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Effects of Climate Change, Habitat Loss, and Emerging Environmental Threats on Bird Diversity: A Review of Ecological Mechanisms, Interactions Among Stressors, and Conservation Strategies

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ABSTRACT: Global bird populations are facing greater impacts from climate change, land-use change, and deterioration of ecosystems, combined with additional anthropogenic and environmental pressures that may combine to impact the survival of populations and individual species. It is especially important to understand these pressures on bird populations because they fulfill many crucial roles in ecosystems, such as seed dispersal and pollination, and control of insect populations; they are also indicators of environmental and ecosystem health.

The purpose of this review is to document the impacts of climate change, habitat loss, and habitat fragmentation on bird diversity and to discuss any further impacts resulting from invasive species, infectious diseases, pollution, pesticides, artificial light at night, bird strikes from energy-related infrastructure, and energy development. The major sections of this review cover the impacts of temperature stress on physiological performance and reproductive output; changes in distribution, timing of migration, and breeding; mismatches between seasonal demands and the food supply; and demographic and genetic impacts of habitat fragmentation and the decline of landscape connectivity.

Published evidence shows that species declines are not always caused by a single factor and an integrated understanding of the variation in responses in species, localities and habitats is needed. Further evidence shows that distributional shifts, sea-level rise, and wider global environmental change can impact species populations in addition to direct habitat loss.

We end this review by suggesting that bird conservation in this region will necessitate a multi-faceted approach of conserving and restoring natural habitats, maintaining connectivity, reducing pollution and sources of mortality, controlling alien species, adopting future climate change models in the planning, and establishing long-term monitoring schemes that focus on abundance, survival, and reproductive success. Finally, we emphasize that the knowledge derived from the above should be complemented with other field studies in additional regions of the Middle East which have so far been poorly studied, in order to better understand regional changes and make conservation decisions based on evidence.

KEYWORDS: bird diversity, climate change, habitat loss, habitat fragmentation, geographical distribution shifts, invasive species, infectious diseases, pollution, migratory birds, biodiversity conservation.

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1. INTRODUCTION

Birds are fundamental to the structure and functioning of ecosystems. They contribute to these processes in numerous ways; for example by dispersing seeds, pollinating some vegetation communities, controlling insect populations, scavenging, and mediating the transfer of nutrients between habitats. In addition, many bird species are sensitive to changes in the environment and are easily studied in the field, and have long records of distribution and abundance. This makes avian indicators particularly valuable for monitoring biodiversity and environmental change.

Although they play a role in ecosystems, studies show that most bird populations are declining in overall abundance. It is estimated that North America has experienced a loss of about 2.9 billion birds since 1970, as estimated from long-term data records, showing that declines are not limited to rarer and threatened species (Rosenberg et al. 2019). But these regional trends should not be assumed to apply globally, since trends differ depending on habitat type, species, and local environmental conditions (Rosenberg et al. 2019).

Worldwide, the review report The State of the World's Birds found that human influences such as habitat conversion, expansion of agriculture, forest clearing, hunting, invasive species, and climate change were some of the significant factors responsible for the increasing conservation concerns around many species. However, the significance of such factors may not always be the same in every case. Loss of habitat can be the most immediate cause in some situations, while food availability, water and reproduction maybe influenced by climate change in others(Lees et al., 2022).

Climate change impacts birds in different ways via increased temperatures, altered precipitation regimes, more frequent extreme weather events, and altered seasonal timing of events. These impacts could lead to changes in the distribution of a species' distribution range towards higher latitudes or altitudes, shifts in migration, arrival or breeding times, or alterations to the habitat that an ecologically specialized species needs. But responses are variable, and the effects of climate change are also mediated by a species' ability to disperse and adapt, the provision of suitable habitats, and changes to resources, competitors, and predators.

Habitat destruction, disturbance and fragmentation alter the amount and quality of habitat available for feeding, nesting and breeding and may also result in population isolation and limited dispersal. When habitat loss occurs in combination with climate change, moving to suitable climatic zones may prove harder for birds, particularly where extensive urban areas, road networks and intensely farmed agricultural areas divide natural habitat. In other words, the issue goes beyond losing habitat cover – it involves falling habitat quality, connectivity and carrying capacity.

Other threats are invasive species, infectious disease, pesticides and chemical pollution, light pollution at night, and collisions with buildings, masts, pylons and wind turbines. These threats may have synergies with climate and habitat change, but such synergies are situation- and species- and scalespecific.

Given this context, this review aims to:

1. Investigate how climate change impacts bird populations via population processes and ecological mechanisms;
2. Evaluate direct and indirect impacts of habitat loss and degradation;
3. Describe the main emerging environmental threats and sources of mortality and population declines;
4. Clarify the importance of multiple-stressors interactions;
5. Address research and management priorities to optimize bird conservation efforts, with particular consideration of the existing knowledge gaps especially in under-represented regions of long-term bird monitoring.

2. EFFECTS OF CLIMATE CHANGE ON BIRDS

2.1. Rising Temperatures and Thermal Stress

Increased temperature is one pathway by which climate change is likely to influence bird physiology, behaviour and reproduction; the extent of impacts depends on local temperature, humidity, water and shade availability, and a species' physiological ability to thermoregulate (Fernando & Gunawardena 2024). At high temperatures, birds may reduce activity during the hottest parts of the day, change sleeping locations and behaviours which favour heat loss, although these adaptations may come with additional costs such as time lost foraging or caring for offspring. If conditions are beyond birds' capacity to thermoregulate, survival and breeding success may be compromised, especially in species with narrow climatic ranges. Species' sensitivity to heat can vary, with responses differing according to body size, physiology, behaviour, habitat and resource availability. Risk assessments should therefore take into account biological performance data in combination with climatic measures, rather than simply using temperature data (Fernando & Gunawardena 2024).

2.2. Shifts in Geographical Distribution

Climatic changes could change the range of geographical distribution of ranges where the species can have a stable population. Some species may move towards higher latitudes and altitudes, while others may move back out of their previous range. The response of species depends on their ability to disperse, the availability of suitable habitat, physical and geographical barriers, and interspecific interaction. A recent review showed that changes in species' ranges are complex processes and not all the changes observed due to increasing temperature change (Lawlor et al., 2024).

"These risks are especially significant for range-restricted, endemic and montane species that might otherwise find new suitable habitat outside the local environment if conditions become unsuitable (warmer) for their ecology. Further, degraded or fragmented habitat may prevent species from expanding to newly suitable (warmer) climate locations (Carey, 2009)."

2.3. Changes in the Timing of Breeding and Migration and Ecological Mismatch

Many bird species have life cycles that are strongly dependent on seasonal variations in temperature and day length, as well as the quantity of resources available to them. This means that if the emergence of insects is hastened by climate change, or the timing of maximum quantity of resources available shifts in birds are not in parity, a discrepancy (or mismatch) may arise, known as an ecological mismatch or phenological mismatch. This mismatch could result in decreased productivity of chick provisioning, or lower reproductive success, if timing of reproduction and/or arrival are out of sync with resource availability especially when chick development depends on food only available within a limited window. An investigation into the impacts of a mismatch should not

just be extrapolated from the effects of temperature, however, but it requires simultaneous observation of the timing of events in bird and prey, and potential differences should be expected not only between migrant and resident species, but between short- and long-distance migrants (Scridel, et al, 2018).

2.4. Sea-Level Rise and Coastal Habitats

Coastal and marsh-breeding and low-lying island-breeding species are at risk from nest flooding, habitat degradation, and diminished foraging habitat. Habitat quality may degrade before a habitat is physically lost due to repeated flooding or nesting failure. A 2024 field study and population model showed that a decline in habitat quality and increased nest inundation can occur before complete habitat disappearance, potentially leading to an earlier population decline than projected by habitat-area models alone. This indicates that it's also important to track habitat quality and reproductive success as the amount of remaining habitat decreases (van de Pol et al., 2024).

3. HABITAT LOSS, DEGRADATION, AND FRAGMENTATION

3.1. Habitat Loss and Degradation

Habitat loss involves the direct conversion of natural habitat to another land use (urbanization, intensive agriculture, mining, roads and dams). Habitat degradation involves loss of habitat quality and/or the loss of the capacity of a habitat to supply food, cover, nesting locations, and protection, with some areas still remaining. These processes negatively impact on birds by reducing available habitat, resources, nesting locations, structure of vegetation and disturbing them with human activities, and over time, the cumulative loss of habitat may reduce an ecosystem's long-term carrying capacity (number of individuals it can support)(Wu et al., 2012). Not all species will react equally to the loss of habitat. Specialist species that rely on specific vegetation structures or environmental conditions may be more negatively impacted than generalist species that will use a greater range of habitats. Likewise, species that utilize different habitats at different stages of their lives may be impacted by the loss of a specific habitat used for feeding or reproduction (Fahrig,2003).

3.2. Habitat Fragmentation and Population Isolation

Habitat fragmentation involves breaking continuous areas of natural habitat into isolated patches separated by roads, farms, urban areas, or other artificial barriers. Some isolated patches may appear suitable for species at a local level, but the isolation can impede movement and therefore make recolonisation, after local extinctions, impossible. The impacts of habitat fragmentation depend on the size and shape of the patches, the distance between patches, the size and quality of the surrounding matrix, and the ability of each species to disperse across that matrix. One possible consequence of habitat fragmentation is an increase in edge effects, with higher levels of human disturbance, altered temperature, humidity, and vegetation structure at the boundary of a habitat patch compared to the interior. Over time, isolation among patches could decrease gene flow between populations; however, accurate population and genetic data are required to determine this (Fischer & Lindenmayer, 2007).

3.3. The Relationship Between Climate Change and Habitat Loss

For many birds, climate change impacts could be compounded if they are unable to migrate to newly suitable areas. In cases where suitable thermal conditions develop in a nearby area but are inaccessible due to unsuitable terrain or barriers (e.g., forested habitat between two islands), species may be unable to colonize the affected area. Disproportionately impacted would be montane species, which may experience a range reduction in suitable climate as the upper limits of suitable conditions moves up the mountain, and for coastal or wetland species that rely on narrow habitats. Conservation actions should incorporate climate information, land use, and connectivity rather than viewing each in isolation (Lu, et al. 2024).

3.4. Agriculture and Changes in Vegetation Cover

Key drivers of decline: habitat change: destruction of lowland and upland forests, grasslands, wetlands; and lower habitat quality of remaining areas. (Potential) mechanisms:−reduced plant species diversity−removal of trees, shrubs, and other semi natural vegetation on the margins of fields−application of pesticides−altered invertebrate or seed abundance measures−destroyed trees and other host plants. (Potential) mitigations:−retention of habitat at field margins and within woodland,−protection of wetlands−reduction of non-essential pesticide applications−in-field remnants of wood and brash−decrease of topsoil removal−mitigation of agricultural land practices to still meet the needs of local bird populations (Xu, et al. 2018).

4. EMERGING ENVIRONMENTAL THREATS AND ANTHROPOGENIC PRESSURES

4.1. Invasive Species

The effects of IAS on native birds include predation on eggs and nestlings, competition for food and nesting habitats, disease transmission, and habitat alteration, with more significant effects on islands, where species sometimes evolved without specific predators and are less likely to have effective behavioural defences against newly introduced predators (Liu, et al. 2024). The impact of introduced predators will vary according to the invasive species, the habitat and the native species involved, so management

programmes should be based on risk analysis and ecological response monitoring and prioritize based on the threat and likelihood of success.

4.2. Infectious Diseases and Avian Health

Birds are also subject to diseases of significance including avian influenza, Newcastle disease, avian malaria, salmonellosis and other viral, bacterial, and fungal diseases. There are several and interacting factors that can influence risk of disease transmission including host density, movement, the density of potential hosts and vectors, weather and climate conditions, as well as changes in land use. It cannot be assumed that climate change will necessarily increase each disease risk across the board, as each pathogen, host and environmental context will respond differently. A recent meta-analysis across the world in Nature in 2024 found that drivers of global change (climate change, land-use change, pollution, changes in biodiversity) were linked to change in disease risks but the effects were context-dependent depending on the host-pathogen system - these findings support the integration of disease surveillance in biodiversity conservation programmes - including biosecurity, new mortality monitoring, and cooperation between the veterinary and environmental/public health communities (Mahon et al., 2024).

4.3. Pollution, Pesticides, and Chemical Contaminants

One such pollution that can be very harmful is chemicals, these include pesticides, plastics, heavy metals, industrial chemicals, and petroleum-based chemicals. Effects can be from behavioural changes or physiological changes, to declined or unsuccessful reproduction, or death. (Hallmann, et al 2014).

Population assessments should not be based solely on presence or absence. Bird abundance may not decline, even if survival and/or reproductive rates are affected for some time. Population surveys should be complemented by appropriate measures of biological or environmental changes, and effects should not be automatically attributed to a specific contaminant. Pesticides may impact on birds directly, through toxic effects, or indirectly through habitat destruction and alteration as a result of a reduction in, or damage to, the abundance of insects, seeds and other food, or by deterioration of agricultural habitat. (Longcore & Rich, 2004).

4.4. Artificial Light at Night

Circadian interactions with artificial light artificially alter orientation, behaviour, and daily activity patterns for some bird species (see for example Emlen, 1998). AI increases the exposure of migratory birds to buildings and may contribute to bird collisions with buildings. The risk of AI to migrating birds at a time of year when migration is likely to occur varies according to light intensity and spectral content, location, on-time, weather, and the behaviour of the subject (Longcore & Rich, 2004). It can be mitigated by reducing unnecessary lighting, reducing illumination below the levels needed for a task, having cut-off and shielded lights, reducing illumination during periods of high risk whenever possible and adopting bird conservation plans for buildings, especially during migration periods (Longcore & Rich, 2004).

4.5. Roads, Buildings, and Power Lines

Infrastructure impacts on birds come from habitat destruction and fragmentation, human disturbance, vehicle strikes, strikes with structures and glass, strikes with power lines. Also, in specific structures, an electrocution may occur. The severity of the impact depends on the type and location of the structures, and the bird community (Loss, et al 2014a).

Incidence and severity of collisions with glass surfaces and power lines may be reduced, and risk of injury or death minimized, through appropriate planning and development design considerations. These could include preferential siting, mitigating measures (e.g. Markers on glass), and monitoring of glass targets following development (Loss, et al 2014b).

4.6. Wind Energy and Renewable Energy Development

Renewable energy can help to reduce greenhouse gases, but some renewable energy schemes have local impact on birds through collision with turbines, habitat modification, and bird avoidance of structures. The fact that individual schemes have local impacts while also mitigating global climate change should be considered in environmental impact assessments, rather than assuming all renewable energy schemes are free of risk and that such risks negate the climate change mitigation benefits of these schemes (Dias, et al,2019). Bird mortality as a result of collisions with wind turbines must be estimated in combination with detection probability and carcass disappearance, otherwise results are likely to underestimate the true extent of the mortality occurring (Nilsson et al., 2023). Recommendations include site avoidance, impact surveys, post installation monitoring, and applying collision mitigations when local evidence supports them (Marques, et al 2014).

5. ANALYTICAL FRAMEWORK FOR ENVIRONMENTAL THREATS, IMPACT MECHANISMS, AND PROPOSED INTERVENTIONS

The following table integrates the principal topics discussed in the original manuscript into a format suitable for a scientific review. Quantifying the magnitude of each threat, however, requires a dedicated assessment of the relevant studies for each species and habitat.

Threat	Potential mechanism of impact	Measurable indicators	Management priority
Climate change	Thermal stress, altered resources, and shifts in seasonal timing	Survival, reproduction, and distributional shifts	Integrating climate projections into conservation planning
Habitat loss	Reduced habitat area, quality, and resource availability	Abundance, nesting density, and habitat quality	Protecting and restoring natural habitats
Habitat fragmentation	Isolation and reduced movement and connectivity	Movement between patches and gene flow	Improving ecological connectivity
Invasive species	Predation, competition, and ecosystem modification	Nesting success, survival, and invasive species distribution	Risk-based invasive species management
Infectious diseases	Increased mortality or reduced biological fitness	Infection rates and mortality	Integrated veterinary and ecological surveillance
Pesticides and pollutants	Toxic exposure or reduced food resources	Exposure indicators, reproduction, and survival	Reducing and monitoring pollution sources
Artificial lighting and buildings	Disrupted movement and bird collisions	Recorded collisions and mortality rates	Lighting management and bird-friendly building design
Roads and power lines	Direct mortality and habitat fragmentation	Recorded mortality and infrastructure use	Spatial planning and preventive measures
Wind turbines	Collisions and habitat avoidance	Mortality estimates corrected for detection probability	Appropriate site selection and post-construction monitoring
Interactions among multiple stressors	Accumulation, synergistic effects, or antagonistic interactions	Integrated population and environmental indicators	Integrated, multi-factorial risk assessment

6. INTERACTIONS AMONG MULTIPLE THREATS

Bird populations are seldom subjected to just one single constraint. Rather, they may be simultaneously affected by climate change, habitat destruction, pollution, and human disturbance. The significance of this is that the effects of more than one factor acting together may not simply be additive; they can interact synergistically, antagonistically, or independently, and can have impacts at different points of the life cycle of the affected species.

For example, as temperatures increase, selection pressure for shaded habitats and water bodies may result in an increase of the demand for these resources, but losing habitats could also lead to a decrease in the supply. Habitat fragmentation could also prevent birds to disperse to areas of suitable climate. However, two species in the same habitats may be affected differently. Some populations may be subject to increased pressures because of the synergy between food shortages and pollutants or infectious diseases, but evidence is needed to show that the observed combined effect can be compared with the effect that can be predicted from exposure to each stressor alone. It cannot be assumed that all simultaneous pressures will necessarily multiply the damage. To tackle this problem, we need research designs that allow models to include all of the above (climate, habitat, pollutants, and measures of bird health) in comparable models. Models should also incorporate different species and locations, and separate direct from indirect effects of environmental pressures on population outcomes.

7. BIRD CONSERVATION STRATEGIES

7.1. Protection of Natural Habitats

Prevention of habitat destruction is one of the most important aims of bird conservation since it can be more successful than reconstructing an ecosystem after drastic habitat change. Examples of priority sites are: natural forests, wetlands, mountains, islands, coastal habitats, breeding sites and stop-over sites.

Priority areas should be selected for their significance to threatened, endemic and migratory species, their vulnerability to pressures, and the potential to sustain their ecological functions.

7.2. Restoration of Degraded Habitats

The work of ecological restoration could encompass reestablishing native plant communities, wetland restoration, protection of riparian plant communities, removal of invasive species where ecologically defensible and enhancement of degraded habitat. Restoration success should not be quantified by how much land has been restored but by ecological indicators, such as presence of target species, increased breeding success, re-established connectivity between habitats and restored ecosystem functioning.

7.3. Improving Habitat Connectivity

Corridors and connected habitat networks could enable birds to move through the landscape between natural areas. Corridors could be especially important when climate changes or if a local habitat declines. The success of corridors depends on the bird species, the surrounding landscape, the design of the corridor, and the risks of movement through the corridor.

Corridors must thus be studied within an overall ecological network, and the use made of them as quantified should be studied without considering that every species necessarily uses them.

7.4. Adaptation to Climate Change

Future climate change scenarios should be built into all bird conservation plans, at the very least to inform decisions about potential future habitat and site selection, and how to maintain connectivity. Areas predicted to be suitable should be preserved, along with water resources and coastal and montane habitat. Species most sensitive to heat should be tracked.

More than one climate scenario must be factored in. Uncertainty about the future of environmental predictions makes adaptive management essential, and conservation actions must be reviewed regularly as more data becomes available.

7.5. Reducing Direct Anthropogenic Threats

Reducing the use of pesticides in farming areas, protecting vegetation and providing nesting sites are important measures that need to be taken for safe road-bird interactions. For urban areas, building design for bird-smart structures and managing lighting can help mitigate collision risk.

Energy and infrastructure projects should be subject to prior environmental assessment and post-construction monitoring, with mitigation options chosen based on the risks found at the given location.

7.6. Strengthening International Cooperation

Throughout their annual cycle, migratory birds use a variety of different habitats: their breeding grounds, their stopover sites, and their wintering ground. As a result, their population is vulnerable to changes in land use and resource management in several countries.

Shared monitoring data, joint conservation objectives on habitats, and collaboration between research, environmental, and veterinary institutions are essential, especially along flyways between nations.

8. FUTURE RESEARCH PRIORITIES

A significant priority is to develop long-term monitoring programmes that can separate natural variation from real long-term change in bird populations. These programmes need to cover not only population counts, but also survival and reproduction, annual numbers of juveniles and change in geographical distribution.

Additional studies should be conducted to explore the synergistic effects of climate change, habitat loss, disease, pollution, and invasives using research designs that enable the causes of these effects to be disentangled. The application of remote-sensing data, automated acoustic monitoring, tracking devices, genetic analyses, and statistical modeling is encouraged, although verifications of field accuracy should be performed.

In the same way, it is necessary to fill gaps of geographical information, especially in areas where temporal series of monitoring data are scarce and where long-term research studies need to be set up. Research and monitoring of wetlands, desert and semi-desert ecosystems, and migratory routes in the Middle East could be of particular interest.

Additionally, the comparability of research should be enhanced by clarifying how abundance, reproduction, and survival measures are defined; record sampling methodology; provide information about uncertainty; and publicize data and code, whenever permitted by the ethical and legal context.

9. CONCLUSIONS

There is scientific consensus that the future of bird diversity will be shaped by complex interactions of climatic, environmental and human pressures-including climate change, habitat loss, degradation and fragmentation. Others are additional stressors, such as invasive species, disease, and exposure to pollutants, pesticides, light, infrastructure and energy.

This is not a complete explanation; these trends cannot be fully explained by considering each factor separately, since the responses differ among species and biomes, and because several stressors can interact in various ways. The most successful bird conservation will combine habitat management with measures to adapt to climate change, improve connectivity, limit mortality and pollution sources, and establish monitoring schemes for abundance, survival and productivity.

Another conclusion of the review is to focus on increasing the geographical scope of research, especially in areas where such data are still scarce. Integrating field monitoring, new technologies, ecological modelling and international collaborations can help identify the most vulnerable species and habitats and lead to a more strategic use of funds.

Thus, the evidence-based conservation approach should be adopted in designing bird conservation strategies, and the practice should be improved by incorporating new findings when such data become available. It is not justified to extrapolate regional findings, and we shouldn't presume that one intervention is suitable for all species and sites. Bird conservation should be part and parcel of biodiversity and ecosystem functioning conservation in a changing world.

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