Priority areas for conservation of and research focused on terrestrial vertebrates

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Abstract: Effective conservation policies require comprehensive knowledge of biodiversity. However, knowledge shortfalls still remain, hindering possibilities to improve decision making and built such policies. During the last 2 decades, conservationists have made great efforts to allocate resources as efficiently as possible but have rarely considered the idea that if research investments are also strategically allocated, it would likely fill knowledge gaps while simultaneously improving conservation actions. Therefore, prioritizing areas where both conservation and research actions could be conducted becomes a critical endeavor that can further maximize return on investment. We used Zonation, a conservation planning tool and geographical distributions of amphibians, birds, mammals, and reptiles to suggest and compare priority areas for conservation and research of terrestrial vertebrates worldwide. We also evaluated the degree of human disturbance in both types of priority areas by describing the value of the human footprint index within such areas. The spatial concordance between priority conservation and research areas was low: 0.36% of the world's land area. In these areas, we found it would be possible to protect almost half of the currently threatened species and to gather information on nearly 42% of data-deficient (DD) species. We also found that 6199 protected areas worldwide are located in such places, although only 35% of them have strict conservation purposes. Areas of consensus between conservation and research areas represent an opportunity for simultaneously conserving and acquiring knowledge of threatened and DD species of vertebrates. Although the picture is not the most encouraging, joint conservation and research efforts are possible and should be fostered to save vertebrate species from our own ignorance and extinction.

Keywords: conservation investment, conservation planning, decision making, priority research areas, protected areas

Áreas Prioritarias para la Conservación e Investigación Enfocadas en Vertebrados Terrestres

Resumen: Las políticas efectivas de conservación requieren del conocimiento integral de la biodiversidad. Sin embargo, la deficiencia de conocimiento todavía obstaculiza las posibilidades de mejorar la toma de decisiones y construir dichas políticas. Durante las últimas dos décadas, los conservacionistas han realizado un gran esfuerzo por asignar los recursos de la manera más eficiente posible, pero en pocas ocasiones han considerado la idea de que, si las inversiones para la investigación también se asignan estrategicamente, probablemente llenarían los vacíos de conocimiento a la vez que mejoran las acciones de conservación. Por lo tanto, la priorización de las áreas en donde podrían realizarse acciones de conservación y de investigación se convierte en un esfuerzo importante que puede avanzar todavía más la maximización del rendimiento de la inversión. Usamos Zonation, una herramienta de planeación de la conservación, junto con las distribuciones geográficas de anfibios, aves, mamíferos y reptiles para sugerir y comparar las áreas prioritarias para la conservación e investigación de los vertebrados terrestres en todo el mundo. También evaluamos el grado de perturbación humana en ambos tipos

Article impact statement: If research investments were strategically allocated, knowledge gaps could be filled and conservation actions improved.

Paper submitted August 2, 2019; revised manuscript accepted January 10, 2020.
de áreas prioritarias mediante la descripción del valor del índice de la huella ecológica humana dentro de dichas áreas. La concordancia espacial entre las áreas prioritarias para la conservación y para la investigación fue baja: 0,36% del área total de suelo mundial. Encontramos que en estas áreas sería posible proteger a casi la mitad de las especies que se encuentran actualmente amenazadas, así como recopilar información sobre casi el 42% de las especies cuya información es deficiente. También descubrimos que 6199 áreas protegidas a nivel mundial están localizadas en dichos lugares, aunque sólo el 35% de ellas tiene propósitos estrictos de conservación. Las áreas de consenso entre la conservación y la investigación representan una oportunidad para simultáneamente conservar y adquirir conocimiento sobre las especies amenazadas de vertebrados y cuya información es deficiente. Aunque el futuro no es alentador, los esfuerzos conjuntos de conservación e investigación son posibles y deberían fomentarse para salvar a las especies de vertebrados de nuestra propia ignorancia y extinción.

Palabras Clave: áreas prioritarias para la investigación, áreas protegidas, inversión en la conservación, planeación de la conservación, toma de decisiones

Introduction

Comprehensive knowledge of biodiversity patterns and dynamics is important for designing effective conservation strategies that mitigate biodiversity loss and avoid threats (Mace 2004). Unfortunately, such knowledge is still far off (Hortal et al. 2015). For instance, only a small fraction of living species has been identified (Mora et al. 2011). Attaining knowledge of other biological aspects of species (e.g., abundance, ecological functions, interactions, and evolution) is even more daunting (Diniz-Filho et al. 2013; Hortal et al. 2015). However, the more information gathered on a given species, the more likely effective conservation action can be delivered (Xu et al. 2017).

Although terrestrial vertebrates are the best known taxa worldwide and usually considered in conservation policies and recommendations (e.g., Rodrigues et al. 2004; Venter et al. 2014), there are still large knowledge shortfalls for these taxa (Jetz & Freckleton 2015; Nori et al. 2018). These shortfalls translate into a large percentage of known vertebrates being categorized as data deficient (DD) (species with insufficient information to assess their conservation status) by the International Union for the Conservation of Nature (IUCN). Moreover, DD species are frequently ignored in conservation planning and policy (Nori & Loyola 2015). Although determining the conservation status of such DD species is essential to effective conservation policies (González-del-Piiego et al. 2019), efforts to do so have, paradoxically, been much less than those focused on defining priority areas for conservation based on current information.

Researchers, nongovernmental organizations, and decision makers have compiled useful information to identify and prioritize key areas for conservation, in which conservation resources can be strategically invested so as to maximize benefit and return on investment. An entire discipline (i.e., Systematic Conservation Planning [SCP]) and computational software (e.g., Moilanen et al. 2014) have been developed to identify priority conservation areas based on biological features and cost (Margules & Pressey 2000). As expected, most prioritization efforts have terrestrial vertebrates as target groups because there is more information on these species than other taxa (Venter et al. 2014; Prieto-Torres et al. 2018).

Analogous to priority areas for conservation, we recently proposed a way to identify priority areas for conducting research that can help target surveys to obtain knowledge on DD species (Nori et al. 2018). We found that if research efforts are strategically distributed, it is possible to acquire information on >80% of DD amphibians within only 0.4% of the world’s terrestrial area. These findings highlight the importance of strategically distributing research funds to fill knowledge gaps as efficiently as possible, potentially maximizing the return on investment. Moreover, prioritizing areas for research can easily be applied to other biological groups and
geographic regions to guide investment and thus more efficiently use research funds while considering a larger proportion of biodiversity.

Aiming to contribute to the generation of knowledge of DD terrestrial vertebrate species and evaluate the potential of conservation areas for such an endeavor, we identified priority areas for research on DD terrestrial vertebrates (amphibians, reptiles, birds, and mammals) and priority areas for conservation of threatened vertebrates; evaluated the spatial congruence between these 2 sets of areas; evaluated the degree of human disturbance within both types of global priority areas to determine the current conservation level of such priority areas and thus define the possibilities and urgency to take action; and defined the most important protected areas (those already established) in terms of both conservation and research priorities.

**Methods**

**Species Data**

We obtained digital range maps (extent of occurrence maps) for 6,591 amphibians, 10,064 reptiles, 11,121 birds, and 5,439 mammals from the IUCN database (IUCN 2018) for amphibians and mammals, the BirdLife International Database (www.birdlife.org) for birds, and the recent global assessment of reptile distributions (http://www.gardinitiative.org/data.html). We selected 2 subsets of species: threatened and DD. Threatened species were all terrestrial vertebrate species in the IUCN categories vulnerable (VU), endangered (EN), and critically endangered (CR): 5970 terrestrial vertebrates total, 2099 amphibians, 1261 reptiles 1438 birds, and 1172 mammals. The DD species were all terrestrial vertebrate species considered DD and that had restricted-range species (IUCN 2012). We considered only restricted-range DD species following our main goal of identifying priority research areas and assuming that local studies could be sufficient to obtain the information needed to categorize these species as threatened or not. To do so, we followed the IUCN criteria and used 20,000 km² as a threshold to define restricted-range species (IUCN 2012).

Based on the species’ range maps, we used the letsR package in R (Vilela & Villalobos 2015) to generate a presence-absence matrix of species across cells of a global grid with a resolution of 0.5° of latitude–longitude. Based on this matrix, we recovered individual raster files representing the distribution of each species with the raster package in R (Hijmans et al. 2019). Given the large number of species and the global extent of our analyses, as well as the bias associated with the source of species’ geographic data (which precludes working at fine spatial resolutions [Ficetola et al. 2013]), we ran the analyses at a spatial resolution of 0.5° of latitude–longitude. Using range maps at finer resolutions would have increased biases related to overinterpretation of the limited information contained in these maps (e.g., commission and omission errors [Peterson 2017]).

**Spatial Prioritization**

Based on the distribution of each data set, threatened and DD species, we conducted different prioritization analyses aimed at determining the 0.5%, 1%, and 5% highest priority terrestrial areas worldwide (1,174,433, 2,348,946, and 5,872,365, respectively). We selected these 3 thresholds ad hoc based on the percentage of species represented in the defined priority areas (see Results). These prioritizations represented the best places for protecting the species (i.e., those with the greatest complementary representation of threatened species) and the best places to conduct research (i.e., those with the greatest complementary representation of DD species).

For both prioritizations, we ran analyses for all terrestrial vertebrates together and then separately for amphibians, mammals, and reptiles. We did not run a separate prioritization for birds because only 26 out of 11,121 (~0.2%) bird species were listed as DD with restricted ranges and, given the nature of SCP protocols, it would not be informative to perform a prioritization analysis under a scenario with virtually no species overlap (as in the case of bird DD species). In total we developed 8 prioritization schemes: priority conservation areas for mammals, amphibians, reptiles, and all terrestrial vertebrates and priority research areas for these same groups.

We ran prioritization analyses in Zonation 4.0 (Moilanen et al., 2014), a systematic conservation-planning decision-support tool. Although Zonation is conventionally used for determining regions where conservation action could be undertaken (Margules & Pressey, 2000), we recently proposed its application for identifying areas where research actions could be taken to fill the knowledge gaps related to DD species (Nori et al. 2018). Zonation produces a complementarity-based ranking of areas by iteratively removing the pixel that leads to the smallest aggregate loss of value.

Each pixel priority level was calculated based on 2 different cell removal rules: additive-benefit function (ABF) and core area zonation. We selected the result with the best performance (i.e., largest average representation of species distributions within the top 1% of the world’s terrestrial area) for each prioritization scenario. Study by Moilanen et al. (2014) contains details on removal rules. For the prioritization of research areas (those with DD species), we assigned positive equal weights of 1 to all
species. In contrast, for the prioritization of conservation areas, we weighted species based on their conservation status: 1, VU; 2, EN; and 3, CR. Given the simplicity of the analyses (without negative features, interactions, masks, etc.), all other parameters were kept as default: warp factor = 10; edge removal = 1; BLP = 0, and so on (details in Moilanen et al., 2014). In sum, priority areas were those with high and complementary concentrations of threatened (priority conservation areas) or DD species (priority research areas).

For each prioritization scheme, we determined the mean and median representation of the target species’ geographic distributions for the top 0.5%, 1%, and 5% of the world’s area based on the performance curves of Zonation (Moilanen et al. 2014 for details). Using a Geographic Information System (GIS) platform, we determined the number of target species (represented as the percentage relative to each total) for each scenario overlapping with the top 0.5%, 1%, and 5% of the world’s area and for the consensus areas (see below) between priority conservation and research areas. We considered species covered by our identified priority areas even if they only occurred in a small fraction of these areas (e.g., 1 grid cell), which for a large number of restricted DD species may represent its complete distributional range.

Additional Analyses

To determine the degree of spatial congruence between priority conservation and research areas, we calculated the percentage of spatial match between these 2 types of priority areas. To do so, we overlaid maps of the top 0.5%, 1% and 5% of the world’s terrestrial area for each scenario and calculated the percentage of overlap (i.e., consensus) between priority areas. Then, in a GIS platform, we calculated the number and percentage of represented target species in the identified consensus areas. We repeated this process to calculate the percentage of overlap for the top 1% priority conservation and research areas between pairs of our evaluated taxa. Using the maptools package for R, we determined the proportion of the top 1% of priority areas (based on priority research and conservation areas and areas of consensus) falling within each country and continents of the world. We did these analyses for all terrestrial vertebrates and separately for each taxon.

We also determined the level of human pressure on natural ecosystems in both kinds of priority areas as well as for the consensus areas. We used the human footprint index 2.0 raster (WCS & CIESIN 2005), which is a complex index created from 9 global data layers. We classified the original human footprint raster into 4 categories with the same number of pixels each (i.e., 25% of the total pixels representing the world’s terrestrial surface): very low human intervention (index values of 0–1); low human intervention (1–12); moderate human intervention (12–26), and high human intervention (26–100). Finally, we overlaid the binary raster of priority areas of terrestrial vertebrates and areas of consensus between conservation and research areas and calculated the percentage of pixels overlapping with each of the 4 categories of human footprint. In addition, we calculated the mean, median, and standard deviation of the human footprint values within the priority areas.

Finally, we identified the existing protected areas that can be simultaneously considered priorities in terms of both conservation and research for terrestrial vertebrates. We overlapped the identified area of consensus between priority conservation and research areas for terrestrial vertebrates with the global network of protected areas (PAs) (IUCN & UNEP 2019). We downloaded the original database of protected areas and filtered all terrestrial PAs with geographically defined boundaries. After that we intersected this subset of PAs with our identified priority areas of consensus and categorized PAs based on their IUCN status, designation type, and degree priority. We defined 3 categories of priority for PAs based on their overlap with the priority consensus areas from the 3 top percentages, 0.5%, 1%, and 5%, of the world.

Results

For the 8 evaluated scenarios, the ABF removal rule showed the best performance (Supporting Information). Results for the top 0.5%, 1%, and 5% of the identified priority areas showed very similar patterns in all cases. Therefore, we describe results only for the top 1% of the world’s area, whereas results for the 0.5% and 5% are reported in Tables 1 and 2. Hereafter, we refer to priority conservation areas and priority research areas as the top 1% of the world for the prioritizations considering threatened and DD species, respectively.

When all 4 vertebrate taxa (mammals, amphibians, birds, and reptiles) were pooled, priority conservation areas encompassed, on average, half of the distributions of threatened vertebrates (median 50%). These conservation areas overlapped with 74% of the threatened terrestrial vertebrates (percentages per vertebrate order in Table 1). In the case of priority research areas for all studied vertebrates, these encompassed, on average, 64% (median 100%) of the distributions of restricted DD species, overlapping in total with 79% of all restricted DD vertebrate species (Table 1).

Priority conservation and research areas, considering all terrestrial vertebrates, had a 36% overlap (i.e., shared 36% of their pixels, which represents 0.36% of the world’s terrestrial surface). This area of conservation and research priority overlapped with almost half (49%) of threatened terrestrial vertebrates and with a slightly
Table 1. Species distribution and richness and human impact in the conservation and research areas identified as among the 0.5%, 1%, and 5% highest priority areas for mammals (MA), amphibians (AM), birds (BI), and all species (ALL).

| Species distributions (%) | Priority type | ALL | MA | AM | RE |
|---------------------------|---------------|-----|----|----|----|
| conservation              | 0.5%          | 38  | 37 | 62 | 45 |
|                           | 1%            | 50  | 48 | 78 | 56 |
|                           | 5%            | 77  | 76 | 97 | 77 |
| research                  | 0.5%          | 46  | 66 | 62 | 65 |
|                           | 1%            | 64  | 84 | 83 | 82 |
|                           | 5%            | 94  | 94 | 95 | 93 |

| Species represented (%)  | Priority type | ALL | MA | AM | BI | RE |
|--------------------------|---------------|-----|----|----|----|----|
| conservation             | 0.5%          | 60  |
|                           | 1%            | 74  |
|                           | 5%            | 96  |
| research                 | 0.5%          | 60  |
|                           | 1%            | 79  |
|                           | 5%            | 94  |

| Overlap with human-impact categories (%) | Priority type | 0.5% | 1% | 5% |
|------------------------------------------|---------------|------|----|----|
| conservation                             | Q1            | 2    |
|                                          | Q2            | 6    |
|                                          | Q3            | 34   |
|                                          | Q4            | 58   |
| research                                 | Q1            | 3    |
|                                          | Q2            | 13   |
|                                          | Q3            | 36   |
|                                          | Q4            | 47   |

\(^a\)Mean of species distributions encompassed in priority conservation and priority research areas.

\(^b\)Number of each type of species (threatened and restricted data deficient), in percentage of the total, that overlap with priority conservation and priority research areas.

\(^c\)Percentage of priority conservation and priority research areas that overlap with each category of the human footprint index: Q1, very low human intervention (human footprint values 0–1); Q2, low human intervention (1–12); Q3, moderate human intervention (12–26); Q4, high human intervention (26–100).

lower percentage (42%) of restricted DD terrestrial vertebrates (Tables 1 & 2; Figs. 1 & 2). As expected, considering a higher percentage of top areas increased the area of consensus between priority conservation and research areas. For instance, for the top 5%, both types of priority areas had a 49% overlap, representing 2.45% of the world’s area. This 2.45% overlapped, in turn, with >70% of both sets of target species (Fig. 1; Tables 1 & 2).

The overlap between priority conservation areas across taxa was generally low. This was also true for the priority research areas between amphibians and reptiles. However, the overlap between mammals and both amphibians and reptiles for the top 1% priority research areas was close to 50% (Supporting Information). Individually, the top 1% priority conservation areas for mammals overlapped with 77% of threatened mammals, encompassing, on average, 48% (median 41%) of the distributions of these species (VU, EN, and CR mammals). The top 1% of priority research areas for mammals overlapped with 86% of DD mammals and encompassed, on average, 84% of DD mammals’ distributions (median 100%). For this taxon, there was a 39% overlap between the top 1% conservation and top 1% research areas. In the case of amphibians, the top 1% priority conservation areas overlapped 90% of threatened species and encompassed, on average, 78% of their distributions (median 70%). Top 1% of priority research areas for amphibians overlapped with 90% of DD species encompassing, on average, 83% of their distributions (median 100%). For amphibians, there was a 51% overlap between the top 1% conservation and top 1% research areas. For reptiles, priority conservation areas overlapped with 75% of threatened reptiles (median 78%), encompassing, on average, 56% of their distributions. Priority research areas for this taxon encompassed a mean of 82% of restricted DD reptiles (median 100%), overlapping 89% of these species. Both areas shared 36% of their pixels (Table 2 & Fig. 2).

Priority conservation areas (top 1%) identified for the combined vertebrate taxa concentrated in particular regions of the world. In fact, almost half (42%) of such priority conservation areas were concentrated in 5 countries (Madagascar, Mexico, Colombia, Peru, and Ecuador). Similarly, 43% of priority research areas for these vertebrates were concentrated in 6 countries (Brazil, Indonesia, Colombia, Mexico, and Peru [Supporting Information]). Consensus areas between the top 1% conservation and research priorities for all terrestrial vertebrates (0.36% of the world) were located...
mainly in the tropical Andes and the western rainforest of India; 51% of these consensus areas were concentrated in 5 countries (Supporting Information). Conversely, there were regions with high concentrations of only one type of priority area but not the other. For instance, Papua New Guinea and the Atlantic Forest of Brazil showed extensive regions of priority research areas, whereas Mexico and Madagascar presented large regions of priority conservation areas (Fig. 2). Priority areas for mammal conservation and research were quite dispersed across the globe, as were the small areas where both priorities overlapped (Fig. 2). For amphibians, priority conservation areas were concentrated in the tropical Andes, Central America, Central Africa, and Madagascar, whereas their priority research areas concentrated in the tropical Andes, Atlantic Forest, and Southeast Asia. For reptiles, priority conservation areas were mainly concentrated in Central America, whereas priority research areas were mainly dispersed across Southeast Asia. Consensus areas for reptiles were less concentrated than those for amphibians but less dispersed than those for mammals. The human impact in both types of priority areas was high in all the analyzed scenarios. Considering all terrestrial vertebrates together, the top 1% priority conservation areas showed an average value of human footprint of 25.7 (SD 13.0, median 26.0); 45% of those areas were located in areas of high human intervention. Similarly, areas of consensus between conservation and research largely overlapped with areas of high human intervention; mean value of human footprint was 28.6 (SD 12.9, median of 28) (Tables 1 & 2; Figs. 1 & 2).

We identified 6199 PAs that overlapped with areas of consensus between priority conservation and research areas for terrestrial vertebrates, of which 661 were PAs of high priority (top 0.5% of the world). Most of these 6199 PAs (93%) are designated as such, but only 35% of these belonged to IUCN categories I-IV. These identified priority PAs had a mean size of 938.9 km$^2$ (SD 18,238.3, median of 14.5) and were larger than the average PA (mean of 248.3 [SD 9947], median of 0.57) (details in Supporting Information).

Discussion

We conducted the first effort to identify priority areas that can be important for simultaneously conducting conservation and research on terrestrial vertebrates. Consensus areas between priority conservation and research areas for the top 1% of the world’s terrestrial surface was low but increased as the selected top percentage increased,
overlapping as much as 49% for the top 5% of the world and representing ~2.5% of its terrestrial surface. Over such a small area of the world, there can occur >70% of threatened and DD terrestrial vertebrates with restricted ranges. As such, investing resources in such consensus areas could be extremely profitable. Indeed, these consensus areas could be considered as priority conservation areas with an additional, highly important advantage: their joint importance for the conservation of threatened species and that they ensure the persistence of strategic areas for conducting research. Research in these areas could eventually fill the knowledge shortfall needed to bring DD species out of this category. This is especially relevant if one considers that many species could become extinct even before they are discovered and that priority research areas can represent areas with a great potential for the discovery of new species (Nori & Loyola 2015; González-del-Pliego et al. 2019).

Beyond the comparisons between priority conservation and research areas, ours is, to our knowledge, the first study to focus on delineating strategic areas to invest research efforts for terrestrial vertebrates. Our results highlight that if research efforts were to be strategically distributed across a small portion of the world’s terrestrial area, it would be possible to generate relevant information to help fill knowledge gaps associated with restricted DD vertebrate species. In fact, it would be potentially possible to survey most DD species (84% of amphibians, 63% of birds, 68% of mammals, and 76% of reptile species) by focusing on just 1% of the world’s surface, which overlaps a large proportion of their already restricted distributions (mean of 64%), as evidenced by half of all restricted DD species having their complete distribution overlapping these priority areas. This is exceedingly relevant if one considers the negative impact of knowledge shortfalls on the effective conservation of species (Nori & Loyola 2015; Hortal et al. 2015) and that the best solution to such knowledge shortfall is prioritizing the basic research needed to bring them out of the DD category (Scherz et al. 2019).
Priority conservation areas, particularly those with high species richness (here, those areas with the greatest complementary representation of threatened species), would also be expected to harbor high concentrations of undiscovered, recently discovered, and poorly known species simply by chance (Meyer et al. 2015), but this is not always the case. The picture is much more complex due to strong anthropogenic effects. Indeed, human history and consequently the history of science has influenced this null hypothesis of a direct relationship between species richness and potential knowledge. Accordingly, biodiversity knowledge and thus knowledge shortfalls are not homogenously distributed across the globe. For instance, there are

Figure 2. Priority conservation (red) and research (blue) areas (1% highest priority areas) and the areas of consensus between them (black) for (a) mammals, (b) amphibians, and (c) reptiles. Key shows the percentage of overlap between priority conservation and research areas and the percentage of represented species of each major taxon.
highly explored and studied biodiversity hotspots (e.g., Mexico or Madagascar) that represent a priority area for conservation but not necessarily for research in the global context, whereas other hotspots remain poorly known (e.g., tropical Andes) and clearly represent priority areas for research as well as conservation. The differential degree of human modification and vulnerability of areas can lead to a mismatch between priority conservation and research areas. For example, based on its topographic and climatic characteristics as well as human development, among other social and economic factors, there are hyperdiverse regions that are still poorly explored (e.g., parts of the Amazon and tropical Africa) and thus may represent priorities for research but not necessarily for conservation, if the latter is based on the degree of vulnerability (Brooks et al. 2006).

The spatial match between priority conservation and research areas was evident when considering terrestrial vertebrates as a whole (from 36% in the top 1% to 49% in the top 5% of such areas being consensus areas) and individual taxa but with considerable differences among them. For instance, most regions where both types of priority areas were congruent for amphibians were also regionally concentrated, mainly in the Tropical Andes, which is consistent with Nori et al. (2015, 2018). Conversely, the pattern was quite different for mammals; conservation and research consensus areas were quite dispersed across the globe. The pattern for reptiles lay between that of mammals and amphibians; consensus areas were generally dispersed across the globe but some were concentrated in certain regions, such as the Tropical Andes, Central America, and Madagascar. Such differences in the geographical distribution of consensus areas among amphibians, mammals, and reptiles could be related to their distinct dispersal abilities, which in turn translate into larger geographic ranges in mammals compared with reptiles and amphibians (Qian 2009; Roll et al. 2017), as well as their historical patterns of discovery (Diniz-Filho et al. 2005). Larger geographic distributions of mammals and reptiles compared with those of amphibians allow them to occupy regions where the latter taxon is generally absent, such as cold and arid regions (Jenkins et al. 2013; Roll et al. 2017), thus increasing available area for conservation and research priorities consensus in the former taxa while also explaining the sparse distribution of such areas for these taxa. Larger distributions can also make species more prone to detection and description (Diniz-Filho et al. 2005), which could explain the decreasing proportion of DD species and their sparse distribution across the globe as consideration moves from mammals, to reptiles, to amphibians.

Despite the heterogeneous distribution of each type of priority area, that some of these areas are spatially congruent is encouraging. Spatial congruence between priority conservation and research areas means that both goals can, in principle, be fulfilled simultaneously. Although we showed that the spatial match between priority conservation and research areas is low, these spatially congruent areas have a great potential for both research and conservation, representing 0.36% (for the top 1% or as much as 2.45% for the top 5%) of the world’s terrestrial area but overlapping with around half (for the top 1% or as much as 70% for the top 5%) of threatened and DD species of each terrestrial vertebrate taxon. Regions where priority conservation and research areas overlap represent strategic regions where investments could be maximized. In other words, if effort were focused in these areas, it would be possible to conduct imperative conservation actions and to fill simultaneously a great portion of the knowledge gap about terrestrial vertebrates. In this context, these priority areas should be a priority for the designation of new PAs that could avoid the extinction of a large proportion of threatened vertebrates and at the same time ensure the persistence (and possibility of research) of a large number of poorly known vertebrate species.

Regarding the current network of PAs, we identified 6199 PAs overlapping with areas of consensus between conservation and research priority areas for terrestrial vertebrates. This finding implies that such PAs could be considered of the highest priority for investment in research and management actions. These PAs represent a small percentage of the total number of PAs (2.55%). The mean and median size of these priority PAs compared with the average PA across the world suggests PA size could explain, at least in part, the identification of such priority PAs. Still, whether large or small, the relevance of these priority PAs relies on its potential usefulness to fulfill conservation and research goals. In addition, less than one-quarter of our identified PAs are established with strict conservation purposes (IUCN categories I–IV). Considering the great human impact on PAs (Jones et al. 2018), it would be necessary for most of our identified PAs to be assigned to categories that ensure strict conservation actions that could also contribute to fill knowledge gaps on DD species.

The human impact across our identified priority areas for conservation and research of terrestrial vertebrates was very high; most of the priority areas overlapped with zones of high values of human footprint index. The degree of human impact was higher in priority conservation areas than in priority research areas, but still considerable for these latter areas. This is not surprising if one considers that direct human impacts are the main threat for vertebrate species (IUCN 2018) and that here priority conservation areas were identified on the basis of threatened species distributions. However, the recognition of a high human impact in priority research areas is a novel and worrying result because it means that filling knowledge gaps on DD species in these areas may be compromised. As such, it would be important to work at finer spatial scales in the identified priority areas.
and to use other essential information, such as proxies of human disturbances (e.g., human footprint) as cost layers with the aim of finding those priority conservation and research areas with the least possible human disturbance.

While many previous studies have generated useful information to guide an efficient distribution of conservation resources (e.g., Rodrigues et al. 2004; Brooks et al. 2006; Venter et al. 2014), the positive feedback between filling knowledge shortfalls and defining spatial conservation priorities has never been considered explicitly. We took the first step toward this goal and presented relevant information aimed to help the strategic distributions of conservation and research resources at a global scale. Although the picture is not the most encouraging (the spatial overlap between priorities for conservation and research is low and the human impact is high), we found that there are areas of special interest, where joint effort is possible and should be extremely profitable. Our goal was the identification of priority conservation and research areas at a global scale as a fraction of the world’s terrestrial surface and not specifically the coverage of whole species distributions (i.e., species targets). Further refinements to our methods could consider such targets and more detailed information on species’ ranges and habitat requirements that would be needed for conservation planning at smaller spatial scales within each priority area to ensure that actual conservation and research actions are undertaken. We confirmed results of and extrapolated on our previous work (Nori et al. 2018): if research efforts were strategically distributed, it would be possible to generate a great amount of information about terrestrial vertebrates useful for conservation purposes and potentially helpful for many others scientific disciplines.

Supporting Information

Species’ distribution in top 1% of the world for each prioritization scenario (Appendix S1), overlap between priority conservation and research among major groups (Appendix S2), countries with the highest percentage of priority areas (Appendix S3), and priority protected areas (Appendix S4) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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