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Biological Conservation xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon

State of the world's raptors: Distributions, threats, and conservation recommendations

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ARTICLE INFO

Keywords:
Ornithology
Bird of prey
Important Bird and Biodiversity Areas
IUCN Red List
Raptors MoU
United Nations Convention on the Conservation of Migratory Species of Wild Animals

ABSTRACT

Raptors provide critical ecosystem services, yet there is currently no systematic, global synthesis of their conservation status or threats. We review the International Union for the Conservation of Nature's Red List to examine the conservation status, distributions, threats, and conservation recommendations for all 557 raptor species. We further assess the significance of Important Bird and Biodiversity Areas (IBAs) for raptor conservation. We also determine which countries contain the most species listed under the Memorandum of Understanding on the Conservation of Migratory Birds of Prey in Africa and Eurasia (Raptors MoU). Raptors, especially Old World vultures, are more threatened than birds in general. Eighteen percent of raptors are threatened with extinction and 52% of raptors have declining global populations. South and Southeast Asia have the highest richness and the largest number of threatened raptor species. By country, Indonesia has the highest richness of raptor species (119) and most declining species (63). China and Russia contain the most Raptors MoU species, although they are not yet signatories to the agreement. Raptor species that require forest are more likely to be threatened and declining than those that do not. Agriculture and logging are the most frequently identified threats, although poisoning is especially detrimental to Old World vultures. Of the 10 most important IBAs for raptors, six are in Nepal. Highest priority conservation actions to protect raptors include preventing mortality and conserving key sites and priority habitats. Improved long-term monitoring would allow for conservation to be appropriately targeted and effectiveness of interventions to be assessed.

1. Introduction

Human activities have accelerated the global rate of biodiversity loss, leading to an extinction crisis (e.g., Ceballos et al., 2017; Dirzo and Raven, 2003). Along with increasing numbers of extinctions, many species are in decline (Ceballos et al., 2017) such that losses of biodiversity could disrupt critical ecosystem services and affect human well-being (Chapin et al., 1998; Şekercioğlu et al., 2004; Amar et al., 2018). Indeed, the catastrophic decline of vultures across the Indian subcontinent following introduction of diclofenac as a veterinary drug for cattle in the 1990s (Oaks et al., 2004), and the subsequent increase in feral dog populations and human rabies infections (Markandya et al., 2008) now serves as a classic example of the perils of species decline.

Beyond the well-documented ecosystem services provided by

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https://doi.org/10.1016/j.biocon.2018.08.012
Received 23 April 2018; Received in revised form 10 August 2018; Accepted 19 August 2018

Please cite this article as: McClure, C.J.W., Biological Conservation (2018), https://doi.org/10.1016/j.biocon.2018.08.012

scavengers and predators (O'Bryan et al., 2018), raptors—e.g., hawks, harriers, kites, eagles, falcons, owls, and vultures—serve as cultural symbols, are indicators of biodiversity and environmental health (Donázar et al., 2016), and can structure biological communities (Bogliani et al., 1999; Sergio et al., 2007). Their high trophic level and generally slow life history make raptors more sensitive to anthropogenic threats (Owens and Bennett, 2000; Sergio et al., 2008) and extinction (Bennett and Owens, 1997) than most other bird species. Finally, compared with most birds, raptors are difficult to monitor because they occur at low population densities and can be difficult to detect (Newton, 1979).

Threats to raptors include, but are not limited to, habitat alteration or destruction (Thiollay, 1985, 1998; Bildstein et al., 1998; Virani and Watson, 1998; Bildstein, 2006; Goriup and Tucker, 2007), intentional killing (Brochet et al., 2017), intentional and unintentional poisoning (Oaks et al., 2004; Ogada et al., 2016; Garbett et al., 2018b), electrocution (Lehman, 2001; Mojica et al., 2018), and climate change (Watson et al., 2011; Monadjem et al., 2013; Franke, 2017; Iknayan and Beissinger, 2018). In numerous countries and regions, legislation exists to protect birds, including raptors, from many of these threats (e.g., Donald et al., 2007). Some legislation, such as the United States' Bald and Golden Eagle Protection Act (1940), is designed to specifically conserve raptor species. Protected areas have been created especially for raptors (e.g., Marti, 1992; Snyder and Snyder, 2000; Watson et al., 2007), and best practices have been developed to prevent raptor mortality (APLIC, 2006; CMS, 2011, 2014). Under the United Nations Convention on the Conservation of Migratory Species of Wild Animals (CMS), the Memorandum of Understanding on the Conservation of Migratory Birds of Prey in Africa and Eurasia (the 'Raptors MoU') is a legally non-binding international agreement to conserve migratory raptors throughout Africa and Eurasia.

To be effective, policy and conservation action must be informed by scientific understanding of the threats raptors face and the range of potential conservation interventions. Despite their charisma and importance to ecosystem function there is currently no systematic global synthesis of the conservation status, threats, or conservation and research needs for all raptors. Here, we analyze BirdLife International's assessments for the International Union for the Conservation of Nature (IUCN) Red List of Threatened Species for all raptor species. We review the extent to which raptor species are threatened or declining and the trends in their extinction risk. We examine the spatial distributions of raptors to determine which countries and ecoregions contain the highest richness of raptor species and the most threatened or declining species. Our analysis takes a global perspective, but we also specifically examine the raptor communities within Raptors MoU range states. We then determine whether ecological traits including migratory status and habitat preferences are associated with raptor conservation status. We also evaluate which Important Bird and Biodiversity Areas (IBAs) are particularly key for raptors and which of these face the greatest threats. Lastly, we determine the threats and stressors affecting the most raptor species and identify priority actions for conservation and research.

2. Methods

We obtained data from BirdLife International's database of Red List assessments (BirdLife International, 2017; IUCN, 2017) for all 557 extant species in the orders Accipitriformes, Falconiformes, Cathartiformes, and Strigiformes. BirdLife International undertakes these assessments as the Red List Authority for all birds on the IUCN Red List. For information regarding the assessment process see documentation from the IUCN Standards and Petitions Subcommittee (2017). We divided raptors into five groups: hawks and eagles (Accipitriformes, excluding Old World vultures), Old World vultures, New World vultures (Cathartiformes), falcons (Falconiformes), and owls (Strigiformes). We separated Old World vultures from other Accipitriformes because they are obligate scavengers and are currently experiencing a different set of threats than birds in the rest of the order.

2.1. Status

The IUCN Red List uses quantitative criteria (Criteria A to E; IUCN Standards and Petitions Subcommittee, 2017) on the size, structure, and trends of species' populations and ranges to classify species into categories of extinction risk (Least Concern, Near Threatened, Vulnerable, Endangered, Critically Endangered, Extinct in the Wild, and Extinct). When there is insufficient information to apply criteria, such that a species may fall in any of the extant categories, it may be considered Data Deficient. Species classified as Critically Endangered, Endangered, and Vulnerable are considered to be 'threatened' with extinction. Red List assessments include estimates of direction of population trend (increasing, stable, decreasing, or unknown). We thus calculated the percentage of raptor species per group within each Red List category and for each direction of population trend. We performed chi-square tests to determine if there were statistically significant differences in numbers of threatened or declining species among our five groups (van der Hoek et al., 2017). We also calculated, for each group, the proportion of threatened species listed under each Red List criterion. To track trends in extinction risk over time, we calculated the Red List Index (see Butchart et al., 2007 for methods) for each group and for all raptors, and compared this with the index for all bird species.

2.2. Regions, countries, and ecoregions

Red List assessments document the countries in which each species occurs. We calculated species richness and number of threatened and declining species per country and per broader geographic region (e.g., North America, Sub-Saharan Africa). We examined results for all countries overall and for CMS Raptors MoU range states, specifically. When examining Raptors MoU range states we only considered species listed in the Raptors MoU (i.e., African-Eurasian migratory raptors; Coordinating Unit of the Raptors MOU, 2015). To estimate richness and number of threatened and declining species per ecoregion, we used ArcGIS to quantify overlap of the species' geographic distributions (BirdLife International, 2017; Handbook of the Birds of the World, 2016) with terrestrial ecoregion designations (Olson et al., 2001). We excluded range polygons with presence classified as 'possibly extinct,' 'extinct,' and 'uncertain,' with origin classified as 'introduced,' 'vagrant,' or 'uncertain,' and with ecoregions classified as 'rock and ice' and 'lake.'

2.3. Ecological traits

Red List assessments contain ecological information such as migratory status and habitat preferences. The latter are coded against a hierarchical habitat classification scheme, with broad Level One habitat types (e.g., 'forest') encompassing more specific Level Two habitats (e.g., 'boreal forest'). We considered classifications that were coded by IUCN as 'Suitable,' meaning 'the species occurs in the habitat regularly or frequently,' hereafter as 'used,' and of 'Major Importance,' meaning that the habitat type is an absolute requirement or the primary habitat in which the species occurs, hereafter as 'required' (http://www.iucnredlist.org/technical-documents/classification-schemes/habitats-classification-scheme-ver3). For each Level One habitat type, we calculated the number of species listed. Because the most frequently listed Level One habitat type was 'Forest' (see Section 3. Results), we compared the proportions of threatened and declining species between species that use and require 'Forest' versus those that do not. To determine whether tropical forest species are more frequently threatened or declining than forest species that do not use or require tropical forests, we further examined the number of threatened and declining species that use and require subtropical/tropical (hereafter, 'tropical') versus non-tropical ('Boreal,' 'Temperate,' and 'Subarctic') forest-types.

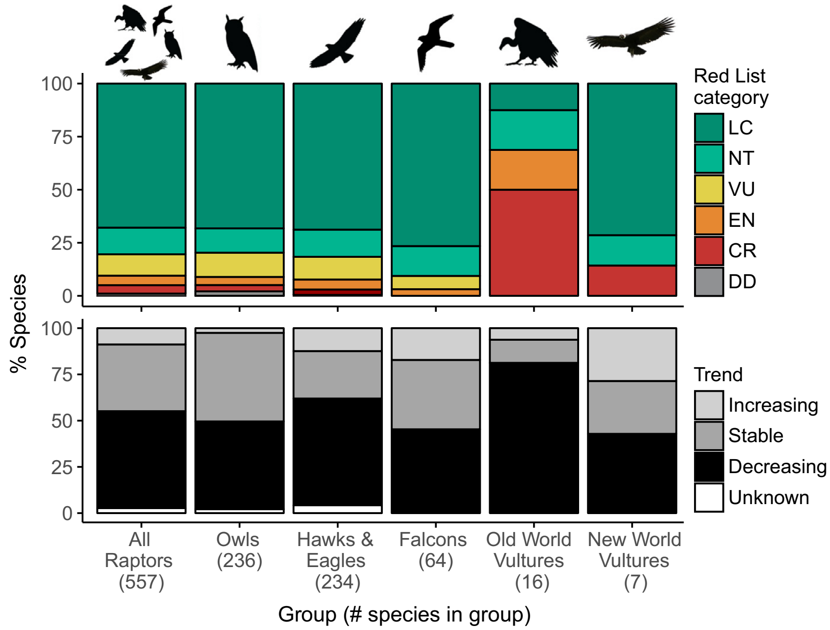

Fig. 1. Percentages of extant raptor species within IUCN Red List Categories (Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), Least Concern (LC), and Data Deficient (DD)), and direction of population trends for each group.

We compared the status and trends of species coded as 'not a migrant' with migratory species (those listed as 'full migrant,' 'altitudinal migrant,' or 'nomadic'; see BirdLife International, 2018 for definitions). We also estimated proportions of forest versus non-forest species that are migratory. We performed chi-square tests to determine if differences in number of threatened or declining species per ecological trait were statistically significant (van der Hoek et al., 2017).

2.4. Threats and stresses

Threats and stresses are classified within Red List assessments using the IUCN/Conservation Measures Partnership threats and actions classification schemes (Salafsky et al., 2008). Threats are defined as the "proximate human activities or processes that have impacted or may impact species" and stresses are the "degraded condition or 'symptom' on the taxon that results from a direct threat" (Salafsky et al., 2008). For example, hunting (a threat) can lead to individual mortality (the stress). We here use the term 'mortality' as defined by Salafsky et al. (2008) as "direct killing or capturing of species," not the other common meaning as a population-level rate of death (e.g., Newton, 1979). Threat magnitude is calculated from scores for scope, timing, and severity following IUCN Threats Classification Scheme (Version 3.2; IUCN-CMP, 2012).

Threats are classified hierarchically with Level One encompassing Level Two classifications. For example, the Level One classification of 'Biological Resource Use' encompasses the Level Two classifications of 'Hunting and Trapping,' 'Gathering Terrestrial Plants,' 'Logging and Wood Harvesting,' and 'Fishing and Harvesting Aquatic Resources.' We analyzed threats at Level One apart from 'Biological Resource Use,' and 'Natural Systems Modifications' (encompassing 'Fire and Fire Suppression,' and 'Dams and Water Management/Use'), which were analyzed at Level Two of the classification scheme, given these represent heterogeneous threat types. We calculated the number of raptor species for which each threat type was listed. In this synthesis, we only report threats for species classed as threatened, and only those threats coded as having Low, Medium, and High impact (therefore removing threats with No/negligible, Unknown, and Past impacts).

2.5. Important bird and biodiversity areas, conservation actions, and research recommendations

IBAs are sites identified as being internationally important for the conservation of the world's birds (BirdLife International, 2014a). We analyzed data on which raptor species occur in sufficient numbers to qualify the site as an IBA under the criteria for IBA identification (i.e., 'trigger species'; BirdLife International, 2014a). For a species to trigger an IBA it must contain populations of one or more threatened, restricted-range (global range < 50,000 km^2), or biome-restricted species; or contain at least 1% of the global population of a congregatory species (Hole et al., 2009). BirdLife International also keeps a list of 'IBAs in Danger': those that have been identified as under particularly severe threat (BirdLife International, 2014b, updated at http://datazone.birdlife.org/site/ibasindanger). We thus examined the importance of each IBA for raptor conservation by calculating richness of raptor trigger species, and number of threatened and declining raptor trigger species for IBAs, in general, and IBAs in Danger, specifically.

We also compiled recommended conservation actions and research needs per species following Salafsky et al. (2008). Research needs are recorded under four Level One categories: 'Research,' 'Monitoring,' 'Conservation Planning,' and 'Other' as well as more specific Level Two classifications such as 'Population trends,' 'Threats,' and 'Taxonomy.' We calculated the number of species in each raptor group for which each category of conservation action and research need was recommended.

3. Results

3.1. Status by taxonomic group

Of the 557 extant raptor species assessed by BirdLife International (2017), 103 (18%) were considered threatened ('Vulnerable,' 'Endangered,' or 'Critically Endangered'), with a further 70 (13%) classified as Near Threatened. As of 2016, all but one of the six Data Deficient species in this dataset were owls (Fig. 1), the exception being New Guinea's Chestnut-shouldered Goshawk (*Erythrotriorchis buergersi*). Over half the species (n = 292, 52%) had declining population trends (Fig. 1), only 9% of species (n = 49) had increasing population trends, and 3% had unknown population trends (n = 15: five owls and 10 hawks and eagles, Fig. 1). Even among the 142 Least Concern species, 38% had declining population trends. A comparison of the proportion of threatened or declining species between the raptor groups, showed the Old World vultures were disproportionately threatened (11 of 16, 69%; $X^2 = 30.48$, df = 4, $p < 0.001$) or declining (13 of 16, 81%; $X^2 = 11.823$, df = 4, p = 0.02; Fig. 1).

The most common reason for classifying a species as threatened or Near Threatened was a 'Small and Declining Population' (Red List criterion C; 45%) followed by 'Rapid Declines' (criterion A; 27%), then a 'Small and Declining Range' (criterion B; 16%) and lastly a 'Very Small Population' (criterion D; 12%; Fig. S1). No species were classified on the basis of a 'Quantitative Analysis of Extinction Risk' (criterion E).

Since 1988, 26 raptors (5%) have qualified for uplisting to higher threat categories owing to genuine deteriorations in their status or increases in threats (six species qualified for more than one uplisting; this also ignores cases of improved knowledge or revised taxonomy). During that same time period, five raptors (1%) have qualified for downlisting owing to genuine improvements in status following conservation interventions (two being downlisted twice). In the 2016 Red List Index, raptors are more threatened (i.e., have lower index values) than birds in general (0.87 vs 0.91). Across all birds, 44% are declining and 13% are threatened (BirdLife International, 2017). Thus, the average raptor species is more likely to be threatened ($X^2 = 11.65$, df = 1, $p < 0.001$) and declining ($X^2 = 13.96$, df = 1, $p < 0.001$) than the average bird species. Old World vultures are the most threatened group among raptors (with a 2016 index value of 0.45; Fig. 2).

3.2. Regions, countries, and ecoregions

South and Southeast Asia, followed by Sub-Saharan Africa, and South America have the most raptor species and the most threatened and declining raptor species (Tables S1, S2). Indonesia is the most speciose country for raptors (119 species) and has the most declining species (63 species), whereas Kenya and Sudan have the most threatened species (14 species, Fig. 3, Table S3). The Raptors MoU range states with the most species listed under the agreement were China (58 species), followed by the Russian Federation (56 species, Table S4). Sudan has the highest number of threatened migratory species that are listed on the Raptors MoU (11 species), while India and China have the highest number of declining species on the MoU (28 species each; Table S4). Of the 865 ecoregions, the East Sudanian Savanna of central and east Africa contained the highest number of raptor species (98 species), and the highest number of threatened raptor species (14 species, Figs. 4, 5, S2; Table S5). The Northern Andean Páramo of Ecuador and Columbia has the highest number of declining raptor species (47 species; Figs. 4, 5, S2; Table S5).

3.3. Ecological traits

Of the 557 species of raptors, 341 (61%) require at least one broad habitat type (i.e., the habitat is important for the survival of the species, either because it has an absolute requirement for the habitat at some point in its life cycle or it is the primary habitat within which most individuals occur). The Level One habitat type, 'Forest' was listed as regularly or frequently used by 473 species and required by 258 species (85% and 46% of all raptor species respectively; Fig. S3, Table S6). Thus, 'Forest' was listed as a used habitat 1.65 times more often than the next most commonly-used habitat type ('Artificial – Terrestrial'; 286 species) and was listed as a required habitat 8.06 times more often than the second most commonly-required habitat type ('Grassland'; 32 species). Proportionally, more species that use 'Forest' are in decline (264, 56%) than species that do not (28, 33%; $X^2 = 13.57$, df = 1, $p < 0.001$), although the proportions of threatened species are roughly equal between forest (91, 19%) and non-forest species (12, 14%; $X^2 = 0.86$, df = 1, p = 0.36; Table S6). Raptor species that require 'Forest' are more likely to be threatened (75, 29%; $X^2 = 34.35$, df = 1, $p < 0.001$) and declining (178, 69%; $X^2 = 51.57$, df = 1, $p < 0.001$) than species that do not (28 threatened, 9%; 114 declining, 38%, Table S6).

Of species that use tropical forest, 87 out of a total of 423 species (21%) are threatened and 249 (59%) are declining. Four out of the 50 forest species that do not use tropical forest (8%) are threatened and 15 (30%) are declining. Thus, proportionally more tropical forest raptor species are threatened ($X^2 = 3.77$, df = 1, p = 0.05) and in decline ($X^2 = 14.00$, df = 1, $p < 0.001$, Table S6) compared non-tropical forest species. Of species that require 'Forest', those requiring tropical forest (239 species, 93%) were more likely to be declining (172 species, 72%) than species that require non-tropical forest (6 species, 32%; $X^2 = 11.60$, df = 1, $p < 0.001$, Table S6). Proportions of threatened species requiring tropical (71 species, 30%) versus non-tropical forest (4 species, 21%) were not significantly different ($X^2 = 0.29$, df = 1, p = 0.59, Table S6).

One quarter (26%) of raptor species were classified as migratory species. Of these 144 migratory species, 8% were classified as threatened whereas 22% of non-migratory species were threatened. Thus, non-migratory species were disproportionately more threatened compared to migratory species ($X^2 = 13.30$, df = 1, $p < 0.001$; Fig. S1). Likewise, the group of non-migratory species had a disproportionately higher number of declining species (57%) compared to the group of migratory species (40%; $X^2 = 11.50$, df = 1, $p < 0.001$; Fig. S1).

Proportionally, fewer raptor species that use (104 species, 22%) or require (33 species, 13%) 'Forest' are migratory compared with species that do not use (40 species, 48%) or do not require forest (111 species, 37%; $X^2 = 23.13$, df = 1, $p < 0.001$). Of species that use 'Forest,' proportionally fewer that use tropical forest are migratory (71 species, 17%) compared with those that do not use tropical forest (33 species, 66%; $X^2 = 60.30$, df = 1, $p < 0.001$). Further, species that require tropical forest are less migratory, as a percentage (19 species, 8%), than species requiring non-tropical forest (14 species, 74%; $X^2 = 62.42$, df = 1, $p < 0.001$). To summarize, forest raptors are less migratory than non-forest-users, and of forest-users, tropical forest users or obligates were less migratory than species that do not use or require tropical forests. Further, forest users, particularly tropical forest users, and non-migratory species are especially threatened.

3.4. Threats and stresses

The most common threat identified for threatened raptor species was 'Agriculture and Aquaculture.' This was the case when analyzing data for all raptor species, and across all groups, with the exception of Old World vultures, for which 'Hunting and Trapping' was listed as the most prevalent threat (Fig. 6). 'Agriculture and Aquaculture' is also the most prominent threat to species across all regions except Europe and Oceania (Table S7). 'Logging and Wood Harvesting' and 'Hunting and Trapping' threatened the second and third largest number of raptor species, respectively (Fig. 6). Within the threat type 'Hunting and Trapping' (Fig. 6), raptor species can be affected by various sub-categories of threats (see Fig. S4, which includes specific threat classes for 'Hunting' and 'Pollution' only). 'Intentional Hunting and Trapping' includes that for food, sport, belief-based use, and falconry, while 'Unintentional Mortality' includes lead poisoning from spent ammunition. Note that the category 'Hunting and Trapping' includes both legal and illegal hunting. 'Pollution' (Fig. 6) encompasses poisoning via pesticides and 'Other' types such as the veterinary drug diclofenac (Fig. S4). 'Service Corridors' includes electrocution and collision with power lines and mortality from vehicle collisions, and 'Energy Production and Mining' encompasses mortality from wind energy production.

These direct proximate threats serve as the sources of stress, which ultimately influence the condition of an ecosystem or species. The two

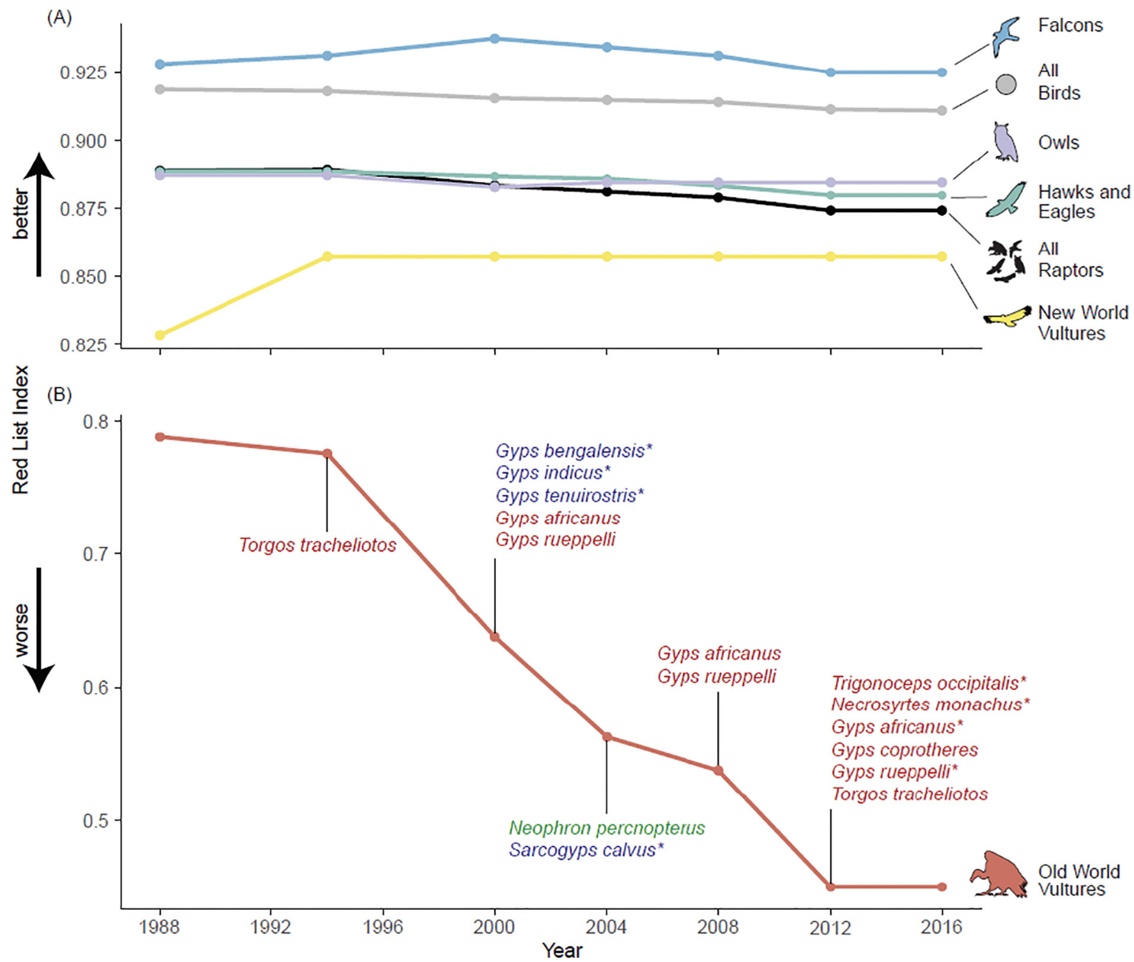

Fig. 2. (A) Red List Indices for 1988–2016 for falcons, all birds, owls, hawks and eagles, all raptors, and New World vultures. (B) Red List Indices for 1988–2016 for Old World vultures; labels indicate the species uplisted in a given year for either African vultures (red), Asian vultures (blue), or the Egyptian vulture (*N. percnopterus*; green), which occurs in both Africa and Asia. Asterisks indicate an uplisting to Critically Endangered. Note that the y-axes are on different scales and that we only present genuine changes in status, not changes due to improved knowledge.

stressors that affected the largest numbers of raptor species were 'Ecosystem Conversion' and 'Ecosystem Degradation' (Fig. S5). The third greatest stressor was 'Species Mortality' (Fig. S5). Cumulatively, 'Ecosystem Degradation,' 'Ecosystem Conversion', and 'Species Mortality' contributed to Medium or High impact stresses for 73, 58, and 28, species, respectively (Fig. S5).

3.5. Important bird and biodiversity areas, conservation actions, and research recommendations

Of the 13,246 IBAs worldwide, 32% had raptors listed as trigger species, 23% were triggered by declining raptor species, and 14% were triggered by threatened raptor species (Fig. S6). Of the 10 IBAs that were triggered by the largest number of declining or threatened raptor species (up to 13 per IBA), six were in Nepal and none were in the New World (Figs. 5, S7; Table S8). Among 338 'IBAs in Danger', 124 (37%) were triggered by raptor species, with the 10 that were triggered by the largest number of declining or threatened species concentrated in the Old World (Fig. S7; Table S8).

The three most frequently recommended conservation actions across all raptor species were 'Land and Water Protection' (24%, 131 species), 'Education and Awareness' (14%, 78 species), and 'Land and Water Management' (13%, 71 species, Fig. 7). Comparing groups, 'Land and Water Protection' was the most frequently listed action for owls (28%, 65 species) and for hawks and eagles (22%, 51 species). 'Education and Awareness' was the most frequently listed action for falcons (55%, 11 species) and for New World vultures (29%, two species, Fig. 7). The most frequently listed actions for Old World vultures were 'Education and Awareness' and 'Law and Policy', each listed for 14 species (88%) in this group (Fig. 7). 'Land and Water Protection' and 'Land and Water Management' were the most frequently recommended actions for raptors across all regions except Central Asia, North Africa, and the Caribbean Islands (Table S9).

Research recommendations emphasized the need to elucidate population sizes and trends. For the majority of species (327, 59%), specific global population sizes had not been estimated. 'Population Size, Distribution, and Past Trends' was thus listed as a research need for nearly one-third of all raptor species (30%, 169 species, Fig. 7). Similarly, 'Population Trends' was the most-listed monitoring need (12%, 68 species, Fig. 7). Baseline population size must be available for a given species to provide population trends (IUCN, 2012). Therefore research into either current or past population levels is a research priority for 42% of raptor species. The only groups for which 'Population Size, Distribution, and Past Trends' were not recommended most frequently were New and Old World vultures which had 'Life History and Ecology', and 'Threats' listed instead, respectively. Only 10 raptor species (six

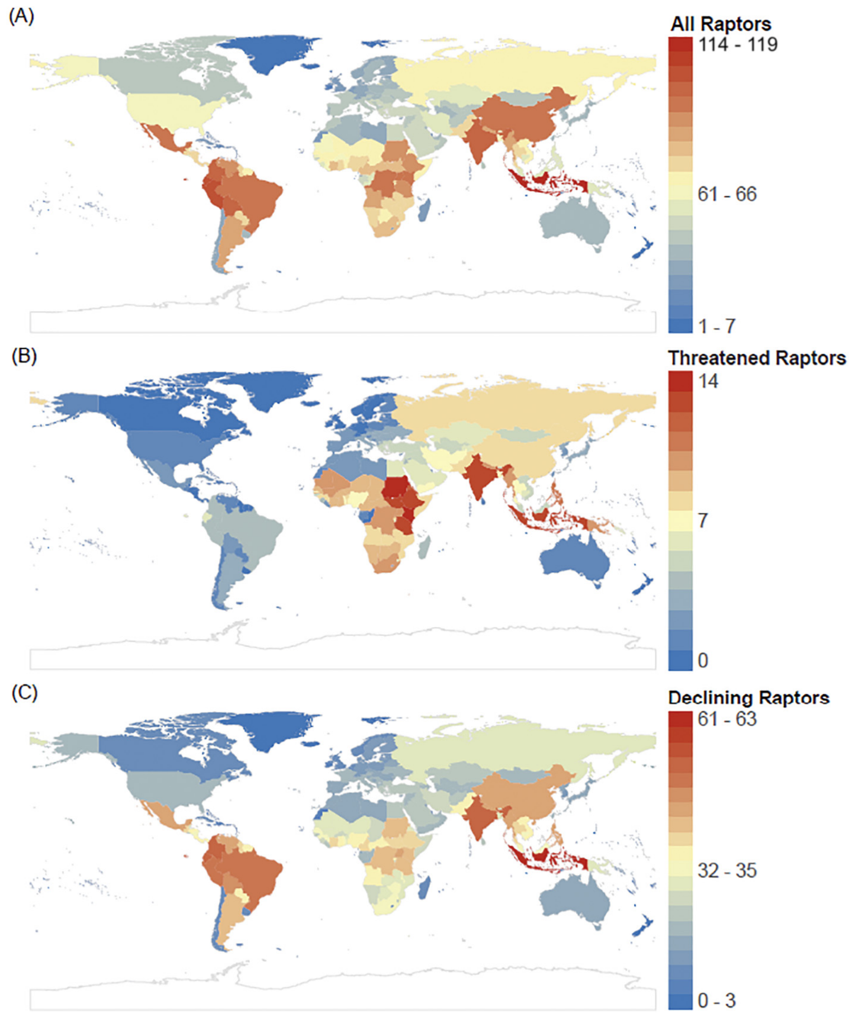

Fig. 3. Maps showing the number of (A) total, (B) threatened, or (C) declining extant raptors per country according to BirdLife International (2017) assessments. Note that the scale represents the number of raptor species and ranges from red, indicating many species, to blue, indicating few species. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

owls, two hawks and eagles, and two falcons) had recommendations for 'Conservation Planning.' Across regions, 'Population Size, Distribution, and Past Trends' was the most recommended 'Research' category for South and Southeast Asia, Sub-Saharan Africa, South America, Oceania, Mesoamerica, and the Caribbean Islands. 'Threats' was the most recommended 'Research' category for West and Central Asia, East Asia, North Africa, North Asia, Europe, and North America (Table S10).

4. Discussion

4.1. Status

Our results indicate that raptors are more imperiled than birds in general, with 52% of raptor species in decline and 18% currently classified as threatened with extinction. Whereas across all bird species, 44% are declining and 13% are threatened. Among raptor species listed as Least Concern, 38% are declining, further supporting assertions that the biodiversity crisis should be viewed not only regarding species extinction, but also population decline (Hughes et al., 1997; Ceballos et al., 2017). The global loss of raptors per se is worrying, not just because of their charisma and flagship role (Sergio et al., 2008), but also because reduced abundance of raptors can have cascading effects on ecosystem functioning through changes in the numbers and behavior of their prey (Brown et al., 1988; Terborgh et al., 2001; Şekercioğlu, 2006). Raptor decline may also lead to loss of ecosystem services (Gaston et al., 2018; O'Bryan et al., 2018), sometimes acutely impacting human wellbeing (Markandya et al., 2008). Therefore, population declines, range contractions, and extinctions of raptors demand investigation into their causes and potential conservation interventions.

Old World vultures are the most threatened group of raptors, with 12 of 16 species listed as Endangered or Critically Endangered and over 80% of species declining. Red List Indices further reveal that Old World vultures have also experienced the greatest deterioration in Red List status of any raptor group since 1988, and possibly any group of birds (Buechley and Şekercioğlu, 2016). Within the last 30 years Old World vultures have faced population crises across South Asia and Africa (Ogada et al., 2012, 2016). Even compared with other avian scavengers, Old World vultures are especially imperiled owing partly to their obligate scavenging behavior (Buechley and Şekercioğlu, 2016), which makes them particularly vulnerable to targeted or unintentional poisoning (Ogada et al., 2016). Encouragingly, populations of vultures across the Indian subcontinent are locally stabilizing as a response to interventions including the initial banning of veterinary diclofenac in 2006 (Cuthbert et al., 2011; Chaudhry et al., 2012; Prakash et al.,

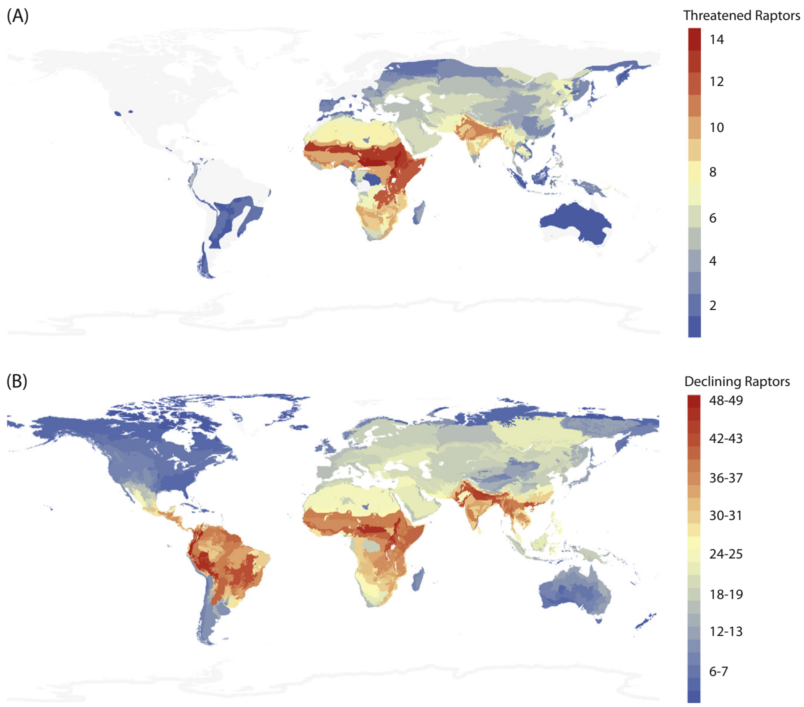

Fig. 4. Maps showing the number of threatened (A) or declining (B) extant raptors per ecoregion according to BirdLife International and Handbook of the Birds of the World (2016) assessments. Note that the scale ranges from red, indicating many species, to blue, indicating few species. See also Fig. S2 for maps based on each raptor group. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2012). However, challenges remain immense in Asia with continued widespread use of diclofenac for cattle and other nonsteroidal anti-inflammatory drugs with potentially similar detrimental effects (Cuthbert et al., 2016; Margalida and Ogada, 2018). Further, despite the knowledge gained from the vulture crisis in Asia, diclofenac has recently been licensed for veterinary use in a number of European Union countries (Margalida and Ogada, 2018) and a coalition of concerned organizations are pressing for a ban to avoid conservation impacts on European scavenging raptors. Concurrently, the African vulture crisis with its different array of threats continues (Ogada et al., 2016; Amar et al., 2018).

4.2. Regions, countries, and ecoregions

Tropical regions, ecoregions, and countries generally contain the vast majority of raptor species (Mindell et al., 2018). South and Southeast Asia and Sub-Saharan Africa are critically important regions for raptors and thus are important geographic areas for conservation action. Indeed, the region of South and Southeast Asia contains 1.5 times as many declining species as stable or increasing species. Given the overall distribution of species, it is perhaps unsurprising that all of the 10 countries with the most threatened raptor species are either in Sub-Saharan Africa or South and Southeast Asia (Table S3).

Seven of the 10 countries with the most threatened raptor species are parties to CMS (Table S3). Embedded in that agreement is guidance related to raptor poisoning and electrocution (CMS, 2011, 2014) and it directs intergovernmental groups to support range states to address these threats. Likewise, the Raptors MoU has produced several Species Action Plans for the conservation and management of raptors (Kovács et al., 2014; Andevski et al., 2017; Botha et al., 2017) with key actions that are vital for the future of raptors in the Old World. Signatories to the Raptors MoU commit on paper to implementing measures such as providing legal protection, conserving habitats and sites important for migratory species, addressing threats, raising awareness of the problems faced by these birds, monitoring populations, and sharing results within the overall aim to conserve migratory raptors. However, the enactment of these plans continues to be hampered for reasons such as inadequate political commitment, funding, or capacity.

There are currently 131 range states within the geographic area covered by the Raptors MoU, of which 59 (including the European Union) are signatories (as of April 2018). China and the Russian Federation hold the most species listed by the Raptors MoU, but neither country has yet signed. Similarly, Ethiopia, South Sudan, and Eritrea are not signatories to the Raptors MoU but are among the 10 countries containing the most threatened raptor species. Encouraging these African and Eurasian countries to sign the Raptors MoU would bring them into this joint conservation effort. Similar efforts that may be beneficial to these conservation goals are those that support implementation of resolutions, action plans, and guidelines of the MoU.

Additional actions could also support conservation of the remaining 83% of raptor species that are non-migratory or outside the African-Eurasian region, and therefore are not listed in the Raptors MoU. Six of the 10 countries and nine of the 10 ecoregions with the highest number of declining raptor species are in South America (Sarasola et al., 2018). Thus, increased efforts are also warranted in South America to prevent common species from becoming threatened. The geographic scope of CMS includes South America, but it may be appropriate to consider expansion of existing agreements or development of new international conservation agreements with a specific focus on raptor conservation across South America.

4.3. Ecological traits

Our study highlights the importance of forests, particularly tropical forests, to raptors. Forests are used by over 80% of all raptor species and are required by nearly half of them. Further, forest species are more likely to be threatened and in decline than non-forest species. Our results thus compliment those of other authors who noted that forests are key to conserving the world's raptors (e.g., Bildstein et al., 1998; Mooney, 1998; Sarasola et al., 2018; Thiollay, 1998) and general biodiversity (Brooks et al., 2006). Of species that use forests, tropical raptors are more likely to be threatened and in decline than those

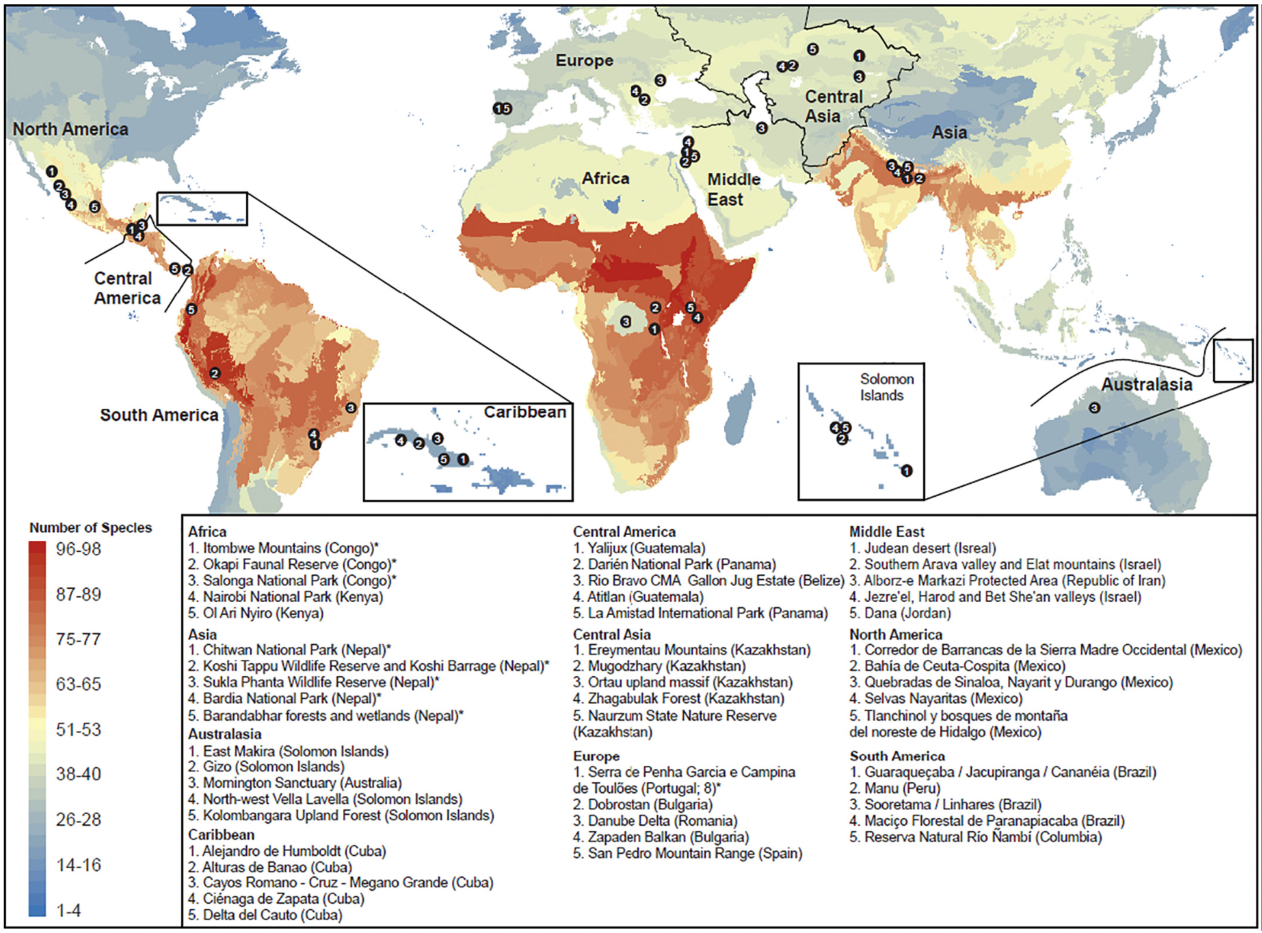

Fig. 5. Map showing the total number of extant raptor species per ecoregion according to BirdLife International and Handbook of the Birds of the World (2016). Points represent the five Important Bird and Biodiversity Areas (IBAs) per geographic region supporting the most raptor trigger species. In the case of ties, we plotted the IBAs with the most threatened, or declining species. Note that IBAs are not mapped here for Oceania. IBAs that are within the top ten most important for raptors globally are indicated by an asterisk in the legend. See Table S9 for the full list of IBAs and their richness of total, threatened, and declining raptor trigger species. Note that the scale ranges from red, indicating many species, to blue, indicating few species. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

outside the tropics. Migratory raptors might have been expected to be particularly vulnerable (Bildstein, 2006), especially given the threats to other migratory bird species (e.g., Sanderson et al., 2006; Both et al., 2009) and because of high mortality experienced during migration (Klaassen et al., 2014). However, we found that migratory raptors were overall less threatened or declining than non-migratory raptors, similar to avian migrants in general (Kirby et al., 2008). Goriup and Tucker (2007) also found that non-migratory raptors were more threatened than migratory raptors in the Afrotropical and Indo-Malayan realms and noted that this discrepancy might be because disproportionately more species with small ranges—which are more likely to qualify as threatened—particularly owls, are non-migratory. Our results suggest that non-migratory raptors tend to be at higher risk of extinction partly because they are likely to permanently reside in the tropics, where deforestation is accelerating (Hansen et al., 2013). Perhaps more importantly, resident tropical species are restricted to smaller geographic ranges and have greater niche specialization (see Şekercioğlu, 2007) and are thus more vulnerable to environmental perturbations including climate change and habitat loss.

4.4. Threats and stresses

According to Red List assessments, the most prominent causes of raptor population declines are habitat destruction and alteration (see also Bildstein, 2006; Bildstein et al., 1998; Goriup and Tucker, 2007; Thiollay, 1998, 1985; Virani and Watson, 1998) via agricultural expansion and logging (Grande et al., 2018). The importance of these threats to birds and other wildlife globally has also been highlighted by previous reviews (BirdLife International, 2013; Joppa et al., 2016; Tilman et al., 2017). With some notable exceptions (Buij et al., 2013; Murgatroyd et al., 2016; Grande et al., 2018), raptors tend to be victims of global expansion of agriculture and logging (Foley et al., 2011; Laurance et al., 2014; Grande et al., 2018). 'Ecosystem Conversion and Degradation' is listed as a Medium or High impact stress for 2.6 times as many raptor species than 'Species Mortality,' although threats causing mortality can have acute effects on raptor populations (e.g., Buechley and Şekercioğlu, 2016; Oaks et al., 2004; Ogada et al., 2016).

Although ranked third for raptors overall, 'Species Mortality' is the most critical stressor to Old World vultures (Fig. S5), with 'Hunting' and 'Pollution' proportionally affecting more Old World vultures negatively than any other raptor group. Old World vultures are often killed for belief-based use (including 'traditional medicine'), killed by poachers,

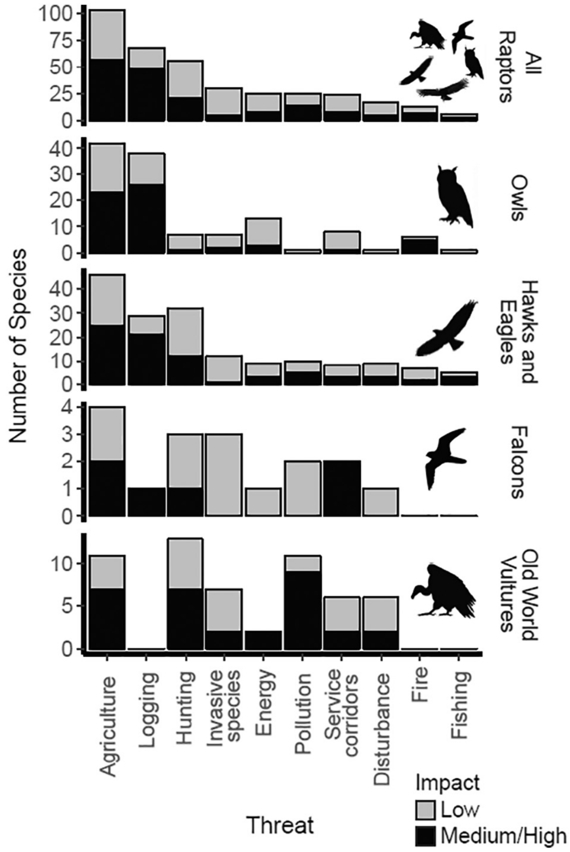

Fig. 6. Number of extant threatened raptor species for which threats were listed as having a Low or Medium/High impact. We only show the top ten threats across all species. Note that New World vultures are omitted because only one species is threatened, and note that shorthand titles are used for threats; for full terms, see the classification scheme at http://www.iucnredlist.org/technical-documents/classification-schemes/threats-classification-scheme.

and poisoned when they feed on deliberately poisoned carcasses (Buechley and Şekercioğlu, 2016; Ogada et al., 2016; Botha et al., 2017). There is also increasing evidence that they, like New World vultures, are exposed to high levels of lead poisoning through spent hunting ammunition (Garbett et al., 2018b).

4.5. Important bird and biodiversity areas, conservation actions, and research recommendations

Given that threats causing habitat destruction and degradation are the most important for raptors, it is unsurprising that 'Land and Water Protection' outranks all other actions recommended for global raptor conservation. This is especially true within species-rich South and Southeast Asia where the most common recommended management action is 'Land and Water Protection,' which is in agreement with conservation priorities suggested for other taxa in the region (Hughes, 2017). Protected areas can be effective means of raptor conservation (Thiollay, 2006) and identifying and safeguarding important sites for raptor populations should be a priority for conserving habitat. Many IBAs have been identified because of the populations of raptor species that they support, and many more support raptor populations in numbers below the thresholds of the IBA criteria. Not all IBAs are protected, however, and we suggest urgent action to safeguard IBAs in danger that support important populations of threatened or declining raptor species. Table 3 of the Raptors MoU identifies key sites for raptors across the range states within Africa-Eurasia and our results (Fig. 5, Table S8) additionally highlight important areas for raptors both globally and regionally.

Although important, identification and designation of protected areas will only conserve raptor populations if accompanied by appropriate monitoring, management, and enforcement actions. Indeed, raptor populations are declining within many designated protected areas (Laurance et al., 2012; Garbett et al., 2018a). Further, for many wide ranging species, particularly those susceptible to poisoning, protected areas alone are unlikely to be sufficient to conserve a species (Van Eeden et al., 2017; Garbett et al., 2018a). Given the threat posed to Old World vultures by poisoning, it follows logically that the most frequently recommended conservation actions within Red List assessments for Old World vultures are 'Education and Awareness' and 'Establishing and Enforcing Law and Policy.' These actions are particularly relevant in Sub-Saharan Africa. With the most species affected by hunting (both legal hunting and illegal killing) and the most species for which 'Education and Awareness' is recommended, our results support the calls for action to prevent accelerated anthropogenic mortality of raptors in Sub-Saharan Africa (Ogada et al., 2016; Botha et al., 2017).

For some species or countries, the conservation action that likely could bring the most immediate change is to improve legislation—including implementation and enforcement, and policy changes, such as improved regulation in the use of poisons or mitigation of dangerous powerlines. For migratory raptors, international cooperation is of particular importance. If properly adopted and enforced, International Species Action Plans such as the recently developed Multi-Species Action Plan to Conserve African-Eurasian Vultures (Vulture MsAP; Botha et al., 2017) provide an important framework for multi-stakeholder action. Inter-governmental task forces to address specific threats, such as the CMS Energy Task Force and the CMS Intergovernmental Task Force on Illegal Killing, Taking and Trade of Migratory Birds in the Mediterranean also serve as important models of international cooperation aimed to protect migratory species.

Examining current and past population trends ranked as the most common research priorities for raptors within Red List assessments. To achieve this goal, researchers should identify additional geographic sites important for raptor conservation while further refining methods to estimate population sizes, distributions, and trends. Although only six raptor species were listed as Data Deficient in 2016, 15 had unknown population trends. For over half of all raptors (357 species), there was no estimate of population size. The IUCN Red List methodology is considered the 'gold standard' in species risk assessment (De Grammont and Cuarón, 2006), but Red List assessments are only as good as the knowledge informing them. During the Asian vulture crisis, populations of three *Gyps* vulture species collapsed by > 96% in 10 years (Prakash, 1999; Gilbert et al., 2002), providing a stark illustration of the need to detect trends quickly to act and conserve species. Development of standardized methods to better monitor raptors across their ranges (e.g., Anderson et al., 2017) would increase our ability to identify and act to address drivers of decline, increasing the accuracy of Red List assessments and the speed at which changes in status can be recognized.

Calls for increased monitoring of raptors are not uncommon (e.g., Andevski et al., 2017; Goriup and Tucker, 2007; Kovács et al., 2014). For example, the Vulture MsAP (Botha et al., 2017) lists several research and monitoring actions as 'essential,' including surveys to estimate population size and distribution. The African Raptor DataBank (ARDB) provides a continent-scale model of a raptor monitoring platform that would improve understanding of population size and status at the global level. In 2012, the ARDB was founded to ascertain the conservation status of raptors across Africa. Professional and citizen scientists contributed data either via a mobile device (Android or iOS) or a standardized spreadsheet. Using roughly 180,000 raptor observations, together with feedback from local experts, researchers estimated the amount of range contraction over the past several decades for raptor

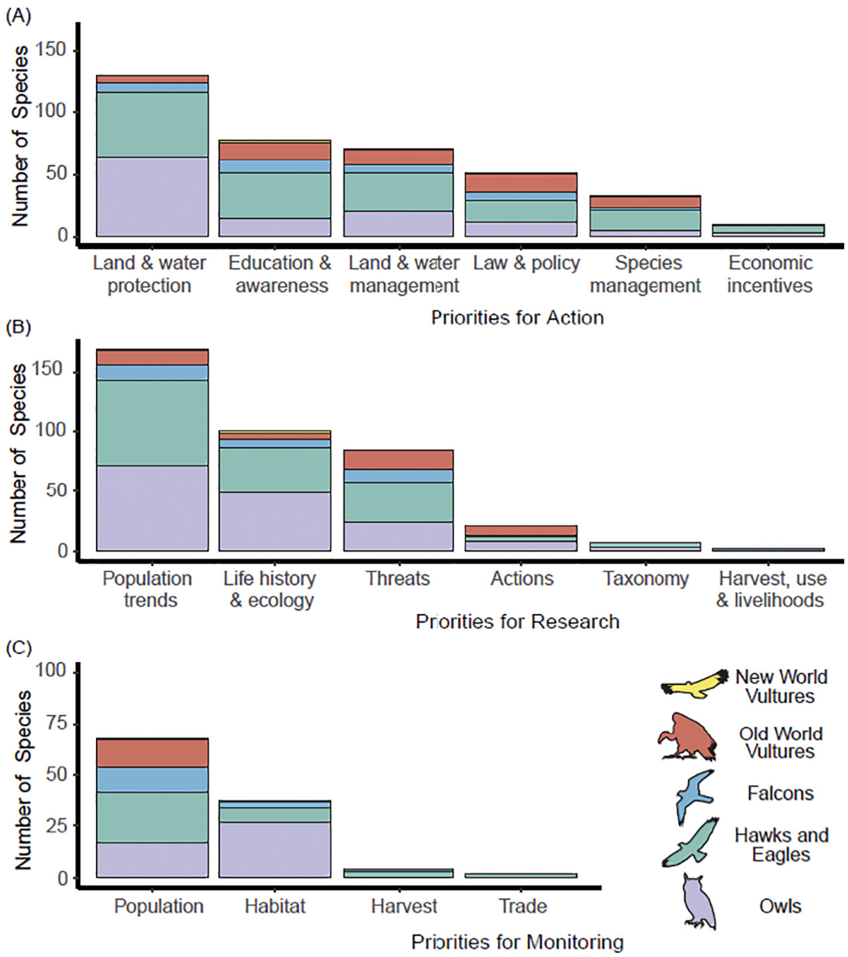

Fig. 7. (A) Priorities for management actions, (B) research, and (C) monitoring recommended for extant threatened raptor as listed by the BirdLife International (2017).

species in Africa (African Raptor Databank, 2017). These data contributed to the uplisting of six vulture species on the IUCN Red List (Amar et al., 2018). The ARDB model is currently being incorporated into The Peregrine Fund's Global Raptor Impact Network (www.globalraptors.org, GRIN)—expanding globally while adding functionality to track population levels and demography. If adopted by raptor researchers and multi-lateral conventions (e.g., CMS), global monitoring programs such as GRIN can combine the efforts of independent researchers around the world to facilitate future Red List assessments, prescribe management actions, and identify critical areas for conservation.

4.6. Conclusions

Although the outlook for global raptor populations seems dire, there is cause for optimism. Conservation action can be effective (Butchart et al., 2006; Hoffmann et al., 2010), especially for raptor populations (Watson, 2018). Indeed, conservation efforts have saved several raptor species from the brink of extinction (e.g., Butchart et al., 2006; Cade and Burnham, 2003; Jones et al., 1995; Snyder and Snyder, 2000). Translocation programs are restoring some populations of threatened raptors (e.g., Alcaide et al., 2010; Ferrer et al., 2014; McClure et al., 2017). Technology is being developed to mitigate mortality at wind power facilities (e.g., Foss et al., 2017; Marques et al., 2014; McClure et al., 2018). And, the next generation of raptor scientists is being trained to monitor and conserve raptor populations into the future (Amar et al., 2018).

Several authors have lamented the lack of knowledge on the status of raptors across much of the globe (e.g., Bierregaard, 1998; Goriup and Tucker, 2007; Virani and Watson, 1998). For many species, the lack of basic information on their distribution and ecological requirements hampers conservation action (Bierregaard, 1998; Virani and Watson, 1998). Increased monitoring of raptor populations, notably in the tropics, would address this information gap. Further, immediate action could change demographic trajectories for common but declining raptor species. We urge national authorities to accelerate their efforts to safeguard these ecologically and culturally important species within their borders with support from other stakeholders, including international cooperation through policy mechanisms. Raptors provide an irreplaceable ecological and cultural service, and their accelerating rarity should be a catalyst for increased conservation action.

Acknowledgements

We thank Chetan Tiwari at University of North Texas for GIS assistance. Thanks also to Nicola Crockford for helpful comments and suggestions, and to the numerous organizations and individuals who have helped to provide information and support to BirdLife International's IUCN Red List assessments. Since establishment of the Coordinating Unit of the Raptors MoU in 2009, core funding has been generously provided by Environment Agency – Abu Dhabi, on behalf of the Government of the United Arab Emirates. We also thank the National Research Foundation of South Africa.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2018.08.012.

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