State of the World's Birds

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Abstract

We present an overview of the global spatiotemporal distribution of avian biodiversity, changes in our knowledge of that biodiversity and the extent to which it is imperilled. Birds are probably the most completely inventoried large taxonomic class of organisms, permitting a uniquely detailed understanding of how the Anthropocene has shaped their distributions and conservation status in space and time. We summarise the threats driving changes in bird species richness and abundance, highlighting the increasingly synergistic interactions between threats such as habitat loss, climate change and over-exploitation. Many metrics of avian biodiversity are exhibiting globally consistent negative trends, with the Red List Index showing a steady deterioration in the conservation status of the global avifauna over the last three decades. We identify key measures to counter this loss of avian biodiversity and associated ecosystem services, which will necessitate increased consideration of the social context of bird conservation interventions in order to deliver positive transformative for nature.

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1.INTRODUCTION

The ~11,000 living birds (Aves) are the best-known class of all living organisms and the most speciose clade of terrestrial vertebrates. Birds are globally near-ubiquitous; they reach their peak diversity in the tropics. Aided by their unmatched capacity for dispersal, birds can be found virtually anywhere on the Earth's surface from pole to pole and at least seasonally from the remotest ocean basins to the most barren desert and highest mountains. Unlike almost all other vertebrates, they can occupy the sky as habitat up to 10 km above the Earth's surface. Most bird species are relatively easy to detect by sight and sound without specialist equipment, and as a result have become a model group for understanding species-environment relationships. Consequently, we understand their taxonomic, functional and phylogenetic diversity, geographic distributions, ecology and conservation status better than for any other comparable group of organisms.

The deeper evolutionary history of Aves remains controversial, with multiple competing definitions that include or exclude different clades within the Dinosauria (1), but many systematists now choose to retain usage of Aves only for a crown group including the last common ancestor of all currently living birds and all of its descendants. Therefore, it was uniquely the avialans from within the Paraves clade of theropod dinosaurs that were not wiped out in the Cretaceous–Paleogene extinction event along with all remaining dinosaurs (2). Diversification of birds, which began in earnest in the Cretaceous, was reset by this mass extinction event, with loss of all arboreal bird taxa associated with devastation of forests globally (3). This great reset was followed however by an explosive adaptive avian radiation in the Tertiary (4), which is now subject to a new set of extinction filters in what may eventually prove to be an ongoing sixth mass extinction across the Holocene-Anthropocene transition.

This new period of turmoil for biodiversity is unique in the planet's history in being driven by the activities of a single species - humans. The resultant loss of avian diversity is again non-random, and so far, has disproportionately affected large, flightless and insular species, with the median mass of extinct species seven times larger than that of extant ones (5), although we may now be seeing the start of a wave of extinctions of continentally distributed species (6).

The goal of this review is to summarise our current understanding of avian biodiversity and assess trends, evaluate drivers of change and identify solutions for conserving and restoring avian biodiversity in the 21st century, drawing on recent advances in our knowledge.

2 GLOBAL AVIAN BIODIVERSITY AND ITS IMPORTANCE

2.1 Birds in space and time

Birds are a truly global taxon, with one or more species occupying all habitats across the Earth's terrestrial surface (Figure 1a). For example, an estimated one million Antarctic Petrels (*Thalassoica antarctica*) nest in a single colony in the Mühlig-Hofmann Mountains 200 km inland in Antarctica (7), while Snow Petrel (*Pagodroma nivea*) colonies have been found up to 440 km inland from the Antarctic coast (8). At the other extreme, colonies of another other seabird - Hornby's Storm Petrel (*Oceanodroma hornbyi*) - were recently discovered for the first time 75 km from the sea in the 'Absolute Desert' region of the Atacama Desert, which harbours virtually no other life (9). Moreover, birds are unlike most groups of organisms in not being tied to a relatively narrow habitable band at the Earth's surface. The sky is the main habitat for many species as diverse as swifts and frigatebirds that eat, sleep and copulate on the wing (10), while many pelagic species may remain on the high seas thousands of kilometres from land for much of the year. A Rüppell's Griffon (*Gyps rueppelli*) that collided with an aircraft at an altitude of 11,300 m (11) and an Emperor Penguin (*Aptenodytes forsteri*) recorded diving to 564 m depth (12) illustrate the range of heights and depths at which birds are physiologically capable of operating.

Most bird species do not, however, occupy such extreme environments, and avian species richness increases at lower latitudes in accordance with the well-established latitudinal diversity gradient, reflecting increasing temperatures, water availability, ecosystem productivity and habitat heterogeneity (Figure 1a). At the finest resolution, a combination of temperature and topographical variability have been found to be the most important predictors of avian species richness globally (13). Avian diversity has also been shaped by the legacy of evolutionary history and variation in diversification rates (14), which are in turn mediated by historical environmental processes (15). As a result, around 80% of bird species are continentally distributed, with the remainder restricted to islands: a disproportionate share considering that islands cover 5.3% of the terrestrial area (16). Over half of all bird species are restricted to the tropics (Figure 1a), but a remarkable 91% of all birds have geographic ranges that intersect at least seasonally with the tropics via migration (17). Avian species richness is unevenly distributed across biogeographic realms, with the Neotropical realm hosting c.36% of all known landbird species, followed by the Afrotropical (c.21%), Indomalayan (c.18%), Australasian (c.17%), Palearctic (c.10%), Nearctic (c.8%) and Oceanic (c.2%) realms (Figure 1a).

2.2 The state of avian taxonomy

The bulk of avian diversity was described in the 18th and 19th centuries, but new species continue to be described, including 266 species between 1946 and early 2012

(18). Most new species have been discovered in tropical latitudes, particularly the Neotropics But new species represented just 14% of the total increase in the number of recognised bird species over this period, with most of this accrual of diversity (1,895 species) associated with taxonomic revisions, in most cases splitting species that had been historically lumped, and underpinned by greater use of vocal and molecular characters in species delimitation (19).

Taxonomic re-evaluation, particularly of large polytypic and/or phenotypically conservative species and species-complexes has also often revealed numerous 'cryptic' species with high plumage similarity but distinct vocalisations and long-diverging evolutionary histories. For example, the number of species of tapaculos in the genus *Scytalopus* has risen from 10 in 1939 to 44 today, with the prospect of still more species waiting to be described (20). Considerable diversification has also occurred in the tropics among species distributed across oceanic islands; for example recent taxonomic revisions of the Red-bellied Pitta (*Erythropitta erythrogaster*) complex (which is scattered across islands between the Philippines and the Solomons) have concluded that the group should be split into between 13 and 17 species (21). It seems likely that this trend towards revaluation of species limits will see the number of bird species continue to rise. Many proposed species 'splits' have not been adopted by global bird taxonomic checklists, but recent research into the genetics of speciation, the limited role of gene flow and the dynamics of hybridization indicate that many phenotypically cryptic taxa may behave as biological species. For example, major Amazonian rivers, which may be several kilometres wide, are barriers to dispersal for many bird species (22). Recent sampling in the headwater regions where many poorly phenotypically differentiated subspecies come into contact has found indications of substantial postzygotic isolation, indicating that they are behaving as biological species with strong selection against hybrids (23). The long lag time in appraising cryptic tropical diversity leaves a taxonomic debt in the tropics and a 'latitudinal taxonomy gradient' (24).

2.3 The importance of birds to ecosystems and culture

Birds contribute towards many ecosystem services that either directly or indirectly benefit humanity. These include provisioning, regulating, cultural and supporting services. Functional roles of birds within ecosystems as pollinators, seed-dispersers, ecosystem engineers, scavengers and predators not only facilitate accrual and maintenance of biodiversity but also support human endeavours such as sustainable agriculture via pest control, for example of phytophagous insects in coffee plantations (25) and rodents in cropland (26). The high vagility of most bird species, especially migratory species, leads to environmental teleconnections linking ecosystem fluxes and processes, sometimes in geographically disparate locations. For example, coral reef fish productivity has been shown to increase as seabird colonies recovered following rat eradication in the Chagos Archipelago (27). Wild birds and products derived from them are also economically important as food (meat, eggs and, in some cases, nests) or guano as fertiliser. By far the most abundant bird on Earth is the domestic chicken (*Gallus gallus domesticus*), of which an estimated 19.6 billion are estimated to be alive at any one time (28). This domesticated form of the Red Junglefowl (*Gallus gallus*) – a tropical forest species from South-East Asia - outnumbers its wild ancestors by several orders of magnitude. Indeed, the biomass of domesticated poultry, largely chickens, is about threefold higher than that of wild birds (29) which may number between 39 and 134 billion individuals (30).

Around 45% of all extant bird species are 'used' in some way by people, primarily as pets (37%) and for food (14%) (31). The cultural role of birds is perhaps more important than for any other taxonomic group: beyond their symbolic and artistic values, birdwatching is a global pastime practiced by millions of people. Garden bird feeding is ubiquitous in much of the Global North, valued at $5–6 billion per year and growing by 4% annually (32). This represents an important opportunity for people to connect with nature, although potentially also results in negative impacts for some non-provisioned species via trophic cascades (32).

The status of birds as a model taxon to ask questions in ecology and evolutionary biology is owed in part to aspects of their life history – largely diurnal, conspicuous and usually easy to identify and study in life, and a 'manageable' number of described species – which means that our knowledge of their distribution in space and time is far better than for other groups of organisms in the tree of life. Consequently, birds have been used as models to understand many macroecological patterns, such as the island biogeography theory, and their co-distributions used to inform conservation priority setting. The ornithological academic corpus is vast in scale, with an average of 1,177 bird conservation papers published in English annually (33). This rapid rate of publication has been helped by the proliferation of open access datasets that provide information on phylogeny (https://birdtree.org), functional traits (34) and species distributions (35). These endeavours are informed by ongoing digitisation of museum collections through sites like GBIF (https://www.gbif.org//),including scans of specimens, as well as mobilisation of vast numbers of citizen scientists through platforms like eBird (https://ebird.org/), which has amassed well over a billion bird records across 60 million checklists collected by over 700,000 users. These data on bird abundance in space and time have enabled assessments of bird abundance distribution in regions where systematic surveys have not yet been possible, along with a collection of rich media useful for addressing a broad range of ecological questions (36). The growth in public participation in bird monitoring and the advent of easy-to-use tools such as eBird enable continental-scale breeding bird surveys, distribution atlases, and development of spatiotemporal abundance models.

3. AVIAN ABUNDANCE IN THE 21ST CENTURY

There is emerging evidence for major changes in abundance of common bird species globally (Figure 2.). Around 48% of extant bird species worldwide (5245) are known or suspected (based on inference from trends in habitat extent/condition and incomplete or anecdotal information) to be undergoing population declines, compared with 39% (4,295) with stable trends, 6% (676) showing increasing populations trends, and 7% (778) with unknown trends (37). Detailed information on population changes in common birds is spatiotemporally patchy, with the best data coming from North America and Europe (Figure 2a,b.). Rosenberg et al. (38) reported that 57% of North American species exhibited declining trends (303 out of 529 species), a net loss of almost 3 billion individual birds since 1970. These losses were most severe in species associated with grasslands, with 74% of species declining, equating to a loss of 700 million breeding individuals across 31 species since 1970. Declines were most prevalent among migratory taxa, with 58% of 419 migrants declining, experiencing a net loss of 2.5 billion individuals, while 54% of 100 native resident species were declining but their combined population was found to have exhibited a modest net increase of 26 million individuals.

The situation is similar in the European Union, where trends across 378 species indicate an overall decrease in breeding bird abundance of 17-19% between 1980 and 2017: a net loss of 560-620 million individuals (39). As in North America, long-distance migratory species have been particularly badly affected, with over 40% of Afro-Palearctic migrants declining substantially since 1970 (40), while resident and short-distance migrants tend to have more stable populations. Farmland species in Europe have declined precipitously: 57% since 1980 (41), driven by agricultural intensification, which has moved eastward with accession of states to the European Union (42). Populations of many woodland species have by contrast been broadly stable across this same period (40), although this masks regional and species-specific variation, with some woodland species declining in the UK for example (39). Elsewhere in the temperate zone, both farmland and woodland bird species have declined in Australia (43), while farmland-specialist species like Brown Shrike (*Lanius cristatus*) and Yellow-breasted Bunting *(Emberiza aureola*) have undergone major declines and range contractions in Japan (44).

Bucking these negative trends have been many wetland bird species in North America and Europe, where wetlands have experienced a net gain in bird abundance of 13% since 1970 (based on summing abundance estimates across species), driven by a 56% increase in waterfowl populations in this period (38), associated with wetland restoration and management for hunting (45). In Europe, there have been similar increases, especially associated with thermally sensitive ‘warm-dwelling’ species (46). At a global scale, the fate of waterbird populations is tied to governance, with populations increasing in regions with higher protected area coverage and decreasing in areas with socio-political instability (47).

Elsewhere, data on long-term trends in common bird species' population abundance from tropical and subtropical latitudes are much scarcer, with some notable exceptions (e.g., Fig. 2). Bird atlas data indicate that at least 50% of forest-dependent birds in South Africa are experiencing range declines (48), but population trends are lacking. Avian abundance in Costa Rica has declined over 12 years (49) and abundance of forest interior species in Amazonia has been shown to have decline over 35 years (50). In other countries, data gaps are being plugged by citizen scientists. For example, long-term trends were estimated with sufficient confidence for 146 species in India, of which nearly 80% were found to be declining (50% of these declining strongly), while just over 6% had stable population trajectories and 14% of species exhibited increasing population trends (51, Figure 2c). Elsewhere there is abundant evidence for the impacts of land-use change on avian communities, but derived from inferences based on comparisons between land-use 'space-for-time swap' studies rather than tracking change in avian abundance within habitats.

4. SPATIOTEMPORAL VARIATION IN EXTINCTION RISK TO BIRDS

The latest assessment of all birds by BirdLife International for the IUCN Red List shows that 1,481 species (13.5% of 10,994 recognised extant species) are currently threatened with global extinction. These include 798 classified as Vulnerable (VU: 7%), 460 as Endangered (EN: 4%) and 223 as Critically Endangered (CR: 2%). A further 52 species are considered to be Data Deficient (DD: 0.5%) as there is insufficient information available to apply IUCN Red List criteria to assess their extinction risk. Population sizes of threatened species span six orders of magnitude, from 1-7 mature individuals of Oahu Alauahio (*Paroreomyza maculata*) to 12,800,000-

47,600,000 mature individuals of European Turtle-dove (*Streptopelia turtur*), but 73% of threatened birds (1,088 species) are estimated to have fewer than 10,000 mature individuals, while 40% (595 species) have fewer than 2500 mature individuals, and 69 have fewer than 50 mature individuals (37). Bird species are non-randomly threatened across the avian tree of life, with richness of threatened species disproportionately high among families such as parrots (Psittaciformes), pheasants and allies (Phasianidae), albatrosses and allies (Procellariiformes), rails (Rallidae), cranes (Gruidae), cracids (Cracidae), grebes (Podicipediformes), megapodes (Megapodidae) and pigeons (Columbiformes) (37). Once phylogeny has been controlled for, extinction risk is associated with greater body size, longer generation times and lower fecundity (52).

More threatened bird species (1,278, 86.4%) are found in tropical than in temperate latitudes (469, 31.7%) (Figure 1b), with hotspots for threatened species concentrated in the tropical Andes, southeast Brazil, the eastern Himalayas, eastern Madagascar and South-East Asian islands (53) However, a higher proportion of temperate-zone restricted species (202, 21.1%) are threatened than tropical-restricted species (1,011, 16.7%). All countries and territories host at least one globally threatened bird species, while ten have more than 75; with Brazil and Indonesia heading the list, holding 171 and 175 respectively. The majority of threatened species (817, 55%) are endemic to single countries or territories, but some species have large ranges spanning many countries (e.g., 129 for Saker Falcon *Falco cherrug),* while 4% of threatened species occur in > 20 countries. Restricted range species are more likely to be threatened, and there are 2,720 species with breeding/non-breeding ranges of <50,000 km^2 (Figure 1c). Some threatened species are also migratory or nomadic (239, 16%) and represent considerable transboundary conservation challenges. Ongoing taxonomic refinement resulting in splitting of polyphyletic species has thus far not had a great impact on the overall proportion of threatened species: newly split species are on average significantly less threatened than species whose taxonomic status remained unchanged (55), although this may change as land-use change intensifies in megadiverse tropical areas such as Amazonia (56).

Repeated assessments of extinction risk for all birds since 1988 provide information on trends in their status. The Red List Index (RLI) illustrates trends in survival probability (the inverse of extinction risk) based on the number of species in each Red List category and number moving between categories between assessments owing to genuine improvements or deterioration in status (31). The RLI has shown a steady deterioration in the conservation status of the global avifauna over the last three decades (Fig. 3). Seventy species have improved in status sufficiently to qualify for lower categories of extinction risk since 1988, almost entirely owing to successful conservation actions. However, this number is outweighed by 391 species that have deteriorated in status sufficient to qualify for higher categories of extinction risk during this period, resulting in an overall decline in the RLI. A recent analysis projected that declines would continue under a ‘Current Business as Usual’ scenario with contemporary economic growth, consumption patterns and energy mix in the absence of new policies (57). Estimates based on current trends predict an overall effective extinction rate (i.e. taking account of movement of species towards extinction, as well as those for which the last individual dies) of 2.17×10^{-4}/species/year, six times higher than the rate of outright extinction since 1500 (58).

5. PATTERNS AND TRENDS IN AVIAN EXTINCTIONS

At least 187 avian extinctions have been confirmed or suspected since 1500, 90% of which pertain to endemic insular species (6) concentrated on the Hawaiian Islands (33 taxa), mainland Australia and islands (8 taxa), the Mascarene Islands (32 taxa), New Zealand (20 taxa) and French Polynesia (16 taxa) (37). Introduced mammals are the primary driver of extinctions of insular bird species: rodents are linked to the extinction of 52 bird species and cats to 40 species (59). Over the last 600 years, the rate of extinctions increased to a peak in the late 19th century, falling slightly through the early and mid-20th Century, before increasing again in the late 20th Century (6, Figure 4). This change reflects a hiatus in insular extinctions and an increase in extinctions of continentally distributed species in highly fragmented tropical regions (Figure 4). Remnant fragments of Atlantic Rainforest in north-east Brazil have emerged as one such focus of extinction, with two species recently lost from this region Cryptic Treehunter (*Cichlocolaptes mazarbarnetti*) and Alagoas Foliage-gleaner (*Philydor novaesi*) and a third extinction, Pernambuco Pygmy-owl (*Glaucidium mooreorum*), strongly suspected (6,60). The Cryptic Treehunter was described as a new species from historical museum specimens after its extinction. Further south in the Atlantic Forest, the Purple-winged ground-dove (*Paraclaravis geoffroyi*) may also have been lost owing to forest loss and fragmentation, but persistent undocumented sightings provide some hope for its continued existence (61). Other species in the same biome are likely to be condemned to extinction unless immediate emergency conservation interventions occur. Even these may be too late for Stresemann's Bristlefront (*Merulaxis stresemanni*) (of which only one individual is known to survive) and Cherry-throated Tanager (*Nemosia rourei*) (with 11 known individuals). While there are no confirmed recent continental extinctions in Asia, a number of threatened species have not been recorded in recent years, and may prove to have been lost this century, including the Critically Endangered Jerdon's Courser *Rhinoptilus bitorquatus* which has not been recorded since 2009 despite searches at the only known locality (37). Although the rate of insular extinctions may have fallen, with many prevented by last-minute conservation interventions (62), insular species are still disappearing: most recently the Poo-uli (*Melamprosops phaeosoma*) last recorded in Maui, Hawaii in 2004 (6).

Extinctions prior to 1500 (baseline date for the IUCN Red List) are difficult to quantify. Fromm & Merri (5) documented 469 species having disappeared over the last 50,000 years, but the most recent estimates suggest that 1,000 species (mostly flightless rails) have been lost from Pacific Islands following prehistoric human colonisation of Polynesia (63). Higher-order taxa endemic to islands have been particularly prone to extinction as result of these historical anthropogenic impacts, with the disappearance of all elephant birds (Aepyornithiformes) from Madagascar and all moas (Dinornithiformes) from New Zealand constituting a major loss of global functional and phylogenetic diversity. Furthermore, undescribed extinctions seem likely to have occurred in some continental systems in the tropics where extensive habitat loss occurred before the advent of scientific specimen collection (64).

Determining recent extinctions can be problematic given the difficulty of detecting the death of the last remaining individual, especially in remote and poorly surveyed locations where many potentially extinct species may occur. Incorrectly classifying a species as extinct risks the “Romeo error” of premature cessation of conservation action (65) and may also lead to a loss of scientific credibility upon later rediscovery of presumed extinct species (66). Media stories of ‘rediscovered’ species that were supposedly extinct are not uncommon, but nearly all of these relate to taxa that had not been classified as Extinct on the IUCN Red List. For example,144 birds were ‘rediscovered’ over a 122-year period since 1889, of which 86% are threatened with extinction, and most of the remainder were extant non-threatened species (67). Of these however, only Cebu Flowerpecker (*Dicaeum quadricolor*) had been previously classified as extinct on the Red List, along with New Zealand Storm-petrel (*Fregetta maoriana*) which was omitted from Scheffers et al. (67). To support more accurate and consistent decisions on when to classify species as extinct, a more robust quantitative approach has recently been developed using information on the timing and reliability of records, timing and adequacy of surveys, and timing, extent and intensity of threats (6).

6. THREATS CONTRIBUTING TO AVIAN BIODIVERSITY LOSS

6.1 Land cover and land-use change

Continued growth of human populations and, especially, of per capita rates of consumption lead directly to conversion and degradation of primary natural habitats and consequent loss of biodiversity (Figures 5, 6). Although global tree cover actually increased between 1982 and 2016, including by 95,000 km^2 in the tropical dry forest biome and by 84,000 km^2 in the tropical moist deciduous forest biome (68), this has been driven by afforestation with plantations (often of non-native species) plus land abandonment in parts of the Global North, with net loss in the tropics. Land-cover changes driven by human activities have been occurring for millennia and are likely to have reduced total bird abundance by between a fifth and a quarter since pre–agricultural times (30). Until recently, relatively few species had been driven to extinction primarily by land-use (69), as most historical land-use change happened at temperate latitudes where species diversity is lower and geographic range sizes are often larger (70). However, ongoing loss of habitat through the 20th and 21st centuries is now imperilling more species, with 1,213 globally threatened species impacted by 'ecosystem conversion', including 165 Critically Endangered species directly threatened by land-use change, and a number of recent extinctions driven by habitat loss (Figure 3, 6).

6.2 Habitat fragmentation and degradation

Habitat loss resulting from land-use change typically occurs concurrently with habitat fragmentation and habitat degradation, which interact synergistically to drive changes in avian community composition. Anthropogenic habitat fragmentation has long been understood to be a major driver of species loss, especially in the tropics. Species with low dispersal capacity may become marooned in habitat patches too small or too degraded by associated edge effects to meet their needs, making local extinction more likely. Bird dispersal capacity decreases at lower latitudes (71 and may partially underpin the stronger negative response to habitat fragmentation among tropical bird populations, which may be six times more sensitive to fragmentation than high latitude species (15). This may reflect low rates of historical disturbance in many tropical regimes from, for example, glaciation and wildfires: environmental filters that may select for less vagile species (15). Many insectivorous tropical rainforest understorey bird species are physiologically incapable of flying continuously more than 100 m (72). In addition, a behavioural reluctance to cross habitat discontinuities renders such species extremely extinction prone in fragmented landscapes (73). Species-area-isolation relationships are one of the strongest ecological rules, and fragment size is a very important predictor of species richness (73), while fragmentation effects remain a major threat to avian biodiversity, especially in the tropics (74). There is, however, emerging experimental evidence of selection pressures acting on members of fragmentation-sensitive guilds to mitigate these impacts. For example, dispersal success was higher for White-shouldered Fire-eyes (*Pyriglena leucoptera*) from fragmented than continuous forest landscapes in dispersal challenge experiments (75).

Disturbance events like selective logging, wildfires, overgrazing by domestic animals and defaunation by hunting can reduce habitat quality, leading to degradation. Degradation affects vast swathes of tropical forests, and different disturbance events interact synergistically with selectively logged forests rendered drier and more flammable due to canopy perforation, and more accessible to hunters and miners due to logging roads and skid trails. In many tropical forest regions, habitat degradation occurs across a larger spatial extent than deforestation; for example, degradation in Amazonia doubles biodiversity loss relative to deforestation (76). Although degraded forests retain fewer species of conservation concern than undisturbed forests, they still have considerable conservation value, far exceeding secondary forests, plantations and non-forest land-uses (77). Forest degradation impacts on birds also include less obvious effects that can impact fitness, such as changes in the production of stress hormones (78). Degradation of grassland and savanna ecosystems is also a major driver of avian biodiversity loss, for example in central and western North America, where rangelands have been subject to overgrazing, fire suppression, ecological succession by woody plants and invasion by exotic grasses, exacerbated by recurrent severe droughts (79).

6.3 Hunting and trapping

Hunting for food (for example, as 'bushmeat'), for sport, trade, or in response to human-wildlife conflicts, can be a driver of habitat degradation, leading to cascading indirect effects on ecosystems as processes such as seed dispersal, herbivory or predation are changed or impaired. This is amplified at lower latitudes owing to a latitudinal gradient in biotic interactions (80). Loss of seed-dispersing species like hornbills results in a disturbance-mediated drift in tree species composition, with cascading impacts on community structure and even forest carbon stocks (81). Functional extinction of large raptors and large mammalian predators owing to conflicts over livestock or game may act in synergy with land-use change to promote mesopredator release, leading to declines in ground-nesting birds (82) or changes in vegetation structure following overbrowsing by burgeoning deer populations. As well as promoting indirect effects, hunting can also drive declines in targeted species, resulting in their endangerment. Loss of large-bodied bird species in accessible unprotected tropical forests is widespread, and may be the most important threat to some species like Wattled Curassow (*Crax globulosa*) and other galliforms in landscapes less affected by habitat loss. Such defaunation can be pervasive; for example, across north-east India, Indochina, Sundaland and the Philippines, large areas of suitable habitat have few species of vertebrates weighing over 1 kg (83). Defaunation is not an exclusively tropical phenomenon, and unsustainable extraction for food, sometimes coupled with sport hunting, remains an issue at temperate latitudes too. For example, 11–36 million birds are estimated to be killed/taken illegally in the Mediterranean region, including 2 million in Italy (84). Migratory birds are at particular risk of over-harvesting. For example, Jiguet et al. (85) recently demonstrated that Ortolan Buntings (*Emberiza hortulana*) trapped in south-west France come from declining northern and western European populations rather than stable populations elsewhere, as claimed by hunting advocates – a finding that supports a ban on the harvest of the species. Hunting may also have significant sublethal effects through disturbance, resulting in reduced habitat quality (86) and indirect lethal impacts through the ingestion of lead shot by target and non-target species (87). Marine over-harvesting also impacts birds, directly through fisheries bycatch and indirectly by prey depletion (88).

Unlike hunting, which is more typically a local phenomenon driven by demand for food or sport, wildlife trade is driven by demands for species as pets or products. For example, Helmeted Hornbills (*Rhinoplax vigil*), which are found across 3,570,000 km^2 of South-East Asia, are now classified as Critically Endangered owing to high demand for their casques in China, resulting in massive depletion of populations, principally in Sumatra and Borneo (89). Scheffers et al. (90) report that 45% of 10,278 bird species have been recorded in wildlife trade, and traded species are more threatened than non-traded ones. Unsustainable levels of hunting and trapping to fuel the wildlife trade is particularly prevalent in Indonesia, and has precipitated an 'Asian Songbird Crisis' with estimates of >3 million White-rumped Shamas (*Kittacincla malabarica*) and >2 million Oriental Magpie-robins (*Copsychus saularis*) held in captivity in Java (91), many of which will have been sourced from elsewhere given the dwindling extent of forest on Java. The trade in wild birds itself is seemingly shifting from physical markets to virtual marketplaces, for example, Siriwat and Nijman (92) found 261 individuals of 17 species of raptors offered for sale on Facebook between February 2017 and January 2019.

6.4 The impact of invasive alien species and disease

Once species richness and phylogeny are accounted for, the bird families under the highest current degree of extinction risk are primarily threatened by invasive alien species, especially in small island systems (93, Figure 4). Predation by introduced mammals such as rats, mice, cats, dogs and pigs is both a major historical driver of avian extinctions and a major contemporary threat (69). Globally, 766 species are threatened by invasive species (with 300 species suffering high or medium impacts). Of those threatened by named invasive species, 572 are threatened by mammals (230 species suffering high or medium impacts) such as Henderson Petrel (*Pterodroma atrata*) threatened by Polynesian Rats (*Rattus exulans*) and domestic cats. Pets or their feral descendants are a major cause of biodiversity loss through disturbance and predation. For example, domestic cats kill an estimated 2.4 billion birds in the US annually (94), while disturbance from dogs can lower habitat availability for many shorebird species (95). The introduction of exotic fish species has also been a key or contributing factor in the extinction of freshwater birds, such as the Alaotra Grebe (*Tachybaptus rufolavatus*), Atitlan Grebe (*Podilymbus gigas*) and Colombian Grebe (*Podiceps andinus*), and remains a significant threat to other waterbird species, through predation, competition and modification of freshwater conditions (37).

There are fewer problems associated with invasive herptiles, with some exceptions, notably the accidental introduction of Brown Tree Snake (*Boiga irregularis*) to Guam in the Pacific, which precipitated the loss of 9 of 11 landbird species, including three endemic species that became globally extinct and another - Guam Rail (*Hypotaenidia owstoni*) - that very nearly did, but was saved by an ex-situ population that has now been successfully reintroduced into the wild (37). Introduced Brown Tree Snakes are also suspected of driving declines in endemic bird species on Saipan in the Mariana Islands (96) and remain a major potential threat to the small vertebrate faunas of many small islands. Impacts of the collapse of the forest bird community on Guam cascade across the ecosystem, leading for example to competitive release of spiders that have attained densities 40 times higher than neighbouring islands (97), and broken mutualistic interactions as plants lose their pollinators, leading to lower recruitment of native plants (98). It is not only non-native vertebrates that cause problems for insular birds; invasive ants of several species are emerging as a threat - especially to seabird colonies by causing nest site abandonment and reducing hatching success, growth rates and survival (99). One of the major threats to Mangrove Finches (*Geospiza heliobates*) in the Galapagos Islands is the invasive alien Avian Vampire Fly (*Philornis downsi*), whose larvae live in the nest base and emerge at night to feed on the blood and tissues of nestlings (100).

A total of 971 alien bird species were introduced accidentally or deliberately to 230 countries and administrative areas between 6000BCE and AD2014, with richness of exotics highest at mid-latitudes (101). Despite being widespread, Baker et al. (102) were only able to identify negative impacts on native bird species arising from the successful establishment of ten species of introduced birds, via hybridisation, competition, disease and brood parasitism. Among the most problematic invasive species is the Mallard (*Anas platyrhynchos*), which threatens the genetic integrity of Hawaiian Duck (*Anas wyvilliana*) and Pacific Black Duck (*Anas superciliosa*) through hybridisation. Most negative interactions involving introduced bird species occur on oceanic islands, with impacts on other bird species in continental systems being rarer, although socioeconomic impacts may be more significant, for example from crop damage (103).

Introduced and domesticated bird species may also pose a risk to wild birds, particularly in insular systems through enhanced disease transmission. For example, avian malaria (*Plasmodium relictum*) was a significant causal factor in the extinction of several native Hawaiian bird species, and regulates both the geographic distribution and abundance of those that persist (104), many of which are now at high risk of extinction (37). Disease is also a threat to species with large population sizes, for example, disease outbreaks (including avian pox) are known to have driven declines in several species of penguins (105), while West Nile Virus is estimated to have reduced the population size of the Yellow-billed Magpie (*Pica nutalli)* by nearly 50% (37). 'Reverse zoonoses' have recently been documented in Antarctica, with visiting humans introducing *Salmonella* and *Campylobacter* bacteria, which have been subsequently found in seabirds (106). Major disease outbreaks associated with garden bird feeders are being increasingly reported in Europe and North America, especially of Trichomonosis caused by infection with the protozoan parasite *Trichomonas gallinae,* which has jumped from pigeons to infect other groups (including birds of prey and passerines), precipitating a 66% decline in the UK population of European Greenfinch (*Chloris chloris*) (32).

6.5 Infrastructure, energy demands and pollution

Concomitant rising demands for energy, and changes in energy infrastructure globally, represent both challenges and opportunities for avian conservation (Figure 5). An increasing green energy matrix should lead to reduction in fossil fuel usage, which should dampen climate change impacts, but some green energy infrastructure like wind turbines can provide significant collision hazards for particular bird species, especially larger-bodied and soaring species (107). Irrespective of the technology used to generate power, the electricity grid is growing at around 5% per year, resulting in a proliferation of new powerlines, which already kill hundreds of thousands to millions of birds every year (108). For some species, like the Great Indian Bustard

(*Ardeotis nigriceps*), powerlines represent the most significant threat to their survival (109).

Other types of human infrastructure also pose threats to bird species, with buildings considered to be the second largest anthropogenic cause of direct avian mortality, killing an estimated 365–988 million birds annually in the United States, especially species that migrate at night (110). Artificial light at night (ALAN - a form of pollution), often associated with buildings, impacts the ability of migrating birds to access cues for navigation and orientation, and can also act as a major sublethal impact to birds if they are forced to stop over in lower quality urban habitats on migration. The pervasive influence of ALAN is well illustrated by the impacts of the September 11 Memorial and Museum's "Tribute in Light" in New York, which is estimated to have influenced ≈1.1 million birds across a seven-day period over 7 years (111).

Petroleum is a significant environmental pollutant across both marine and terrestrial ecosystems, often as a result of oil spills, which may vary from infrequent but catastrophic oil-well blowouts or marine vessel spillages to smaller-scale terrestrial leaks from refineries, pipelines and land transport. Most reported oil spills emanate from the Northern Hemisphere, particularly around North America, which to an extent matches geographical locations of production, but also likely encompasses considerable reporting bias. Chilvers et al. (112) reviewed impacts from publicly available databases on spills and found that of 1,702 reported spills, 312 were reported as having impacted wildlife, including birds in 45% of cases. Oil affects birds directly through physical contact, inhalation and ingestion, and indirectly by reducing habitat quality and prey populations. Plastics, a derivative of petroleum, are one of the most abundant sources of anthropogenic litter and an emerging threat to biodiversity, especially marine life. Birds may be impacted by direct or indirect ingestion, through entanglement ("ghost" fishing gear is often made from plastic) and habitat degradation, resulting in a continuum of lethal and sublethal effects impacting at least 226 seabird species (113). Plastic ingestion is common in procellariiform seabirds, including the only species so far with inferred population impacts from plastic ingestion: Flesh-footed Shearwater (*Puffinus carneipes*) (114).

6.6 Agrochemical and pharmaceutical usage

Environmental pollution can have both direct and indirect impacts on birds, causing direct mortality by poisoning, reductions in breeding success, and declines in habitat quality and resource availability (Figure 4). Pollution, in addition to agricultural and industrial sources, impacts at least 225 threatened species. Sixty years after the publication of Rachel Carson's influential book 'Silent Spring', agrochemicals remain a major threat to wild birds; 2.7 million individual birds are estimated to die annually in Canada alone from pesticide ingestion for example (94). Sublethal impacts of pesticides are also widespread. For example, the neurotoxic neonicotinoid insecticide imidacloprid has been shown to have contributed to declines in insectivorous bird populations in the Netherlands via depletion of their insect food resources (115). Declines in insect populations resulting from pollution caused by biocides, fertiliser and artificial light may underpin loss of avian abundance observed across much of Europe and North America (116). Pharmaceuticals used in animal husbandry are also a major threat to some necrophagous species, for example the veterinary diclofenac has precipitated catastrophic declines in *Gyps* vultures in Asia (37) and has been authorised for sale in several European countries where it may cause similar harm (117). Cumulative impacts of fertiliser use are also a major indirect threat, especially to waterbirds and seabirds, as they may lead to the creation of hypoxic aquatic ‘dead zones’ as energy is diverted from consumers to microbes. Increase in fertilizer usage is generally associated with negative impacts on aquatic bird populations, although these are slowly reversible if pollution can be reduced (118). Increased nutrient loads may also contribute to multiple impacts facing some bird populations and driving population declines. For example, Common Eider (*Somateria mollissima*) populations in the Baltic/Wadden Sea face a combination of top-down and bottom-up processes - direct population regulation by predation of breeding females by resurgent White-tailed Eagle (*Haliaeetus albicilla*) populations and indirect bottom-up regulation by nutrient concentrations in seawater affecting their mussel prey (119).

6. 7 Climate Change

Species are already responding in diverse ways to changes in temperature and precipitation regimes, with modelling efforts indicating that these changes are likely to become more dramatic as the 21st century progresses. There is already extensive evidence for range contractions and range expansions mediated by differing life histories and geographical contexts. For example, Rushing et al. (120) found that ranges of resident birds in North America have expanded along their northern margin whilst those of migratory species have contracted at their southern margin. This pattern of varying responses by migratory guilds has also been observed in Europe, North America and India, where climate change is considered to be a major driver of change, for example in Finland where 37% of species were shown to have expanded their ranges whilst 35% underwent range contractions, with long-distance migratory species worse-affected (121). Tropical bird species are anticipated to be especially threatened given their restricted ranges leave them with very narrow climate niches, with predictions of hundreds of extinctions driven by climate change by 2100

(122).Tropical mountain-top species are likely to be worst affected, and there is already ample evidence of upslope range-shifts, even resulting in local extinction, for example in the Cerro de Pantiacolla in Peru where a 2017 expedition failed to detect 8 of 16 ridgetop specialists recorded in 1985 (123). Species occupying the polar regions may be especially negatively impacted given that warming impacts are more pronounced at high latitudes.

Climate change contributes to a suite of impacts facing migratory species. Howard et al. (124) found that European long-distance migrant birds are likely to face more protracted and longer migratory journeys in future, necessitating additional refuelling stopovers. Migratory birds also face a threat of phenological mismatch if they are unable to time their arrival and onset of reproduction with pulses of resource availability (125). Those that do advance arrival times run the risk of inclement weather when breeding earlier, causing higher mortality (126). Climate dipoles are lasting and predictable fluctuations in temperature appearing at two different geographic locations at the same time; they are responsible for the generation of 'ecological dipoles' determining species distributions in space and time (127). For example, they determine interannual variation in distribution of irruptive species like Pine Siskins (*Spinus pinus*) (128). Climate change is likely to disrupt these teleconnections, resulting in far-reaching impacts on climate niches of avian species. Again, they may be especially problematic for highly migratory species, and interact with other threats such as land-cover change (129). Some hope for birds to keep pace with global change comes from evidence of avian morphological adaptation to climate change, with reductions in body size in North American species demonstrated over a 40-year period (130).

6.8 Global trade teleconnections

Global trade teleconnections now increasingly underpin biodiversity loss, with agricultural and silvicultural commodities like beef, oil seed crops and timber shipped across the globe (17). In 2011, 33% of biodiversity impacts in Central and South America and 26% in Africa were driven by consumption in other parts of the world (131). It is not only movement of goods that may affect birds via impacts on habitats, but also movements of people, with, for example, 62 Critically Endangered and Endangered bird species (especially seabirds and waterbirds) threatened by tourism (132), although ecotourism and hunting tourism provide an important economic incentive for biodiversity conservation in some contexts (e.g. southern Africa). In the wake of the Covid-19 pandemic, African protected areas facing reduced funding through a collapse in tourism, restrictions on the operations of conservation agencies, and increased poaching, tree cutting, artisanal mining and protected area encroachment (133). Some positive evidence of transitory reductions in anthropogenic impacts on birds as a result of the pandemic have also emerged. For example, Schrimpf et al. (134) looked at the response of 82 bird species in pandemic-altered areas of North America and found differences in distribution in 80% of species, most of which increased in urban habitat and near major roads, especially where lockdowns coincided with peak bird migration.

7. SOLUTIONS TO LOSS OF AVIAN DIVERSITY

Efforts to stem the tide of avian extinctions and loss of wider abundance through the 21st century require a substantial expansion of existing efforts, as well as a focus on new ones and a solid knowledge-base of threats to individual species and their severity (Figure 6). Key actions required include effective conservation of the most important sites, mitigation of key direct threats, broader scale policy responses, and targeted recovery actions for those species for which threat-mitigation and site/habitat conservation are insufficient (Figure 7). All of these actions will require much greater attention to the human context and social dimensions of environmental issues, as the success of each depends on changes in human behaviour.

Site-based conservation is the single highest priority action for 76% of threatened bird species (135). Extensive efforts over the last four decades have made considerable progress in identifying the most important locations for conserving bird species. Over 13,600 Important Bird and Biodiversity Areas (IBAs) - sites of significance for conservation of birds - have now been identified worldwide, covering 6.7% of land and 1.6% of oceans (totalling 3.1% of the Earth's surface area), and representing 83% of all Key Biodiversity Areas (KBAs) identified to date (136). A subset of 127 KBAs have been identified as 'Alliance for Zero Extinction' sites because they hold the last remaining population of one or more of 185 Critically Endangered or Endangered bird species. Many IBAs are covered by protected areas: 20.1% are completely and 44.6% are partially covered by protected areas. The remainder are either priorities for targeting designation of new or expanded protected areas, or for recognising 'Other effective area-based conservation measures' (OECMs), such as community-managed reserves and other types of management outside protected areas that benefit biodiversity without necessarily having this as a stated objective (137). Given many governments' recent commitment to expand protected areas and OECMs to cover 30% of their territories, and ongoing negotiations through the Convention on Biological Diversity to adopt an equivalent global target for protecting and conserving 30% of land, sea and freshwater ecosystems, there is a timely opportunity to substantially scale up site-based (IBA/KBA) conservation for threatened bird species in the coming decade. This needs to occur alongside much stronger efforts to manage these sites effectively, tackling key threats, preventing habitat loss and degradation, and restoring habitat where needed. Far too many protected areas currently fail to meet their management objectives and are effectively 'paper parks'.

Protection and effective conservation of key sites must be complemented by broader-scale policy measures to retain and restore natural habitats in wider landscapes and in the oceans. Valuing primary habitats, either through Reducing Emissions from Deforestation and forest Degradation (REDD+) schemes, which create a financial value for the carbon stored in forests, or via best-practice resource management such as low-intensity logging, are likely to be key pathways to maintain and expand these habitats. Land abandonment is increasingly ceding space for birds in secondary habitats. Secondary forests are ubiquitous across the tropics and their value for species of conservation concern tends to increase with their age (138). There is thus an urgent need for the incentivisation of habitat restoration on privately owned lands, without compromising food security, which will require shifts in consumption patterns (17). Global-scale modelling has indicated that habitat restoration is key to mitigating the conjoined climate and biodiversity crises, with a modest restoration of 5% of converted lands in priority areas potentially averting 60% of expected extinctions and at the same time sequestering 299 gigatonnes of CO_2, with forests and wetlands as priority habitats (139). Alongside traditional conservation 'goal-orientated' approaches, rewilding offers a complementary approach that focuses on restoring lost ecological processes mediated by species interactions and is often dependent on reintroduction of lost species or domesticated ecological surrogates (140). This has amplified calls to refocus some agri-environmental subsidies: from marginal farming to large-scale rewilding projects, although this can be delivered along a continuum of de-intensification from wilder farming to nominal wilderness. Care needs to be taken however to avoid perverse impacts, especially surrounding tree-planting on ancient grassland biomes (141).

Nevertheless, the sustainable management of production landscapes may still be key for bird conservation, especially in the tropics where they overlap with biodiversity hotspots, and may provide conservation opportunities for bird species with highly localized distributions. Within those rural landscapes, remnants of native ecosystems, linear habitats (e.g., riparian vegetation, hedgerows), and even crops may be used as landscape management tools for bird conservation by providing habitat and connectivity, including for threatened and range-restricted species (142). Market-based solutions and economic incentives in production landscapes may be used to further leverage bird-friendly habitats (143).

Addressing unsustainable exploitation of birds requires awareness-raising and enforcement to prevent illegal killing and taking of birds (for food, sport, pets, etc., and persecution), even in European countries (144). Sustainable management of hunting of birds is often hampered by inadequate information on harvest levels - particularly for migratory species like shorebirds that cross national frontiers and require flyway-level monitoring policy approaches (145). In tandem with delivering meaningful protection and appropriate bag limits, more efforts need to be made to foster pro-environmental actions among hunters. The success of a huge public-private partnership, including the North American hunting NGO Ducks Unlimited, was driven by a well-funded government policy - the North American Wetlands Conservation Act - which catalysed the restoration of millions of hectares of wetlands to successfully boost game numbers; it remains a good example of success that has not been widely replicated (45). Over 160 native bird species have benefited from at least 1,084 successful eradications of invasive animals on 806 islands worldwide to date (37). For example, Black-vented Shearwater (*Puffinus opisthomelas*) recovered spectacularly on Isla Natividad, Mexico following pig, goat and cat eradication.

Telecoupled threats to biodiversity need to be met with coordinated conservation solutions. Information flows can be used to leverage pressure on multinational companies and governments to pursue sustainable practices via, for example, moratoria on deforesting commodities, certification schemes, zero-deforestation pledges, and a focus on affluent consumers in emerging and high-income economies (146). Given the link between ineffective governance and biodiversity loss, there is a critical need for efforts to strengthen governance, particularly in the Global South (47). However, solutions to avian biodiversity loss need to be socially just, and will likely be strengthened by knowledge co-creation by and for local actors, such as community-based monitoring. Bird conservation can even function as an incentive for joint cooperative actions between communities divided by strife, as a form of bottom-up conflict transformation (147).

For species on the brink of extinction, the 'emergency room' option of ex-situ conservation measures may be necessary. These directly averted extinction of over a dozen bird species in the last three decades, including six Extinct in the Wild species (62). The role of zoos or other ex-situ facilities remains an essential conservation strategy for 45 bird species, and a prudent approach for a further 192 species (148). Many threatened birds are found in taxonomic families for which there is virtually no history of captive husbandry, and hence there may be unforeseen challenges. For species like Alagoas Antwren (*Myrmotherula snowi*), captive-breeding may be the only option likely to secure its short-term future (60). In this case, any ex-situ work would need associated investment to secure land for habitat restoration, as the species is disappearing because of forest loss, fragmentation and degradation. In other cases, it is illegal wildlife trade, rather than habitat loss which has been the most important threat, yet working with local private bird-keepers may be critical to acquire husbandry knowledge and to source birds for conservation breeding programmes, as has been the case in Java with Black-winged Starling (*Sturnus melanopterus*) and Sumatran Laughingthrush (*Garrulax bicolor*) (149). The possible extinction of Purple-winged Ground Dove (*Paraclaravis geoffroyi*) of the Atlantic Forests of South America was easily preventable, as there had been a large ex-situ population maintained by private breeders, but legislative changes effectively made this illegal at a time when the species was fast disappearing from the wild (61). Co-opting experienced private bird-breeders may be important in some cases and may even need to involve amnesties for illegal possession of Critically Endangered species and surrender of those birds to conservation breeding initiatives.

Ornithologists also have to address data gaps in order to understand which species and habitats are in greatest need of conservation interventions (150). There has been a renewed commitment by conservationists to finding innovative solutions to limit biodiversity decline, especially in the face of climate change, such as use of Artificial Intelligence (AI; 151). Successful application of such innovative techniques holds huge potential for mobilising new data to inform IUCN Red List assessments of species, especially for poorly known species. Additionally, if appropriately applied, AI techniques can help to address current biodiversity data collection and monitoring challenges, which will help reduce cost and labour intensity associated with data collection. Quantifying and celebrating avian conservation successes can be facilitated by the application of the IUCN Green Status of Species: a new global standard to measure how close a species is to being fully ecologically functional across its range, and how much it has recovered as a result of conservation efforts (152).

Conclusions

In contrast to the situation for many other taxa, we have a very good understanding of spatiotemporal patterns of diversity in the Class Aves, and the measures needed to recover populations of most threatened species. A lack of progress in conserving these species usually reflects a lack of resources or political will, rather than a lack of knowledge of what needs to be done. For declines in commoner species, there is often greater uncertainty in the relative importance of sometimes dozens of threats and their often-interlinked drivers, hampering efforts to identify the most cost-effective interventions that can be applied at landscape scales. Nevertheless, in general, we have sufficient information to determine the key actions required to halt and reverse avian biodiversity loss. The growing footprint of the human population represents the ultimate driver of most threats to avian biodiversity, so the success of solutions will depend on the degree to which they account for the social context in which they are implemented, and our ability to effect changes in individual and societal attitudes and behaviours (153). Emerging concepts of conservation social science can inform efforts to address biodiversity loss (154) and to achieve more effective and sustainable conservation outcomes (155), linking birds to human well-being, sustainability, climate resilience, and environmental justice.

Summary Points

1. Birds are a globally ubiquitous and very well studied group and offer a unique opportunity to assess the health of an entire limb of the evolutionary tree of life, and the environment more generally.

2. Globally, there has been a deterioration in the conservation status of the majority of bird populations, including that of many formerly abundant species, especially at temperate latitudes.
3. Threatened species are concentrated in the tropics, which host the richest avian diversity.
4. Most avian extinctions have occurred historically on islands, but a wave of extinctions now appears to be impacting continentally distributed species.
5. The most significant threats to avian biodiversity are habitat loss, fragmentation and degradation coupled with human overexploitation and invasive alien species.
6. Climate change is an important emerging driver of change in bird communities, and is a particular concern for tropical montane, polar and migratory species.
7. A portfolio of conservation interventions is available to prevent bird extinctions, with considerable success already documented through evidence-based conservation actions.
8. Reversing the wider loss of avian biodiversity and abundance is a considerably greater challenge, necessitating transformative change across all sectors of society.

Future Issues

1. Further research is needed to determine the degree to which birds are effective indicators for other taxa: which groups are least well predicted by avian distributions and trends, and in which regions and habitats are birds less effective as proxies.

2. Reliable estimates of population abundance and change not inferred from habitat remain elusive for most species, especially in the tropics.
3. There remain gaps in our knowledge of the relative importance of different threats to each species, and their cumulative impacts; not all factors causing significant avian mortality are necessarily driving population declines.
4. Novel and more effective solutions applied at scale are needed to facilitate demand-reduction for overharvested wild birds.
5. Green energy transitions are essential to limit dangerous climate change, but can have negative impacts on birds if inappropriately implemented.
6. Improved understanding is needed of how interactions between species benefiting from anthropogenic activities may unleash trophic cascades affecting rarer species.
7. Eradication of populations of invasive alien species can be spectacularly effective, but there are challenges in scaling them up to larger islands and continents.
8. Countries in the Global South support considerably more avian biodiversity by virtue of biogeography and land-use history, so Global North governments must play a greater role in financing conservation of tropical diversity.
9. Novel approaches and scaled-up efforts are needed to shift human societies onto economically sustainable development paths within planetary boundaries in order to reverse declines in avian biodiversity.

Terms and Definitions list

1. **Anthropocene**: current geological epoch defined by overwhelming influence of humanity on the Earth system.
2. **Avialan:** animals belonging to the clade Avialae, which includes all birds and several dinosaurian relatives.
3. **Cryptic species**: species which may appear phenotypically similar but are genetically quite distinct (and often separable by other non-morphological traits e.g., vocalisations).
4. **Ecosystem services**: benefits to people provided by the natural environment, and often linked to the health of ecosystems
5. **Deforestation**: the process of completely removing (i.e., clear-cutting) all forest vegetation, normally to be replaced by an anthropogenic land-use.
6. **Habitat degradation**: disturbance to natural habitats that does not involve wholesale destruction of the habitat, but which impairs ecosystem functions
7. **Functional extinction**: when the population size of a species is reduced so substantially that it no longer plays a significant role in ecosystem function
8. **Invasive alien species**: an organism introduced into a novel environment where it causes harm to other native species.
9. **Ex-situ conservation**: the conservation of species outside their natural habitat e.g., captive-breeding programmes.
10. **Teleconnections**: Socioeconomic-environmental interactions over distances, such as international trade, tourism, migration, foreign investment, species invasion, payments for ecosystem services, and transfer of water, information and technology.

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Figure 1. The nature of avian species richness: a) all species b) all threatened species (species in the global IUCN Red List categories of Vulnerable, Endangered and Critically Endangered) and c) all restricted-range species (those with a breeding/non-breeding range of <50,000 km^2; source: BirdLife International (37).

Figure 2. Population abundance indices for bird species dependent on major habitat types in a) North America b) Europe c) India and d) Botswana and Uganda which use data on the relative abundance of typically common bird species as indicators of the state of nature. Note that in graph c) the data were placed into time periods of differing intervals, such that the first data point refers to anything before 2000, the datapoint for 2003 refers to 2000-2006, that for 2009 refers to 2007-2010, and that for 2012 refers to 2011-2012. Source: a) North American Breeding Bird Survey and wetland bird surveys (courtesy of John Sauer USGS Patuxent Wildlife Research Center); b) Pan-European Common Bird Monitoring Scheme (EBCC/BirdLife International/RSPB/CSO); c) Data from eBird curated by the State of India's Birds Partnership; d) Wotton et al. (52).

Figure 3. Red List Index for all bird species, showing trends in aggregate survival probability over time. Icons show examples of species downlisted to lower categories of extinction risk (green) or uplisted to higher categories of extinction risk (red) owing to genuine improvements or deteriorations in status. Text indicates the threats driving these changes, or mitigated to enable improvements. Arrows show the approximate timing of transitions between Red List categories.

Figure 4. Number of bird extinctions per quarter-century on islands and continents since 1500. Source: Butchart et al. (6), BirdLife International (37).

Figure 5. Threats to the world's birds, showing a) the number of species impacted by each broad class of threat, b) the number of species impacted by specific types of biological resource use and agriculture, c) the number of species impacted by each type of stress caused by these threats, and d) the number of species affected by different numbers of high or medium impact threats. Source: BirdLife International (37).

Figure 6. High- or medium-impact threats affecting five globally threatened bird species, and the underlying drivers of these threats. Source: BirdLife International (37).

Figure 7. Examples of successful bird conservation efforts, and the top ten actions implemented for species that have been downlisted on the IUCN Red List. Source: BirdLife International 2020.

Figure 1.

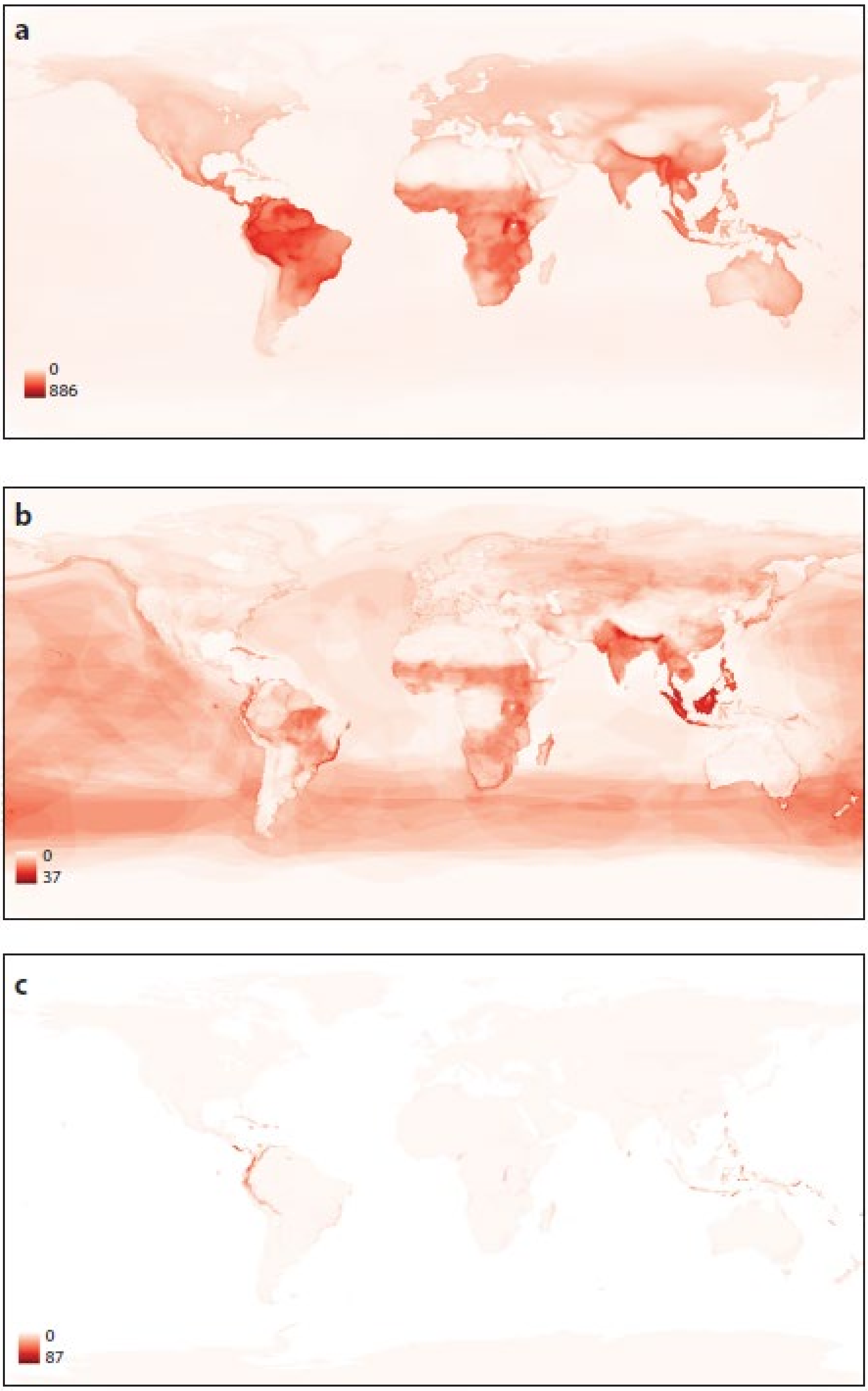


Figure 2.

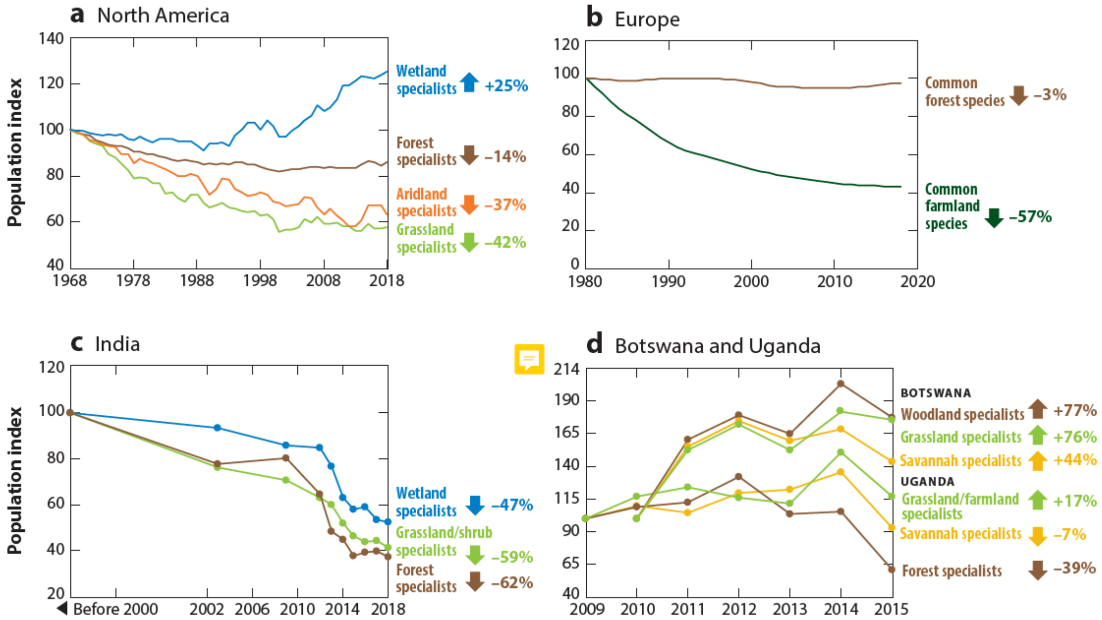
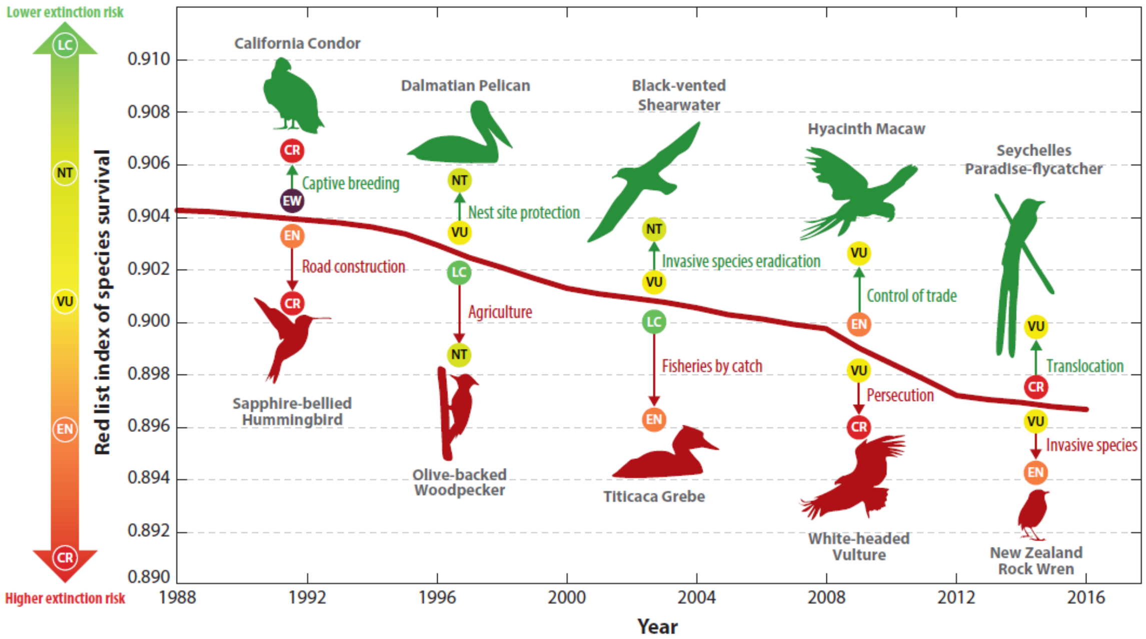

a North America
Population index
140
120
100
80
60
40
1968
1978
1988
1998
2008
2018
Wetland specialists +25%
Forest specialists −14%
Aridland specialists −37%
Grassland specialists −42%
b Europe
120
100
80
60
40
20
0
1980
1990
2000
2010
2020
Common forest species −3%
Common farmland species −57%
c India
Population index
120
100
80
60
40
20
Before 2000
2002
2006
2010
2014
2018
Wetland specialists −47%
Grassland/shrub specialists −59%
Forest specialists −62%
d Botswana and Uganda
214
190
165
140
115
90
65
40
2009
2010
2011
2012
2013
2014
2015
BOTSWANA
Woodland specialists +77%
Grassland specialists +76%
Savannah specialists +44%
UGANDA
Grassland/farmland specialists +17%
Savannah specialists −7%
Forest specialists −39%

Figure 3.



Lower extinction risk
Higher extinction risk
LC
NT
VU
EN
CR
Red list index of species survival
0.910
0.908
0.906
0.904
0.902
0.900
0.898
0.896
0.894
0.892
0.890
1988
1992
1996
2000
2004
2008
2012
2016
Year
California Condor
CR
Captive breeding
EW
EN
Road construction
CR
Sapphire-bellied Hummingbird
Dalmatian Pelican
NT
Nest site protection
VU
LC
Agriculture
NT
Olive-backed Woodpecker
Black-vented Shearwater
NT
Invasive species eradication
VU
LC
Fisheries by catch
EN
Titicaca Grebe
Hyacinth Macaw
VU
Control of trade
EN
VU
Persecution
CR
White-headed Vulture
Seychelles Paradise-flycatcher
VU
Translocation
CR
VU
Invasive species
EN
New Zealand Rock Wren

Figure 4.

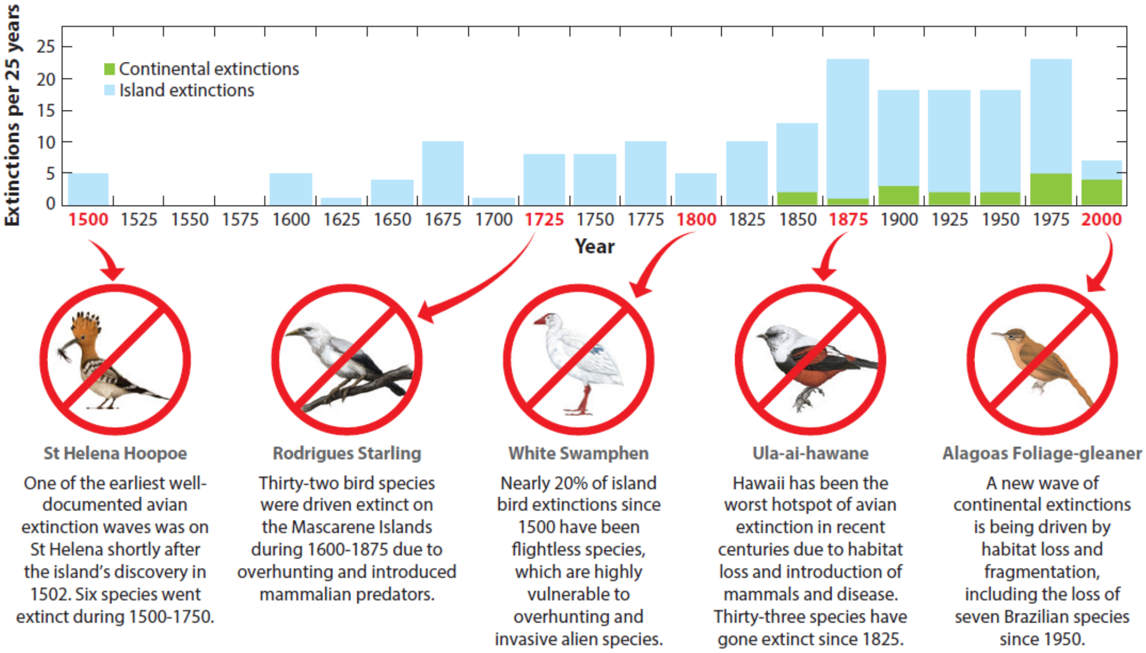

Extinctions per 25 years
25
20
15
10
5
0
Continental extinctions
Island extinctions
1500
1525
1550
1575
1600
1625
1650
1675
1700
1725
1750
1775
1800
1825
1850
1875
1900
1925
1950
1975
2000
Year
St Helena Hoopoe
One of the earliest well-documented avian extinction waves was on St Helena shortly after the island's discovery in 1502. Six species went extinct during 1500-1750.
Rodrigues Starling
Thirty-two bird species were driven extinct on the Mascarene Islands during 1600-1875 due to overhunting and introduced mammalian predators.
White Swamphen
Nearly 20% of island bird extinctions since 1500 have been flightless species, which are highly vulnerable to overhunting and invasive alien species.
Ula-ai-hawane
Hawaii has been the worst hotspot of avian extinction in recent centuries due to habitat loss and introduction of mammals and disease. Thirty-three species have gone extinct since 1825.
Alagoas Foliage-gleaner
A new wave of continental extinctions is being driven by habitat loss and fragmentation, including the loss of seven Brazilian species since 1950.

Figure 5.

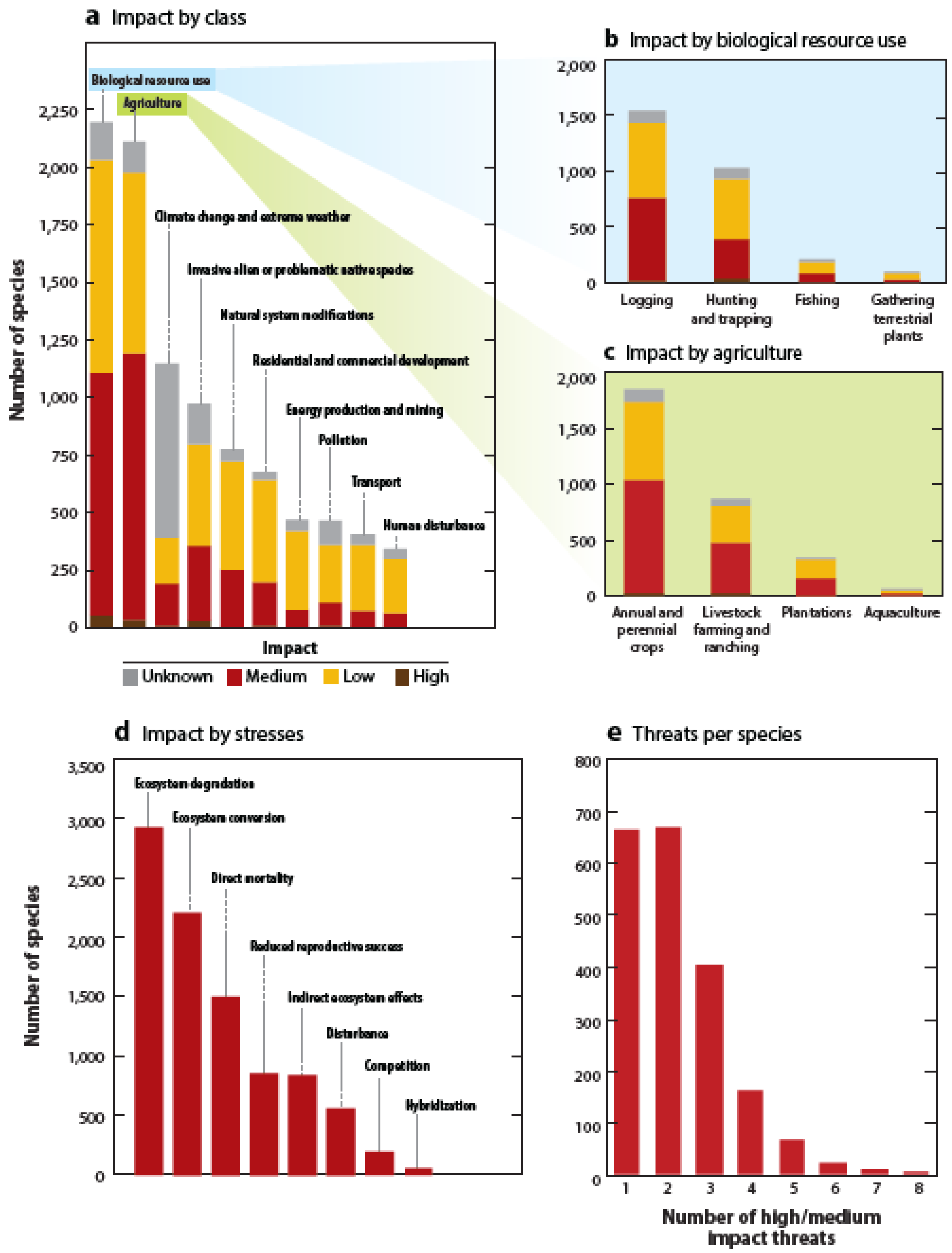
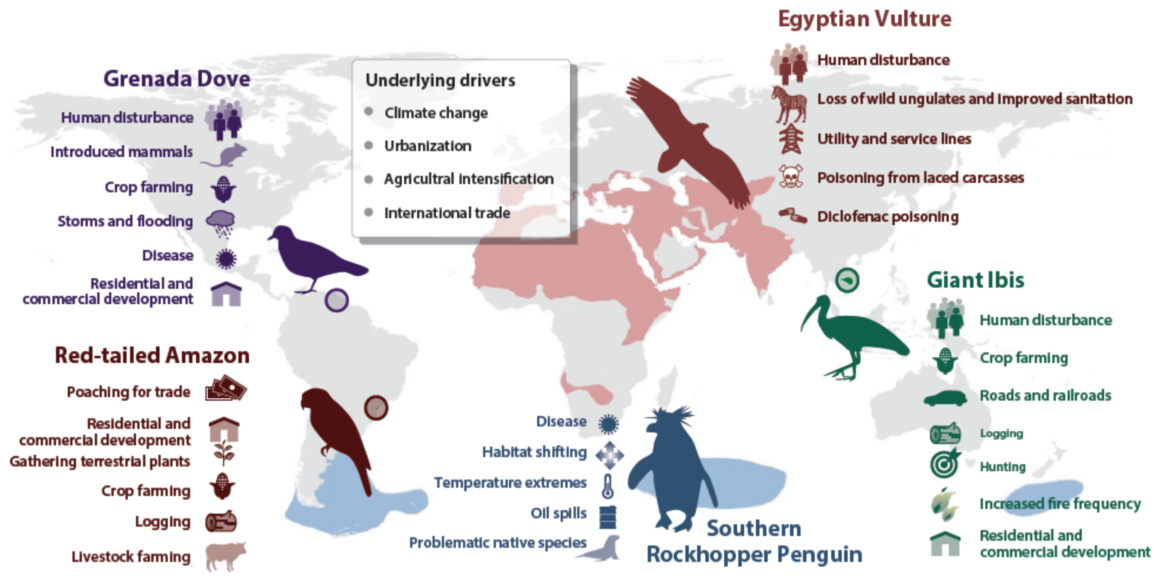
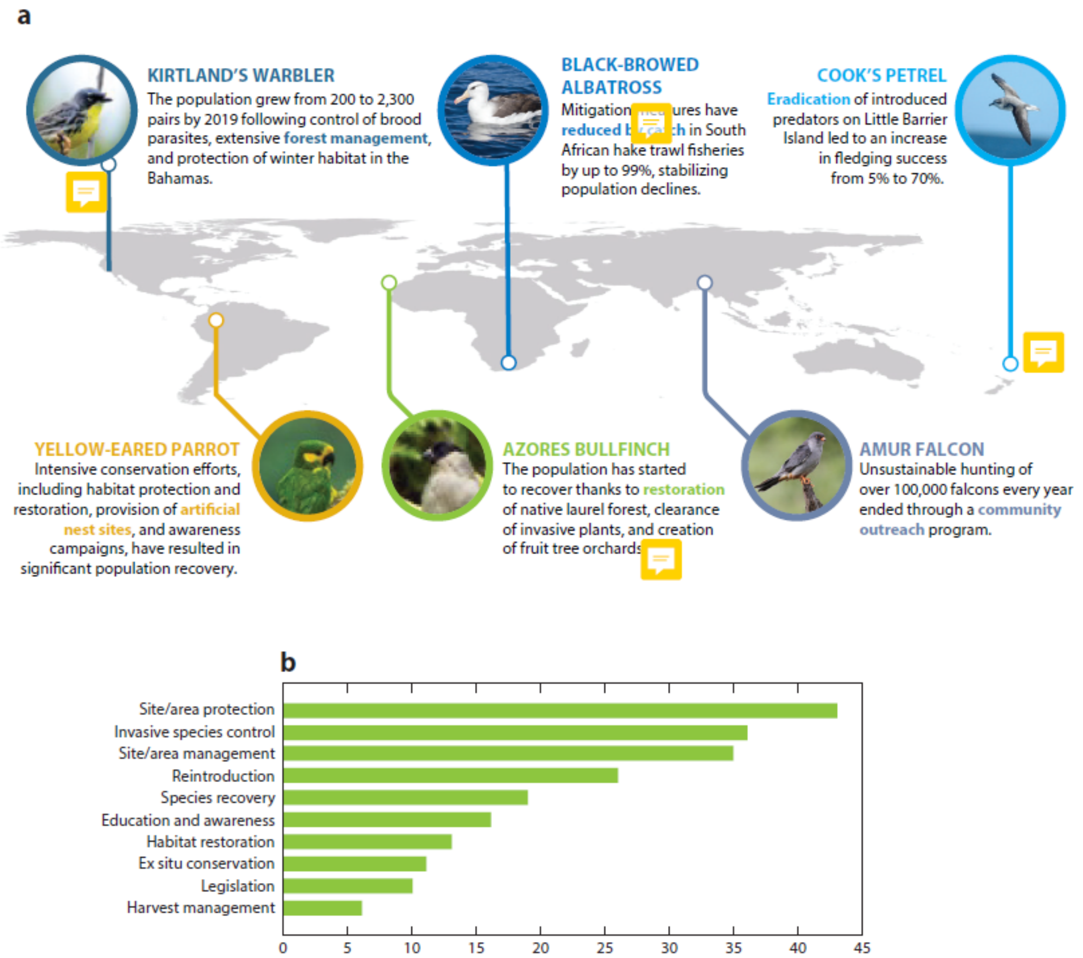

a Impact by class
Number of species
Biological resource use
Agriculture
Climate change and extreme weather
Invasive alien or problematic native species
Natural system modifications
Residential and commercial development
Energy production and mining
Pollution
Transport
Human disturbance
Impact
Unknown
Medium
Low
High
b Impact by biological resource use
Logging
Hunting and trapping
Fishing
Gathering terrestrial plants
c Impact by agriculture
Annual and perennial crops
Livestock farming and ranching
Plantations
Aquaculture
d Impact by stresses
Ecosystem degradation
Ecosystem conversion
Direct mortality
Reduced reproductive success
Indirect ecosystem effects
Disturbance
Competition
Hybridization
e Threats per species
Number of high/medium impact threats

Figure 6.



Egyptian Vulture
Human disturbance
Loss of wild ungulates and improved sanitation
Utility and service lines
Poisoning from laced carcasses
Diclofenac poisoning
Grenada Dove
Human disturbance
Introduced mammals
Crop farming
Storms and flooding
Disease
Residential and commercial development
Underlying drivers
Climate change
Urbanization
Agricultral intensification
International trade
Red-tailed Amazon
Poaching for trade
Residential and commercial development
Gathering terrestrial plants
Crop farming
Logging
Livestock farming
Disease
Habitat shifting
Temperature extremes
Oil spills
Problematic native species
Southern Rockhopper Penguin
Giant Ibis
Human disturbance
Crop farming
Roads and railroads
Logging
Hunting
Increased fire frequency
Residential and commercial development

Figure 7.


a
KIRTLAND'S WARBLER
The population grew from 200 to 2,300 pairs by 2019 following control of brood parasites, extensive forest management, and protection of winter habitat in the Bahamas.
BLACK-BROWED ALBATROSS
Mitigation ures have reduced b ch in South African hake trawl fisheries by up to 99%, stabilizing population declines.
COOK'S PETREL
Eradication of introduced predators on Little Barrier Island led to an increase in fledging success from 5% to 70%.
YELLOW-EARED PARROT
Intensive conservation efforts, including habitat protection and restoration, provision of artificial nest sites, and awareness campaigns, have resulted in significant population recovery.
AZORES BULLFINCH
The population has started to recover thanks to restoration of native laurel forest, clearance of invasive plants, and creation of fruit tree orchard
AMUR FALCON
Unsustainable hunting of over 100,000 falcons every year ended through a community outreach program.
b
Site/area protection
Invasive species control
Site/area management
Reintroduction
Species recovery
Education and awareness
Habitat restoration
Ex situ conservation
Legislation
Harvest management
0
5
10
15
20
25
30
35
40
45