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Global raptor research and conservation priorities: Tropical raptors fall prey to knowledge gaps

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Abstract

Aim: Raptors serve critical ecological functions, are particularly extinction-prone and are often used as environmental indicators and flagship species. Yet, there is no global framework to prioritize research and conservation actions on them. We identify for the first time the factors driving extinction risk and scientific attention on raptors and develop a novel research and conservation priority index (RCPI) to identify global research and conservation priorities.

Location: Global.

Methods: We use random forest models based on ecological traits and extrinsic data to identify the drivers of risk and scientific attention in all raptors. We then map global research and conservation priorities. Lastly, we model where priorities fall relative to country-level human social indicators.

Results: Raptors with small geographic ranges, scavengers, forest-dependent species and those with slow life histories are particularly extinction-prone. Research is extremely biased towards a small fraction of raptor species: 10 species (1.8% of all raptors) account for one-third of all research, while one-fifth of species have no publications. Species with small geographic ranges and those inhabiting less developed countries are greatly understudied. Regions of Latin America, Africa and Southeast Asia are identified as particularly high priority for raptor research and conservation. These priorities are highly concentrated in developing countries, indicating a global mismatch between priorities and capacity for research and conservation.

Main conclusions: A redistribution of scientific attention and conservation efforts towards developing tropical countries and the least-studied, extinction-prone species is critical to conserve raptors and their ecological functions worldwide. We identify clear taxonomic and geographic research and conservation priorities for all raptors, and our methodology can be applied across other taxa to prioritize scientific investment.

KEYWORDS

avian biology, biogeography, conservation biology, conservation prioritization, ecology, extinction, ornithology, predator

1 | INTRODUCTION

The impact of human activities on ecosystems worldwide has led to a biodiversity crisis (Barnosky et al., 2011). The current rate of species extinctions is estimated to be as much as 1,000 times greater than pre-human levels, approaching levels that merit recognition as Earth's sixth mass extinction event (Barnosky et al., 2011). Loss of species and populations leads to loss of ecosystem services and compromises ecological processes (Şekercioğlu, 2010), resulting in direct impacts on human well-being (Cadotte, Carscadden, & Mirotchnick, 2011; World Health Organization, 2005). For terrestrial ecosystems, habitat alteration and climate change are expected to be the greatest drivers of biodiversity loss (Barnosky et al., 2011). Because biodiversity and threats are unevenly distributed around the globe, and funding for biodiversity conservation is limited, identifying drivers of extinction risk and prioritizing funding, research and conservation efforts is critical to maximize the efficacy of investments (Brooks et al., 2006). Encouragingly, such conservation prioritization mechanisms are increasingly being put into practice on the ground to increase the efficacy of conservation investments (Sinclair et al., 2018).

To date, biological research and conservation has been affected by taxonomic and spatial biases (Brodie, 2009; Brooke, Bielby, Nambiar, & Carbone, 2014; Ducatez & Lefebvre, 2014). Most biodiversity occurs in the tropics (Dirzo & Raven, 2003) where a disproportionate amount of species are threatened with extinction (Dirzo & Raven, 2003), and where there are high levels of human poverty and social inequality (Velasco et al., 2015). However, most research occurs in Europe and North America (Velasco et al., 2015), in direct contrast to where the need is generally greatest. Although increasing a species' threat status can cause increased interest and research in some species (Manga, 2006), overall, threat status is not a driver of research effort in mammals (Brooke et al., 2014). Among birds, non-threatened species are actually studied roughly twice as much as threatened ones (Ducatez & Lefebvre, 2014). The majority of research occurs on the largest, most visible and/or "charismatic" species, where most researchers live and where there is more funding available (Griffiths & Dos Santos, 2012; Martín-López, González, & Montes, 2011). Further, feedback loops can focus research and conservation efforts on charismatic species and already identified issues, inhibiting our ability to adequately assess the status of most species and to document and address emerging threats (Martín-López et al., 2011). Basic ecological research is integral to determining the status, population trends and threats to a species, as well as for developing effective conservation plans (Cook, Hockings, & Carter, 2010; Ferraro & Pattanayak, 2006; Sutherland, Pullin, Dolman, & Knight, 2004). Thus, when identifying species conservation priorities, it is important to not only rely on existing indices of threat or extinction risk but to also incorporate how much we know about them (De Lima, Bird, & Barlow, 2011).

Raptors (i.e., birds of prey) are globally distributed, are commonly used as ecological indicators due to their high trophic level, often serve as umbrella or flagship species for conservation programmes and serve as important cultural icons linking humans to the natural world (McClure et al., 2018; Sergio et al., 2008; Vazquez-Martin, Cufí, Oliveras-Ferraros, & Menendez, 2007). Raptors are also disproportionately more threatened with extinction compared to other avian and non-avian groups, due to their ecology and life-history (McClure et al., 2018). As a large and diverse group, raptors encompass multiple ecological foraging guilds, including carnivores, insectivores, piscivores and scavengers. As important top predators in most ecosystems, raptors regulate vertebrate prey populations both directly via predation (Kross, 2012), and indirectly, by creating a landscape of fear (Abramsky, Rosenzweig, & Subach, 2002). These top–down pressures stabilize food webs (Ives & Dobson, 1987), promoting high species richness from co-occurrence in ecosystems (Brown, Kotler, Smith, & Wirtz, 1988). Insectivorous raptors influence prey populations, behaviours and evolution, which can have direct economic impact on the agricultural industry (Şekercioğlu, 2006a; Şekercioğlu, Whenny, & Whelan, 2016), while piscivorous raptors serve as important ecological links, transferring nutrients between aquatic and terrestrial ecosystems (Şekercioğlu, 2006b). Raptors also include vultures, which are thought to inhibit disease outbreaks and regulate populations of insects, facultative scavengers and mesopredators (Buechley & Şekercioğlu, 2016a).

The Aichi Target 19 of the Convention on Biological Diversity (CBD; Secretariat of the Convention on Biological Diversity, 2014) calls for urgent efforts to improve the level of knowledge of biodiversity so that it can be shared, transferred and ultimately put into practice through an evidence-based approach. However, there is no study to date that quantifies and maps the research and conservation priorities for raptors worldwide. This knowledge gap is particularly glaring given that raptors are a key functional guild, keeping ecosystems in balance and providing important ecosystem services that support human societies (O'Bryan et al., 2018). Ultimately, improving knowledge on these species to aid their conservation will help to achieve the CBD goals and will also help achieve the Sustainable Development Goals (SDGs; www.un.org) aimed at protecting the planet and ensuring prosperity for all.

Therefore, we here aim to answer the four following questions: (a) What drives the extinction risk of raptors? (b) What drives scientific attention on raptors? (c) What are the highest priority species and locations to target future research? (d) Where are global raptor research and conservation priorities located relative to socioeconomic indices that reflect human capacity for conservation? To answer these questions, we used a large global database of avian ecological traits (Şekercioğlu, 2012a), combined with extrinsic factors, to model drivers of extinction risk and scientific attention on raptors. We developed a novel Research and Conservation Priority Index (RCPI) that combines scientific attention with conservation priority (Red List status) of each species. We then identified global priority areas for raptor research and conservation and analysed where the priorities are relative to national-level socioeconomic indices. This prioritization approach effectively revealed global patterns in extinction risk and scientific attention on raptors that can be applied to other taxa.

2 | MATERIALS AND METHODS

2.1 | Raptor database

Following the traditional broad classification of raptors, we included in our analyses all extant species in each of four taxonomic orders: *Accipitriformes* (hawks, eagles, kites, Old World vultures, etc.), *Cathartiformes* (New World vultures), *Falconiformes* (falcons and caracaras) and *Strigiformes* (owls; Ferguson-Lees & Christie, 2001; König & Weick, 2008). We follow BirdLife International's "Checklist of the Birds of the World" (2019) taxonomy. We compiled data on the status and ecology of each species from a database containing key traits on the ecology and conservation of all bird species (hereafter "BirdBase"). BirdBase was initially created from a survey of 248 literature sources (Şekercioğlu, Daily, & Ehrlich, 2004) and is updated regularly (latest update December 2018). We then refined the data set using four key sources recognized as global authorities on the species (BirdLife International, 2019; Del Hoyo, Elliot, & Sargatal, 2018; Ferguson-Lees & Christie, 2001; König & Weick, 2008). In total, we compiled the following traits for each species: generation length, geographic realm, island restriction, primary habitat, habitat breadth, forest dependency, foraging guild, diet breadth, migratory status, range size, population trend, threat status, the per cent of a species range that is protected, and mean human development and governance indices across each species range (see Supporting Information Appendix S1 for a detailed summary of each trait).

2.2 | Raptor research

To quantify the amount of research on each raptor species, we extracted the number of peer-reviewed articles on each species published from 1900 through the end of 2017 in agricultural and environmental fields using the online search engine Scopus (www.scopus.com; Deikumah, Mcalpine, & Maron, 2014). Scopus is the largest indexer of research content (Falagas, Pitsouni, Malietzis, & Pappas, 2007), including journals, books and conference papers, which pass scientific integrity selection criteria. Scopus is used widely in scientific literature reviews, offering broader content coverage and more consistency than competitors (e.g., Web of Science, Google Scholar; Falagas et al., 2007). Although our principal intent was to identify conservation priorities, we included all agricultural and environmental publications, because all ecological research on species, not just conservation-focused papers, may ultimately contribute to successful conservation planning (Courchamp, Dunne, Maho, May, & Hochberg, 2015; Fraser et al., 2018). The number of publications per species indicates how well-studied a species is, enabling us to highlight research gaps.

To search for the number of publications on each species, we used the following formula and recorded the results:

"TITLE - ABS - KEY"
(which limits the search to the title, abstract and keywords)
+
Each species' full binomial scientific name, as well as any alternative binomial scientific names (from alternative or older taxonomies), separated by the phrase "OR"
+
"AND PUBYEAR > 1900 AND PUBYEAR < 2018"
(which limits publications to 1900 - 2017)
+
"AND(LIMIT - TO (SUBJAREA, "AGRI") OR LIMIT - TO (SUBJAREA, "ENVI"))
(which limits the search to environmental and agricultural science publications)

To test whether there was a biased research distribution (i.e., if species had more or fewer publications than expected), we compared the observed distribution of publications across all species to a null distribution. Our null expectation was that every publication be assigned randomly to a species so that, by chance, some species will receive more research. This is analogous to the abundance of each species in a community and thus we employed a broken-stick model (MacArthur, 1957), which randomly and simultaneously breaks up a stick of length c into n pieces where c is the number of publications and n is the number of species. We used a chi-square test to compare the goodness of fit of our observed distribution against the null distribution. We report the number of species that are appropriately studied (which we define as falling within 10% of the null distribution), over-studied and understudied.

2.3 | Modelling extinction risk and scientific attention

We next identified the factors driving extinction risk and scientific attention on raptors. To do so, we used random forests, a machine-learning technique that identifies nonlinear relationships among multiple predictor variables. Random forests have several advantages over traditional linear models: (a) they do not assume data independence; (b) categorical and continuous variables can be incorporated without being transformed; (c) they are little affected by outliers; and (d) they predict outcomes based on a nested structure, revealing different potential pathways to a predicted outcome (Davidson, Hamilton, Boyer, Brown, & Ceballos, 2009). Further, random forests are robust at predicting drivers of extinction risk among phylogenetically related species (Bielby, Cardillo, Cooper, & Purvis, 2009; see Cutler et al., 2007 for an overview of the theory and application of random forests in ecology).

In the first random forest, we modelled extinction risk in raptors to identify how traits can interact with anthropogenic conditions to contribute to extinction risk (Murray, Rosauer, McCallum, & Skerratt, 2011). We used a combination of intrinsic species traits that are known to influence extinction risk (taxonomic family, geographic realm, geographic range, generation length, island restriction, primary habitat, habitat breadth, forest dependency, foraging guild, diet breadth and migratory status; i.e., Buechley & Şekercioğlu, 2016a) and extrinsic sociopolitical variables (human development index, governance index and human population density) averaged across each species' range (see Supporting Information Appendix S1). Note that geographic range size is an important factor in the Red List threat determination process (IUCN, 2016), and thus, some authors have excluded these traits from extinction risk analyses (Jones, Fielding, & Sullivan, 2006). However, species cannot be listed as threatened solely on the basis of range size, rather requiring at least two additional symptoms of extinction risk to be listed (e.g., severely fragmented population, population decline, and/or extreme population or distribution fluctuations; Collen et al., 2016; IUCN, 2016). Accordingly, we deem range size important to include, particularly because it has been shown to be among the most important predictors of extinction risk in other studies (Cardillo et al., 2008; Davidson et al., 2009). Following Purvis, Gittleman, Cowlishaw, and Mace (2000), our dependent variable was derived from IUCN Red List threat status (Least Concern, Near Threatened, Vulnerable, Endangered, Critically Endangered). Six Data-Deficient species were removed from this analysis. We treated extinction risk as an ordinal variable (Luiz, Woods, Madin, & Madin, 2016), adopting recent advance in random forest applications for ordinal data (Janitza, Tutz, & Boulesteix, 2016). For comparison, we also ran a model with extinction risk as a continuous variable (Least Concern = 1, Near Threatened = 2, Vulnerable = 3, Endangered = 4, Critically Endangered = 5), following Purvis et al. (2000) (Supporting Information Appendix S2). In the second random forest analysis, we modelled the number of research publications (a continuous variable) for each species by the same traits as used in the extinction risk model, with the addition of population trend and threat status, to identify factors driving scientific attention in raptors (i.e., Verde Arregoitia, 2016).

We used an unbiased tree algorithm (Hothorn, Hornik, & Zeileis, 2006) in the models, which accounts for many categorical and continuous variables, and determined the relative importance of predictor variables with a ranked probability score (RPS, for the extinction risk model with an ordinal dependent variable) and a conditional variable importance measure (CVI, for the models with a continuous dependent variable), which account for correlation among predictor variables (Janitza et al., 2016; Strobl, Boulesteix, Kneib, Augustin, & Zeileis, 2008). A higher RPS or CVI indicates greater importance, while variables of little or no importance have values close to zero or negative (Janitza et al., 2016; Strobl, Malley, & Tutz, 2009). We set the number of trees (*ntree*) to 1,000, and the default number of classification variables used to calculate the split at each node (*mtry* = 5). We present partial dependence plots to graphically demonstrate the relationship between the most important predictors and the dependent variables (extinction risk or research coverage). Because partial dependence plots are not available for ordinal random forest models, and as there was high concordance between ordinal and continuous extinction risk models (Supporting Information Appendix S2), we report partial dependence plots from the continuous extinction risk model. All random forest analyses were implemented in the "party" package (Hothorn, Hornik, Strobl, & Zeileis, 2015) in R (Version 3.5.1; R Development Core Team, 2012).

2.4 | Raptor research and conservation prioritization

We developed the Research and Conservation Priority Index (RCPI) based on each species' conservation status and number of publications. Scientific research and conservation are inextricably linked because research on the basic ecology of a species and ecosystem is essential for assessing the status of species and for developing effective conservation plans (Cook et al., 2010; Ferraro & Pattanayak, 2006; Fraser et al., 2018; Sutherland et al., 2004). Thus, we created an index of priority that weighs both of these important components of species conservation. RCPI ranged from 0.1 (low priority) to 1.0 (high priority). Threat status had a linear effect on RCPI, equivalent to the numeric threat status (as above) divided by 10, ranging from 0.1 (Least Concern) to 0.5 (Critically Endangered). This assumes that threat categories are discrete approximations of an underlying pattern of increasing extinction risk from low to high Red List categories, which we deemed appropriate given that IUCN Red List classifications are based on quantitative criteria used to separate species into categories of threat along a continuum of extinction risk (Cardillo et al., 2004; Collen et al., 2016; Purvis et al., 2000) and because our random forest models of extinction risk (see methods above) showed high concordance between ordinal and continuous treatment of threat categories (Supporting Information Appendix S2). Data-deficient species (n = 6) were given a weight of 0.3 (the same as Vulnerable), because we deemed them to be of relatively high conservation and research priority, but perhaps lower priority than species known to be either Endangered or Critically Endangered (Butchart & Bird, 2010). The number of publications had a curvilinear effect on RCPI, such that as the number of publications declined, RCPI increased exponentially. This was decided because an additional study on a species with one or a few studies is generally relatively more important than an additional study on a well-studied species. We quantified this relationship as follows:

$$\mathrm{RCPI} = \mathrm{TS}/10 + (1 - \mathrm{log1p}(\mathrm{nP})/\mathrm{log1p}(\mathrm{mP}))/2$$

where TS = threat status (1–5), nP = number of publications for each species and mP = the maximum number of publications on any species (i.e., Common Barn owl, *Tyto alba*, 734 publications). We use the log1p function to handle zeros, for species that have no publications. Taken to the limits, a Critically Endangered species with zero publications has an RCPI of 1, whereas the Least Concern and most-studied Common Barn owl has an RCPI of 0.1. See Supporting Information Appendix S3 for plots of hypothetical and realized RCPI values.

Next, we developed maps showing global patterns of raptor research and conservation priority, using the software Zonation (version 4.0; Moilanen et al., 2014). Zonation prioritizes landscape units (i.e., raster cells) by iteratively ranking them by aggregate conservation value, while accounting for complementarity. Here, we used the additive benefit function that promoted representation of all species, favouring sites with high species richness, while considering species' proportional distribution in a given cell area (Arponen, Heikkinen, Thomas, & Moilanen, 2005; Moilanen et al., 2014). We ran five separate prioritization analyses, using all raptors, and the four major subgroups of raptors (as defined above; hawks and eagles, owls, falcons and vultures), with each species weighted by its respective RCPI value. The species range maps were obtained from BirdLife International (2019), and all range map layers were rasterized to a 10 × 10 km resolution, resulting in a global prioritization map at that resolution. For each prioritization exercise, we applied a mask that restricted the spatial extent of each analysis to the area within which at least one species of raptor occurred. The resulting maps revealed global priority areas. For comparison, we also present species richness maps.

2.5 | Socioeconomic factors

Lastly, we sought to identify geo-political, sociodemographic and environmental factors associated with country-level RCPI values. Accordingly, we again used random forests to model mean RCPI values with development, governance, human population density and the per cent protected area extracted for each country worldwide. This was done because most conservation actions take place at the country level, and we wanted to identify trends in raptor priority relative to socioeconomic factors. Mean RCPI for each country was derived from the final global spatial prioritization map for all raptor species. The mean RCPI value for a country therefore reflects the average importance of a country for raptor research and conservation.

3 | RESULTS

There are 557 extant raptor species globally (an additional eight species have gone extinct since 1500, see Supporting Information Appendix S4). Owls (Strigiformes) and hawks and eagles (Accipitriformes, minus vultures) account for most raptors—42.4% (236 species) and 42.0% (234 species), respectively—while falcons (Falconiformes) account for 11.5% (64 species) and vultures (both New and Old World vultures in the Cathartiformes and Accipitriformes orders) account for 4.1% (23 species) of raptors. Raptor diversity is greatest in tropical regions: Indo-Malaya is the most diverse realm, with 26.8% of all raptor species, followed by the Neotropics (23.9% of species) and Afrotropics (20.1% of species). Only 2.7% and 2.2% of raptor species are restricted to the Palearctic (northern Eurasia) and Nearctic (North America) realms, respectively. Over a quarter of raptors (27.5%) are island-restricted, most of which are found in Indo-Malaya (70.6%, 108 of 153 species). Over half (52.2%) of all raptor species have declining populations, while 36.3% are stable, 8.8% are increasing, and 2.7% have unknown trends. Over two-thirds of raptors (67.9%) are Least Concern, 12.0% Near Threatened, 9.9% Vulnerable, 6.1% Endangered, 3.1% Critically Endangered and 1.1% Data Deficient (for a more detailed summary, see Supporting Information Appendix S5).

3.1 | Extinction risk

The random forest model explained 45.7% of the variance in extinction risk in raptors. The most important ecological predictors of extinction risk were range size, foraging guild, generation length and forest dependency (Figure 1). Specifically, species with smaller ranges are at greater risk of extinction, as are scavengers, those that have high forest dependency, and species with longer generation lengths (Figure 2). Variable importance scores computed based on extinction risk treated as either ordinal or continuous showed high concordance (Supporting Information Appendix S2). For a detailed summary of the proportion of extinction-prone species by each ecological group, see Supporting Information Appendix S5.

3.2 | Scientific attention

Our literature search yielded 16,712 raptor-focused research articles published in agricultural or environmental journals between

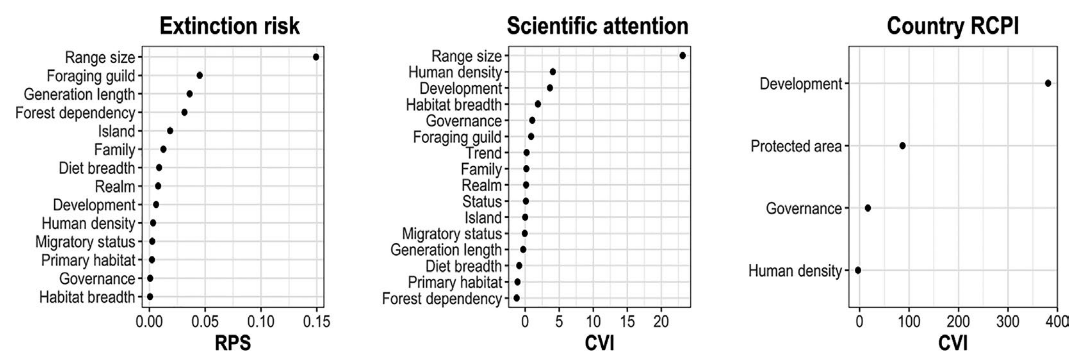

FIGURE 1 Permutation importance scores for random forest models evaluating the importance of ecological traits predicting raptor extinction risk, scientific attention, and mean country-level research and conservation prioritization index scores. Predictor variables are ranked by either ranked probability score (RPS, ordinal dependent variable) or conditional variable importance (CVI, continuous dependent variables), which measure the relative importance of each variable. A higher RPS or CVI value is indicative of a more important variable, variables near or less than zero are unimportant. Note that the extinction risk plots here are based on ordinal, not continuous, treatment of the dependent extinction risk variable (see Supporting Information Appendix S2 for a comparison). See Supporting Information Appendix S1 for a full description of the variables

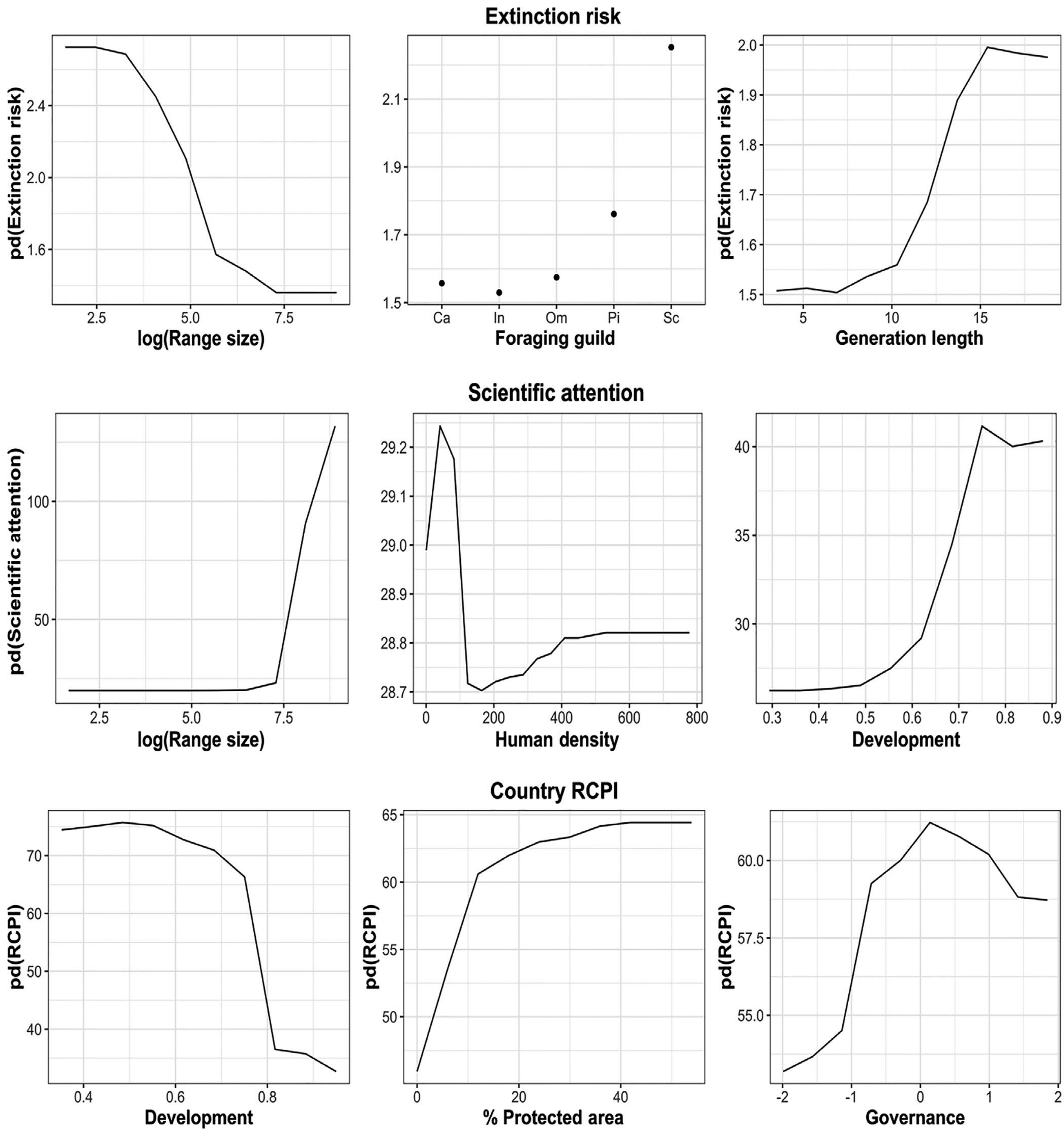

FIGURE 2 Partial dependence plots demonstrating the relationships between the top predictors of extinction risk, scientific attention, and country-level research and conservation prioritization index (RCPI) in raptors. Partial dependence indicates the dependence of the dependent variable on the specified predictor variable while controlling for the effects of all the other predictors in the model. Here, a higher partial dependence value indicates higher extinction risk, scientific attention or country-level RCPI score, respectively. Foraging guild categories are Ca = carnivore, In = insectivore, Om = omnivore, Pi = piscivore, Sc = scavenger; and forest dependency categories are H = high, L = low, M = medium, N = non. See Supporting Information Appendix S1 for a full description of the predictors. Note that the extinction risk plots here are based on continuous, not ordinal, treatment of the dependent extinction risk variable (see Supporting Information Appendix S2 for a comparison)

1900 and 2017. The top ten most researched species were as follows: (a) Common Barn owl (*T. alba*, 734 publications), (b) Peregrine Falcon (*Falco peregrinus*, 720), (c) Bald Eagle (*Haliaeetus leucocephalus*, 621), (d) Northern Goshawk (*Accipiter gentilis*, 566), (e) Golden Eagle (*Aquila chrysaetos*, 548), (f) Common Kestrel (*F. tinnunculus*, 484), (g) American Kestrel (*F. sparverius*, 456), (h) Spotted Owl

(*Strix occidentalis*, 452), (i) Eurasian Buzzard (*Buteo buteo*, 441) and (j) Eurasian Sparrowhawk (*A. nisus*, 377). Only one of these species, Spotted Owl, was classified as globally Near Threatened; the rest are Least Concern. These ten species accounted for 1.8% of all raptor species and 32.3% of all raptor research. Further, the top quartile of raptors ranked by the number of research publications (139 species) accounted for 91.6% (15,306 publications) of all raptor research, while the bottom quartile (139 species) accounted for only 0.1% (24 publications) of research. Over half (56.0%, 312 species) of all raptor species had five or fewer publications, 16.2% (90 species) had one publication and 20.8% (116 species) had no publications (Figure 2). Of the species that had no publications, 48 (41.4%) were extinction-prone (i.e., falling within any Red List classifications from near threatened to critically endangered), 64 (55.2%) were Least Concern, and four (3.4%) were Data Deficient. This observed taxonomic bias in research distribution was significantly different from the null distribution (χ^2 = 18,983, *df* = 556, *p* < 0.0001). Overall, 55 species (9.9%) were over-studied and 493 species (88.5%) were understudied.

The random forest model explained 53.0% of the variance in scientific attention. The most important predictor of scientific attention on raptors was geographic range size (Figure 1). Species with larger ranges received more scientific attention (Figure 3). Specifically, those species in the largest quartile of range sizes received 77.9% of all research publications. Additional important predictors were human population density and human development (Figure 1), with greater scientific attention on species inhabiting areas of lower human population density and higher human development (Figure 3). For a detailed summary of the number of publications by ecological group, see Supporting Information Appendix S5.

3.3 | Research prioritization

Our research and conservation prioritization index (RCPI) ranked species' priority based on threat status and number of publications. Global priority maps for all raptors, as well as subgroups (hawks and eagles, falcons, owls and vultures), are shown in Figure 4. The tropics are high priority for raptor research and conservation, with highest priorities for all raptors concentrated in Indo-Malayan (i.e., Southeast Asia), Afrotropical and Neotropical realms. Broadly, similar patterns apply to hawk and eagle, and falcon subgroups, while the owl priority map also indicated parts of temperate North America and East Asia as being relatively high priority. For vultures, South Asia and sub-Saharan Africa were critical. The five lowest priority species were Common Barn owl (RCPI = 0.100), Peregrine Falcon (0.101), Bald Eagle (0.113), Northern Goshawk (0.120) and Golden Eagle (0.122), all of which are Least Concern and have >500 publications. In contrast, Annobon Scops-owl (*Otus feae*, RCPI = 1), endemic to the small West African island of Annobon, was the highest priority species overall because it was Critically Endangered and our Scopus literature search identified no publications focused on this species. Three species were tied for second highest priority: Cuban Kite (*Chondrohierax wilsonii*), Flores Hawk-eagle (*Nisaetus floris*) and Siau Scops-owl (*Otus siaoensis*), each of which was Critically Endangered with only one identified research publication (RCPI = 0.947). Plumbeous Forest falcon (*Micrastur plumbeus*; RCPI = 0.800) and Taita falcon (*Falco fasciinucha*; RCPI = 0.6643), both classified as Vulnerable, were the highest priority falcons. Critically Endangered Red-headed (RCPI = 0.812), Slender-billed (RCPI = 0.806) and Ruppell's (RCPI = 0.800) vultures were the highest priority vultures. See Supporting Information Appendix S6 for a list of the top five priority species by geographic realm, Supporting Information Appendix S7 for the full list of raptor species' threat status, population trend, number of research publications, and RCPI values, and Supporting Information Appendix S8 for the full list of countries with mean RCPI values, and indices of development, governance, protected area and human population density.

3.4 | National level correlates of raptor research and conservation priority

The random forest model based on development, governance, human population density and protected area coverage explained 38.6% of the variance in country-level mean RCPI scores. Development was strongly predictive of mean RCPI values, while protected area coverage and governance had intermediate predictive power and human population density had little to no predictive power (Figure 1). Specifically, countries below a threshold development score of approximately 0.75 were higher priority (on a scale of 0–1; to contextualize, Poland, South Korea and Israel all have development scores near that level), as were countries with higher protected area coverage, and countries with intermediate governance scores (Figure 2).

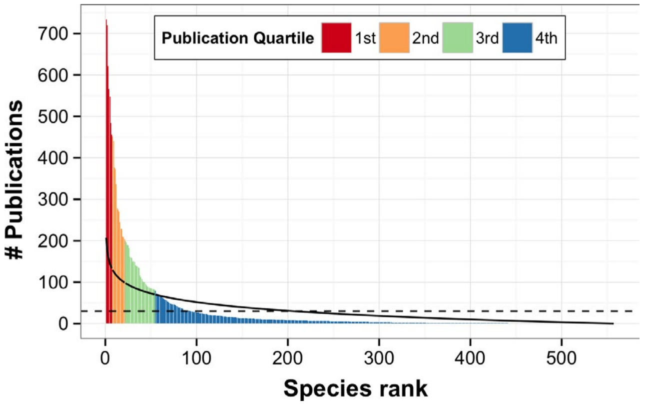

FIGURE 3 The number of research publications identified in our literature search for each raptor species. On the *x*-axis, species are ranked in descending order, based on the number of research publications for that species (i.e., the 1st, that is, most-studied, species had >700 publications, while the 500th species had 0 publications). Publication quartiles indicate the number of species, ranked from most to least studied, that account for one-quarter of all research on raptors. The seven most researched species accounted for one-quarter of all publications (1st quartile; red), followed by 14 species (2nd quartile; orange), 33 species (3rd quartile; green) and 503 species (4th quartile; blue). The dashed line is the mean number of publications across all raptor species (30.0), and the solid line is the null research distribution prediction based on the broken-stick model

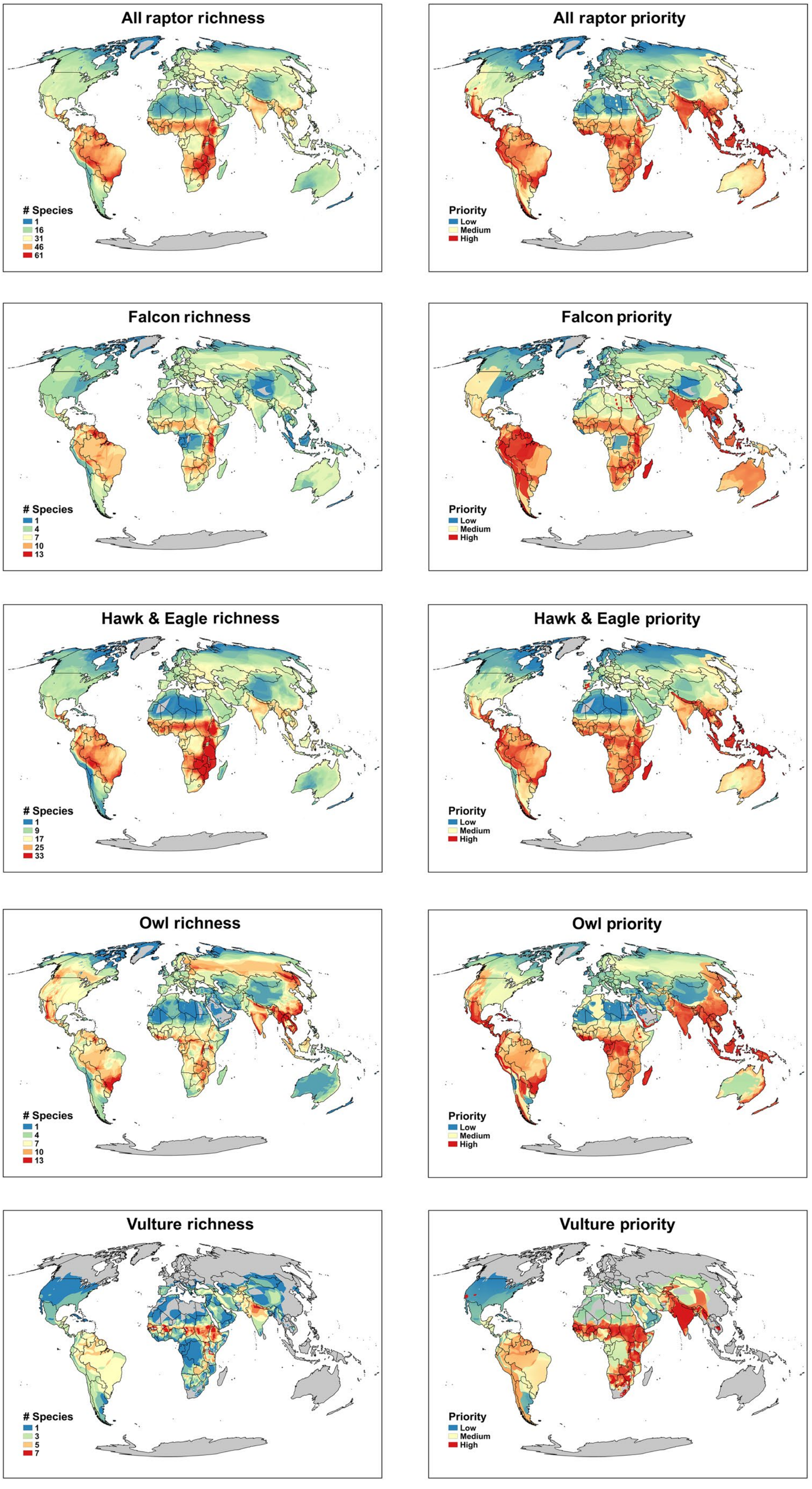

FIGURE 4 Raptor research and conservation priorities and species richness maps for all raptors, and raptor subgroups (hawks and eagles, falcons, owls and vultures)

For the full list of countries, national-level indicators and mean national RCPI rankings, see Supporting Information Appendix S8.

4 | DISCUSSION

Here, we identified drivers of extinction risk, highlighted patterns in scientific attention and identified research and conservation priorities for raptors worldwide. Species with small ranges, scavengers, those highly dependent on forest and with slower life histories were more threatened with extinction. Meanwhile, species with small ranges and inhabiting less developed countries were particularly understudied. Ten species (1.8% of all raptors) received nearly one-third of all raptor research (32%), while over one-fifth of all raptors (21%, 116 species) had zero research publications. Our research and conservation priority index (RCPI) provided a species-by-species priority ranking (see Supporting Information Appendix S7) and our global prioritization maps highlighted important regions and countries to focus research (Figure 4). Owls were the least-studied group of raptors, and therefore the highest overall priority for future research, while vultures were the most extinction-prone, and thus the group in need of the most urgent conservation investment. Tropical regions of Central and South America, Sub-Saharan Africa and, particularly, Southeast Asia were the highest priority for investment because they hosted the highest number of total species, understudied species and extinction-prone species. Lastly, we identified a strong negative relationship between country-level development and RCPI, indicating a mismatch between priority and capacity for research and conservation on a national level. Overall, these findings call for a shift in scientific and conservation resources towards developing countries. Our prioritization exercise could increase the efficacy of raptor conservation investments and could be applied to other taxa to help set priorities for other groups.

4.1 | Extinction risk

Our results support and augment previous research identifying drivers of extinction risk in vertebrates (Buechley & Şekercioğlu, 2016a; Davidson et al., 2012; Murray et al., 2011; Purvis et al., 2000). The primary driver of extinction risk in raptors is range size (Figure 1), as species with small ranges are at much greater risk of extinction (Figure 2). Our results corroborate other studies, supporting claims that range size is likely the single best predictor of extinction risk in terrestrial vertebrates (Fisher, Blomberg, & Owens, 2003; Harris & Pimm, 2008). Species with small ranges are more extinction-prone for a host of reasons, including that their small range sizes typically result in small population sizes and range-restricted species are highly vulnerable to habitat alterations or stochastic events (Purvis et al., 2000). Thus, it is recommended that raptors with small ranges, particularly island-restricted species, be the target of increased research and conservation investment (Sodhi, Şekercioğlu, Barlow, & Robinson, 2011). Indeed, of the eight raptor species that have gone extinct since 1500, all of them were island-restricted (Supporting Information Appendix S4).

Foraging guild was another strong predictor of extinction risk. This result was largely driven by scavengers, particularly vultures, being highly extinction-prone. Vultures have experienced the most rapid decline in conservation status of any group of birds in recent years, resulting from catastrophic population declines in South Asia and Africa caused primarily by toxic chemicals in carrion (Buechley & Şekercioğlu, 2016a). Of the 22 vulture species, nine are critically endangered, three are endangered, four are near threatened, and six are least concern. Accordingly, we recommend urgent investment in vulture research and conservation, particularly in South Asia and Africa, not only to save these species from extinction, but also to preserve the critical nutrient cycling and disease regulating ecosystem services that vultures provide (Buechley & Şekercioğlu, 2016a, 2016b).

We also show that raptors that are highly dependent on forests are at an elevated risk of extinction. Our results corroborate findings demonstrating the importance of forest preservation for raptor conservation worldwide (McClure et al., 2018; Morrison, Young, Romsos, & Golightly, 2011). Forests are used by over 80% of all raptor species and more forest-dependent raptors are in decline than those dependent on any other habitat type (McClure et al., 2018). Lastly, species with longer generation lengths were also at higher risk of extinction (Figure 2). This finding has been shown in other studies and is likely due to the fact that long-lived species are typically less able to compensate for increased mortality with increased fecundity (Buechley & Şekercioğlu, 2016a; Purvis et al., 2000).

4.2 | Scientific attention

Research on raptors is extremely biased towards a small fraction of raptor species (Figure 3). Ten raptor species accounted for one-third of all raptor research, whereas one-fifth of all raptors have no publications. Threatened raptors and those with declining populations are less studied (Supporting Information Appendix S5). Similar patterns have been shown across birds (Ducatez & Lefebvre, 2014) and mammals (Brooke et al., 2014). This is particularly troubling from a species conservation point of view. With increasing global change, conservation actions need to be implemented with urgency. The lack of scientific knowledge on species means that, in many cases, threats and population declines may be overlooked, and conservation actions are taken with limited understanding of species ecology (Cook et al., 2010; Sutherland et al., 2004).

Range size was the most important predictor of scientific attention, a result that has been shown in other taxa (Brooke et al., 2014; Ducatez & Lefebvre, 2014). This may be due to a number of reasons, including that species with smaller ranges inherently come into contact with fewer people and potential researchers, and are more likely to occur in the tropics (following broad patterns in diversity and endemism), where there is generally less capacity and funding for research (Brooke et al., 2014; Ducatez & Lefebvre, 2014). Range-restricted species are also more likely to be habitat specialists, particularly forest specialists, and in many cases are restricted to islands, making them less visible and generally harder to study. Because range-restricted and specialized bird species are both more extinction-prone (Şekercioğlu, 2011) and understudied, we strongly recommend prioritizing their research and conservation.

Human population density and human development index (a composite index that includes human health, education and wealth) were also strongly predictive of scientific attention. Not surprisingly, human development had a positive effect on scientific attention: species inhabiting more developed countries were more studied. Our model also demonstrated that species inhabiting regions of low human population density received more scientific attention (Figure 2). This is an interesting result that merits further investigation, but is likely driven, at least in part, by much of South and East Asia having little-studied raptor species and very high human population densities, while well-studied species inhabiting the Palearctic and Nearctic had relatively low human population densities across their ranges (for example, see the case of well-studied raptor populations in Finland; Saurola, 2009).

Our detailed summary of research by ecological group demonstrates several additional patterns in scientific attention on raptors (Supporting Information Appendix S5). Across all species, Indo-Malayan species were the most understudied, followed by Afrotropical, Neotropical and Austral species. This geographic bias in research is in direct contrast to patterns of global biological diversity, but is widespread across taxa (Deikumah et al., 2014; Sitas, Baillie, & Isaac, 2009; Verde Arregoitia, 2016). The most-studied raptor species restricted to a tropical realm was the White-backed Vulture (*Gyps africanus*), which inhabits Africa, is Critically Endangered and was the 48th most-studied species. Overall, owls are the most understudied group of raptors, likely because they are mostly nocturnal, often cryptic and a highly species-rich group with many species occurring within small geographic ranges in the tropics (König & Weick, 2008). Among all raptors, insectivores and species with specialized diets are relatively understudied. We suspect that insectivores are understudied because they are typically smaller and perhaps deemed less charismatic, and are composed of many forest-dwelling raptors, particularly owls. Furthermore, species whose primary habitats are either desert or forest are highly understudied. Deserts and (tropical) forests are challenging habitats to work in, regarding accessibility, logistics for research and sometimes safety, which likely influences the lack of research on species in these habitats (Tobias, Şekercioğlu, & Vargas, 2013). Lastly, only about one-fifth (20.5%) of raptors are long-distance migrants, yet they receive a large majority of all research (64.9%) and are heavily over-represented in the literature relative to altitudinal migrants, nomads and, particularly, non-migratory (sedentary) species, even though long-distance migrants are less extinction-prone both among raptors (Supporting Information Appendix S5) and among birds in general (Şekercioğlu, 2007). That full migrants are more studied is not altogether surprising, because they tend to occur in both temperate and tropical regions, have very large geographic ranges, come into contact with many people, and migration is a field of ecological research in and of itself (Newton, 2010). Nonetheless, this bias towards migrants can obscure the fact that most raptors are not migratory and that resident species with smaller ranges are generally more vulnerable to extinction (Horns & Şekercioğlu, 2018).

4.3 | Research prioritization

Broad swaths of tropical Central and South America, Sub-Saharan Africa, and South and Southeast Asia scored as the highest priority areas for all raptors, while temperate parts of North America, Eurasia and North Africa scored as relatively low priority (Figure 4). This is partially driven by the greater species richness in tropical regions. However, note that although any given island in Southeast Asia may have relatively low species richness, most of these islands scored as relatively high priority, because they harbour range-restricted, endangered and little-studied species that are highly prone to extinction (Sodhi et al., 2010). Indeed, the biodiversity crisis in Southeast Asia (Sodhi, Koh, Brook, & Ng, 2004) has resulted in nearly half (47%) of all raptor species in this realm being extinction-prone. Madagascar is also very high priority for all groups, except for vultures which do not occur there, and similarly threatened by habitat destruction (Brooks et al., 2006). For falcons, the Amazon basin forest is particularly important, while for owls, Central America, the Atlantic Forest of Brazil, the Congo basin forest and Southeast Asia are the most important, but also parts of temperate East Asia and western North America. For hawks and eagles, large areas of tropical Central and South America, Africa, and South and Southeast Asia were high priority. As expected, highest priority areas for vultures are in South Asia and Sub-Saharan Africa, where vulture populations have experienced catastrophic declines in recent decades, and where several species are classified as Critically Endangered (Buechley & Şekercioğlu, 2016a, 2016b; Ogada et al., 2016). The vulture prioritization map also highlights much of Central and South America as relatively high priority for vultures: six vulture species are found in the Neotropics, and they have received relatively little attention.

Similar research and conservation priority gaps have been identified in other studies using other metrics and other taxa (Deikumah et al., 2014; Trimble & van Aarde, 2012), indicating that the priority regions identified herein are expected to be of high priority for research and conservation broadly.

4.4 | National level correlates of raptor research and conservation priority

Human development was a strong predictor of raptor priorities at the country level (Figure 2), with less developed countries generally being much higher priority. Tropical countries harbour proportionally greater biodiversity, yet they tend to have relatively lower development indices compared to temperate countries (Balmford & Whitten, 2003; Waldron et al., 2013). Thus, our results provide further evidence of a well-known mismatch between the need and capacity for research and conservation. Importantly, specific training and support for early-career conservationists has been shown to have similar geographic discrepancies (Elliott, Ryan, & Wyborn, 2018). However, this also indicates a potential opportunity, whereby funding and expertise from Europe and North American countries in particular (either from non-profits, governments, or private investors) could be invested in developing countries to simultaneously promote biodiversity conservation, poverty reduction and sociopolitical development in the places that need it most (Şekercioğlu, 2012b). Although the costs of conservation often fall locally, the benefits from conserving biodiversity, including existence and aesthetic values and ecosystem services, are spread nationally and globally (Balmford & Whitten, 2003). Therefore, to conserve biodiversity effectively and in a more egalitarian way, it is imperative that there be a wealth and expertise transfer from developed countries, which lie primarily in temperate regions, to highly biodiverse and developing tropical countries (Balmford & Whitten, 2003; Waldron et al., 2013). See Supporting Information Appendix S8 for the full list of countries with mean RCPI values, and indices of development, governance, protected area and human population density.

4.5 | Study limitations

Although our literature search and resulting research and conservation prioritization approach appropriately prioritized species based on our goals (i.e., species that are more threatened and less studied), there are several caveats to our findings that should be considered. For one, our literature search provides an index of scientific attention, and not a full account of the research history for each species, because some publications may have been overlooked by our search methods. It should thus not be used as an absolute measure of research on raptor species (i.e., a research index value of 0 does not necessarily mean that there has never been any research on that species). Further, our literature search included all research published on a species within agricultural and environmental fields, rather than solely publications focused on conservation. This was done because we deem an understanding of the basic ecology of a species—including aspects of diet, breeding biology, physiology, home range, movement ecology, etc.—to be critical for designing and implementing conservation efforts (Cook et al., 2010; Ferraro & Pattanayak, 2006; Fraser et al., 2018; Sutherland et al., 2004). Nonetheless, we recognize that some publications may be more relevant for conservation practice than others.

We treat each species in our prioritization exercise as a unit of conservation importance. To do so, we used the most up-to-date avian taxonomy (BirdLife International's "Checklist of the Birds of the World," 2019). Importantly, as our collective knowledge of avian taxonomy changes, and species are lumped or split, this will affect any species-based prioritization exercise. As species are lumped, they will become lower priority and as they are split (as is the tendency), the newly split species will become higher priority. Further, we prioritized raptor taxa at the species level, but we recognize that subspecies are often targets of research and conservation efforts. For example, despite the Least Concern status of the Aplomado Falcon (*Falco femoralis*), the northern subspecies (*F.s. septentrionalis*) is endangered in the United States and is declining in other parts of its range (Macías-Duarte et al., 2016). This subspecies has thus been the subject of major reintroduction, management and research efforts (McClure, Pauli, Mutch, & Juergens, 2017a). The Puerto Rican Sharp-shinned hawk (*Accipiter striatus venator*) is another example of a subspecies being nearly extinct (Gallardo & Vilella, 2017), although the species is Least Concern. Conversely, conservation efforts for the Cape Verde Kite, previously considered by some to be a distinct species (*Milvus fasciicauda*; Ferguson-Lees & Christie, 2001), were virtually abandoned once it was determined to be non-monophyletic (Johnson, Watson, & Mindell, 2005). Our analysis thus applies to the species level and current knowledge of avian taxonomy. Accordingly, as taxonomy and conservation status changes, and new research is published, our results should be updated to reflect the current state of knowledge.

We also recognize that research and conservation prioritization could be structured around different viable goals, including preserving evolutionary distinctness (Jetz et al., 2014; Redding & Mooers, 2006), ecological functions (Cadotte et al., 2011) or investigating pressures from an issue-based approach (e.g., investigating impacts of climate change; Bellard, Bertelsmeier, Leadley, Thuiller, & Courchamp, 2012; Harris et al., 2011). Indeed, as evolutionary distinctness and ecological function variables become updated to match current avian taxonomy, they could and, we believe, should be incorporated into future prioritization efforts. We also recognize that in-depth research on one species can lead to ecological understanding that can be applied across taxa (i.e., a model system approach). For example, extensive research of Peregrine Falcons focused on pesticide effects and eggshell thinning had profound impacts on raptor conservation worldwide (Cade, Lincer, White, Roseneau, & Swartz, 1971). Also, some well-studied species lack basic research on causes of population declines, which inhibits their conservation as well (McClure, Schulwitz, Buskirk, Pauli, & Heath, 2017b). Overall, we believe that different prioritization exercises have strengths and weaknesses (Wilson, Carwardine, & Possingham, 2009), and, that our results should thus be interpreted in conjunction with others to help target priorities based on specific goals. It is notable, however, that the broad patterns in conservation priority that we identify for raptors are consistent with priorities identified across other taxa (Brooks et al., 2006; Davies et al., 2006; Jetz et al., 2014).

5 | CONCLUSIONS

To effectively conserve global raptor diversity, it will be imperative to reallocate capacity and funding for research and conservation towards understudied and high conservation priority regions and species, as highlighted in this study. Filling these knowledge and conservation gaps will likely have important implications spanning far beyond the raptor guild considered here. As indicator, umbrella and flagship species that provide key ecosystem functions and services, conserving raptors through efforts to increase knowledge and capacity will provide a disproportionate contribution towards achieving ambitious international targets for biodiversity conservation (e.g., Strategic Goal E: "Enhance implementation through participatory planning, knowledge management and capacity building" of the CBD; Convention on Biological Diversity, 2010) and for sustainable development of human societies (see the United Nations "Sustainable Development Goals"; United Nations Development Program, 2018).

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DATA ACCESSIBILITY

See Supporting Information Appendix S7 for the final database of raptors, number of publications and raptor research prioritization index (RCPI). See Supporting Information Appendix S8 for the final database of country mean RCPI scores and socioeconomic indices.

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BIOSKETCH

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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