Review Article

Climate Change and Birds: A Critical Review of Evolutionary, Behavioural, and Reproductive Responses

Abstract- Climate change is now the major driver of biodiversity loss and its effects on species distribution, physiology, and ecology are having a profound effect on the way species are managed. Birds, being sensitive to environmental changes, are therefore good indicators of climate change-induced ecological change. This research reviews the current evidence on the impact of climate change on birds, focusing on their evolution, their behaviour - foraging and migration, and their reproductive success.

The increasing temperatures and altered precipitation have disrupted avian phenology and have caused the birds to experience a mismatch between their food availability and the most important events in their life history such as breeding and migration. Climate-driven changes in breeding timing and migration times have negatively impacted reproductive and survival rates in many species. New evidence suggests that micro-evolutionary responses such as the reduction of body size associated with warming could affect fitness across migration routes.

Despite the increasing evidence for phenotypic plasticity, there is little evidence that evolutionary adaptation will speed up with climate change. The cumulative impact of climate change and ecological change, habitat changes, and climatic stressors have serious consequences for avian lives worldwide. This review highlights some important research gaps and underscores the need for interdisciplinary and multi-scale approaches to understand and respond to climate change impacts on avian biodiversity.

Key words - Avian biodiversity, climate change, avian phenology, bird migration, global warming, avian reproduction, temperature

I. INTRODUCTION

Climate change represents one of the most significant anthropogenic pressures on global ecosystems, with far-reaching consequences for biodiversity and ecological stability. Over recent decades, global temperatures have increased at an accelerated rate, surpassing historical climatic variability and intensifying environmental stress across terrestrial and aquatic systems. These rapid changes are altering ecological processes, reshaping species distributions, and disrupting long-established biological interactions.

Among vertebrates, birds have emerged as particularly sensitive indicators of environmental change due to their high metabolic rates, mobility, and dependence on seasonal cues for migration and reproduction. As a result, avian species provide critical insights into the ecological impacts of climate change across spatial and temporal scales. Evidence suggests that climate change affects multiple components of the avian life cycle, including migration timing, breeding phenology, and survival, often through complex and interrelated mechanisms (see Figure 1).

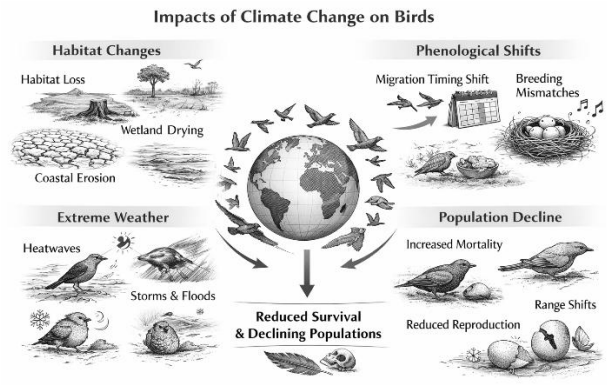

Figure 1: Conceptual framework of climate change impacts on avian systems

One of the most widely documented responses of birds to climate change is the alteration of phenological events. Many species are advancing the timing of migration and breeding in response to warmer temperatures; however, these shifts are not always synchronized with changes in food availability or habitat conditions. This phenomenon, commonly referred to as phenological mismatch, can lead to reduced reproductive success and population declines. For example, earlier onset of spring may trigger premature breeding, while peak food resources, such as insect abundance, may not align with nestling demands.

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In addition to behavioural responses, climate change is increasingly recognized as a driver of evolutionary and physiological changes in birds. Studies have documented reductions in body size and morphological traits in response to warming environments, suggesting potential adaptive or stress-induced responses. However, the extent to which these changes reflect true evolutionary adaptation versus phenotypic plasticity remains a subject of ongoing debate. This distinction is critical, as plastic responses may provide short-term resilience, whereas long-term survival depends on the capacity for genetic adaptation.

Furthermore, migratory species are particularly vulnerable to climate change due to their reliance on multiple geographically distinct habitats. Climatic changes along migratory routes can create mismatches in environmental conditions, affecting energy balance, survival, and reproductive outcomes. Such multi-scale impacts underscore the complexity of climate-driven ecological disruptions and highlight the need for integrated approaches to study avian responses.

Despite a growing body of literature, existing research remains fragmented, often focusing on isolated aspects such as migration or reproduction without considering their interconnected nature. There is a pressing need for comprehensive reviews that integrate evolutionary, behavioural, and reproductive perspectives to better understand the cumulative impacts of climate change on avian systems.

II. Thematic Literature Review

This review aims to critically analyze and synthesize existing research on climate change and birds and to analyse the impact on evolutionary responses, foraging behaviour, migration patterns, and reproductive success and offspring dynamics.

2.1. Evolutionary Responses to Climate Change

Climate change is increasingly recognized as a selective force that affects evolutionary trajectories across taxa. For avian species, changes in the climate are reflected in **phenotypic plasticity** that might even be **microevolutionary adaptations**. But how much evolutionary change is visible, and not just physiological or behavioural changes, is still a matter of debate.

One of the most common evolutionary responses in birds is the reduction of **body size** with increasing temperatures. Long-distance migrating birds such as the red knot (*Calidris canutus*) have been shown to grow older and lose body size and shorter bill lengths, probably because they experience altered development as a result of warmer Arctic conditions. These morphological changes have environmental implications for survival as well, particularly for birds on wintering grounds that have shorter bill lengths that restrict access to deeper in-ground prey and lower survival rates. This shows us that climate-induced changes in one region of the world can impact fitness across the entire migration time in many birds.

Besides changes in morphology, climate change is also affecting the **microclimatic niches of species**, also associated with survival and **physiological performance**. Long-term field surveys in tropical montane ecosystems have found that deviation from the temperature-humidity balance of a microclimate is associated with decreased body mass and survival of understorey insectivorous birds. These findings indicate that even small changes in microclimate can lead to strong selective pressures especially in species with a narrow ecosystem of acceptable tolerances. In addition, these niches shift at the same time as human degradation of the ecosystem and the impact on avian populations.

There is no clear evidence for rapid genetic adaptation to contemporary climate change. Most of the variation in avian phenology (i.e. earlier breeding or migration) is explained by phenotypic plasticity: it is a response to environmental factors but not genetic change.

Plasticity can be very helpful to the short term but it is limited by the ecological environment and may not be enough in the face of fast or extreme climate change. The difference between plastic and evolutionary responses is critical. Plastic responses may buffer populations in the short term but long-term survival is dependent on the ability of species to adapt. There is evidence that climate change may be faster than the rate at which the avian species can evolve due to factors such as generation time, genetic diversity and specialization of the environment. Also, the responses to climate change are not universal among the species. Birds who live in a more stable environment (e.g. in a tropical or high elevation area) can have narrow thermal tolerances and may be more susceptible to climate-induced selective pressures. In generalist species with broader ecological niches, the responses they make are more adaptive.

So, as climate change is clearly influencing avian morphology, physiology, and ecological niches, there is no strong evidence for fast evolutionary adaptation. In most cases, responses to climate change are phenotypic and not genetic. This raises important questions regarding the resilience of bird populations in the face of a fast-changing climate. Future work on this should be done longitudinal and genomic to understand plastic and evolutionary processes and predict species' adaptive ability to adapt to a rapidly changing environment.

2.2. Changes in Foraging Behaviour and Ecological Interactions

Climate change has changed the way we interact with nature by altering the resources, trophic systems and habitats. In avian species, foraging behaviour is particularly sensitive to the changes

as it is directly related to energy acquisition, survival and reproductive success. Food availability and timing disturbances are now seen as critical influences on avian populations.

One of the most important impacts of climate change on avian foraging is the phenological mismatch between birds and their food sources. Many bird species are so dependent on seasonal peaks in prey availability (e.g. insects) in order to cope with the high energetic demands of breeding and rearing chicks. However, changes in temperature and precipitation are making these peaks more erratic; birds that breed on the basis of historical environmental indicators may be less likely to find food in the beginning stages of their lives. The mismatch has been widely documented and is considered a key factor for reduced reproductive success and population decline.

Changes in habitat make these impacts, too, and they are likely to influence prey abundance and availability. For instance, in tropical forest ecosystems, habitat degradation coupled with climatic warming can lead to significant shifts in arthropod communities that are the primary food source for many insectivorous birds. In such environments, changes in microclimatic conditions (e.g., higher temperature and reduced humidity) can decrease prey abundance and diversity so birds may change their foraging behaviour or broaden their diet.

Some bird species have behavioural flexibility, for example in diet, foraging location, and activity patterns. Generalist species in particular may adapt to other food sources or exploit new habitats, thus partially accommodating the variability of resources. Specialist species *(birds that depend on only one kind of food or specific habitat)* are often less adaptable and more vulnerable to nutritional stress and population decline.

Climate change also affects foraging efficiency through habitat organization and access. Temperature variations and rainfall patterns change vegetation distribution and can affect the abundance of food. Extreme weather *(droughts, storms and heat waves)* can also affect prey availability or foraging ability. Not only does that impact energy availability and body condition but also longer-term survival.

Importantly, the effects of altered foraging behaviour are not only on individual fitness levels but on ecological processes. Birds are predators, pollinators and seed dispersers. Disruptions to their foraging behaviour can then ripple through food webs and affect the interaction of species and ecosystem functioning.

Despite the increasing recognition of the impacts of foraging behaviour, current studies tend to treat foraging behaviour in isolation and fail to link it to other life-history processes such as migration and reproduction. In reality, these processes are rather intertwined. For example, the lack of food during migration stopovers can affect energy reserves and lead to poor breeding performance. Similarly, poor nutrition during the breeding period leads to lower survival rates and less chick recruitment.

In sum, climate change is transforming avian foraging behaviour through multiple, interdependent processes from phenological change, habitat change and trophic evolution. Some species are able to adapt to change in behaviour, but the adaptive behaviour is insufficient to compensate for the negative effects of environmental change. Understanding the link between foraging ecology and other life-history processes is therefore essential to predict the long-term consequences of climate change on avian populations in the future.

2.3. Migration Patterns and Phenological Shifts

Avian migration is one of the most complex and finely-tuned biological processes which depends on environmental cues such as temperature, photoperiod, and resources. These cues are being disrupted by climate change and migration patterns are changing dramatically in timing, duration and spatial location. Such changes have profound consequences for survival, reproduction and population evolution.

One of the most frequently observed responses to climate change is the migration timing improvement in temperate regions. Many bird species are now arriving earlier at their breeding sites, in response to warmer spring temperatures. This change is generally interpreted as a phenotypic response to changing environmental conditions and birds can migrate earlier to match earlier availability of resources. But the degree of adjustment is different between species, and some species do not follow up on changes in environmental conditions.

In addition to timing, climate change is affecting migration periods and routes. Multi-species studies show that birds are shortening or changing their migratory routes in response to changing climatic conditions (e.g., temperature gradients and habitat). Some species that have traditionally migrated long-distance are now partially migratory or even living in places where they were previously wintering - and so it’s adaptive responses to different conditions in those locations.

Migratory species are especially vulnerable to climate change because they depend on multiple geographically different habitats during their annual cycle. Changes at breeding grounds, stopover sites, and wintering grounds can involve complex interactions which lead to spatial and temporal mismatch. For example, good environmental conditions on breeding sites can not be found along migration routes, leading to higher energetic costs and death. The potential vulnerability of migratory species is exacerbated by their high energetic demands and the need for optimal timing to exploit peak resource availability.

One of the consequences of climate-related changes in migration is phenological mismatches in different phases of the migration cycle. Birds that start migration based on internal cues (e.g., photoperiod) may not be able to adjust their timing to suit rapidly changing environments. Therefore, they may arrive at breeding sites too early, unable to navigate the unfavourable weather conditions or too late, and are thus unable to have their eggs in the optimal range of food. Such mismatches can adversely affect reproductive success and overall fitness.

In addition to temporal shifts, climate change is driving geographical redistribution of migrating species. Poleward and altitudinal range shifts are increasingly reported, indicating that species track suitable climatic conditions. Such shifts can lead to new areas and even the abandonment of previously occupied habitats. But not all species have the same capacity to move, especially those with very poor dispersal ability or specific habitat requirements.

Extreme weather events, which are more frequent and intense with climate change, also complicate migratory dynamics. Storms, heatwaves and droughts can directly impact migratory birds by increasing mortality during transit or decreasing the availability of critical stopover resources. These random events add more uncertainty to already complex migratory systems.

Despite the rapid progress in tracking the dynamics of migration, there are still gaps in the knowledge. Many studies are focused on a single species or a particular area and cannot generalize the findings to more general ecological contexts. Furthermore, migration and other life-history processes such as foraging and reproduction have not been thoroughly studied.

2.4. Impacts on Reproductive Success and Offspring Dynamics

Reproduction is one of the most climate-sensitive phases of the avian life cycle since it is closely synchronized with the environment to maximize the survival of the offspring. Climate change is now breaking this connection and breeding timing, reproductive success, and offspring fitness are being affected drastically. These changes have a direct impact on the population dynamics and long-term survival of the species.

One of the most widespread responses to climate change is in breeding phenology, and breeding phenology is particularly developed in temperate regions. Rising temperatures have been shown to trigger earlier egg-laying in most bird species. Nonetheless, the effects of earlier breeding are also highly context-dependent. A meta-analysis of long-term research shows that climate warming has changed not only the timing but also the length of breeding seasons and thus has far different effects on different species. Multi-brooded species benefit from longer breeding seasons (the breeding seasons of multi-brooded species lead to increased reproductive success), whereas single-brooded species may become less fertile and less successful.

The reason for these results lies in the mismatch between breeding timing and food availability. Success for birds is about the timing of nestling demand against food availability in the environment, especially for insectivorous species. Climate-driven changes in temperature and precipitation can disrupt this alignment, and the chicks may have less food available during the chick-rearing stage. These mismatches cause chicks to shrink in size and survival rate and, ultimately, lead to less recruitment to adult populations.

Climate change has influenced reproductive processes directly through timing mismatches as well as physiological and environmental factors. Elevated temperatures, extreme weather events, and precipitation patterns can affect egg survival, incubation success, and nest stability. Heatwaves, for one thing, can cause embryo mortality or lead parents to leave nests due to thermal stress. A higher frequency of storms and excessive rainfall can result in nest destruction or flooding, also affecting reproductive success.

Climate change also affects the quality and development of offspring. The extent to which parenting is changing due to fewer food sources or higher levels of energy can affect the quality and quantity of resources available for eggs and chicks. For example, maternal investment in eggs (e.g., vitamin and mineral diets) has long-term effects on offspring fitness (i.e., immune system and survival) that can be transferred to her eggs and chicks. These maternal impacts show indirect but significant impacts of climate change on population outcomes.

Recently, temperature-driven changes in breeding environments can affect the start and end of reproductive periods as well. In high-elevation species, for instance, warmer pre-breeding conditions may increase the pace of breeding, while high temperatures later in the season shorten the period. This dual effect highlights the sensitive dynamic of climate effects on reproductive dynamics, as gains in one phase may be offset by constraints in another.

Migratory species are particularly vulnerable because they depend not only on breeding conditions but also on the events that happen when migrating and at wintering. Low energy reserves due to poor foraging conditions along migration routes can delay breeding or reduce clutch size, further exacerbating local climatic changes.

Climate change is putting pressures on avian reproduction in such multiple ways that breeding timing, success rates, and quality of offspring are affected by climate change in both a direct and indirect way. Some species are able to adapt to climate change, but these are becoming an issue with more and more phenological mismatches, extreme weather events, and resource shortages making life difficult for the birds in terms of reproduction.

2.5. Distribution Shifts and Habitat Changes

Climate change is driving dramatic changes in the geographical distribution and habitat availability of avian species worldwide. As temperature and precipitation patterns change, birds are moving across different areas in search of the right environment. The distributional shifts are one of the most visible and well-documented ecological responses to climate change and have wide-ranging implications for biodiversity conservation and ecosystem stability.

A common pattern observed across different studies is the poleward and altitudinal shift in species distributions. Birds living in mountainous and high-latitude regions are moving towards higher elevations and latitudes where climate conditions remain within their physiological tolerances. In fact, modelling studies on Himalayan pheasants indicate significant upward and latitudinal movement in the habitat range in future climate scenarios that may push species into increasingly limited “sky island” habitats. These

range shifts can lead to increased competition, reduced genetic diversity, and more risk of extinction, especially for endemic and range-restricted species.

Climate change is also modifying the habitat structure and quality at a local level and so is the distribution of species. Temperature changes and precipitation changes affect nesting sites, sheltering, and food sources. These changes in habitat are further exacerbated by anthropogenic factors such as deforestation, land-use change, and urbanization, which are interlinked to climate change to increase ecological pressure on bird populations.

Another important issue is the disconnect between changing species ranges and existing conservation approaches. Protected areas are usually established based on species distributions and do not necessarily cover suitable habitats under changing environmental conditions. As species move beyond the protected zones, their habitat loss and human disturbance increases. Climate impact studies indicate that existing conservation approaches may not be adequate in the current environment where species distributions are changing with climate change.

Climate change is also affecting the distribution of migrating species, which need to travel through multiple habitats throughout their year. Poor environmental conditions along migration routes, including loss of stopover sites and poor resource availability, can disrupt migration and lower survival rates. Many studies have shown that migratory species are more vulnerable to climate change because of their geographical spread but synchronistically located ecosystems.

And not all species respond to climate change the same way. Generalist species with wider ecological tolerances might expand their ranges or adapt to altered habitats, while specialist species (especially those restricted to a particular ecological niche) are more likely to experience range contraction and population decline. This differential response could lead to the formation of different communities, with the biotic homogenization of species and the loss of unique ecological communities.

2.6. Vulnerable Bird Groups under Climate Change

Climate change does not impact every avian species on the same basis, but is most likely to affect specific groups of avian species with a particular life-history, restricted environmental tolerances and complex ecological relationships. Migratory species, tropical birds, habitat specialists and high-altitude species have been identified as particularly vulnerable in the literature *(more details in figure 2)*.

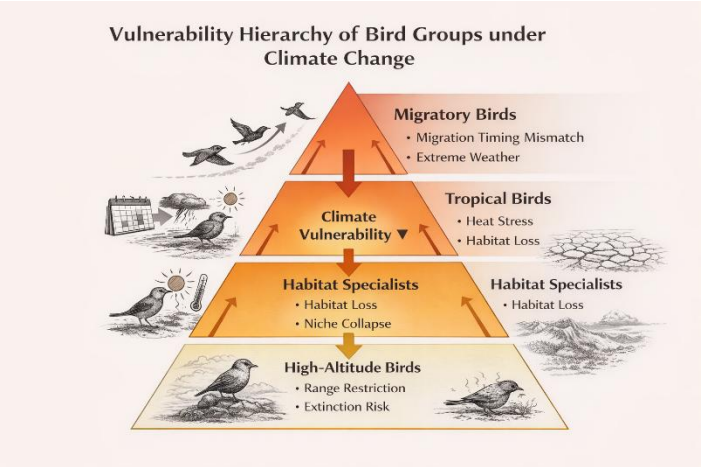

Figure 2: Vulnerability hierarchy of bird groups under climate change

2.6.1. Migratory Species

Migratory birds are among the most climate-sensitive groups. They depend on more than one geographically distinct habitat during the course of their year-round life cycle. The timing of migration, resource availability, and breeding conditions of these animals are at the heart of their susceptibility. Climate change disrupts this synchronization by altering temperature regimes and seasonal cues, and so there is a mismatch between arrival at breeding grounds and peak food availability.

There have been studies that have made remarkable progress in migration timing, migratory routes and migration duration changes. However, these changes are often insufficient to cope with the changes of climate quickly. Extreme weather events like storms and droughts along migration routes also result in mortality and energy depletion and could affect reproductive success. As such, migratory species suffer from the double threat of multi-location exposure to climate change and are thus at increased risk of population decline.

2.6.2. Tropical Birds

Tropical bird species are widely considered as one of the most vulnerable groups to climate change due to their narrow thermal tolerances and limited physiological flexibility. Tropical birds evolved under relatively stable climatic conditions and are therefore less able to adapt to rapid temperature increases.

There have been significant population declines in tropical bird communities, leading to reductions of up to one-third in some regions due to climate-induced stressors. Rising temperatures, combined with habitat degradation, lead to poorer body condition, lower survival rates, and altered ecological interactions. Moreover, tropical ecosystems are also under increasing pressure from deforestation and land-use change, and this adds to climate change. So even modest increases in temperature can cause significant ecological damage to tropical bird species.

2.6.3. Habitat Specialists

Bird species that live in highly specialized ecological niches are particularly vulnerable to climate change because they have a limited capacity to adapt to changing environmental conditions. Such habitat specialists are so dependent on specific vegetation types, microclimatic conditions, and prey communities that they are extremely sensitive to habitat change.

Climate change influences habitat structure by changing temperature, precipitation, and disturbance conditions, and this changes ecosystem structure and leads to habitat loss.

2.6.4. High-Altitude and Montane Species

The high-altitude and montane bird species are particularly susceptible to climate change due to the phenomenon of elevational range shifts. When temperatures rise, birds tend to migrate to higher altitudes in search of habitable climate. But as the higher altitude rises, the habitat shrinks and the available area decreases.

This "mountaintop effect" significantly increases extinction risk, especially for endemic species with limited ranges. Also, climate change could change the timing of resource availability and alter altitudinal migration patterns, which would also impact survival and reproduction. From mountainous regions, such as the Himalayas, species distribution and vulnerability to temperature changes and habitat fragmentation have been reported.

The inability of these animals to migrate beyond physical limits shows the severe constraints of climate change that make high-altitude birds one of the most at-risk groups globally.

III. Critical Analysis and Research Gaps

Despite the rapid development of the literature on climate change and avian ecology, there are still many important gaps and limitations that hinder the full understanding of species responses.

One of the most important limitations is the fragmentary nature of existing research. Many studies are focused on a few aspects of avian biology, such as migration, reproduction, or foraging (in fact, foraging and migration are often done on their own in birds). But as we will highlight in this review, those life-history traits are highly interrelated and climate-induced changes in one domain will often lead to others. For example, if foraging can be changed, then reproductive success will also be affected, and if migration happens, then survival and breeding will be affected.

There is also a major gap in the evidence for true evolutionary adaptation. While morphological and phenological alterations are widely noted, most studies have attributed the adaptation to phenotypic plasticity instead of heritable genetic changes. This has led to serious concerns about the long-term resilience of avian populations; plastic responses may not be sufficient under rapidly changing climatic conditions. Longitudinal and genomic studies are needed to unpack plastic and evolutionary mechanisms.

Geographical and taxonomic biases also limit our knowledge. Most of the studies have been conducted in temperate regions, especially Europe and North America, and tropical ecosystems—such as those in India—remain underrepresented. This is because tropical species tend to have narrower thermal tolerances and are more susceptible to climatic perturbations. Likewise, research is biased toward well-studied or charismatic species such that many ecologically important but less well-studied taxa are not well-studied.

There are no long-term, high-resolution datasets that capture the multi-generational responses to climate change. Many of the studies are based on short-term data and do not capture long-term trends or adaptive processes. The lack of consistent and standardized monitoring throughout regions also makes comparisons harder.

The other major limitation is the insufficient combination of climate models with ecological and behavioural data. Although the predictive models have advanced a lot, they do not account for species-specific traits, ecological interactions, or adaptive abilities, so they are very uncertain in predicting future distribution and population dynamics.

Existing conservation strategies are based on static assumptions of species distributions which do not account for the dynamic nature of climate-driven range shifts. The gap between ecological research and policy implementation lowers the success of conservation efforts.

To fill these gaps, we need integrated, interdisciplinary, and long-term research approaches that integrate ecological, evolutionary, and climatic perspectives. Such approaches are essential to improve predictions and inform effective conservation strategies.

IV. United Nations Initiatives Addressing Climate Change Impacts on Avian Species

The United Nations (UN) has played a central role in addressing the impacts of climate change on biodiversity, including avian species, through a combination of international treaties, conservation frameworks, and global action plans *(summary provided in Table 2, Appendix A).* Among these, the United Nations Environment Programme (UNEP) serves as the primary coordinating institution, facilitating scientific assessments and policy responses aimed at mitigating biodiversity loss. Within this framework, the Convention on the Conservation of Migratory Species of Wild Animals (CMS) represents the most significant global agreement specifically targeting migratory species, including birds.

4.1. Global Policy Framework: CMS and Associated Agreements

The CMS, established under UNEP in 1979, is the only global intergovernmental treaty dedicated exclusively to the conservation of migratory species and their habitats. It provides a legal and institutional framework through which countries collaborate to protect species that traverse international boundaries. The

convention emphasizes coordinated international action, recognizing that migratory birds are affected by environmental changes across multiple geographic regions during their annual life cycles.

A key strength of the CMS lies in its ability to generate specialized agreements and memoranda of understanding (MoUs) tailored to specific taxa or regions. For avian species, one of the most prominent instruments is the African-Eurasian Migratory Waterbird Agreement (AEWA), which focuses on the conservation of over 250 waterbird species across Africa and Eurasia. AEWA promotes coordinated conservation actions, including habitat protection, sustainable use, and international cooperation across migratory flyways.

AEWA, CMS has facilitated several regional agreements, such as the Central Asian Flyway Action Plan, which is particularly relevant to South Asia and India. These frameworks aim to conserve migratory bird populations by protecting critical habitats, enhancing monitoring systems, and strengthening transboundary collaboration.

4.2. Addressing Climate Change within UN Conservation Strategies

Climate change has increasingly been recognized within UN frameworks as a major driver of avian population decline. CMS strategic plans explicitly include actions to mitigate and adapt to climate change impacts on migratory bird species, emphasizing habitat resilience, range shift planning, and ecosystem restoration. This reflects a shift from traditional conservation approaches toward more dynamic, climate-adaptive strategies.

UN assessments indicate that migratory species are particularly vulnerable to climate change due to their reliance on multiple habitats across continents. Recent reports highlight that nearly half of migratory species are experiencing population declines, with climate change acting in combination with other stressors such as habitat loss and pollution. These findings underscore the urgency of integrating climate considerations into biodiversity conservation.

The UN has also emphasized the concept of flyway-based conservation, which recognizes that protecting isolated habitats is insufficient for migratory species. Instead, conservation efforts must encompass entire migratory routes, including breeding, stopover, and wintering sites. This approach is particularly relevant in the context of climate change, as environmental conditions may shift differently across these regions, creating complex ecological mismatches.

4.3. Key UN Initiatives and Programs

4.3.1. World Migratory Bird Day

One of the most visible UN-led initiatives is World Migratory Bird Day, jointly organized by UNEP, CMS, and AEWA. This global awareness campaign highlights the ecological importance of migratory birds and the threats they face, including climate change. The initiative promotes international cooperation and public engagement, emphasizing that migratory birds "connect people, ecosystems and nations" and are increasingly threatened by climate-induced environmental changes.

4.3.2. Habitat Protection and Restoration Programs

UN initiatives prioritize the protection and restoration of critical habitats, particularly wetlands, which are essential for many migratory bird species. Through agreements such as AEWA and CMS action plans, countries are encouraged to establish protected areas, restore degraded ecosystems, and maintain ecological connectivity across flyways. These measures are crucial for enhancing the resilience of avian populations to climate variability.

4.3.3. Mitigation of Anthropogenic Threats

In addition to climate change, the UN addresses related anthropogenic threats that exacerbate avian vulnerability. These include:

- Illegal killing and trade of birds
- Habitat fragmentation due to infrastructure development
- Pollution and poisoning

CMS Conferences of the Parties (COP) have adopted resolutions to reduce these threats, including measures to mitigate the impacts of energy infrastructure and linear developments on migratory species. For example, initiatives promoting bird-friendly energy systems—such as modifying power lines and reducing light pollution—aim to reduce mortality during migration.

4.3.4. Species-Specific Action Plans

The UN framework also includes species-specific conservation action plans, targeting vulnerable bird groups such as raptors, waterbirds, and grassland birds. These plans typically involve habitat protection, monitoring, research, and public awareness strategies, implemented through international cooperation among range states.

4.4. Integration of Science and Policy

A defining feature of the UN approach is the integration of scientific research with policy development. Through global assessments and monitoring programs, the UN provides evidence-based guidance for conservation planning. These assessments highlight key climate-driven impacts on birds, including:

- Shifts in migration timing and routes
- Changes in species distribution
- Phenological mismatches between breeding and food availability
- Increased mortality from extreme weather events

Such findings inform policy decisions at both international and national levels, enabling governments to design adaptive conservation strategies.

4.5. Critical Evaluation of UN Initiatives

While the UN has established a comprehensive framework for avian conservation, several challenges remain. One major limitation is the variation in implementation across countries, particularly in developing regions where resources and capacity may be limited. Additionally, there is a significant data gap in tropical regions, including parts of Asia and Africa, which limits the effectiveness of global assessments.

V. India's Initiatives to Address Climate Change Impacts on Avian Species

India, as one of the world's most biodiverse countries and a key region along major migratory flyways, has increasingly recognized the vulnerability of avian species to climate change. The country's approach to addressing these impacts is embedded within broader frameworks of biodiversity conservation, climate policy, and ecosystem management. While not always explicitly bird-centric, several national initiatives, policies, and programs contribute significantly to mitigating climate-induced risks to avian populations *(refer Table 3, Appendix A)*.

5.1. Policy Framework and National Commitments

India's response to climate change and biodiversity conservation is guided by national and international commitments, including the National Action Plan on Climate Change (NAPCC) and the National Biodiversity Action Plan (NBAP). These frameworks emphasize ecosystem resilience, habitat conservation, and sustainable resource management, which are critical for avian survival.

The NAPCC outlines eight national missions, several of which indirectly benefit avian species. For instance, the National Mission for Sustaining the Himalayan Ecosystem addresses climate impacts in high-altitude regions, which are particularly important for endemic and migratory bird species. Similarly, the National Mission for a Green India focuses on afforestation and ecosystem restoration, contributing to habitat availability for forest-dependent birds.

India is also a signatory to international agreements such as the Convention on Migratory Species and actively participates in regional initiatives like the Central Asian Flyway Action Plan. These commitments reinforce the country's role in protecting migratory bird populations affected by climate change across transboundary landscapes.

5.2. Habitat Conservation and Protected Area Networks

A cornerstone of India's conservation strategy is the establishment and management of protected areas, including national parks, wildlife sanctuaries, and Ramsar wetlands. These areas provide critical habitats for both resident and migratory birds.

Wetlands, in particular, play a crucial role in supporting avian diversity. India has designated numerous wetlands under the Ramsar Convention, recognizing their ecological importance for migratory waterbirds. Conservation and restoration of wetlands are essential for mitigating the impacts of climate change, as these ecosystems regulate hydrological cycles and support food availability.

However, climate change poses challenges to these habitats through altered precipitation patterns, increased frequency of droughts, and wetland degradation. Consequently, there is a growing emphasis on ecosystem-based adaptation, which integrates habitat conservation with climate resilience strategies.

5.3. Species-Focused Conservation Initiatives

India has implemented several species-specific conservation programs that indirectly address climate change impacts. Notable among these are initiatives targeting critically endangered birds such as vultures and bustards.

The Vulture Conservation Programme, led by government agencies and conservation organizations, addresses population declines caused by poisoning and habitat loss. While initially focused on veterinary drug impacts, the program increasingly considers broader environmental stressors, including climate change.

Similarly, the conservation of the Great Indian Bustard—one of the most threatened bird species—has gained national priority. Efforts include habitat protection, captive breeding, and mitigation of threats such as power line collisions, which may be exacerbated by changing environmental conditions.

These species-specific initiatives highlight India's shift toward targeted conservation strategies, although integration with climate adaptation remains an evolving area.

5.4. Monitoring, Research, and Citizen Science

India has made significant progress in avian monitoring and data collection, which are essential for understanding climate change impacts. Organizations such as the Bombay Natural History Society (BNHS) play a leading role in long-term bird research and conservation.

Citizen science initiatives, particularly the eBird India platform, have revolutionized data collection by enabling large-scale monitoring of bird populations and migration patterns. These datasets provide valuable insights into changes in species distribution, phenology, and abundance in response to climate variability.

5.5. Climate Adaptation and Ecosystem-Based Approaches

India's climate policy increasingly emphasizes ecosystem-based adaptation (EbA) as a strategy to address biodiversity loss. This approach focuses on maintaining and restoring ecosystems to enhance their resilience to climate change, thereby benefiting avian species.

Programs under the Green India Mission and other afforestation initiatives aim to increase forest cover and improve ecosystem

services. Similarly, watershed management and wetland restoration projects contribute to maintaining habitats critical for birds.

However, the effectiveness of these initiatives depends on their ability to account for species-specific ecological requirements and the dynamic nature of climate-driven habitat changes.

5.6. Challenges and Limitations

Despite significant progress, India faces several challenges in addressing climate change impacts on avian species:

Data Gaps:
Limited long-term studies on climate–avian interactions, particularly in tropical ecosystems
Fragmented Approach:
Conservation efforts often focus on habitat or species without integrating climate change explicitly
Anthropogenic Pressures:
Rapid urbanization, land-use change, and infrastructure development exacerbate climate impacts
Policy Implementation:
Variability in enforcement and coordination across states

These challenges highlight the need for more integrated and interdisciplinary approaches that combine climate science, ecology, and policy *(a comparative summary with UN action plan compared with India's approach is summarised in Table 4, Appendix A)*.

VI. Conclusions

Climate change is exerting profound and multifaceted impacts on avian species, influencing their evolutionary trajectories, behavioural ecology, migration dynamics, reproductive success, and geographical distribution. This review demonstrates that these effects are not isolated but deeply interconnected, with disruptions in one component of the avian life cycle cascading across others. Phenological mismatches, habitat alteration, and the increasing frequency of extreme weather events have emerged as critical drivers of population decline and ecological instability.

While some species exhibit adaptive responses through phenotypic plasticity and behavioural flexibility, the rate and magnitude of climate change increasingly exceed the adaptive capacity of many avian populations. The limited evidence for rapid evolutionary adaptation, coupled with significant research gaps—particularly in tropical and underrepresented regions—highlights the urgent need for integrative, long-term, and multi-scale scientific investigations.

At the global level, the United Nations has established a robust and evolving framework to address these challenges through international cooperation, policy integration, and targeted conservation initiatives. Instruments such as the Convention on Migratory Species (CMS) and the African-Eurasian Migratory Waterbird Agreement (AEWA) provide essential platforms for coordinated action across migratory flyways, while global programs emphasize habitat protection, threat mitigation, and public awareness. However, the effectiveness of these frameworks depends on strengthened implementation, enhanced data collection, and deeper integration of ecological and climate science.

At the national level, India has developed a multifaceted approach to avian conservation that includes policy initiatives, habitat protection, species-specific programs, and expanding research efforts. Although many of these initiatives indirectly address climate change impacts, there is growing recognition of the need to explicitly integrate climate adaptation into conservation planning. Strengthening monitoring systems, improving data availability, and aligning national strategies with global frameworks will be critical for enhancing the resilience of avian species in the region.

Ultimately, safeguarding avian biodiversity in a rapidly changing climate requires a holistic and coordinated approach that bridges science, policy, and practice across scales. Birds, as highly sensitive indicators of environmental change, not only reflect the health of ecosystems but also serve as early warning signals of broader ecological disruption. Ensuring their survival is therefore essential not only for biodiversity conservation but also for maintaining the integrity, functionality, and resilience of global ecosystems in the face of ongoing climate change.

VII. Appendix

Appendix A & B.

VIII. References

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COMPETING INTERESTS DISCLAIMER:Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

APPENDIX A

Table 1 - Vulnerability of Bird Groups under Climate Change

Category	Key Impact	Evidence	Risk Level
Migratory Birds	Migration mismatch, mortality	Timing shifts, extreme weather	● Very High
Tropical Birds	Heat stress, population decline	25–38% decline observed	● Very High
Habitat Specialists	Habitat loss, niche collapse	Ecosystem restructuring	● High
High-altitude Birds	Range compression, extinction risk	Elevation shifts, habitat shrinkage	● Very High

Table 2 - United Nations Actions on Avian Climate Change

Area of Action	Initiative / Framework	Key Actions	Relevance to Climate Change
Global Treaty	Convention on Migratory Species (CMS)	International cooperation, species protection, habitat conservation	Addresses multi-country impacts across migration routes
Regional Agreements	AEWA (African-Eurasian Waterbird Agreement)	Wetland conservation, species monitoring	Protects critical habitats affected by climate change
Flyway Approach	Central Asian / African-Eurasian Flyways	Conservation across entire migration routes	Reduces mismatch across breeding, stopover, wintering sites
Policy Integration	CMS Strategic Plans	Climate adaptation, ecosystem resilience planning	Integrates climate change into biodiversity conservation
Awareness	World Migratory Bird Day	Global campaigns, public engagement	Highlights climate threats to birds
Species Programs	Raptors, Vultures, Waterbirds Plans	Targeted conservation, habitat restoration	Focus on vulnerable species under climate stress
Threat Mitigation	CMS COP Resolutions	Reduce poisoning, illegal killing, infrastructure impact	Tackles combined climate + human pressures
Research & Monitoring	Global Assessments (CMS Reports)	Data collection, vulnerability assessments	Identifies climate-sensitive species and trends
Habitat Restoration	UNEP Ecosystem Programs	Wetland restoration, biodiversity conservation	Enhances climate resilience of bird habitats

Table 3 - India's Actions on Avian Climate Change

Area of Action	Initiative / Policy	Key Actions	Relevance to Climate Change
National Policy	National Action Plan on Climate Change (NAPCC)	Ecosystem resilience, climate adaptation missions	Supports habitats critical for birds
Biodiversity Policy	National Biodiversity Action Plan (NBAP)	Conservation planning, ecosystem protection	Addresses climate-driven biodiversity loss
International Commitment	CMS & Central Asian Flyway	Migratory bird protection	Aligns with global climate conservation efforts
Habitat Protection	Protected Areas & Ramsar Sites	Wetland conservation, habitat protection	Safeguards climate-sensitive ecosystems
Afforestation	Green India Mission	Forest restoration, carbon sinks	Enhances habitat availability
Species Programs	Vulture & Bustard Conservation	Targeted species recovery programs	Addresses vulnerable species under climate stress
Research	Bombay Natural History Society (BNHS)	Long-term avian studies	Generates climate impact data
Citizen Science	eBird India	Large-scale bird monitoring	Tracks climate-driven changes in distribution
Ecosystem Adaptation	Wetland & watershed restoration	Habitat resilience programs	Reduces climate vulnerability
Awareness	National campaigns & NGOs	Public engagement	Promotes conservation behaviour

Table 4 - Comparative Analysis (UN vs India)

Aspect	United Nations Approach	India's Approach
Scale	Global, multi-country	National, region-specific
Focus	Migratory species, flyways	Habitat + species conservation
Strategy	Policy frameworks + international cooperation	Policy + implementation programs
Climate Integration	Explicitly integrated into CMS strategies	Indirect, still evolving
Data & Monitoring	Global assessments, reports	Limited but improving (citizen science)
Strength	Coordination across borders	Ground-level implementation
Limitation	Weak enforcement globally	Data gaps, fragmented implementation

APPENDIX B

Table 5 - Region-wise Analysis (India vs Global Insights)

Aspect	India (Tropical Context)	Global (Temperate/Polar Context)
Temperature Impact	High vulnerability due to already warm baseline; heatwaves increasing mortality	Gradual warming; some species benefit from milder winters
Migration Patterns	Less studied; evidence of disrupted migration and local movements	Well-documented shifts in migration timing and routes
Foraging Behaviour	Strong impact due to monsoon variability and insect availability changes	Seasonal mismatch between insects and breeding widely observed
Reproduction	Heat stress, nest failure, and breeding disruption common	Earlier breeding; mixed outcomes depending on species
Evolutionary Response	Limited research; potential high vulnerability due to narrow tolerance	More evidence of phenotypic plasticity and some morphological changes
Habitat Change	Rapid habitat loss + climate stress (dual pressure)	Climate-driven shifts more dominant than land-use in some regions
Data Availability	Limited long-term datasets; research gap	Extensive long-term monitoring data available
Species Vulnerability	Higher (tropical specialists, narrow niches)	Moderate (generalist species more adaptable)
Conservation Response	Emerging; policy and research still developing	More structured conservation frameworks and climate adaptation strategies

Table 6 - Detailed Comparison of Key Studies

Author(s) & Year	Focus Area	Key Findings	Research Gaps / Limitations
Bhuva et al. (2025)	Migration, breeding, conservation	Climate change disrupts migration timing, breeding synchrony, and increases mortality	Limited to regional (India-focused) evidence; lacks long-term datasets
van Gils et al. (2016)	Evolution (body size)	Warming leads to smaller body size in migratory birds, reducing survival	Focus on single species; limited generalization across taxa
Charmantier & Gienapp (2013)	Evolution vs plasticity	Most avian responses are phenotypic plasticity, not genetic evolution	Lack of long-term genetic data to confirm evolutionary adaptation
Carey (2009)	Phenology, life cycle	Climate change disrupts synchronization between breeding and food availability	Broad review; lacks species-specific empirical validation
Bharadwaj et al. (2025)	Microclimate, survival	Microclimatic shifts reduce body mass and survival in tropical birds	Limited geographic scope; needs multi-region comparison
Halupka & Halupka (2017)	Reproduction	Breeding seasons shifting; multi-brooded species benefit, single-brooded decline	Mostly Northern Hemisphere data; limited tropical representation
Niffenegger et al. (2025)	Breeding phenology	Earlier breeding onset but shortened breeding duration in some species	Focus on alpine species; limited applicability to lowland ecosystems
Osbourne (2025)	Migration	Migration timing and routes changing due to climate shifts	Limited methodological depth; lacks long-term tracking validation
Martay et al. (2023)	Migratory species (global)	Climate affects migration routes, survival, and distribution at global scale	Limited species-specific analysis; broad generalizations
Chhetri et al. (2021)	Distribution modeling	Species shifting to higher altitudes and latitudes	Model-based predictions; limited field validation
Srinivasan et al. (2019)	Habitat & vulnerability	Thermal tolerance determines species vulnerability to environmental change	Focus on specific region (Himalayas); limited global comparison
UNEP/CMS (2010)	Policy & migration	Migratory species highly vulnerable due to multi-location exposure	Policy-focused; lacks detailed ecological mechanisms
Blount et al. (2001)	Offspring physiology	Egg quality and maternal investment influence offspring fitness	Not climate-specific; indirect relevance