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(REVIEW ARTICLE)

Climate change and its effects on bird diversity in tropical ecosystems: A focus on the amazon basin and central America

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Abstract

Climate change is emerging as a significant driver of biodiversity loss, particularly in tropical ecosystems. The Amazon Basin and Central America, both rich in avian diversity, face profound ecological shifts due to rising temperatures, altered precipitation patterns, and increasing extreme weather events. This review explores the impacts of climate change on bird diversity in these regions, emphasizing the vulnerability of species with narrow ecological niches and those dependent on stable forest ecosystems. Through an examination of observed and projected climate trends, physiological and ecological responses of birds, and conservation strategies, this paper highlights critical knowledge gaps and the urgent need for adaptive management. It underscores the importance of integrated, region-specific conservation strategies and the role of local communities in mitigating climate impacts. The paper calls for a holistic approach to conservation that incorporates climate resilience, habitat restoration, and long-term monitoring to protect the avian diversity essential to these tropical ecosystems.

Keywords: Amazon Basin; Avian Diversity; Central America; Ecosystem and Habitat

1. Introduction

Climate change, defined as long-term alterations in temperature, precipitation, and weather patterns, has become one of the most pressing environmental challenges of the 21st century. The effects of climate change are not only altering the physical environment but also reshaping biological systems, with profound implications for biodiversity. Among the most vulnerable ecosystems to climate change are the tropical forests, which are not only rich in biodiversity but also provide critical ecosystem services [1]. These ecosystems, including the Amazon Basin and Central America, are home to a substantial proportion of the world's avian species, many of which are endemic and highly specialized to their environments.

Birds are integral to the functioning of tropical ecosystems, playing crucial roles in pollination, seed dispersal, pest control, and nutrient cycling. As such, they are considered vital indicators of ecosystem health [2]. The tropical avifauna, however, is facing unprecedented threats due to climate change. These impacts manifest in various ways, including shifts in habitat suitability, alterrations to migration to patterns, and disruptions to reproductive cycles. [3]. The current body of research highlights the growing concern that climate change will exacerbate the existing threats to tropical birds, such as deforestation, habitat fragmentation, and hunting.

The Amazon Basin, often referred to as the "lungs of the Earth," is a vast, tropical rainforest spanning across several countries in South America, including Brazil, Peru, Colombia, and Venezuela. This region is one of the most biodiverse on the planet, hosting around 1,300 bird species, many of which are endemic [4]. Similarly, Central America, which includes countries such as Costa Rica, Panama, and Guatemala, is a critical biodiversity hotspot, with over 600 bird

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species, including numerous migratory species [5]. The ecosystems of these regions, however, are under increasing stress from the combined impacts of climate change and human activity.

The climate of the Amazon Basin and Central America has been undergoing significant changes over the past several decades. Temperature increases in both regions have been consistent, with the Amazon Basin experiencing a rise of approximately 0.6–1.0°C since the 1960s, and projections indicating further warming by 2–4°C by the end of the century under high-emission scenarios [6]. Precipitation patterns are also undergoing alterations, with some parts of the Amazon becoming drier and others experiencing increased rainfall variability [7]. Central America, on the other hand, has witnessed a consistent decline in precipitation, particularly during the mid-summer drought, a phenomenon that has lengthened in recent years [8]. These changes not only affect the overall ecological balance but also influence the availability of food, nesting sites, and other critical resources for birds.

The impact of climate change on bird species in tropical ecosystems is complex and multifactorial. Birds are particularly vulnerable to climate change due to their sensitivity to temperature extremes, changes in habitat availability, and modifications to food sources. A significant body of research has highlighted how rising temperatures and shifting rainfall patterns have already resulted in the mismatch between food availability and breeding cycles, particularly for insectivorous birds, whose reproductive success is highly dependent on the abundance of insects [9]. For instance, in the Amazon, studies have shown that drought-induced forest stress has led to a reduction in insect populations, which in turn has affected the diet and breeding success of several bird species [10].

Another major effect of climate change on tropical birds is shifts in habitat suitability. Birds that are highly specialized to particular environmental conditions, such as the Resplendent Quetzal in Central America, are particularly at risk [11]. As climatic conditions change, the habitats that these species rely on may no longer be suitable. For example, shifts in temperature and humidity are causing cloud forests to recede upwards in elevation, forcing montane species like the Quetzal to migrate to higher altitudes in search of suitable habitats. However, such shifts may not always be feasible due to geographical barriers, limited dispersal capacity, or the increasing fragmentation of forest habitats due to deforestation and human encroachment [12].

Migration patterns are also being disrupted by climate change. Migratory bird species in Central America, such as the Black-throated Green Warbler, are experiencing altered arrival and departure times due to changes in seasonal weather patterns. The timing of food availability is becoming increasingly unpredictable, leading to mismatches in the timing of migration and breeding, which can affect the survival and reproductive success of these species [13]. The disruption of these migratory patterns is particularly concerning as migratory birds often rely on a series of habitats across regions, and changes in one location can have cascading effects throughout their migratory routes.

Despite the growing body of research, several key gaps remain in understanding the full scope of climate change's impact on tropical bird species. One critical area is the lack of long-term monitoring data. While some studies have documented the effects of climate change on birds over relatively short periods, few have examined long-term trends across entire ecosystems

[14]. This is particularly problematic in remote areas such as the Amazon Basin, where access and funding for comprehensive monitoring programs are limited. As a result, much of the data on climate change impacts on birds is patchy, and it is difficult to predict how populations will respond over the coming decades.

Additionally, many species have not been studied in depth, particularly migratory birds and species with narrow ecological niches. While charismatic species such as the Harpy Eagle and the Resplendent Quetzal have received attention, smaller, less-known species that play important ecological roles are often neglected in climate change research. Furthermore, the synergistic effects of climate change with other anthropogenic pressures, such as habitat fragmentation, deforestation, and pollution, have not been fully explored. These combined pressures are likely to have far greater impact than climate change alone, yet most studies tend to examine these factors in isolation [15].

The integration of climate adaptation strategies into conservation planning is another challenge. While there have been efforts to protect critical habitats and increase the connectivity of protected areas in the Amazon and Central America, these efforts are often insufficient to counter the rapid pace of climate change [16]. More research is needed to develop conservation strategies that are climate-resilient, considering the projected changes in climate, land-use patterns, and species distributions.

This review aims to synthesize current knowledge on the effects of climate change on bird diversity in the Amazon Basin and Central America, with a focus on species vulnerability and conservation challenges. The review provides an in-depth

look at the current state of tropical bird populations in these regions. Furthermore, the review highlights key knowledge gaps in climate change and biodiversity research and suggests future directions for research and policy interventions. Ultimately, the paper aims to contribute to the broader conversation on how best to conserve bird diversity in the face of climate change, providing recommendations for region-specific conservation strategies.

2. Tropical Ecosystems and Avian Biodiversity

Tropical ecosystems, renowned for their dense vegetation, consistently warm temperatures, and high humidity, are among the most biologically productive and diverse ecosystems on Earth. These regions are home to an unparalleled variety of flora and fauna, with tropical forests, montane regions, and wetlands hosting the majority of the world's species [17]. Avian diversity in these ecosystems is particularly remarkable, with tropical birds occupying a wide range of ecological niches and exhibiting a variety of behavioral and physiological adaptations [18]. Two regions, the Amazon Basin and Central America, are especially significant as both are rich in resident and migratory bird species, making them critical focal points for understanding the impacts of climate change on bird populations.

The Amazon Basin, often referred to as the world's largest tropical rainforest, spans over 5.5 million square kilometers across nine countries in South America, including Brazil, Peru, Colombia, and Venezuela. This immense biome supports a staggering 1,300 bird species, accounting for approximately 13% of the world's total bird species [19]. The region's unparalleled biodiversity can be attributed to its complex geography, which includes a vast network of rivers, a multitude of distinct forest strata, and a variety of microhabitats. These features provide a multitude of ecological niches that support an extraordinarily high level of endemism species. For instance, the canopy and understory guilds, which include species such as toucans, parrots, and antbirds, exhibit specialized adaptations to the dense, vertical structure of the forest [20].

Endemism in the Amazon is particularly prominent in bird species that occupy specialized habitats within these different forest layers. Birds such as the Harpy Eagle (Harpia harpyja) and the Great Jacamar (Jacamaralcyon tridactyla) are prime examples of species with adaptations that enable them to thrive in the Amazon's layered, multi-stratum forest ecosystem. These species often have highly restricted ranges and specific habitat requirements, making them particularly vulnerable to disturbances such as deforestation, climate change, and habitat fragmentation [21]. In addition to these resident species, the Amazon also serves as a critical migratory stopover for species traveling along the Americas flyway, such as the Swainson's Thrush and other neotropical migrants [22].

While smaller in geographic extent compared to the Amazon, Central America plays a similarly critical role in global avian biodiversity. Stretching from southern Mexico to Panama, this region is a biodiversity hotspot that harbors over 900 bird species across a range of habitats, including montane forests, cloud forests, mangroves, and coastal wetlands [23]. Central America also functions as a vital migratory corridor, especially for species traveling between North and South America. Species such as the Black-throated Green Warbler and Ruby-throated Hummingbird rely on Central American habitats during their seasonal migrations, utilizing the region as a refueling station during long journeys [24].

One of the distinguishing features of Central American avian biodiversity is its altitudinal gradient, which provides a diversity of habitats at different elevations. From the lowland rainforests of Panama to the cloud forests of Costa Rica, species occupy a range of ecological niches tied to altitude and microclimate. Montane species, such as the Resplendent Quetzal (Pharomachrus mocinno), are particularly abundant in these highland areas, where the rich flora supports a range of specialized bird species. This gradient also contributes to the region's high levels of endemicity, as species are often adapted to specific elevational zones [25].

Like the Amazon, Central America's bird populations are not only subject to climate change impacts but also face significant threats from habitat loss and fragmentation. Tropical deforestation, agriculture, and urbanization have contributed to substantial habitat degradation in both regions, forcing many species to move or adapt to increasingly degraded environments. Central America's bird species are also highly sensitive to the timing and availability of food sources, particularly in migratory species. Climate-driven shifts in the phenology of flowering plants and insects can create mismatches between the timing of bird migration and the availability of food, thereby affecting reproduction and survival rates [26].

Birds play an indispensable role in maintaining ecological balance in tropical ecosystems. They contribute to a range of ecosystem services, including pollination, seed dispersal, pest regulation, and forest regeneration [27]. Many plant species in tropical rainforests rely on birds for pollination, with species such as hummingbirds and fruit doves playing central roles in facilitating plant reproduction. Similarly, birds such as toucans and parrots are crucial for seed dispersal, ensuring the regeneration of forest cover and maintaining plant diversity. By consuming a variety of seeds, birds help

maintain the genetic diversity of plant communities, enabling forests to recover after disturbances such as storms or fires [28].

Furthermore, birds are integral to pest regulation in tropical ecosystems. Insects, small mammals, and other pests are controlled by the predatory activities of birds, particularly insectivorous species. In areas like the Amazon, where insect populations can explode under favorable conditions, the absence or decline of insectivorous birds can result in an increase in pest populations, which may negatively impact plant health and crop yields. This ecological service is increasingly under threat as the populations of these birds decline due to climate-induced habitat changes [29].

Despite their critical ecological roles, many tropical bird species are vulnerable to the impacts of climate change and human activity. Species with narrow ecological niches or limited dispersal capacities are especially at risk, as they are often unable to adapt quickly to rapidly changing environmental conditions [30]. For example, species that rely on specific forest types or microclimates may find their habitats altered or reduced in size due to changes in temperature and precipitation patterns. Montane birds, such as the Pink-headed Warbler in Central America, face the additional threat of climate-induced shifts in cloud forest elevations, which forces them to move upwards in search of suitable habitat, often without the availability of adequate refuges [31].

Moreover, migration patterns in tropical birds are becoming increasingly unpredictable. Studies have shown that climate change is affecting the timing and routes of migration for both resident and migratory species. Altered timing of seasonal rains, food availability, and temperature fluctuations can cause mismatches in breeding schedules, which negatively impact bird survival and reproductive success. In some cases, migratory birds may arrive in breeding grounds either too early or too late, missing critical food resources or encountering unsuitable environmental conditions [32].

The Amazon Basin and Central America represent some of the most biologically diverse regions in the world, particularly with regard to avian species. However, they are also among the most vulnerable to climate change [33]. As the climate continues to shift, the survival of many bird species will depend on their ability to adapt to rapidly changing conditions. The combination of habitat loss altered food availability, and changes in breeding cycles will create challenges for both resident and migratory birds. Given the important ecological roles that birds play, the decline of tropical avian species would have cascading effects on the health of these ecosystems.

Conservation efforts must be tailored to the specific needs of these ecosystems and the species that depend on them. Integrating climate change adaptation strategies into broader conservation planning is critical to preserving both avian diversity and the ecological services that birds provide. Protecting and restoring habitats, expanding protected areas, and strengthening migratory corridors are just some of the strategies that can mitigate the impacts of climate change on tropical bird populations. Long-term monitoring and research are essential to understand the evolving threats and to implement adaptive conservation measures that support both the species and ecosystems of the Amazon and Central America.

3. Climate Change Trends in the Amazon and Central America

Climate change, driven primarily by rising concentrations of greenhouse gases, has significantly impacted on the environmental conditions in tropical regions such as the Amazon Basin and Central America. These changes are increasingly evident in the form of rising temperatures, altered precipitation patterns, and an increased frequency of extreme weather events [34]. While global climate models predict similar trends for tropical regions worldwide, localized factors such as deforestation, land-use changes, and forest degradation exacerbate the vulnerability of ecosystems in these regions, amplifying the effects of climate change on biodiversity [35].

Both the Amazon Basin and Central America have experienced consistent increases in average annual temperatures over recent decades. In the Amazon Basin, the average temperature has risen by approximately 0.25–0.5°C per decade since the 1970s, with projections indicating a continued rise of 2–4°C by the end of the century under high-emission scenarios [36]. These temperature increases are not only significant on their own but also have cascading effects on ecological processes. For example, higher temperatures can lead to increased evapotranspiration, reducing soil moisture and stressing plant and animal species, including birds, that depend on consistent water availability.

Similarly, Central America has witnessed a rise in temperatures of 0.7–1.2°C between 1960 and 2020 [37]. This warming trend is accompanied by an increase in the frequency and intensity of heatwaves, which can push species beyond their physiological tolerance thresholds. The impacts are particularly pronounced in regions such as Costa Rica and Panama, where montane and cloud forest ecosystems are especially sensitive to temperature fluctuations. These forests, which

harbor numerous endemic bird species, depend on stable climatic conditions, including cool temperatures, high humidity, and consistent rainfall [38]. Any increase in temperature disrupts these delicate balances, threatening species such as the Resplendent Quetzal and the Black Guan, which are already limited in their altitudinal distribution.

In addition to rising temperatures, precipitation patterns in both the Amazon Basin and Central America have become more unpredictable and variable. In the Amazon, rainfall has become more erratic, with prolonged drought periods in some regions, especially in southern Amazonia, while other areas are experiencing excessive rainfall. Drought events in 2005, 2010, and 2015 linked to both climate variability and deforestation have led to significantly reduced river levels and increased tree mortality, altering the structural integrity of the forest [39]. Forest canopies, critical for many bird species, have been particularly affected, with tree mortality resulting in reduced shelter and food sources for avian populations. These conditions also affect forest regeneration, as a lack of water reduces the growth and survival rates of saplings, ultimately diminishing habitat availability for species [40].

The occurrence of flooding in some parts of the Amazon, coupled with rising temperatures, has further complicated these climatic impacts. Forest flooding, often exacerbated by extreme rainfall, can alter the microclimate of forest habitats and disrupt the reproductive cycles of species that depend on stable nesting conditions. Species such as the Amazonian Poison Frog and various bird species that breed in lowland areas are increasingly at risk as rising waters inundate their nests, leading to reduced reproductive success and population declines [41].

In Central America, precipitation patterns are similarly shifting. While some regions have experienced increased rainfall, particularly during the rainy season, others are facing prolonged dry spells [42]. As with the Amazon, these shifts threaten montane ecosystems, including cloud forests, which rely on a consistent moisture input for the survival of both flora and fauna. The deforestation and degradation of these high-elevation forests further exacerbate these climate-driven disruptions. The loss of tree cover increases the runoff during heavy rains, leading to soil erosion and reduced water retention, which, in turn, undermines the stability of cloud forests [43]

One of the most concerning consequences of climate change in both the Amazon and Central America is the increasing frequency and severity of exreme weather events. Droughts, forest fires, flooding, and tropical storms have all become more common in recent decades [44]. The Amazon Basin has seen an increase in the frequency of severe drought events, such as those in 2005, 2010, and 2015, which have had devastating effects on both the physical structure of the forest and its biodiversity. Prolonged dry periods and reduced rainfall contribute to the dieback of trees, especially those dependent on the wet conditions of the rainforest, which are critical to the survival of many bird species [45]. Additionally, these dry conditions increase the risk of forest fires, which, coupled with human activities such as land clearing, further degrade bird habitats. The southern and eastern regions of the Amazon are particularly vulnerable to these events, where deforestation has created a landscape that is increasingly susceptible to fire outbreaks [46].

Similarly, in Central America, tropical storms and hurricanes have become more frequent and intense. Between 2000 and 2020, the region experienced an increase in the number of category 4 and 5 hurricanes, which cause devastation to both natural habitats and human infrastructure [47]. These storms not only result in direct mortality for birds but also cause extensive damage to breeding and foraging habitats. Migratory species, which rely on predictable stopover sites during migration, are particularly at risk as these storms can damage critical habitats or cause displacement of species along their migration routes. The Caribbean coast of Central America is especially vulnerable, with countries like Honduras and Nicaragua regularly facing the brunt of these extreme events [48].

The combined effects of rising temperatures altered precipitation, and increased frequency of extreme weather events have profound implications for the bird populations in the Amazon Basin and Central America. For resident bird species, such as the Harpy Eagle and the Resplendent Quetzal, climate-induced changes in habitat structure, food availability, and reproductive timing are increasing pressures on their survival [49]. Migratory birds, such as those traveling along the Americas flyway, face compounded risks due to unpredictable weather patterns, disruptions in stopover habitats, and changes in the availability of food along their migratory routes. These disruptions can lead to increased mortality, reduced reproductive success, and range shifts, as species are forced to relocate to new habitats that may not be optimal for survival [50].

Furthermore, the ecosystem services provided by birds, such as pollination, seed dispersal, and pest control, are likely to be disrupted by the decline of bird populations. As these species decrease in number, the ability of tropical ecosystems to recover from disturbances, such as storms or fires, will be hampered. The cascading effects of reduced bird populations could ultimately lead to a decline in overall biodiversity, as the balance of ecological interactions is disrupted [51].

The impacts of climate change on the Amazon Basin and Central America are complex and multifaceted, with significant implications for avian biodiversity and ecosystem stability. While temperature increases, altered precipitation patterns, and extreme weather events are affecting these regions, the compounding effects of deforestation and land-use change have only amplified these impacts. The urgency of addressing these issues through comprehensive climate change adaptation strategies is clear. Long-term monitoring, habitat protection, and restoration efforts are essential to mitigate the impacts of climate change and ensure the resilience of both bird populations and the ecosystems that sustain them. Figure 1 and 2 illustrates the temperature anomalies and rainfall trend respectively.

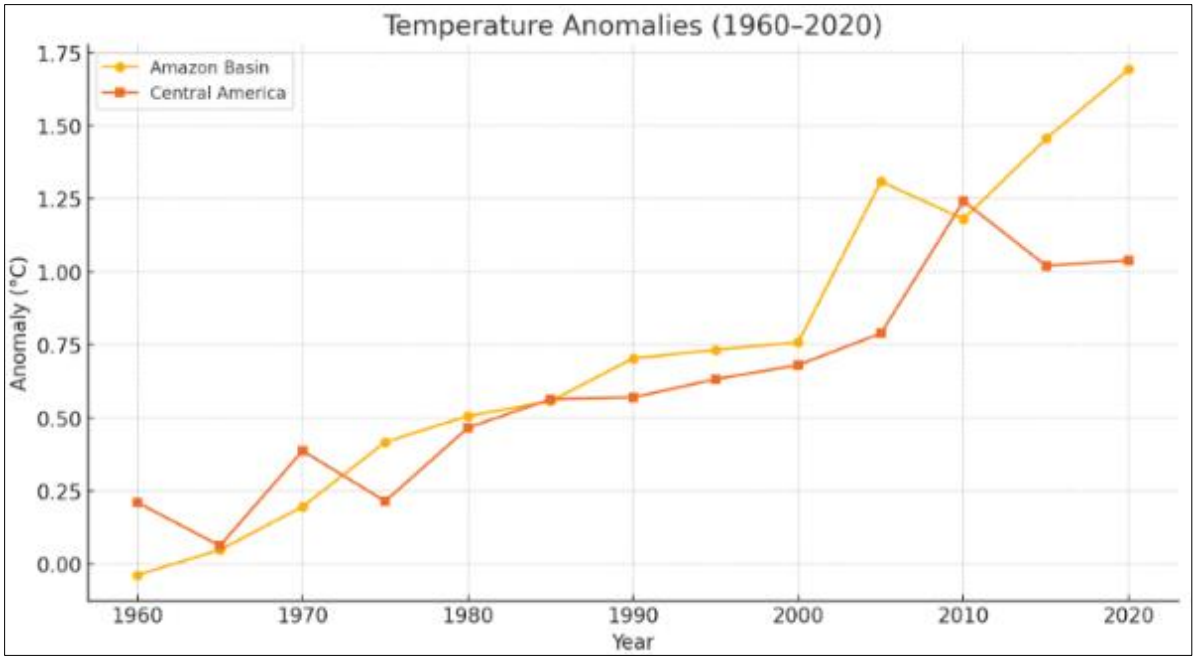

Figure 1 Climate Change Trends in the Amazon and Central America: Temperature Anomalies (1960-2020)

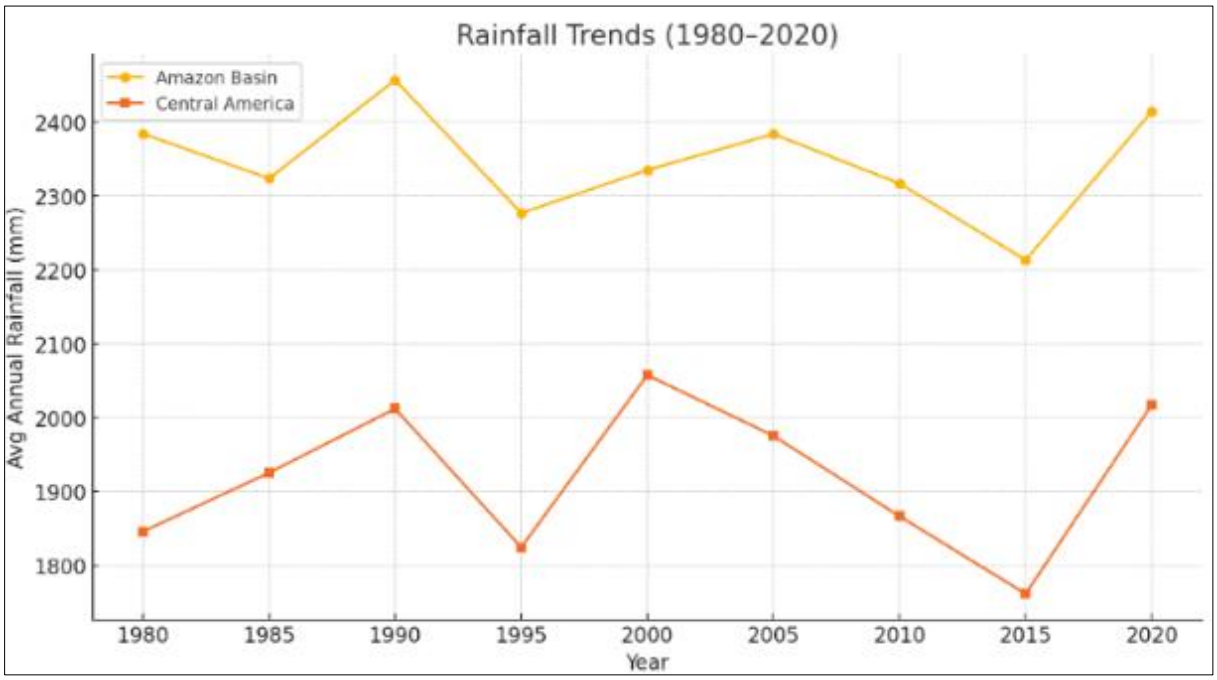

Figure 2 Climate Change Trends in the Amazon and Central America: Rainfall Trends (1980-2020)

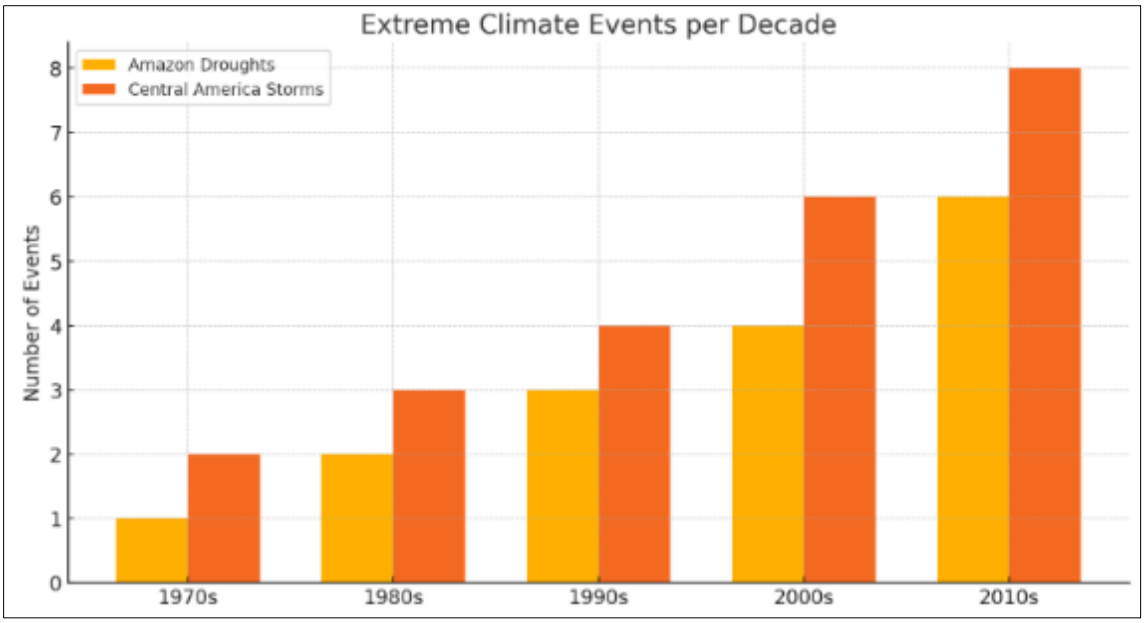

Figure 3 Increasing Frequency of Droughts in the Amazon and Storms in Central America

4. Impacts of Climate Change on Bird Diversity

Climate change poses a profound threat to bird diversity in tropical ecosystems, particularly in biodiversity hotspots like the Amazon Basin and Central America. Avian species in these regions are affected through multiple pathways, including habitat loss and transformation, phenological shifts, range contractions, and altered interspecific interactions. These pressures are compounded by ongoing land-use changes, leading to increased extinction risk for both resident and migratory birds [52].

4.1. Amazon Basin Case Study

The Amazon Basin, with its vertically stratified forest architecture and climatic heterogeneity, supports one of the most diverse avian assemblages in the world. This region is home to a complex mosaic of canopy, midstory, and understory guilds, with many species exhibiting high degrees of habitat specialization and endemicity. However, the increasing frequency of droughts, forest fires, and changing rainfall regimes has triggered marked ecological disruptions [53].

Research shows that habitat fragmentation and the degradation of forest edges primarily due to warming and altered precipitation disproportionately affect interior forest specialists such as antbirds (Thamnophilidae), woodcreepers (Dendrocolaptidae), and manakins (Pipridae). These species rely on the stable microclimates of mature forests for foraging and nesting. Repeated droughts have been shown to disrupt insect populations in the understory, leading to food scarcity and population declines among insectivorous birds [54]. For instance, a longitudinal study conducted near Manaus, Brazil, revealed significant reductions in the abundance of understory insectivores after recurrent drought and fire events between 2005 and 2015, highlighting the cumulative impact of climatic stressors on avian communities [55].

Additionally, many bird species are undergoing range shifts moving either to higher elevations or deeper forest interiors in an attempt to maintain suitable thermal niches. However, the Amazon's low topographic variation limits upward migration, and fragmented landscapes hinder dispersal, especially for non-migratory species with small home ranges. Species with limited physiological tolerance and poor dispersal abilities are thus increasingly vulnerable to local extirpations [56].

4.2. Central America Case Study

In Central America, the impacts of climate change on birds are further compounded by the region's role as a migratory bottleneck and its steep elevational gradients, which support distinct ecological zones within short distances. Rising temperatures and shifts in rainfall patterns have disrupted both resident and migratory bird populations [57].

Migratory songbirds such as flycatchers (Tyrannidae), warblers (Parulidae), and vireos (Vireonidae) are increasingly arriving earlier in the spring or delaying their autumn departures. This shift, known as a phenological mismatch, often

results in misalignment between the birds' reproductive cycles and the peak availability of insects or fruit, reducing chick survival and breeding success.

In montane regions, warming temperatures are driving cloud forests upward, shrinking suitable habitats for high-elevation specialists such as the Resplendent Quetzal (Pharomachrus mocinno) and Pink-headed Warbler (Cardellina versicolor) [58]. These birds often lack the mobility or adaptability to track these elevational shifts, especially where mountaintops or steep cliffs constrain further upward movement. In Guatemala and Costa Rica, range contractions for several cloud forest species have already been documented, accompanied by decreasing population trends [59].

Lowland and coastal forests, including mangrove habitats, are increasingly threatened by tropical storms, hurricanes, and sea-level rise. The intensification of storms observed over the past two decades has resulted in direct mortality of birds, destruction of nesting trees, and long-term alteration of vegetation structure [60]. Fragmentation and drying of these forests, particularly in Nicaragua and Honduras, have also reduced the number of viable stopover habitats for long-distance migrants. This is especially concerning for species that depend on a network of high-quality sites during their migrations, such as Swainson's Thrush (Catharus ustulatus) and Wood Thrush (Hylocichla mustelina) [61].

4.3. Shared Impacts Across Both Regions

While the Amazon and Central America differ in topography, ecosystem structure, and species composition, climate change has driven convergent impacts on bird communities in both regions:

- **Phenological Mismatches**: Changes in rainfall and temperature patterns have led to asynchronous timing between breeding and food availability. This mismatch is particularly harmful to insectivorous birds whose chicks depend on seasonal insect blooms [62].
- **Elevational Range Shifts and Habitat Compression**: As species move to higher or cooler areas, habitat becomes compressed, especially in mountainous regions where the available area decreases with elevation. This increases interspecific competition and may lead to local exclusions [63].
- **Increased Disease Susceptibility:** Warmer temperatures have expanded the altitudinal range of avian malaria and other parasites. Birds that have not historically been exposed to these diseases, such as those in highland forests, now face new pathogen pressures, as observed in Costa Rica's Talamanca Range and parts of the Andes [64].
- **Shifts in Community Composition**: Climate change, along with habitat degradation, is favoring generalist and invasive species over specialists and endemics. This trend leads to biotic homogenization, reducing the ecological uniqueness of tropical forests and weakening ecosystem resilience [65].
- **Reduced Reproductive Success**: Unstable weather conditions particularly prolonged droughts and heavy rainfall during nesting seasons have led to lower fledging success rates, increased egg predation, and nest abandonment [66].

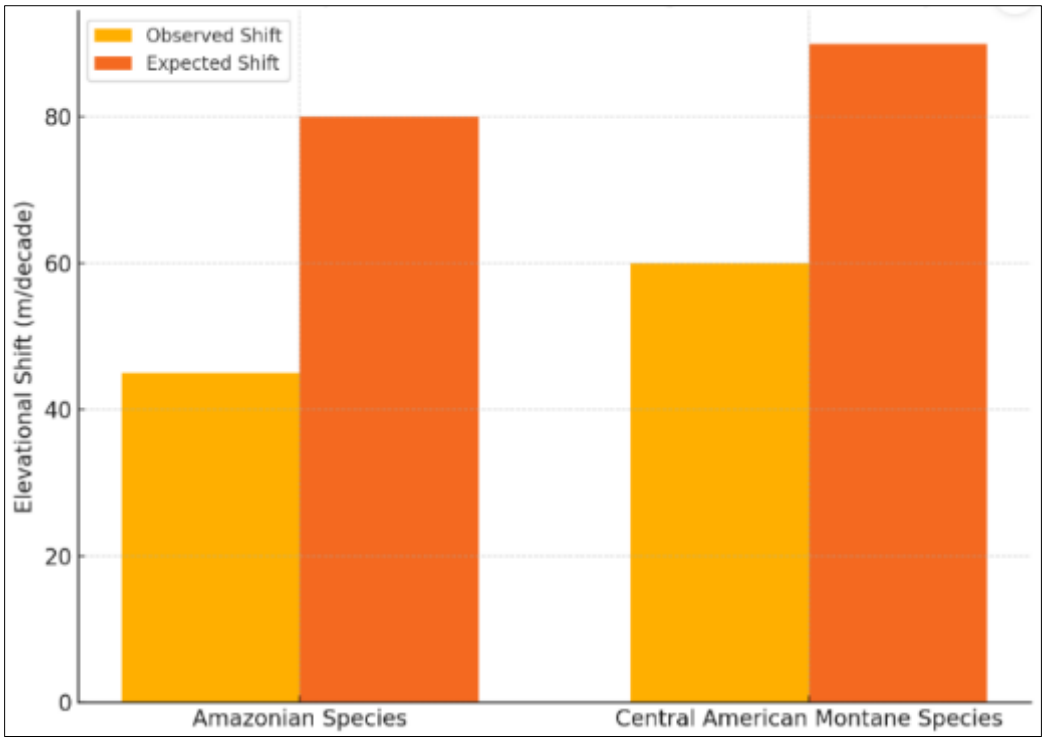

Figure 4 Comparison between Observed vs. Expected Elevational Range Shifts

5. Conservation and Mitigation Strategies

The accelerating pace of climate change and its compounding effects on avian biodiversity in tropical ecosystems demand proactive, integrated conservation and mitigation strategies. Both the Amazon Basin and Central America, while distinct in their ecological profiles and governance structures, face parallel challenges requiring locally adapted yet globally informed interventions [67]. The success of such efforts hinges on maintaining habitat connectivity, enhancing ecosystem resilience, fostering community participation, and embedding biodiversity considerations into broader climate policies.

5.1. Amazon Basin Approaches

The Amazon Basin, encompassing over six million square kilometers of tropical forest, remains a global priority for biodiversity conservation and climate regulation. In recent decades, conservation in the region has increasingly emphasized large-scale forest protection, landscape connectivity, and fire mitigation as central responses to climate-driven biodiversity loss [68].

A cornerstone of Amazonian conservation strategy has been the REDD+ mechanism (Reducing Emissions from Deforestation and Forest Degradation), which aims to provide financial compensation to governments, communities, and landowners for maintaining forest cover [69]. By engaging indigenous and local communities who often possess deep ecological knowledge REDD+ projects have shown promise in curbing deforestation while delivering co-benefits for biodiversity conservation, including the protection of critical bird habitats.

However, the efficacy of such initiatives is uneven. While protected areas like the Central Amazon Conservation Complex (CAC) in Brazil and the Yasuní National Park in Ecuador represent bastions of avian diversity, their isolation within a matrix of increasingly deforested landscapes can limit their effectiveness [70]. Fragmentation leads to edge effects that disproportionately impact forest-interior bird species and those with limited dispersal capacity. Landscape-scale restoration through the creation of forest corridors, buffer zones, and reforestation of degraded lands is essential for facilitating species movement in response to shifting climate envelopes [71].

Another growing concern is the increasing incidence of forest fires, often exacerbated by drought and land conversion for agriculture. Birds inhabiting the understory and ground layer, such as tinamous (Tinamidae) and antthrushes (Formicariidae), are especially vulnerable to fire-related habitat loss [72]. In response, countries like Brazil have

initiated early-warning systems, remote sensing technologies, and policy frameworks aimed at fire prevention and rapid response, though implementation remains inconsistent [73].

5.2. Central America Approaches

Central America's position as a biogeographic corridor and its relatively small land area make habitat connectivity and climate adaptation crucial for avian conservation. The region has pioneered community-based conservation models, underpinned by ecotourism, environmental education, and decentralized governance [74].

Initiatives such as the Mesoamerican Biological Corridor (MBC) represent a regional effort to conserve biodiversity by maintaining ecological connectivity across eight countries from southern Mexico to Panama [75]. The MBC facilitates the movement of migratory species, including many Neotropical migrants that breed in North America and winter in Central American forests [76]. Its success, however, varies depending on national commitment and funding continuity.

Costa Rica stands out for its Payments for Environmental Services (PES) program, which incentivizes private landowners to conserve or restore forests, thereby supporting avian habitats indirectly through improved forest structure and reduced fragmentation [77]. These payments are funded through a national fuel tax, demonstrating a creative policy linkage between fossil fuel consumption and ecosystem conservation.

In highland regions, reforestation and agroforestry efforts have proven critical for combating the "elevational squeeze" faced by montane bird species [78]. For example, the restoration of native tree species in the Talamanca Highlands has facilitated the return of high-elevation specialists like the Resplendent Quetzal (Pharomachrus mocinno), providing breeding and foraging resources in formerly degraded areas [79].

However, the region's conservation effectiveness is challenged by limited enforcement capacity, land tenure conflicts, and political instability in certain countries, including Honduras, Nicaragua, and Guatemala [80]. These limitations undermine the sustainability of conservation gains and increase the vulnerability of bird populations to both climatic and anthropogenic pressures.

5.3. Shared Mitigation Priorities

While ecological contexts differ, both regions share several key priorities for mitigating the impacts of climate change on bird diversity. These include:

- **Strengthening and Expanding Protected Area Networks**: Existing reserves must be expanded and better managed to accommodate species' climate-driven range shifts. Climate corridors should be embedded into reserve design to facilitate ecological migration [81].
- **Mainstreaming Biodiversity into National Climate Policy**: Conservation goals must be integrated into Nationally Determined Contributions (NDCs) and climate adaptation frameworks, ensuring that mitigation strategies do not unintentionally harm critical habitats [82].
- **Long-Term Ecological Monitoring**: Sustained monitoring of bird populations and their ecological parameters is vital for detecting early signs of climate stress and guiding adaptive management [83].
- **Community-Based Adaptive Management**: Involving indigenous peoples and local communities (IPLCs) in co-management fosters social equity and enhances ecological outcomes. Community monitoring can also improve data coverage in remote areas [84].
- **Global Emission Reductions**: Ultimately, global climate mitigation particularly through decarbonization of energy systems and reduced land-use emissions is indispensable. Without stabilizing global temperature increases, even the most robust conservation efforts may prove insufficient in halting biodiversity decline [85].

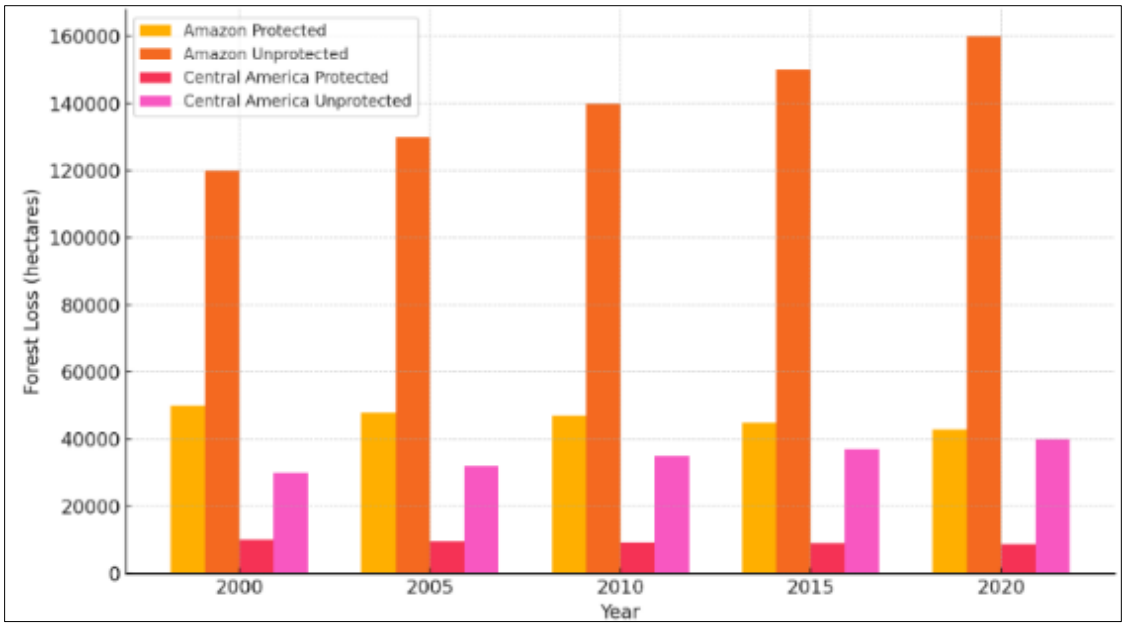

Figure 5 Forest Loss in Protected vs Unprotected Areas in the Amazon and Central America (2000-2020)

6. Knowledge Gaps and Future Research

Despite growing awareness of the profound implications of climate change on avian biodiversity, substantial knowledge gaps persist especially in the ecologically complex and data-poor regions of the Amazon Basin and Central America. These gaps hinder the ability of conservationists, policymakers, and researchers to design targeted, science-based responses to emerging threats. A comprehensive understanding of these limitations is essential to inform future research priorities and conservation planning.

6.1. Insufficient Long-Term Monitoring

A fundamental obstacle in climate biodiversity research in the tropics is the lack of consistent, long-term ecological datasets. Although landmark initiatives such as the Biological Dynamics of Forest Fragments Project (BDFFP) in Brazil have provided valuable insights into fragmentation and species persistence, such studies are few and geographically limited. Large portions of the Amazon Basin and Central America particularly remote, seasonally flooded forests, montane zones, and dry forest ecosystems remain biologically under-inventoried [86].

This data scarcity undermines the detection of trends in population decline, range shifts, and phenological changes. Moreover, the absence of temporal depth in many studies impedes the attribution of observed ecological changes specifically to climate change, as opposed to other concurrent anthropogenic factors.

6.2. Underrepresentation of Tropical Species in Climate Models

Most species distribution models (SDMs) and climate impact assessments rely on data derived from temperate regions, where species tend to have broader climatic tolerances and more flexible ecological niches. Such assumptions often do not translate well to tropical birds, which frequently exhibit narrow thermal limits, strong habitat specificity, and high sensitivity to microclimatic variation [87].

Without incorporating physiological, behavioral, and demographic data specific to tropical species, predictions about species persistence, range shifts, and extinction risk remain imprecise. For instance, SDMs may overestimate adaptive capacity or dispersal ability, leading to underestimations of vulnerability. There is a critical need for region-specific modeling frameworks that integrate fine-scale climate data, species-specific traits, and biotic interactions [88].

6.3. Interactions with Other Environmental Threats

Climate change does not operate in isolation. Rather, it interacts synergistically with other environmental stressors including deforestation, agricultural expansion, mining, urbanization, invasive species, and pollution to compound

threats to avian populations [89]. However, studies that explicitly explore these cumulative or interactive effects remain scarce.

For example, how does forest fragmentation alter the microclimatic buffering capacity of habitats during drought events? What is the combined impact of increasing fire frequency and logging on cavity-nesting birds? Such multifactorial dynamics are likely more representative of real-world conditions but are often underrepresented in empirical research and models.

6.4. Gaps in Migratory Bird Research

While some progress has been made in understanding migratory bird responses to climate change, much of this research is biased toward well-known North American breeders such as warblers (Parulidae) and tanagers (Thraupidae) [90]. Lesser-known Neotropical migrants and intra-tropical migrants remain poorly studied, especially those that do not breed in temperate zones.

Moreover, there is a critical lack of data on stopover ecology, wintering habitat use, and phenological shifts in migration timing and breeding across Central America. The deployment of advanced tracking technologies such as GPS telemetry, automated radio telemetry (e.g., Motus Network), and stable isotope analysis remains limited due to logistical and financial constraints. Expanding the use of such tools would provide much-needed insights into movement ecology, habitat connectivity, and climatic thresholds for migratory birds.

6.5. Socioecological and Cultural Dimensions

Climate change impacts on birds are also mediated by human systems, yet the socioecological aspects of avian conservation are seldom explored in tropical research. Local communities, especially indigenous and rural populations, often act as de facto stewards of tropical forests. However, their perceptions of climate change, cultural values regarding birds, and adaptive capacities are not sufficiently incorporated into research frameworks.

Studies examining how climate-driven changes in bird abundance affect ecosystem services, livelihoods, or traditional knowledge systems could significantly inform community-based conservation strategies. Integrating social science methodologies including ethnography, participatory mapping, and political ecology into ornithological research can enhance the relevance and uptake of conservation interventions.

6.6. Future Research Directions

To overcome the aforementioned challenges and advance climate-resilient conservation, future research should prioritize the following strategies

- **Expand Long-Term Monitoring Networks**: Establish and support long-term observatories and transects across underrepresented biomes, incorporating elevational, latitudinal, and seasonal gradients to capture spatiotemporal dynamics.
- **Improve Model Precision with Local Data:** Incorporate species-specific physiological and ecological traits into predictive models, and calibrate SDMs using regionally relevant climate scenarios.
- **Address Multistressor Interactions**: Design experimental and observational studies that jointly assess the impacts of climate and other anthropogenic pressures, such as land-use change and invasive species.
- **Enhance Migratory Bird Tracking**: Broaden the taxonomic and geographic scope of migratory bird research, utilizing modern tracking tools and encouraging cross-border data sharing and collaboration.
- **Foster Interdisciplinary Approaches:** Promote transdisciplinary research that bridges natural and social sciences, linking ecological processes with governance, policy, and community resilience.
- **Support Citizen Science and Community Monitoring:** Leverage the potential of citizen science platforms, such as eBird and iNaturalist, to fill data gaps while fostering public engagement and local capacity

7. Conclusion

Climate change represents a profound and escalating threat to avian diversity in tropical ecosystems, with the Amazon Basin and Central America among the region's most acutely affected. Rising temperatures, altered precipitation regimes, and an increase in the frequency and intensity of extreme weather events are already reshaping habitats, disrupting migratory and breeding cycles, and jeopardizing the survival of both endemic and migratory bird species.

Across both regions, a consistent pattern emerges: species with narrow ecological niches, limited dispersal abilities, and strong dependencies on stable forest microclimates are disproportionately vulnerable. Although some generalist and climate-tolerant species may persist or even expand their ranges, these gains are insufficient to counterbalance the broader trends of community homogenization, local extinctions, and declining functional diversity.

Mitigating these impacts demands a multifaceted response. Key strategies include expanding and strengthening protected area networks, restoring habitat connectivity through ecological corridors, integrating climate adaptation into biodiversity planning, and promoting sustainable land-use practices. Crucially, these ecological interventions must be coupled with inclusive governance frameworks that center the rights, knowledge, and stewardship of local and Indigenous communities.

The review also underscores the urgent need to close critical knowledge gaps particularly in the areas of long-term ecological monitoring, species-specific climate modeling, and the interaction between climate and other anthropogenic stressors. Greater integration of socioecological research, advanced tracking technologies, and community-based science will be essential to building more responsive and resilient conservation strategies.

Tropical birds are not only keystone components of ecological function facilitating seed dispersal, pollination, and insect regulation but also hold deep cultural, aesthetic, and scientific value. Their decline signals more than a biodiversity crisis; it reflects a broader unraveling of ecosystem integrity under climate stress. Protecting these species in an era of rapid environmental change requires renewed global cooperation, sustained scientific investment, and a long-term commitment to equity and ecological sustainability.

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