Priority areas for conservation of and research focused on terrestrial vertebrates

Javier Nori [1, 2, *]
Rafael Loyola [3, 4]
Fabricio Villalobos[5]

[1] Universidad Nacional de Córdoba, Facultad de Ciencias Exactas, Físicas, y Naturales, Centro de Zoología Aplicada. Rondeau 798 , Córdoba (5000) Argentina

[2] Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Instituto de Diversidad y Ecología Animal (IDEA). Av Vélez Sarsfield 299 Córdoba, (5000) Argentina.

[3] Laboratório de Biogeografia da Conservação, Departamento de Ecologia, Universidade Federal de Goiás, Goiânia, Goiás, Brazil.

[4] Fundação Brasileira para o Desenvolvimento Sustentável, Rio de Janeiro, Rio de Janeiro, Brazil.

[5] Laboratorio de Macroecología Evolutiva, Red de Biología Evolutiva, Instituto de Ecología, A.C. Xalapa, Veracruz, México.

***Corresponding author's address:**

Javier Nori | email: Address: Rondeau 798, Córdoba, Córdoba, Argentina | Phone: +54 9 351 4332055

Running title: Global conservation and research

Keywords: Conservation planning; conservation investment; decision making; priority research areas; protected areas.

Keywords: Conservation planning; conservation investment; decision making; priority research areas; protected areas.

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

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1111/cobi.13476.

Abstract

Effective conservation policies require comprehensive knowledge on biodiversity. However, knowledge shortfalls still remain, hindering our possibilities to improve decision making and built such policies. During the last two 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 the return on investment. Relying on conservation planning tools and geographical distributions of amphibians, birds, mammals, and reptiles we suggest and compare priority areas for conservation and research focused on terrestrial vertebrates worldwide. We also evaluate the degree of human disturbance within both types of global priority areas. While the spatial concordance between priority conservation and research areas was low, comprising 0.36% of the world's land area where both priorities overlap, such consensus areas represent a unique opportunity for simultaneously conserving and acquiring knowledge for threatened and data deficient species of vertebrates. In this combined area (0.36% of the world's land), it would be possible to protect almost half of the currently threatened species and to gather biological information for nearly 42% of the known data deficient species. We also found that 6199 protected areas worldwide are already located in such places, although only 35% of them have strict conservation purposes. We have taken a first step towards promoting a positive feedback between filling knowledge shortfalls and defining spatial conservation priorities, aimed to help the strategic allocation of conservation and research resources at a global scale. While the picture is not the most encouraging yet, joint efforts are possible and should be fostered to save vertebrate species from our own ignorance and from their extinction.

Introduction

A comprehensive knowledge on biodiversity patterns and dynamics is important for designing effective conservation strategies that mitigate biodiversity loss and avoid threats (Mace 2004). Unfortunately, we are still far from having such comprehensive knowledge (Hortal et al. 2015). For instance, we only know a small fraction of living species (Mora et al. 2011). Knowledge on 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). Given that it is impossible to plan the conservation of what we don't know; the more we know about a given taxon, the more we can contribute to deliver accurate conservation actions (Xu et al. 2017).

Although terrestrial vertebrates are the best-known taxa worldwide and usually considered in conservation policies and recommendations (i.e. 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; those 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 when formulating conservation planning and policy (Nori & Loyola 2015). Although determining the conservation status of such DD species is essential to guide accurate conservation policies (González-del-Pliego et al. 2019), efforts to do so have, paradoxically, been much smaller than those focused on defining priority areas for conservation based on the available information.

During the last decades, researchers, NGOs, and decision makers developed useful information to identify and prioritize key areas for conservation, in which conservation resources can be strategically invested as to maximize benefit and return on investment. Indeed, an entire discipline (i.e. Systematic Conservation Planning, SCP) and computational software (e.g. Moilanen et al. 2014) have been developed aiming to identify priority conservation areas based on biological features and cost (Margules & Pressey 2000). As expected, most prioritization efforts have used terrestrial vertebrates as target groups given the larger availability of information for these species relative to other taxa (Venter et al. 2014; Prieto-Torres et al. 2018).

Analogous to priority areas for conservation, we have recently proposed a way to identify priority areas for conducting research that can help targeting surveys to obtain knowledge on DD species (Nori *et al.* 2018). We showed that if research efforts were strategically distributed, it would be 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 in order 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 on DD terrestrial vertebrate species and evaluate the potential of conservation areas for such endeavor, here we: (i) identify priority areas for research on DD terrestrial vertebrates (amphibians, reptiles birds, and mammals) as well as priority areas for the conservation of threatened vertebrates; (ii) evaluate the spatial congruence between these two sets of areas; (iii). evaluate 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 (iv) define 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 6591 amphibians, 10,064 reptiles, 11,121 birds, and 5439 mammals. To obtained these range maps, we used the IUCN database (IUCN 2018) for amphibians and mammals, the BirdLife International Database (www.birdlife.org) for birds and the recent global assessment of reptiles distributions (http://www.gardinitiative.org/data.html). Then, we selected two subsets of species: i) Threatened species: all terrestrial vertebrate species within the IUCN threatened categories (i.e. vulnerable, VU; endangered, EN, critically endangered, CR), totaling 5970 terrestrial vertebrates (2099 amphibians, 1261 reptiles 1438 birds, and 1172 mammals) and ii) DD species: all terrestrial vertebrate species considered as Data Deficient (DD) and that had restricted distributional ranges (< 20000 km^2), resulting in 2529 DD species (1354 amphibians, 733 reptiles, 26 birds, and 416 mammals), which represents 80% of total number of extant terrestrial vertebrate DD species. 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 20000 km^2 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 0.5º of latitude-longitude. Based on this matrix, we recovered individual raster files representing the distribution of each species using 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 decided to run the analyses at a spatial resolution of 0.5º of latitude-longitude. Indeed, using range maps at finer resolutions would increase even more the biases related to over-interpretation of the limited information contained in these maps (e.g. commission and omission errors; Peterson 2017)

Spatial prioritization

Based on the distribution of each dataset, threatened and DD species, we conducted different prioritization analyses aimed at determining the top 0.5%, 1% and 5% of the world's terrestrial area (1,174,433 km^2, 2,348,946 km^2, and 5,872,365 km^2, respectively). We selected these three thresholds *ad hoc* considering the percentage of species represented in the defined priority areas (see results). These prioritizations represent the best places for protecting the species (i.e. those with the greatest complementary representation of threatened species) and best places to conduct research (i.e. those with the greatest complementary representation of DD species).

First, for both prioritizations, we ran analyses considering 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 are listed as DD with restricted ranges and, given the nature of SCP protocols, it would not be informative to perform a prioritization analyses under a scenario with virtually no species overlap (as in the case of bird DD species). In total, we developed eight prioritization schemes: (1) priority conservation areas for all terrestrial vertebrates, (2) priority research areas for all terrestrial vertebrates, (3) priority conservation areas for mammals, (4) priority research areas for mammals, (5) priority conservation areas for amphibians, (6) priority research areas for amphibians, (7) priority conservation areas for reptiles, (8) priority research areas for reptiles.

We ran prioritization analyses using Zonation v4.0 (Moilanen et al., 2014), a systematic conservation planning decision support tool. While Zonation is a software conventionally used for determining regions where conservation action could be undertaken (Margules & Pressey, 2000; Ciarleglio et al., 2009), 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.

Here, each pixel priority level was calculated based on two different cell removal rules: Additive-Benefit Function (ABF) and Core Area Zonation (CAZ), then we selected the result with the best performance (i.e. the largest average representation of species distributions within the top 1% of the world's terrestrial area) of each prioritization scenario. (check Moilanen *et al.* 2014, for details about 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 for VU, 2 for EN and 3 for CR species. In addition, 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; etc. (see Moilanen et al., 2014 for details). In sum, priority areas were those with high and complementary concentration 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). In addition, using a 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 to be covered by our identified priority areas even if they only occurred in a small fraction within these areas (e.g. one 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 two types of priority areas. To do so, we overlapped maps of the top 0.5%, 1% and 5% of the world's terrestrial area for each scenario and calculated the percentage of overlap ("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 in order to calculate the percentage of overlap for the top 1% priority conservation and research areas between pairs of our evaluated taxa. Also, using the `maptools` package for R, we determined the proportion of the top 1% of priority areas (considering priority research and conservation areas, and areas of consensus) falling within each country and continents of the world. We did these analyses for terrestrial vertebrates and separately for each taxon.

We also determined the level of human pressure on natural ecosystems found within both kind of priority areas as well as for the consensus areas. To do this, we used the Human Footprint Index v2.0 raster (WCS & CIESIN 2005), which is a complex index created from nine global data layers. We classified the original Human Footprint raster into four 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 (values of Human Footprint from 0 to 1); low human intervention (values from 1 to 12); moderate human intervention (values from 12 to 26) and high human intervention (values from 26 to 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 four 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 as priorities in terms of both conservation and research for terrestrial vertebrates. To do so, 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 first downloaded the original database of protected areas and filter all terrestrial PAs with geographically defined boundaries, after that we intersected this subset of PAs with our identified priority areas of consensus, then we categorized PAs considering their IUCN status, designation type and degree priority. We defined three categories of priority for PAs based on their overlap with the priority consensus areas from the different top percentages; 0.5, 1 and 5% of the world.

Results

For the eight evaluated scenario ABF removal rule showed the best performance (see Supplementary Table S1). Results considering 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 referred to "priority conservation areas" or "priority research areas" as the top 1% of the world for the prioritizations considering threatened and DD species, respectively.

When all four vertebrate taxa (mammals, amphibians, birds and reptiles) were pulled together, priority conservation areas encompassed, on average, half of the distributions of threatened vertebrates (median = 50%). In addition, these conservation areas overlapped with 74% of the threatened terrestrial vertebrates (see Table 1 for percentages per vertebrate order). 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, overlapped in 36% (i.e. shared 36% of their pixels, which represent 0.36% of the world's terrestrial surface). This area of simultaneous conservation and research priority overlapped with almost half (49%) of threatened terrestrial vertebrates and with a slightly lower percentage (42 %) of restricted DD terrestrial vertebrates (Tables 1 and 2, Figures 1 and 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 priority areas overlapped in 49%, representing 2.45% of the world's area. This 2.45% overlapped, in turn, more than 70% of both target species sets (Figure 1; Tables 1 and 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. Interestingly, however, the overlap between mammals and both amphibians and reptiles for the top 1% priority research areas was close to 50% (Supplementary Table S 2). 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, Figure 2 for details).

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 was concentrated in five countries (Madagascar, Mexico, Colombia, Perú and Ecuador). Similarly, 43% of priority research areas for these vertebrates was concentrated in six countries (Brazil, Indonesia, Colombia, Mexico and Perú, see Supplementary Table S3). Consensus areas between the top 1% conservation and research priorities for all terrestrial vertebrates (0.36% of the world) was mainly located in the Tropical Andes and the western rainforest of India, with 51% of these consensus areas concentrated in five countries (Table S3). Conversely, there were regions with high concentration of only one type of priority areas 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 (Figure 2). Priority areas for mammal conservation and research were quite dispersed across the globe, as was the small areas where both priorities overlapped (Figure 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 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 30.1 (median = 28.0, sd = 13.2), with 49% of priority conservation areas overlapping with our category four of HF, representing areas of high human intervention. The top 1% priority research areas showed an average value of human footprint of 25.7 (median = 26.0, sd = 13.0) with 45% of those areas located in areas of high human intervention. Similarly, areas of consensus between conservation and research largely overlapped with areas of high human intervention, with a mean value of Human Footprint of 28.6 (median = 28, sd =12.9; Tables 1 and 2, Figures 1 and 2).

We identified 6199 PAs that overlapped with areas of consensus between priority conservation and research areas for terrestrial vertebrates, from 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 belong to IUCN categories I-IV. These identified priority PAs showed a mean size of 938.9 km^2 (median = 14.5, sd= 18238.3 km^2), being larger than the average PA (mean= 248.3, median = 0.57, sd= 9947 km^2; see Supplementary Table S4 for a detailed list).

Discussion

We have conducted the first effort to identify priority areas that can be important for simultaneously conducting conservation and research actions 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, representing ~2.5% of its terrestrial surface. Over such a small area of the world, there can occur more than 70% of threatened and data deficient 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 to ensure the persistence of strategic areas for conducting research, which can eventually fill our knowledge shortfall needed to bring DD species out of such category. This is especially relevant if we consider 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, this is, to our knowledge, the first study to focus in delineating strategic areas to invest research efforts for terrestrial vertebrates and findings are encouraging. 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 filling the 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 in just 1% of the world's surface, which overlaps a large proportion of their already restricted distributions (mean= 64%), as evidenced by half of all restricted DD species having their complete distribution overlapped by these priority areas. This is exceedingly relevant if we consider 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 concentration of undiscovered, recently discovered, and poorly known species simply by chance (Meyer et al. 2015), but this is not always the case. We face a much complex picture in which humans have had a strong influence. 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 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 even today (e.g. Tropical Andes) and clearly represent priority areas for research as well as for conservation. In addition, 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 hyper-diverse regions that are still poorly explored (like the part of the Amazon or 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) as well as for 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, agreeing with previous findings (Nori et al. 2015, 2018). Conversely, the pattern was quite different for mammals, with conservation and research consensus areas being quite disperse across the globe. The pattern for reptiles lay between that of mammals and amphibians, with consensus areas generally being dispersed across the globe but with some of these being concentrated in certain regions such as the Tropical Andes, Central America, and Madagascar. Such differences on 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 to 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 to 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, as well their sparse distribution across the globe, from mammals to reptiles and amphibians.

Despite the heterogeneous distribution of each type of priority areas, for conservation and for research, the fact 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 simultaneously fulfilled. While 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 threaten and DD species of each terrestrial vertebrate taxon. Indeed, regions where priority conservation and research areas overlap represent strategic regions where investments could be maximized. In other words, if we focused our efforts in those areas, it would be possible to conduct imperative conservation actions, filling 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 high 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 highest priority for investment in research and management actions. These PAs represent a little percentage of the total number of PAs (2.55%). The mean and median size of these priority PAs compared to the average PA across the world suggests that 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, it is interesting to note that only less than a 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 that most of our identified PAs 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 is very high, with most of these priority areas overlapping with zones of high values of Human Footprint. The degree of human impact is higher in priority conservation areas than in priority research areas, but still considerable for these latter areas. This is not surprising if we consider that direct human impacts are the main threat for vertebrate species (IUCN 2018) and that here, priority conservation areas have been 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 of our study, meaning 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, including other essential information such as proxies of human disturbances (e.g. human footprint) as cost layers, with the aim to find 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 (Rodrigues et al. 2004; Brooks et al. 2006; Venter et al. 2014; Albuquerque & Beier 2015; Prieto-Torres et al. 2018), the positive feedback between filling knowledge shortfalls and defining spatial conservation priorities has never been explicitly considered. Here, we have taken a first step towards this goal and presented relevant information aimed to help the strategic distributions of conservation and research resources at a global scale. While 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 showed that there are areas of special interest, were joint effort are possible and should be extremely profitable. It is worth reminding that our goal here 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 proposal could certainly considered such targets as well as more detailed information on species' home 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. Finally, we reinforce and extrapolate our previous findings (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 not only for conservation purposes but potentially helpful for many others discipline of science.

References

Albuquerque F, Beier P. 2015. Global patterns and environmental correlates of high-priority conservation areas for vertebrates. Journal of Biogeography **42**:1397–1405. John Wiley & Sons, Ltd (10.1111). Available from http://doi.wiley.com/10.1111/jbi.12498 (accessed February 20, 2019).

Brooks TM, Mittermeier R a, da Fonseca G a B, Gerlach J, Hoffmann M, Lamoreux JF, Mittermeier CG, Pilgrim JD, Rodrigues a SL. 2006. Global biodiversity conservation priorities. Science **313**:58–61. Available from http://www.ncbi.nlm.nih.gov/pubmed/16825561 (accessed July 12, 2012).

Diniz-Filho JAF, Bastos RP, Rangel TFLVB, Bini LM, Carvalho P, Silva RJ. 2005. Macroecological correlates and spatial patterns of anuran description dates in the Brazilian Cerrado. Global Ecology and Biogeography **14**:469–477.

Diniz-Filho JAF, Loyola RD, Raia P, Mooers AO, Bini LM. 2013. Darwinian shortfalls in biodiversity conservation. Trends in Ecology & Evolution **28**:689–695. Available from http://linkinghub.elsevier.com/retrieve/pii/S0169534713002127 (accessed October 2, 2013).

González-del-Pliego P, Freckleton RP, Edwards DP, Koo MS, Scheffers BR, Pyron RA, Jetz W. 2019. Phylogenetic and Trait-Based Prediction of Extinction Risk for Data-Deficient Amphibians. Current Biology **29**:1557–1563.e3. Cell Press. Available from https://www.sciencedirect.com/science/article/abs/pii/S0960982219304038 (accessed July 16, 2019).

Hijmans RJ et al. 2019. Package raster: Geographic Data Analysis and Modeling. Available from https://cran.r-project.org/web/packages/raster/raster.pdf.

Hortal J, de Bello F, Diniz-Filho JAF, Lewinsohn TM, Lobo JM, Ladle RJ. 2015. Seven Shortfalls that Beset Large-Scale Knowledge of Biodiversity. Annual Review of Ecology, Evolution, and Systematics **46**:523–549. Annual Reviews . Available from http://www.annualreviews.org/doi/10.1146/annurev-ecolsys-112414-054400 (accessed February 11, 2019).

IUCN. 2012. IUCN Red List Categories and Criteria: Version 3.1Second edi. Switerland and Cambridge, UK.

IUCN. 2018. IUCN Red List of Threatened Species. Version 2017.3. Available from https://www.iucnredlist.org/ (accessed January 23, 2019).

IUCN, UNEP. 2019. The World Database of Protected Areas (WDPA). Available from https://www.iucn.org/theme/protected-areas/our-work/world-database-protected-areas (accessed February 12, 2019).

Jenkins CN, Pimm SL, Joppa LN. 2013. Global patterns of terrestrial vertebrate diversity and conservation. Proceedings of the National Academy of Sciences **110**:E2602–E2610. Available from http://www.pnas.org/cgi/doi/10.1073/pnas.1302251110 (accessed June 27, 2013).

Jetz W, Freckleton RP. 2015. Towards a general framework for predicting threat status of data-deficient species from phylogenetic, spatial and environmental information. Philosophical transactions of the Royal Society of London. Series B, Biological sciences **370**:20140016. The Royal Society. Available from http://www.ncbi.nlm.nih.gov/pubmed/25561677 (accessed February 11, 2019).

Jones KR, Venter O, Fuller RA, Allan JR, Maxwell SL, Negret PJ, Watson JEM. 2018. One-third of global protected land is under intense human pressure. Science **360**:788–791.

Available from http://www.sciencemag.org/lookup/doi/10.1126/science.aap9565.

Mace GM. 2004. The role of taxonomy in species conservation. Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences **359**:711–719. Available from http://www.royalsocietypublishing.org/doi/10.1098/rstb.2003.1454 (accessed July 3, 2019).

Margules CR, Pressey RL. 2000. Systematic conservation planning. Nature **405**:243–53. Nature Publishing Group. Available from http://www.ncbi.nlm.nih.gov/pubmed/10821285.

Meyer C, Kreft H, Guralnick R, Jetz W. 2015. Global priorities for an effective information basis of biodiversity distributions. Nature Communications **6**:1–8. Nature Publishing Group. Available from http://dx.doi.org/10.1038/ncomms9221.

Moilanen A, Pouzols FM, Meller L, Veach V, Arponen A, Leppänen J, Kujala H. 2014. Spatial conservation planning methods and software ZONATION. User Manual. C-BIG Conservation Biology, Helsinki, Finland.

Mora C, Tittensor DP, Adl S, Simpson AGB, Worm B. 2011. How many species are there on earth and in the ocean? PLoS Biology **9**:1–8.

Nori J, Lemes P, Urbina-Cardona N, Baldo D, Lescano J, Loyola R. 2015. Amphibian conservation, land-use changes and protected areas: A global overview. Biological Conservation **191**:367–374. Elsevier B.V. Available from http://linkinghub.elsevier.com/retrieve/pii/S0006320715300355.

Nori J, Loyola R. 2015. On the worrying fate of Data Deficient amphibians. Plos One **10**:e0125055. Available from http://dx.plos.org/10.1371/journal.pone.0125055.

Nori J, Villalobos F, Loyola R. 2018. Global priority areas for amphibian research. Journal of Biogeography **45**:2588–2594. Wiley/Blackwell (10.1111). Available from http://doi.wiley.com/10.1111/jbi.13435 (accessed December 6, 2018).

Peterson AT. 2017, August 1. Problems with reductive, polygon-based methods for estimating species' ranges: reply to Pimm et al. 2017. John Wiley & Sons, Ltd (10.1111). Available from http://doi.wiley.com/10.1111/cobi.12929 (accessed February 11, 2019).

Prieto-Torres DA, Nori J, Rojas-Soto OR. 2018. Identifying priority conservation areas for birds associated to endangered Neotropical dry forests. Biological Conservation **228**:205–214. Elsevier. Available from https://www.sciencedirect.com/science/article/pii/S0006320718304075 (accessed December 6, 2018).

Qian H. 2009. Global comparisons of beta diversity among mammals, birds, reptiles, and amphibians across spatial scales and taxonomic ranks. Journal of Systematics and Evolution **47**:509–514.

Rodrigues ASL et al. 2004. Effectiveness of the global protected area network in representing species diversity. Nature **428**:640–3. Available from http://www.ncbi.nlm.nih.gov/pubmed/15071592 (accessed November 7, 2013).

Scherz MD, Glaw F, Hutter CR, Bletz MC, Rakotoarison A, Köhler J, Vences M. 2019. Species complexes and the importance of Data Deficient classification in Red List assessments: The case of Hylobatrachus frogs. Plos One.

Venter O et al. 2014. Targeting Global Protected Area Expansion for Imperiled Biodiversity. PLoS Biology **12**:e1001891. Public Library of Science. Available from https://dx.plos.org/10.1371/journal.pbio.1001891 (accessed February 11, 2019).

Vilela B, Villalobos F. 2015. letsR: a new R package for data handling and analysis in macroecology. Methods in Ecology and Evolution **6**:1229–1234. Available from http://doi.wiley.com/10.1111/2041-210X.12401 (accessed April 29, 2016).

Watson JEM, Dudley N, Segan DB, Hockings M. 2014. The performance and potential of protected areas. Nature **515**:67–73. Nature Publishing Group, a division of Macmillan Publishers Limited. All Rights Reserved. Available from http://dx.doi.org/10.1038/nature13947 (accessed November 5, 2014).

WCS, CIESIN. 2005. Last of the Wild Project, Version 2, 2005 (LWP-2): Global Human Footprint Dataset (Geographic). NASA. NASA Socioeconomic Data and Applications Center (SEDAC)., New York, USA. Available from http://dx.doi.org/10.7927/H4M61H5F.

Xu W et al. 2017. Reassessing the conservation status of the giant panda using remote sensing. Nature Ecology & Evolution **1**:1635–1638. Available from https://www.nature.com/articles/s41559-017-0317-1 (accessed February 11, 2019).

Table

Table 1: Description of species representation (distribution and richness) and human impact in the identified priority conservation and priority research areas across different top values (column tops: TOP 0.5%, TOP 1% and TOP 5%) and taxonomic groups (considering all species and each taxon separately; ALL; MA: mammals; AM: amphibians; BI: birds). Top rows ("Percentage of species distributions") describe the mean of the species distributions that is encompassed in priority conservation and priority research areas. The middle rows ("Percentage of species represented") describe the number of each type of species (Threatened and restricted DD), in percentage from the total, that overlap with priority conservation and priority research areas. Bottom rows ("Percentage of overlap with Human

impact categories") describe the percentage of priority conservation and priority research areas that overlaps with each category of the Human Footprint Index; where Q1: very low human intervention (values of Human Footprint from 0 to 1); Q2: low human intervention (values from 1 to 12); Q3: moderate human intervention (values from 12 to 26), and Q4: high human intervention (values from 26 to 100).

			TOP 0.5%				**TOP 1%**				**TOP 5%**			
	Priority type		**ALL**	**MA**	**AM**	**RE**	**ALL**	**MA**	**AM**	**RE**	**ALL**	**MA**	**AM**	**RE**
Percentage of species distributions	**Conservation**		**38%**	37%	62%	45%	**50%**	48%	78%	56%	**77%**	76%	97%	77%
	Research		**46%**	66%	62%	65%	**64%**	84%	83%	82%	**94%**	94%	95%	93%
Percentage of species represented	**Conservation**	**ALL**	**60%**				**74%**				**96%**			
		MA	**52%**	66%			**69%**	77%			**88%**	89%		
		AM	**70%**		76%		**84%**		90%		**97%**		97%	
		BI	**58%**				**70%**				**83%**			
		RE	**50%**			67%	**65%**			75%	**83%**			84%
	Research	**ALL**	**60%**				**79%**				**94%**			
		MA	**45%**	79%			**68%**	86%			**95%**	95%		
		AM	**67%**		74%		**84%**		90%		**95%**		95%	
		BI	**41%**				**63%**				**85%**			
		RE	**55%**			77%	**76%**			89%	**93%**			93%
Percentage of overlap with Human impact categories	**Conservation**	**Q1**	**2%**				**2%**				**3%**			
		Q2	**6%**				**10%**				**14%**			
		Q3	**34%**				**36%**				**38%**			
		Q4	**58%**				**49%**				**45%**			
	Research	**Q1**	**3%**				**4%**				**6%**			
		Q2	**13%**				**13%**				**19%**			
		Q3	**36%**				**39%**				**37%**			
		Q4	**47%**				**45%**				**38%**			

Table 2: Description of overlap, species representation and human impact in the areas of consensus between priority conservation and priority research areas across different top values (columns: TOP 0.5%, TOP 1% and TOP 5%) and taxonomic groups (considering all species and each taxon separately; ALL; MA: mammals; AM: amphibians; BI: birds). Top rows ("Percentage of overlap between priority areas") describe the area of consensus –

percentage of shared pixels – between priority conservation and research areas for each analyzed group. The middle rows (“Percentage of species represented”) describe the percentage of each type of species (Threatened and restricted DD) that overlap with areas of consensus between priority conservation and priority research areas. Bottom rows (“Percentage of overlap with Human impact categories”) describe the percentage of consensus areas that overlaps with each category of the Human Footprint Index; where Q1: very low human intervention (values of Human Footprint from 0 to 1); Q2: low human intervention (values from 1 to 12); Q3: moderate human intervention (values from 12 to 26), and Q4: high human intervention (values from 26 to 100).

			TOP 0.5%	**TOP 1 %**	**TOP 5 %**
Percentage of overlap between priority areas		ALL	**31%**	**36%**	**49%**
		MA	**26%**	**39%**	**55%**
		AM	**35%**	**51%**	**69%**
		RE	**28%**	**36%**	**51%**
Percentage of species represented	**Threatened**	ALL	**33%**	**49%**	**72%**
		MA	30%	46%	74%
		AM	40%	57%	80%
		BI	35%	52%	71%
		RE	22%	36%	58%
	Data Deficient	ALL	**24%**	**42%**	**74%**
		MA	18%	46%	68%
		AM	25%	40%	76%
		BI	11%	20%	56%
		RE	27%	43%	76%
Percentage of overlap with Human impact categories		Q1	1%	1%	2%
		Q2	5%	9%	11%
		Q3	34%	34%	38%
		Q4	56%	55%	50%

Figures Legends

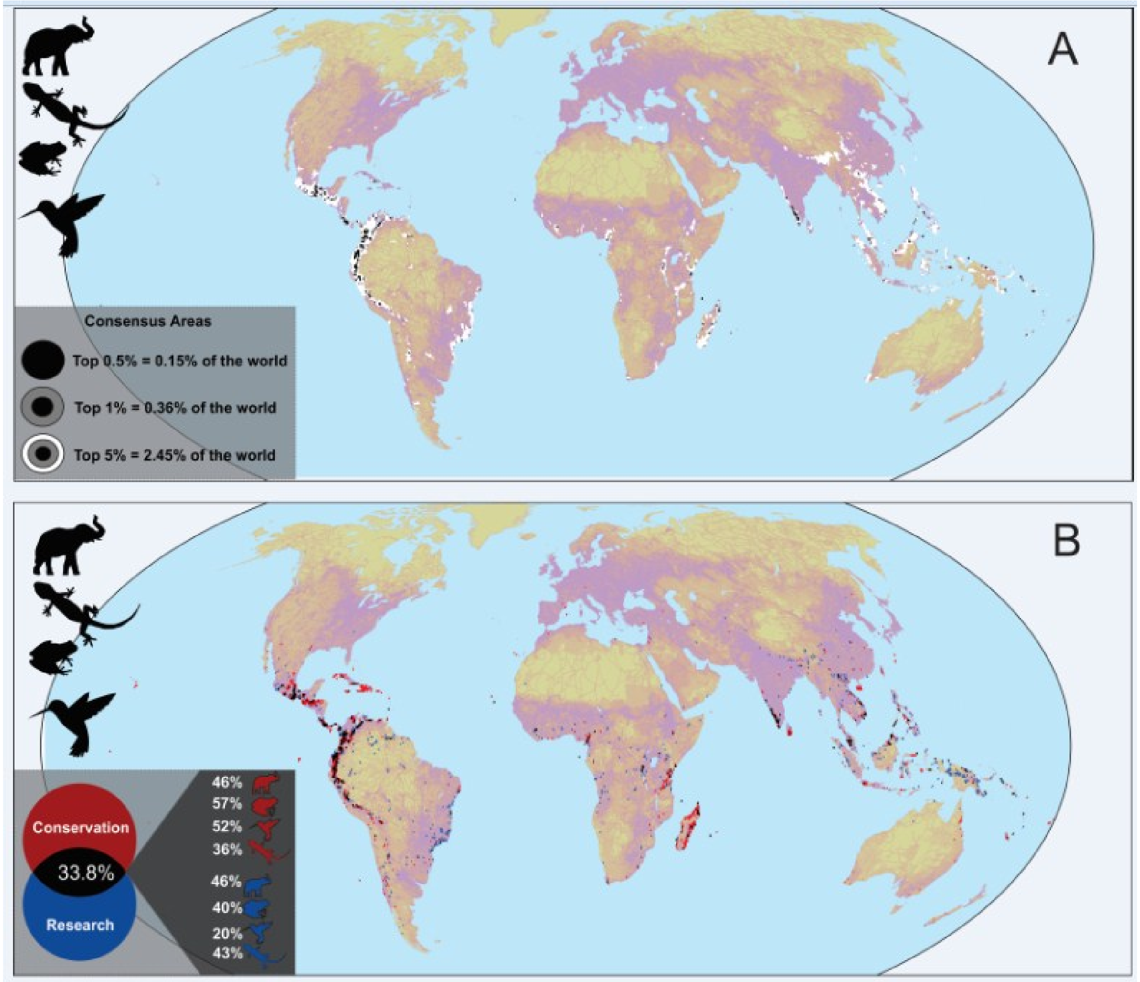

Figure 1: (A) Consensus between priority conservation and research areas of terrestrial vertebrates for the top 0.5%, 1% and 5% of the world's terrestrial area. The circles of the legend show the percentages of the world's terrestrial surface represented in each case (top 0.5%, 1% and 5% respectively). (B) Maps showing priority conservation (red) and research (blue) areas (top 1% of the world) and the areas of consensus between them (black), considering all terrestrial vertebrate major taxa (top map). The figure's box shows the percentage of overlap between priority conservation and research areas and the percentage of represented species of each major taxa.

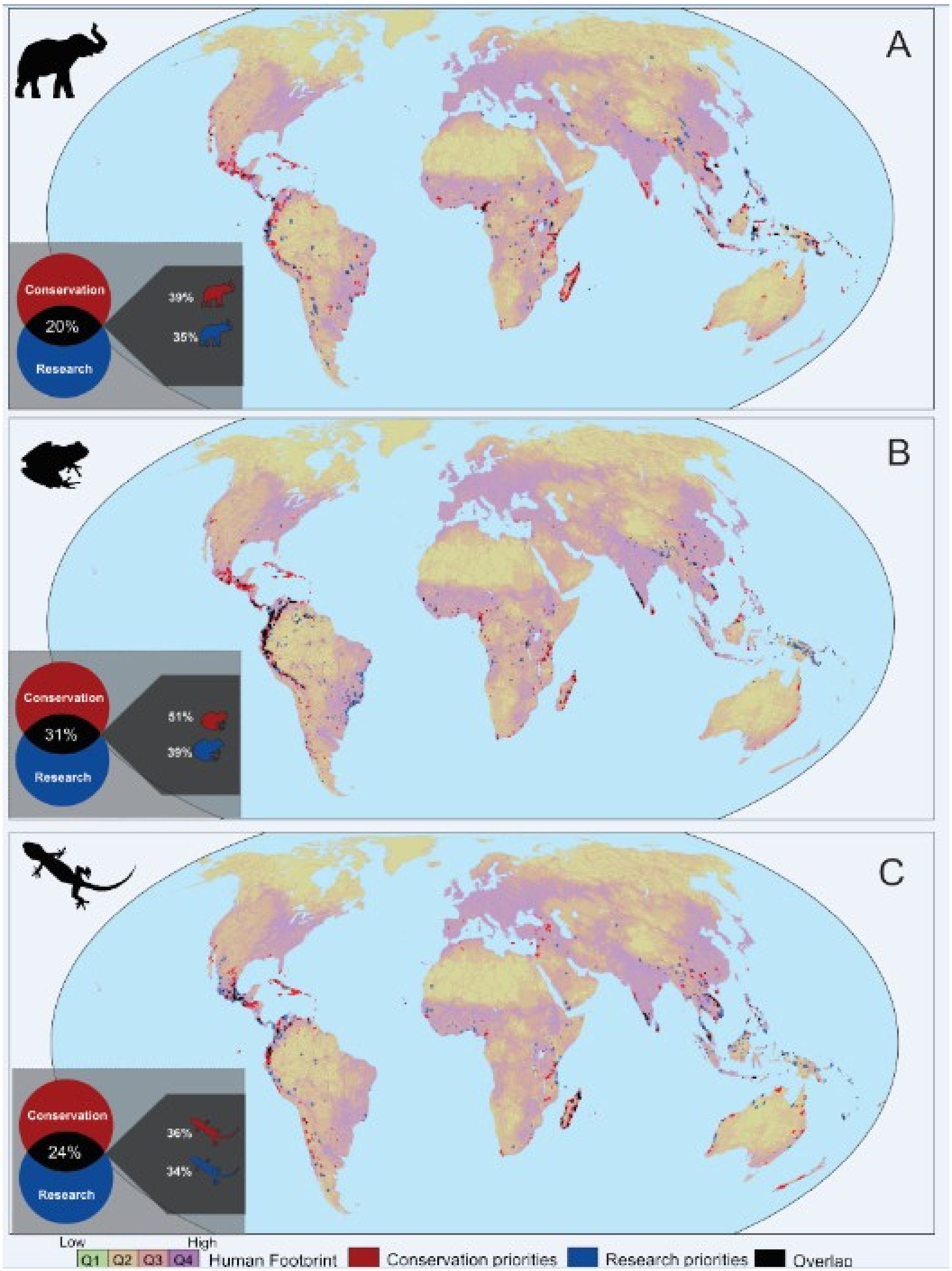

Figure 2: Maps showing priority conservation (red) and research (blue) areas (top 1% of the world) and the areas of consensus between them (black), considering mammals (A), amphibians (B), and reptiles (C). The figure's box shows the percentage of overlap between priority conservation and research areas and the percentage of represented species of each major taxa.