Castro-Prieto[1,*], Maya Quiñones[2], and William A. Gould[2]

Abstract - Our goal was to describe the biodiversity and associated landscape diversity and forest cover characteristics within the network of terrestrial protected areas in Puerto Rico. We conducted spatial analysis to quantify different indicators of diversity at these sites. We found that protected areas in Puerto Rico overlap the most species-rich regions on the island, encompass a diverse landscape, are dominated by core forest, and include predicted habitats for 31 threatened vertebrate species analyzed here. However, when we calculated the proportion of the biodiversity features that are actually protected, we concluded that most of them need better representation within protected areas. Other available conservation mechanisms that enhance biodiversity conservation could be employed in addition to expanding the current network of protected areas.

Introduction

The establishment of protected areas is the most frequently employed strategy to promote in situ biodiversity by conserving natural habitat, preventing its conversion to other uses, and reducing anthropogenic threats (Beale et al. 2013, Chape et al. 2005, Joppa et al. 2008). Hence, over the past 20 years, protected lands have increased in area; they currently occupy 15% of the global land surface and 3.4% of the oceans (Juffe-Bignoli et al. 2014).

Quantifying the extent of protected areas (Jenkins and Joppa 2009) represents the most-used indicator to track international progress towards achieving UN Millennium Development Goals for 2020 through its Aichi Biodiversity Target 11 that seeks to protect 17% of terrestrial areas and 10 percent of nationally administered marine areas (http://www.cbd.int/sp/targets/). However, simply increasing the extent of protected areas may not be effective in achieving conservation goals (Chape et al. 2005).

To address this global concern, recent studies have provided assessments that quantified the ecological performance of a large network of protected areas (Butchart et al. 2015, Cantú-Salazar and Gaston 2010, Craigie et al. 2010, Gaston et al. 2008, Joppa and Pfaff 2011) and evaluated their role in reducing land-cover change and deforestation (Andam et al. 2008, Bruner et al. 2001). In addition, several tools have been developed to assess management effectiveness in protected areas (PAME), including the rapid assessment and prioritization of protected areas management (RAPPAM) and the management effectiveness tracking tool (METT) (Leverington et al. 2010).

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Protected areas in the insular Caribbean occupy approximately 11–15% (25,804 km^2–36,000 km^2) of the land surface (Chape et al. 2008). These protected sites were established to safeguard what is considered to be one of the 35 global biodiversity hotspots, which were designated because of their high species-richness, endemism, and level of threat (Myers et al. 2000). The Caribbean is home to ~ 14,526 plant and terrestrial vertebrate species, half of which are endemic to the region (Conservation International 2015), and 912 are reported as threatened in the Red List of the International Union for Conservation of Nature (IUCN 2014). Caribbean islands are particularly vulnerable to extreme weather events, including hurricanes, tropical storms, and projected rising sea levels due to climate change, which could threaten the region's ecosystems and biodiversity. In addition, approximately 43 million people inhabit these islands (World Bank 2015), and urban areas are expanding on many of them (Stein et al. 2014). Due to the relatively higher vulnerability faced by species and natural ecosystems on islands compared to continents (Simberloff 2000), a clear understanding of the current effectiveness of protected areas in promoting biodiversity conservation in the region would be useful. This information is fundamental to identify conservation gaps and plan strategies to increase the protection of fragile ecosystems and vulnerable species in the Caribbean.

We sought to describe the biodiversity within the terrestrial network of protected areas in Puerto Rico. To achieve this goal, we quantified the landscape diversity inside protected areas because this variable is positively correlated with habitat diversity and niche availability (Diacon-Bolli et al. 2012, Kumar et al. 2006). In addition, we analyzed forest structure in protected areas to estimate forest quality (Turner 2005)—a variable very relevant to this study because forests are the main habitat for most terrestrial species in Puerto Rico (Gould et al. 2007). For example, gaps or perforations in forest cover (Table 1) indicate habitat fragmentation which would affect biodiversity conservation (Krauss et al. 2010). We also determined the proportion of high and very high species-richness areas, predicted habitats for threatened species under protection in Puerto Rico, and calculated how much of the critical wildlife areas (CWAs) and important bird and biodiversity areas (IBAs) are inside the current network of protected areas. CWAs were mapped by the Puerto Rico Department of Natural and Environmental Resources and represent important compendiums of species and habitats of concern (Ventosa-Febles et al. 2005). BirdLife International (www.birdlife.org) has identified IBAs throughout the world. These areas include sites of international significance for biodiversity conservation, particularly endangered, endemic, and migratory birds. Species richness, CWA, and IBA layers used in this study represent the most up-to-date biodiversity maps currently available for Puerto Rico.

Our study updates information first reported by the Puerto Rico Gap Analysis Project (Gould et al. 2007) to identify key biodiversity areas inside and outside the current network of protected areas in Puerto Rico, the starting point for conservation planning at the landscape level.

Methods

Study area

Puerto Rico, ~8900 km^2 in area, is located in the Caribbean Archipelago. The island has a tropical climate, with mean annual precipitation ranging between 500 mm and 4400 mm, and a mean annual temperature between 19.4 °C and 29.7 °C (Daly et al. 2003). Puerto Rico has a complex geomorphology and soils represented by alluvial, volcanic, sedimentary, limestone, and serpentine substrates, and a steep topography that includes coastal plains, cliffs, hills, and mountains up to 1300 m in elevation. At a coarse scale, land cover in Puerto Rico is 39% forest, 32% grassland, 13% woodland and shrubland, 11% urban, 3% herbaceous wetlands, 1% forested wetlands, 1% inland water, and less than 1% natural barrens (Gould et al. 2007). Puerto Rico's terrestrial biodiversity encompasses at least 2780 species of plants (Joglar 2008) and 361 native vertebrates including 277 birds, 52 reptiles, 19 amphibians, and 13 mammals (Joglar 2005, Joglar et al. 2007).

Protected-areas data

In this study, we analyzed a total of 95 protected areas that represent 8.2% (735.6 km^2) of the island's land surface and associated cays (Gould et al. 2011). Protected areas in Puerto Rico have a mean size of 7.5 km^2 (range = <0.1 km^2–114.0 km^2, median = 2 km^2). Eighty-one protected areas are smaller than 10 km^2, and 40 of these are smaller than 1 km^2 (Fig. 1). The Puerto Rico Department of Natural and Environmental Resources (DNER) manages or co-manages ~58%

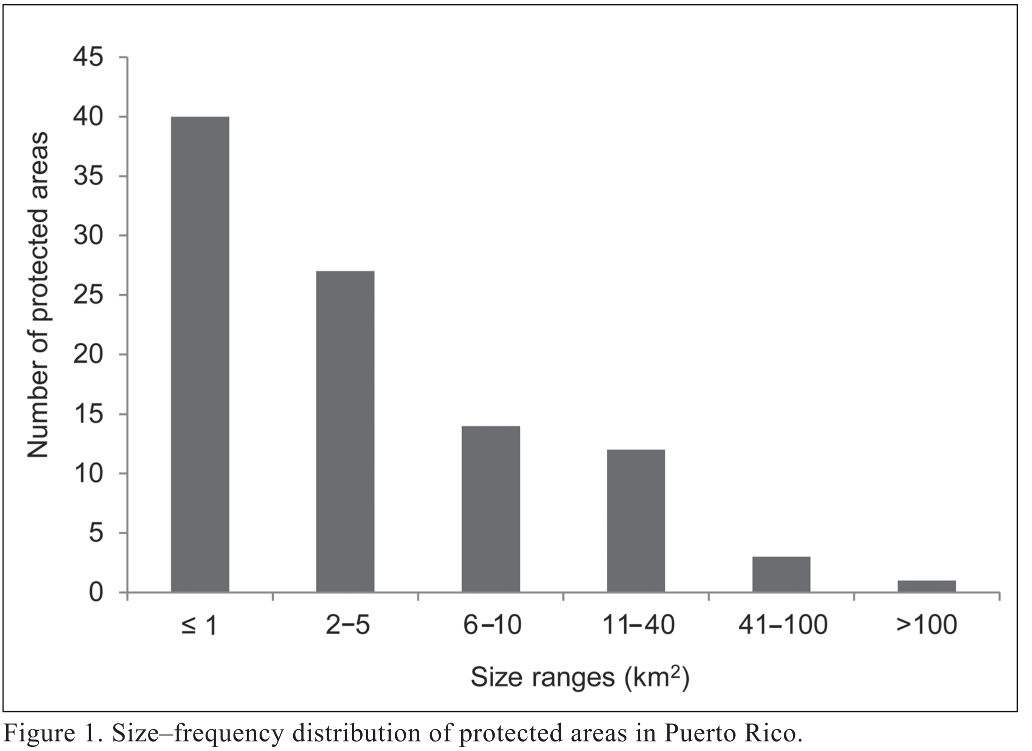

Figure 1. Size–frequency distribution of protected areas in Puerto Rico.

(425.7 km^2) of the protected areas, the federal government (US Forest Service and US Fish and Wildlife Service) ~28% (206.5 km^2), the non-governmental organization Para La Naturaleza ~13% (98.25 km^2), and other institutions about 1% (Quiñones et al. 2013).

Habitat characteristics

Landscape diversity. We quantified landscape diversity in protected areas according to vegetation cover and ecological life zones (ELZs). The Holdridge ecological life-zone classification (ELZ) provides information about vegetation based on climatic, latitudinal, and elevation features (Ewel and Whitmore 1973). In Puerto Rico, there are 6 ELZs: subtropical rainforest, subtropical dry forest, subtropical wet forest, subtropical moist forest, subtropical lower montane wet forest, and subtropical lower montane rainforest (Ewel and Whitmore 1973). We used the land-cover 2000 map generated by the Puerto Rico gap analysis (Gould et al. 2007). This map was derived from Landsat ETM+ satellite images with a spatial resolution of 15 m x 15 m, resulting in 70 land-cover classes (Gould et al. 2007). For our analysis, we selected a subset of 56 vegetation classes that included all vegetation forms, and excluded human-created and non-vegetated covers (e.g., developed, rocky cliffs). We used the Shannon diversity index (H) to calculate the landscape diversity for each landscape feature. This index takes into account both the number of species (analogous to vegetation covers or ELZs), and their relative abundances (evenness or equitability) (Nagendra 2002). It is calculated with the equation

$$H = -SUM\,[(p_i)^*\, ln\,(p_i)],$$

where p_i is the relative abundance (or proportion) of different vegetation-cover classes or ELZs (S) inside each protected area. A value of $H = 0$ represents the lowest landscape diversity, and values ≥1 represent a landscape with high diversity. For both landscape features, we classified the landscape diversity in 5 categories: very low (0 ≤ 0.29), low (0.30–0.59), intermediate (0.60–0.89), high (0.90–1.19), and very high (≥1.20).

Forest configuration. We conducted a morphological spatial-pattern analysis (MSPA) to quantify the amount and configuration of the forests in protected areas. The MSPA classifies a raster binary image (e.g., forest vs. non-forest) into 7 classes according to the arrangements of its pixels: core, bridges, islets, loops, edges, perforations, and branches (Table 1; Vogt et al. 2007a, b). We developed the raster binary image (forest vs. non-forest) using a simplified version of the 2000 PRGAP land-cover map that classifies the island into 8 classes (i.e., forests, woodland and shrubland, grasslands, forested wetlands, herbaceous wetlands, inland water, natural barrens, and built-up surface; Gould et al. 2008). For our analysis, we reclassified all woody vegetation (i.e., forests, forested wetlands, woodlands and shrublands) as foreground (= 2), all other vegetation types as background (= 1), and created a missing data category (= 0) for all remaining classes. The MSPA only describes forest pixels in the foreground.

Vertebrate diversity

Species richness. We used the predicted species-richness distribution maps generated by the PRGAP for 201 species of terrestrial vertebrates (Gould et al. 2008). The PRGAP modeled predicted distributions by combining all major habitat elements considered to influence the occurrence of a species across its range and intersecting occurrence records for the species. For example, they identified habitat features (e.g., elevation, vegetation type) important for each species on topographic and land-cover maps at 15-m spatial resolution and then overlaid the species-occurrence records defined within 24-km^2 hexagons (Gould et al. 2008). These hexagons represented the minimum mapping unit for interpreting species' geographic range extent. They extracted habitat features from the literature and species-occurrence records from long-term surveys, reports, and publications. Experts reviewed all data and final distribution maps used for modeling (Gould et al. 2008). The total number of species modeled to occur in each 15-m pixel indicated species richness. They generated predicted distribution maps for 97 resident bird, 25 migratory bird, 47 reptile, 18 amphibian, and 14 mammal species, of which 187 (93%) were native and 14 (7%) were exotics. We used natural breaks to group the geospatial layer of species richness into 5 categories: very low (0–16 species), low (17–34 species), intermediate (35–47 species), high (48–59 species), and very high (60–90 species).

Table 1. Morphological spatial-pattern analysis classes, with description and explanation of the potential contribution of each class in conservation planning (P. Vogt, Institute for Environment and Sustainability, Ispera, Italy, pers. comm).

Class	Description	Relevance for planning
Core	Forest pixels whose distance to non-forest pixels is greater than the given edge-width (1 pixel = 15 m)	Focus class for biodiversity conservation, least fragmented.
Bridge	Set of contiguous non-core forest pixels that connect at least 2 different cores	Structural connectors or corridors that could potentially be used by some species to move across the landscape
Edge	Outer core-boundary	Some species prefer to dwell in the foreground/background interface.
Perforation	Similar to edges, but corresponding to the inner boundary of the core area	Perforations inside core habitat are a sign of fragmentation.
Loop	Similar to bridges but ends are connected to the same core area	Informs about connectivity.
Islet	Isolated forest patches that are too small to contain core pixels	May be the result of forest loss, but may also be important as stepping stones between cores. Focus class for restoration.
Branch	Pixels that do not correspond to any of the previous 6 categories	May be the result of a bridge or corridor getting interrupted, or if it continues growing it may provide connectivity. Focus class for restoration.

Finally, we calculated the representation of each species–richness category in protected areas, with particular interest in high and very high species-richness regions.

Predicted habitats for threatened species. Using the predicted species-richness distribution maps, we calculated the percentage of predicted habitat currently under protection for 31 threatened species—12 birds, 9 reptiles, 7 amphibians, and 3 mammals. Twenty of these species are endemic and 11 are non-endemic but native to Puerto Rico. Native or indigenous refers to species that occur in an area naturally without human intervention (Manchester and Bullock 2000).

Critical wildlife areas (*CWAs*) *and important bird and biodiversity areas* (*IBAs*). The CWAs in Puerto Rico were identified according to faunal composition and abundance, with emphasis on endangered and/or endemic species occurrence, presence of critical habitat, and level of threat on habitats and species (Ventosa-Febles et al. 2005). The CWAs occupy ~1120.95 km^2 (853.13 km^2 terrestrial, 267.82 km^2 marine) of Puerto Rico's main island, associated cays, and surrounding water. IBAs have been identified in Puerto Rico according to the distribution of 55 key bird-species that include endangered, vulnerable, near-threatened species, birds with restricted ranges, and avian species that aggregate in flocks (BirdLife International 2015). Puerto Rico has a total of 20 IBAs that occupy ~1971.86 km^2 of the island (1434.61 km^2 land, 537.24 km^2 marine; Anadón-Irizarry et al. 2009). We calculated the proportion of terrestrial CWAs and IBAs in protected areas.

Results

Landscape diversity

Landscape-diversity indices derived from vegetation-cover classes ranged from very low to very high (0–2.19, mean = 1.14, median = 1.14); forty-four protected areas (46.3%) had a very high landscape diversity, 26 (24.7%) a high landscape diversity, 11(10.4%) intermediate, 8 (7.6%) low, and 6 (5.7%) very low (Fig. 2). Diversity indices based on ELZs ranged from very low to intermediate (0–0.70, mean = 0.09, median = 0). When we used ELZs as a metric, 90 of 95 protected areas had low and very-low landscape diversity (Fig. 2).

Forest configuration

Forests classified as core occupied an area of 3412.96 km^2 in Puerto Rico (Fig. 3). Almost 16% (543.74 km^2) of this core forest was in protected areas (Table 2). Core forest was the most abundant class in protected areas and accounted for 91.74% of the total forest area protected; edge and perforation were the second- and third-most abundant classes (Table 2).

Species richness

The predicted species richness in protected areas ranged from very low to very high. The very high and high species-richness regions in Puerto Rico occupied ~1200 km^2, and 2270 km^2, respectively. The network of protected areas captured 10.55% (126.55 km^2) of the very high and 13.19% (299.34 km^2) of the high species-richness regions on the island (Fig. 4 A, B).

Threatened species, CWAs, and IBAs

The total predicted habitat for 31 threatened species in Puerto Rico occupied an area of 4.85 km^2, 1.43 km^2 (29.5%) of which occurs within a protected area.

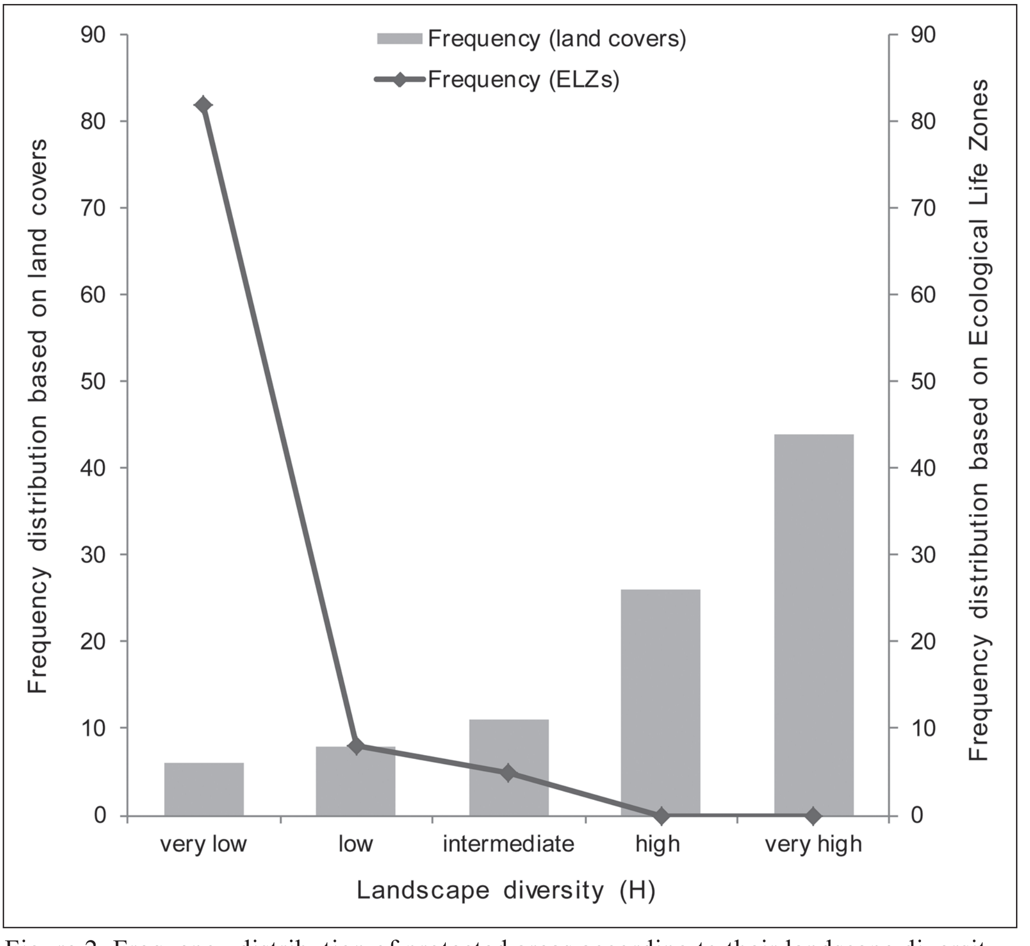

Figure 2. Frequency distribution of protected areas according to their landscape diversity.

Table 2. The extent and relative abundance of forest classes in protected areas and islandwide, and the overall proportion of protection for each class.

	Inside protected areas		Island-wide		
Forest class	Area (km^2)	Relative abundance (%)	Area (km^2)	Relative abundance (%)	In protected areas (%)
Core	543.74	91.74	3412.96	72.25	15.93
Edge	22.11	3.73	569.46	12.06	3.88
Perforation	14.44	2.44	276.98	5.86	5.21
Branch	4.32	0.73	182.00	3.85	2.37
Loop	3.96	0.67	100.77	2.13	3.93
Bridge	2.82	0.48	115.50	2.45	2.44
Islet	1.32	0.22	65.92	1.40	2.00
Total	592.71	100.00	4723.58	100.00	35.78

The proportion of predicted habitat under protection for individual species ranged from 0% to 100% (mean = 47%) (Table 3). For 5 critically endangered species, 5 endangered, and 10 vulnerable species, ≤50% of their predicted habitat is protected (Table 3). In addition, we found a negative correlation between species' island-wide distribution and percentage of habitat protected (r_s = -0.56, $P < 0.001$). Sixty-eight percent (591.9 km^2) and 41% (590.7 km^2) of the terrestrial component of CWAs and IBAs, respectively, occur in protected areas (Fig. 5).

Discussion

Eighty-two percent of the protected areas in Puerto Rico are smaller than10 km^2, an area generally considered to be too small to maintain viable populations and to buffer anthropogenic threats from outside (Cantú-Salazar and Gaston 2010). However, our results on landscape diversity indicated that the small size of protected areas in Puerto Rico is not necessarily a determinant of the biodiversity it encompasses. According to the diversity index used here, 70% of the protected areas in

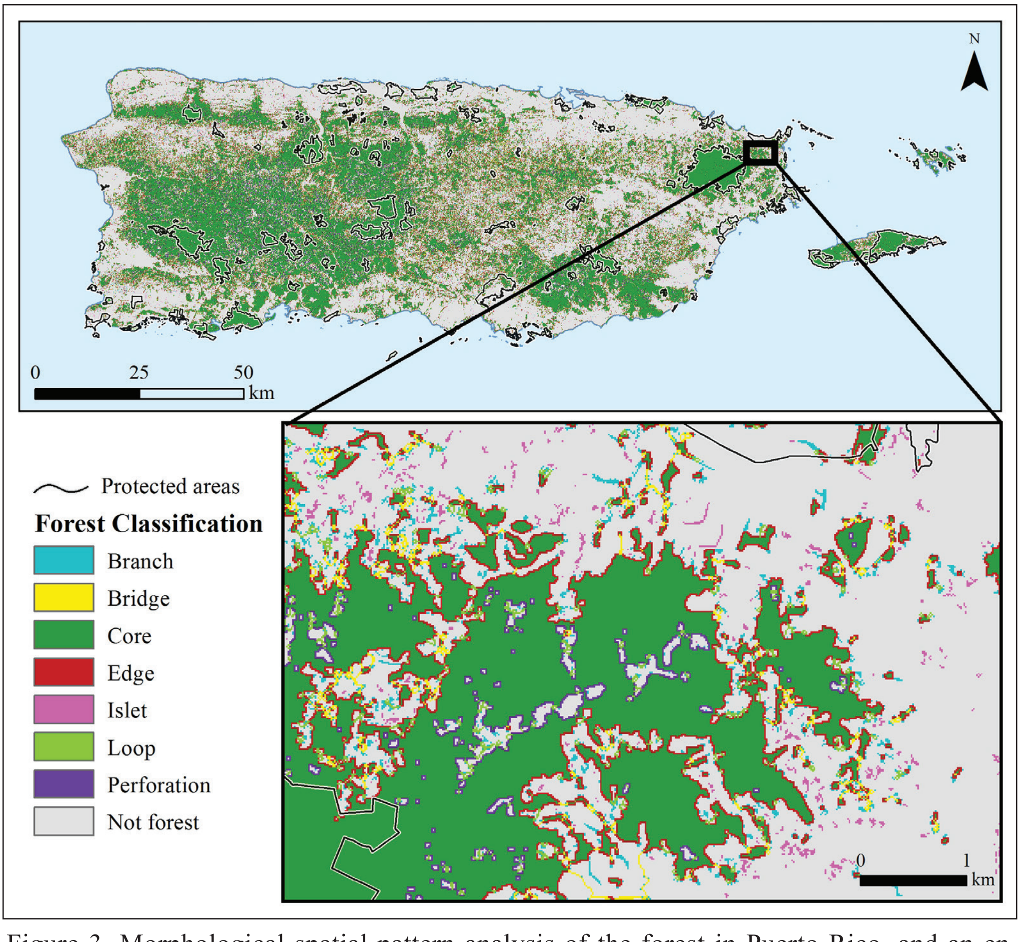

Figure 3. Morphological spatial-pattern analysis of the forest in Puerto Rico, and an enlarged sub-region in the northeast to show detailed interpretation of forest classes.

Puerto Rico encompass high and very high landscape diversity associated with an expected high diversity of habitats and species. We suggest that this index could be used as an indicator of biodiversity in small tropical islands in the Caribbean with similar geology, ecology, and land-use history.

However, we identified 2 main limitations of this diversity index for use as an indicator of biodiversity in protected areas. First, it is important to have a good

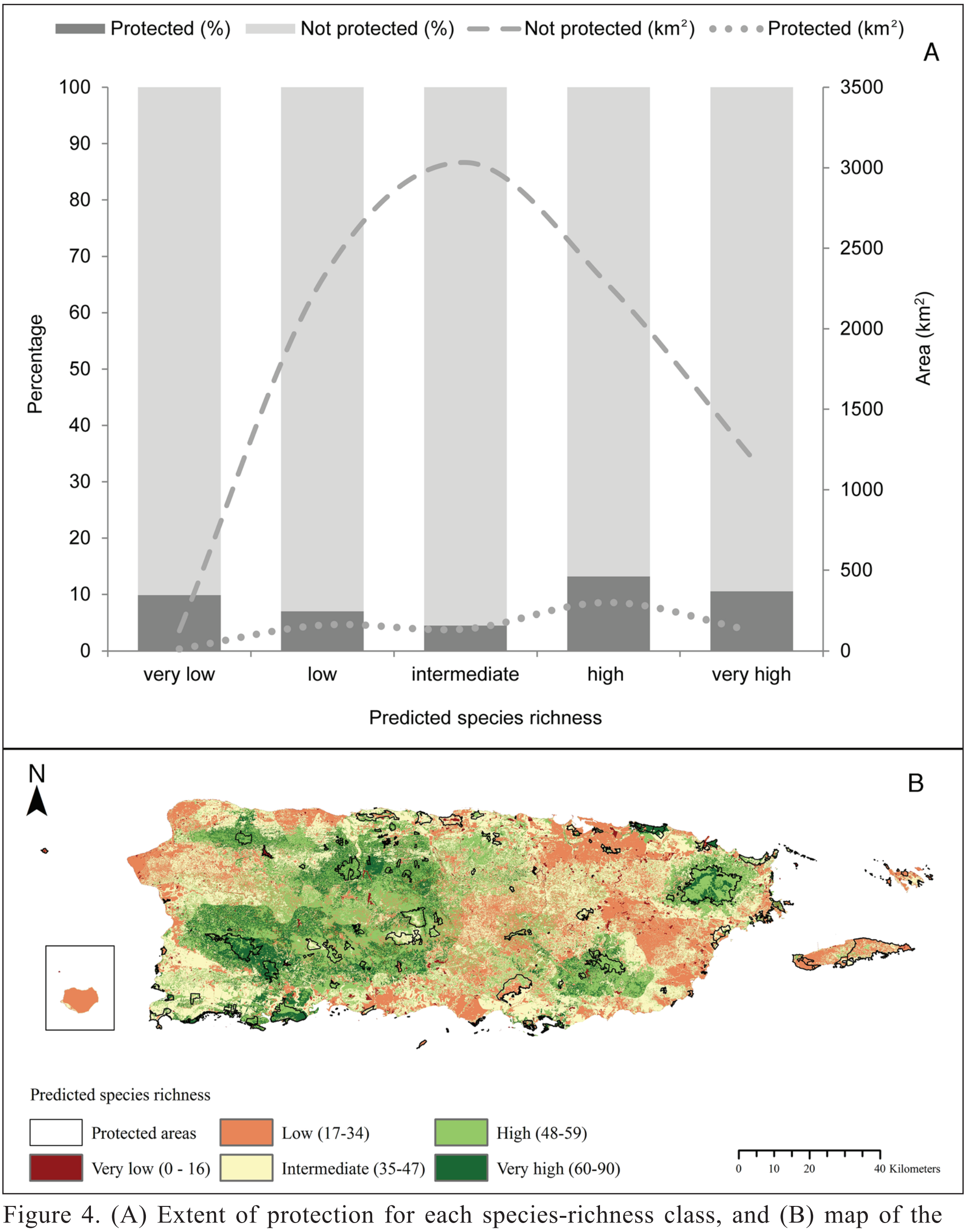

Figure 4. (A) Extent of protection for each species-richness class, and (B) map of the predicted species richness in Puerto Rico.

Table 3. Total overall and percentage protected of predicted habitat for 31 threatened species in Puerto Rico. Information on the legal and conservation status of each species is also described. V = vulnerable, CE = critically endangered, and E = endangered.

Species name	Group	Island-wide habitat area (m^2)	Protected habitat (%)	US Endangered Species Act status	Distribution class and conservation status
Eleutherodactylus cooki Grant	A	9000	0	Threatened	Endemic, V
Eleutherodactylus eneidae Rivero	A	31,275	64	Not Listed	Endemic, CE
Eleutherodactylus jasperi Drewry & Jones	A	6075	22	Threatened	Endemic, CE
Eleutherodactylus locustus Schmidt	A	1350	83	Not Listed	Endemic, V
Eleutherodactylus portoricensis Schmidt	A	21,825	61	Not Listed	Endemic, V
Eleutherodactylus richmondi Stejneger	A	37,575	54	Not Listed	Endemic, V
Peltophyrne lemur Cope	A	3600	69	Threatened	Endemic, CE
Accipiter striatus venator Wetmore	B	63,675	45	Endangered	Native, CE
Agelaius xanthomus (Sclater)	B	98,1225	25	Endangered	Endemic, E
Amazona vittata (Boddaert)	B	5625	24	Endangered	Endemic, CE
Anas bahamensis L.	B	78,300	58	Not Listed	Native, V
Buteo platypterus brunnescens Danforth & Smyth)	B	22,1850	25	Endangered	Endemic, CE
Caprimulgus noctitherus (Wetmore)	B	158,850	24	Endangered	Endemic, E
Dendrocygna arborea (L.)	B	178,425	50	Endangered	Native, CE
Fulica caribaea Ridgway	B	24,975	26	Not Listed	Native, V
Oxyura jamaicensis (Gmelin)	B	115,875	49	Not Listed	Native, V
Patagioenas inornata (Vigors)	B	390,600	24	Endangered	Native, E
Pelecanus occidentalis L.	B	645,075	38	Endangered	Native, E
Setophaga angelae Kepler & Parkes	B	66,600	40	Not Listed	Endemic, V
Erophylla sezekorni (Gundlach)	M	144,900	31	Not Listed	Native, V
Brachyphylla cavernarum Gray	M	73,125	34	Not Listed	Native, V
Monophyllus redmani portoricensis Miller	M	164,925	34	Not Listed	Endemic, V
Chilabothrus inornatus (Reinhardt)	R	882,225	17	Endangered	Endemic, V
Chilabothrus monensis granti (Stull)	R	8775	77	Endangered	Native, CE
Chilabothrus monensis monensis (Zenneck)	R	900	100	Endangered	Endemic, V
Ctenonotus cooki Grant	R	52,875	44	Not Listed	Endemic, E
Ctenonotus poncensis Stejneger	R	16,7850	30	Not Listed	Endemic, V
Cyclura cornuta stejnegeri Barbour and Noble	R	900	100	Threatened	Endemic, E
Mabuya mabouya sloanei (Daudin)	R	303,975	25	Not Listed	Native, V
Sphaerodactylus micropithecus Schwartz	R	450	100	Endangered	Endemic, CE
Xiphosurus roosevelti Grant	R	14,625	86	Endangered	Endemic, CE

understanding of the scale of the landscape features selected to calculate the index. For example, our results suggest high biodiversity for 1 landscape feature (vegetation cover) despite a finding of low landscape-diversity for another (ELZs). An explanation for this contradictory result is the larger extent of ELZs in comparison to land-cover data and the size of most protected areas on the island. Second, the assumed generality of a positive relationship between landscape diversity and species biodiversity should be locally tested because biodiversity might depend on attributes other than landscape diversity. For example, one study conducted in Japan found that bird species whose geographic distribution is small were most diverse in less-diverse landscapes (Katayama et al 2014).

We found that existing protected areas conserve the predicted habitats for all but 1 threatened species modeled by PRGAP. However, predicted habitats here rely on occurrence records that only provide information about the probability that a species occurs or not in a particular location. Hence, more complex studies are needed to understand if species are being successfully protected not only in terms of their presence/absence, but also according to attributes of species conservation assessed at the population level including: population viability, ecological functionality, genetic robustness, health, representativeness in terms of its current and historical range, and resiliency (Redford et al. 2011). We found that protected areas encompassed similar proportions of the regions with very high and very low species richness, which indicates the importance of understanding landscape variation in biodiversity and a landscape design approach to maximize biodiversity conservation in prioritizing new areas to protect.

In general, unprotected regions with high species-richness, and that are CWAs or IBAs occurred in lands adjacent to existing protected areas (Fig. 5) where protected areas are portions of larger regions with similar ecological characteristics such as the karst region in the north of the island. These unprotected sites

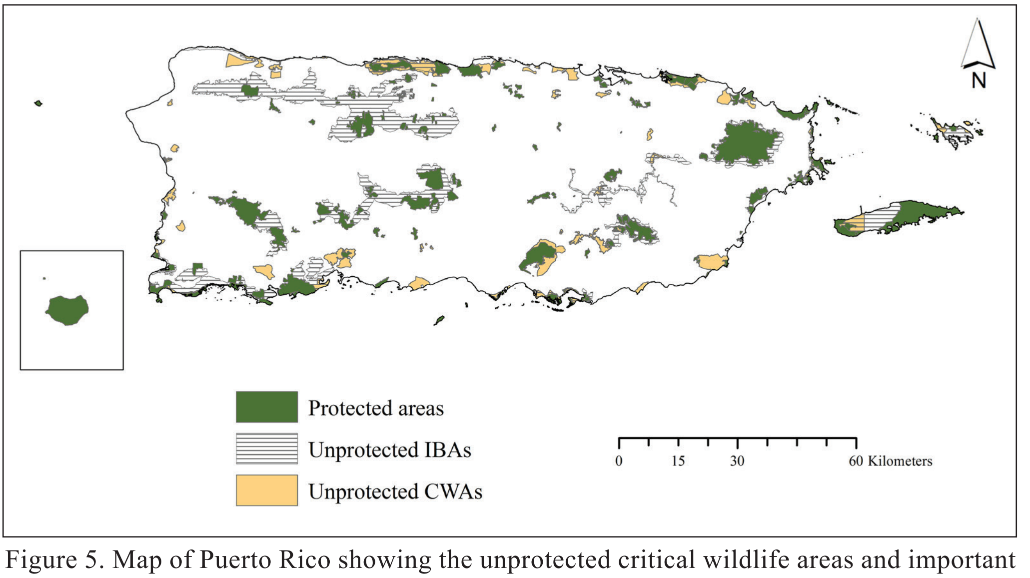

Figure 5. Map of Puerto Rico showing the unprotected critical wildlife areas and important bird and biodiversity areas.

would be affected by future land development, which have been characterized by extensive urban sprawl over the previous several decades (Martinuzzi et al. 2008) even in non-urban zoning districts (López-Marrero and Hermansen-Báez 2011). In general, land development on the island has been occurring in the lowlands, near roads, close to existing urban areas, and in ecological zones with the least amount of protection (Helmer 2004, Helmer et al. 2008, Keenaway and Helmer 2007). Although the human population has been declining in Puerto Rico during the last decade (US Census Bureau 2015), there is a continuing need to integrate conservation in land-use planning as new housing units, roads, and other developments keep expanding on the island.

Conclusion and Recommendations

Protected areas in Puerto Rico are effective in conserving species because they are located within the most species-rich regions on the island and because they include sites classified as CWAs or IBAs. Additionally, they encompass diverse landscapes, are dominated by core forest, and include predicted habitats for 31 threatened vertebrate species analyzed here. However, when we calculated the proportion of these biodiversity features that are actually protected, we concluded that most of these features need better representation within the current network of protected areas.

In addition to expanding the current network of protected areas, biodiversity conservation within Puerto Rico could be enhanced through enforcement and promotion of existing conservation mechanisms, including implementation of an island-wide land-use plan (Junta de Planificación 2014), better communication of actions required to mitigate land development (e.g., land acquisition and transference to the DNER), and an improved designation of critical habitats under the Endangered Species Act. In the case of El Yunque National Forest, the largest protected area in Puerto Rico, better interagency collaboration in planning and enforcement of conservation regulations in the surrounding lands would improve conservation of biodiversity and ecosystem services both within and outside the national forest. Studies show that promoting forested coverage beyond the administrative boundary of a protected area increases the effective size of the area conserved and its capacity to conserve viable populations, species richness, and ecosystem services (DeFries et al. 2005, Hansen and DeFries 2007, Hull et al. 2011, Zaccarelli et al. 2008).

Finally, government programs that support biodiversity conservation on private lands, such as the US Forest Service Forest Stewardship Program (USDA-FS 2014) and the US Fish and Wildlife Service Partners for Wildlife (USFWS 2014) which assist and incentivize private landowners to manage part of their land for conservation, should be supported and promoted. Even in urbanized landscapes, practices such as encouraging wildlife-friendly gardens and infrastructure (e.g., wildlife-friendly plants, lighting) represent opportunities for education and for involving citizens in biodiversity conservation (Dearborn and Kark 2009, Goddard et al. 2010).

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Literature Cited

Anadón-Irizarry, V., J. Corven, V. Méndez-Gallardo, J. Salguero-Faría, and J. Schwagerl. 2009. Puerto Rico and US Unincorporated Territories. Pp. 317–328, *In* C. Devenish, D.F. Díaz Fernández, R.P. Clay, I. Davidson, and I. Yépez Zabala (Eds.). Important Bird Areas of the Americas: Priority Sites for Biodiversity Conservation. BirdLife Conservation Series No. 16. BirdLife International, Quito, Ecuador.

Andam, K.S., P.J. Ferraro, A. Pfaff, G.A. Sanchez-Azofeifa, and J.A. Robalino. 2008. Measuring the effectiveness of protected-area networks in reducing deforestation. Proceedings of the National Academy of Sciences of the United States of America 105(42):16,089–16,094.

Beale, C., N. Baker, M. Brewer, and J. Lennon. 2013. Protected-area networks and savannah-bird biodiversity in the face of climate change and land degradation. Ecology Letters 16:1061–1068.

BirdLife International. 2015. Partnership for nature and people. Available online at http://www.birdlife.org/. Accessed April 2015.

Bruner, A.G., R.E. Gullison, R.E. Rice, and G.A. da Fonseca. 2001. Effectiveness of parks in protecting tropical biodiversity. Science 291:125–128.

Butchart, S.H.M., M. Walpole, B. Collen, A. van Strien, J.P.W. Scharlemann, R.E.A. Almond, J.E.M. Baillie, B. Bomhard, C. Brown, J. Bruno, K.E. Carpenter, G.M. Carr, J. Chanson, A.M. Chenery, J. Csirke, N.C. Davidson, F. Dentener, M. Foster, A. Galli, J.N. Galloway, P. Genovesi, R.D. Gregory, M. Hockings, V. Kapos, J.F. Lamarque, F. Leverington, J. Loh, M.A. McGeoch, L. McRae, A. Minasyan, M. Hernández Morcillo, T.E.E. Oldfield, D. Pauly, S. Quader, C. Revenga, J.R. Sauer, B. Skolnik, D. Spear, D. Stanwell-Smith, S.N. Stuart, A. Symes, M. Tierney,T.D. Tyrrell, J.-C. Vié, and R. Watson. 2015. Shortfalls and solutions for meeting national and global conservation area targets. Conservation Letters 00:1–9.

Cantú-Salazar, L., and K.J. Gaston. 2010. Very large protected areas and their contribution to terrestrial biological conservation. BioScience 60:808–818.

Chape, S., J. Harrison, M. Spalding, and I. Lysenko. 2005. Measuring the extent and effectiveness of protected areas as an indicator for meeting global biodiversity targets. Philosophical Transactions of the Royal Society of London, Biological Sciences 360:443–455.

Chape, S., M. Spalding, and M. Jenkins (Eds.). 2008. The World's Protected Areas: Status, Values, and Prospects in the 21st Century. Prepared in association with UNEP World Conservation Monitoring Centre. University of California Press, Berkeley, CA, USA. 366 pp.

Conservation International 2015. Caribbean Islands. Available online at http://www.cepf.net. Accessed 18 May 2015.

Convention on Biological Diversity. 2013. Aichi Biodiversity Targets. Available online at http://www.cbd.int/sp/targets/. Accessed 15 November 2013.

Craigie, I.D., J.E. Baillie, A. Balmford, C. Carbone, B. Collen, R.E. Green, and J.M. Hutton. 2010. Large-mammal population declines in Africa's protected areas. Biological Conservation 143:2221–2228.

Daly, C., E.H. Helmer, and M. Quiñones. 2003. Mapping the climate of Puerto Rico, Vieques, and Culebra. International Journal of Climatology 23:1359–1381.

Dearborn, D., and S. Kark. 2009. Motivations for conserving urban biodiversity. Conservation Biology 24:432–440.

DeFries, R., A.J. Hansen, A.C. Newton, M. Hansen, and J. Townshend. 2005. Isolation of protected areas in tropical forests over the last twenty years. Ecological Applications 15:19–26.

Diacon-Bolli, J., T. Dalang, R. Holderegger, and M. Bürgi. 2012. Heterogeneity fosters biodiversity: Linking history and ecology of dry calcareous grasslands. Basic and Applied Ecology 13:641–653.

Ewel, J.J., and J.L.Whitmore. 1973. The ecological life zones of Puerto Rico and the US Virgin Islands. USDA Forest Service Research Paper ITF-18. Río Piedras, PR, USA. 72 pp.

Gaston, K., K.J. Gaston, S. Jackson, L. Cantú-Salazar, and G. Cruz-Piñon. 2008. The ecological performance of protected areas. Annual Review of Ecology and Systematics 39:93–113.

Goddard, M.A., A.J. Dougill, and T.G. Benton. 2010. Scaling up from gardens: Biodiversity conservation in urban environments. Trends in Ecology and Evolution 25:90–98.

Gould, W., C. Alarcón, B. Fevold, M. Jiménez, S. Martinuzzi, G. Potts, M. Solórzano, and E. Ventosa. 2007. Puerto Rico Gap Analysis Project: Final Report. US Geological Survey, Moscow, ID, USA and the USDA Forest Service International Institute of Tropical Forestry, Río Piedras, PR, USA. 159 pp.

Gould, W., C. Alarcón, B. Fevold, M. Jiménez, S. Martinuzzi, G. Potts, M. Quiñones, M. Solórzano, and E. Ventosa. 2008. The Puerto Rico Gap Analysis Project Volume 1: Land cover, vertebrate-species distributions, and land stewardship. General Technical Report, International Institute of Tropical Forestry, US Forest Service-Department of Agriculture, Río Piedras, PR, USA. 39 pp.

Gould, W., M. Quiñones, M. Solórzano, W. Alcobas, and C. Alarcón. 2011. Protected natural areas of Puerto Rico, 1:240,000 research map. International Institute of Tropical Forestry, US Forest Service-Department of Agriculture, Río Piedras, PR, USA.

Hansen, A., and R. DeFries. 2007. Ecological mechanism linking protected areas to surrounding lands. Ecological Applications 17:974–988.

Helmer, E. 2004. Forest conservation and land development in Puerto Rico. Landscape Ecology 19:29–40.

Helmer, E.H., T.J. Brandeis, A.E. Lugo, and T. Kennaway. 2008. Factors influencing spatial pattern in tropical-forest clearance and stand-age: Implications for carbon storage and species diversity. Journal of Geophysical Research: Biogeosciences 113:1–14.

Hull, V., W. Xu, W. Liu, S. Zhou, A. Viña, J. Zhang, M.N. Tuanmu, J. Huang, M. Linderman, X. Chen, Y. Huang, Z. Ouyang, H. Zhang, and J. Liu. 2011. Evaluating the efficacy of zoning designations for protected-area management. Biological Conservation 144:3028–3037.

International Union for Conservation of Nature (IUCN). 2014. Red list of threatened species. Available online at http://www.iucnredlist.org/about/summary-statistics#Table8. Accessed 27 August 2014.

Jenkins, C.N., and L. Joppa. 2009. Expansion of the global terrestrial protected-area system. Biological Conservation 142:2166–2174.

Joglar, R. 2005. Biodiversidad de Puerto Rico: Vertebrados Terrestres y Ecosistemas. Serie de Historia Natural. Editorial Instituto de Cultura Puertorriqueña, San Juan, PR, USA. 563 pp.

Joglar, R.L. (Ed.). 2008. Biodiversidad de Puerto Rico: Agustín Stahl, flora, hongos. La Editorial, Universidad de Puerto Rico, San Juan, PR, USA. 301 pp.

Joglar, R., A. Álvarez, T.M. Aide, D. Barber, P.A. Burrowes, M. García, A. León-Cardona, A.V. Longo, N. Pérez-Buitrago, A. Puente, N. Ríos-López, and P.J. Tolson. 2007. Conserving the Puerto Rican herpetofauna. Applied Herpetology 4:327–345.

Joppa, L.N., and A. Pfaff. 2011. Global protected-area impacts. Proceedings of the Royal Society, Biological Sciences 278:1633–1638.

Joppa, L.N., S.R. Loarie, and S.L. Pimm, 2008. On the protection of "protected areas". Science 105:6673–6678.

Juffe-Bignoli, D., N.D. Burgess, H. Bingham, E.M.S. Belle, M.G. de Lima, M. Deguignet, B. Bertzky, A.N. Milam, J. Martinez-Lopez, E. Lewis, A. Eassom, S. Wicander, J. Geldmann, A. van Soesbergen, A.P. Arnell, B. O'Connor, S. Park, Y.N Shi, F.S. Danks, B. MacSharry, and N. Kingston. 2014. Protected Planet Report. UNEP-WCMC. Cambridge, UK. 70 pp.

Junta de Planificación. 2014. Memorial del plan de usos de terreno. Guías de ordenación del territorio (borrador para vistas públicas). 130 pp.

Katayama, N., T. Amano, S. Naoe, T. Yamakita, I. Komatsu, S. Takagawa, N. Sato, M. Ueta, and T. Miyashita. 2014. Landscape heterogeneity–biodiversity relationship: Effect of range size. PloS One 9: e93359.

Kennaway, T., and E. Helmer. 2007. The forest types and ages cleared for land development in Puerto Rico. GIScience and Remote Sensing 44:356–382.

Krauss, J., R. Bommarco, M. Guardiola, R. Heikkinen, A. Helm, M. Kuussaari, R. Lindborg, E. Öckinger, M. Pärtel, J. Pino, J. Pöyry, K. Raatikainen, A. Sang, C. Stefanescu, T. Teder, M. Zobel, and I. Steffan-Dewenter. 2010. Habitat fragmentation causes immediate and time-delayed biodiversity loss at different trophic levels. Ecology Letters 13:597–605.

Kumar, S., T.J. Stohlgren, and G.W. Chong. 2006. Spatial heterogeneity influences native and nonnative plant-species richness. Ecology 87:3186–3199.

Leverington, F., K.L. Costa, J. Courrau, H. Pavese, C. Nolte, M. Marr, L. Coad, N. Burgess, B. Bomhard, and M. Hockings. 2010. Management-effectiveness Evaluation in Protected Areas: A Global Study. 2nd Edition. The University of Queensland, Brisbane, Australia. 89 pp.

López-Marrero, T., and L.A. Hermansen-Báez. 2011. Urbanization trends and zoning around El Yunque National Forest Fact sheet. USDA Forest Service, Southern Research Station, Gainesville, FL, USA. 4 pp.

Manchester, S.J., and J.M. Bullock. 2000. The impacts of non-native species on UK biodiversity and the effectiveness of control. Journal of Applied Ecology 37:845–886.

Martinuzzi, S., W. Gould, and O. Ramos-González. 2007. Land development, land use, and urban sprawl in Puerto Rico: Integrating remote sensing and population-census data. Landscape and Urban Planning 79:288–297.

Myers, N., R.A. Mittermeier, C.G. Mittermeier, G.A. da Fonseca, and J. Kent. 2000. Biodiversity hotspots for conservation priorities. Nature 403:853–858.

Nagendra, H. 2002. Opposite trends in response for the Shannon and Simpson indices of landscape diversity. Applied Geography 22:175–186.

Quiñones, M., W. Gould, J. Castro, and S. Martinuzzi. 2013. Spatial analysis of Puerto Rico's terrestrial protected areas. 1:240,000. IITF-RMAP-03. US Department of Agriculture, Forest Service, International Institute of Tropical Forestry, Río Piedras, PR, USA.

Redford, K.H., G. Amato, J. Baillie, P. Beldomenico, E.L. Bennett, N. Clum, R. Cook, G. Fonesca, S. Hedges, F. Launay, S. Lieberman, G.M. Mace, A. Murayama, A. Putnam, J.G. Robinson, H. Rosenbaum, E.W. Sanderson, S.N. Stuart, P. Thomas, and J. Thorbjarnarson. 2011. What does it mean to successfully conserve a (vertebrate) species? BioScience 61:39–48.

Simberloff, D. 2000. Extinction-proneness of island species: Causes and management implications. Raffles Bulletin of Zoology 48:1–9.

Stein, S., M. Carr, G. Likens, and S. Comas. 2014. Islands on the edge: Housing development and other threats to America's Pacific and Caribbean Island forests. A forests on the edge report. General Technical Report NRS-137. US Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA, USA. 55 pp.

Turner, M.G. 2005. Landscape ecology in North America: Past, present, and future. Ecology 86:1967–1974.

US Census Bureau. 2015. 2014 population estimate. Available online at http://www.census.gov/. Accessed May 2015.

US Department of Agriculture-Forest Service (USDA-FS). 2014. State and private forestry. Available online at http://www.fs.usda.gov/main/iitf/spforestry. Accessed 12 September 2014.

US Fish and Wildlife Service (USFWS). 2014. Partners for Fish and Wildlife Program in the Caribbean. Available online at: http://www.fws.gov/caribbean/es/partners. Accessed 13 September 2014.

Ventosa-Febles, E.A., M. Camacho Rodríguez, J. Chabert Llompart, J. Sustache Sustache, and D. Dávila Casanova. 2005. Puerto Rico critical wildlife areas. Puerto Rico Department of Natural and Environmental Resources, Bureau of Fish and Wildlife, Terrestrial Resources Division. San Juan, PR, USA. 392 pp.

Vogt, P., K. Riitters, C. Estreguil, J. Kozak, T.G. Wade, and J.D. Wickham. 2007a. Mapping spatial patterns with morphological-image processing. Landscape Ecology 22:171–177.

Vogt, P., K. Riitters, M. Iwanowski, C. Estreguil, J. Kozak, and P. Soille. 2007b. Mapping landscape corridors. Ecological Indicators 7:481–488.

World Bank. 2014. The World Bank: Data. Available online at http://data.worldbank.org/country. Accessed 15 November 2014.

Zaccarelli, N., K.H. Riitters, I. Petrosillo, and G. Zurlini. 2008. Indicating disturbance content and context for preserved areas. Ecological Indicators 8:841–853.