Refining Biodiversity Conservation Priorities

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Abstract: *Although there is widespread agreement about conservation priorities at large scales (i.e., biodiversity hotspots), their boundaries remain too coarse for setting practical conservation goals. Refining hotspot conservation means identifying specific locations (individual habitat patches) of realistic size and scale for managers to protect and politicians to support. Because hotspots have lost most of their original habitat, species endemic to them rely on what remains. The issue now becomes identifying where this habitat is and these species are. We accomplished this by using straightforward remote sensing and GIS techniques, identifying specific locations in Brazil's Atlantic Forest hotspot important for bird conservation. Our method requires a regional map of current forest cover, so we explored six popular products for mapping and quantifying forest: MODIS continuous fields and a MODIS land cover (preclassified products), AVHRR, SPOT VGT, MODIS (satellite images), and a GeoCover Landsat thematic mapper mosaic (jpg). We compared subsets of these forest covers against a forest map based on a Landsat enhanced thematic mapper. The SPOT VGT forest cover predicted forest area and location well, so we combined it with elevation data to refine coarse distribution maps for forest endemic birds. Stacking these species distribution maps enabled identification of the subregion richest in threatened birds—the lowland forests of Rio de Janeiro State. We highlighted eight priority fragments, focusing on one with finer resolved imagery for detailed study. This method allows prioritization of areas for conservation from a region >1 million km^2 to forest fragments of tens of square kilometers. To set priorities for biodiversity conservation, coarse biological information is sufficient. Hence, our method is attractive for tropical and biologically rich locations, where species location information is sparse.*

Key Words: Atlantic Forest, GIS, hotspots, prioritization, remote sensing

Refinación de las Prioridades de Conservación de la Biodiversidad

Resumen: *Aunque hay acuerdo generalizado sobre las prioridades de conservación a escalas mayores (i. e., sitios prioritarios para la conservación de la biodiversidad), los límites son muy gruesos como para definir metas de conservación prácticas. La refinación de la conservación de sitios prioritarios significa la identificación de localidades específicas (parches de hábitat individuales) de tamaño y escala realistas para ser protegidos por gestores y apoyados por políticos. Debido a que los sitios prioritarios han perdido la mayor parte de su hábitat original, las especies endémicas dependen del que permanece. Ahora el asunto es identificar donde están el hábitat y las especies. Logramos lo anterior mediante técnicas directas de percepción remota y de SIG para identificar localidades específicas importantes para la conservación de aves en el sitio prioritario Bosque del Atlántico en Brasil. Nuestro método requiere de un mapa regional de la cobertura forestal actual, así que exploramos seis productos populares para el mapeo y cuantificación de bosques: campos continuos MODIS y una cobertura de suelo MODIS (productos preclasificados), AVHRR, SPOT VGT, MODIS (imágenes de satélite) y un mosaico GeoCover Landsat thematic mapper (jpg). Comparamos subconjuntos de estas coberturas forestales con las de un mapa basado en un Landsat enhanced thematic mapper. La cobertura forestal SPOT VGT predijo bien la superficie y localización del bosque, así que lo combinamos con datos de altitud para refinar los mapas generales de distribución de aves endémicas de bosques. La sobreposición de estos mapas de distribución permitió la identificación de la subregión más rica en aves amenazadas—los bosques en bajíos del Estado de Río de Janeiro. Dimos relevancia a ocho fragmentos prioritarios, con atención*

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en uno con imágenes de resolución fina para estudio en detalle. Este método permite la priorización de áreas para conservación de fragmentos de decenas de kilómetros cuadrados en una región >1 millón km^2. La información biológica general es suficiente para definir prioridades de conservación de la biodiversidad. Por lo tanto, nuestro método es atractivo para localidades tropicales y biológicamente ricas, para las que la información sobre la ocalización de las especies es escasa.

Palabras Clave: Bosque del Atlántico, percepción remota, priorización, SIG, sitios prioritarios para la conservación

Introduction

Tropical forest destruction is severe, resulting in the highest extinction rates of any global ecosystem (Wilson 1992; Skole & Tucker 1993; Pimm et al. 1995; Myers et al. 2000; Pimm & Raven 2000). In large part, stemming these losses requires protecting what forest remains and setting priorities for such actions. Globally, we know where the priorities are. There is close agreement among the hotspots of Myers et al. (2000), the endemic bird area (EBA) analyses by BirdLife (Stattersfield et al. 1998), ecoregions (Olson et al. 2001), and other quantitative mapping exercises (Wege & Long 1995; Manne et al. 1999; Jetz & Rahbek 2002; Myers 2003).

The next course of action is to refine conservation priorities down to scales at which managers can work. There is already an extensive literature on prioritizing areas for conservation. Some computationally sophisticated methods prioritize areas based on a detailed knowledge of species distributions (e.g., Jennings 2000; Cowling et al. 2003*a*, 2003*b*). These approaches, so compelling for species-rich and taxonomically well-surveyed places (such as the United States and South Africa), rarely extend to tropical forests, where distributional data are few. With rare exceptions, they have not been applied to hotspots, where, by definition, there are high levels of both species endemism and habitat loss (Myers et al. 2000).

Here, we describe a method that helps identify areas of a practical size to help prioritize, conserve, and manage species-rich tropical forests. To exemplify the approach, we focused on threatened birds endemic to Brazil's Atlantic Forest. Our procedure advances the science of conservation prioritization by identifying forest fragments of a few tens of square kilometers that contain the most threatened birds from an ecoregion of more than 1 million km^2.

The process is simple, intuitive, and relatively fast. The method also helps with generating practical goals to produce concrete results. These characteristics will facilitate its understanding and appeal for people charged with managing tropical biodiversity. Moreover, because production costs are low, it eliminates quibbling over whether conservation dollars are better spent on improved prioritization schemes or on protecting more land.

Determining what areas are important for conservation requires knowing where habitat remains. Information on species distributions is also vital. Detailed knowledge of species ranges, however, is not necessarily required. A more moderate approach is to assume one must know both the detailed distribution of species and remaining habitats. Even if one accepts this approach, a key practical consideration is how expensive (in time or resources) it will be to uncover the distribution of species versus the distribution of remaining habitats. The expense of the former is self-evident, but what about the latter?

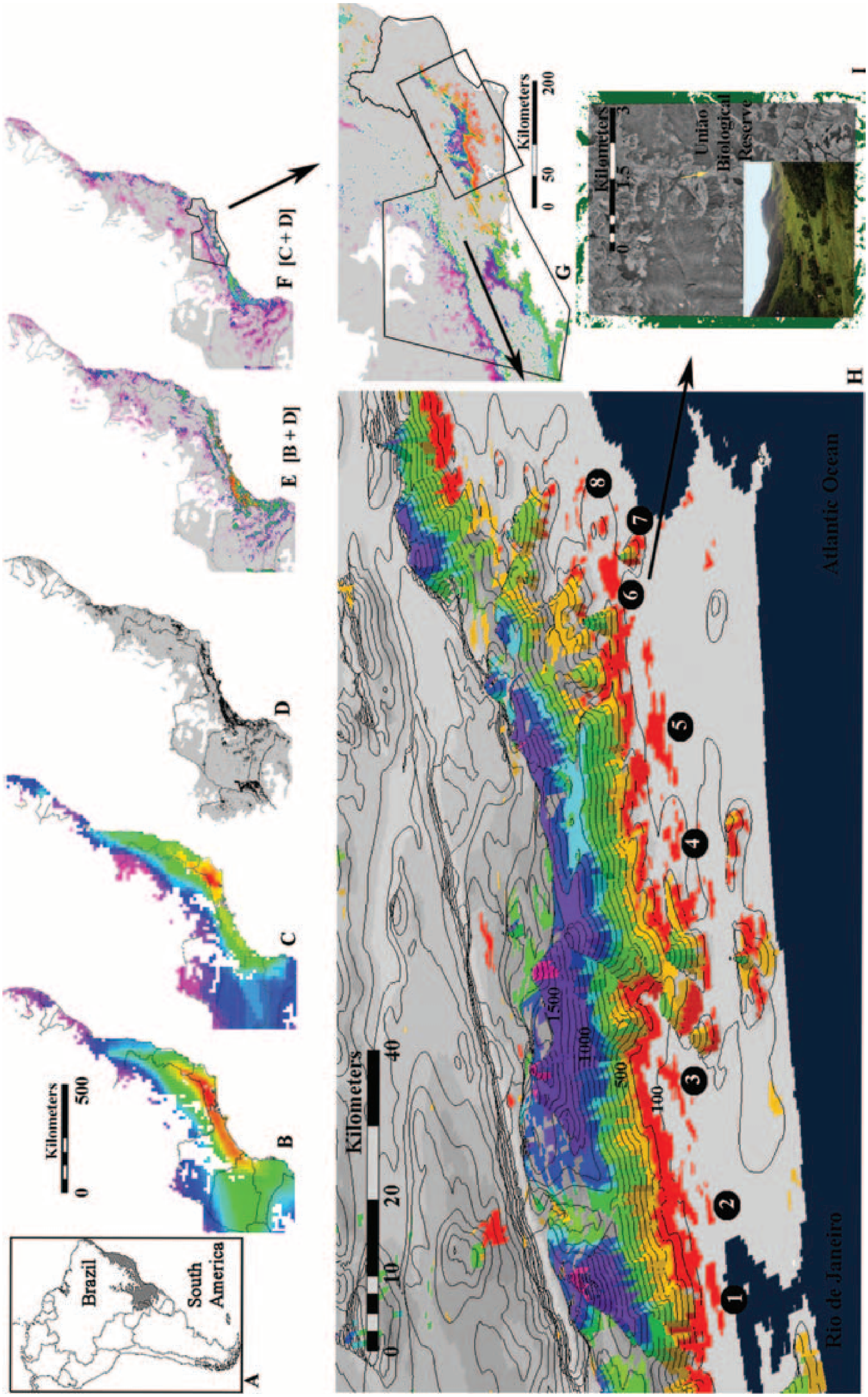
In some cases the task of setting priorities is disconcertingly simple. As an extreme example, Cebu in the Philippines has only one small patch of forest remaining (Pimm 2001). It holds the island's known endemics and, almost certainly, its unknown ones too. When habitat loss becomes this acute, whatever habitat remains becomes the priority.

On average, tropical forest hotspots covered roughly 1 million km^2, of which 100,000 km^2 remain (Myers et al. 2000). Protecting the remainder is the priority (Pimm et al. 2001) and probably the most influential action that can reduce future extinctions (Pimm & Raven 2000). Unfortunately, the costs of protecting hotspots are high (Pimm et al. 2001) because the remaining habitat is still too large for immediate protection. Is all remaining habitat equally important? The answer is surely, no. Even within a hotspot certain areas hold more threatened species than others. In addition, some fraction of the remaining forest may be in patches too small and isolated to have much conservation value (Brooks et al. 1999; Ferraz et al. 2003). Unless special circumstances warrant their attention (e.g., the last refuge of an endemic species), small fragments should receive lower priority relative to larger, more connected areas.

Methods

Study Area

Historically, Atlantic Coastal Forests of Brazil (Fig. 1a) extended 1,193,030 km^2 (Harris & Pimm 2004). This is one of the most endemic-rich areas of the world. It houses 8000 endemic plants, 73 endemic mammals (Myers et al.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2000), and 199 endemic birds (Parker et al. 1996). We considered 176 of the birds endemic to forests (Harris & Pimm 2004), of which the World Conservation Union (IUCN) categorizes 60 as threatened (IUCN 2003). Maps of species richness (at a quarter-degree scale) identified the entire seaboard of eastern Paraná, São Paulo, and half of Rio de Janeiro State as the richest areas in the Atlantic Forest for all birds and central Rio de Janeiro State for birds that are already threatened (Figs. 1b & 1c). This is likely because geometric constraints on ranges alone lead to richness peaks in the middle (Colwell & Lees 2000; Pimm & Brown 2004).

Maps of species richness founded on historical distributions do not indicate important areas today. Deforestation across the Atlantic Forest is extreme; <10% of the original habitat exists (Harris & Pimm 2004). The deforestation is also spatially heterogeneous, with most areas containing no forest at all. Much of the habitat in the areas identified as important, based on historical species distributions, is gone.

Refining Conservation Priorities

We used a three-step method to refine conservation priorities in the Atlantic Forest. First, we mapped the remaining habitat (evergreen forest), generating a prediction of remaining forest for the entire region. We could have used Landsat thematic mapper (TM) (1985–present) or Enhanced thematic mapper (ETM+) (1999–2003 [year of malfunction]) imagery to make this map. We chose not to because the imagery is expensive, analyzing multiple scenes is labor intensive, and Landsat's fine scale is unnecessary for this regional step. (Both sources of Landsat TM imagery are spectrally similar, except the ETM+ imagery contains a 15-m panchromatic band and improved radiometric and geometric accuracy.) Instead we evaluated six other imagery products that differ in their spatial resolution and temporal availability to make this regional forest map. We then compared their forest maps against another forest map generated from Landsat ETM+ imagery for a subset of the Atlantic Forest. In this comparison, Satellite Pour L'Observation de la Terre Vegetation (SPOT VGT) imagery predicted forest area and location well, so we selected it for generating a map of the remaining Atlantic Forest.

Second, using our prediction of remaining forest plus species range and elevation data, we determined the subregion forming the conservation priority for threatened birds (Rio de Janeiro State). Lastly, in this subregion, we refined the conservation priority specifically to lowland evergreen forests. We selected eight forested sites rich in threatened species and focused on one with fine-grain imagery and aerial photographs for further study.

Making a Regional Forest Cover Map

Generating forest maps at regional scales requires satellite imagery analysis. It is important to match this objective with suitable types and formats of input imagery. A primary consideration is the imagery's spatial resolution. Generally, the smaller an image's spatial resolution (pixel size), the less area it maps. For example, were we to use Landsat ETM+ imagery (30 × 30 m) to map the entire Atlantic Forest, it would require approximately 75 scenes. The computational issues are significant (and the imagery costs are expensive, up to US$45,000). Additionally, we already know that more than 90% of the region is deforested and has little, if any, conservation value (Harris & Pimm 2004). Our application demands mapping the entire region, but applying considerable effort to cover vast areas we know are deforested seems inappropriate.

Region wide, an ecologically relevant map does not require high spatial detail. For example, the resolution of regional sensors spans 250 m to 1 km. Such imagery

Figure 1. Refining conservation priorities in Brazil's Atlantic Forest: (a) South America, all countries outlined in black, dark gray is the Atlantic Forest ecoregion (Olson et al. 2001); (b) richness of all forest endemic birds (174 species); (c) only threatened birds (58 species), hotter colors indicate more species (maximum [red] 141 birds in b and 31 species in c); (d) remaining Atlantic Forest in black (mapped using SPOT VGT satellite imagery); (e) remaining ranges (stacked and summed) for all forest endemic birds based on elevation and map in d, the warmer the color the more species represented (magenta [1–8], purple [9–23], blue [24–31], cyan [32–54], green [55–90], orange [91–96], and red [97–115]); (f) remaining ranges (stacked and summed) for all threatened forest endemic birds based on elevation and map in d; (g) magnified region in f; (h) overlay of f on a digital elevation model (ramping in grays from light to dark), illustrates the priority conservation area for most threatened birds, and serves as a visualization of conservation prioritization based on basic species presence and elevation data, plus a map of recent forest cover (numbers are priority forest fragments for conservation management and restoration [Table 1] and black lines are contour intervals every 100 m). In f, g, and h, colors represent the following numbers of species: magenta, 1–3; purple, 4–6; blue, 7–10; cyan, 11–14; green, 15–17; orange, 18–20; and red, 21–23. The black outline in f and g indicates the area where we compared regional forest covers based on different satellite imagery sensors and sources. (i) Fragment 6 (Table 1), magnified with a panchromatic aerial photograph, Landsat ETM+ forest classification (green), and ground view (fragment on the left) (yellow arrow is the 250-m gap between the fragment and unprotected forest to the west).

supplies adequate resolution for prioritizing subregions from an expanse >1 million km^2. Overall, maps generated from regional sensors provide an accurate picture of where forested habitat remains.

To evaluate the types of satellite imagery designed for regional analyses, we used three different sources (AVHRR, SPOT VGT, and MODIS). We also evaluated the ability of a jpg composite based on Landsat TM data (the GeoCover Landsat TM mosaic, produced by the Earth Satellite Corporation, Rockville, Maryland) to map the Atlantic Forest. Lastly, our analysis included two preclassified products (MODIS Continuous Fields and a MODIS derived land-cover based on MODIS imagery).

The advanced very high resolution radiometer (AVHRR, five spectral bands) (http://www.class.noaa.gov/nsaa/products/welcome) and SPOT VGT (four bands) (http://www.spot-vegetation.com/) have a 1-km^2 spatial resolution. Although the spectral bands of AVHRR are tailored for discerning atmospheric phenomena (engineered as a weather satellite), many investigators have relied on AVHRR for land-cover analysis since its inception in the 1970s. The SPOT VGT is optimized to record terrestrial spectral reflectance and has been orbiting since 1998.

Images generated from the moderate resolution imaging spectroradiometer (MODIS) (http://edcimswww.cr.usgs.gov/pub/imswelcome/) date from February 2000 to present. MODIS is a hyperspectral sensor, but only 7 of the 36 bands are useful for vegetation mapping. These bands are spectrally similar to those of the Landsat TM and ETM+ sensors. For daily land-cover imagery, the sensor comes in two-band (250-m^2) and seven-band (500-m^2) resolved products (known as MOD09GQK and MOD09GHK, respectively).

We also analyzed two existing land-cover products derived from MODIS: a MODIS 500-m^2 Global Vegetation Continuous Field product (http://glcf.umiacs.umd.edu/data/modis/vcf/) and a MODIS-derived global land cover (MOD12Q1) with 1-km^2 resolution (Friedl et al. 2002). The MODIS Global Vegetation Continuous Field product comes in three layers: percent tree canopy cover, percent herbaceous cover, and percent bare cover. We used the percent tree canopy cover, considering anything greater than 60% tree cover as forest. From our knowledge of the Atlantic Forest, areas with tree-cover values less than 60% tended to include habitats other than forest.

A team at Boston University generates the 1-km^2 resolution MOD12Q1 (global land cover) based on a full year of MODIS imagery (Friedl et al. 2002). Their legend uses a 17-category International Geosphere-Biosphere Program (IGBP) classification scheme (http://edcdaac.usgs.gov/modis/mod12q1.asp). We considered that pixels classified as evergreen broadleaf represented the Atlantic Forest.

There is another source available to map the Atlantic Forest at a regional scale. Recently, the National Aeronautics and Space Administration (NASA) ordered three global Landsat TM (and ETM+) data buys for 2000, 1990, and the 1970s (Tucker et al. 2004). They provide nearly complete global coverage for these years, and the images are distributed at a reduced price (http://edcsns17.cr.usgs.gov/nsdp/). The Earth Satellite Corporation created mosaics for the global 1990 Landsat TM scenes into a variety of composite tiles (https://zulu.ssc.nasa.gov/mrsid/). These are three-band pictures, with 11 of them covering Brazil's Atlantic Forest.

All these imagery products are free, with the exception of SPOT VGT. Although the pricing of SPOT VGT varies, mapping the entire Atlantic Forest with SPOT VGT is possible for under US$1000.

Satellite Imagery Comparisons

We compared three aspects of the satellite images and products: area, location, and quality of forest predicted. To make the comparisons, we used an approximately 96,000-km^2 subset of Atlantic Forest (Fig. 1f). Maps of threatened species richness (quarter-degree scale) identified this area as having the most species of threatened birds (Fig. 1c).

The GeoCover Landsat TM mosaic, preclassified products, and satellite imagery all matched spatially, except for the AVHRR image. We geometrically corrected the AVHRR image to match the others. For all of the imagery products (AVHRR, MODIS, SPOT VGT), we used recent, dry-season imagery.

To generate maps of recent forest cover, we classified the MODIS (MOD09GHK product), AVHRR, GeoCover Landsat TM mosaic, and SPOT VGT imagery by using supervised classification and maximum likelihood decision rules. Locations found in *Key Areas for Threatened Birds in the Neotropics* (Wege & Long 1995) provided the coordinates of sites with primary (or at least good quality) forest. *Key Areas* identifies the most important locations for conserving the 290 globally threatened birds in the Neotropics and coordinates information for the habitats that hold them. The locations present in our subset of Atlantic Forest formed the basis of our "primary forest signatures." We visited some, but not all of the sites.

AREA

To evaluate how each prediction mapped forest area, we clumped contiguous forest pixels into fragments and then removed (filtered) them from small to large, comparing the remaining areas. For example, at the 10-km^2 scale, all areas classified as forest that were <10 km^2 were excluded from both the Landsat ETM+ classification and the product to which it was being compared (Fig. 2). We reported the percentage of Landsat ETM+ area that each of the competing predictions mapped. The area covered by clouds in any single image was removed from all the other images before calculating forest area.

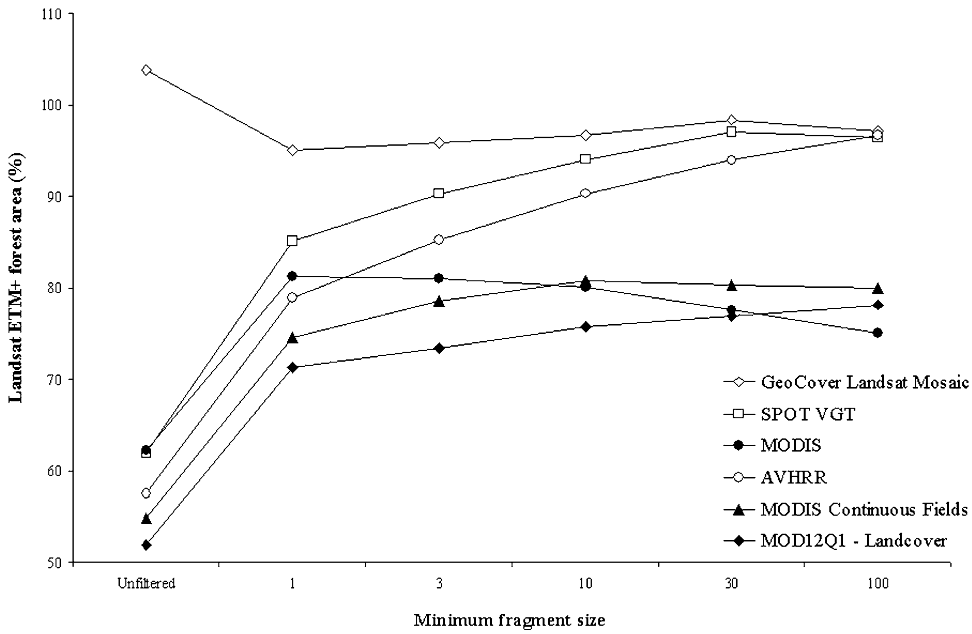

Figure 2. Comparisons among percent forest cover area predicted by the GeoCover Landsat TM mosaic, MODIS, SPOT VGT, AVHRR, MODIS Continuous Fields, and MOD12Q1 imagery compared with a Landsat ETM+ forest prediction for the same site. The region analyzed is shown in Fig. 1f. The comparison begins with unfiltered predictions and proceeds to larger fragment sizes, where fragments smaller than the minimum fragment size specified (square kilometers) are eliminated from all classifications.

LOCATION AND QUALITY

To evaluate the location and quality of forest mapped, we compared each prediction's spatial attributes against the Landsat ETM+-based forest cover (Fig. 3). All comparisons had forest fragments of <1 km^2 removed. Such areas generally have little long-term conservation value for birds (Willis 1979; Stouffer & Bierregaard 1995; Brooks et al. 1999; Ferraz et al. 2003) other than their usefulness in building corridors at finer scales.

We began by quantifying the percentage of the Landsat ETM+ forest prediction inside every 1×1 km pixel on the other maps. (This was also performed at 500×500 m for relevant predictions.) These percentages were binned into 10 equal categories, with the bin values corresponding to the proportion of Landsat ETM+ forest predicted in the coarser cells (Fig. 3, horizontal axis). The larger the bin value, the more Landsat ETM+ forest area was predicted in each of the coarser cells (indicating greater amounts of forest). Fragmented areas formed bins 5 and below (less than 50% forest coverage). We calculated the intersection between these bins and all pixels predicted to be forest for each of the maps.

For example, the upper left grid (Fig. 3) contains 16 hypothetical cells. The values in each cell represented the percentage of the Landsat ETM+ forest predicted inside them (now at the same resolution as the regional sensor with which it is being compared). The light gray shading indicates another forest map that also predicts some of these cells as forest. Of the four pixels that contained 95% forest according to Landsat ETM+ (bin 10), our coarser forest map captured three of them (75%). In other words, it predicted three cells that are 95% covered with the Landsat ETM+ forest prediction. The coarser forest prediction also mapped 60% of the pixels in bin 8 (71–80% covered by the Landsat ETM+ prediction), 67% in bin 7, and 50% in bins 3 and 4. We evaluated the six forest covers in this manner and calculated the percentage of times they intersected the bins (Fig. 3, vertical axis). Because the GeoCover Landsat TM mosaic is also resolved at 30×30 m, before this comparison we calculated its percent forest in 500×500 m pixels and considered pixels $\geq$60% to be forest.

Lastly, we investigated the fractal dimension of areas in the Landsat ETM+ forest prediction missed by the coarser forest maps (mixed pixels). At times, the coarser resolution sensors predicted forest for pixels that were only half covered with forest according to the finer resolved Landsat ETM+ sensor (bin 5). If the spatial arrangement of the 30×30 m pixels predicted to be forest by the Landsat ETM+ were spread out, it would help explain why the1 $\times$ 1 km or 500×500 m sensors did not map them. On the other hand, the coarse sensors may include these pixels as forest if their distribution were clumped. We found no differences in fractal dimension between these mixed pixels classified and unclassified as forest by the coarse sensors.

Mapping the Remaining Atlantic Forest

The SPOT VGT worked well in our comparative analysis (see Results), so we used it to map the entire Atlantic Forest with supervised classification methods and images spanning 1998–2000 (Harris & Pimm 2004). Locations for our classification signatures came from positions identified in *Key Areas for Threatened Birds in the Neotropics* (Wege & Long 1995).

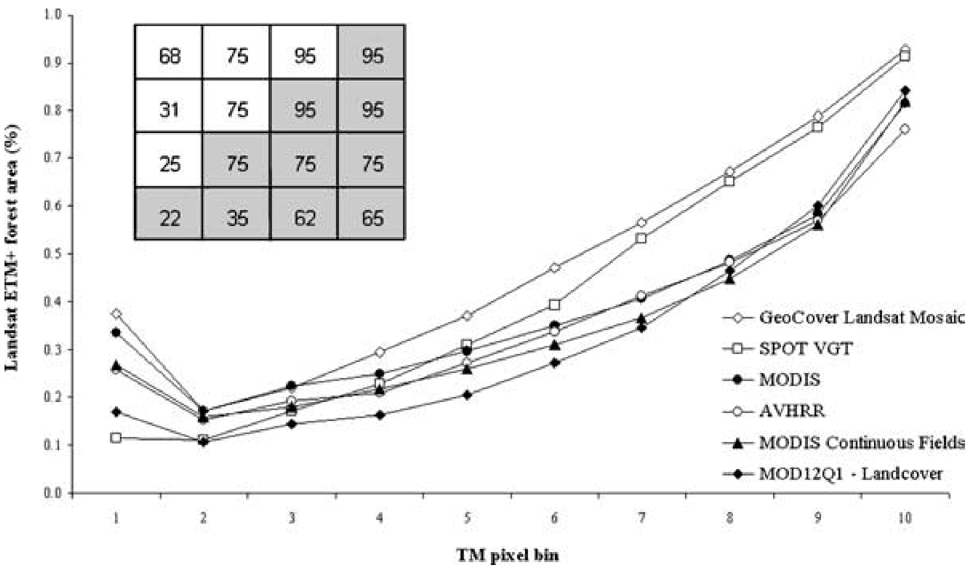

Figure 3. Comparisons among the locations of forest cover predicted by the GeoCover Landsat TM mosaic, MODIS, SPOT VGT, AVHRR, MODIS Continuous Fields, and MOD12Q1 imagery. The grid subset in the upper left is a hypothetical case (see text). Each forest prediction is compared with the percentage of the Landsat ETM+ forest map that it overlays, in a 1 × 1 km or 500 × 500 m cell, depending on the respective imagery's resolution. Bin sizes correspond to the percentages of the Landsat ETM+ forest prediction present in coarser grid cells (i.e., bin 9 = 81–90% Landsat ETM+ forest coverage in a coarser cell).

SELECTING THE SUBREGION

To find the most species-rich areas, we focused on 174 forest endemic birds. We used 137 range maps created by Mehlman et al. (1999) and 37 by BirdLife International (2001). We excluded two threatened birds from the analysis: the Alagoas Curassow (*Mitu mitu*), which is extinct in the wild (BirdLife International 2001), and the Restinga Antwren (*Formicivora littoralis*), which lives only in restinga (BirdLife International 2001).

Maps of species richness are not helpful in identifying areas of conservation priority if they do not account for species elevation requirements or remaining habitats. We illustrated this by overlaying the original (historical) ranges for all 174 species (Fig. 1b) and the 58 threatened species (Fig. 1c) separately. Intense deforestation is implicit in the map of threatened species richness, because it is most responsible for threat in the first place (Balmford & Long 1994). Yet, to advance, we must explicitly map the remaining habitat and determine where species live now.

To map where species live now, we refined each bird's original (historical) range with a 1-km resolution digital elevation model (Hastings et al. 1999), relying on each species' specific elevation requirements (Harris & Pimm 2004). Next, all ranges were superimposed over our estimate of remaining forest. The models retained only the intersection between bird ranges and the forest cover, creating maps of species' remaining ranges. The areas that remained are the only places these forest endemics have to survive. We then stacked and summed the 174 range maps for all the forest endemics.

Two locations hold the greatest numbers of species: São Paulo State (spilling into Paraná) followed by Rio de Janeiro State (Fig. 1e). If our goal were to protect the most endemic species, we could immediately focus our attention on these areas.

Perhaps a more compelling approach is to focus on threatened species (Lombard et al. 1999). We already know they face particularly high risks of extinction. The IUCN formally classifies one-third of the Atlantic Forest birds as threatened (categories of endangered, critically endangered, and vulnerable [IUCN 2003]). When we mapped the region's 58 threatened species, the previous centers of species richness, based on all birds, were reduced to a subregion at Rio de Janeiro State (Fig. 1f).

REFINING THE SCALE

In Rio de Janeiro, the priority area for threatened birds is lowland forest—they hold the most threatened species. (This priority area is illustrated by overlaying our map of threatened species richness over a digital elevation model [Fig. 1h].) In this area we identified eight lowland forest fragments as possible priority areas for conservation. Each is separated from larger, contiguous areas of forest and was predicted to contain the most (21–23) threatened birds (Fig. 1h). Reestablishing links between these fragments and larger areas of forest is a high conservation priority because isolated fragments tend to lose their

Table 1. Eight important forest fragments in Rio de Janeiro State for conserving threatened endemic birds, ranked by their proximity to large, contiguous forested areas.

Fragment number in Fig. 1	*Currently protected*	*Name*	*Area (km^2)*	*Closest distance to contiguous forest (km^2)*
6	yes	União Biological Reserve	36	1
1			32	1
4			23	1.8
5	yes	Poço das Antas Biological Reserve	62	2
3			34	3.5
2			8	4
8			12	5.4
7	yes	Morro do São João	11	7.3

species to extinction faster than larger areas (Ferrraz et al. 2003). We sorted these fragments based on their proximity to large, contiguous forest (Table 1). The area and distance estimates came from our SPOT VGT-based forest classification.

Results

Importance of Remaining Habitat

Identifying priority conservation areas based only on maps of species richness generated poor results. In our example (Figs. 1b & 1c), maps of species richness emphasized the northern highlands of Rio de Janeiro State as a priority. The highest species richness was 141 species for all birds and 31 species for threatened birds. In actuality, the most important areas were in the southeastern lowlands of the state. Once remaining forest and elevation were accounted for, the greatest species overlap was 115 for all birds and 23 for threatened species. In short, maps of historical species richness identified priority areas that are no longer forested, with little biodiversity to conserve.

Satellite Imagery Comparison

The performance of each product for generating regional forest maps depended on its scale. The Landsat-based maps predicted more forest cover area because they detected small fragments that the others missed (Fig. 2). The other methods performed poorly at the unfiltered scale but improved and were broadly similar at the 1-km^2 scale. At fragment sizes $\geq$10 km^2, the three MODIS products plateaued at about 80%, whereas the amounts by SPOT and AVHRR continued to rise. The GeoCover Landsat TM mosaic consistently reported accurate estimates of forest cover across all fragment size categories (i.e., it stayed close to the 100% line). In general, however, the sensors captured broadly the same area.

All the forest cover maps (except for the map based on AVHRR) predicted locations of contiguous forest well. More than 80% of the time their estimates of forest cover included the same locations containing 90–100% of forest according to the Landsat ETM+ map (Fig. 3). In more fragmented areas the GeoCover Landsat TM mosaic and SPOT VGT mapped the highest amounts of forest in all bins down to the 50% level (bin 5). They reported forest most accurately. The remaining predictions performed remarkably similarly but were not as good at mapping forest location and quality.

Product Evaluation

Based on our study site, and comparing the amount of area mapped plus the location and quality of that mapped forest, the GeoCover Landsat TM mosaic and SPOT VGT performed best. Although the GeoCover's resolution may be too fine for our application, the multiple Landsat scenes were already combined into relatively few tiles. This markedly reduced processing time. The MODIS maps performed reasonably well in mapping location but fell short on overall area. The AVHRR prediction reported area well but performed the worst in mapping forest in the right places.

Overlaying the SPOT VGT forest map on the Landsat ETM+ prediction (each unfiltered) helped illustrate that SPOT VGT picked up core, primary forest (or at least good-quality forest) (dark gray in Fig. 4). It missed small fragments and edge (light gray in Fig. 4). There were hardly any places where SPOT VGT missed the core forest, a few edge regions where SPOT VGT predicted forest but Landsat ETM+ mapped none (black), and many edges and small forest remnants where the ETM+ predicted forest and SPOT VGT did not (light gray).

Identifying Important Forest Fragments

Rio de Janeiro State led in threatened bird richness (Figs. 1f & 1g). According to our SPOT VGT prediction, the amount of forest remaining in Rio de Janeiro State is 8,650 km^2. The total area of the original Atlantic Forest was 1,193,030 km^2 (Harris & Pimm 2004). Moving in from the regional to subregion scale narrowed our focus more than 99%.

Within this subregion, most threatened birds are lowland species, found on the southern boundary of the Serra dos Órgãos (Fig. 1h). These lowland forests are nearly destroyed, with what remains bordering the mountains. This forms the area of highest conservation priority.

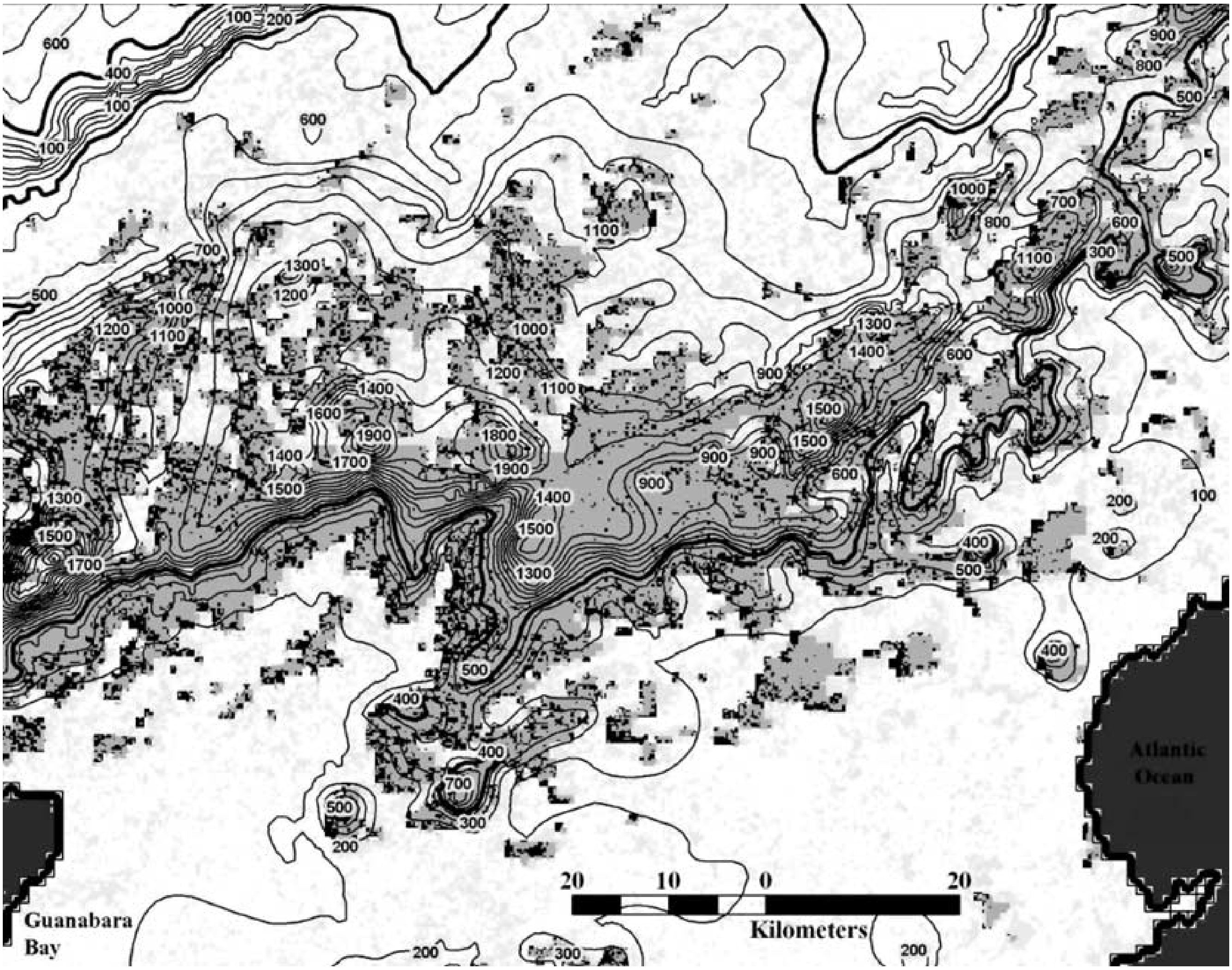

Figure 4. Comparison of forest maps generated by coarse and fine sensors (light gray, unfiltered Landsat ETM+ forest classification; black, SPOT VGT forest classification; and dark gray, intersection of the two). Black contour intervals are spaced 100 m apart, and 500-m contours are the thickest lines.

Here we identified eight forested locations meriting conservation activity. At least three are already under some degree of protection. The largest fragment closest to an expanse of intact forest is União Biological Reserve. It is known to contain 17 globally threatened birds (Alves et al. 2000) and a threatened primate, the golden lion tamarin (*Leontopithecus rosalia*) (Rylands et al. 2003). We predicted the presence of 23 threatened bird species, although this requires further ground surveys to corroborate. The nearest neighbor to União lies westward, a forested mountain ringed with lowland forest. According to SPOT VGT, a deforested gap of 1 km separates the two fragments.

An aerial photograph shows the gap between these forested areas (yellow arrow in Fig. 1i). The subset is another photograph taken from the northern side of the gap, facing south. Measured on the ground, the gap is only 250 m wide.

Discussion

Imagery Requirements and Options

We chose SPOT VGT to generate our map of current forest because it performed well in our comparative analysis. It picked up core, contiguous forest—the most important areas for preserving Atlantic Forest birds. The SPOT VGT is also available throughout the year, which allows one to distinguish between forest types (evergreen from deciduous) across seasons.

The AVHRR and MODIS can also account for seasonality. The wide band widths in AVHRR may hamper its spectral resolution and limit its vegetation mapping capability. This could explain why it captured adequate area but performed poorest on location. The MODIS contains more spectral bands than AVHRR (and SPOT VGT) and has greater radiometric resolution (16 bit vs. 8 bit). These qualities are advantageous for differentiating land cover. Although the MODIS land cover also considers seasonality, the MODIS Continuous Fields product does not. Regardless, all the MODIS products performed reasonably well. Their consistency lends support to our selection of 60% as a reasonable cutoff for forest when using the MODIS Continuous Fields product in this area.

Although the GeoCover Landsat TM mosaic was most accurate in our subset, the product is a mixture of the best cloud-free images from any season. This may make it harder to separate forest types. Its good performance, however, suggests that it has the potential to simplify basic land-cover classifications. Recently, the 2000 GeoCover Landsat ETM+ mosaic was released (https://zulu.ssc.nasa.gov/mrsid/). We also expect this product to advance investigations on current levels and patterns of global deforestation.

Each imagery type mapped forest well enough to ultimately identify Rio de Janeiro State as the subregion to conserve threatened birds. (Small rectification anomalies and temporal differences in imagery may account for some of the differences between them.) This versatility among processed (MOD12Q1 and MODIS Continuous Fields), raw imagery (SPOT VGT, MODIS, AVHRR), and composite data (GeoCover Landsat TM and ETM+ mosaics) is advantageous. By happenstance, cloud cover may mask some imagery but not others. Plus, the processed imagery we examined holds extreme value for those with little remote sensing training or ability to purchase imagery analysis software. Differentiating among forest types remains an issue, and this can limit the options. The important message is that the products are available and most are free.

União Biological Reserve

To further exemplify our method of conservation prioritization, we focused in detail on União Biological Reserve (hereafter União). Although União is not the only conservation priority area in the whole Atlantic Forest, it is important for conserving threatened birds.

The good news is that União has protection as a biological reserve. The bad news is that it is too small (36 km^2) to retain its species in the long term and thus requires a connection to neighboring forest. The nearest neighbor is westward, about 250 m away. Although the gap is relatively short, it may be impassible for many species of birds (Develey & Stouffer 2001; Laurence et al. 2004). Filling this gap with forest would increase its effective size and ability to house threatened species. Now begins a different challenge, on-the-ground implementation. This involves stakeholder involvement, capacity building, and other creative mechanisms performed by conservation planners working in the area.

To learn more, we visited the site. We discovered that one farmer owns the land in the small gap (Fig. 1i). Periodically he burns this land to enhance livestock grazing, which prevents forest regeneration. One possibility is to negotiate a stop to the grazing, which would allow the forest to regenerate naturally or via restoration activities. This would most likely require compensation payments to the landowner or possibly a direct purchase of the land to expand the reserve.

Another potential obstacle is a small dirt road traversing the gap (Fig. 1i, yellow arrow). It could present a barrier for birds and other species, even if the surrounding area returns to forest. Although the road receives little traffic, tanker trucks full of water appear to be the primary users. The water comes from a spring flowing from the forested mountain opposite União, supplying regional urban centers. Conservation planners must consider this circumstance as well.

Habitat Extensions

We focused on mapping forest habitats because tropical forest vegetation holds most of the Earth's species. Yet our method is not habitat (or species) specific. Mapping other vegetation types can be accomplished with similar techniques. As long as the imagery provides meaningful spectral information (at a useful scale) to discern the vegetation of interest, mapping it is possible. Even heterogeneous habitats such as savannas can be mapped as a mixed habitat type at scales coarser than mapping trees and grasslands separately (Jenson 1986; G.M.H. unpublished data). This enables modeling more species, even habitat generalists. The latter is accommodated by simply incorporating the relevant habitat variables (plus other ecological and social variables when available). The ease at which this mapping occurs, however, depends on the specificities of the habitat of interest. For example, mapping all grasslands would generally be simpler than mapping a specific grassland type.

When generating original maps is not desirable, other options include preclassified products such as the MODIS Landcover and MODIS Continuous Fields. Perhaps more promising are newly released global vegetation maps, the Global Land Cover 2000. These maps are produced by the Joint Research Center of the European Commission and more than 30 partner institutions around the world (full description at http://www-gvm.jrc.it/glc2000/). The maps are prepared using SPOT VGT satellite data, with each map developed by region. For consistency, a global legend consists of 22 distinct land-cover types. Each region also has its own separate classification legend, therefore accounting for regional variability. Because these vegetation maps are based on SPOT VGT, span the entire globe, and account for seasonality, we believe they will be very useful to refine conservation priorities for many species in a variety of areas and habitats.

Each of the maps evaluated here would have identified the same subregion as the conservation priority. Likewise, we expect them to map the priority area for species in other habitats orders of magnitude below current delineations. Once identified, focusing in with Landsat ETM+ imagery or aerial photos enables further refining the priority area to manageable levels.

Not all the habitat we identified as remaining ranges for tropical forest birds is equally viable. Some area will invariably miss other attributes influencing species presence (e.g., bamboo fruiting, hunting pressure). Such information, where and when available, can assist in refining conservation priorities at the local scale.

Prioritization Extensions

Within the Atlantic Forest, other forests will also form important priority conservation areas. Some species would remain unprotected if preservation in Rio de Janeiro State were the sole conservation strategy (such as endemic birds found only in Alagoas). In response to situations such as this, prioritization studies often employ selection algorithms to identify areas for conservation based on specific targets (Howard et al. 1998; Pimm & Lawton 1998; Lombard et al. 1999; Noss et al. 2002; Cowling et al. 2003*a*).

We had a different objective. Here we used a method that refines biological hotspots to manageable levels, at a scale significantly smaller than current delineations. Although we mapped priority areas to capture the most threatened birds, the broader message is that once species' remaining ranges are identified, this information can feed into a variety of prioritization schemes. Pressing conservation and management goals may be the amount of area protected or a certain amount of locations protected for species singly or in groups. By demonstrating how to refine species-rich areas to manageable levels, we are optimistic that others will incorporate and apply this information to their needs.

Conclusion

Many conservationists wish to preserve the entire remaining land area of biological hotspots, which are rich in species but low in habitat, such as the Atlantic Forest of Brazil. Although conservation wants the lot, funding, politics, and the amount and spatial extent of remaining forest complicate this goal. Moreover, in each hotspot, not all the remaining habitat is equally important. To make hotspot conservation manageable, the remainder must be prioritized.

Refining hotspot conservation means identifying specific locations (individual habitat patches) of realistic size and scale for managers to protect and politicians to support. This goal requires a map of remaining habitat, and we explored six satellite imagery sources and products to generate one. Although we used SPOT VGT imagery in our example, each of the products would have led us to the same subregion of conservation importance.

By incorporating elevation and species range data, we found most threatened birds reside in the remaining lowland forests of Rio de Janeiro State. The majority of this area is divided into isolated fragments. Here we identified eight priority areas, which can lead to precise conservation and management action for these forests and birds. These local priorities are narrow in their geographical scope, being orders of magnitude smaller than the recognition of the hotspot as a global priority. One such local priority, União Biological Reserve, is as an important forest fragment only 250 m from larger and contiguously forested areas. The conservation priority here is to restore this gap to forest.

Many species endemic to biological hotspots are threatened with extinction. Ensuring their survival means refining conservation priorities to identify and manage the places where they live. To accomplish this, the method herein requires only straightforward remote sensing and GIS skills to integrate maps of remaining habitat, elevation data, and basic species information. The process is not habitat or species specific.

Although the vegetation and geophysical data required for this exercise grow finer, detailed information on species ranges lags behind. This makes our approach even more applicable, and timely, for prioritizing other biodiversity hotspots and important locations where species' distributional data are few.

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