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CONSERVATION ECOLOGY

Incorporating explicit geospatial data shows more species at risk of extinction than the current Red List

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The IUCN (International Union for Conservation of Nature) Red List classifies species according to their risk of extinction, informing global to local conservation decisions. Unfortunately, important geospatial data do not explicitly or efficiently enter this process. Rapid growth in the availability of remotely sensed observations provides fine-scale data on elevation and increasingly sophisticated characterizations of land cover and its changes. These data readily show that species are likely not present within many areas within the overall envelopes of their distributions. Additionally, global databases on protected areas inform how extensively ranges are protected. We selected 586 endemic and threatened forest bird species from six of the world's most biodiverse and threatened places (Atlantic Forest of Brazil, Central America, Western Andes of Colombia, Madagascar, Sumatra, and Southeast Asia). The Red List deems 18% of these species to be threatened (15 critically endangered, 29 endangered, and 64 vulnerable). Inevitably, after refining ranges by elevation and forest cover, ranges shrink. Do they do so consistently? For example, refined ranges of critically endangered species might reduce by (say) 50% but so might the ranges of endangered, vulnerable, and nonthreatened species. Critically, this is not the case. We find that 43% of species fall below the range threshold where comparable species are deemed threatened. Some 210 bird species belong in a higher-threat category than the current Red List placement, including 189 species that are currently deemed nonthreatened. Incorporating readily available spatial data substantially increases the numbers of species that should be considered at risk and alters priority areas for conservation.

INTRODUCTION

Determining species' vulnerability to extinction and quantifying the extent of habitat loss and fragmentation are vital to conservation. These assessments inform the overall state of biodiversity through estimates of extinction rates (*1*) and the progressive increase in risk that species suffer over time. Individual species assessments are vital in understanding the threats and in prioritizing conservation actions. Moreover, limited budgets force practitioners to prioritize some areas over others globally (*2*) and locally (*3*). Areas where high concentrations of endemic and endangered species coincide with habitat loss are priorities for conservation (*3*–*6*).

The international authority for assessing extinction risk is the IUCN (International Union for Conservation of Nature) Red List (*7*). It has a very widely used protocol that classifies species into different categories of risk using a formal set of criteria. The list uses rigorously objective criteria, is transparent, and is democratic in soliciting comments on species decisions. The process regularly updates species status, and all the associated data are publicly accessible. Certainly, individual countries make their own decisions and may set management policies based on the IUCN assessments. For example, De Grammont and Cuarón (*8*) compare and contrast assessments for the Americas. Nonetheless, global assessments are essential.

The Red List and its associated criteria were conceived 25 years ago (*9*). Although an impressive achievement, it is nonetheless showing its age. We find serious inconsistencies in the way species are classified. We contend that it is possible to improve this well-established process by the inclusion of readily available and easy-to-include geospatial data. Moreover, when one does this, the relative risks of species change substantially. Given the multiple advances in geospatial data sets, the system could be greatly improved, and so could the conservation decisions that result from the process. We provide suggestions for simple and widely applicable enhancements.

In brief, whereas there are alternative pathways to designating a species to be at risk of extinction, the most common one involves the combination of a small geographical range size and the presumption of continuing loss of habitat that will shrink that range still further. (Certainly, some species suffer additional threats from hunting or collection, even threatening species with relatively large ranges.) Furthermore, the geographical range is typically the area over which a species is found, essentially the kind of map that one finds in familiar field guides and that the IUCN protocols call the "extent of occurrence" (*10*). Typically, the species will not be present throughout the area. There are various suggestions for producing more refined maps of where a species might occur—the "area of occupancy." These suggestions need to be applied globally across many taxa, and that is what we do here, starting with the extents of occurrence.

Geospatial data on elevation have been available for over a decade (*11*), and forest cover products have improved steadily with the development of new classification algorithms that take advantage of satellite imagery at a 30-m resolution (*12*). We show that these data can greatly improve current estimates of extinction risk by making them more consistent and comparable across species and regions. These improvements are fundamental to monitoring the progress of those species already deemed threatened. Moreover, by periodically evaluating species' ranges, the habitat loss within them, and the degree of protection granted to them, we can streamline the process of evaluating species' risks and update these assessments. This is especially important in tropical areas, where fast-paced deforestation is a reality (*12*) and protected areas may have varying degrees of success (*13*).

Using readily available geospatial data on bird distribution ranges, elevation, and forest cover, we assessed extinction risk and conservation priorities for endemic birds in tropical biodiversity hotspots. We

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selected six geographic regions that provide habitat for significant concentrations of endemic birds (Fig. 1). We focused on endemic and threatened birds of tropical moist forests because these habitats support most of the terrestrial animal (*2*) and plant (*14*) species. Thus, the fates of these birds are intertwined with those of a significant portion of global biodiversity (the Supplementary Materials provide details on how we defined our study species).

Briefly, we refined the published geographical ranges by the known elevational ranges of species, using globally available digital elevation maps. We then further refined the ranges by how much forest habitat remains for forest-dependent species. Inevitably, after refining ranges by elevation and forest cover, ranges shrink. The critical question is whether they do so consistently. For example, refined ranges of critically endangered species might reduce by (say) 50%, but so might the ranges of endangered, vulnerable, and nonthreatened species. If this were to be the case, then the relative risks of species would not be changed. Vitally, this is not the case. In most troubling cases, we find that the species that are currently "not threatened" have refined ranges that are broadly of the same size as the species currently deemed "critically endangered." Moreover, we show that the readily available data on how much of a species range is protected show that these cases are not species that are particularly well protected. Our methods also explicitly show the degree to which remaining ranges are fragmented (and to what extent) (*15*), but we defer a global assessment of fragmentation to a later paper.

Of course, starting from the extent of occurrence and reducing the area a species is likely to occur within it is not the only way to produce more detailed maps of a species' range. An important alternative is in the large literature on taking specific observations, relating them to environmental variables, and modeling the species' range [for example, see study by Elith *et al.* (*16*)]. Our choice is a practical one: we need to assess many species across large areas, and not selected examples, if we are to achieve our aims. Alternative methods have not been widely applied, although a study by Goldsmith *et al.* (*17*) is a marked exception to map all the plants of the Americas, albeit on a geographically coarse scale.

We emphasize that what our methods produce are neither extent of occurrence nor areas of occupancy but something intermediate that embraces widely available and relevant data that improve the decision-making process. This paper follows in a series of regional studies and specific examples (*3*, *5*, *15*, *18*–*20*) that we deem essential to understanding the complexity of the problems and to which we will often refer.

RESULTS

Range refinement

We start with the original range maps published by BirdLife International (*21*). We refined these original ranges by the known elevational limits of each species using the SRTM 90m Digital Elevation Model (*11*) and by the remaining forest cover using 30-m-scale forest cover products (*12*). As a result, we had three different range maps for each species: the original range map (Fig. 2, blue outline), one refined by elevation data (Fig. 2, teal fill), and a final one refined by elevation and forest (Fig. 2, black fill).

Threat assessment

Using the refined ranges, we assessed threat using the IUCN's thresholds for the extent of occurrence for threatened categories: critically endangered (<100 km^2), endangered (<5000 km^2), and vulnerable (<20,000 km^2). We use these thresholds as a benchmark and acknowledge that the maps we produce are neither the extent of occurrence nor the area of occupancy but rather reflect potentially suitable habitat for each species. We chose to use the extent of occurrence because our maps are not depictions of where individuals are but rather where the suitable habitat is for them to be. Objectively, there should be an

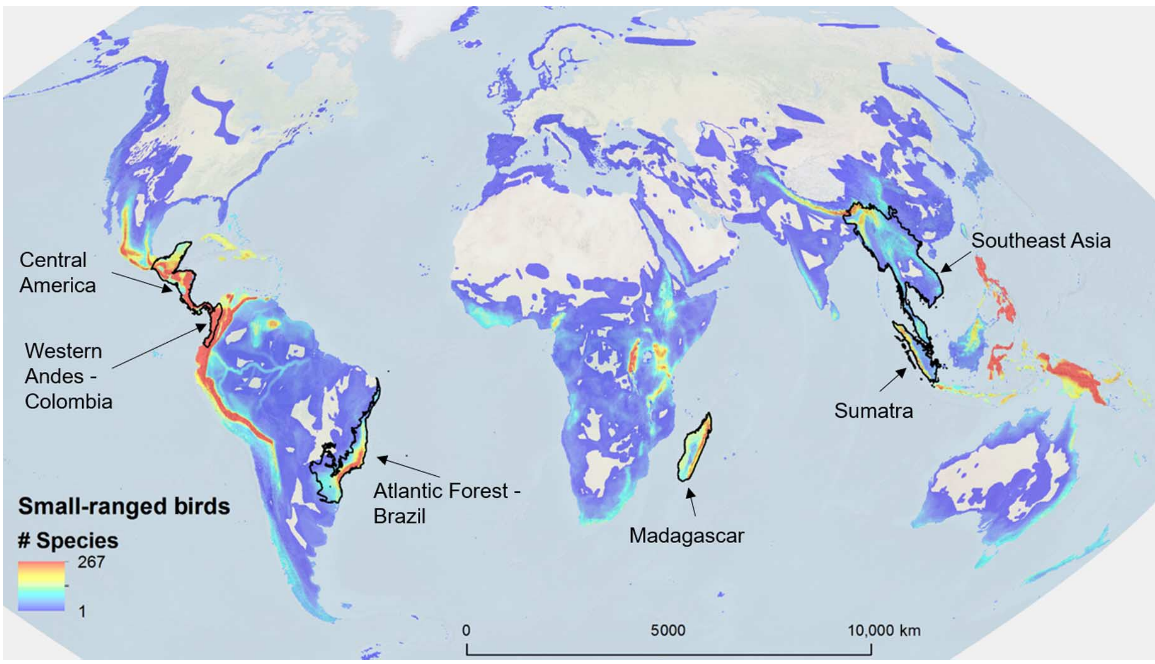

Fig. 1. Small-ranged birds. Six study regions outlined in black were overlaid on a map of concentration of small-ranged birds (*n* = 4964 species with ranges smaller than the median) from BirdLife International and NatureServe (*37*).

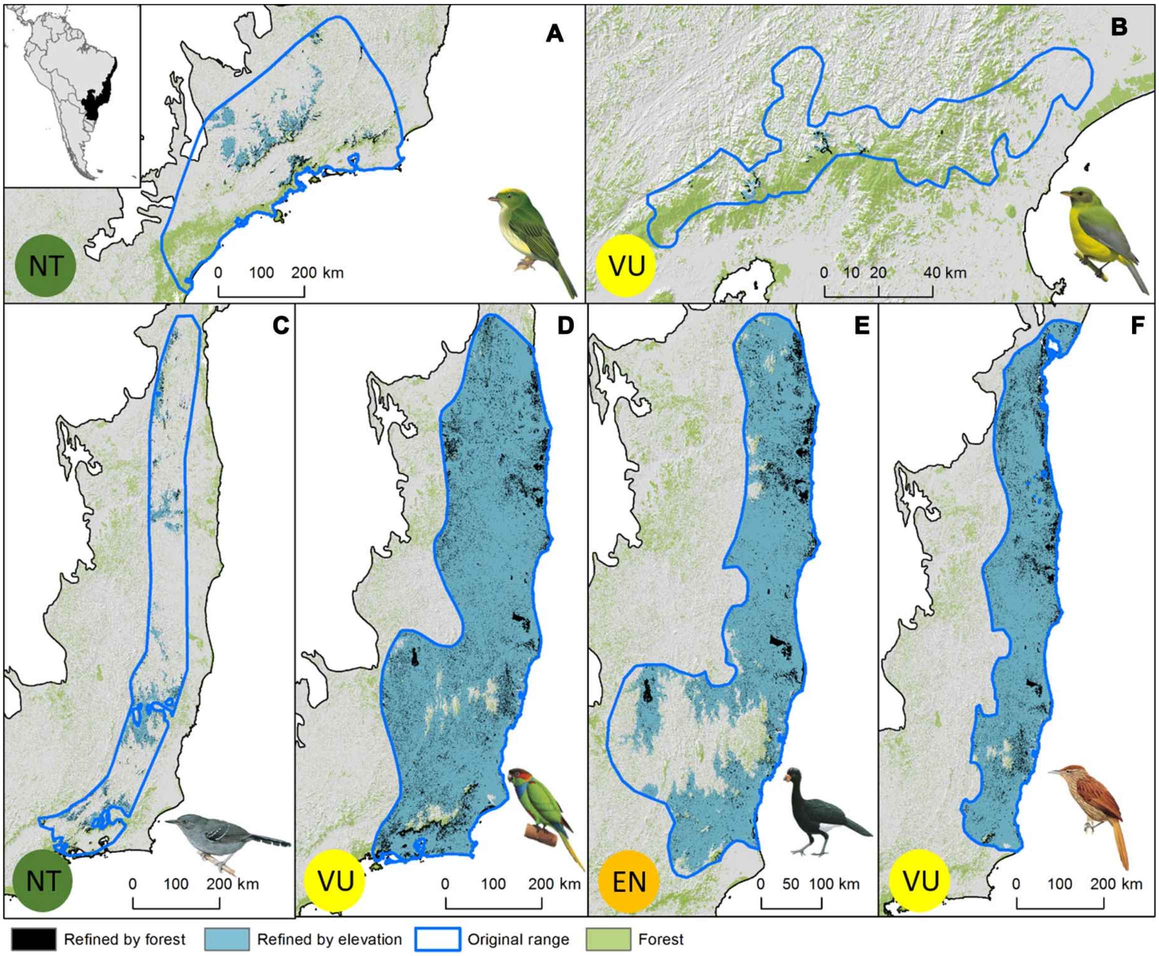

Fig. 2. Range refinement process. Blue outlines show original range from Jenkins *et al.* (*2*); light blue fill shows range after being refined by elevation, and black fill shows range after being refined by elevation and forest for six endemic birds of the Atlantic Coast Forest in Brazil: (**A**) Serra do Mar tyrant-manakin (*Neopelma chrysolophum*), (**B**) grey-winged cotinga (*Tijuca condita*), (**C**) Rio de Janeiro antbird (*Cercomacra brasiliana*), (**D**) ochre-marked parakeet (*Pyrrhura cruentata*), (**E**) red-billed curassow (*Crax blumenbachii*), and (**F**) striated softtail (*Thripophaga macroura*). Bird illustrations from del Hoyo *et al.* (*34*) were reproduced with permission.

additional threshold for the extent of suitable habitat, but given that it does not exist yet, we err on the conservative side and use the extent of occurrence.

For all analyses of threat, we only included species whose original (unrefined) range was at least 80% within our study regions, assuring that our assumptions of threat were applicable to most of the species' range. We calculated the range size for each species at each step of the refining process: original range, refined by elevation, refined by forest (Fig. 2), and applied criterion B1 in the IUCN Red List Categories and Criteria guidelines (*7*).

Figure 3 provides an example of this kind of assessment for the Atlantic Forest of Brazil; examples for the other five regions are in the Supplementary Materials. For 55 species (56%), the IUCN's current category matches the category we recommend solely on the basis of range size. Fifteen species are placed in higher-threat categories than those only based on range size (three critically endangered, six endangered, and six vulnerable). We present examples of six endemic birds to illustrate how our suggested method is useful for species whose main cause of endangerment is habitat loss.

Birds primarily endangered by forest loss, like the Serra do Mar tyrant-manakin (*N. chrysolophum*), grey-winged cotinga (*T. condita*), Rio de Janeiro antbird (*C. brasiliana*), and striated softtail (*T. macroura*), have small refined ranges that match the thresholds for threatened categories. For species suffering from hunting pressure, like the red-billed curassow (*C. blumenbachii*) in the Atlantic Forest, the IUCN classification is endangered despite its large range. Another case in which the IUCN assigns a higher-threat category is the ochre-marked parakeet (*P. cruentata*), which is threatened by the pet trade. These cases are evidence of the completeness of the IUCN classification scheme, and we acknowledge that the use of this additional information is essential.

However, habitat loss and degradation are the biggest threat to most of the species in the world's most biodiverse places (*4*), and especially in the Atlantic Forest (*22*). Our refining process for the Atlantic Forest recommends placing 27 (27%) species in higher-threat categories based on the available forest. For 23 species currently deemed near-threatened or of least concern, the refined range size suggests that they should be recognized as vulnerable (18 species) and endangered (5 species). This is also the case for four species currently classified as vulnerable, which should be endangered (two species) and critically endangered (two species). One of the species that we found should be up-listed from its current vulnerable status to critically endangered is the grey-winged cotinga (*T. condita*), one

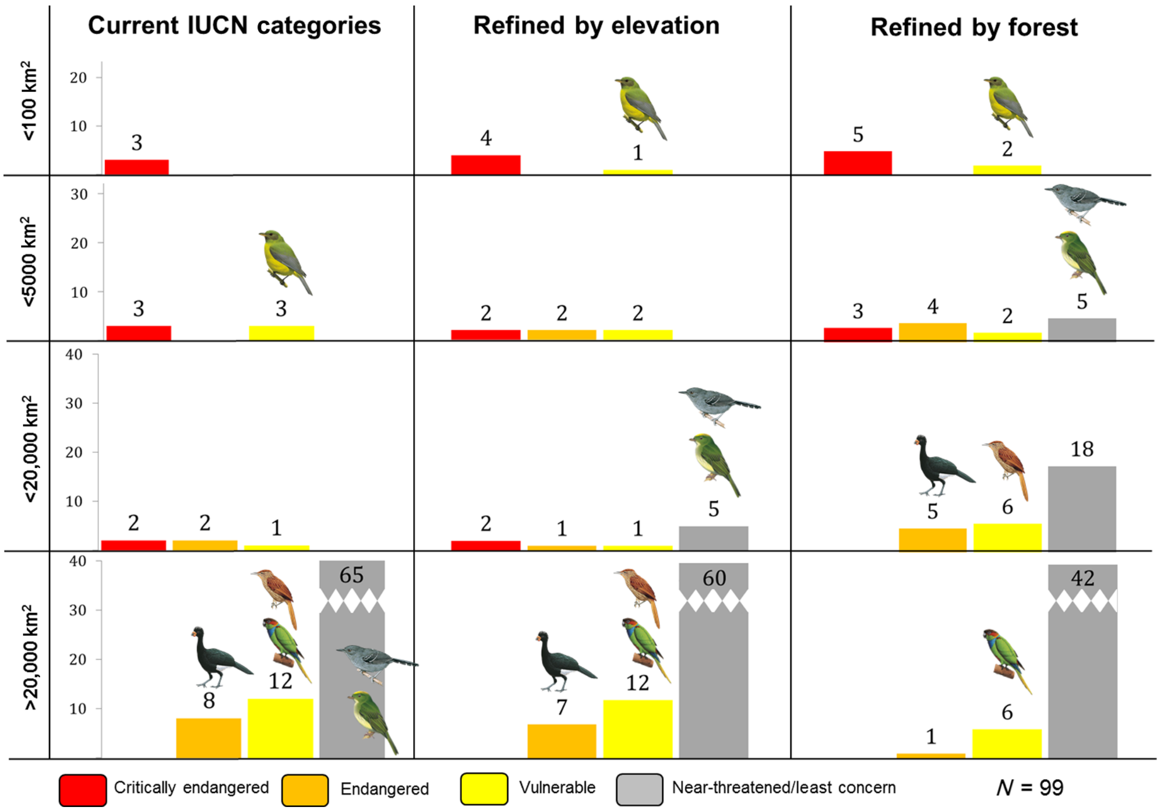

Fig. 3. Threat category reassessment for the Atlantic Forest of Brazil throughout the range refining process. The left axis shows thresholds for the extent of occurrence of IUCN threat categories: critically endangered (<100 km^2), endangered (<5000 km^2), vulnerable (<20,000 km^2), and nonthreatened (>20,000 km^2). The solid bars reflect the current global IUCN categories. Bird illustrations show examples for six endemic birds from Fig. 2 (Serra do Mar tyrant-manakin, grey-winged cotinga, Rio de Janeiro antbird, ochre-marked parakeet, red-billed curassow, and striated softtail). Illustrations from del Hoyo *et al.* (*34*) were reproduced with permission.

of the most poorly known and rarely observed birds. This result agrees with our previous recommendation for up-listing this bird on the basis of its fragmented habitat, small population size, and vulnerability to climate change (*18*).

Figure 4 summarizes our findings for all the study regions. All regions present similar patterns of up-listing recommendations, especially for species currently deemed nonthreatened (figs. S1 to S5).

The question that follows is whether elevation range, remaining forest cover, and the extent to which ranges are protected are factors already implicitly incorporated into the IUCN criteria. For example, the IUCN classifies some birds and mammals as critically endangered when their original ranges are >20,000 km^2 and some as vulnerable when their original ranges are >100,000 km^2. The IUCN uses expert knowledge of additional threats including but not limited to whether the species is hunted, the specificity of its habitat requirements, estimates of population size, how much habitat remains, and how well it is protected. In short, some might assert that decisions on the risks experienced by individual species may be correct even if the assessors did not explicitly use geospatial data. Even in cases in which this assertion is correct, using explicit quantitative criteria would greatly improve this process.

We understand that the criteria for endangerment that the IUCN uses are based on the original ranges—extents of occurrence—not on our refined ones, which are inevitably smaller. The IUCN uses an original range of 20,000 km^2 as an important benchmark. Our use of the same extent aims to identify additional species of concern. These are species that the IUCN does not deem threatened and yet have small geographical ranges once remaining habitat is assessed. We show an example of this for our six study regions in Fig. 4, where there are substantial numbers of species of concern. For example, in addition to 10 species that are already recognized as being critically endangered, we find an additional 2, 7, and 8 species that are endangered, vulnerable, and nonthreatened, respectively, that have refined ranges <100 km^2.

Again, we stress that we are not surprised that, in refining ranges, more species fall below any given threshold—be it 20,000 or 100 km^2. Rather, we find that when we refine the ranges of some species currently deemed nonthreatened, their ranges become as small as those of species currently deemed threatened.

In addition to the range size, refined ranges are fragmented and probably have degraded fragments because of habitat loss. These results are significant because in all our study regions, loss of forest cover continues to threaten biodiversity (*23*–*26*).

Degree of protection under protected areas

Using the World Database on Protected Areas (*27*) and the range maps refined by elevation and forest, we calculated the fraction of a species' range within protected areas. Perhaps those species that the IUCN does not consider threatened but have small refined ranges might be disproportionately better protected by the network of protected areas. Data on the fractions of ranges protected reject this possibility because most of the species recommended for up-listing have less than 10% of their habitat protected (Fig. 5). The lack of

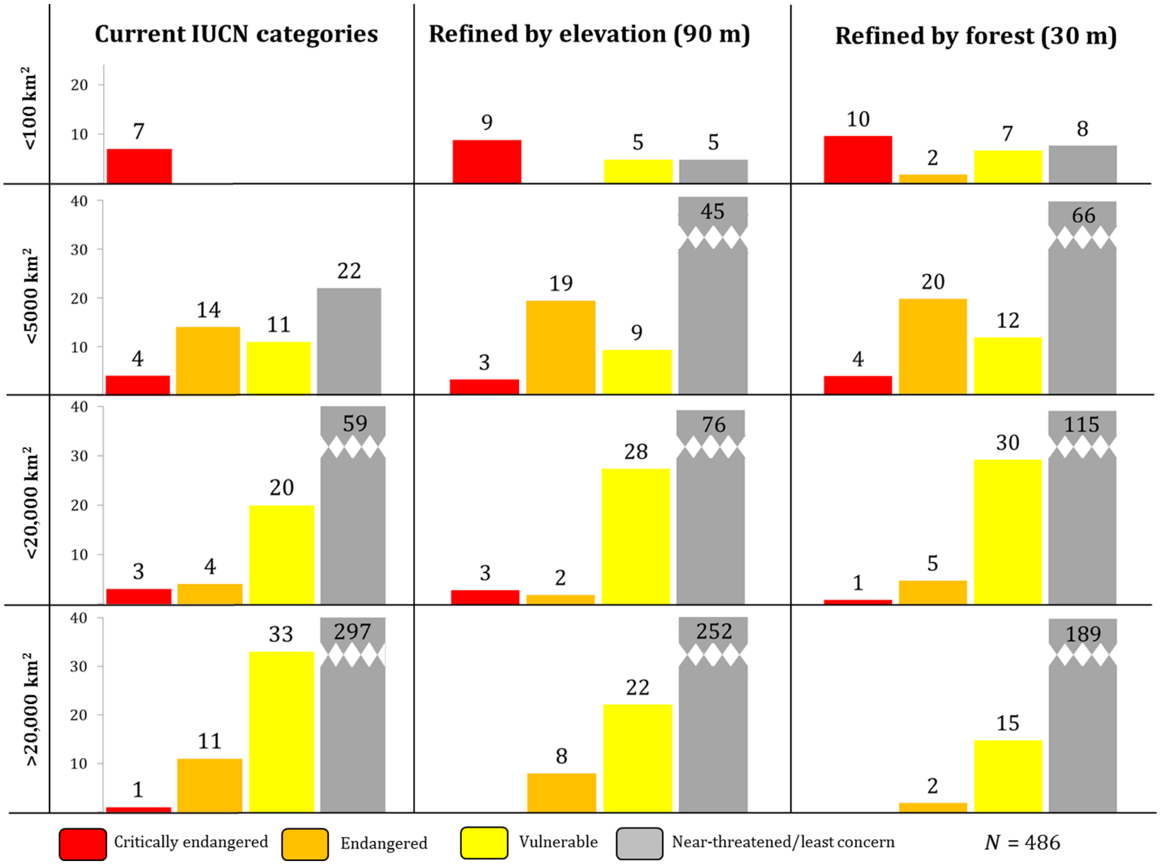

Fig. 4. Threat category reassessment for the six regions throughout the range refining process. The left axis shows thresholds for the extent of occurrence of IUCN threat categories: critically endangered (<100 km^2), endangered (<5000 km^2), vulnerable (<20,000 km^2), and nonthreatened (>20,000 km^2). The solid bars reflect the current global IUCN categories. The regions included are as follows: Atlantic Forest in Brazil, Central America, Western Andes in Colombia, Madagascar, Sumatra, and Southeast Asia.

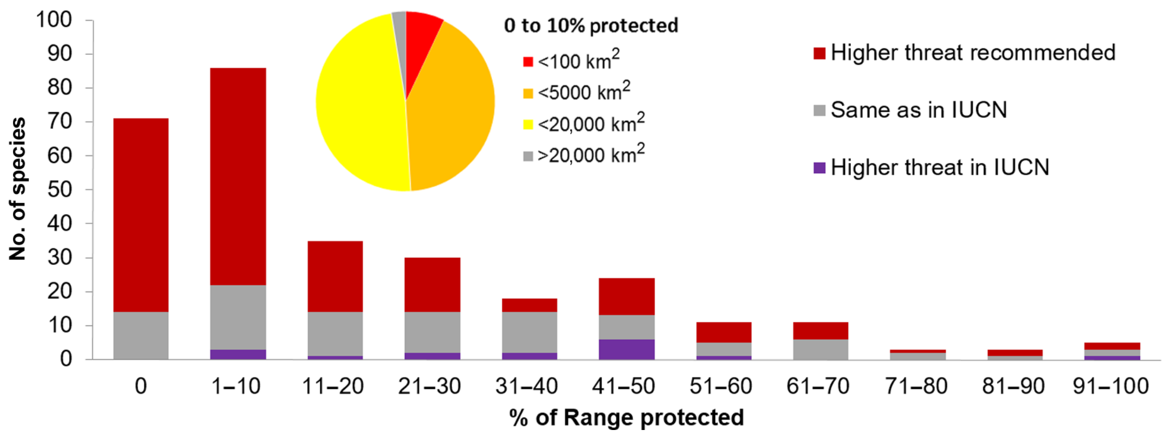

Fig. 5. Percentage of range within protected areas for current and recommended threatened birds in six biodiversity hotspots. Percentage of the range refined by elevation and forest that is within the protected areas for species classified as threatened by either IUCN or our analyses (that is, critically endangered, endangered, or vulnerable). In red are those species that have refined ranges comparable to species with a higher level of threat than what IUCN suggests. Those in gray have the same level, and those in purple are in a lower level. The Atlantic Forest, Central America, the Western Andes of Colombia, Madagascar, Southeast Asia, and Sumatra have 57, 93, 23, 39, 65, and 20 species, respectively. The pie chart shows the distribution of range sizes for the 0% and 1 to 10% range protected categories (*4*).

protection of many threatened birds is especially worrying given that deforestation persists even within protected areas and that the effectiveness of these areas varies (*13*).

Conservation priorities change as ranges are refined

To refine conservation priorities for each study region, we added the ranges of all selected species at each step to show areas of high concentration of endemic and threatened species. These differ too when species ranges are refined by elevation and remaining forest in our study regions. Figure 6 provides examples for the six study regions. Refining by elevation narrows down conservation priorities, and these often concentrate in the mountains, where most endemic species are (Fig. 6, B, C, E, and F). Further refining by available forest is essential to focus efforts on the remaining forest fragments, and can inform restoration efforts in areas where the forest has been lost or fragmented. When mapping conservation priorities, the fact that refining ranges as we do here can change the extent and location of priority areas is vital to consider for conservation planning at local scales.

DISCUSSION

If we apply range size criteria based on the refined ranges, 27 species (6% of all species evaluated) would be placed in lower-threat categories than their current IUCN assignments, although factors other than habitat loss may threaten these species. In the case of 249 species (51%), our suggested threat categories match those determined by the IUCN currently. For 210 species (43%), we suggest a higher-threat category than that currently assigned by the IUCN. In this group of species, a marked group of 189 species are currently classified as near-threatened or of least concern, when their refined range size indicates

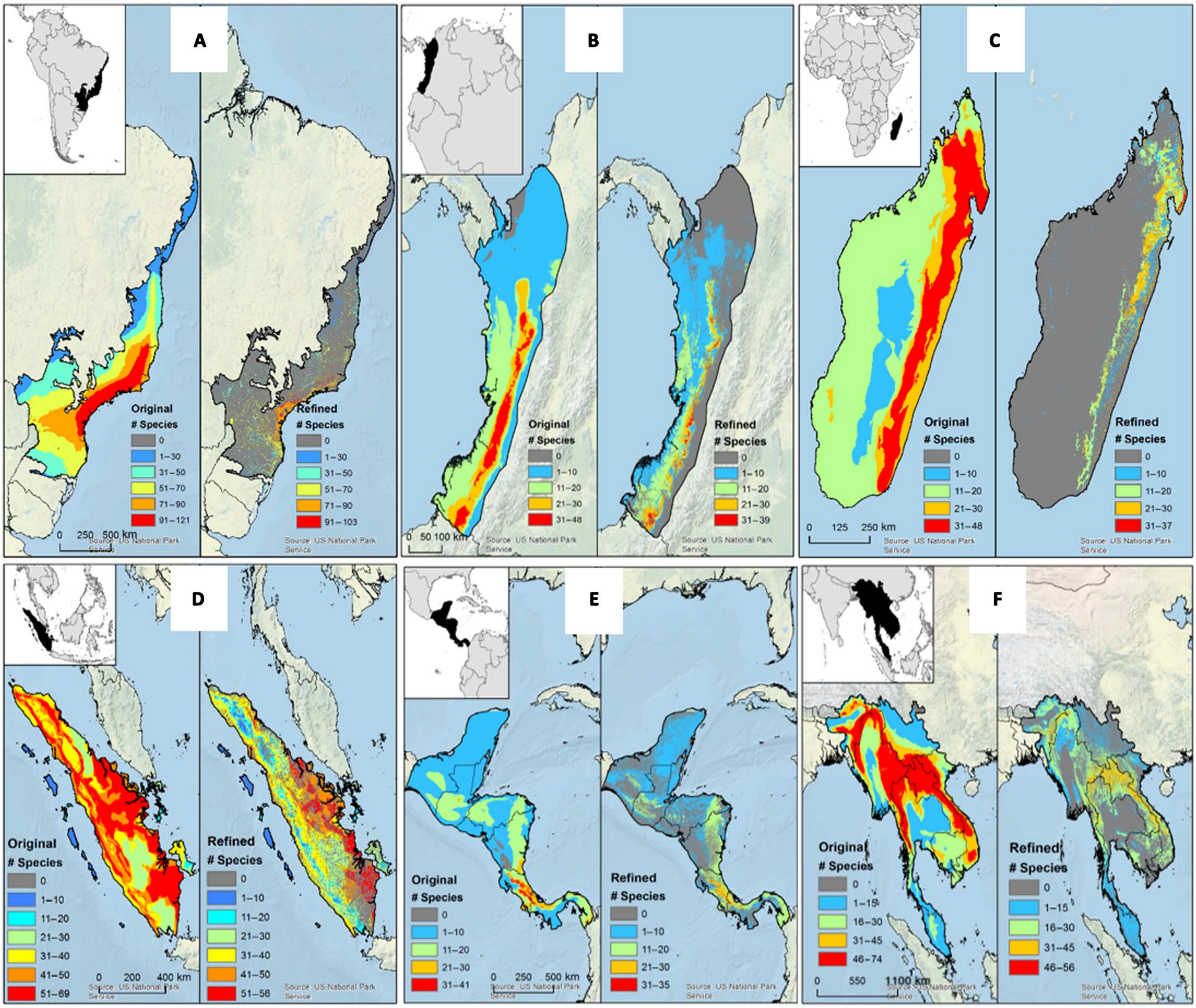

Fig. 6. Concentrations of endemic and threatened bird species in six biodiversity hotspots. Left: Original ranges. Right: Ranges after refined by elevation and forest. (**A**) Atlantic Forest in Brazil. (**B**) Western Andes in Colombia. (**C**) Madagascar. (**D**) Sumatra. (**E**) Central America. (**F**) Southeast Asia.

they might be vulnerable (115), endangered (66), and critically endangered (8) (Fig. 4).

In summary, we show that incorporating geospatial data into the Red List evaluations extends the existing IUCN assessment process and changes extinction ratings for those species threatened by habitat loss. We identified 43% of our study species as potentially more threatened than previously thought and show that most of their ranges are not protected by the current protected areas network. The most parsimonious interpretation of our results is that there are substantially more species at risk than what the IUCN currently asserts.

Our methods offer the opportunity to apply conservation priorities at different scales, spanning urgent to long-term conservation actions, and with the possibility of monitoring over time [as suggested by Margules and Pressey (*28*)]. We present a flexible method that not only can be applied by global organizations but also can be downscaled by local governments and nongovernmental organizations for more urgent and effective conservation action, using better forest products and specific elevation limits data for the region and complementing with other priorities [for example, see studies by Ocampo-Peñuela and Pimm and Jenkins *et al.* (*3*, *19*, *29*)].

We have caveats. First, in refining by elevation, we take the minimum and maximum elevations across a species range. Especially for widely distributed species, this estimate may be too inclusive, because the species may have narrower elevation limits in particular parts of the range. Using narrower elevation limits for these species would result in even smaller refined ranges than those we have suggested. Of course, the species of greatest concern are those with the smallest ranges, for which geographical variation in elevation limits is less likely to be a concern.

Second, adding more information on a species distribution helps our understanding of its status. So why do we focus only on elevation, remaining habitat, and the fraction of range protected? Simply, these variables are of undeniable importance across all species and are simple to incorporate. As noted above, we recognize that there are attempts to improve on the area of occupancy on the basis of better location and behavioral data. Simple, readily available modifications to published range maps are going to be the way forward that we can apply to most species.

Our methods may result in commission and omission errors, as described by other authors (*30*). Knowledge of species continues to expand, and in some cases, bird ranges may truly extend beyond the current polygons (omission errors). Although these errors are important, they can only be solved through continuing searches for birds in the field, as we have done in Colombia (*3*). The far greater immediate errors are the commission errors that we attempt to reduce here.

Third, the classification of risk depends on both the small range size and the presumption of continuing loss of habitat. In some cases, one can directly detect continuing loss of range with repeated surveys of remaining forest cover [for example, see study by Tracewski *et al.* (*31*)]. That said, we take the fact that a species may have little remaining habitat within what experts have designated its extent of occurrence to be sufficient to justify concern. Limited studies (*15*) often show massively fragmented ranges when one refines ranges by the remaining habitat—all a consequence of habitat destruction. Visual inspection of the remaining ranges suggests that the problem of fragmented ranges is ubiquitous. A further cause for concern is that we show that many species have little or none of their ranges within protected areas so that there is little to prevent the continuing loss of habitat.

Fourth, the reason we preceded this study with regional case studies and some species-specific ones is that expert opinions must always add to the decisions. Local studies of land cover may be better informed about the conversion of forests to tree plantations, for example, which global forest assessments miss (*32*). There will always be additional local information on a multitude of factors that we discuss in these studies—and many that others cover—which means that the process of risk assessment cannot be completely automated.

That said, mapping remaining habitat is an essential step that should be incorporated into current criteria and evaluation guidelines. With the rapid advance in technology, the availability of global land cover data sets, and the method proposed, extinction risk assessments and conservation priorities could be evaluated periodically to identify new species of concern and monitor those already threatened. By evaluating the extent to which a species is protected under protected areas, the IUCN could further prioritize those species in the most urgent need of conservation action.

An organization as important as the IUCN needs to take advantage of new technologies, algorithms, information, and automation of processes that can currently take decades. We acknowledge that our analyses could be improved by the creation of a new threshold for a "refined extent of occurrence" and an extension to other taxa. We have a simpler solution.

Our recommendation is succinct and modest. In discussing a species' risk of extinction, it would be entirely simple to add one sentence, of the kind, "species A has an extent of occurrence of X km^2, of which only Y km^2 is within the known elevational bounds of the species, and which at best only Z km^2 has remaining natural habitat; only Q% of that remaining habitat is currently protected." This sentence would greatly aid those who manage endangered species and prioritize which areas should be protected.

MATERIALS AND METHODS

Additional details on methods are in the Supplementary Materials, where table S1 provides a list of the species analyzed.

Study regions

We selected six widely recognized major biodiversity hotspots. The Western Andes of Colombia boundaries are defined in a previous study by Ocampo-Peñuela and Pimm (*3*), and those for Southeast Asia are described by Li *et al.* (*32*); Sumatra and Madagascar are both oceanic islands. Here, we define Central America as the biogeographical region covering the area from Panama to the Tehuantepec Isthmus in Mexico.

Study species

To classify birds as forest species, we applied a set of criteria to the "Habitats" and "Altitude" categories in BirdLife International's species fact sheets (*21*). There are two levels of habitat categories (levels 1 and 2) and a measure of importance (major or suitable). We selected only species that had "forest" listed as their "major" habitat regardless of the level (and including species that also had additional habitats listed as "major") or had forest listed as "suitable" habitat but no other habitat type listed as "major." If a habitat other than forest was listed as "major," we did not include the species. Using these criteria, we analyzed species that need forest for all or some part of their life cycle. To select endemic birds, we selected species with at least 80% of their original range (before refining) within our study regions.

Range refinement

We started with version 4 range maps published by BirdLife International and NatureServe for the 586 bird species in the six study regions (Fig. 2A). Those maps often included areas that were not suitable for the species because they were not at the right elevation or have lost available habitat. As we have done for Central America (*33*), the Atlantic Forest of Brazil (*19*), Colombia (*3*), China (*5*), and Southeast Asia (*32*), we refined the existing range maps by elevation and habitat—in this case forest. To refine by elevation, we used the SRTM 90m Digital Elevation Model (*11*) and selected only areas that were within the preferred elevation for each species (Fig. 2B). We determined these preferred elevations as the maximum and minimum elevation at which the species has been observed, as described in the *Handbook of the Birds of the World Alive* (*34*) and by BirdLife International.

When the elevation was 0, we used 100 m as the maximum elevation. Once we refined the range map by elevation, we used 30-m forest cover maps to refine by remaining habitat. For all regions except the Western Andes and Atlantic Forest, we created the 30-m forest cover classification using the Global Forest Change data set version 1.2 by Hansen *et al.* (*12*).

To create binary classifications, we used a threshold of 60% to define forest/nonforest classifications. We used this threshold on the continuous tree cover data for 2000 and used loss-and-gain products to estimate forest cover in 2014. For the Western Andes and the Atlantic Forest, we used in-country forest cover maps that had been ground-truthed to check classification accuracy. For the Western Andes, we used a forest cover product at a 30-m scale published by Sánchez-Cuervo *et al.* (*35*), and for the Atlantic Forest, we used a map produced by Fundação SOS Mata Atlântica (*36*) and selected regions classified as forest and "restinga."

Threat category reassessment

We calculated the range size after each refining step and used IUCN thresholds for the extent of occurrence to identify species with range sizes within the thresholds of threatened categories. We followed this process for the original ranges from BirdLife International, those refined by elevation, and ranges refined by elevation and forest. During the process, we kept current IUCN categories to examine how these changed after our refining process.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/2/11/e1601367/DC1

Additional notes on methods

fig. S1. Threat category reassessment for Central America throughout the range refining process.

fig. S2. Threat category reassessment for Madagascar throughout the range refining process.

fig. S3. Threat category reassessment for Southeast Asia throughout the range refining process.

fig. S4. Threat category reassessment for Sumatra throughout the range refining process.

fig. S5. Threat category reassessment for the Western Andes of Colombia throughout the range refining process.

table S1. Lists of bird species included in extinction risk and conservation priority analyses for the Atlantic Forest of Brazil, Central America, the Western Andes of Colombia, Southeast Asia, Madagascar, and Sumatra.

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